AN ANALYSIS OF A WORLDWIDE STATUS FOR MONITORING AND ANALYSIS OF DAM DEFORMATION

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PREFACE

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PREFACE

This technical report is a reproduction of a report submitted in partial fulfillment of the requirements for the degree of Master of Engineering in the Department of Surveying Engineering, November 1992. The research was supervised by Dr. Adam Chrzanowski, and funding was provided partially by the Natural Sciences and Engineering Research Council of Canada.

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ABSTRACT

The primary role of dam deformation surveys is to examine regularly the conditions of the dam and its overall safety. The state of monitoring programs has been a growing concern by many countries and professional groups at the national and international levels. Canada is no exception. Canada's dams are generally characterized as having poorly designed monitoring systems and inadequate instrumentation. Today, this is no longer considered justifiable. This research is one of a series of steps in an attempt to rectify this situation. It was initiated as the initial *stepping stone* to a formalized set of proposed guidelines form which monitoring specifications can be written for each individual dam. The work is based on a collection of material from questionnaire forwarded to 79 member organizations of the International Commission of Large Dams (ICOLD) and from available literature on the monitoring and analysis of dam deformation (mainly ICOLD Bulletins, and reports of the International Federation of Surveyors (FIG) Study Group on Deformation Measurements).

One of the major conclusion of the survey is that Surveying Engineers have had very little involvement in dam deformation. One of the reason suggested is that Survey Engineers may not be promoting or educating themselves adequately in the field of dam deformation. Consequently, this lead to the subsequent objective: to take the initiative to attempt to improve this situation by providing junior Surveying Engineers with example of the major types of large dams ($h > 15$ m) and the basic principles on their behaviour, and the methods used to monitor and analyze their deformations.

Some of the other key issues that have resulted from this research include: (1) there is obvious lack of communication and/or understanding amongst profession in the field of deformation, (2) the realization of the proposed monitoring guidelines is largely dependent on having a legislation in place to enforce monitoring of all large dams, (3) Canada is the single leading country in the development of a global integration technique which utilizes both geodetic and geotechnical observables into a simultaneous deformation analysis, and (4) the successful implementation of new developments in the field of deformation measurements supports the need to continue on using both geodetic and geotechnical means in modelling dam deformation.

In support of the monitoring guidelines this research recommends the need for further studies to determine the frequency and accuracy requirement of the observables, and the minimum number and type of instruments that must be included in all the major types of large dams.

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CHAPTER 1

INTRODUCTION

1.1 Background Information

According to the International Commission on Large Dams (ICOLD) (1977), a major international organization that is involved in all aspects of dam safety and construction, a large dam is either:

(1) above fifteen meters in height, measured from the lowest portion of the general foundation area to the crest, or

(2) between ten and fifteen metres in height, provided that it complies with at least one of the following conditions:

  (a) the length of the dam's crest is greater than or equal to 500 metres,

  (b) the capacity of the reservoir formed by the dam is greater than or equal to one million cubic metres,

  (c) the maximum flood discharge of the dam is greater than or equal to 2000 cubic metres per second,

  (d) the dam has especially difficult foundation problems, or

  (e) the dam is of an unusual design.

There are over 36,000 large dams in the world today. It is common knowledge among the Engineering Profession that dam safety is seriously affected by the aging of the structure. Today, this is of great concern since many dams in the world are more than 50 years old. In addition, on the average, dams are being built at a rate of 337 per year, excluding China, and it is estimated that by the year 2000 the total number will increase to well over 40,000, by which almost 90% will be over 20 years old (*World Register of Dams*, 1988; Laffite, 1990). Unlike most engineering structures that can be subjected to test loads, dams are first tested under actual loads, the first time being during the initial filling of the reservoir (Thomas, 1976). Dams are constantly subject to displacement and deformation due to internal and external loads that cause deformation and permeability of structure and its foundation. The resulting abnormal changes in dams are much more dangerous and complex than in most other engineering structures. In order to recognize these changes as early as possible, it is essential that engineers and dam owners monitor them to ensure that the destructive potential restrained by the dam does not increase with time. Instrumentation is a means of providing information on how the dam is performing and with this information remedial measures, if required, can be implemented in a timely fashion to avoid serious damage.

Deformation monitoring, analysis, and prediction of dams have been a growing concern by many countries and professional groups at national and international levels. Among the most active organizations which are directly or indirectly involved with the development of new methods and techniques for the monitoring and analysis of dam deformation are (CANCOLD, 1992a; Chrzanowski et al., 1992):

1. **ICOLD**. ICOLD is a formal, non-government association of national dam

engineering groups (e.g., the Canadian National Committee on Large Dams (CANCOLD)) which provides a forum for exchange of knowledge, experience and new ideas in dam engineering. The ICOLD consists of approximately 5,000 specialists from approximately 80 national memberships and has been concerned with dam safety throughout the world since its constitution in 1928. These specialists include practising engineers, geologists, and scientists from governmental and private organization, consulting firms, universities and construction companies. The organization has long recognized the necessity for having proper control on the design, construction, operation and maintenance of dams. Since the late sixties ICOLD has focused on subjects such as dam safety, monitoring and performance, and reanalysis of older dams. Major problems or new developments are dealt with in depth by the ICOLD Technical Committees, each ultimately contributing to the enhancement of dam safety. The committee which deals specifically with monitoring of dams is the Committee on Monitoring of Dams and their Foundations.

2. **International Federation of Surveyors (FIG).** The FIG's Study Group 6C has significantly contributed to the recent development of new methods for the design and geometrical analysis of integrated deformation surveys and new concepts for global integrated analyses and modelling of deformations. This work was accomplished by an *ad hoc* Committee on Deformation Analysis chaired by Dr. A. Chrzanowski from the Surveying Engineering Department at the University of New Brunswick (UNB). The work of the *ad hoc* committee

is summarized in four progress reports (Chrzanowski et al., 1981; Heck et al., 1982; Chrzanowski and Secord, 1983; Chrzanowski and Chen, 1986) and the final report by Chrzanowski and Chen (1990). The work of the committee resulted in a development of the *UNB Generalized Method* which has been successfully applied to deformation analyses of earthfill and concrete dams in Canada (Mactaquac hydro-electric power generating station in Fredericton, New Brunswick) and abroad (USA, Venezuela).

Although dam failures are usually sudden, it should in the majority of the cases be possible to predict when conditions might become serious. The necessity for observing the behaviour of dams has been recognized by engineers for over a century. Noted is the 25 metre high Remscheid Dam in Germany in 1894 where the crest of the dam was noted to deflect 27 millimetres during filling of the reservoir (Thomas, 1976). Furthermore, the need for monitoring systems and precise surveillance surveys on dams was expressed to the Civil Engineering Profession in 1967 during the conference of the ICOLD in Istanbul, Turkey (Keene, 1974). There is an obligation on the owner of any dam to ensure himself and the public that the structure behaves in accordance with the design, both at initial filling of the reservoir and in the long term (Thomas, 1976). Dam safety has always been fundamental to the Engineering Profession and concerns about potential failures are increasingly important because of the growing concentration of population in downstream areas (IWP & DC, 1989a).

ICOLD recommends that inspection and monitoring should be considered as a regular professional review of the dam; it should be concerned with the adequacy and safety of the dam in accordance with the state of the art at that particular time, as well as with measurements made on the dam (and foundations) to determine any predicted or extraordinary behavioral trends (Thomas, 1976).

1.2 Aim of the Report

Despite the works and the involvement of Canadians within FIG and ICOLD, Canada's dam safety programs, in general, are still characterized as having poorly designed monitoring schemes, inadequate instrumentation, lack of calibration facilities, insufficient accuracy of measurements and out-dated methods in the geometric analysis of deformation measurements (Chrzanowski, 1990). According to members of the Topographic Engineering Centre (TEC) of the U.S. Army Corps of Engineers (COE) a similar situation exist in the United States (Frodge, 1992a). This is considered unjustifiable and it was therefore decided that some form of action was required to attempt to rectify this situation. As a result, this research was initiated as the initial *stepping stone* to a formalized set of guidelines from which monitoring specifications can be written for each dam, for both new and existing sites. Thus, the primary aim of this report has been to collect relevant information and references on existing resources, standards and procedures for dam deformation surveys which can be used to initiate these guidelines.

This report is based on a collection of material from a questionnaire forwarded to 79 ICOLD member countries and from available literature on the monitoring and analysis of dam deformations within these countries (mainly ICOLD Bulletins and Congresses, and reports of the FIG Study Group on Deformation Measurements). The questionnaire asked for the following information:

(1) Updated number of existing dams. How many of them are being monitored using geodetic and/or geotechnical/structural instrumentation?

(2) Existing national and/or local standards and specifications for dam monitoring

(3) Publications either in technical journals or proceedings of conferences which describe monitoring of dam in the given country.

Twenty nine (37%) responded to the survey. Detailed summaries proposed by the authors are attached as Appendix I. The analysis of the summaries is presented in Chapter 3 and it is organized in such a manner that the information can be used directly to achieve the primary aim of this report.

Part of this report has been included in the UNB Report on Existing Resources, Standards and Procedures for Precise Monitoring and Analysis of Structural Deformations for the COE (Chrzanowski et al., 1992). The COE acknowledges this work and has come to recognize that a multidisciplinary effort is required in establishing unified guidelines for monitoring and analysis of structural deformations.

Various experts on deformation analysis have experienced that too often even within the same organization or institution one may find examples of two different professional groups, for instance Geotechnical and Survey Engineers, who will work on the same structure but do not exchange information on their methods and results of their analysis. Ironically, the other extreme is that Survey Engineers have had limited involvement in dam deformation surveys and when they have been involved, their professional opinion at times has been ignored or even explained as being erroneous (e.g., Waco Dam failure in Texas; Stroman and Karbs, 1985). According to the survey this still holds true today in over 86% of the countries that responded. While there may be a number of reasons for this, the results of this survey suggest that the major ones are: (1) lack of communication or understanding regarding the capabilities among the professions involved, and (2) Survey Engineers not promoting or educating themselves adequately in the field of dam deformation.

Thus, the subsequent purpose of this report is to take the initiative to attempt to improve this situation by exposing Survey Engineers (especially at the junior level) to the major types of large dams existing in the world today and provide them with the basic principles on their behaviour, the factors effecting their normal behaviour and the primary methods used to monitor their behaviour. This information is presented in Chapter 2. A summary, conclusion and recommendations are included in Chapter 4.

Note that a description of the methods and instrumentation used by each country is beyond the scope of this report. Some background information on the major types of monitoring systems and methods of data analyses are given in Chapter 2. In most cases this information can be obtained from the references provided. The reader is cautioned when judging the general status of monitoring surveys from the national reports and answers to the questionnaire. The reports are often based on a few selected examples, perhaps the best instrumented or best analyzed dams, which can create a very optimistic picture in comparison with the real situation (Chrzanowski et al., 1992). Canada and USA are no exception.

As a whole, the report does not claim to be complete: it does not include all of the countries surveyed and the information from untranslated foreign documents collected from the survey. However, it should portray the current world situation with respect to the techniques and data analysis used to monitor the deformation of the major types of large dams.

CHAPTER 2

MAJOR TYPES OF LARGE DAMS: THEIR BASIC BEHAVIOUR AND PRINCIPLES USED TO MONITOR AND ANALYZE THEIR DEFORMATIONS

2.1 General

As aforementioned, the intent of this chapter is to provide Surveying Engineers (particularly junior engineers) with some basic knowledge and background on: (1) the most common types of large dams that exist in the world today, (2) how these dams generally behave, and (3) some of the most significant quantities that need to be monitored. Also, included is a brief discussion with examples of the instrumentation, monitoring systems (e.g., geodetic, geotechnical and structural) and the basic methods of analyses (e.g., geometrical and physical) that are used to analyze the deformation of a large dam.

2.2 Dam Types

The two major types of large dams existing in the world today are embankment and concrete (or masonry). Table 2.1 illustrates that in 1988 large embankment dams represented 82.7% (29,974) of the world's total large dams (36,235) and that Canada, with about 608 large dams, ranked amongst the top ten in the world (*World Register of Dams,* 1988). Historians have shown that the technology of dams have a long history dating as far back as 5,000 years (Thomas, 1976).

Due to the differences in construction materials, the behaviour of concrete dams is significantly different from that of embankment dams. In concrete dams, deformation is assumed to be elastic and any permanent deformation may be caused either by the adaptation of the foundation to the new load, aging of concrete, or foundation rock fatigue. In the case of embankment dams the deformation is usually permanent. Permanent vertical settlement of the fill material continues at a decreasing rate for decades after construction, while permanent horizontal deformation of the embankment is caused by the reservoir water pressure. Furthermore, the deformation values vary considerably between the two types; millimetres or centimetres for concrete, and centimetres or decimeters for embankment dams.

Table 2.1
Number of Dam Types by Country
(after *World Register of Dams*, [1988, pp.19-21])

ICOLD Member Countries	**Dam Types**				
	Embankment	**Concrete/Masonry**			**Total**
		Gravity	**Arch & Multiple Arch**	**Buttress**	
1. China	17,473	539	785	23	18,820

ICOLD Member Countries	**Dam Types**				
	Embankment	**Concrete/Masonry**			**Total**
		Gravity	**Arch & Multiple Arch**	**Buttress**	
2. USA	4,694	537	192	36	5,459*
3. Japan	1,484	674	52	18	2,228
4. India	998	138	1	-	1,137
5. Spain	151	515	47	24	737#
6. Korea (Rep of)	675	15	-	-	690
7. Canada	387	195	9	17	608
8. UK	413	91	17	14	535
9. Brazil	391	107	8	10	516
10. Mexico	343	144	11	5	503
Remaining 69 Countries	2,965	1,225	611	201	5,002
TOTAL (%)	**29,974 (82.72)**	**6,261 (17.28)**			**36,235**

Note:

* According to the *United States Committee on Large Dams (USCOLD) Register of Dams* the current total is 5,469 dams (Sharma, 1992).

As of December 1991 Spain had a total of 1,031 dams (Yagüe, 1992)

2.2.1 Embankment Dams

ICOLD (1977) defines an embankment dam as any dam constructed of natural excavated material or industrial waste material placed without the addition of binding materials other than those inherent in the natural material. In the past, and to some extent at present, embankment dams have been constructed from the most readily available materials such as loose rock, gravel, sand, silt, mine or industrial waste, rock flour and clay. The fill material is placed with sloping sides and with a length greater than its height. These dams are most suited in areas where the foundation material is of earth or sand, or where the materials for construction are so expensive that an embankment type of dam is more economical. ICOLD (1977) categorizes embankment dams as:

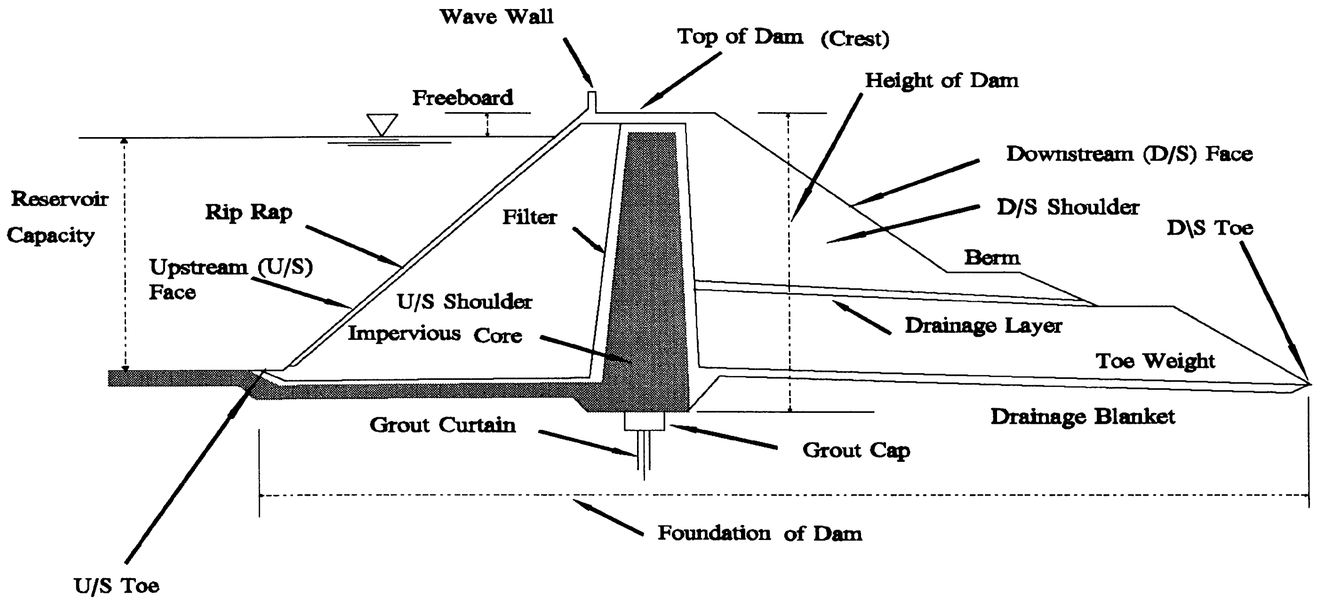
1. **Earth Dam or Earthfill Dam.** An embankment dam with more than 50% of its total volume formed of compacted, fine-grained material obtained from a burrow area.
2. **Rockfill Dam.** An embankment dam with more than 50% of its total volume comprised of compacted, crushed or dumped pervious natural stone.
3. **Hydraulic Fill.** An embankment dam constructed of materials, often dredged, which are transported and placed by suspension in flowing water.

Advances in the science of soil and construction methods have led to the design of very diversified and complicated types of embankment dams. For example, an embankment dam can be a mine tailing dam which is a special type of hydraulic fill dam that is constructed from waste materials from mining operations. Embankment dams are usually zoned in some manner, such as an impermeable zone (core) supported by the balance of the embankment (see Figure 2.1a) to ensure safety in terms of strength, control of seepage and control of cracking. In remote areas, the rockfill dam with an impervious core of natural material is perhaps the most widely used type of embankment dam, mainly because the cost of imported materials, such as cement, is very high. It is not difficult to understand that embankment dams must not be considered as simple structures. Each dam is unique; its water tightness and stability are directly related to the materials used for construction and the materials upon which it is founded. Figures 2.1a and 2.1b illustrate some typical cross-sections of embankment dams (Thomas, 1976).

Impervious cores and homogeneous earth dams are considered the most important components in embankment dam safety (Combelles, 1991). In general, the main problems associated with embankment dams are as follows: (1) seepage through the dam or through the foundation, causing pore water pressures in the fill and the foundation, (2) settlement of dam and/or foundation, (3) deformations due to internal and/or external stresses, and (4) slope stability (both upstream and downstream). In fact the most dangerous process in embankment dams is piping (the progressive development of internal erosion by seepage, appearing downstream as a hole discharging water), which may be caused by cracking and fines entrainment. This may occur because of an inadequate downstream filter behind the core, or because the earth in a homogeneous dam does not possess the necessary healing properties (Combelles, 1991). In many cases dam failure due to piping is reputed to be quick, but there have been cases where visible sand deposits at the toe of the embankment dam had shown that piping had already begun for some period of time (Bonazzi, 1990).

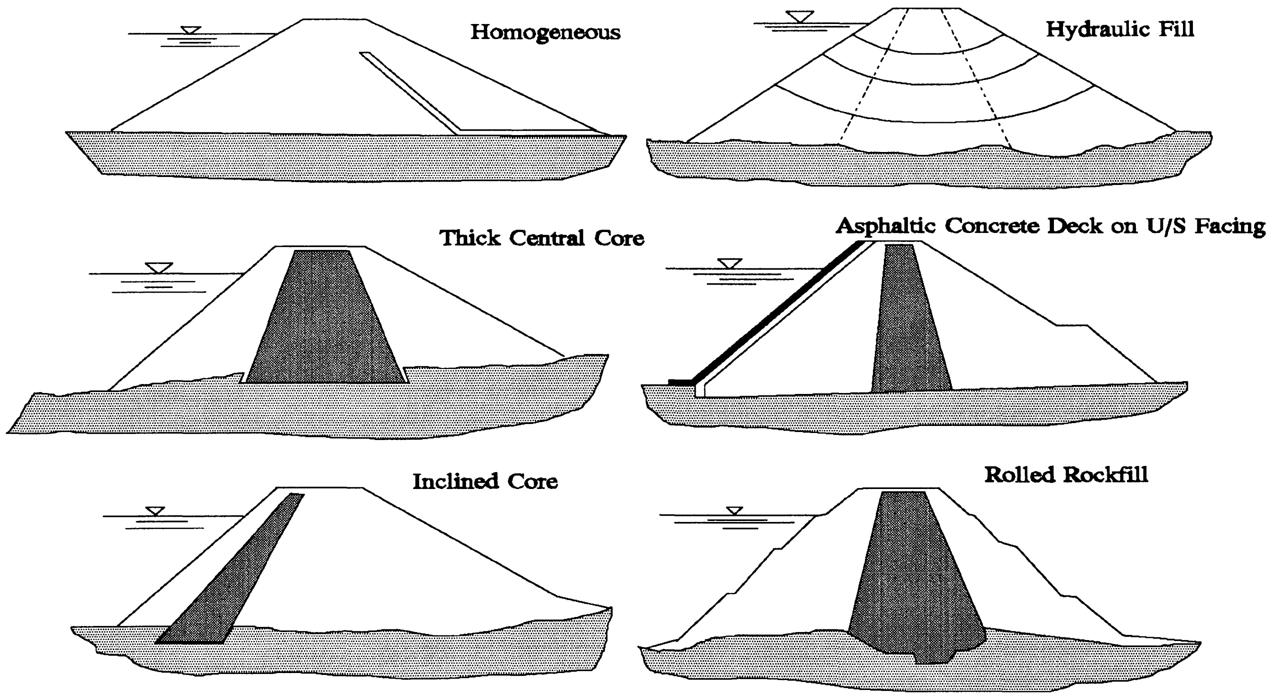
At the ICOLD's XIV Congress, Mr. Budweg of Brazil provided some statistical data on dams which had deteriorated or failed in the past. These statistics showed that embankment dams had the highest rate of failure (IWP & DC, 1982). This trend was further confirmed in 1989 by a U.S. survey of 5,500 large dams which showed that 90%

Figure 2.1a



DETAILED CROSS-SECTION OF EMBANKMENT DAM
(from ICOLD, [1977, p. 62])

Figure 2.1b



TYPICAL CROSS-SECTIONS OF EMBANKMENT DAMS
(after ICOLD, [1977, pp. 66-67])

of dam accidents involved embankment dams. About 50% of these accidents originated in the foundation and nearly 25% were caused by a piping mechanism (IWP & DC, 1989a).

At a conference in the Federal Republic of Germany under the topic of "Re-assessing the Safety of Dams in Europe" (IWP & DC, 1990), it was recommended that the most important conditions to be monitored in embankment dams are: (1) general deformations in the dam and abutments, (2) local deformation in the dam or underground (including settlements), (3) internal pressures, especially in the core and in the body of the dam and if possible, underground, and (4) the amount and chemical composition of the seepage water.

2.2.2 Concrete Dams

There are three basic types of concrete or masonry dams: Gravity Dams, Arch Dams and Buttress Dams. The major problem in concrete dams is cracking, and one which engineers are continuously trying to understand. Cracking is always a concern to dam operators but it only affects safety if it disrupts the transmission of shear stress (Combelles, 1991). The main causes of cracks are (IWP & DC, 1989a):

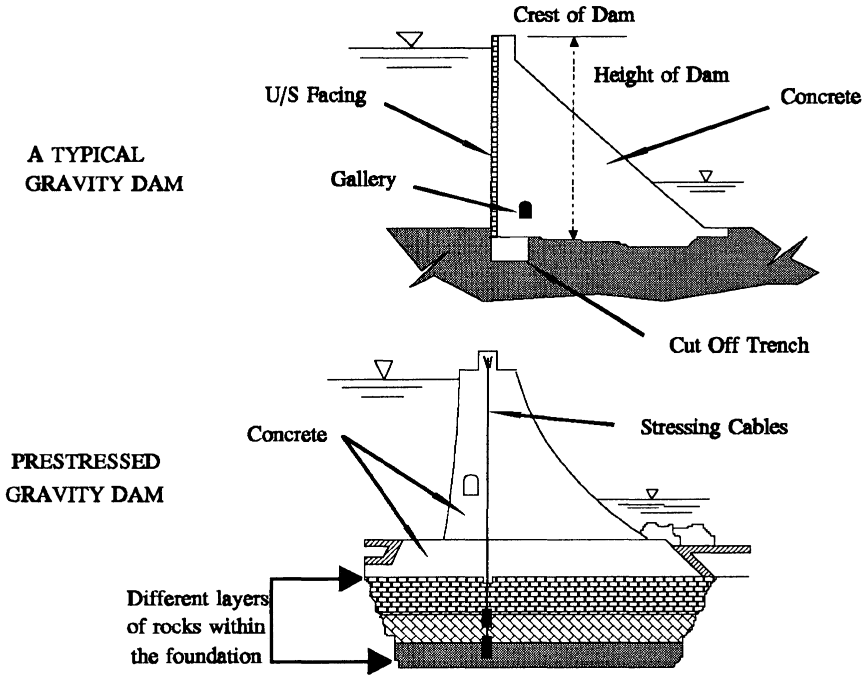
1. *Internal* causes such as hydration heat (resulting in shrinkage) or alkali silicate reaction (resulting in swelling).
2. *External* causes such as change in temperature, foundation settlement, and dynamic loads (e.g. earthquakes).

From experience, the French have found that practically all problems in concrete dams are related to volume changes (shrinkage or swelling). Concrete is a very fragile material and a global or localized volume change induces tensile stresses which cause cracking and eventually leakages and associated complications. Some concrete dams have also been damaged by deformation of their abutments, such as the Zeuzier in Switzerland, but it was determined that this was a far less frequent occurrence than concrete swelling or shrinkage (IWP & DC, 1990).

In one case in Norway, the operation of the floodgates had become difficult because of the swelling of the concrete pillars. It was confirmed that alkali-aggregate reaction had taken place at the dam and because of the low mean temperatures, the chemical reaction was so slow that it had taken approximately twenty years for the cracking to become visible (IWP & DC, 1990). A similar example in Canada occurred at the Mactaquac Dam in Fredericton, New Brunswick. In the mid 1970s, an opening of a vertical construction joint was noticed upstream from the turbine/generator blocks in the powerhouse. Although a number of theories were put forward to explain the abnormal structure deformations and behaviour of the concrete, alkali-aggregate reaction was determined to be the prime cause of the deformation (Chrzanowski et al., 1991).

2.2.2.1 Gravity dams

ICOLD (1977) defines gravity dams as those constructed of concrete, zoned concrete and/or masonry and which rely on their weight for stability. Gravity dams have more or less a triangular cross-section (see Figure 2.2), with the base width related to the height as to ensure stability against overturning, sliding, or foundation crushing. In effect, the



TYPICAL CROSS-SECTIONS OF GRAVITY DAMS
(from Thomas, [1976, pp. 245-272])

Figure 2.2

force of the water is retained by the massive weight of the masonry or concrete which develops a shearing resistance between the dam and the foundation. Gravity dams are normally categorized as curved gravity dams (curved in plan), arch-gravity dams (arch dams which are only slightly thinner than gravity dams), hollow gravity dams or cellular gravity dams (gravity dams of hollow construction), ogee dams (overflow dams or weirs where the crest, the downstream slope and the bucket have an S form of curve in cross-section) and, depending on their construction, special gravity dams (ICOLD, 1977). To further improve their stability, gravity dams and other concrete dams may be constructed from prestressed or post tension concrete. However, due to the uncertainties concerning the corrosion of steel in cables which are embedded in concrete, relatively few new dams have been designed and built as prestressed dams (Thomas, 1976). Solid gravity dams are the most popular type, except when narrow canyon width makes the arch-type dams preferable.

Gravity dams are often curved, with an upstream radius ranging between 350 and 400 metres for aesthetic reasons, to increase the discharge capacity (e.g., a radius of 250 metres increases the crest length by about ten percent), and to provide an additional factor of safety against ultimate failure. In addition, gravity dams and other concrete dams contain galleries (see Figure 2.2) to provide access for inspection, to monitor behaviour of the dam, and to perform remedial work, if necessary (Thomas, 1976).

In gravity dams the expansion joints between blocks of concrete are much weaker than the mass of the concrete. Any indication of loss of structural integrity in the dam or the foundation will manifest itself at the joints. Therefore, where the movement is anticipated instrumentation should be installed to monitor both relative movement between the blocks and absolute movement of each block with respect to a fixed point outside the area of influence (Bartholomew and Haverland, 1987).

According to IWP & DC (1990), the most important conditions to monitor in gravity dams are: (1) uplift pressure, (2) general and local deformations in the dam and the abutment, (3) overall temperature (to help interpret the deformations), and (4) the amount and chemical composition of the seepage water.

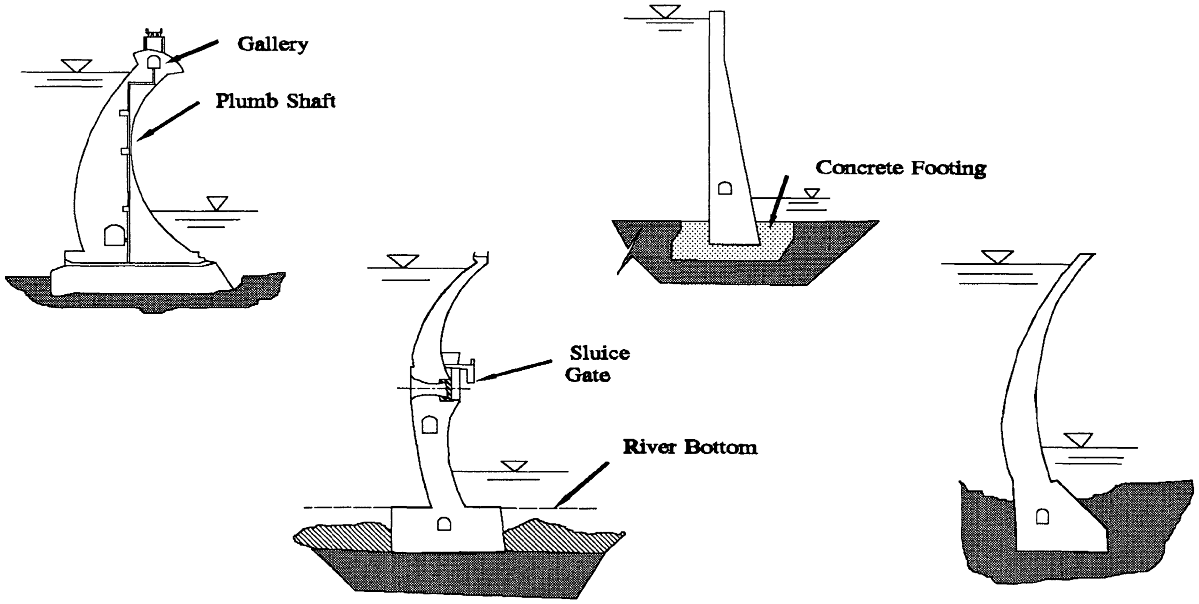
2.2.2.2 Arch dams

By definition, an arch dam is a concrete or masonry dam with its base thickness less than 0.6 times its height (h). It is curved in plan to allow a transfer of the major forces from the water load to the abutments (ICOLD, 1977). The configuration of an arch dam continues to undergo modifications to improve its structural strength and aesthetic appeal. Like most engineering structures, there are no standard shapes; the trend is to obtain the most economically safe solution (Thomas, 1976). Figures 2.3a and 2.3b depict some typical cross-sections and an example of a complete layout of an arch dam.

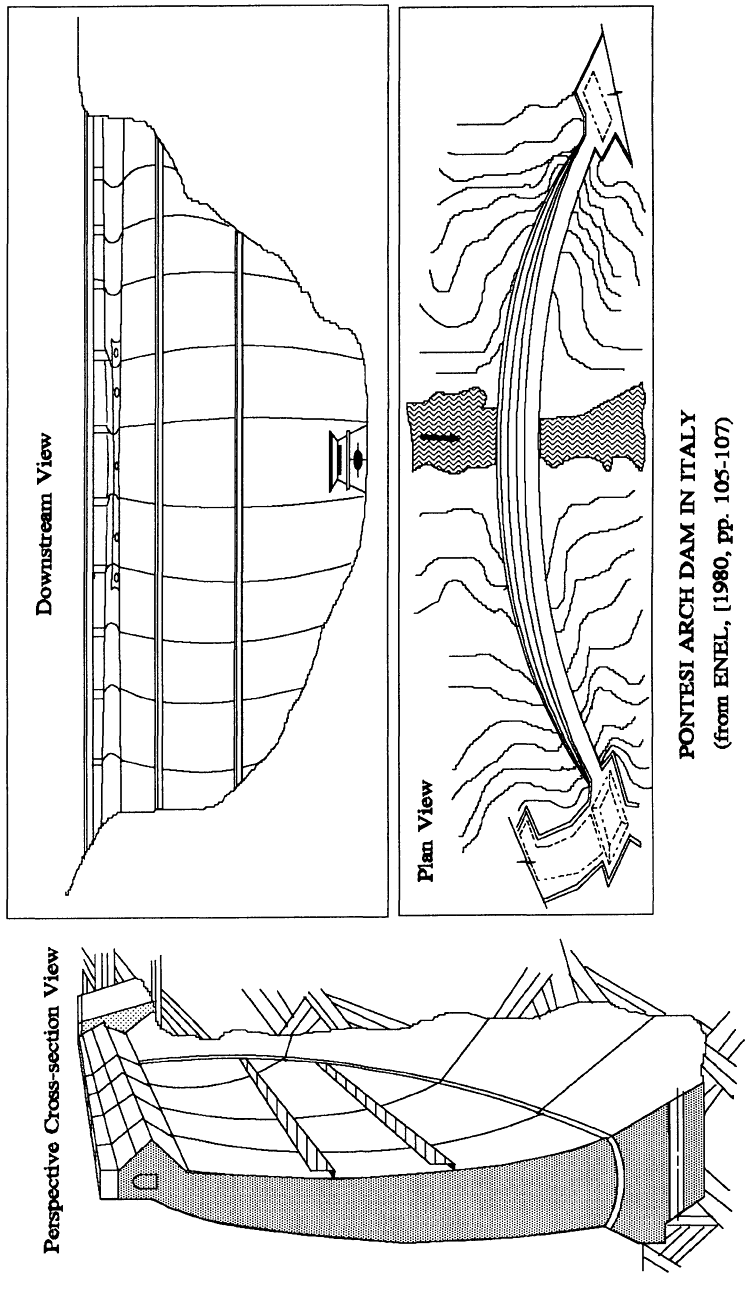
Arch dams are placed into three general classifications (ICOLD, 1977):

1. **Constant Angle Arch Dam.** An arch dam in which the angle subtended by any horizontal section is constant throughout the entire height of the dam (see Figure 2.4).
2. **Constant Radius Arch Dam**. An arch dam in which every horizontal segment of slice of the dam has approximately the radius of curvature (see Figure 2.4).

Figure 2.3a



TYPICAL CROSS-SECTIONS OF ARCH DAMS
(from Thomas, [1976, pp 283-350])



PONTESI ARCH DAM IN ITALY
(from ENEL, [1980, pp. 105-107)

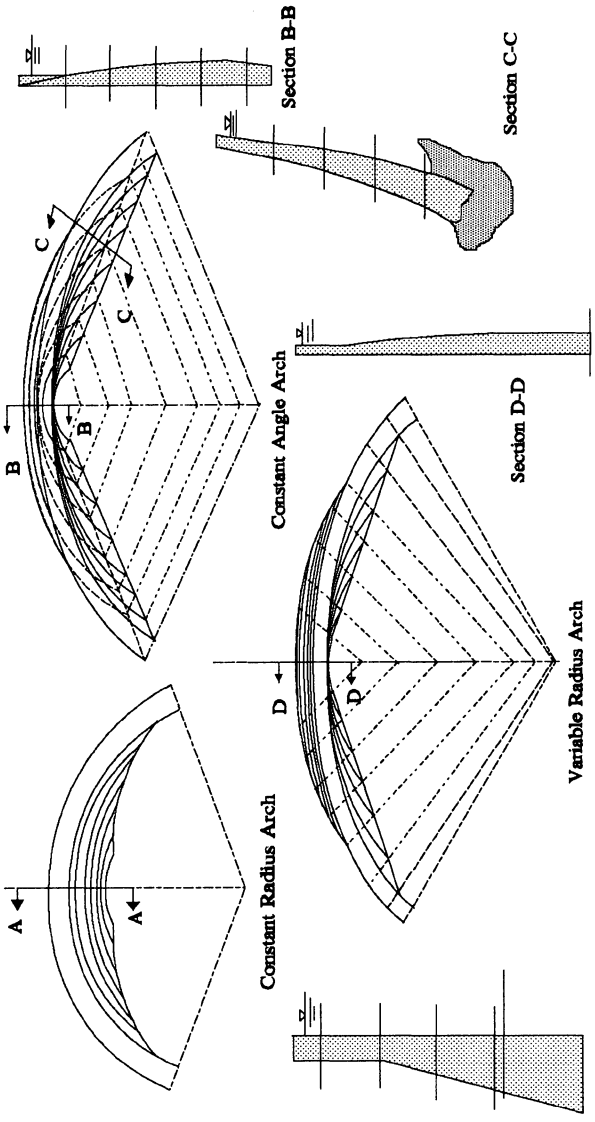
Figure 2.3b

3. **Double Curvature Arch Dam**. An arch dam which is curved vertically as well as horizontally.

As shown in Figure 2.4, their complexity is further increased when two or more of the above design methods are combined or varied (variable radius arch dams).

For simplicity, the behaviour of arch dams is such that the force of the water acting on the face of the dam is transferred by the arching action to the abutments. Unlike gravity dams, arch dams are not designed to resist shear stresses due to the force of the water acting upon the dam. Primarily, the foundation for an arch dam must have sufficient strength to carry, at minimum, the weight of the dam itself. As a result, the force of the water is usually transferred to the banks at the ends of the arch. This type of behaviour makes arch dams best suited for locations where the river banks are relatively steep and are preferably of solid rock. For instance, arch dams are widely used in relatively narrow canyons, and where the canyon walls consist of sound rock capable of withstanding the arch thrust from the water loads. They also generally require less concrete and can therefore be constructed at a lower cost than gravity dams.

Concrete swelling in arch dams produces cracks along the toe of the dam which directly results in an upstream tilting. In the case of shrinkage, it may cause the dam to lean downstream (i.e., the blocks will tend to rotate about a horizontal plane along the foundation). Also, if the grout curtain beneath the dam is placed too far upstream, the downstream leaning of the dam provoked by the shrinkage may cause the grout curtain to separate from the dam thus, allowing the reservoir water pressure to move further beneath the dam. Arch dam foundation can also give rise to foundation stability problems



EXAMPLES OF DIFFERENT TYPES OF ARCH GEOMETRY
(from Thomas, [1976, pp. 313-314])

Figure 2.4

(manifested by sliding or piping) when the concrete in the grout curtains have continued to shrink (Bonazzi, 1990). Because arch dam behave monolithically, their displacement (deformation) is the most important parameter that should be readily monitored. The most significant displacement are those that take place in a horizontal direction (Bartholomew and Haverland, 1987).

Because the water load is carried laterally to the abutments, uplift forces are not as important in arch dams as they are in gravity dams. There is always sufficient weight within the arch itself to oppose the uplift (Thomas, 1976). Although arch dams react somewhat differently than gravity dams, the conditions which are the most important to monitor in arch dams are basically the same as those in gravity dams; only their order of importance is different. In particular, the uplift pressure for arch dams is considered to be the second least important measurement.

2.2.2.3 Buttress dams

A buttress dam consists of a water-tight structure supported at intervals on the downstream side by a series of buttresses. A buttress is a support built against a wall, or in the case of a dam, a support against the water-supporting element of the dam. Buttress dams can take on the following forms (ICOLD, 1977):

1. **Flat Slab Dam, Ambursen Dam or Deck Dam.** A buttress dam in which the upstream part is a relatively thin, flat slab usually made of reinforced concrete.
2. **Arch Buttress Dam or Curved Buttress Dam**. A buttress dam which is curved in plan.

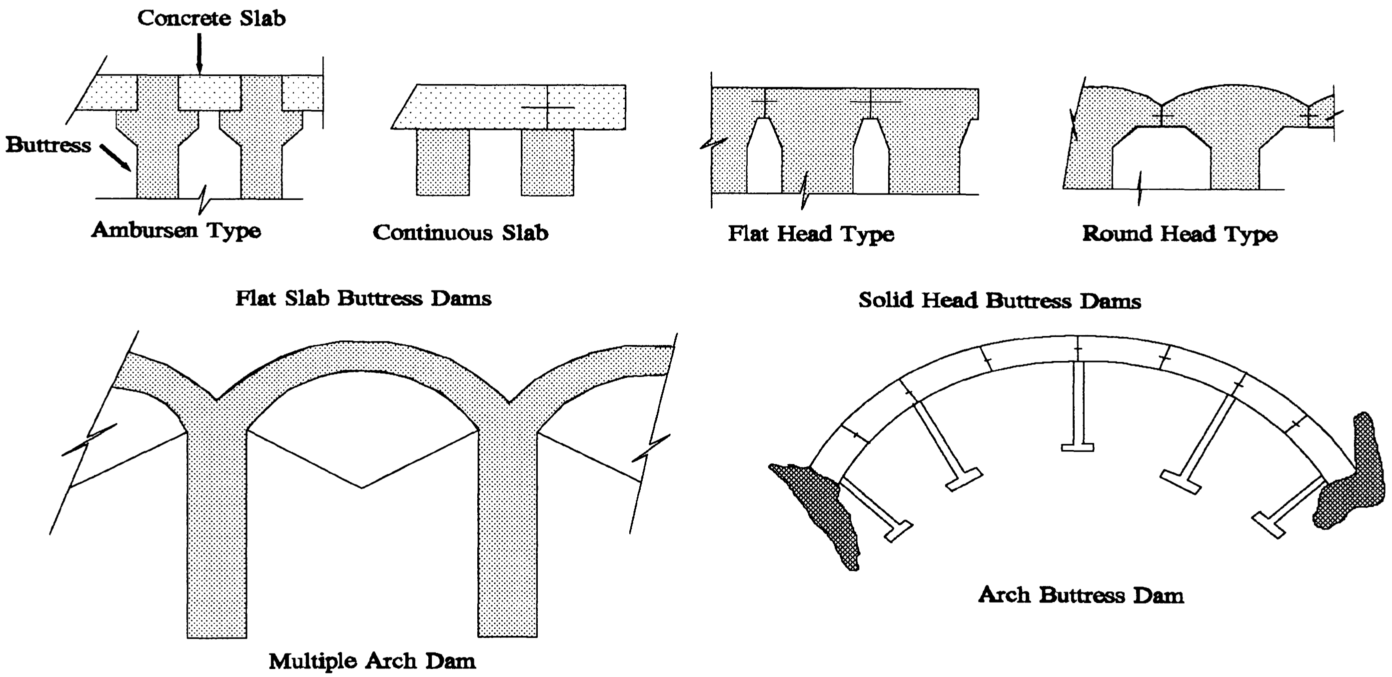
3. **Multiple Arch Dam**. A buttress dam with the upstream portion comprised of a series of arches.
4. **Solid Head Buttress Dam**. A buttress dam in which the upstream end of each buttress is enlarged to span the gap between buttresses.

Figures 2.5a and 2.5b illustrate some examples of the horizontal- and cross-sections of the different forms of buttress dams listed above. The principal structural elements of a buttress dam are the water-supporting upstream face and the buttresses (see Figure 2.5b). There are many different types of buttress dams being constructed, but as illustrated in Figure 2.5a, it is primarily the water-supporting elements which depict the different designs. A subdivision of these different types may be the *slender* and the *heavy* design of the water-supporting element and the buttress (ICOLD, 1974).

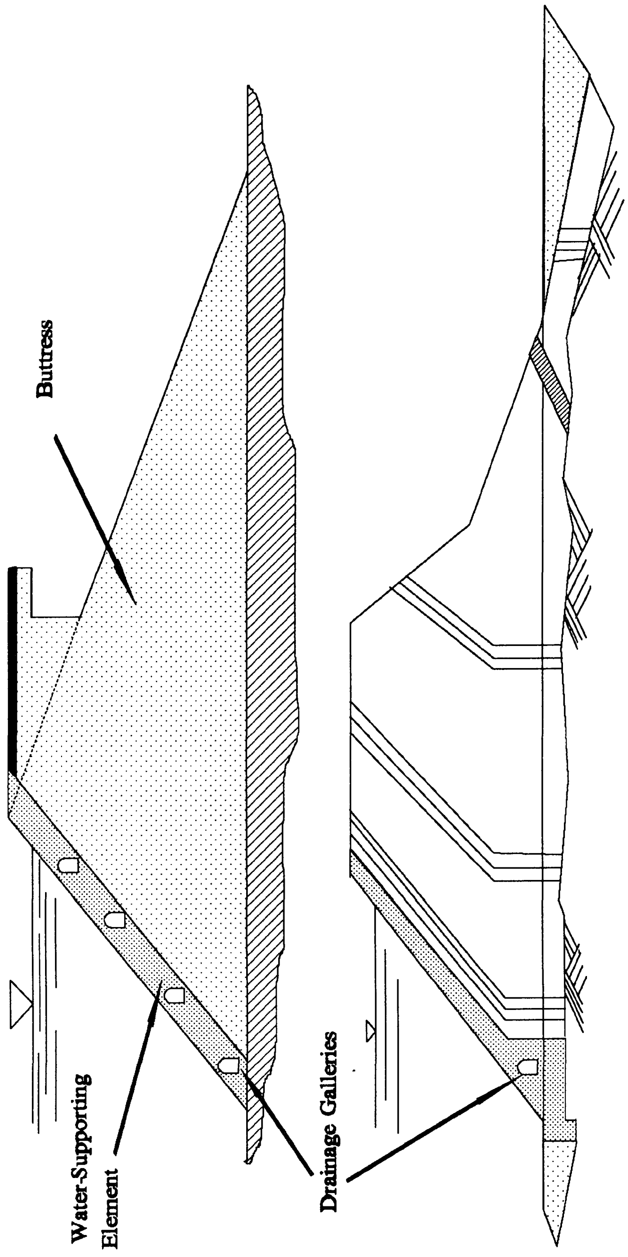
Buttress dams are particularly applicable in wide valleys where sound rock foundations are an exception rather than the rule. Exceptions require a thorough investigation of the river bottom especially for rigid dams such as the multiple arch-types.

The main advantage of buttress dams is the financial savings (ICOLD, 1974). They require less concrete than solid-gravity dams and are generally constructed in a shorter time. The water load on a buttress dam is transmitted from the upstream face to the foundation by means of the buttresses. It is claimed that another major advantage of buttress dams, including hollow-gravity dams, is that the uplift forces acting on the dam are minimal. The free drainage of the foundations between the buttresses considerably reduces the uplift on their bases (Thomas, 1976). Therefore, buttress dams are ideal in areas which have very pervious foundations. Like gravity dams, buttress dams exhibit

Figure 2.5a



TYPES OF BUTTRESS DAMS
(after Thomas, [1976, p. 354])



TYPICAL CROSS-SECTIONS OF BUTTRESS DAMS
(after Thomas, [1976, pp. 353-374])

Figure 2.5b

the same structural integrity problem caused by the expansion joints between its concrete blocks (Bartholomew and Haverland, 1987). Experts such as Serafim (1982) and Bartholomew and Haverland (1987) leads one to conclude that the conditions to be monitored for buttress dams are identical to those for gravity dams.

2.3 Monitoring Schemes

Basically, two types of measuring techniques are used to monitor the deformation of dams (Chrzanowski et al., 1991):

(1) *geodetic* surveys (e.g., terrestrial, photogrammetric, space positioning methods and special survey techniques), and

(2) *geotechnical/structural* measurements (e.g., tiltmeters, strainmeters, extensometers, and plumb-line).

Geodetic methods provide relative displacements of points on the deformable body or absolute displacement of the object points with respect to reference points which are assumed to be stable. Traditionally, *geotechnical/structural* measurements have been used to determine relative displacement within the structure of the dam. However, with technological advancements, especially in high precision directional (including vertical) borehole drilling, it is now possible to use geotechnical methods to determine absolute displacement. For example, inverted plumb-lines and borehole extensometers anchored deep enough into the bedrock outside the deformation zone can determine the absolute displacement of object points to an accuracy comparable and even exceeding that of geodetic surveys (Chrzanowski et al., 1991).

The advantages and disadvantages of both methods are discussed by Chrzanowski (1986) and an excellent review of geotechnical instrumentation is given by Dunnicliff (1988). In addition to the geometric measurements provided by the geodetic and geotechnical methods, depending on the type of dam, there are also non-geometric parameters measured. These include temperature, water and pore pressures, seepage and in-situ stresses.

It would be extremely difficult, if not impossible, to develop rules that outline the types of measurements to be made for each and every type of dam to be constructed. The type of monitoring scheme is usually unique to each dam, not only because of its type, but also because of the site conditions, construction technique, and the special ailments that the dam might inherit. There are, however, some instruments that are recommended for all dams, while others are recommended only in special cases (Jansen, 1980). Even today, in many countries professionals still do not agree on the number of instruments and the frequency of the observations. Table 2.2 illustrates some of the common types of instruments used to monitor embankment and concrete dams. Furthermore, ICOLD (1988) gives recommendations on the minimum type of instruments that should be used initially for both concrete and embankment dams.

Because of the differences between embankment and concrete dams already stated in section 2.2, a monitoring scheme cannot be designed in the same manner for both types of dams. With concrete dams, it is important to observe the behavioral trends in both the elastic and plastic (permanent) deformation. Analyses consists of comparing measured

Table 2.2
Typical Instrumentation Used to Monitor Dams
(after ICOLD, [1982, pp. 33-37 & 1988, pp. 27-35])

Quantity Measured	Instrument	Remarks
Vertical Displacements	● Hydrostatic levels ● Precision topographic levelling devices ● Extensometers ● Theodolite ● Settlement gauges	● Measure upward (heave) and downward displacements.
Angular Displacements	● Clinographs ● Clinometers ● Slope indicators	
Horizontal Displacements	● Direct or inverted pendulums ● Theodolites ● Collimation ● EDMI	
Strain	● Strain gauges	● The principle purpose is to measure the state of stress in a plane parallel to the external face of the structure. Preferably their are embedded in the concrete during construction.
Settlement	● Settlement meters ● Levelling instruments ● Wire and bar strain gauges	● Measurements taken of the foundation (for any type of dam) or the dam proper (for earth and rockfill dams).
	● Cross-arms (USBR type)	● Used for detecting individual layers of the embankment.
Uplift and Pore Pressure (also water tables or ground water level)	● Piezometers (open or closed types) ● Water gauges ● Pressure gauges	
Seismic Movements	● Seismographs ● Accelograph (or displacement recorders)	● Strong motion type of accelographs are used detect ground motion frequencies in the foundation, at different points on the dam. Seismographs are used to record earthquakes near the reservoir area.
Humidity	● Hydrometers	● Measurements are taken of the air and in the dam.

Quantity Measured	**Instrument**	**Remarks**
Temperature	● Mercury thermometers ● Thermoelectric couple ● Vibrating wire thermometers	● Measurements of air and within the body of the structure (particularly important for concrete dams).
Rainfall Measurements	● Rain gauges	
Leakage and Flow	● Flumes and weirs with different systems of measurements (optical, electrical or mechanical)	● Measurements are taken of seepage, leakage and drainage flow in selected parts of dam.
Turbidity	● Turbidity-meters	● Measure quantity of fine materials and chemicals suspended in the water in the downstream side of the dam.
Water Level Measurements	● Pneumatic level gauges ● Float system ● Stadia rod system ● High precision hydrostatic balance	● Measurement of depths in the reservoir.
Joint and Crack Measurements	● Joint meters ● Deformeters	● Measurements of variations in the openings and sliding of joints and fissures.
Stress	● Direct stress meters (or gauge) ● Direct strain gauge	● Measurements of tension and compression stresses. They are design for direct measurement of stresses without resorting to the modulus of elasticity.

deformation with predicted normal behaviour. Whereas, with embankment dams, permanent deformations trends should be intimately monitored for any sign of abnormality. Monitoring instruments, at minimum, should be located where: (1) the maximum deformations are expected, (2) the deformation is small but is considered to be critical to the safety of the dam, and (3) a deformation phenomenon is to be observed. For example, for thin arch dams, special attention should be given to the central cantilever, abutment and abutment rock. For multiple-arch and buttress dams, monitoring points should be placed at the head and at the downstream slope of each buttress. Figures 2.6 through 2.8 illustrate some typical examples of monitoring schemes that are being applied concrete and embankment dams.

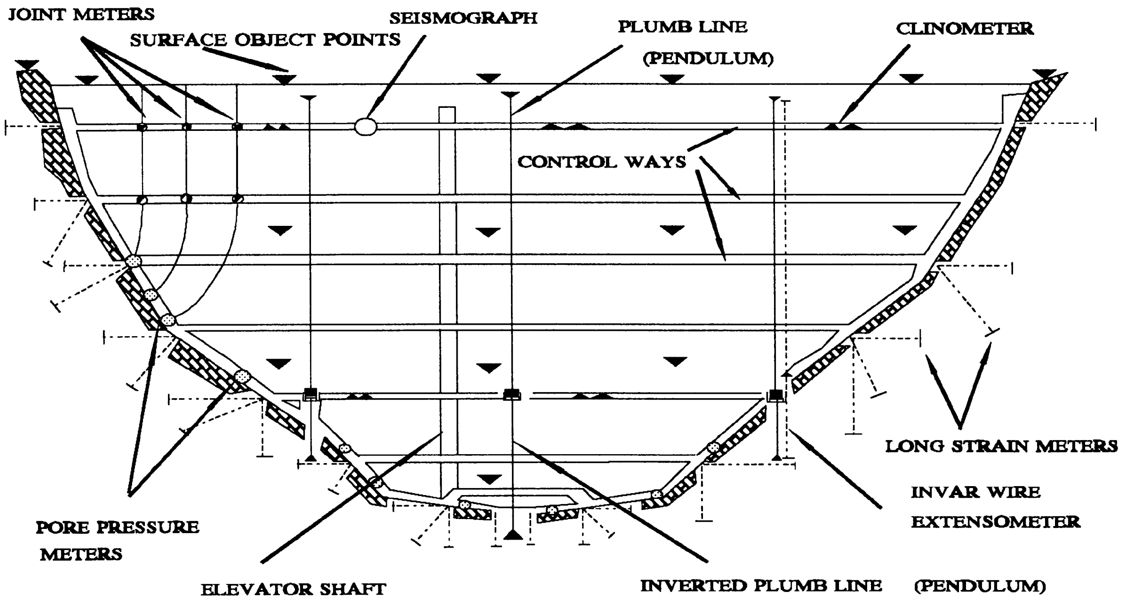
2.4 Methods of Deformations Analysis

The analysis of dam deformation surveys are distinguished by two different methods: *geometric* and *physical analysis*. In the first case, the information on the acting forces and stresses, and on the physical properties of the body are of no interest to the interpreter whereas, in the second case, the load-deformation relationship may be modelled using either a *statistical* or *deterministic* method. The basic concepts of the these deformation analysis are discussed in the proceeding sections. The principles are primarily based on reports from Chrzanowski et al. (1981) and Chen and Chrzanowski (1986).

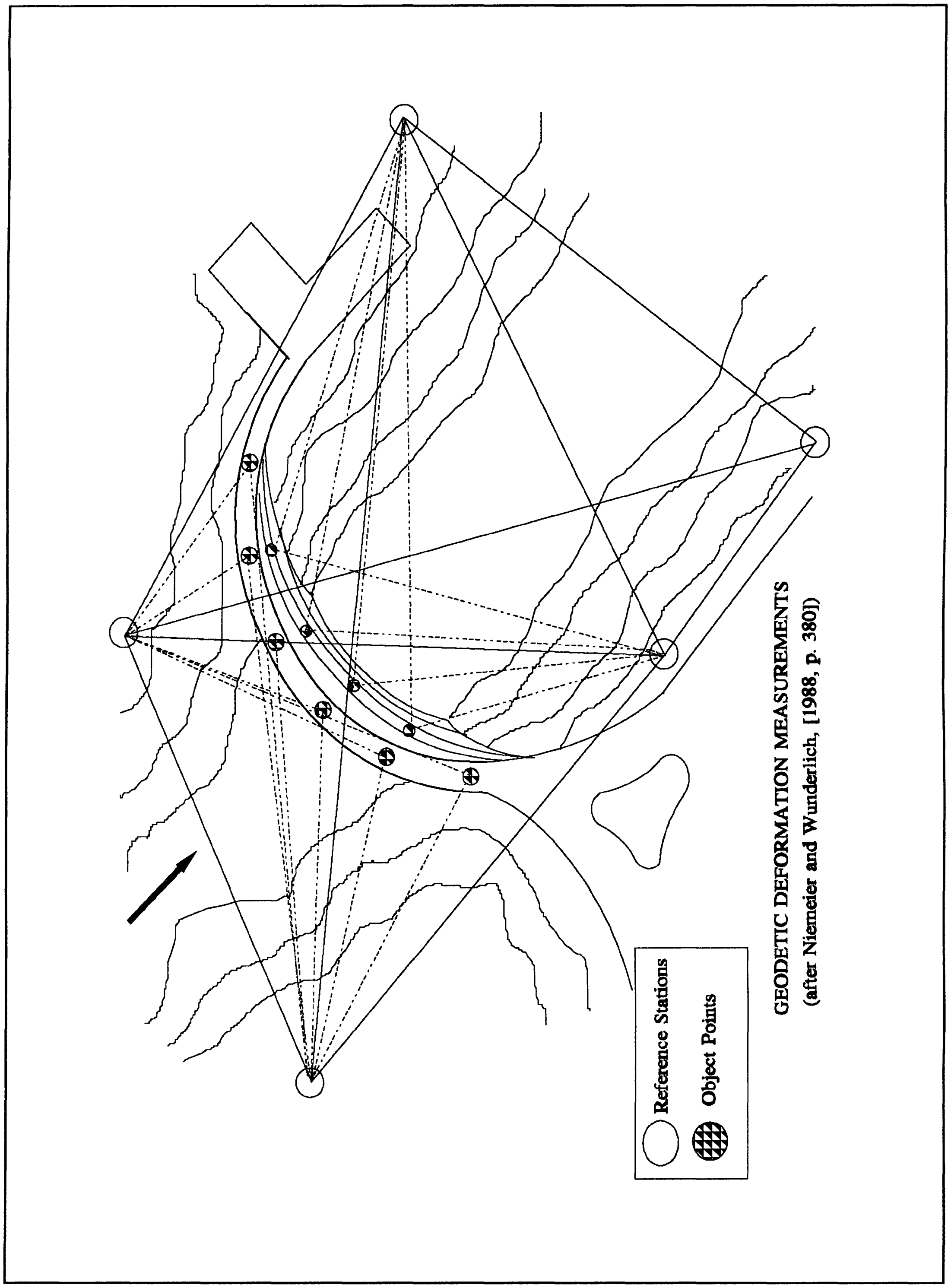
2.4.1 Geometric Analysis

Geometric analysis is used to describe the state of a deformable body, and its change in shape and dimension. This method is of particular importance when the deformable structure must satisfy certain geometrical conditions, such as the crest alignment of a dam, or the knowledge on the developed strains in the material is required. The analysis can be either *relative* (i.e., the movement of a block of the body with respect to its other blocks — Figure 2.9) or *absolute* (i.e., the rigid body movement of the entire deformable body with respect to an assumed stable reference system — Figure 2.9). Modelling *relative* movement is more complicated because, in addition to the possible point

Figure 2.6



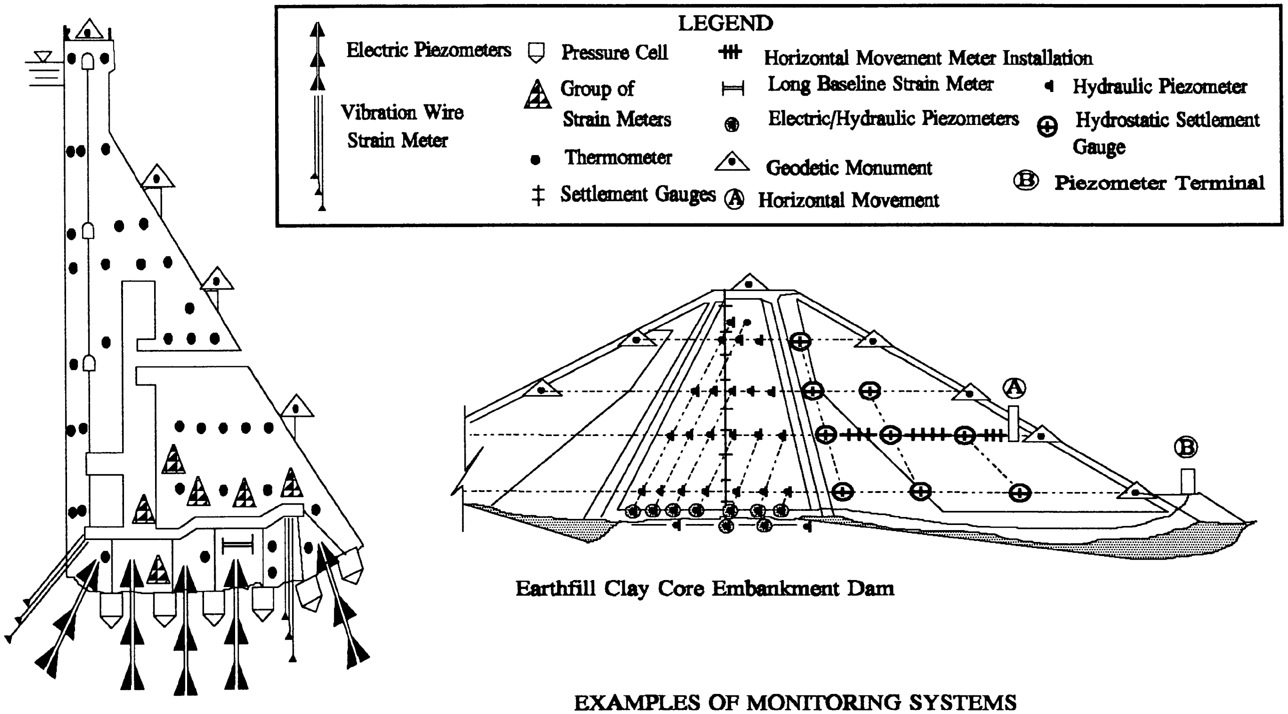
EXAMPLE OF THE INSTRUMENTATION OF A CONCRETE DAM
FOR RELATIVE AND ABSOLUTE MONITORING
(after Niemeier and Wunderlich, [1988, p. 379])



GEODETIC DEFORMATION MEASUREMENTS
(after Niemeier and Wunderlich, [1988, p. 380])

Figure 2.7

Figure 2.8

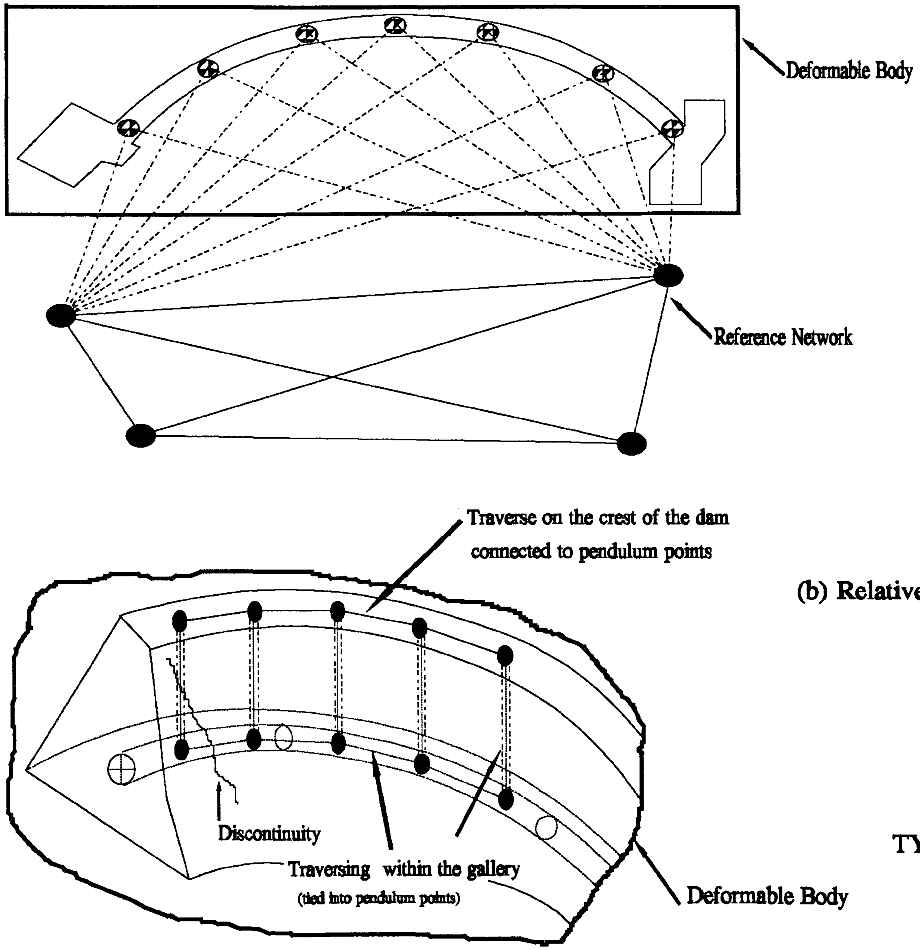


Concrete Gravity Dam

Earthfill Clay Core Embankment Dam

EXAMPLES OF MONITORING SYSTEMS
OF CONCRETE AND EMBANKMENT DAMS
(after, Serrano et al., [1991, pp. 1205-1206] and ICOLD, [1969, p. 22])

Figure 2.9



(a) Absolute Monitoring Network

(b) Relative Monitoring Network

TYPES OF GEOMETRIC NETWORKS

displacements, all of the points undergo *relative* movements caused by strains in the body material and by *relative* rigid translations and rotations of parts of the body if discontinuities in the material (for instance, large cracks in a concrete dam) are present. In the case of modelling *absolute* movements, the problems are less complicated. When determining the *absolute* movements of object points, any unstable reference points (caused by local movements and/or movements of the monumentations of the survey markers) must be identified first before the *absolute* displacements of the object points can be calculated. If not, the calculated displacements of the object points and subsequent analysis of the deformation of the structure will be distorted.

Over the past decades several methods for the (geometric) analysis of reference networks have been developed in a number of countries within the auspices of the aforementioned FIG Study Group. Noted is the concept of a global integration (Chrzanowski et al., 1990), the *UNB Generalized Method*, developed by the University of New Brunswick (UNB). The global integration method was developed for the purpose of enhancing the understanding of the mechanics and behaviour of deformable bodies. The generalized method utilizes any type of geodetic and geotechnical observations in a simultaneous deformation analysis. It is applicable to any type of geometrical analysis, both in time and space, including the detection of unstable points in the reference networks, and determination of strain components and relative rigid body motion within relative networks (Chen, 1983). In summary, the approach consists of the following basic steps (Chrzanowski et al., 1992):

(1) a trend analysis of the data (includes identifying unstable reference points) and

selecting a few deformation models that match the trend and make physical sense,

(2) the least-squares fitting of the model(s) into the observation data and performing statistical tests of the model(s),

(3) selecting the "best" model that has the minimum possible coefficients with the highest possible significance (preferably at a significance level greater than 95%) and which gives the smallest possible quadratic form of the residuals, and

(4) a graphical representation of the displacement field and the derived strain field.

The research on the global integration is still in progress. For a detailed description of this method and practical examples, the reader is referred to Secord (1984). Some examples of the final graphical outputs of the UNB Generalized Method are illustrated by Figure 2.10. Figure 2.10 gives a graphical display of the displacement field and the strain field derived from the best fitted deformation model.

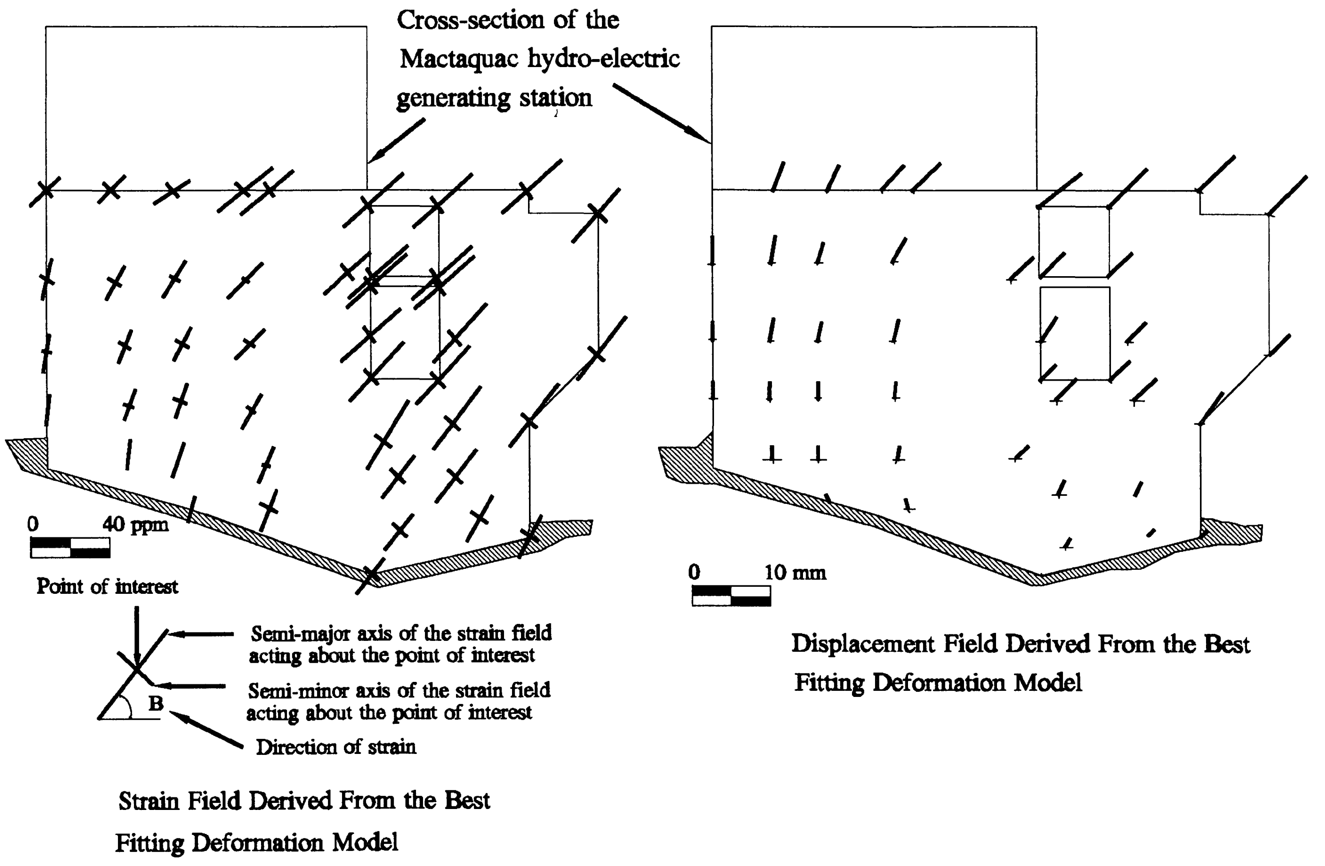
2.4.2 Physical Analysis

In the physical analysis, the load-deformation relationship is modelled. This may be accomplished by using one of the following methods: *statistic, deterministic* or *hybrid* models.

2.4.2.1 Statistic (stochastic) model

The statistical method uses a regression analysis to analyze the correlation between the observed deformations (i.e., effects such as rotations rigid body displacement, strains due to change in dimension and shape) and observed causative quantities (i.e., loads

Figure 2.10



Note: Approximate scales

AN EXAMPLE OF THE APPLICATION OF THE UNB GENERALIZED METHOD
(from Chrzanowski et al., [1991, pp. 556-557])

induced by surface forces, e.g, water loads, and body forces, e.g., weight, thermal expansion, inertia). With this model the forecasted deformations can then be obtained from measured causative quantities. The model's reliability to predict future deformation is a function of the number of observations, both causative quantities and response effects (i.e., with a larger number of observations a higher degree of correlation can be obtained between the causative and effects which in turn provide better estimates of the model parameters). This method cannot only be used to model the observed displacements but, also to monitor quantities such as stress, pore water pressures, tilt of the foundation, etc. An example of an application of this model is given in Figure 2.11.

2.4.2.2 Deterministic model

The deterministic model uses the information on the sizes and locations of loads, properties of the materials (e.g., modulus of elasticity, poison ratio), and physical laws governing the stress-strain relationships to derive the relationship between the causative quantities and effects. From this relationship, the deterministic model provides information on the expected deformations. There are basically two steps in deterministic modelling: the first step is to use the finite element method (FEM) to determine the displacements at discrete water elevations; and the second step is to use the least square method to determine the best fit polynomial to the discrete displacements calculated by the FEM model. The polynomial (displacement function) is then used to describe the general relationship between the effects and the loads. For example, when modelling the deformation of a dam, the dam and its foundation are first subdivided into a finite mesh

Figure 2.11

Seasonal Components for the Displacement Using a

Delta 2000 Automatic Collimatro for the Period 1973-1978

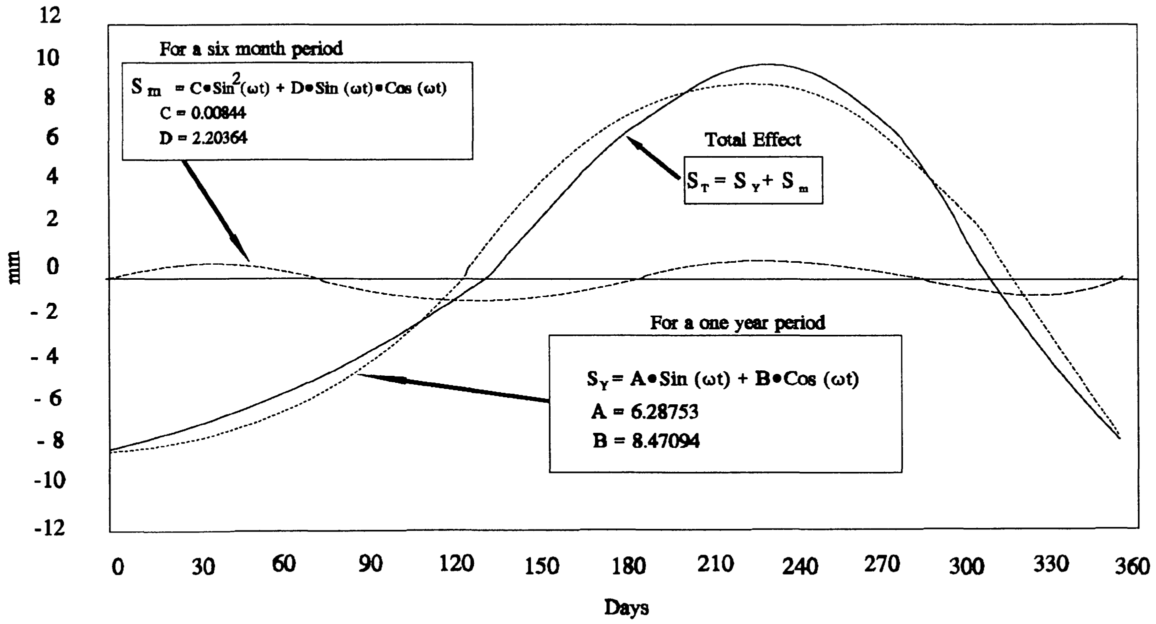


DIAGRAM OF THE RESULTS OF A STATISTICAL MODEL

(from ENEL, [1980, p. 56])

(Figure 2.12) to compute the displacement of points of interest at an assumed discrete water level. Then, a displacement function with respect to the water level is obtained by least square fitting of a polynomial to the discrete displacements computed by the FEM (Figure 2.12). Finally, with this polynomial one can compute the expected displacements at any desired water levels.

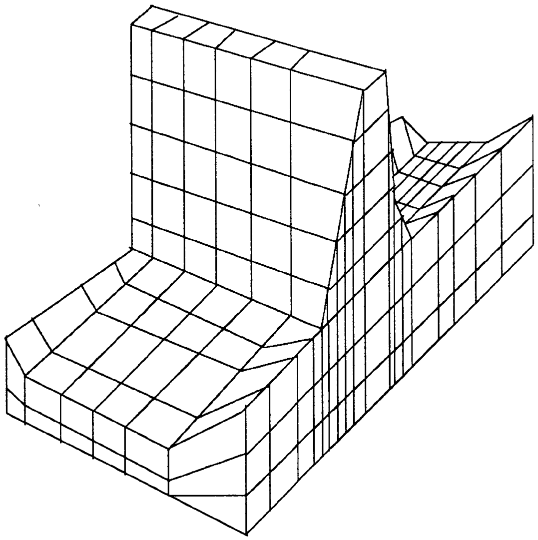
2.4.2.3 Hybrid model

The hybrid model is a combination of the statistic and deterministic models. As aforementioned, the statistical method requires a large amount of observation before it is has some degree of reliability. This makes the statistical method unsuited during the early stage of the dam operation when only short sets of observations are available. In this case, the deterministic method is very advantageous. However, due to many uncertainties in deterministical modelling, such as the imperfect knowledge of the behaviour of some materials, and approximations used in the calculations, the computed displacements may be significantly different from the observed values. Thus, the deterministic model can be enhanced by combining it with the statistical method (i.e., the knowledge of the expected structural behaviour obtained from the statistical model is used to *tune up* the deterministic model). For a detailed description of this method the reader is referred to ENEL (1980) and Chen (1988).

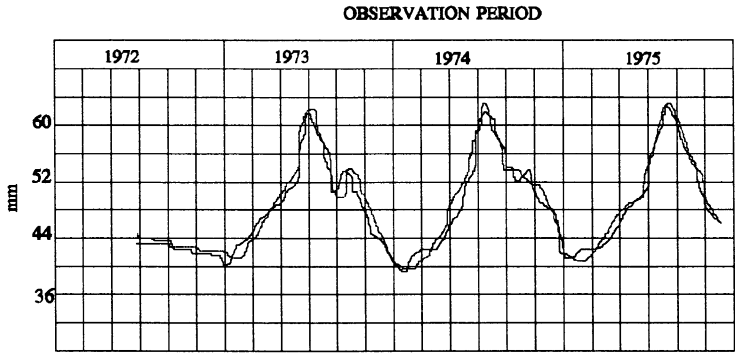
2.5 Conclusion

This chapter has provided some background information about the major types of

Figure 2.12



A 3-D Finite element mesh of a central block of a gravity dam.



Superposition of measured displacements (.........) with theoretical values (____) at a particular sight in a given given direction.

FINITE ELEMENT MESH AND FORCASTED DISPLACEMENT (mm) BY USING A DETERMINISTIC MODEL FOR THE PERIOD 1972-1975 (after ENEL, [1980, p. 169 & p. 88]) dams that exist and are still being constructed today. More importantly, it has illustrated, for each dam-type, the basic principles of their behaviour, the factors affecting their normal behaviour, and the methods used to monitor and analyze this behaviour. Each dam-type has its advantages and disadvantages. The type of dam to be constructed will usually depend largely on economics and the site situation.

With respect to the major conditions which should be monitored for each dam-type, the largest discrepancies between the dam-types exist solely with embankment dams. For concrete dams (gravity, arch and buttress dams), the major conditions to be monitored are generally the same. All three dam-types inherit one of the major problems associated with concrete dams: cracking primarily due to external and internal causes. However, this does not exclude the fact that each dam behaves differently and must be considered as a unique case, one which requires a monitoring system that is best suited for that particular site.

CHAPTER 3

ANALYSIS OF THE WORLDWIDE REVIEW

3.1 General

In May 1992 a survey, in the form of a questionnaire (see section 1.2), of 79 ICOLD member countries was conducted to determine the current status of dam deformation across the world. Of the 79 countries, 29 (37%) responded: Argentina, Australia, Austria, Bangladesh, Brazil, Canada, China, Cyprus, Czechoslovakia, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Netherlands, New Zealand, Norway, Portugal, South Africa, Spain, Sri Lanka, Switzerland, Thailand, United Kingdom (UK), United States of America (USA) and Uruguay. The results of the survey are summarized by country in Appendix I. Although 37%, statistically, may not be considered a reliable percentage from which one may establish sound conclusions of the results, the facts that the 29 countries own and operate approximately 32,700 (90%) of the world's total large dams, include the major world leaders in dam design and construction techniques (e.g., Italy, Japan, Switzerland), and represent a global cross-section of the world, should make this survey fairly accurate in depicting the current status of monitoring and analysis of the deformation of large dams across the world.

This chapter presents the analysis of the summaries which should furnish sufficient amount of material to "pave the way" for those who will be responsible for drafting the aforementioned unified dam monitoring guidelines. The chapter includes an executive summary of Appendix I and summaries of: (1) the various types of instruments that are currently being used to monitor the world's large dams, (2) the most recent national developments in monitoring instrumentation, (3) the monitoring guidelines and/or standards/specifications used by each country, (4) the recommended accuracies of the measurements, (5) the recommended frequencies of the measurements, and (6) the types of data analyses that are considered unique and/or the most advanced in the area of deformation. Included in item (4) are two samples of monitoring specifications — one from the Swiss National Committee on Large Dams (SNCOLD), and the other from New Zealand's major dam owner, the New Zealand Electric Corporation (ECNZ). If additional information or clarification on the material discussed in this chapter is required, the reader is referred to Appendix I and/or the references provided.

3.2 Executive Summary

An executive summary numerically summarizing the information presented in Appendix I is given in Table 3.1. The table furnishes anticipated, and somewhat surprising and unexpected results.

Overall, dams are still being monitored by both geodetic and geotechnical/structural methods. Although, one method is preferred over the other, dams are continually being

Table 3.1
Executive Summary of the Worldwide Survey
Dam Deformation

Country	Actual or Preferred Method of Monitoring			Dam Safety Legislation in Place		Standards & Specifications for Monitoring		Include Automation in as Part of the Monitoring Systems	Reference Made that Geodetic System Have Been Designed
	Geodetic Instr.	Geotech. & Structural Instr.	Both	General	Includes Monitoring	National	Indiv. Org.		
Argentina			X	X			X[3]	X	
Australia			X	X[2]			X[3]	X	X
Austria		X[1]			X			X	
Bangladesh									
Brazil		X[1]							
Canada			X	X[2]			X[3]	X	
China			X		X	X		X	
Cyprus	X[1]*								
Czechoslovakia			X		X	X			
France		X[1]			X			X	
Germany	X[1]			X					X

Country	Actual or Preferred Method of Monitoring			Dam Safety Legislation in Place		Standards & Specifications for Monitoring		Include Automation in as Part of the Monitoring Systems	Reference Made that Geodetic System Have Been Designed
	Geodetic Instr.	Geotech. & Structural Instr.	Both	General	Includes Monitoring	National	Indiv. Org.		
Greece	X^{1*}						X		
Hungary	X^{1}				X	X			X
Ireland		X^{1}							
Italy		X^{1}		X				X	
Japan			X		X			X	
Korea		X							
Netherlands		X		X					
New Zealand	X^{1}						X		X
Norway			X		X		X	X	
Portugal			X		X		X	X	
South Africa			X		X			X	
Spain			X						
Sri Lanka			X						
Switzerland	X^{1*}				X	X^{4}	X	X	

Country	Actual or Preferred Method of Monitoring			Dam Safety Legislation in Place		Standards & Specifications for Monitoring		Include Automation in as Part of the Monitoring Systems	Reference Made that Geodetic System Have Been Designed
	Geodetic Instr.	Geotech. & Structural Instr.	Both	General	Includes Monitoring	National	Indiv. Org.		
Thailand			X	X					
UK		X[1]			X			X	
USA			X	X[2]				X	
Uruguay			X						
Total	6	8	14	8	11	4	8	14	4

Table 3.1 (Contd.)
Executive Summary of the Worldwide Survey
Dam Deformation

Country	Major Dam Owners		Separate Authority Within the Organization Responsible for Surveillance	Separate Organization Dedicated to the Development of New Equipment	Include Seismic Monitoring	Common Practise to Have Surveyors Involved in Monitoring
	Private Owner	Provincial or Federal Organizations				
Argentina		X			X	
Australia		X	X		X	X
Austria			X		X	
Bangladesh		X	X			
Brazil						
Canada		X	X		X	
China		X				X
Cyprus						
Czechoslovakia			X	X		X
France		X	X	X		

Country	Major Dam Owners		Separate Authority Within the Organization Responsible for Surveillance	Separate Organization Dedicated to the Development of New Equipment	Include Seismic Monitoring	Common Practise to Have Surveyors Involved in Monitoring
	Private Owner	Provincial or Federal Organizations				
Germany		X	X	X		
Greece		X				
Hungary			X			
Ireland		X				
Italy		X	X	X	X	
Japan	X	X	X	X	X	
Korea		X				
Netherlands			X			
New Zealand		X				
Norway	X	X	X	X		
Portugal			X	X	X	
South Africa		X	X			

Country	Major Dam Owners		Separate Authority Within the Organization Responsible for Surveillance	Separate Organization Dedicated to the Development of New Equipment	Include Seismic Monitoring	Common Practise to Have Surveyors Involved in Monitoring
	Private Owner	Provincial or Federal Organizations				
Spain					X	
Sri Lanka		X	X			
Switzerland			X			X
Thailand		X	X		X	
UK		X	X	X	X	
USA		X	X		X	
Uruguay						
Total	2	19	19	8	11	4

Notation: X^1 = The country still uses both methods to monitor its dams.
X^{1*} = Within that country some dams are monitored solely using the preferred method indicated.
X^2 = Within that country, some form of legislation is in place within only certain provinces or states.
X^3 = The specifications have been developed by organizations within only certain provinces or states.
X^4 = The national specifications have been proposed (in draft form).

instrumented so that they can be monitored by either means. Only two countries, Korea and Netherlands, reported that their dams are monitored using strictly geotechnical/structural instrumentation. The biases towards either geodetic or geotechnical instrumentation seem to be correlated with the level of education and experience in the method preferred. For example, in Germany and Switzerland, where the geodetic surveying education and the number of Surveying Engineering specialists are high, geodetic surveying techniques play the dominant role in monitoring large dams. Whereas, in Italy, France and UK, where education in Surveying Engineering does not have a long standing tradition, geotechnical techniques are preferred (Chrzanowski et al., 1992).

Table 3.1 illustrates that, overall, legislation for control of safety aspect of dams is still lacking in some countries, especially with respect to monitoring. Sixty-six percent of the countries have some form of dam safety legislation, but in only 38% of the countries the legislation includes monitoring. Ironically, most of these are developed countries (e.g., Canada, USA, Italy, UK, Germany). Furthermore, only three countries reported having national specifications for dam monitoring (Switzerland having only recently proposed national specifications). The remaining countries noted that monitoring specifications are usually developed by individual dam owners. It would seem that in most cases the decision involving risks is still left up to the private sector or authorities in charge of the dams who in some cases do not have the experienced professional personnel necessary to insure the highest level of safety possible, particularly in the area of geodetic monitoring. This for example, in addition to the reasons given by

Chrzanowski (1990), may be another factor contributing to the current problems with Canada's dam safety programmes: poorly designed monitoring schemes, inadequate instrumentation, lack of calibration facilities, insufficient accuracy of measurements and, one of the most serious problems, the use of out-dated methods in the geometric analysis of deformation measurements (Chrzanowski, 1990).

ICOLD has long recognized the necessity for having proper control over the design, construction, operation and maintenance of dams. The need for monitoring systems on dams was expressed to the Civil Engineering Profession back in 1967 during the ICOLD conference in Istanbul, Turkey. At the time, it was identified that every effort should be made to have all of the world's large dams placed under technical observation, and to have their behaviour monitored on a regular basis and in all unusual circumstances (Keen and Asce, 1974). This compounded with the long history of dam failures across the world would lead one to believe that after so many years there should be no excuse why there is still a lack of control over the monitoring of very sensitive and potentially destructive structures such as large dams. Unfortunately, ICOLD has no jurisdiction over the implementation of their dam safety guidelines or any other guidelines related to dam safety. The responsibility to promote the works of the ICOLD to both government agencies and private consortia rests on the National Committee members. For example, in Canada, the joint CANCOLD—Canadian Dam Safety Association Safety Committee (CDSA) is responsible for insuring that all dam owners and operators are made aware of dam safety matters (Larocque, 1992). This of course, does not assure that private industries or national companies will implement or even consider CANCOLD's recommendation. Unfortunately, there are numerous cases in history where governmental intervention leading to some form of legislation has come about only as a reaction to prominent dam failures. Two well known examples are the UK and USA (Penman and Kennard, 1982; Duscha, 1984).

Canada with over 608 large dams has been very fortunate in that it has not yet experienced failures causing loss of life. However, according to Koropatnick (1990) there have been several incidents recorded which could have resulted in serious consequences had remedial measures not been taken. The question is, like most countries, should Canada wait until a disasters involving the loss of lives, the destruction of the environment or significant economic damage occur before the government becomes involved in dam safety issues? This author's simple answer is no, and that CANCOLD with the support of the CDSA should make all possible efforts to communicate to the Canadian Government the need for legislation in order to enforce national dam safety programs which would include a unified set of guidelines for the monitoring and surveillance of large dams. When safety is an issue, the government has the responsibility to the public to insure that all efforts are made to minimize or ideally eliminate the hazards which may endanger man and the environment.

The vital element of a dam safety program in any country is the legislation that governs the regulatory aspects of dam safety (Price, 1990). Without government involvement there is no assurance that any guidelines or specifications will be implemented. The government should retain the authority and power to issue permits for procedures and for the operation and maintenance of dams and must periodically confirm that the organization responsible for the dam abides by the rules and regulations set out in the dam safety guidelines and/or specifications. The important issue is that a set of rules are in place and that one or more levels of government or government agencies is responsible to enforce these rules and regulations. An example of a country who has gone to this extreme is Switzerland. For instance, the Swiss *Dam Regulations Act* stipulates that all equipment and monitoring methods proposed for use on Swiss dams are subject to approval by the Swiss Federal Surveillance Authorities (ICOLD, 1989).

Table 3.1 displays that in over half of the countries (66%) the majority of large dams are owned and operated by either federal or provincial organizations. In addition, most dam owners already have a separate department or directorate responsible for the control and implementation of their surveillance programme. Therefore, by having some group or body responsible for the implementation of a surveillance program already in-place, this should give national committees more bargaining power in persuading the government to legislate dam monitoring.

Considering that over 89% of the countries still use both geodetic and geotechnical methods to monitor their dams, it is startling to find out that in only 14% of countries the authors made any comments or references that they actually designed a geodetic system when equipping dams with geodetic instruments. Another surprising fact is that surveyors have been employed in dam deformation monitoring in also merely 14% of the countries. Although these two items go hand-in-hand, Table 3.1 illustrates that there is no correlation between them. This may not be totally correct, but the results are strictly based on the facts reported by the countries' representatives. However, if the two were assumed to be correlated there would still be only 24% that would make full use of surveyors and geodetic methods to monitor dams, which is not a significant improvement from 14%.

Today when every year, dam safety is being seriously affected by the aging of the structure, like the safety legislation dilemma, this situation is uncalled for. The safety of all dams is particularly difficult and complex at the best of times. For many dams, although the most critical time is during its first filling, it may take several years before any adverse conditions become apparent (Jansen, 1980). For example, with concrete dams the damage from alkaline reaction may not be apparent until it is too late. In most cases, one method of monitoring is not sufficient to confirm or even make any reliable conclusions of the causes of the deformation. A prime example is the aforementioned Mactaquac Dam in Fredericton, New Brunswick (section 2.2.2). Surveyors at the University of New Brunswick used observations from geodetic and geotechnical/structural instrumentation in one integrated analysis to confirm that the alkali-aggregate reaction was the prime cause of the abnormal structure deformation and behaviour of the concrete.

In addition, the fact that surveyors are not included in dam deformation monitoring indirectly underlines that there is a lack of collaboration and communication between professionals such as Geotechnical, Structural, and Surveying Engineers on a global scale. Chen and Chrzanowski (1986) also noted that in the majority of the cases, Surveying Engineers have not been considered in the interpretation of deformations. In the area of geodetic deformation surveys, a monitoring team consisting of unqualified and inexperienced personnel can lead to careless surveillance and misleading data which would defeat the purpose of a monitoring system and would consequently have serious implications on the safety of the dam. A reliable dam safety program is one that calls for an organization with a multi-disciplinary use of talent. For example, the cooperation of Surveying Engineers, who are very knowledgeable on data acquisition and specialists such as Geotechnical, Structural and Rock Mechanics Engineers who have an intimate knowledge of the behaviour of structures, soils and rock, is indispensable to the successful interpretation of the measured results and therefore minimize the uncertainty inherent in all dams. By participating in the interpretation of deformation surveys, Surveying Engineers would have the added benefit of gaining a good understanding of deformable bodies, which in turn would contribute to the optimum design of monitoring schemes (Chen and Chrzanowski, 1986).

The ideal case would be to have the proposed multi-disciplinary model involved in all phases of the project, including the design and construction stage and as part of the technical staff that is responsible for the surveillance of the dam throughout its life span. Engineers realize that failures occur where the dam and its foundation is weakest, in which case the design focuses on the potential weaknesses. Having prior knowledge of these weaknesses, the composition of the dam, the foundation, the surrounding area and the anticipated behaviour of the dam, experts such as Surveying and Geotechnical Engineers can advise Structural Engineers on the best available surveying and geotechnical equipment and methods that can be feasibly implemented during and after construction.

Although it has not been summarized in Table 3.1, the review indicates that Canada is the only country that has developed the concept of a global integrated monitoring systems (see section 2.4.1), in which observations from geodetic and geotechnical instrumentation are simultaneously analyzed to determine the behaviour of a deformable body.

Table 3.1 also shows that countries such as Italy, France, Germany and UK take dam monitoring quite seriously by going so far as to establish a separate organization dedicated specifically to the development of new monitoring equipment. The remaining two items in Table 3.1, automation and seismic monitoring, are strictly there as references for those who will be responsible for drafting the guidelines. The interested party can refer to those countries for additional information when implementing these two components into the guidelines.

3.3 Instruments Used to Monitor the World's Large Dams

The major types of monitoring instruments reported by the 29 countries are summarized in Tables 3.2a and 3.2b. There are a number of factors considered when selecting the complexity and extent of monitoring system used on a dam. These include: the potential loss of life, the type of dam, the size of the dam, the environment within which the dam is to be constructed, the unique features of the dam, the remoteness of the site, and to a large extent, the current state of the economy at that time. The review shows that some of the differences in the types of instruments used between countries lie in the level of sophistication of the instruments and where the instruments are used within the dam. For example, South Africa takes a rather simplistic approach to dam monitoring. In South Africa, dams are situated in remote areas hundreds kilometers from the organization responsible for dam safety and therefore, authorities do not consider it feasible to have sophisticated equipment on site. However, for the exception of the newly developed instrumentation and monitoring techniques (Table 3.3), the survey indicates that generally, there are no significant differences between countries in the types of instrumentation used in both concrete and embankment dams.

Table 3.2a
Summary of Instruments Used to Monitor Concrete Dams

Quantity Measured	Instrument or Method Suggested or Used	Remark
Uplift and pore pressures	· Uplift pressure cell (hydrostatic type) · Piezometer (stand pipe, twin-tube hydraulic) · Concrete temperature transmitter · Pressure cells (pneumatic, hydraulic, or electrical) · Monometric cell (manometer) · Closed borehole	
Hydraulic loads	· Load cell · Manometer	· To measure water loads acting on the dam.
Water level	· Levelling staff · Hydrostatic balance · Pressure balance · Staff gauge · Float	
Relative Displacements	· Instruments for determining horizontal and vertical movements primarily within the internal structure of the dam.	

Quantity Measured	Instrument or Method Suggested or Used	Remark
	· Plumb line or pendulum (direct or inverted) · Extensometer (wire, rod, tape, multi-point, multi-rod, multi-wire, surface or internal) · Wire alignment · Sliding micrometer · Collimation (or optical alignment) · Inclinometer (normal mode) · Deflectometer · Rockmeter · Foundation deformation meter · Embankment settlement points · Hydrostatic levelling · Strain gauges or meters	· Instruments such as extensometers (for the exception of the CERN Distinvar which can only be used in the horizontal plane) they can be used to measure the change in length between two or more points in any plane. · The normal mode (probe) inclinometers are usually used to measure lateral ground movements in abutments, foundation or embankment.
	· Instruments that can be used to measure tilt (rotation with respect to a vertical plane) or rotation with respect to an horizontal plane.	
	· Tiltmeter (or clinometer) · Inclinometer (in a fixed position) · Deflectometer · Pendulum (direct or inclined)	· Inclinometer in the fixed mode is used to measure progressive changes in the angle of inclination at set locations within the casing of the borehole.
Stress/Strain	· Teleformeter · Telepressmeter · Stress/strain meters or gauges (Carlson or vibrating wire electrical resistance types)	
	· No- or zero-stress strain meters	· Used to obtain data regarding the volume changes that take place within the concrete in the absence of loads.
	· Flat jacks	· For surface stress and rock stress.
	· Relief Methods	· Borehole devices with stress tension tubes.
	· Creep cells	· To provide the evolution of the deformation and data to determine stress.
	· Electric deformeter	· Embedded in concrete to measure local deformation to check for stress.

Quantity Measured	Instrument or Method Suggested or Used	Remark
	· Sliding micrometer · Contact strain meter · Flat plate	
Absolute displacement	· Precision levelling · Triangulation (angles) · Trilateration (distances) · Collimation · Traversing (angles) · Triangulateration (angles and distances)	· Absolute displacement of points is still being determined by traditional geodetic methods. The advancements in this area has been primarily with the equipment used to perform the surveys (see Table 3.3)
Seepage leakage and flow	· Open trench measuring flumes (e.g., Parshall type) · Weirs (V-notch, rectangular, trapezoidal) · Volumetric measurements with calibrated containers · Drainage curtains · Leakage meters · Visual monitoring · Venturimeter · Sonar measurements	
Concrete temperature	· Thermometer (resistance type) · Thermocouple · Face thermometer · Borehole thermometer · Construction thermometer	· Abandoned after construction.
Seismic activity	· Velocity transducers · Microseismographs	
	· Seismographs	· Seismographs are used to record earthquakes near the reservoir area.
	· Strong motion accelerographs	· Strong motion accelerographs are used to detect ground motion in the foundation and at different points on the dam

Table 3.2b
Summary of Instruments Used to Monitor Embankment Dams

Quantity Measured	Instrument or Method Suggested or Used	Remark
Pore pressure	· Piezometers (e.g., foundation electric vibrating wire, pneumatic, hydraulic, single or stand pipe, twin-tube, and porous-tube type)	· Piezometers are the most common type of instruments across the world used to measure water levels, and excessive hydrostatic and pore pressure underneath (open system) or within the embankment (closed system). · They can be used in an open system (single- or twin-tube) where the measurements are made from the surface and the water level is generally below the surface or in a closed system (pneumatic, hydraulic, electric) where the measurements are made remotely and the water level can be at any location.
	· Pore pressure gauge · Observation well · Pore pressure measuring weir	
Total pressures and Loads	· Telepress meter · Earth pressure cell (electric, pneumatic) · Total pressure gauge · Piezometer · Flat plate device · Load cell · Stress meter	· Total pressure cells are used primarily to monitor total static pressure acting on a plane surface. They help to define the magnitude of the major stresses.
Water Level	· Hydrostatic balance · Pressure balance · Float · Levelling staff · Staff gauge · Light gauge · Acoustic gauge	
Relative Displacement	· Instruments used to measure relative vertical and horizontal movements.	

Quantity Measured	Instrument or Method Suggested or Used	Remark
	· Radiosonde system	· A radiosonde system measures deflection in the vertical, horizontal or at any angle in the dam)
	· Inclinometer (normal mode) · Extensometer (wire, rod, tape, multi-point, multi-rod, multi-wire) · Pendulum (inverted or direct) · Surface settlement points · Strain gauges or meters · Relative shear displacement device · Wire alignment (e.g., invar wire) · Cross-arms · Electromagnetic torpedoes in horizontal tube · Optical alignment · Shear strips · Levelling · Hose levelling devices · Deflectometer	
	· Devices used to measure rotations or tilts	
	· Tiltmeter (clinometer) · Inclinometer (fixed mode or face slope type) · Pendulum (inverted or direct)	
	· Devices to measure cracks internal or external of the dam.	
	· Deflectometer · Vibrating wire extensometer · Micrometer · Deformeter · Dilameter	· Vibrating wire extensometers are used extensively in measuring movement and cracks of earth dams near the abutments.

Quantity Measured	Instrument or Method Suggested or Used	Remark
Settlement	· Settlement cells (pneumatic, hydraulic) · Settlement meter or gauge (vertical type) · Hydrostatic settlement gauges · Settlement plates · Magnetic disk around inclinometers · Hose levelling device · Vertical rod or wire extensometer · Settlement magnets · Hydraulic levels · Settlement points · Cross-arms	
Absolute displacement	· Precision levelling · Triangulation (angles) · Trilateration (distances) · Collimation · Traversing (angles) · Triangulateration (angles and distances) · Hydrostatic levelling	· Same remarks as for concrete dams Table 3.2a).
Seepage and flow measurements	· Open trench measuring flume (e.g., Parshall type) · Weirs (V-notch, rectangular, trapezoidal) · Volumetric measurements with calibrated container · Drainage curtain · Leakage meter · Observation well · Gauging station · Discharge from piezometers · V-notch cell · Standard cell · Sonar gauges	

Quantity Measured	Instrument or Method Suggested or Used	Remark
Stress and Strain (in dam and foundation)	· Face strain meter · Pressure cell · Horizontal strain gauge · Sliding micrometer · Uniaxial stress meter · Zero-stress strain meter · Extensometer · Flat jack	· Earth pressure cells with a piezometer installed near it gives effective stress. · Strain is measured where there is potential cracking (e.g., near the abutments or between different materials of the embankment dams) · Flat jacks are used for determining the state of stress of the rock beneath or in the abutments of the dam.
Seismic activity	· Seismicscope · Seismic triggers · Peak acceleration recorders · Strong motion acclerographs · Seismographs	
Analysis of seepage	· Turbidity meters · Hydrochemical analysis device	
Temperature of soil or foundation	· Thermometer (electric resistance type)	

Table 3.3
Recent National Developments in Instrumentation/Methods for Monitoring Dams

Country	Equipment or Method	Remarks
Austria	Acoustic emission devices	To measure cracks in concrete or rock masses.
	Laser plumb line	Used as an alternative to wire plumb lines for measuring displacement of points in inclined shafts.
	Magnetic measuring devices	To detect asphaltic concrete core wall deformation.
	Special level indicating devices	To detect the interior deformation of a dam.

Country	Equipment or Method	Remarks
	Intelligent hand-held computer	To record measurements of those instruments that have not yet been automated.
Brazil	Horizontal plate gauges	Used to monitor horizontal displacement normal to the axis of the dam.
China	Coordinameter	Electronic sensor capable of measuring displacements up-to 50 mm with an accuracy of ± 0.10 - 0.18 mm.
	Remotely controlled laser alignment system	
	High-precision hydrostatic level	Fully automatic, capable of measuring tilts with an accuracy of ± 0.001 second of arc.
France	Telependulum (induction type)	A pendulum that can be read remotely.
	Distofor	Detects a continuous log of movement along a borehole with no friction between the sensor and the borehole.
	Extensofor	Similar to the distofor except that it is mobile and it is lowered into the borehole each time a reading is required.
	Ultrasonic flow meter	Installed in weirs to determine water levels (accuracy of ± 1.0 mm)
	Optical Telependulum	It can determine the position of a plumb line without contact with an accuracy of 1/100 mm.
	SAFTEL (safety telemeasurements)	A monitoring tool used to remotely retrieve measurements taken by electronic devices.
	TAM-TAM	A decentralized tool designed to process measurements taken on the structure. The measurements can be associated with monitoring or with the environment, reservoir management, operating procedures, etc.

Country	Equipment or Method	Remarks
	Thermodynamic monitoring	A monitoring method which consists of placing a group of thermometers, extensometers and total pressure cells every 5 m vertically in a selected section of the dam. It has been used to determine the effects of external temperatures on the dam during construction.
Germany	Combination of automatic theodolite/tachometer system and differential GPS	This is only a proposed system.
	Crack-detection sensors	Designed to continuously monitor the formation and sizes of cracks in concrete dams and heavy concrete structures.
	High energy EDM	The high energy allows the measurement of short distances (up-to 200 m) to natural flat surfaces without the use of reflectors (e.g., EDM Pulsar 500).
Italy	Ladir laser systems	Used for surveying the dynamic displacement of dams.
	Thermography systems	Used to study the surface's thermal condition.
	Sonic log and cross-hole	Used to diagnose the state of health of the concrete.
Japan	Optical fibre cable	For transmitting information (a very useful countermeasure against electronic storms).
	Ultra red laser	For automatic distance measurements.
	Submersible remote control robot system	A submerged inspection systems to inspect dam gates, piers, foundation and slopes.
Netherlands	Ground probing radar	Used to detect erosion of channels behind stone blocks of estuary dams.
Norway	Failure detector	A detector which warns of a partial or total failure of the dam (a wire will rupture opening the circuit attached to the detector).

Country	Equipment or Method		Remarks
South Africa	Borehole stress meter		A vibrating wire instrument installed in a borehole to measure stress variations in concrete.
	3-Dimensional crack meter		A 3-D displacement crack monitoring device with an accuracy of ± 1.0 mm.
Spain	Seepage cloth method		A special designed cloth which when placed over a concrete surface any seepage water will tarnish the cloth, indicating the general shape of the infiltrated zone and an approximate rate of the seepage.
Switzerland	Electronic theodolites	Leica (Wild) T2002	Equipped with microprocessing controlled biaxial sensors (electronic tiltmeters) which can sense the mislevelling of the theodolite to an accuracy better than 0.5" and automatically corrects both vertical and horizontal direction read outs.
		Leica (Wild) T3000	
	EDM	Leica (Wild) DI2002	Offers a standard deviation of ± 1.0 mm over short distances (up to 200 m)
		Leica (Wild) DIOR 3002	Uses high energy transmitted signal making it possible to measure short distances (up to 200 m) directly to walls or natural flat surfaces with an accuracy better than 10 mm.
	Total station	Leica (Wild) TC2002	Combines the theodolite Leica (Wild) T2002 with the EDM Leica (Wild) DI2002 linked to a computer to create a total survey station which allows for direct field measurements (simultaneously) of distances and horizontal and vertical positions of the observed points.
		Leica (Wild) APS	Fully automatic monitoring systems based on computerized and motorized total station. Used for continuous monitoring of deformation.
		Georobot III	

Country	Equipment or Method		Remarks
	Levelling	Leica (Wild) N2000	Digital automatic levelling systems with height and distances readout from encoded levelling rods.
		Leica (Wild) NA3000	
	Optical plummets	Leica (Wild) ZL (Zenith)	Both can be equipped with laser and offer an accuracy of 1/20,000.
		Leica (Wild) NL (Nadir)	
	3-Dimensional coordinate systems	Leica (Wild) TMS	Two or more electronic theodolites linked to a microcomputer creating a 3-D positioning system with on-line calculations of coordinates.
UK	Settlement index (S_I) $S_I = \frac{S}{1000 \cdot H \cdot Log(t_2/t_1)}$		The index is used to interpret the results of crest settlement to asses the performance of embankment dams.
	Index ratio (IR) $IR = (\sigma_{ha}/\gamma_w h_w)$		Used as an indicator of the susceptibility of hydraulic fracture (i.e., if IR > 1.0 hydraulic fracture is unlikely to occur).
USA	Stream potential method		Both are used to monitor seepage in embankment dams. The stream potential method is based on the principle that water which is low in total dissolved solids generates an electrical current when forced to flow under laminar (no turbulent) flow conditions through porous earth material. Whereas the thermotic surveys is based on the principle that flowing ground water influences the near-surface soil temperature.
	Subsurface temperature monitoring (thermotic monitoring)		
	Electronic distance measuring equipment (EDME)		An example is Terrameter LDM2 (by Terra Technology), a dual frequency instrument which can give an accuracy of better than 1 ppm.

Country	Equipment or Method	Remarks
	Continuous deformation monitoring systems (CDMS)	A fully automated GPS system to perform high precision surveys of the dam structure. A trial system installed on an existing dam reported accuracies of ± 3 mm rms both horizontally and vertically over a 300 m baseline.

Notwithstanding the significant difference in the behaviour and construction between concrete and embankment dams (see section 2.2), Tables 3.2a and 3.2b show that there is a considerable overlap in the types of instruments used to monitor both types of dams. Generally, the greatest differences lie in how and where the instruments are used in relation to the dam and its foundation. For example, piezometers in embankment dams are generally used to measure the hydrostatic pore pressures within the internal structure of the dam and its surroundings, whereas in concrete dams they are generally located in the foundation rock to measure the uplift water pressure (see Figure 2.8).

Overall, Tables 3.2 and 3.3 illustrate that there is an array of different types of simple and sophisticate instruments being used and developed to monitor dam deformations. Consequently, this makes the task of selecting the optimum instruments which are best suited to monitor the desired deformation, where to locate them, and how to combine them into one integrated monitoring scheme very challenging for the designers of monitoring systems (Chrzanowski et al., 1992).

3.4 Guidelines, Standards and Specifications for Dam Monitoring

Section 3.2 established that, to date, only three countries have developed national standards and specifications for dam monitoring. However, Table 3.4 shows that in the majority of the remaining countries, when designing or selecting a monitoring system, dam owners use either guidelines developed by their own National Committees or those published by ICOLD. Table 3.4 provides a fairly comprehensive list of international publications for those who are interested in obtaining more details on how the countries have structured their monitoring guidelines. In addition to those publications quoted in Table 3.4, other sources which provide reputable guidelines on the techniques and instrumentation for monitoring large dams are ICOLD Bulletins N°21 (ICOLD, 1969), N°23 (ICOLD, 1972), N°60 (ICOLD, 1988) and N°68 (ICOLD, 1989).

From a surveyor's perspective the greatest disadvantage with these guidelines is that they do not provide any instructions for the design and processing of the geodetic monitoring network. Surprisingly, according to Chrzanowski et al. (1992) although there are some reputable books on specialized geodetic instrumentation, there is no current manual or book which covers all aspects of geodetic monitoring.

Table 3.4
Summary of Monitoring Guidelines and/or Standards/Specifications Used by Various Countries

Country	Guidelines and/or Specifications Used for Monitoring
Argentina	· Specifications developed by individual dam owners based on international standards set out by ICOLD Bulletins and other publications
Australia	· Specifications developed by individual dam owners based on ANCOLD guidelines · ANCOLD (1976) - Guidelines Operation, Maintenance and Surveillance of Dams · ANCOLD (1983) - Guidelines for Dam Instrumentation and Monitoring Systems

Country	Guidelines and/or Specifications Used for Monitoring
Austria	· ICOLD Bulletin N° 41 (for measurement frequencies)
Brazil	· BNCOLD Guidelines based on those published by ICOLD
Canada	· British Columbia - Operation and Maintenance Manual based on ICOLD Standards · Quebec - Technical Regulations, Standards and Procedures · Manitoba - Procedures based on guidelines published by US Army Corps of Engineers and ICOLD's Check List on Dam Safety · Alberta - Proposed Standards and Specifications for Deformation Surveys (proposed by the University of Calgary Alberta)
China	National Specifications: · Technical Specifications for Monitoring of Concrete Dams (1992) (in Chinese) · Specifications for Embankment Monitoring (in draft)
Cyprus	· Guidelines specified by the designer of each dams
Czechoslovakia	· National Standards (in Czechoslovakian)
France	· Guidelines as specified in their National Regulations
Germany	· Guidelines prepared by members of the State Dam Committee which provide the minimal level for monitoring and control
Greece	· Specifications as stipulate by the dam owners
Hungary	· National Standards/Specifications (in Hungarian)
Italy	· ITALCOLD Guidelines
Japan	· Manual of Instrumentation and Monitoring of Dams (1964) (in Japanese) · Criteria of Monitoring and Inspection of Dam Structures (1973) (in Japanese) · Guidelines of Design and Monitoring of Dams (1981) (in Japanese) · Guidelines of Monitoring of Safety of Dams (1982) (in Japanese)
New Zealand	· Specifications as stipulated by individual dam owners
Norway	· The designer is responsible for the monitoring program (or specifications) based on the Norwegian Code of Practice, but the specifications are subject for approval by the regulating authority
Portugal	· Developed by individual dam owners based on the country's Code of Practise
South Africa	· Department of Water Affairs' (DWA) Steps to the Design of a Monitoring System (for more details see Table I.23) · ICOLD Bulletin N° 41
Spain	· SPANCOLD is in the process of preparing general specifications (a draft is anticipated some time in 1992)

Country	Guidelines and/or Specifications Used for Monitoring
Sri Lanka	· SLNCOLD Bulletin N° 2
Switzerland	· Specifications developed by individual owners based on the Swiss Dam Safety Regulations (SNCOLD, 1985) · Proposed National Specifications (Biedermann et al., 1988)
Thailand	· Dam owners follow the Dam Safety Code of Practise (adopted from Finland's Natural Board of Waters and Environment) and the Safety Evaluation of Existing Dams (adopted from the U.S. Bureau of Reclamation)
UK	· Engineering Guide to the Safety of Embankment Dams (Building Research Establishment (BRE) Report BR71, 1990) · Engineering Guide to Seismic Risk to Dams in the United Kingdom (published by BRE)
USA	· Federal Guidelines for Dam Safety (1979) · General Consideration on Reservoir Instrumentation (1981) by USCOLD Committee on Measurements · USCOLD Publication, General Considerations Applicable to Performance Monitoring of Dams (1986) · Concrete Dam Instrumentation Manual (1987), US Bureau of Reclamation · Embankment Dam Instrumentation Manual (1987), US Bureau of Reclamation · Instrumentation for Concrete Structures (1980), Engineer Manual, EM 1110-2-4300, US Corps of Engineers · Instrumentation of Earth and Rockfill Dams: Part 1 of 2, Groundwater and Pore Pressure Observations, (1971) and Part 2 of 2, Earth Movement and Pressure Measuring Devices, (1976), Engineer Manual, EM 1110-2-1908, US Army Corps of Engineers · General Considerations on Reservoir Instrumentation, report by USCOLD Committee on Measurements (1979/1981) · Seismic Instrumentation in Dams (1975), USCOLD Committee on Earthquakes · Geotechnical Instrumentation for Monitoring Field Performance (1988), by J. Dunnicliff · Components One (Safety Inspection of Dams) and Three (Data Review, Investigation and Analysis, and Remedial Action for Dam Safety) of the Training Aids for Dam Safety (TADS) Program established by the *ad hoc* steering committee comprising of USBR, COE, FEMA, ASDSO and USCOLD

Chrzanowski et al. (1992) suggests that the few countries who developed national standards and specification, mainly Eastern European countries, including China, developed them during the time when they were still a part of the "communist block."

Consequently, these specifications were developed for unrealistic conditions under government dictatorship and ownership of all dams within those countries.

Tables 3.5a and 3.5b illustrate two of the best examples of monitoring specifications collected from the survey. Table 3.5a are specifications that are currently being used by New Zealand's major dam owner, the New Zealand Electric Corporation (ECNZ), and Table 3.5b are specifications that have been proposed by the Swiss National Committee on Large Dams (SNCOLD) as their national standards/specifications. Note that ECNZ's specifications reflect only geodetic observations however, SNCOLD's specifications are more complete (i.e., they include the required accuracies of measurements made by both geodetic and geotechnical/structural instrumentation). Unfortunately the details of the national specifications from Hungary and Czechoslovakia, two of the three countries that have implemented national monitoring standards/specifications, could not be reproduced or commented on since they were not provided in English.

Table 3.5a
Sample Specifications Currently Used by the New Zealand Electric Corporation (ECNZ)
(Campbell, 1992)

Quantity Measured	Recommended Accuracy
Horizontal observation	· the standard deviation of the final mean of direction/angle should be $\sigma \leq \pm 1.5''$
Vertical angles	· the standard deviation of the final mean angle should be $\sigma \leq \pm 2.0''$
Height by vertical angle	· the accuracy of the final height should be ≤ ±5.0 mm
Distances	· all distances are to be accurate to within ≤ ±3.0 mm

Quantity Measured	Recommended Accuracy
Precise levelling	· maximum difference between pairs of reading between two consecutive marks should be ≤ ±0.7 mm · maximum difference between forward and backward sights between bench marks should be ≤ ±3.0mm√km · for concrete structures - maximum difference between two consecutive marks should be ≤ ±0.3 mm · precise levelling is carried out to 1.0mm√km
Optical pluming	· accuracy of the final results should be ≤ ±3.0 mm
Crack or joint movement	· cracks or joints with markers < 500 mm apart a measurement accuracy of ≤ ±0.2 mm is required
Offsets	· accuracy of the observations should be ≤ ±2.0 mm

Table 3.5b
Sample Specification for Monitoring Concrete Dams Recommended by the Swiss National Committee on Large Dams (SNCOLD) (Biedermann et al., 1988)

Quantity Measured	Examples of Measuring Method or Device Used	Recommended Accuracy
Water level	·Pressure balance ·Float ·Staff gauge ·Manometer	± 10 cm
Concrete temperature	·Electric thermometer	± 1.0°C
Earth pressure	·Earth pressure cell	± 5% of the total overburden (0 to 3 N/mm^2
Displacement along a vertical line	·Plumb line (directed or inverted)	± 0.2 mm ± 1% of 1.5M (where M = max calculated deflection)
Displacement along a horizontal line	·Vertical alignment	± 0.2 mm ± 1% of 1.5M (where M = max calculated deflection)
	·Levelling	± 1.0 mm
Variations in length and deflections along boreholes	·Rod or wire extensometers	± 0.5 mm

Quantity Measured	Examples of Measuring Method or Device Used	Recommended Accuracy
Special displacements of individual points	·Triangulation/trilateration	≤ ± 3.0 mm (for measuring stations and important reference points) ≤ ± 5.0 mm (for all other points)
Movement of cracks and joints	·Micrometer ·Deformeter ·Dilatometer ·Deflectometer	± 0.05 mm
Local deformation to check stresses	· Electronic Deformeters (embedded in concrete with temperature measuring devices)	± 0.2 N/mm^2 (stress) ± 0.2°C (temperatures)
Quantity of seepage and drain water	· Volumetric measurements (with calibrated containers)	± 0.05 l/s ± 5% to 10% of 2M (where M = max expected discharge)
	·Weir ·Flumes	± 5% of 2M (where M = max expected discharge)
	· Venturimeters (measurement of pressure differential in pipes) · Sonar (measurement of velocity of flow in pipes)	± 5% of 2M (where M = max expected discharge)
Uplift and water pressures in foundation and rock joints	· Open borehole/stand devices (piezometers)	± 0.2 mm ± 1% of M (where M = total length of the borehole)
	· Closed borehole by pressure indication by high precision manometers	± 0.5 mm ± 1% of M (where M = total height between manometer and dam crest)
	· Pneumatic, hydraulic, or electrical pressure cells	± 0.5 mm ± 1% of M (where M = total height between cell and dam crest)

It should be noted that the standards and specifications for deformation surveys developed by the University of Calgary (Teskey, 1988) for the Alberta Environment Canada, are not considered very good examples of type specifications which can be readily adapted to dam deformation monitoring. The specifications do not only relate strictly to geodetic monitoring surveys, but they are also considered very vague and incomplete. For example, the specifications do not provide any information on the accuracies required to monitor dams, and they lack detail and information on the analysis of monitoring surveys. The type of information that the specifications provide includes: specifications on the construction of survey monuments, the proper use and procedures when setting-up geodetic instruments, and the major sources of errors and corrections that should be made in the observations (e.g., index of refraction, zero-error correction for EDMIs).

The only accuracies which could be correlated from the review are those given in Tables 3.6a and 3.6b. These tables give a range of recommended accuracies required to measure certain quantities within concrete and embankment dams. The review and the tables indicate that there is no common standard of accuracy requirements between countries, however the accuracies for concrete dams generally seem to be somewhat closer to each other. This may be due to the fact that concrete dams can be modelled more accurately than embankment dams.

Chrzanowski et al. (1992) recommend that:

(1) For concrete dams, the accuracy for monitoring both horizontal and vertical displacement should be around 1 to 2 mm.

(2) For embankment dams, the accuracy should be approximately 10 mm for horizontal displacements, and 5 to 10 mm for settlements during construction; and 5 mm and 3 to 5 mm for the horizontal and vertical displacement respectively, during normal operation.

Chrzanowski et al. (1992) also state that the accuracy (at the 95% probability level) of the monitoring measurements should be equal to at least 0.25 of the predicted value of the maximum deformation within the time interval of the repeated measurements.

Table 3.6a
Range of Accuracies Recommended for Monitoring Concrete Dams

Quantity Measured	Country			
	China	Hungary	Switzerland	New Zealand
Spatial horizontal displacement	±1.0 - 1.5 mm	±1.0 - 1.5 mm	≤ ±3.0 mm for measuring stations and important reference points ≤ ±5.0 mm for the remaining points	
Spatial vertical displacement	±1.0 - 1.5 mm		≤ ±3.0 mm for measuring stations and important reference points ≤ ±5.0 mm for the remaining points	
Crack movement			≤ ±0.05 mm	≤ ±0.2 mm (for markers < 500 mm apart)
Precise levelling		≤ ±0.2 mm or better	≤ ±1.0 mm	≤ ±0.3 mm

Table 3.6b
Range of Accuracies Recommended for Monitoring Embankment Dams

Quantity Measured	Country	
	China	Switzerland
Spatial horizontal displacement	≤ ±10.0 mm (during construction) ≤ ±5.0 mm (during normal operation)	≤ ±5.0 mm (for important points) ≤ ±10 mm (for other points)
Spatial vertical displacement	±5.0 - 10.0 mm (during construction) ±3.0 - 5.0 mm (during normal operation)	≤ ±5.0 mm (for important points) ≤ ±10 mm (during normal operation)

One important fact that should be included in the monitoring guidelines is that despite the recommended accuracies, once any abnormal deformations are noted, there should be no limit, other than economics, in striving to obtain the maximum attainable accuracy. The reason given, is that the greater the accuracy of the measurements, the simpler it will be to determine the cause(s) or the mechanism(s) of the unpredicted deformations (Chrzanowski et al., 1992).

3.5 Frequency of Measurements

One of the key objective of a monitoring system is to be able to detect any sign of abnormality in the behaviour of the structure reasonably early so that immediate corrective actions can be taken to prevent serious damages or even a major disaster from occurring. To achieve this objective a monitoring program has to be structured such that the number (frequency) of measurements are sufficient to detect the abnormality and yet not overly abundant that it becomes uneconomical. The frequency of measurements generally vary depending on the quantity measured (e.g., in embankment dams, seepage measurements are taken more often than horizontal displacement) and in which stage the measurement is taken (i.e., during construction, first filling, first 3 to 5 years or normal operations, or after a significant event such as a flood or an earthquake). In the case where a fully automatic data acquisition system is used, the frequency of measurements does not impose any problems (i.e., the frequencies can be preprogrammed for any desired time interval). The advantages and limitations of automation are well outlined by Chrzanowski et al. (1992). The countries that are considered to have well established automated monitor systems are listed in Table 3.1.

The frequency of measurements recommended by a number of countries in Appendix I are summarized in Tables 3.7a and 3.7b. Tables 3.7a and 3.7b indicate that, in the majority of the cases, there are considerable differences between countries in the required frequency of observations. The only indication where two or more countries agree on a particular frequency of an observable is where the tables do not have an entry "X" under the "minimum" column. This does not occur very frequently however, it does occur in concrete dams (Table 3.7a) significantly more often than in embankment dams (Table 3.7b). Moreover, the range of frequencies (maximum and minimum) tend to be closer in concrete dams than in embankment dams. Again, this may stem from the fact that concrete dams can be modelled more accurately than embankment dams.

Table 3.7a
Summary of Range of Frequencies for Instruments Used in Concrete Dams

Type of Instrument	During Construction		Initial Filling		During Normal Operation	
	Max.	Min.	Max.	Min.	Max.	Min.
Piezometer	1/week		1/day	1/week	1/week	4/year
Uplift Pressure	1/week		1/day	1/week	1/week	1/month
Observation Wells	1/week		1/week		1/day	1/month
Water Levels	1/week		1/week		1/month	
Seepage Measurements (weirs, flumes, etc.)	1/week		1/day	1/week	1/day	1/month
Visual Seepage Monitoring	1/week		1/week		1/month	
Concrete Temp. by Thermometer	1/day	1/week	1/week	1/2 weeks	1/month	
Joint & Crack Meters	1/week		1/day	1/week	1/2 weeks	1/month
Stress & Strain Meters	1/week		1/week		3/month	1/month
Deflectometers	1/week		1/day	1/week	3/month	1/month
Total Pressure Cells	1/week		1/week	1/month	3/month	1/month
Load Cells	1/week		1/week		1/month	
Pore Pressure	1/week		1/day	1/week	3/month	1/month
Foundation & Rock Deformation	1/day	1/week	1/day	1/week	1/2 weeks	4/year
Plumblines	1/day	1/week	1/day	1/week	1/week	1/month
Inclinometers	1/week		1/day	1/week	1/month	
Collimation			1/day	1/week	1/2 weeks	4/year

Type of Instrument	During Construction		Initial Filling		During Normal Operation	
	Max.	Min.	Max.	Min.	Max.	Min.
Embankment Settlement Points			1/day	1/month	1/month	2/year
Multipoint Extensometers	1/week		1/day	1/week	1/week	1/month
Geodetic Surveys (EDM, theodolites, etc.)	1/month		continuously (1/day)	1/month	1/month	1/year
Reservoir Slide Monitoring System			1/day	1/month	1/month	4/year
Rock Movement	1/week		1/day	1/week	1/2 weeks	1/month
Visual Inspection			1/day		1/day	1/month
Seismic Activity	continuously		continuously		continuously	

Table 3.7b
Summary of Range of Frequency for Instruments Used in Embankment Dams

Type of Instrument	During Construction		Initial Filling		During Normal Operation	
	Max.	Min.	Max.	Min.	Max.	Min.
Piezometers	Frequently (1/week)	1/month	1/day	1/week	1/week	2/year
Pore Pressure Cells	2/month		1/day	1/week	5/month	1/month
Total Pressure Cells (vibrating wire, pneumatic, other)	1/week	1/month	1/week	2/month	3/month	1/year

Type of Instrument	During Construction		Initial Filling		During Normal Operation	
	Max.	Min.	Max.	Min.	Max.	Min.
Seepage Measurements (weirs, flumes,etc.)	1/day	1/month	1/day	1/week	1/day	1/month
Observation Wells	1/2 weeks	2/month	2/week		1/week	1/month
Internal Vertical Movements Devices	frequently	each time a unit is completed	1/week	1/month	3/month	1/6 years
Foundation Settlement	frequently (1/week)	each time a unit is completed	1/day	1/month	2/month	1/year
Internal Settlement Sensors	frequently (1/2 weeks)	1/month	1/week	1/month	2/month	1/year
Inclinometer	frequently (1/2 weeks)	1/2 months	1/week	1/month	6/month	1/year
Extensometer	2/week	1/month	2/week	1/month	3/month	1/2 months
Tiltmeters	1/2 weeks	1/month	1/week	1/month	6/month	4/year
Measurement Points (embankment structural, surface)	1/2 weeks	1/month	2/week	1/month	3/month	1/3 years
Water Quality	1/2 weeks	1/month	1/day	1/month	6/month	2/year
Seismic Activity	continuously		continuously		continuously	
Geodetic Surveys (EDM, Theodolite, etc.)	1/month		1/week	1/month	4/year	1/year
Visual Inspection	1/month		1/day		1/day	1/moth

Notation: 1/day = one or a set of measurements per day.

1/2 weeks = one or a set of measurements every 2 weeks.

3.6 Analysis of Deformation of Large Dams

The basic principles of the types of analyses that are commonly used to model dam deformation have already been discussed in section 2.4. There is no doubt that the type and level of sophistication of the model used largely depends on the availability of electronic computers.

With the exception of few countries including Australia, Germany, New Zealand and Switzerland, who tend to lean towards the use of geometric analysis, the survey reveals that most countries employ the physical analysis (either statistic or deterministic) to model the structural deformation of dams. In addition, there are countries like Korea and Thailand who still apply a rather primitive approach to data analysis which consists of a graphical display of the temporal trends of individual observables.

Italy, is currently considered the leading nation in the physical modelling of dam deformation. Ente Nazionale per L'Energia Elettrica (ENEL), an Italian national power agency and Italy's largest dam owner, has been the key player in the development of the advanced computational procedures of the physical analysis. Of the three types of physical models (statistic, deterministic and hybrid), the deterministic and hybrid models are the most often used models for analysing the behaviour of Italians dams (ICOLD, 1989). A thorough description of the physical models and examples of the application of the models are given in ENEL (1980).

Following closely behind Italy, is France with the back-analysis approach. The back-analysis method is somewhat parallel to the hybrid model technique. It consists of using *in situ* measurements taken during and/or after construction to re-calibrate the deterministic model and make it react in the same manner as the dam. French experts claim that this method is better in predicting the behaviour for future stages of construction and operation. Another slightly different approach commonly used by the French, is to compare instrument readings with the design values calculated by analytical models of the finite element type; the mathematical model versus the actual structure (ICOLD, 1989).

Overall, the UK's experience and knowledge in the design and behaviour of dams have been primarily with embankment type dams. This stems from the fact that the majority of the dams within the scope of the country's reservoir act are embankment dams (some 2,000 dams). On the basis of this experience, the British Research Establishment (BRE), an organization dedicated to conducting research into the safety of embankment dams (Charles and Tedd, 1991), recently developed the so called *settlement index* and the *simple index ratio* (see Table 3.3). This is a purely empirical method which can be readily used by dam owners to quickly assess the performance of their dams. The *settlement index*, which is a function of the height of the dam, the crest settlement and the epochs between the completion of the dam and when the measurement of the crest settlement was taken, is used to interpret the results of the crest settlement in order to assess the performance of the dam. The *simple index ratio* is the ratio of the total horizontal stress acting in the direction along the axis of the dam over the full reservoir pressure at the depth of measurement. It is used as an indicator of the susceptibility to hydraulic fracture. Other examples of similar developments within the UK are given by Charles and Tedd (1991).

In the area of deformation analysis, the most significant finding of this study is that Canada, within the auspices of FIG, leads in the development of new concepts in the global integrated analysis of deformations in engineering and geoscience projects. The concept of global integration has been developed by the Engineering and Mining Surveying Research Group at the University of New Brunswick. With respect to modelling dam deformation, the main feature that sets the global integration method apart from all the other methods previously discussed is that it allows the utilization of both geodetic and geotechnical/structural observation into one simultaneous integrated analysis. This method has been successfully applied to dams in Canada and abroad (Chrzanowski et al., 1991). A brief description of this method is given in section 2.4.1. Although FIG is an international federation, due to the aforementioned lack of inter-disciplinary cooperation and insufficient exchange of information, FIG's developments have not yet been widely adapted in practice. This situation also exists at the national level, surprisingly in Canada who has given "birth" to the method.

CHAPTER 4

GENERAL REMARKS, CONCLUSIONS AND RECOMMENDATIONS

For those Surveying Engineers who are interested in pursuing a challenging career in dam deformation monitoring, this report provides them with some basic background information and examples of the major types of large dams that they will likely to encounter. More importantly, this report has summarized, analyzed and collated information from a worldwide review on dam deformation monitoring (Appendix I) to assist those individuals who will be responsible for drafting monitoring guidelines. Some of the conclusions and recommendations resulting from this work are supported by a recent UNB report sponsored by the U.S. Army Corps of Engineers (Chrzanowski et al., 1992). It is advised that before drafting the guidelines, the responsible individuals seriously consider the conclusions and recommendations presented by Chrzanowski et al. (1992) and forthwith. Note that the recommendations have been coupled with the following conclusions.

(1) The 29 (37%) of the 79 ICOLD member countries that responded to the survey own and operate approximately 32,700 (90%) of the world's total large dams, include the major world leaders in dam design and construction techniques, and represent a global

cross-section of the world. This, coupled with the fact that practically all of the national reports are based on the views and experience of large organizations who own and operate the majority of the large dams within their country, assures one that this review is fairly accurate in depicting the current status of monitoring and analysis of the deformation of large dams across the world. However, one is cautioned that the reports often generalize the status on the basis of a few selected examples, creating a very optimistic picture in comparison with the actual situation.

(2) The analysis of the review has shown that, on a global scale, surveyors have had very little or no involvement in the monitoring of dam deformation. This is somewhat surprising when the majority of the world's large dams are continually being monitored by geodic techniques (Table 3.1). In the past decades or so, technological advancements have forced professionals to become very specialized in their field of expertise. Consequently, this has contributed to a lack of understanding amongst professions and to some extent in overlaps in the developments of new technology. This is indubitably evident in the field of deformation studies. Reputable international organizations such as ICOLD and FIG, who have a common interest, and can very well benefit from eachothers works, unfortunately have not been known to cooperate or exchange any information. This is also true between individual professions and, to some extent, within a profession itself. For example, Civil Engineers have very little knowledge of the capabilities and educational background of Surveying Engineers, and vice versa. Surveying Engineers are capable of offering a service which no other profession can, but unless they understand the needs of others and properly promote themselves, they will not have the opportunity

to apply their expertise to their fullest.

Professionals have a responsibility to their profession and to society to educate themselves so that they can apply their skills in the manner which serves the best interest of the public. Therefore, it is recommended that senior surveyors and educators take on the added responsibilities to advise the general public and, particularly other professionals on all of the possible types of services that surveyors are capable of providing. Judging from the results of this review, dam deformation monitoring is certainly one area where surveyors need to promote and expose themselves more. This area offers an ideal opportunity where well rounded educated surveyors can excel and prove themselves. In dam deformation monitoring, surveyors will likely work with a number of other professionals including Civil and Geotechnical Engineers and Technologists. This exposure, in the long term, should benefit the surveying profession as a whole.

It is in the best interest of National Committees on Large Dams (e.g., CANCOLD, USCOLD) to insure that they are well informed of other national organizations or agencies that are involved with deformation studies, particularly FIG. When dealing with international organizations and sensitive research material, if required, it is advised that a Memorandum of Understanding (MOU) be negotiated between the interested parties. This will not only protect their proprietorship and copyright of their work, but it will guarantee a "free" exchange of information between the organizations.

(3) National monitoring standards/specifications are available in very few countries (Table 3.1). The same can be said about the existence of dam monitoring legislation (Table 3.1). To monitor dams, in most countries, dam owners and operators use some

form of guidelines which have been developed by one or more organization (Table 3.4). Some dam owners have established their own standards/specifications based on their own experience (Table 3.4). The analysis in section 3.4 indicates that there is no common standard between countries (Tables 3.6 and 3.7). Also, if one had to choose between the national specifications that have already been implemented and those proposed by individual organizations, none can serve as an example for direct implementation in the monitoring guidelines.

With the current technology in both geodetic and geotechnical instrumentation, at cost one may practically achieve almost any instrumental precision however, this may not be practical when, in most cases, only certain accuracies are required. The results of this research show that there is a definite need for a more detailed study to determine the actual requirement of the measurements' accuracies for both concrete and embankment dams. Furthermore, for each type of observation, the study should attempt to identify why a certain accuracy is required.

Most countries agree that the design of a monitoring system is entirely system dependant (i.e., the expected behaviour of the dam largely depends on the dam-type and its interaction with the foundation and surrounding geological environment). Realistically, it is practically impossible to prepare rigid national standards that are applicable to all dams. Monitoring standards/specifications must be designed to suit each individual dams however, there are a number of observations that are common to each major dam-type (i.e., concrete and embankment). It would, therefore, be feasible to structure the monitoring guidelines such that they can be readily "tailored" into detailed specifications to suite a specific dam. According to Chrzanowski et al. (1992), the processes that could, and perhaps should be standardized are: the calibration of instruments and the procedures for data analysis and management.

The realization of monitoring guidelines is largely dependent on the success of legislating monitoring of all large dams. As aforementioned, without government involvement there is no assurance that any guidelines or specifications will be implemented. For all practical purpose this would defeat the prime objective for having the guidelines. National Committees on Large Dams are in an ideal position to initiate the process of legislation. However, this should not refrain other responsible professions from becoming involved. That is, the professions that are directly affected by this issue should insure that they support their national committees what may be undoubtedly a very challenging task. Considering the government's agenda and the political environment in the country, and assuming that in most countries the implementation of a legislation is a very bureaucratic process, it may be a number of years before the government will even respond to such a request. Therefore, it is recommended that all possible efforts be made by national committees to communicate to their government the immediate need for monitoring legislation at the earliest conceivable time.

(4) There is an array of different types of instruments available for monitoring dam deformation (Tables 3.2a and 3.2b). However, with the exception of the recent developments in instrumentation and monitoring techniques (Table 3.3), there are generally no significant differences between countries in the types of instruments that they use. Although one method is preferred over the other, overall dams are still being

monitored by both geodetic and geotechnical means. The biases between the two techniques are commonly produced by a lack of specialists with a complete knowledge of both geotechnical and geodetic measurements.

Geodetic and geotechnical methods, in many ways, complement each other and create some degree of redundancy in the observations. Furthermore, when both types of observables are used in a simultaneous analysis, it is has been shown that one can improve his or her knowledge and understanding of the overall behaviour of the deformable body. The recent developed *global integration and global analysis* (section 2.4.1) is an example of a method that has successfully illustrate this concept. The method has been successfully applied, in Canada and abroad, to determine the causes of unforseen deformations in dams that no other technique or expert was able to explain. Although its been argued otherwise, the facts evidently support the need to continually monitor dams using both geodetic and geotechnical means.

(5) Overall, in the majority of the countries, the methods of the physical analysis are used at various levels of sophistication, with Italy leading the way. Canada, on the other hand, within the auspices of the FIG, is the single leading country in the development of the concept of the aforementioned *global integration and global analysis* technique. Unfortunately, with the exception of a few individual cases, the method has not yet been widely adapted in practise, in Canada or abroad. This may be due to the aforementioned lack of cooperation and communication between professionals and organizations who have the same interest.

The UK is the only country that has tried to generalize the use of the statistical method of the analysis by developing numerical indices (Table 3.3) which are used to describe the performance of dams.

In support of the above, it is recommended that FIG make an effort to inform ICOLD and its national committees of the concept of global integration so that it may be made known to all large dam owners. As aforementioned, it is beneficial to both organization to insure that they keep each other informed of any new developments on a regular basis.

It is also recommended that the global integration method be included in the monitoring guidelines. However, one must insure that the guidelines stipulate that this method be used only by an inter-disciplinary teams of experts consisting of Geotechnical, Civil, and Surveying Engineers specialized in both geometrical and physical analyses. The proper use of the integrated method requires an intimate knowledge on data analysis and the physical behaviour and modelling of deformable bodies. One is cautioned that if the method is used blindly by untrained individuals, the results may be misinterpreted therefore, falsifying any conclusions made from the analysis. In the case of dams, this may lead to structural problems and possibly serious safety implications.

(6) Another area where countries do not seem to agree upon, is with the frequency of the observations. Tables 3.7a and 3.7b show that there are significant differences between countries in the required frequency for both concrete and embankment dams. This certainly underlines that there is a great deal of uncertainty in the frequency of observables in all types of dams.

It is recommended that more research efforts be invested in this area. Anticipating that this will not be a simple process, the task should be a research topic in itself.

(7) Dam monitoring deals with a very complex and specialized area and therefore, it would only be appropriate that the guidelines be prepared by a responsible group of experts specializing in geotechnical, structural, and surveying deformation measurements. Furthermore, this group of experts should also become involved in the drafting of the aforementioned monitoring legislation so that the regulations introduced will be realistic and workable, with proper regards to safety.

(8) Additional recommendations which are supported by both this research and Chrzanowski et al. (1992) are: (a) a monitoring system of geodetic/geotechnical instrumentation should be designed simultaneously at the design stage of the dam in cooperation of the aforementioned group of experts, (b) in support of the preparations of the monitoring guidelines and specifications, there is a requirement for a manual which includes all current aspects of geodetic monitoring surveys, form the pre-analysis and design of networks to the interpretation of the analysis, (c) large dam owners should employ surveyors or individuals who are educated in the analysis of deformation measurements, and (d) a detailed study should be initiated to determine the minimum number and the type of instrument that must be included to monitor each dam-type (gravity dam, buttress dam etc.).

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APPENDIX I

WORLD WIDE STATUS OF MONITORING AND ANALYSIS OF DAM DEFORMATION

I.1 General

According to the *World Register of Dams* (1988) there were a total of 36,235 large dams ($h > 15$ m) in operation around the world in 1988. This includes 29,974 embankment (earth- and/or rock-fill) dams, 4,180 gravity and 1,592 arch dams. About half of the total number of large dams are in China (18,820). USA with a total of 5,469 large dams ranked second and Canada seventh with 608. Table I.1 lists the number of dams broken down into the major types which are owned by the top ten ICOLD member countries. Between 1951 and 1986, an average of 337 dams were being constructed per year, excluding China. In China the average rate was 523 dams per year. The former Soviet Union, instead of listing 132 dams, it should probably account for 2,000 or 3,000 dams once those built by the Ministry of Agriculture and local authorities are added. This would rank the Soviet Union third behind China and USA.

There are a total of 79 countries registered with ICOLD. In order to obtain information on the procedures used in monitoring and analysis of dam deformations, a questionnaire (see Chapter 1) was forwarded to representative of all the ICOLD member countries.

A total of 29 countries (37%) from the 79 surveyed responded: Argentina, Australia, Austria, Bangladesh, Brazil, Canada, China, Cyprus, Czechoslovakia, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Netherlands, New Zealand, Norway, Portugal, South Africa, Spain, Sri Lanka, Switzerland, Thailand, United Kingdom (UK), United States of America (USA) and Uruguay. The information in this appendix is based on a collection of material from the questionnaire and from available literature, particularly from ICOLD Bulletins, Proceedings of ICOLD International Congresses, reports from the FIG Study Group on Deformation Measurements and other relevant publications. More emphasizes has been given to USA and Canada. Note that the order in which the countries are reviewed is strictly in alphabetical order.

Table I.1
Number of Dam Types by Country
(after *World Register of Dams*, [1988, pp.19-21])

ICOLD Member Countries	Dam Types				
	Embankment	Concrete/Masonry			Total
		Gravity	Arch & Multiple Arch	Buttress	
1. China	17,473	539	785	23	18,820
2. USA	4,694	537	192	36	5,459[*]
3. Japan	1,484	674	52	18	2,228
4. India	998	138	1	-	1,137
5. Spain	151	515	47	24	737[#]

ICOLD Member Countries	Dam Types				
	Embankment	Concrete/Masonry			Total
		Gravity	Arch & Multiple Arch	Buttress	
6. Korea (Rep of)	675	15	-	-	690
7. Canada	387	195	9	17	608
8. UK	413	91	17	14	535
9. Brazil	391	107	8	10	516
10. Mexico	343	144	11	5	503
Remaining 69 Countries	2,965	1,225	611	201	5,002
TOTAL (%)	**29,974 (82.72)**	**6,261 (17.28)**			**36,235**

Note: * According to the USCOLD Register of Dams currently there are 5,469 dams in the USA (Sharma, 1992).
As of December 1991 Spain registered 1,031 dams (Yagüe, 1992).

I.2 Argentina

Argentina has 98 large dams officially registered, some of which are monitored using solely geodetic instrumentation or both geodetic/geotechnical instrumentation (Aisiks, 1992).

Argentina has no national standards for dam monitoring. There is, however, a legislation stating that each of its 25 provinces is responsible for all dams under their jurisdiction. The current privatization of the majority of the federally owned state companies will force the State Commissions to enforce supervision and monitoring of dams by the new owners. Currently, dams owned by state organizations such as Agua y Energia Electrica S.E. and Hidronor S.A. have formulated their own specifications. These specifications are based on the international standards set out by the ICOLD bulletins and other publications.

The standard practice is to duplicate the instruments at critical points in the monitoring system or by observing the same point using two distinct types of instruments based on different principles (e.g., plumb line & traverse, and settlement gauge & levelling). Other normal practices adopted by Argentina's dam owners is to use automated data acquisition systems and seismic instrumentations in the monitoring scheme. Surveillance of dams is conducted daily by a full time staff observing and detecting any discrepancies from the regular behaviour (Naum and Aguilera, 1982).

The weakness in the monitoring system lies with the geodetic survey systems and the methods used in analyzing the data. For example, in the Alicura Dam, in the Northwestern Argentina, the geodetic network is not accurate enough to detect small displacements in the most critical areas of the dam. Instead, the data from the extensometer, pendulums and load cells are used to detect these small changes (Pujol and Andersson, 1985). For the deformation analysis, the geodetic and geotechnical data are analyzed independently. Furthermore, the geotechnical data is separated and analyzed using different numerical models. Stress-strain Models are used to analyze data from load cells and strain gauges and Seepage Models are used to analyze data from piezometers (Botta et al, 1985). There is no one common method of analysis that combines the data from geodetic and geotechnical instrumentations into one integrated monitoring scheme to determine the overall behaviour of the structure.

A typical monitoring scheme used for deformations in Argentina is summarized in Table I.2. It lists the types, numbers and location of the instruments installed and the parameters measured within the Alicura Dam (Pujol and Andersson, 1985). The reader is referred to Botta et al. (1985), Pujol and Andersson (1985) and Naum and Aguilera (1982) for a more comprehensive description on the behaviour and the installation of the instruments and the numerical models applied to the Alicura Dam.

The above information is the most current information found on dam monitoring in Argentina. According to Mr. E.G. Aisiks, Chairman of the Argentina National Committee on Large Dams, the references provided give a good representation of deformation monitoring of dams in Argentina (Aisiks, 1992).

Table I.2
List of Instruments Installed in the Alicura Embankment Dam, Argentina
(after Pujol and Andersson [1985, pp. 394-397])

Measured Parameters	Instrument Type	Instrument Location	Qty.
Water Pressures (pore-water & interstitial pressures)	Electrical piezometers, vibrating wire	Foundation Core Filters, shells Left bank	60* 49* 7* 40*
	Pneumatic piezometers	Core Filter, shells	22 13
	Open piezometers Casgrande type	D/s Shell foundation Left bank	8 45
Total pressures	Electrical pressure cells, vibrating wire	Core	13*
	Pneumatic pressure cells	Core	2*
Total forces	Load cells, vibrating wire	Left bank only	8*
	Load cells, vibrating wire	Left bank only	3
	Load cells, strain gauge	Left bank only	4

Measured Parameters	Instrument Type	Instrument Location	Qty.
Relative displacements	Extensometers Distofor type	Left bank only	7*
	Extensometers, multiple bars, micro metre reading (1 direction)	Left bank only	6
	Extensometers, single bar, electrical reading (1 direction)	Core	16
	Inclinometers (2 directions)	Core, u/s filter, d/s shell	5
	Pendulums, inverted (2 directions)	Left bank only	2
	Joint displacement devices (3 directions)	Left bank only	60
Settlements (internal)	Magnetic discs around inclinometer tubes	Core (3 inclnom.) D/s shell (1 inclinom.)	130
	Pneumatic settlement cells	Core U/s shell	11
Displacements (by geodetic survey)	Bench marks (theodolite or distancemeter readings, levelling)	Crest, Berms on d/s shell Left bank	8 13 42
Accelerations (earthquake induced)	Strong motion accelerographs SMA-1, interconnected system	Crest, D/s shell slope Left Bank	1 2 3
	Peak acceleration recorders	Crest, D/s shell slope Left bank	7 4 1
	Seismic triggers, interconnected	Left bank	3
	Seismicscope	Crest, D/s shell slope Left bank	1 2 3
Seepage	V-notch weirs (remote reading planned)	Station at dam toe Left bank	2 6

Note: * indicates connection to the automatic data acquisition system

I.3 AUSTRALIA

Australia has approximately 409 large dams (*World Register of Dams*, 1988). The majority of the dams have been developed by state authorities responsible for the conservation and distribution of water for irrigation. These major authorities form the membership of the Australian National Committee on Large Dams (ANCOLD) (ICOLD, 1989). Overall, Australia has maintained a good dam safety record with the last dam failure having occurred in 1929. This safety record can be attributed to the fact that the majority of the dams are engineered, owned and operated by public authorities who have their own regular surveillance programs (Cantwell and Anderson, 1984).

In 1972, ANCOLD proposed that each state should legislate for a single control authority independent of the existing agencies which engineer and/or own dams. This control authority would insure that all dams are adequately designed, constructed, operated, maintained and monitored. By 1982 each state responded to some degree to ANCOLD's proposal. As of 1984 there was effective Dam Safety Legislation in only two states, New South Wales and Queensland. Furthermore, New South Wales is the only state that legislated for the aforementioned separate Control Authority (Cantwell and Anderson, 1984). However, the positive outcome of ANCOLD's actions is that today all of the public authorities responsible for dams have developed their own surveillance programs which include specifications for dam monitoring. For example, the Hydro-Electric Commission of Tasmania has a Safety Dam Unit (SDU) which performs the inspections of the dam, and reviews deformation surveys, instrumentation readings and leakages and maintenance data (Fitzpatrick et al., 1982).

Over the years ANCOLD has been the driving force in establishing Australia's dam safety practice. It has promulgated surveillance of dams. In fact, ANCOLD has published the following sources which reflect the current practice used in the surveillance and monitoring systems for the major dams in Australia (ICOLD, 1989):

1. ANCOLD (1976) - *Guidelines Operation, Maintenance and Surveillance of Dams.*
2. ANCOLD (1983) - *Guidelines for Dam Instrumentation and Monitoring Systems.*

A very comprehensive summary of these documents can be found in the report by ANCOLD in ICOLD (1989).

The complexity and extent of the monitoring system used on a dam is influenced by the "hazard rating" of the dam which is based on the potential economic loss and loss of life as a result of a structural or mechanical failure. However, once the monitoring system is selected it is assessed for conformity with the current standards of design, construction, maintenance and operation of large dams. After doing so, if required, a more comprehensive surveillance/monitoring system is installed. The ANCOLD Guidelines consider routine inspection and review systems fundamental to monitoring/surveillance and essential complements to the instrumentation system. In the design phase of large dams, the trend is to use numerical analysis techniques to estimate the anticipated stresses and deformations exerted by the dam. This provides the logic for the design of the instrument systems in monitoring the conformity of the dam with acceptable behaviour patterns.

The systems which are considered in planning and development monitoring requirements for new and existing dams as described include:

(1) visual inspection and reviews,

(2) seepage measurement and analysis,

(3) groundwater/seepage pressure measurement,

(4) surface displacement and strain measurements,

(5) internal displacement and strain measurement,

(6) stress and load measurement systems,

(7) hydrometeorlogical, and

(8) seismicity monitoring.

A typical surveillance team consists of a competent staff made up of professionals and sub-professionals. For example, the Thomson Dam in Melbourne, Victoria, is regularly monitored by Caretakers, Engineers, Geologists and Surveyors (Robins and Walsh, 1989). Overall, the geotechnical/structural equipment used in these measuring systems vary from simple instrumentations (groundwater observation wells, strain gauges, extensometer, joint meters) to sophisticated instrumentations (e.g., pressure measuring tips providing registers of pressure at discrete locations or seismographs with timing accuracy of 0.01 second for periods up to one month, allowing very accurate location of earthquakes). Seismic monitoring is applied only to large dams. This is carried out by using or partly integrating the regional seismographic network and strong-motion sensor system installed randomly in the dam and its foundation. Surface displacements are determined by precise survey methods. These methods are used to register absolute movement of the dam and its abutments. Precise Survey systems are generally based on a triangulation and/or trilateration network with a high degree of accuracy. Different methods and accuracies are used for embankment and concrete dams. The number and position of survey targets, and the permissible accuracy and tolerances are determined by the designer, but the methods and equipment used are determined by survey personnel.

The ANCOLD report gives some examples of the types of instrumentation systems used to monitor four of Australia's major dams. Table I.3a illustrates some typical instrumentations used in five concrete faced rockfill embankment dams on the Pieman River on the west coast of Tasmania (Knoop and Lack, 1985). The frequency of the readings varies from very frequently during the construction and first filling to less frequently when the structure has reached a stable condition and recurrence pattern of behaviours are established. For unusual events and in special circumstances such as after an earthquake, or rapid draw down or flood conditions in excess of the normals, increased frequencies of observations is warranted (ICOLD, 1989). An example of such a monitoring program is given by Table I.3b (Murley, 1983).

In the latter part of 1980, the Department of Surveying and Land Information of the University of Melbourne conducted a study of Australia's automated management and improved presentation of dam monitoring data. This study concluded that a wide variety of approaches to automated management of data have been adopted by the majority of the state authorities and organizations responsible for the dam monitoring. The majority of these organizations have adopted PC systems as opposed to main frame systems. Overall, the automated recording of observations is considered well developed, but problems are still encountered with the automatic reading and recording of dam instrumentations (Sterling and Benwell, 1989).

Table I.3a
Number/Types of Instruments Installed in Five Concrete Face Rockfill Embankment Dams on the Pieman River, Tasmania
(after Knoop and Lack, [1985, p. 1107])

Type of Instruments	Mackintosh	Tullagardine	Murchison	Bastyan	Lower Pieman
Hydrostatic settlement cell	8	5	4	4	5
Survey targets	20	12	6	11	9
Crest clinometer base	3				
Face slope inclinometer	1		1	1	1
Perimetric joint meter	*4.12	2.5	8.16	3.6	3.8
Face joint meter, pin set	+12.34		8	4	10.10
Face strain meter	*20.34		5.29		
Embankment dilation meter	4				
Embankment pressure meter				*2.5	3.6
Foundation Piezometer	14				8
Leakage weir	1	1	1	4	6

Notes:

1. *4.12 means four location, twelve instruments installed in sets at orthogonal direction or in rosettes.
2. +12.34 means twelve joint meters, thirty-four sets.

Table I.3b
Instrumentation Systems and Monitoring Frequencies(a)
(Based on Table 9, ANCOLD Guidelines for dam Instrumentation and Monitoring Systems)
(from Murley, [1983, p. 13])

Instrumentation and Monitoring System	During First Filling	Routine Monitoring Operational Phase	Remarks
Visual Inspection: check for cracks, settlement, slips	Daily	Daily and Weekly	Visual inspections by reservoir resident staff to be complemented by routine annual(d) inspection by surveillance and operation.
Seepage Measurement	Daily	Weekly (where risk/hazard rating of dam allows less frequent visual inspection, carry out seepage measurements in conjunction with visual inspections)	A complete series of readings of instrumentation monitoring systems should be taken at time of routine inspection.
Chemical Analysis of Seepage	If seepage is significant	6/month to establish seasonal patter of storage and seepage chemistry.	
Pore Pressure Measurement: foundations and dams.	Frequency as may be necessary to adequately define trends in behaviour with application water loading and development of seepage patterns.	3/month(b) Annually(c)	
Surface Displacement		6/month until seasonal pattern is established then annually.	
Internal Displacement		3/month(b) Annually(c)	
Internal Stress Measurement		3/month(b) Annually(c)	
Hydrometeorlogical	Operational requirement	Operational requirement	Continuity of monitoring may extend to service phase for major gated spillway operation.
Seismological	Continuous	Continuous	

Notes:

(a) Frequencies are generalised, particular circumstances, adverse trend in behaviour or risk/hazard ratings may dictate more frequent monitoring. After unusual event, such as rapid drawdown, filling or earthquake, carry out partial or full monitoring as appropriate.
(b) Suggested maximum interval, initial 3-4 years until dam and foundations exhibit stable characteristics.
(c) Maximum interval, subsequent years, regardless of satisfactory behaviour.
(d) After initial 5 years, subject to satisfactory behaviour, surveillance inspection interval may be increased progressively to 5 year interval.

Like most countries, the data from the numerous instruments within the monitoring system is processed and analyzed independently. The analysis often includes the recording of data in a continuous graphical form for ease of recognition of trends and comparison with design prediction of behaviour (ICOLD, 1989). The survey data from distance measuring instruments (e.g., EDM Wild DI-2000) and settlement measuring instruments (e.g., Jena Ni and 005A Ni-3 Automatic Levels) are also analyzed separately using developed or commercial software packages providing a least square solution (Sterling and Benwell, 1989). Case studies of existing dams by Knoop and Lack (1985), Barnet and Funnell (1983), and Fitzpatrick et al. (1982) illustrate some good examples of the types of graphical analysis used to compare the theoretical and measured data whereas Sterling and Benwell (1989) give examples of the software packages used for analyzing the survey data.

I.4 Austria

Austria owns and operates approximately 123 dams, of which 80% (99) are concrete dams: 82 gravity and 17 arch (*World Register of Dams*, 1988). According to Duscha (1990), a survey by the ICOLD Committee on Dam Safety disclosed that Austria has indeed some form of dam safety legislation. In addition, the Austrian National Report (ICOLD, 1989) claims that in Austria the responsibility of dam surveillance is designated to an authority (e.g., General Water Right Authority) and that dam owners are obligated to assign a dam operator.

Furthermore, according to the Austrian National Report, dam owners have an obligation to inform the authority in charge of the dam surveillance of the organization selected to operate the dam. The designated operators are not only responsible for the overall operation of the dam and its pertinent structures, but also for the entire monitoring program. This includes recording and evaluating the measurements, preparing the annual or monthly reports, and maintaining the monitoring system. Consequently, for all of the dams within its jurisdiction, the surveillance authority has to review the reports and inspect each dam every 5 years (ICOLD, 1989; Ludescher, 1985). Based on the information provided by Duscha (1990) and the Austrian National Report in ICOLD (1989) it will be assumed that dam monitoring is in fact included in the Austrian regulations.

The majority information gathered on Austria reveals that Austrian dams are generally monitored using geodetic, geotechnical, and structural instrumentation. High precision geodetic surveys include levelling (of dam crests, slopes, embankments and abutments), alignment surveys (for non-curved gravity dams) and traverse (preferred for arch dams). Table I.4 illustrates an example of one of Austria's more comprehensive surveillance system. The system is used to monitor Austria's largest dam, the Kölnbrein Dam (200 m high). Regrettably the percentage of the total number of dams that are currently monitored could not be determined from the information available. However, due to the fact that a large number of Austrian dams are situated in remote locations, more emphasize is placed on the installation of instruments that are readily automated (i.e., geotechnical/structural instruments). A sample list of dams which have been automated is given in ICOLD (1989).

According to the Austrian National Report (ICOLD, 1989), when considering any dam-type the following factors apply: (1) seepage and water pressure measurements constitute the main parts of the monitoring system, and (2) periodic geodetic measurements must be performed on all dams constructed in areas where there are potential landslides. With respect to the frequency of the measurements, the Austrian follow the guidelines suggested in ICOLD Bulletin N° 41. As an example, provided is Table I.5 which gives the monitoring frequency program that has been applied to five large dams in the Glockner-Kaprun Hydro-Electric Power Development.

Table I.4
Instrumentation of Kölnbrein Arch Dam in Austria
(from Ludescher, [1985, p. 799])

Quantities Measured	Instruments	No. of Instruments	Number of Reading Points	
			Total	No. Automated
Loads	Pressure balance for measuring reservoir water level	1	1	1
	Uplift pressure cells	41	41	25
	Stand pipe piezometer	154	154	124
	Concrete temperature transmitter	79	79	63

Quantities Measured	Instruments	No. of Instruments	Number of Reading Points	
			Total	No. Automated
Displacement	Plumb line	17	34	17
	Clinometer	52	52	0
	Invar-wire extensometer	16	16	16
	Rod-type extensometer	137	137	76
	Sliding micrometer	26	982	0
	Contraction joint opening transmitter	115	137	0
	Geodetic points * levelling * traverse * target	205	262	0
Strain and stress	Teleformeter	84	84	64
	Telepressmeter	29	29	28
Flow	Leakage	12	12	12
Seismic Activity	Macroseismic	1	1	1
	Microseismic	2	6	6
	Acoustic emission	2	4	4
Meteorological data		7	7	7
Total		980	2,038	444

Table I.5
Monitoring Frequencies for the Concrete Dams of Glockner-Kaprun Hydro-Electric Power Development in Austria (after Breitenstein et al., [1985, p. 1126])

Type of Measurement	Frequency
Inspection	Weekly
Control measurements	
Additional measurements	

Type of Measurement	**Frequency**
Geodetic survey	Annually
Inspection with experts	
Inspection with authority	Every 5 years

Some of Austria's recent developments in the area of instrumentation for deformation monitoring include:

(1) acoustic emission devices to measure cracks in concrete or rock masses,

(2) laser plumb lines as an alternative to wire plumb lines,

(3) magnetic measuring devices to detect asphaltic concrete core wall deformations,

(4) special level indicating devices to determine the interior deformation of the dam, and

(5) an intelligent hand-held computer to record measurements of those instruments that have not been automated.

The above instruments have already been trialed and installed in new and existing dams. Another important piece of equipment that is included in most of the dam sites is a television camera. Considered as part of the automated system, the camera is used to provide an overall view of the dam structure (Breitenstein et al., 1985).

The analysis of the data consists of using deterministic models during the first filling, and a statistical-based mathematical model such as the multiple linear regression model after several filling periods (i.e. once more data has been collected). The results of the regression analyses are later used to improve the parameters of the deterministic model as well as to identify possible long term changes in the measured data. For the most part, the results of the analyses are presented in graphical and/or tabular form. The Austrian National Report in ICOLD (1989) suggest that the analysis of the data should be performed by dam experts and specialists with a statistical background.

For a more comprehensive review of the dam monitoring practices described in this section, the reader is referred to the Austrian National Report in ICOLD (1989). Furthermore, additional examples of monitoring systems used in Austrian dams are given by Schober and Lercher (1985).

I.5 Bangladesh

The only information on Bangladesh is that it has only one large dam, an earthfill type, which is monitored by the Bangladesh Power Development Board (Rahman, 1992).

I.6 Brazil

There are 516 large dams officially registered in Brazil. Seventy five percent of these dams (391) are embankment type dams (*World Register of Dams*, 1988). The most important dams are monitored using geodetic and/or geotechnical/structural instrumentation (Miguez de Mello, 1992).

There are no national or local standards/specifications for dam monitoring. The Brazilian National Committee on Large Dams has issued dam owners general instructions related to dam safety. These instructions are based on the guidelines published by the ICOLD (Miguez de Mello, 1992).

From a review of a number of articles by authors such as Seifart et al. (1985), Guedes and Coelho (1985), Caric et al. (1985), Lima et al. (1985), Filho et al. (1985) and Blinder et al. (1992) one can conclude that the instrumentation used to monitor earth and concrete dams are typical of those used by the majority of the ICOLD member countries. Overall, the monitoring schemes consists primarily of:

(1) geodetic benchmarks for high precision trilateration and levelling, and

(2) geotechnical/structural instrumentation including direct or inverted pendulum, thermometers, piezometers, electric strainmeters, electric jointmenters, electric stress meters, inclinometers, hydrostatic settlement cells and the most recent instrument the horizontal plate gauge used to monitor the horizontal displacement normal to the axis of the dam.

This review also indicated that dam monitoring in Brazil is predominantly based on geotechnical/structural techniques.

The analysis of Brazilian dams may consists of comparing the behaviour of the dam described by the data furnished by the monitoring instruments with that described either by FEM or by statistical model and/or a physical model (a miniature model of a selected section of a dam reproduced to scale). The data from the models is used as approximate limit values (Caric et al., 1985). The statistical model is based on the Gauss-Markoff Functional Probabilistic Model (H.G.M.). The H.G.M. model establishes a link between the effect variables (those characterizing the structural response) and the cause variables (e.g., upstream and downstream water level, ambient temperatures, concrete temperature, strain, stress, leakage flow). Some of the advantages of the H.G.M. model are that it is simple to use, it requires no knowledge of geometry of the structure nor the mechanical property of the materials and it can be used to model any kind of effect on any types of dams (Guedes and Coelho, 1985). Guedes and Coelho (1985) describe the model in detail and provide several examples of how the model is applied to existing Brazilian dams.

Whichever model is used, the analysis is applied exclusively on points of interest within the dam. For example, the theoretical displacement at a point in the dam is compared to the actual displacement measured by a plumbline at that point. These results are commonly presented in a graphical or tabular form over time.

I.7 Canada

Canada operates about 608 large dams, ranking amongst of the top ten in the world (*World Register of Dams,* 1988). The country has been blessed in that it has not yet experienced failures causing loss of life. However, there have been several incidents recorded which could have resulted in serious consequences had remedial measures not been taken (Koropatnick, 1990).

In Canada, the Canadian Federation empowers the ten provinces to develop and control their national resource. The management of water and power generation rests with the Provincial Government. The provinces are therefore responsible for dams in their jurisdiction, including licensing, regulation and public safety. In most provinces, dams are owned and operated by provincial "hydro" organizations. The Dam Safety Committee instituted in 1980 by Canadian National Committee on Large Dams (CANCOLD) undertook a study of regulations across Canada. The study revealed that all provinces and territories have enabling legislation that is very general in nature, lacking in specifics related to safety programmes and surveillance. Currently, Alberta, British Columbia (B.C.) and Québec are the only provinces that have developed specific safety practices supported by regulations and the administrative staff to implement them. (Brunner, 1983; *Dam and Canal Safety Regulations,* 1983; Tawil, 1984; Dascal, 1991; Koropatnick, 1990). An excellent review of the laws and regulations governing the safety of dams in Canada is given by Tawil (1985) and Tawil (1984).

Alberta is the first province to institute laws governing safety of dams: the Dam and Canal Safety Regulations enacted in 1978 (*Dam and Canal Safety Regulations,* 1983). The regulations are administered by the Dam Safety Branch which has produced guidelines for licensing and design flood criteria with respect to dam size and hazard potential. The legislation covers the inventory of approximately 1,200 dams more than eight meters in height or 60,000 cubic meters or more in capacity (*Dam and Canal Safety Regulations*, 1983; Tawil, 1984). Also, the Research Management Division of the Alberta Environment sponsored the Department of Surveying Engineering of University of Calgary to develop standards and specifications for deformation surveys (Teskey, 1988). These standards and specification relate only to geodetic monitoring surveys. They lack detail and technical information on the analysis, and can be used as examples from which one can improve.

British Columbia used existing legislation to formulate a very comprehensive surveillance programm which includes the licensing, classification guidelines and inspection frequencies. In 1979, BC Hydro, the power authority in British Columbia, embarked on a study to evaluate 54 dams constructed before 1960. This evaluation lead to the remedial work of several dams between 30 and 60 years old. Also emerging from this appraisal, was the need to review B.C. Hydro's organization related to safety of dams. One of the most important outcome of the review is the creation of a new position of Director of Dam Safety in 1981 (Tawil, 1984). The Director's responsibility is to coordinate and oversee that all of the necessary steps are taken in order to fulfil B.C. Hydro's commitment to safety. Another aspect of the B.C. Hydro's Dam Safety Program is the preparation and updating of Operation and Maintenance Manuals for all of its dams. B.C. Hydro is said to be committed to maintain safety standards consistent with standards such as those established by ICOLD (Brunner, 1983).

In Québec, the Hydro-Québec dam safety policy was enacted in October 1985. The act defines the principles regarding the operation, surveillance and maintenance of dams in order to prevent or limit the consequences of potential failures. The act is implemented by the Civil Works Division in each region and by the Dam Safety Directorate from the Generation, Transmission and Distribution Branch. Since the implementation of the act, two very significant objectives have been achieved. The first objective was achieved at the end of 1990 when the Dam Safety Directorate had implemented nine technical regulations, sixteen standards and three procedures concerning dam surveillance and safety evaluation. The second objective achieved is that a list of terms and expressions used in dam safety has been drafted with the aim to provide precise definitions and allow standardization of dam surveillance and behaviour evaluation throughout the province. Another major activity of the Dam Safety Directorate is the training of surveillance personnel. The Directorate has provided courses to field inspectors up to the end of 1990 while training programs for the engineering staff is scheduled to start this year in 1992, if not already started (Dascal, 1991).

In the province of Manitoba, the Manitoba Hydro became particularly involved in dam safety in 1974 when surveys of two older dams (Seven Sisters and Great Falls) revealed extensive concrete deterioration which presented a serious safety hazard. As a result rehabilitation programs were started in 1978 and a formalized Safety Surveillance program was approved in 1979. Although the new program provided guidelines for monitoring the conditions and ongoing performance of various structures, it was not complete in providing an overall dam safety program. The program was eventually expanded in 1987 to include a number of safety guidelines published by the US Army Corps of Engineers (COE) and those listed in ICOLD's *Check List on Dam Safety.* One of the components that was adopted by Manitoba Hydro is that for each dam, the instructions on the instrumentation and monitoring is to be included in the dam Operating and Maintenance Manuals (Koropatnick, 1990). According to Koropatnick (1990), the current program is consistent with modern day practices in Dam Safety Engineering.

In the remaining provinces, progress towards dam safety varies greatly. The need for programs to ensure public safety is recognised but the overall progress is slow and usually hindered by inadequate funding. Although one may conclude that, in general, Canadian dams are adequately attended, some shortcomings still persist (Tawil, 1984).

Some of the common problems with Canada's dam safety programmes include poorly designed monitoring schemes, inadequate instrumentation, lack of calibration facilities, and insufficient accuracy of measurements. One of the most serious problems which requires immediate attention, at the national level, is the use of out-dated methods in the geometrical analysis of deformation measurements (Chrzanowski, 1990). The physical interpretation of deformation surveys requires knowledge from a matrix of interdisciplinary experts.

There are two known institutions in Canada that have significantly contributed to the progress in the area of integrated monitoring and analysis of deformations. These are the Surveying Engineering Departments at the University of New Brunswick (UNB) and University of Calgary.

Over the past fifteen years, the Engineering and Mining Surveying Research Group at UNB has been intensely involved in interdisciplinary research in the development of new techniques and new methods for the integrated monitoring and analysis of deformations in engineering and geoscience projects. The research has led to the development of the UNB Generalized Method for Deformation Analysis (Chen, 1983). The method is supported by a software package DEFNAN written in FORTRAN 77 which can be executed either on an IBM 3090 mainframe or on an IBM compatible Personal Computer(Chrzanowski et al., 1990). As aforementioned, the UNB Generalized Method can be applied to any type of structures and it utilizes different types of geodetic and geotechnical measurements in a simultaneous analysis. This method has been successfully implemented in many types of engineering and geoscience projects. For example, it has been used for ground subsidence studies, in oil fields in Venezuela and in mining areas in Canada, Poland and China; and for deformation analyses of concrete dams and earthfill dams in the USA, Canada and Venezuela (Chrzanowski and Szostack-Chrzanowski, 1986; Chrzanowski, 1990). In dam deformation studies in Canada, the UNB Generalized Method has been applied extensively in cooperation with NB Power in an integrated analysis of deformations of the structures at the Mactaquac hydro-electric power generating station in New Brunswick (Chrzanowski et al., 1989). The method, though used by NB Power, has not yet been adopted by other provinces. The main reason being generally the inadequate educational background of those in charge of the analyses.

The current research in UNB is focused on an optimal combination of deterministic modelling of deformation with results of the geometrical analysis of deformation observations for the integrated analysis and physical interpretation. The deterministic modelling is supported by software FEMMA for 2-D and 3-D elastic and visco-elastic finite element analysis (Szostak-Chrzanowski and Chrzanowski, 1991). A similar method, developed by the University of Calgary is said to perform an integrated analysis of deformations by combining a physical model (finite element) of the structure with the actual deformation measurements on the structure. The method has been applied to large fill dams, the Calgary Olympic Oval and large diameter buried pipelines (Biacs and Teskey, 1989). The research at both UNB and University of Calgary has put Canada into a leading position in international developments of new methods for deformation analysis.

Although there are some shortfalls in the way Canadians maintain and monitor their dams, Canadian organizations such as CANCOLD and the Canadian Dam Safety Association (CDSA) are continuing their efforts to increase the awareness of dam safety through annual conferences and publications. The CDSA was originally instituted by CANCOLD to assemble and review information on the existing rules and regulations governing dams in various parts of Canada. One of its key findings was that although all jurisdictions have enabling legislation which set the responsibility for operation and maintenance with the dam owners, the legislation is not specific on monitoring and surveillance (Tawil, 1985). CDSA also organizes annual conferences where its members have an opportunity to present papers and exchange information on a number of subjects ranging from performance monitoring to legislation and remedial works (Anderson, 1990). CANCOLD contributes to dam safety in Canada through its membership with ICOLD and its participation in some of ICOLD's special committees. CANCOLD also has a Dam Safety Committee which has the role of insuring that all dam owners and operators are made aware of dam safety matters. Recently, in 1992, the CANCOLD Dam Safety Committee and CDSA became a joint CANCOLD-CDSA committee so that both will benefit from the work done within ICOLD (Larocque, 1992). As members of ICOLD, CANCOLD is in an ideal position: it has direct access to ICOLD publications; it is in direct contact with an overwhelming number of international experts on dams; and it can exchange information with the other 78 or so ICOLD members in an unilateral, bilateral or multilateral agreement. One of CANCOLD's latest report is its national report to the ICOLD Committee on Monitoring of Dams and their Foundations published in ICOLD (1989). The report is CANCOLD's views on the instrumentation concepts and installations related to new and existing large Canadian dams. Unfortunately CANCOLD's report in ICOLD (1989) is very general in nature, however it does bring forth some concepts that Canadians believe to be an important part of a dam monitoring program. The report omits the aforementioned developments at the University of New Brunswick and Calgary which have been the results of works within the activities of FIG rather than ICOLD.

Overall, Canada is in agreement with most countries in that the extent and scope of instrumentation to be installed in a dam should be determined early in the design stage. Canada also recognizes that knowledgeable people should be assigned to the surveillance program to ensure that the monitoring of the dam and reservoir slopes is properly carried out. The types of monitoring instruments that should be included in concrete and embankment dams, as recommended by CANCOLD, are summarized at Table I.6. With respect to the monitoring frequencies CANCOLD recommends the following: during filling piezometers and seepage weirs are to be read once-a-day, others once-a-week and surface surveys once-a-month. These frequencies are to be maintained until the reservoir has reached full pool and for a few months after. Once the structure has reached a normal pattern of behaviour, the frequency of the readings may be lengthened to suit the requirements of the design engineer (ICOLD, 1989). Examples of monitoring frequencies that have been implemented on two Canadian dams are given at Tables I.7a (Revelstoke Dam), I.7b (La Grande Complex) and I.7c (Bennet Dam). Table I.7c also includes the obtained accuracy of the measurements. CANCOLD comments on some of the advantages and the requirements of automated monitoring systems, however it does not express whether or not these systems have been implemented in Canadian dams. CANCOLD's report falls very short in what was stated to be one of the key elements to a successful monitoring program, the analysis of the observation data. The report simply states that: during the filling of the reservoir the data should be analyzed as soon as it is available; the observers should be trained to take accurate observations and not to cover-up any reading that appear to be inconsistent with the previous readings; and the data should be documented and given to engineering office for assessment (ICOLD, 1989).

Table I.6
Instruments that Should be Used to Monitor Concrete and Embankment Dams: As Recommended by CANCOLD (after ICOLD, [1989, pp. 77-80])

QUANTITIES MONITORED	INSTRUMENT	REMARKS
CONCRETE DAMS		
Deformation	Surface survey points	* located on the dam crest and along the d/s face to monitor both horizontal and vertical movement
	Plumblines, pendulums, plummets	* located in wells on shafts to monitor tilt
	Rod-extensometers	* extending from the base of the dam into the rock to monitor foundation displacement
	Inclinometers	* casings drilled into bedrock and grouted into the dam to monitor foundation movement
	Tiltmeters/plumblines	* located in concrete mass to measure tilt movement (a series of electric tiltmeters can be used to replace a manually read plumbline)
	Jointmeters	* imbedded into the concrete to monitor opening or closing of contraction joints and cracks
Temperature and Stress/Strain Measurements	Thermometers	* should be embedded to measure mass concrete temperature changes
	Construction Thermometers	* located throughout the dam to monitor temperature during the construction (they are abandoned as construction proceeds)

QUANTITIES MONITORED	**INSTRUMENT**	**REMARKS**
	Stress and Strain Meters (Carlson strain meters, vibrating wire strain gauges, resistance type gauges)	* a minimum of 3 stress meters are required to calculate the principal stresses (vertical, horizontal and 45°) * they are not to be used in concrete dams with height below 25 m and anticipated stresses below 700 Kpa * strain meters may be used in areas that may be in tension
Piezometric Pressure and Water Flow Measurement	Piezometers and other appropriate instruments	* devices to measure piezometric pressure in shear zones in foundation rock, at concrete/rock interface and adjacent to penstock
	Electronic open-trench-type flumes	* to measure flows in the galleries from the foundation drains and leaks in the dam
EMBANKMENT DAMS		
Pore Pressure	An appropriate type of piezometer to suit the location and material in which the pressure is being used	* should be accurately measured at locations where seepage occurs * in some cases it is best to isolate dam seepage into various areas of the dam by constructing isolation dykes within the dam
Deformation Measurements	Surface settlement points	* in general as per concrete dams
	Vertical measurement gauges, extensometers	* usually anchored to bedrock and rise as the fill is raised
	Slope indicator devices	* to measure horizontal movement transverse and parallel to the axis
	Hydraulic settlement devices	* installed within the dam fill provide an alternate means of measuring the internal consolidation of the fill or foundation
Horizontal Deformation Within the Fill	Aquaducer probe, Cross-arms (another means is by operating a latchcone inside a horizontal movement gauge casing installed perpendicular to the dam axis in the d/s shell)	* measured in critical areas where the dam fill is subject to large horizontal loadings

QUANTITIES MONITORED	INSTRUMENT	REMARKS
Stress Within Dam Fill	Earth pressure cells Earth pressure cells installed with piezometers near the cell	* placed at certain critical locations like steep abutments or narrow gorges and at earthfill-concrete interface * earth pressure cell measure the total pressure * earth pressure cell with a piezometer installed near it gives the effective stress * these measurements give indications if hydraulic fracture of the fill or arching between internal zones is taking place
Horizontal Strain Measurements	Horizontal strain gauges	* should be placed in areas of potential tensile cracking such as steep abutments and abrupt changes in elevations of foundation rock * they are usually anchored at one end of the dam in the abutment rock or to concrete abutment structures

Note: Other quantities that should be measured include reservoir level, ambient temperatures, rainfall and snowfall measurements, frost depth penetration and seismic activities (a must for all large dams).

Table I.7a
Frequency of Instrument Readings at Revolstoke Embankment Dam (Canada)
(from ICOLD, [1989, p. 87])

Stage		Instrument				
		Core piezometer	**Foundation and shell piezometer**	**Vert. movement gauge**	**Hor. Movement gauge**	**Hor. Strain gauge**
During Construction		frequently by field staff				1/month
Reservoir filling		1/2 days	1/2 days	1/week	2/month	2/month
After the first res. filling	first 6 months	1/week	1/week	1/month	1/month	1/month
	6 months to 1.5 yrs	2/month	2/month	4/year	4/year	4/year

Stage		Instrument				
		Core piezometer	**Foundation and shell piezometer**	**Vert. movement gauge**	**Hor. Movement gauge**	**Hor. Strain gauge**
	1.5 to 2.5 years	2/month	2/month	4/year	4/year	4/year
	2.5 to 6.5 years	6/year	6/year	2/year	2/year	2/year
	subs. years	2/year	2/year	1/year	2/year	1/year

Stage		Instrument				
		Surface Monument	**Earth Pressure Cell**	**Weir and Well**	**Strong Motion Accelerograph**	**Visual Inspection**
During Construction		1/month	1/month	1/month	continuous	1/month
Reservoir filling		1/month	2/month	1/2 days	continuous	1/day
After the first res. filling	first 6 months	1/month	1/month	1/week	continuous	1/day
	6 months to 1.5 yrs	4/year	4/year	2/month	continuous	1/week
	1.5 to 2.5 years	4/year	4/year	2/month	continuous	1/week
	2.5 to 6.5 years	2/year	2/year	6/year	continuous	2/month
	subs. years	1/year	1/year	2/year	continuous	1/month

Table I.7b
Frequency of Instrument Readings of the Embankment Dams at La Grande Complex (Canada) (from ICOLD, [1989, p. 88])

STAGE		INSTRUMENTS						
		Sealed Piezometer	**Casagrande Type Piezometer**	**Inclino meter**	**Frost**	**Surface Monument**	**Extens., Total Pressure Cell and Settlement Cell**	**Weir**
During Constr	Constr. Period	1/month	1/month	6/year	-	-	1/month	-
	Interim Period	1/season	1/season	1/season	-	-	1/season	-
Res. Filling		1/2 days	1/day	2/month	1/ month	2/month	2/month	2/ week
After the 1st Res. Filling	First Year	1/week	1/week	6/years	1/ month	1/month	1/season	2/ week
	Second Year	2/month	2/month	1/season	1/ month	1/season	1/season	1/ week
	Third Year	6/years	1/month	2/year	1/ month	2/year	2/year	1/ month
	Subs. Year	2/year	4/year	1/year	1/ month	1/year	1/year	6/year

Table I.7c
Instrumentation Frequency and Accuracy at Bennet Embankment Dam in British Columbia (Canada) (from Taylor et al., [1985, p. 189])

INSTRUMENT	NO. INSTALLED	ACCURACY	FREQ. OF MONITORING
Foundation piezometers (standpipe 26, pneumatic 4)	30	± 3 mm	quarterly
Embankment piezometers (telmac 8, hydraulic 38)	46	± 3 mm	quarterly
Stress/strain meters	4/11	1 unit	quarterly

INSTRUMENT	NO. INSTALLED	ACCURACY	FREQ. OF MONITORING
Cross-arm Devices	2	V - ± 3 mm	annually till 1975
Slope indicators	10	H - ± 1 mm	less frequently since 1975
Surface settlement pts	54		
Levels		± 12 mm $\sqrt{}$(km)	Annually
Offsets		± 15 mm	Annually
Displacement points	17	± 3 mm	Annually
Survey control		± 4 mm $\sqrt{}$(km)	Annually
Seepage measurements			
Flumes	7	± 3 mm	quarterly
Weirs	3	± 3 mm	weekly

For more information on the types of monitoring systems applied to some of Canada's dams, the reader is referred to a number of articles written by CANCOLD members in the ICOLD Proceedings of the Fifteenth Congress on Large Dams, Q56, Vol I (e.g., Eisenstein and Brandt, 1985; Klohn et al., 1985; Taylor et al., 1985), in the Proceedings of the 5th International (FIG) Symposium on Deformation Surveys (Chrzanowski et al., 1988; Wroblewicz et al., 1988), as well as in the Proceedings of the International Conference on Safety of Dams (Paré, 1984). CANCOLD has recently advertised that the ICOLD Bibliographic Software (Release 1.01) is now available to its members. The software has been developed by a consultant under the permanent supervision of the ICOLD Committee on Bibliography and Information and the Swiss National Committee on Large Dams. Canada was one of 14 countries that sponsored this project (CANCOLD, 1992b). In addition, CANCOLD publishes its own bibliography, the most recent being *Bibliography of Papers on Dams in Canada* 1990 (Acres International, 1990), which includes a dedicated list of published literature related to observation of dams under Group IV Observation Methods and Results.

I.8 China

China is an ancient country with a long history of dam construction dating back as early as 240 B.C. (Junchun, 1985). In 1988 China registered 18,820 large dams, about 52% of the total dams within the 79 ICOLD member countries (*World Register of Dams*, 1988). The status of monitoring these dams can be summarized as follows (Chonggang, 1992):

(1) 90% of the reservoirs with a capacity larger than 100 million cubic meters are monitored,

(2) 30-40% of the reservoirs with a capacity between 10-100 million cubic meters are monitored, and

(3) reservoirs with a capacity below 10 million cubic meters are not monitored at all.

China's latest contribution to the construction of dams has been the development of the roller compacted concrete (RCC) method. This method of construction, initiated in 1979, has been proven to be very economical. For instance, the construction period of the Kengkou Dam, the first RCC gravity dam completed in 1986, was reduced by about one year, and the investment cost by about 17%. Today there are at least eight

RCC dams in operation with the first RCC arched gravity dam scheduled to be completed in 1992. The instrumentation systems for RCC dams are common to standard concrete dams. Despite its economical advantages, the RCC method requires further research regarding the analysis of the surveillance data, the possibility of constructing very high dams (greater than 150 meters) and the problems associated with the behaviour and mixture of the concrete (Chonggang, 1991).

China has placed deformation surveys high on its priority list. In the past it has experienced tragic events resulting from unpredicted failures of engineering and geological structures. Consequently, the State has implemented specifications for monitoring engineering structures, mining facilities and crustal movements. Currently, China has national regulations directing that any large engineering structure must be monitored (Chen, 1988). The specifications and regulations that govern the monitoring of Chinese dams are (Chonggang, 1992):

1. *Regulations of Reservoir Safety* (national standards published in Chinese in 1991)
2. *Technical Specifications for Monitoring of Concrete Dams* (published in 1992 in Chinese)
3. *Specifications for Embankment Monitoring* (still being written)
4. *Interim Statute for Dam Safety Management of Hydropower Stations* (edited by Large Dam Safety Supervision Center, Ministry of Energy in Hangzhou).

The accuracy, procedures and survey frequency for different types of structures are in accordance to the specifications issued by the corresponding State ministries. Table

I.8 is a summary of the specifications used for monitoring dams (Chen, 1988).

In China, each power station employs a survey team of five to ten persons to routinely monitor the deformation of the dam. The majority of the engineers responsible for the supervision of the deformation surveys have a bachelor degree in surveying or geodesy (Chen, 1988).

The Chinese plan the monitoring scheme during the design stage of the project. Conventional geodetic surveys using EDM Instruments, with ranges up to 50 km and accuracies of 5 mm ± 1 ppm, are widely used. Geotechnical/structural monitoring devices include traditional instruments (e.g., strain meters, stress meters, pore water pressure gauges and thermometers) and/or recently developed instruments (e.g., telemetric coordinameters capable of measuring displacements up to 50 mm with an accuracy of ± 0.10-0.18 mm, remotely controlled laser alignment systems and fully automatic high-precision hydrostatic level tiltmeter capable of measuring tilts with an accuracy of 0.001 second of arc) (Chen, 1988). In addition to using instruments and surveillance methods stipulated by the specifications, considerations are given to design and implementation of specific monitoring schemes according to unique features of the structure or its foundation (Dehou and Quanlin, 1985). Dehou and Quanlin (1985) present a good example of the monitoring scheme and the data analysis used for the Gezhouba project in the Three Gorges of the Yangtze River.

Table I.8
Main Requirements for Dam Deformation Surveys in China
(from Chen, [1988, p. 140])

	Concrete Dams	**Earth-rockfill Dams**
Quantities Monitored	* Foundation subsidence & tilt deflections * Horizontal displacements * Pore water pressure * Seepage * Temperature of concrete * Stresses of the concrete	* Horizontal displacements * Vertical displacements * Pore water pressure * Seepage
Monitoring Accuracy	Horizontal displacement: 1.0 - 1.5 mm Vertical displacement: 1.0 - 1.5 mm	* During construction Horizontal displacement: 10.0 mm Vertical displacement: 5.0 - 10.0 mm
		* During Operation Horizontal displacement: 5.0 mm Vertical displacement: 3.0 - 5.0 mm
Monitoring Frequency	During Filling of the Reservoir	
	7.0 - 10.0 days	7.0 - 10.0 days
	From Full Filling to Achieving Stability (3 - 5 yrs)	
	0.5 -1.0 month	1.0 month
	During Normal Operations	
	1.0 - 3.0 month	3.0 months

China's experience in automated monitoring systems is limited to automatic data collectors. However, research experts such as Dehou and Quanlin (1985) believe that establishing an automated monitoring system capable of interpreting structural behaviours correctly and timely is extremely important for the safety of large hydraulic structures.

In China, the common practice is to integrate different survey techniques to detect, locate and eliminate any gross errors introduced by surveys. For instance, on top of a concrete dam, the horizontal and vertical displacements of a construction block can be determined using optical alignment and precise levelling. The displacements from this survey can then be compared with the displacement in the galleries determined, for example, by laser and tensioned wire alignment systems (Chen, 1988).

The physical interpretation of dam deformation surveys is realized by statistical models, deterministical models using the Finite Element Method (FEM) or the combination of both. Due to the uncertainties of deformation and ignorance of non-elastic behaviour in the deterministic model, the calculated displacements will generally depart from the observed values. Thus, the deterministic model is improved using a statistical method (least square solution) that estimates the residuals and the unknown coefficients of the model (Chen, 1988). With the current methods of data analysis, the observations from geodetic, geotechnical/structural systems are processed and analyzed separately. The geodetic data is processed and analyzed by surveyors and the goetechnical and structural data by civil engineers. The reader is referred to Junchun (1985) for some practical examples of monitoring and analysis of earth and rockfill dams in China.

I.9 Cyprus

Little was found on the status of deformation in Cyprus. According to Mr. Kyrou, a representative of the Cyprus National Committee on Large Dams, there is no available publication which deals with the monitoring of dams. Cyprus is a small country officially registering 48 large dams. Only 16 dams are known to have instrumentation.

Of these 16 dams, 9 have both geodetic and geotechnical instrumentation and the remaining 7 have only geodetic instrumentation (Kyrou, 1992).

The geodetic system consists of geodetic instrumentation with several vertical and horizontal surface indicators (monuments). The types and numbers of geotechnical instruments vary from dam to dam. The geotechnical instruments include such devices as extensometer, horizontal and hydraulic overflow settlement devices, hydraulic piezometers, inclinometers, pneumatic piezometers, vibrating wire piezometers, stand pipe piezometers, total pressure cells, United State Bureau of Reclamation (USBR) settlement gauges and settlement magnets (Kyrou, 1992).

There are no national or local standards/specifications for dam monitoring in Cyprus. Dam monitoring is based on guidelines specified by the designer of each dam (Kyrou, 1992).

I.10 Czechoslovakia

Czechoslovakia has 142 large dams officially listed. All of its dams are monitored, however the extent of the monitoring systems depend on the importance and the failure risk factor of the dam (Satrapa, 1992).

In Czechoslovakia the safety supervision of dams has been in existence for over 30 years. The form of the organization providing this service is determined by the legislation implemented in 1975. Under this regulation the operators of the dam are responsible for dam surveillance through the safety organizations authorized by the Ministry. This safety organization assumes the leading role in the supervision and shares the responsibility according to the contract specifications (Šimek, 1982). The organizations employ experts such as Civil, Survey, and Hydrochemical Engineers, and technicians in the fields of Civil Engineering, surveying, mechanics and electronics. Some of the engineers and technicians are specialized and trained to solve problems in areas including stability analyses, mathematical methods, computer programming and special measuring instruments and methods. Furthermore, the organization's specialists have easy access to scientific and research institutions. These institutions assist them by providing information outside the specialists' scope of knowledge or, when needed, they perform unique field or laboratory measuring techniques (Šimek, 1980).

The national standards governing the supervision of dams outline the rules for dam monitoring and supervision in accordance to four categories (I through IV) reflecting the importance of the dam and its risk factor. A copy of these standards was obtained from Mr. Ladislav Satrapa, Assistant Professor on Dam Construction at the Czech Technical University, but unfortunately, no specific information could be deduced from them because they have not yet been translated into English (Satrapa, 1992).

A typical dam safety programme for dams in categories I-III will contain (Šimek, 1980; Šimek, 1985)

a. the instrumentation data and observation methods used,

b. the time intervals of regular measurements (including visual observations),

c. the time of visits of the dam attendant,

d. the time of the control inspection,

e. the requirements for submitting reports and assessments of the first results,

f. the limit values (maximum expected values as defined operational conditions) of the observed phenomena, and

g. the requirements for forwarding documents (including the assessment of the actual technical state of the dam and any remedial measures introduced or planned) to the authorities.

In setting up such a safety programme, the Czech start from trying to answer the question "Why are the measurements to be taken?" rather than "What is to be measured?" They consider which results and what development of the quantities measured are to be regarded as limit or as critical. Using mathematical models (e.g., Finite Element Method) all possible efforts are made to estimate, in advance, every possible signs of any defect to install instruments that would make it possible to detect these phenomena early enough, to localize the flaw and estimate its hazards (Šimek, 1982).

The Czech have no rules or technical standards governing the number of instruments to be incorporated in a dam of a certain type or form. On the whole, the types of instruments used on Czechoslovakian dams are the same as those used by other European nations (e.g., Germany, Switzerland). Their methods of observations is based on the principle that the basic picture of the behaviour of the dam can be obtained by periodic observation of movements at carefully selected characteristic points in galleries and profiles and by establishing a system of water pressure meters and seepage measuring points (Šimek, 1980).

Geodetic systems of cross-sections and longitudinal sections and height levels of control points are used for observing the behaviour of the dam as a whole. With the exception of the trial observation period, the frequency of complex measurements of absolute movements of all control points has been reduced. Although excessive number of control points are placed, only a few well selected points are used in order to obtain frequent check-ups of changes in the relative movements of these points. The remaining points are used in the event of an investigation of future anomalies. The measuring intervals are in accordance with the requirement that the expected movements between two measurements should be greater than the measurement error of 2 ppm. This allows time to perform more important and possibly more frequent and less time-consuming measurements. For example, if not frequently monitored, the relative movement of two mutual control points in footing galleries may result in an unexpected disconnection in the bedrock which could lead to unfavourable consequences (Šimek, 1985).

Like the displacements, the water pressure measurements are taken at certain points only. The total discharge of seepage water from the foot drain and other water collectors must be measured as frequently as possible (Šimek, 1985). These measurements are graphed or tabulated and then compared to the predicted values determined by mathematical formulae.

Another method of surveillance which was implemented on the Nýrsko Dam and Šance Dam is terrestrial photogrammetry. Pláni̇čka and Nosek (1970) concluded that terrestrial photogrammetry with time basis (two simultaneous photographs of the same object with the same axes of exposure taken in different time) for measurement of deformation for rockfill dams is practically as accurate as the conventional geodetic method. It was also concluded that this method is less expensive, provides a perfect photographic record of the dam at all phases, it facilitates the additional evaluation of deformations apart from the movable points and increases the safety of the surveyors during the construction phase (Pláni̇čka and Nosek, 1970).

From all of the different surveillance methods applied to dams, preference is given to daily visual inspection. Experience has shown that 70% of all anomalies, defects, deformations and seepage were detected by visual observations (Šimek, 1985).

The Czech have considered automated measuring systems, but the high cost of implementing a fully automated monitoring system has led them to discard the idea. Currently, installed in some of their dams are a remote signalling devices warning the dam attendant's office, that the limit value of the phenomenon observed (e.g., relative movement, water pressure, seepage) has been attained. Computers are used by the central office to keep records of important facts, to analyze and test the reported results of the measurements and to analyze the future development trends (Šimek, 1985).

A literature review of a number of papers from the Czechoslovakia National Committee on Large Dams, published in the proceedings of the ICOLD Congresses from 1948 to 1991, shows that seepage measurements and uplift pressures are the two most frequent and important quantities measured in Czechoslovakian dams. Also, from this review, other than seepage and uplift pressures, no information was found on the types of analysis applied to the raw observations from geodetic and/or goetechnical/structural instrumentations to determine the overall behaviour of the dam. However, from Šimek's (1980) comment that the types of instruments used on Czechoslovakian dams are the same as those used by other European nations, one can conclude that the methods of analysis are also similar to those of other European nations (i.e., using statistical-, deterministic-, or hybrid-models to determine the expected behaviour and compare it with the measured observations to determine if the difference is within a specified safety tolerance).

I.11 France

France has 468 large dams officially registered. Over half the 468 dams (310) are concrete dams comprising primarily of gravity dams (188) (*World Register of Dams*, 1988). There are numerous reports and case studies written on the safety and monitoring of French dams. A large number of these reports have been published in the Proceedings of the ICOLD Congresses but, consequently the majority of them, if not all, are written in French without English versions. The only English written report found on the status of dam monitoring in France is the one submitted by the French National Committee on Large Dams to the ICOLD Committee on Monitoring of Dams and their Foundations. This report was published in ICOLD (1989) and provides a fairly comprehensive overview of dam monitoring in France. The report is primarily based on the experience in dam monitoring of the Electricité de Françe (EDF) who owns and operates over 150 large dams in France. In fact, a more recent figure given by Mr. F. Lèfevre of EDF, is that EDF is responsible for the operation of 230 dams more than 15 meters high (IWP & DC, 1992). A summary of the French National Committee's report is provided in the proceeding discussion.

France is an example where government intervention has resulted in the development of an effective and homogeneous system of inspection and surveillance of dams. The French law, dated 14 August 1970, requires inspection and surveillance of all dams more than 20 metres high and those whose failure would result in the loss of human life (ICOLD, 1989). The components of the law which are believed to be fundamental to dam monitoring are (ICOLD, 1989):

(1) the surveillance of the dam is the responsibility of its owner,

(2) a special Government Department ensures that the surveillance is properly carried out by the dam owner,

(3) the Government Department makes its own visual inspections each year, and a full inspection five years after first filling and every ten years subsequent, and

(4) for older dams the Government Department has a prioritised list of the dams to be reviewed with which it invites the dam owners to submit a report to the Permanent Technical Committee on Dams containing the recommendations on the instruments to be installed.

The French power agencies are self contained and incorporate the following typical divisions (ICOLD, 1989):

(1) a Construction Division which undertakes the design and construction of the dam, and it is given the responsibility for dam safety during the construction and first filling,

(2) a Generation and Transmission Division who is in charge of the operation and maintenance of the dam, and

(3) a Research and Development Division who is responsible to conduct studies and tests on materials and structures, and it ensures that it is informed on the results of monitoring.

Some of the additional responsibilities of the divisions are the installation of instruments, collecting the measurements, data processing and interpretation of the results.

In order to ensure that close liaison is maintained between all of the departments there is a Monitoring Committee consisting of a representative from all of the divisions. The Committee's official role is to coordinate monitoring policy and practices between the divisions, and to disseminate information on existing and proposed installation. Note that this does not exclude the fact that if required outside experts may be called upon.

Some of the key principles of dam monitoring in France include simplicity, reliability (of instruments and measurements), redundancy, selective monitoring (i.e., read a selective number of key instruments) and semi-automation (i.e., interpretation of measurements and safety evaluation remains to be a task of an engineer). The monitoring schemes adopted by the French comprise of both geodetic, and geotechnical/structural instrumentation. However, depending on the type of dam, one method is preferred over the other. For example, for arch dams the policy for monitoring is to use primarily geotechnical instruments. The argument against the use of geodetic methods is that in France most arch dams are situated in difficult terrain or in high mountainous areas where it is extremely demanding for skilled personnel to access the sites with high precision instruments. In addition, with geodetic methods there is a necessity to check the observation stations against other stable reference points. On the other hand, for arch dams, surveys are used only on those dams with thin arches where pendulums cannot be incorporated in the structure (e.g., in the shafts and galleries of the dam) (ICOLD, 1989).

For concrete and embankment dams the instrumentation used by the French to monitor the dams consist mainly of:

1. **Concrete Dams**. Surface monuments for levelling and trilateration (using EDM), pendulums (direct or inverted plumblines); extensometers; strain meters (particularly in multiple arches and in buttresses); inclinometers; piezometers; pore pressure cells (in soils); and seepage measurement devices.
2. **Embankment Dams**. Survey targets fixed on concrete beams sunk deep into the fill for plane triangulation and direct levelling; internal movement measuring devices such as hydraulic level, extensometers with vibrating wire or induction sensors, and electromagnetic torpedoes in horizontal tubes; and open pipe piezometers, and hydraulic (USBR type) or electric pore pressure cells.

Examples of existing dams that are being monitored using these types of instruments can be found in ICOLD (1989).

EDF's recent advancements in monitoring instrumentation have been developments in telemetric data acquisition which include telependulum (induction type), distofor and extensofor. The telependulum is basically a pendulum that can be read remotely. The distofor yields a near continuous log of movements along a borehole with no friction between the sensor and the bore hole. The extensofor is similar to the distofor except that it is mobile and is lowered into the hole each time a reading is taken (ICOLD, 1989). The most recent developments include (Goubet and Guérinet, 1992; IWP & DC, 1992):

(1) *Thermodynamic Monitoring*. This method consists of placing in groups every five meters vertically, thermometers, extensometers and total pressure cells in selected cross-sections of the dam. Preliminary tests conducted on the Riou Dam, in the French Alps, concluded that the effect of external temperature during construction and the disturbances caused by the phenomena at the dam face.

(2) *Ultrasonic Flow Meter.* This instrument is installed on weirs to determine water levels. Its accuracy has been recorded to within 1 mm.

(3) *Optical Telependulum.* The pendulum is capable of determining the position of a plumb line without contact within an accuracy of one-hundredth of a millimeter.

(4) *Safety Telemeasurements (SAFTEL).* A remote monitoring tool which allows the user to remotely retrieve the results of measurements taken by electronic devices installed on the structure. The system has already been installed on 12 French dams. The ultrasonic flow meter and optical telependulum were designed specifically for use with SAFTEL.

(5) *TAM-TAM.* A decentralized tool designed to assist operators to process measurements taken on the structure. These measurements could be either those associated with monitoring, or with areas such as the environment, reservoir management, operating procedures, etc.

Note that SAFTEL and TAM-TAM can be used separately or together.

During the construction and filling the initial analysis of the data consists of plotting the observations of significant parameters against time, concrete or fill level and reservoir level (e.g., concrete strain against reservoir level). Subsequently as more measurements are collected more detailed statistical analysis are done. For example, for concrete dams one can determine the reversible elastic effects of concrete due to the changes in water level and temperature. Also, using the relationships between the displacement temperature relationship and the displacement water level relationships one can correct time related movements for water level and temperature effects. These time related movements are then plotted on a graph and the behaviour of the dam is considered to be normal if and only if the movements fall within a specified dispersion band.

Another approach that the French have taken in the analysis of data is to compare the instrument readings with those calculated from FEM analysis during the design. For fill dams a back-analysis approach is applied where the in situ measurements taken during and/or after construction are used to calibrate the deterministic model and make it react in the same way as the dam. The back-analysis approach is considered to be better for predicting the behaviour for future stages of construction and operation.

After a number of years, with a large quantity of data available, statistical analyses modelling is done. Eventually *performance models* are developed by fitting an equation to the results using hydrostatic load, time of measurement, and time measured from the original measurement as variables. These models are then used to separate reversible temperature and load effects from the irreversible. Examples of this type of analysis can be found in ICOLD (1989).

I.12 Germany

Germany has a total of 261 large dams officially listed in the *World Register of Dams* (1988). The only information found on the dam safety program in Germany is that of the state of Nordrhein-Westfalen. The material presented hereinafter is based on a number of technical papers written by members of the German International Committee on Large Dams and other German experts in the field of deformation monitoring.

In January 1990, Germany hosted a conference to address several issues related to the safety of dams in the state of Nordrhein-Westfalen. In Nordrhein-Westfalen the water authorities are responsible for inspecting and maintaining the safety standards of the dams. The state regulations stipulate that a dam has to meet "generally recognized technical standards" based on the current technology, as well as on the experience of specialists in the field. These standards have been established and published by a number of scientific and technical organizations, in particular the Deutsche Institut für Normung (DIN). Recently, however, it has been recognized that the key areas requiring additional attention are: (1) a review of monitoring and control measurements, and (2) the need for establishing guidelines for the frequency of measurements and methods for evaluating the results. Guidelines prepared by a working group of experts from the State Dam Committee have already established the basis for setting the minimum level for monitoring and control (IWP & DC, 1990).

Articles written by Schenk (1988), Rissler (1991), Idel and Wittke (1991) clearly illustrate that German dams are monitored using classical geodetic, and geotechnical/structural techniques. However, the inclusion of geotechnical instrumentation to monitor dams has been a recent trend that has only begun in the past ten to fifteen years. For example, the Fürwigge Dam was not monitored with geodetic equipment until 1986 as part of the German Dam Safety Program (Rissler, 1991). Idel (1982) shows that primitive methods such as simple open and/or pumped drains were still being used to determine seepage and hydrostatic pressures for earthfill and masonry dams up to the latter 1970. Furthermore, although modern dams such as the Primstal Dam (1981) have been designed with both geodetic and geotechnical instrumentations, the German geotechnical/structural monitoring systems when compared with those used on Italian dams, seem to be inferior. Table I.9 illustrates the detailed monitoring program applied to Primstal Dam.

The Germans, like the Swiss, still seem to place more emphasize on geodetic measurements. For example, with respect to new advancements in the area of monitoring techniques, the emphasis has been on the development of new geodetic systems. Some of the modern techniques proposed include automatic theodolite/tacheometer systems, terrestrial photogrammetry and differential GPS (Niemeier and Wunderlich, 1988). Niemeier and Wunderlich (1988) go as far as suggesting a future monitoring system comprising of the combination of differential GPS-positioning and automatic theodolite/tacheometer system. The authors claim that this system will be able to determine the actual position of the dam in real time and that it will also be possible to connect the system with internal geotechnical monitoring devices (e.g., centring the GPS antennas above the plumbline shafts). Table I.10 shows the comparison of the three proposed methods as well as the classical triangulation/trilateration techniques. A recent development in geodetic equipment is the EDM Polsar 500. This electronic distance measuring device uses a high energy transmitted signal which allows measurements of short distances (up to 200 m) directly from the observer to natural flat surfaces without the use of reflectors.

Table I.9
Monitoring System of the Primstal Embankment Dam (Germany)
(from Schenk, [1988, p. 765])

Measurements	Instruments and Location	Intervals of Measurements	Remarks
Deformation of Dam and Dam Axis	Settlement gauges, Displacement gauges, horizontal geodetic measurements at sealing face	2/a (2 per year) 1/a (1 per year)	Until guarantee time (1987) After 1987 and during impoundment at every 10 meters drawdown
Settlements of Concrete Structures	Geodetic measurements of gallery and bottom outlet	1/a (1 per year)	
Stress Measurements	Total pressure gauges, bottom outlet	1/a (1 per year)	
Discharge of Drainage System	Drains of asphaltic sealing, Concrete drains, drainage shafts d/s	daily weekly	Visual control Measurement
Inspection	Plant	daily	
Hydrochemical Analysis	reservoir and drainage system, outside piezometer	2/a (2 per year)	
Piezometer, Observation Wells, Natural Springs	Gallery, abutments and d/s slope, valley floor, discharge of piezometer	daily weekly	Visual control Measurement

Table I.10
Critical Comparison of Various Geodetic Techniques (German)
(from Niemeier and Wunderlich, [1986, p. 385])

Approach	**Terrestrial (Geodetic)**		**Terrestrial Photogrammetric**	**Satellite Supported**
Method	**Triangulation Trilateration**	**Automatic Monitoring**	**Close Range Photogrammetry**	**Differential GPS Phase Measurements**
Overall Accuracy	≤ ± 1-2 mm	≤ ± 3 mm	≤ ± 6 mm	≤ ± 3 mm
Reliability and Sensitivity	Familiar and approved procedures to ensure success. Clear terms and measures of assessment.	Less control stations. More frequent observations. Prediction by filters. Alternatives at total system breakdown?	Not sufficient for targets. Non-targeted points determinable. Subsequently calibration parameters are part of solution.	4 observation limit. Redundancy demands at least 3 receivers and sophisticated planning of session sequence. Transformation problems for subsequent terrestrial surveys.
Cost	Skilled survey parties. Precision instruments can be dedicated to various other purposes.	High expenditure. Attractive rate of utilization. Immobility drawback.	Customary camera. Precision comparator.	Still exclusive purchase price of receivers. Receiver pools? Experienced operator for data processing.
Usefulness	Only targeted points suitable for measurement.		Conclusive survey: behaviour of entire structure.	Accessible sites free from obstructions. No electronic disturbances.
	Common deformation analysis programmes.	Simultaneous monitoring of sliding slopes		
Connection	Conventional	Conventional	Conventional	Antenna above plumbing shaft.
	Strong link if loop-holes in top gallery	Difficult or poor link between survey systems inside and outside the dam.		
Long-term Stability	High effort to keep EDM-correlation under control.	Changes will be quickly revealed.	Several reference distances (loss of reference mark involves transformation problems)	

Approach	**Terrestrial (Geodetic)**		**Terrestrial Photogrammetric**	**Satellite Supported**
Method	**Triangulation Trilateration**	**Automatic Monitoring**	**Close Range Photogrammetry**	**Differential GPS Phase Measurements**
Absolute Stability	High additional effort, often not practicable.			No problem if dual ban receiver.
Repetition	Seasonal	Seasonal	Seasonal	Probably continuous.
Observation Time	3 days	In minutes	1/2 day	Depends only on system availability and number of receivers.
	Heavily dependent on weather conditions.			
Processing (response time)	Zero epoch: in days Subsequent epoch: 1 day Real time when observations are compared in situ.	Real time and automatic. Telemetric transmission of parameters and results. Alarm property.	In reasonable time when using analytical plotter.	Depends on noise level, cycle slips and experience. It might amount to days when ephemeris are degraded.

The only recent advancements known in the area of geotechnical equipment has been the optical fibre crack-detection and crack-width sensors. These sensors are designed to continuously monitor the formation and sizes of cracks in concrete dams and heavy concrete structures. The theory and the application of the sensors are well described by Haug et al., (1991).

Germany and Canada are the only two countries in this study who have demonstrated the use of sophisticated computational methods for the optimal design and analysis of the geodetic monitoring surveys. For a comprehensive description of the German methodology for the design of control networks the reader is referred to Gruendig (1986). Case studies of existing dams illustrating the applications of least squares adjustment and statistical analysis are given by Bill et al. (1985) and Heck (1985).

Although the Germans can be considered fairly advanced in the area of geodetic deformation networks, they have not yet investigated the possibility of integrating geodetic observations with geotechnical/structural observations.

I.13 Greece

Greece has 22 large dams. Sixteen of the 22 dams are owned by the Public Works Corporation and the remaining 6 dams are evenly distributed amongst the Ministry of Public Works, the Ministry of Agriculture and the Athens Water Board (Stavropoulou, 1992). Although there is no official register of all Greek dams, a total of 13 dams have been registered in the *World Register of Dams* (1988).

Greece has no national standards or regulations for dam monitoring. Dam owners have their own specifications which are unique to each dam (Stavropoulou, 1992).

The majority of Greek dams are monitored by geodetic means. Of the total dams, approximately 100% are monitored using exclusively geodetic techniques and 50% are monitored using both geodetic and geotechnical techniques. Table I.11 summarizes the monitoring systems and the measuring frequencies applied to those dams owned by the Public Power Corporation of Greece. The quantities illustrated in Table I.11 are said to be representative of those used to monitor all Greek dams (Stavropoulou, 1992). After a careful review of Table I.11 it would seem that the geodetic and geotechnical instruments and monitoring techniques used to monitor the behaviour of Greek dams are typical and somewhat elementary.

Table I.11
Types of Monitoring Systems and Measurement Frequencies Applied to Dams Owned by the Public Power Corporation of Greece (after, Stavropoulou [1992])

Name of Dam (age of dam in yrs)	Type of Dam	Type of Monitoring System		Frequency of Measurements	
		Geodetic	Geotechnical	Geodetic	Geotechnical
Louros (38)	Arch gravity	Crest settlements	-	Once a year	-
Ladon (37)	Hollow gravity	Crest settlements	-	Once a year	-
Plastiras (32)	Arch	Crest settlements	Inverted pendulum, clinometers	Once a year	Once a month
Kremasta (26) *	Earthfill (with clay core)	Settlements (crest u/s, slope d/s) Horizontal displacement	Cross-arms	Twice a year	(not operational)
Kastraki (23)	Earthfill (with clay core)	Same as for Kremasta Dam	-	Once a year	-
Polyphyto (16) **	Rockfill (with clay core)	Vectors of crest displacements	Strain gauges in the core and shells of the embankment	Twice a year	(not operational)
Pournary (13) ***	Earthfill (with clay core)	Same as for Kremasta Dam	Combined Idel instruments (settlements and horizontal displacements)	Once a year	Once a month (only settlement)
Assomata (7) ***	Earthfill (with clay core)	Same as for Kremasta Dam	Combined Idel instruments (settlements and horizontal displacements) Linear strainmeters	Once a year	Once a month
Sfikia (7) ***	Rockfill (with clay core)	Same as for Kremasta Dam	Linear strainmeters	Once a year	Once a month

Name of Dam (age of dam in yrs)	Type of Dam	Type of Monitoring System		Frequency of Measurements	
		Geodetic	Geotechnical	Geodetic	Geotechnical
Stratos (4) ***	Rockfill (with clay core and cut-off diaphragm wall)	Crest settlements and horizontal displacements	Combined Idel instruments (settlements and horizontal displacements)	Once a year	Once a month (only settlements)
Pigai Aoos (3) ***	Rockfill (with clay core)	Settlements and horizontal displacement of crest and d/s slope	Combined Idel (settlements and horizontal displacements)	Once a year	Once a month
Politses (3) ***	Rockfill (with clay core)	Crest settlements	-	Once a year	-

Note: * Abutment movements are measured by inverted pendulum and rock extensometers.
** The movements of major landslide next to Polyphyto Dam are being monitored meticulously with the following methods:
a. Levelling;
b. Horizontal displacements (distance from a stable point outside the landslide); and
c. Rybars (geotechnical instruments similar to rock extensometers but with cables instead of rods. They are installed in boreholes.
*** Abutment slope movements monitored by rock extensometers and inclinometers.

I.14 Hungary

Hungary has 18 large dams officially listed. Eleven of the 18 dams are continually monitored using predominately geodetic instruments. However, it is uncertain whether or not the remaining seven are monitored (Varsa, 1992).

For decades, the Structures Surveillance Section of VITUKI has been the organization responsible for inspecting all of the hydraulic structures in Hungary. Hungary has developed national standards/specifications for dam monitoring. A copy, unfortunately in Hungarian, has been obtained from Mr. I.M. Nagy, the Secretary of the Hungarian Committee on Large Dams. The specifications are divided into six parts based on the different types of hydraulic structures within Hungary. These specifications were developed based on measurements and experience gained over a period of eight years (1981-1988). The national importance of the specifications was dictated by the regulations (Order No. 4/1986) set out by the President of the National Water Authority. This regulation contains a list of structures which must be included in the obligatory surveillance programme (Gresz and Szalaváry, 1992).

Their surveillance programme consists of stability checks, hydraulic measurements and material testing (Gresz and Szalaváry, 1992). The stability checks are done primarily by precise geodetic surveys. Benchmarks are designed to permit the measurement of both vertical and horizontal displacements. The horizontal displacements are determined by offset measurements, or a combination of offset measurements and resections, and the vertical displacement are measured by precision levelling. The desired accuracy for horizontal measurements are to be within ±1.0-1.5 mm and the vertical measurements are to confirm movements of ±0.2 mm or better. Overall, the survey network is designed with great care. Some of the factors which are considered into the design of the survey scheme are the local topography, the structural features of the dam and its elements, the optimum time of the day to make the measurements, the types of materials over which the line of site will crosses over during the construction and operation and the best types of instruments and methods to use over various terrains (Hamavas, 1979).

To examine the hydraulic stability of the dam, especially for embankment dams, regular checks of the seepage discharge through, under and around the dams are made. These measurements are used to determine and insure that parameters such as uplift forces and hydraulic gradients do not exceed the values reckoned by the designer. The most popular method used to measure these parameters are piezometer wells placed strategically around the dam and in the dam body, some extending into the soil layer below the foundation (Hamavas, 1979).

The current method of analyzing the measured data is known as the GARIN programme. This new method of analysis is based on the forgoing trend analysis technique. The GARIN programme was developed to overcome some of the deficiencies exhibited by the trend analysis method (e.g., one deficiency is that the regression coefficient determined from the results is too general in nature to identify any additional effects). Generally the GARIN Programm is a multiregression analysis where the natural impacts and phenomena considered are correlated. With this method the user is free to choose the number and the types of functions (up to a maximum of three). From the statistical analysis of the error function a reliability parameter (MP) is formed. This reliability parameter reveals the randomness of the residual term; it is random if MP is less than unity or there is a regular error if MP is greater than unity. In addition, a set criteria defined as the guarantee index (GI) is derived. Any value above this limit indicates that there is an error in the data series.

The GARIN Programme is applied to both the geodetic survey data and the hydraulic data. A case study using the data from the surveillance measurements of the Tiszalök River Dam concluded that by using the GARIN method it is possible to determine whether damage is liable to occur or not and derive the occurrence associated with failure of the structure. Although the GARIN method takes into account other influences such as temperature and water level, like the deterministic technique, it is applied to a data series recorded at a single station over a period of time. Gresz and Szalavári (1992) give two examples of how the GARIN method is applied to a levelling data series measured at a benchmark and to a ground water well data series from an observation well.

I.15 Ireland

Ireland has a total of 15 large dams. Of these 15 dams, 7 are embankment and 8 are concrete type dams (*World Register of Dams*, 1988; Richardson, 1992). In Ireland, the principal agencies involved with the design, construction and maintenance of hydraulic structures are the Electricity Supply Board of Ireland (ESBI) and their consultant ESBI Atkins International Ltd. (Richardson, 1992).

Ireland has no national or local standards for dam monitoring. However, "alert values" based on normal operating conditions are used to insure the safe operation of dams. These values have been established from analyses of results of comprehensive studies and record reviews of existing dams. The way that the "alert values" work is that the readings from instruments are inputted into a computer programm and then compared against their corresponding "alert value" assigned for those particular points and instruments. Consequently if the readings are above the "alert values" then some form of action is taken. Instrument readings are inputted into the computer programm weekly or monthly, depending on the instrument type (Richardson, 1992).

All concrete dams are monitored solely by geotechnical/structural means (jointmeters, extensometers, uplift pipes, relief holes, inclinometers and thermocouples). However, if required, in certain instances crest alignment measurements are made (Richardson, 1992). Although no information was found with respect to the monitoring of embankment dams, it can be assumed that like concrete dams embankment dams are also monitored using primarily geotechnical/structural instruments.

I.16 Italy

In 1988, according to the *World Register of Dams* (1988), Italy had officially registered 440 large dams. Of these 440 dams, there are 97 arch concrete dams, 205 massive gravity concrete dams, 23 buttress concrete dams, 10 multiple-arch concrete dams, 24 rockfill dams and 81 earth dams. A recent figure on the current number of dams could not be obtained since the Italian Committee on Large Dam (ITCOLD) is in the process of updating their dam inventory for inclusion in the next issue of the World Register of Dams (Bonaldi, 1992).

Italy has no national specifications applicable to dam monitoring. The design, construction and operation of dams fall under regulations enacted on November 1, 1959. Since then, the regulations have been integrated into the Technical Regulations dated March 24, 1982. The regulations are general in nature and prescribe the safety rules by which authorities must abide by ICOLD (1989). The design of the measuring system depends upon the dam type, life span, size and the reservoir capacity as well as the possible risk to human life. However, the ITCOLD has recommended general guidelines defining the type of measurements and instruments that should be used to monitor concrete and earthfill type dams. These are given by Tables I.12a-I.12c (concrete dams) and Tables I.13a-I.13b (earthfill dams). The guidelines have been included in ICOLD (1989) as part of the ITCOLD's report. The key requirements of a measuring system are (ICOLD, 1989):

(1) the system should be designed and installed by specialized personnel,
(2) visual inspections should always be made,
(3) redundant observations should be conducted by observing the same points using different instruments,
(4) for automated systems alternatives should be made available to perform the measurements manually, and
(5) there should be a minimum amount of time (next to nil) between the execution of the measurement and the final analysis.

The Legislation commissions the overall supervision of dams to the Dam Service and Civil Engineering Offices of the Technical Department of the Ministry of Public Works. Dam Services and the Civil Engineering Offices play very important roles in all phases of the project. For example, during the operation of the dam, Dam Service and the Civil Engineering Offices are responsible for carrying out surveillance of the structure. They also visit the dam at least twice a year, during minimum and maximum reservoir levels if possible, and conduct periodic checks of telephone, radio links and other signal and alarm systems (ICOLD, 1989).

Table I.12a
Environmental Measurements in Italian Concrete Dams
(from ICOLD, [1989, p. 156])

Quantity Measured	Construction	Temporary Operation and trial test	Operation	Instruments
Air temp.	*	o	o	Thermometers
Snow & rain fall	o	o	o	Snow & rain gauge
External pressure	o	o	o	Barometers
Humidity	o	o	o	Hygrometers
Water temp.	-	o	o	Thermometers
Water level	-	*	*	Levelling staff, hydrostatic balance
Ice thick.	-	o	o	
Bathometry	-	o	*	Sonic and radar sounding

Table I.12b
Measurements Within the Dam Body of Italian Concrete Dams
(from ICOLD, [1989, p. 56])

Qty. to be Measured	Constr.			Temporary Operation and Trial Test			Operation			Instruments
	GR	BU	AR	GR	BU	AR	GR	BU	AR	
Horizontal displacement	-	-	-	**	**	**	**	**	**	Triangulation, collimation, direct and inverted plumb line
Vertical displacement	*	*	-	**	**	*	*	*	o	Topographic or hydrostatic levelling
Rotations	*	*	-	**	**	*	*	*	o	Movable or fixed clinometers

Qty. to be Measured	Constr.			Temporary Operation and Trial Test			Operation			Instruments
	GR	BU	AR	GR	BU	AR	GR	BU	AR	
Movements of joints	o	o	o	*	*	*	o	o	o	Dilatometers, joint meters, extensometers
Movements of cracks	**	**	**	**	**	**	**	**	**	Dilatometers, joint gauges, extensometers, acoustic emission
Concrete temp.	*	*	*	o	o	o	o	o	o	Thermometers
Concrete deform.	o	o	o	o	o	o	o	o	o	Extensometers
Stresses	o	o	o	o	o	o	o	o	o	Stress meters
Seepage	-	-	-	-	**	**	**	**	**	Weirs, volumetric measurements

Table I.12c
Measurements in the Foundation of Italian Concrete Dams
(from ICOLD, [1989, p. 156])

Qty. to be Measured	Constr.			Temporary Operation and Trial Test			Operation			Instruments
	GR	BU	AR	GR	BU	AR	GR	BU	AR	
Horizontal displacement				**	**	**	**	**	**	Inverted plumb lines, inclinometers
Vertical displacement	*	*	*	**	**	*	*	*	o	Topographic or hydrostatic levelling, extensometers
Rock deformation	o	o	o	o	o	o	o	o	o	Extensometers
Elastic modulus	o	o	o	o	o	o				Sonic core, seismic velocity
Stresses	o	o	o	o	o	o				Stress meters

Qty. to be Measured	Constr.			Temporary Operation and Trial Test			Operation			Instruments
	GR	BU	AR	GR	BU	AR	GR	BU	AR	
Under and pore pressures				**	**	*	*	*	o	Pressure cells, stand pipe piezometers, manometric cells
Under-seepage				**	**	**	**	**	**	Weirs, volumetric measurements

Table I.13a
Environmental Measurements in Italian Earthfill Dams (from ICOLD, [1989, p. 157])

Quantity Measured	Construction	Temporary Operation and trial test	Operation	Instruments
Air temp.	o	o	o	Thermometers
Snow & rain fall	o	o	o	Snow & rain gauges
External pressure	o	o	o	Barometers
Humidity	o	o	o	Hygrometers
Water temp.	-	o	o	Thermometers
Water level	-	*	*	Levelling staff, hydrostatic balance
Ice thick.	-	o	o	
Bathometry	-	o	*	Sonic and radar sounding

Table I.13b
Measurements Within the Dam Body and the Foundation of Italian Earthfill Dams (from ICOLD, [1989, p. 157])

Qty. to be Measured	Construc-tion		Temporary Operation and Trial Test		Operation		Instruments
	UF	C	UF	C	UF	C	
Settlements	**	**	**	**	*	*	Topographic or hydrostatic levelling
Horizontal displacements			**	**	*	*	Triangulation, collimation, inverted plumb line, inclinometers, extensometers, invar wires
Deformations	*	*	*	*	o	o	Extensometers
Total pressures	o	o	o	o	o	o	Pressure gauges
Pore pressure in the dam body		**	**	**	**	**	Pressure cells
Pore pressure and ground water level in the foundation	**	**	**	**	*	*	Pressure cells and stand pipe piezometers
Seepage			**	**	**	**	Weirs, volumetric measurements
Turbidity			o	*	o	*	Turbidity meters

Notes on Tables:

Relevance of safety levels:
** Critical situation (up to collapse)
* Out of service (total or partial)
o Check

GR = Gravity dam
BU = Buttress dam
AR = Arch dam
UF = Upstream waterproof
C = Impermeable core

Dam safety in Italy is primarily based on the comparison of instrumental data with forecasted data from simple (statistical) models or more sophisticated (deterministic) models. The degree of risk and safety for a dam is established during the design stage.

During this stage a reference model is defined. This model establishes the quantities that must be observed and how they are expected to behave. The two major types of models applied to Italian dams are the "a posteriori regressive model (statistical model)" and the "a priori deterministic model." The data from the instruments are independently graphed and compared to the predicted data from one of the two models. For older dams and those with special problems, the current practice is to perform a check-up or a "certified control" every ten years. This may include re-designing the structure to determine the reference model and/or revising the entire measuring system in place and verifying its completeness and adequacy. A complete list of what is reviewed during these visits can be found in the Italian national report in ICOLD (1988).

Italians have developed a strategy (ENEL, 1980) for combining the statistic and deterministic modelling in dam deformation analyses. Statistical models consist of correlations between environmental quantities (e.g., impounded water level, ambient temperatures) and structural effects (e.g., displacements). The correlation is derived from statistical analysis of past data. With the deterministic models, the aim is to derive the effects from the causes by applying known laws of materials and knowledge of the local conditions (e.g., geometry, material properties). The cause quantities are those which induce changes in the structure and the effects are the responses of the structure to the variations of the cause quantities. To improve the analysis, the two models are often used together to form what is known as the hybrid model. Here the knowledge of the expected structural behaviour obtained from the statistical model is used to "tune-up" the deterministic models. Overall, the deterministic and hybrid models are the most often used models for analyzing the behaviour of Italian dams (ICOLD, 1989).

The estimated values obtained by the models are taken as the reference values from which the observations (measured effects) are assessed. If the difference between the forecasted effects and the measured effects is within specified tolerance bands, then this confirms the hypothesis that the dam behaves as the model predicted. To visualize what is happening, the measured deformation from an instrument and the predicted deformation from the model are presented and compared in graphical forms (ENEL, 1980).

The tolerance bands are determined from the standard deviation of the forecasted model and the actual measurement. It is estimated on the basis of the data gathered for the normal behaviour of the structure over a period of two to three years. There are three tolerance bands: (1) the first band equalling to twice the standard deviation within which the behaviour of the dam is classified as normal; (2) the second band equalling to three times the standard deviation within which the dam is said to be experiencing slight irregularities; and (3) the third band which is based on the ultimate strength data of the physical and/or mathematical model of the structure causes suspicions of serious irregularities (ICOLD, 1989). The numerical simulation of the deterministic models are realized by a Finite Element mathematical model. A description of the deterministic model and the application of both types of models are given in the *Comportamento Delle Grandi Dighe Dell'ENEL* (ENEL, 1980).

The Italians assign little importance to geodetic measurements. Their aim is to obtain measurements as quickly as possible and thus their efforts are focused primarily on a system of instrumentation that can be easily automated. The geodetic systems are very simple, comprising a series of plumblines, inclinometers, collimation, bench marks and horizontal survey targets, each analyzed separately. This methodology has limited geodetic measurements and analysis to a one-dimensional case. Examples of the most common types of instruments used in the monitoring system are given at Tables I.12a-c and I.13a-b. Some of the recent developments in instrumentations are the Ladir (laser systems for surveying the dynamic displacements of dams) and thermography (systems to study the surface's thermal conditions) (ICOLD, 1989). Some current Italian developments in instrumentations is sonic tomography (sonic log and sonic cross-hole) for diagnosing the state of health of concrete (Bertacchi et al., 1991). Bertacchi et al. (1991) provide a good description of the method and some examples of its application.

Their seismic surveillance system is a complex system consisting of sensors and hardware for acquiring, recording and processing the data. The system is made up of either "distributed" equipment (direct recording using accelerographs or seismographic recorders) or "centralized" equipment (recording the seismic phenomena to a centralized system using communication cables) (ICOLD, 1989).

The major criteria for the frequency of measurements that have been applied by the Italians are listed in Table I.14. The table has been constructed from the guidelines provided by the ITCOLD's report in the ICOLD, (1989). The frequencies of the measurements depend on factors such as the quantity to be measured, the life span of the structure, the sensitivity of the measuring device, the regulations specified by the authorities and other special requirements (ICOLD, 1989).

Excellent examples of the types of monitoring systems and analysis applied to some of the major Italian dams are included in the aforementioned *Comportamento Delle Grandi Dighe Dell'ENEL* (ENEL, 1980), Bonaldi et al. (1984), Bonaldi et al. (1984) and Piccinelli et al. (1985).

Table I.14
Measurement Frequencies Applied to Italian Dams
(from ICOLD, [1989, p. 161])

Instruments	Frequency of Measurements
Pendulums, piezometers	Bi-weekly
Inclinometers, strain-gauges, uplift pressure manometers	Monthly
Collimation and settlement devices	Quarterly
Levelling and geodetic measurements	Semi-annually or annually
Ambient quantities	Daily
Seepage	Daily

1. Maximum time between readings of the most critical measurements should not exceed 15 days.
2. For automated measuring systems recording of data may be done daily.
3 During the filling of the reservoir at each stages of the filling , at minimum, one complete series of measurements, and processing and analysis of the data with the design model data should be done.

I.17 Japan

Japan has 2,228 large dams which are owned by either the government or private owners (Hayashi et al., 1987; *World Register of Dams*, 1988). There has been a reduction in the number of arch dams built because of the decrease in favourable sites. Consequently mainly rockfill and concrete gravity dams have been constructed, followed by earthfill dams. Japan is well known for the development of the Roller Compacted Dam (RCD) construction method. The RCD construction method reduces the volume of concrete and formwork and uses common equipment such as bulldozers and dump trucks to transport and place the cement. Today, further research is being done to improve the RCD technology to build large dams up to 155 meters high (Nakazawa, 1991).

The Japanese government has taken a fairly conservative approach to dam safety. Dam safety has been achieved through the implementation of studies, the involvement of experts, the careful planning of monitoring systems and the use of specialized construction methods, design criteria and guides. The current regulations regarding the criteria for the design and monitoring of Japanese dams are specified in the following four guides (Hayashi et al., 1987):

1. *Manual of Instrumentation and Monitoring of Dams*, published by the Federation of Electric Power Companies, 1964 (in Japanese)
2. *Criteria of Monitoring and Inspection of Dam Structures*, published by the Japanese Committee on Large Dams (JANCOLD), 1973 (in Japanese)
3. *Guidelines of Design and Monitoring of Dams*, published by the Bureau of Agricultural Construction and the Ministry of Agriculture, Forestry and Fisheries, 1981 (in Japanese)
4. *Guidelines of Monitoring of Safety of Dams*, published by the Public Works Institute and the Ministry of Construction, 1982 (in Japanese).

The effective use of instrumentations and monitoring and the proper analysis of the recorded data are outlined in the regulation guide published by the Public Work Research Institute. The regulations commission the Ministry of Construction as the Safety Administration and Monitoring of Dams. Some of the quantities stipulated in the design criteria are: (1) the permissible pore and uplift pressures in different types of dams and foundations, (2) the allowable stresses due to temperature gradients in concrete dams, (3) the treatment of fractured zones in the foundation rock and the corresponding safety factor, and (4) the seismic coefficients for different types of dams and regions (Hayashi et al., 1987).

Japan places a high priority on the seismic monitoring of dams. The country is located on a very active seismic region. Its dams have suffered from seismic shocks from more than 45 earthquakes between 1943 and 1980. Fortuitous, the damages to the dams have been negligible resulting in minor leakages, settlements and deformations which were repaired immediately (Hayashi et al., 1987). An extensive amount of scientific and theoretical research has been conducted to study the resistance of dams to earthquake.

Consequently, whenever new findings are made they are immediately applied to dam design and construction (Kuroda and Baba, 1985). For example, a recent development has been the electro-magnetic recorders for multi-channel data collection. In addition the systems have been improved by including accelerometers, velocity meters and displacement meters. (Hayashi et al., 1987).

Many experts agree that the design of a monitoring system depends upon several factors including the type of dam, its size and the environment within which it is constructed. Despite this fact there are some common quantities (rotations, displacements, settlements) that are measured within the same classification of dams. For example, JANCOLD has published a very comprehensive table (see Table I.15) outlining what they believe to be the essential instruments that should be included in the major types of concrete and earthfill dams. This table includes the purpose of the instruments during the construction and maintenance stages. The frequency of monitoring is given by the guidelines reproduced in Tables I.16a and I.16b. Included is also Table I.16c, an actual frequency program that is being implemented on the Miyama Dam located in a high seismic region of Japan (Hasegawa and Kikusawa, 1988). These tables show that the frequency of monitoring is not only a function of time but also a function of the type of dam, seismic activity and flooding. The selection of a monitoring system that is best suited for a dam involves (ICOLD, 1989):

(1) identifying the elements that characterize the safety of the dam and its foundation,
(2) determining the quantities that best describe the behaviour of the dam,
(3) selecting the best instruments for obtaining these quantities,
(4) determining the number and the optimum distribution of instruments, and
(5) determining the frequency of the observations.

Table I.15

Types of Instrumentations Applied to Japan's Concrete and Fill Dams (from Hayashi et al., [1987, pp.4-5])

			Purpose	**Sensor**
Concrete Dam	Gravity	Construction	* Control of temperature * Inspection of leakage	Thermometer, Joint meter, Strain meter
		Maintenance	* Deformations of dam and foundation * Inspection of leakage from foundation	* Sighting survey, Plumb line * Piezometric hall, Measuring weir
	Hollow Gravity	Construction	* Control of cracking in web plate and diamond head * Deflection	Thermometer, Joint meter, Strain meter, Stress meter
		Maintenance	* Inspection of leakage * Deformation of dam and foundation	Leakage meter, Strain meter, Plumb line, Thermometer, Piezometer hall, Sighting survey
	Arch	Construction	* Deflection and joint movement * Control of temperature * Control of cracking	Thermometer, Joint meter, Strain meter, Stress meter, Plumb line, Sighting survey
			* Observation of rock deformation and leakage around the discontinuous planes	Sighting survey, Plumb line, Strain meter, Stress meter, Rock deformeter, Deflect meter, Measuring weir

			Purpose	Sensor
Fill Dam	Rockfill (Center Core Type)	Construction	* Control of excess pore water pressure during embankment * Control of compaction * Relative displacement among core, filter and rock abutment	Pore water pressure gauge, Soil pressure gauge, Relative settlement gauge, Relative shear displacement gauge, Radio isotope density meter, Strain meter in inspection gallery
		Maintenance	* Settlement, lateral deformation * Pore water pressure * Shear deformation on the abutment, leakage	Sighting survey, Strain meter, Soil pressure meter, Deflect meter, Rock deflect meter, Pore pressure measuring weir, Shear deformation meter, Strain meter and deflect meter in gallery
	Rockfill (Surfacing Type)	Construction	* Inclination and stress in surface pavement * Soil pressure, pore pressure, settlement, horizontal displacement, compacted density	Stress meter of reinforcement, Inclinometer, Soil pressure gauge, Pore pressure gauge, Settlement gauge, Deflection meter
		Maintenance	* Control of surface cracking * Leakage, settlement, pore pressure	Measuring weir, Settlement gauge, Pore pressure gauge, Stress meter of reinforcement
	Earthfill	Construction	* Soil pressure during embankment * Pore pressure, settlement of soil layer, lateral displacement, density	Soil pressure gauge, Pore pressure gauge, Piezometer hall, Settlement meter, Horizontal displacement meter, Radio active density meter
		Maintenance	* Leakage * Settlement, pore pressure * Lateral deformation	Sighting survey, Soil pressure, Deflectmenter, Pore pressure gauge, Measuring weir, Piezometric hall

		Purpose	Sensor
Slope around reservoir	Maintenance	* Leakage * Horizontal deformation * Settlement * Inclination	Piezometric hall, Land slide inspector

Table I.16a
Monitoring Frequency of Japanese Dams (from Hayashi et al., [1987, p.4])

	Type of dam	QUANTITIES TO BE MONITORED								
		Leakage	Deformation	Uplift or pore press	Piezo. height	Temp	Stress or soil press.	Strain or shear displ.	Inspec of dam	Seismic obs
First impounding	Gravity dam	1/day	1/day	1/day	-	1/7 days	1/7 days	1/7 days	1/day	Starter sets at about 1 cm/s^2
	Arch dam	1/day	1/day	1/day	-	1/3.5 days	1/7 days	1/7 days	1/day	
	Rockfill dam	1/day	1/7 days	1/day	-	-	1/7 days	1/7 days	1/day	
	Earth dam	1/day	1/7 days	1/day	1/day	-	1/7 days	1/7 days	1/day	
5 years after impounding	Gravity dam	1/7 days	1/7 days	1/7 days	-	1/month	1/month	1/month	1/month	Starter sets at about 2 cm/s^2
	Arch dam	1/7 days	1/7 days	1/7 days	-	1/0.5 month	1/month	1/month	1/month	
	Rockfill dam	1/7 days	1/month	1/7 days	-	-	1/month	1/month	1/month	
	Earth dam	1/7 days	1/month	1/7 days	1/7 days	-	1/month	1/month	1/month	

	Type of dam	QUANTITIES TO BE MONITORED								
		Leakage	Deformation	Uplift or pore press	Piezo. height	Temp	Stress or soil press.	Strain or shear displ.	Inspec of dam	Seismic obs
Long term	Gravity dam	1/month	1/month	1/month	-	-	- month	- month	1/month	Starter sets at about 5 cm/s^2
	Arch dam	1/month	1/month	1/month	-	1/month	- month	- month	1/month	
	Rockfill dam	1/month	1/3 months	1/month	-	-	-	-	1/month	
	Earth dam	1/month	1/3 months	1/month	1/month	-	-	-	1/month	

Table I.16b
Monitoring Frequencies of Japanese Dams for Specific Cases
(from Hayashi et al., [1987, p. 5])

	Type of dam	QUANTITIES TO BE MONITORED								
		Leakage	Deformation	Uplift or pore press	Piezo. height	Temp.	Stress or soil press.	Strain or shear displ.	Inspec of dam	Seismic obs.
1 Week after flood discharge	Gravity dam	1/day	1/day	1/day	-	1/7 days	-	-	1/day	Starter sets at about 1-2 cm/s^2
	Arch dam	1/day	1/day	1/day	-	1/7 days	1/7 days	1/7 days	1/day	
	Rockfill dam	1/day	-	1/day	-	-	-	-	1/day	
	Earth dam	1/day	-	1/day	1/day	-	-	-	1/day	

	Type of dam	QUANTITIES TO BE MONITORED							
		Leakage	Deformation	Uplift or pore press	Piezo. height	Temp.	Stress or soil press.	Strain or shear displ.	Inspec of dam	Seismic obs.
1 Week after seismic shook	Gravity dam	1/day	1/day	1/day	-	1/7 days	-	-	1/day	
	Arch dam	1/day	1/day	1/day	-	1/7 days	1/7 days	1/7 days	1/day	
	Rockfill dam	1/day	-	1/day	-	-	-	-	1/day	
	Earth dam	1/ day	-	1/day	1/day	-	-	-	1/day	

Table I.16c
Monitoring Frequencies of Miyama Rockfill Dam in Japan
(from Hasegawa and Kikusawa, [1988, p. 206])

ITEM	INSTRUMENT	FREQUENCY
Uplift	pressure gauge	4 per month
Sedimentation	acoustic method	1 per year
Crest displacement	theodolite	1-8 per year
Joint displacement of membrane	jointmeter	5 per month
Reinforced bar	extensometer	5 per month
Gallery concrete	extensometer	5 per month
Earth pressure	pressure cell	5 per month
Membrane deformation	inclinometer	5 per month
Joint opening along gallery	joint meter and thermometer	daily
Rotation of gallery	inclinometer	3 per month
Leakage	triangle weir (V-notch)	daily

The design of automated monitoring systems is based on the advantages and disadvantages of the systems. For example, information from the automated system is very susceptible to corruption by the improper maintenance of monitoring sensors, therefore if automation is to be used, it is essential that experts be included as part of the monitoring requirements. Although automated systems are a consideration, they do not replace visual inspection. As shown in Tables I.16a and I.16b, visual inspection of any dam is an essential observation during the first impounding and throughout its life span (Hayashi et al., 1987).

With the exception of surfacing type rockfill dam, Table I.15 illustrates that Japan's regulations direct that monitoring systems comprise of both geodetic and geotechnical/structural instrumentations. These instruments do not differ significantly from those used by other countries. For any dam, the Japanese regard leakages and deformations to be the most important quantities to monitor and that during the first impounding and after an earthquake it is very important to inspect the dams weak points and its foundation (Hayashi et al., 1987). The surveillance methods for evaluating existing dams is essentially similar to those applied to newly constructed dams (Satake et al., 1985).

According to Hayashi et al. (1987), some of the new monitoring instruments that were still under development in 1987 include:

1. *Optical Fibre Cable* for transmitting information, a very useful countermeasure against electrical storms
2. *Ultra Red Laser* for automating distance measurements
3. *Remote Control Robot System*, used to inspect the dam's gate, pier, aqueduct, foundation rock and slopes.

The observations from the surveillance system are analyzed independently using statistical (regression) analysis based on the progressive history of the structure. The results of the analysis are compared with those predicted from Finite Element Methods (FEM) and presented in graphical forms. In embankment dams, the FEM is also used in analyzing the predicted pore water pressure with those calculated with the measured values. Several examples of these analyses are given by Hayashi et al. (1987) and papers written by the members of JANCOLD in the Proceedings of the International Congress on Large Dams (e.g., Fifteenth International Congress on Large Dams, Vol. I, Q.56 ,1985; Sixteenth International Congress on Large Dams, Vol. II, Q.61 & Vol. III, Q.62, 1988).

I.18 Korea

There are 690 large dams officially registered in Korea (Lee, 1992). Although the installation of instruments in dams is considered to be a common practice, there are currently only 22 (31%) of the 690 dams being monitored in Korea (Sonu, 1985; Lee, 1992).

Korea has no national standards, specifications or publications that deal with dam monitoring. The responsible organizations for hydraulic structures are: (1) the Dam Operation Department of Korea Water Resources Corporation; (2) the Rural Development Institute of the Rural Development Organization; and (3) the Construction Department of Korea Electric Power Corporation (Lee, 1992). The only known involvement of the Korean government in the area of dam construction has been with the establishment of an integrated development plan for its four major river basin. The construction of dams for the purpose of flood control, power generation, and water supply for industry and agriculture is based on this plan (Kim and Kim, 1982).

A review of selected case studies from members of the Korean National Committee on Large Dams on the behaviour of dams and the performance of instruments installed in existing dams suggests that the dam monitoring in Korea is realized exclusively by using geotechnical means (Kim, 1979a; Kim, 1979b; Sonu 1985). These case studies show that the common types of instruments used to monitor Korean dams include primarily; electric detector and recorders similar to steel cross arms (horizontal displacement), hydraulic piezometers (water level), pore pressure meters, multi-face soil pressure meters, hydrostatic settlement gauges (uneven vertical settlement), stainless steel point gauges installed on concrete boxes (surface and crest settlement), horizontal movement gauges (internal horizontal movement) and vertical movement gauges (internal vertical movement) (Sonu, 1985).

The types of analyses used to determine the safety and the behaviour of the dam are very simple and straightforward. The observations from the monitoring instruments are presented either in graphical (e.g., the vertical displacement of a selected point may be plotted as a function of some specified time interval) or tabular form (Kim, 1979b; Sonu, 1985). From all of the references quoted in this section, other than using FEM methods to estimate the behaviour of the dams, there are no indications or suggestions that some form of mathematical evaluation (statistical or deterministic) is applied to the analysis of the data.

I.19 Netherlands

The 10 large dams that are registered in the Netherlands are all estuary dams (Duivendijk, 1992). Estuary dams are tidal dams located on river mouths constructed primarily to prevent flooding of coastal boundaries from storm surges and other hazardous hydrological events. The Dutch have no standards for monitoring their dams. However, beginning in 1992 the local authorities will be responsible for the safety of flood protection systems in the Netherlands. The authorities will then be legally compelled to submit a report on the quality of the dikes and estuary dams to the national government every 5 years (Sip and Deen, 1991; Duivendijk, 1992).

Estuary dams are extremely long, ranging up to several kilometers in length. The design and function of estuary dams are different form those of traditional dams which in turn make their behaviour and loads acting on the structures also different. Normally the loads on the estuary structure will not exceed or even reach the design loads and therefore, there is a low probability that the structure will be monitored under the designed conditions. The types of surveillance systems used to monitor estuary dams differ from the typical geodetic and geotechnical techniques. The primary sub-systems of a surveillance program for estuary dams include: (1) a static and dynamic load monitoring system to measure hydro-static pressure distribution, wave spectra, and current and wind velocities, (2) a structural monitoring system to verify the loads and stresses on the steel gates and concrete structure, and (3) a sub-soil monitoring systems to measure the stability and deformation of the subsoil (Nelissen et al., 1985).

From the literature reviewed, the Dutch do not seem to use any form of geodetic techniques to monitor their estuary dams, and the geotechnical instrumentation that they do use is limited to pore pressure gauges and inclinometers (Nelissen et al., 1985). Subsoil conditions along the dam or dike may be monitored using a combination of electromagnetic and geo-electric measurements and a limited number of borings and cone penetration tests. Statistical methods are then used to determine the characteristic values of the soil parameters to determine the conditions of the sub-soil. Furthermore, deterioration which cannot be detected from visual inspections (e.g., erosion of channels behind stone block revetment), special techniques have been and are continuously being developed and improved. One such techniques is the ground probing radar to detect erosion of the channel behind a stone block revetment (Sip and Deen, 1991).

I.20 New Zealand

In New Zealand, state owned corporations and private consortia own and operate a total of 83 large dams (*World Register of Dams*, 1988). The major owner of large dams is the Electricity Corporation of New Zealand (ECNZ), a state owned enterprise. Another large player in the area of hydraulic structures is the Works Corporation of New Zealand who has designed most of New Zealand's large dams and acts as a consultant for the majority of the deformation surveys, particularly those for ECNZ (Cavanagh, 1992; Campbell, 1992). Consequently, the following discussion is based on ECNZ and the Works Corporation experiences with dam deformation and may not entirely reflect the standard monitoring procedures practised throughout New Zealand.

ECNZ has been performing deformation surveys to study the behaviour of structures since 1930, however it was not until after 1969 that the surveys became a standard practice within the organization. Today, ECNZ maintains a regular dam safety program which includes deformation surveys. Each dam is considered a unique case and monitored according to the specifications explicitly designed to examine the behaviour of its structure (Campbell, 1992). The specification (Currie, 1991) outlines: the required capabilities of the instruments to be used for each type of measurements (levelling, distances and angles); the necessity to calibrate the instruments; the number of sets of observations to obtain the required accuracy; the type of survey scheme to be performed and when it is warranted (i.e., Type A , B, or C - each reflecting the number of stations to be observed and the frequency of the survey); the type of adjustment; how the data is to be presented; the report format; and how the data is to be stored.

With regards to the procedures, the specification seems to be somewhat complete, but it would be considered unethical to comment on the validity of the procedures since the appendices referred to by the author were not forwarded with the specifications. However, a point that may be considered somewhat controversial is that from the proceeding quote one may be lead to conclude that the Works Corporation intentionally designs the layout of its geodetic networks and that unlike most other organizations it does not randomly place the monuments in the most convenient locations (section 3.2 of Currie, 1991):

> "Type B surveys are undertaken in approximately August annually. They are designed to provide an annual statement on the integrity of the Arapuni structures from a minimum of field work."

The specifications cited above and other technical papers on the monitoring of existing dams published by the Works Corporation of New Zealand show that the majority of dams in New Zealand are monitored strictly by geodetic means (Dale, 1985; Forster, 1986; Currie, 1991). Overall, the geodetic methods include precision surveys composed of horizontal (e.g., triangulation, trilateration and triangulateration) and vertical (e.g., levelling and optical plumbing) control networks using high precision instruments (e.g., Wild T2000S EDM, Wild DI20 theodolite and Invar Staves, Wild ZNL optical plummet) (Currie, 1991). Geotechnical instrumentation in ECNZ's dams are rather scares and primarily limited to tiltmeters. For example, for the Ohau Power Station, the addition of merely two tiltmeters to the existing geodetic survey system was considered sufficient to provide a better quality of monitoring (Campbell, 1992).

With available software the networks are adjusted in 1-D, 2-D or 3-D using least square adjustment. If required, scale corrections and similarity transformations are performed on the coordinates of the control network to obtain the best fit of all of the surveys taken of the network at different epochs. To analyze the results and remove cyclic effects due to quantities such as air and water temperatures, the adjusted horizontal and vertical deformation are graphed against the mean monthly air and water temperatures. For each surveys the results stored on floppy disc accessible by MS-DOS (Dale, 1985; Forster, 1986).

The reader is referred to Forster (1986) who provides a reasonably thorough description of how the least square adjustment is applied to analyze the data from an existing dam.

I.21 Norway

There are 250 large dams in Norway of which only 140 of them are instrumented with monitoring equipment (Molkersrod, 1992). As in most countries, dams in Norway are owned and operated by either private, semi-private or national organizations.

In Norway each dam is dealt with separately. There are no national or local standards and specification, however since 1981 the provisions for monitoring the performance of all of Norwegian dams has been regulated by the Norwegian *Code of Practise for Dams* (Nilsen et al., 1982; Molkersrod 1992). The regulations are not detailed or specific with respect to the scope of the monitoring program or the length of time that the measurements are to be continued (i.e., what is to be monitored and for how long). Nevertheless, the Code does specify that seepage and surface measurements are mandatory for all large dams and that plans are to be made in advance for providing instrumentation of the amount and type that is deemed necessary to monitor the performance of the dam in question (Dibiagio and Kjærnsli, 1985). The detailed design of proposed monitoring programm is the responsibility of the designer, but it is subject for approval by the regulating authorities (ICOLD, 1989). The federal agency responsible for the supervision and regulations of Norwegian dams is the Water Resources Directorate within the Norwegian Water Resources and Electricity Board who controls all water power resources in Norway. Within this directorate the supervision of dams is performed by a special division, the Technical Supervision Division, known as VVT. The regulations empowers VVT with the authority to set requirements for the technical qualifications of personnel responsible of control and maintenance of dams. VVT also has its own inspectors who undertake independent inspections and have access to the dam owners' surveillance records (ICOLD, 1989).

Another organization who has had a major influence on the measuring techniques and instruments selected for use in the monitoring programs has been the Norwegian Geotechnical Institute (NGI). Through contracts NGI has designed, procured, and installed monitoring instruments for most of Norwegian dam owners, in particularly for large dams. In some cases NGI has also been involved with performing the measurements, processing the data and reporting on the status of the dams (Dibiagio and Myrvoll, 1985).

Contrary to the regulations, Nilsen et al. (1982) state that in spite of the large number of dams constructed in the past 25 years the amount of instrumentation in Norwegian dams has not been extensive and when compared with the practices in many other countries the methods can be considered to be very modest. Furthermore, ICOLD (1989) and Nilsen et al. (1982) suggest that very little effort is placed on monitoring concrete and masonry dams and that most of the energy has been focused on the methods and types of equipment used to monitor embankment dams. This situation is apparent from the fact that all of the research material gathered on this subject deals strictly with the instrumentation of embankment dams (i.e., Nilsen et al., 1982; Dibiagio and Kjærnsli, 1985; Dibiagio and Myrvoll 1985; Myrvoll et al., 1985; ICOLD, 1989; Torblaa, 1991). Thus, the information presented here onwards will strictly reflect Norway's current practices for monitoring embankment dams.

Aside from the regulations another set of guidelines which was set forth by the

Royal Decree in 1965 is the public warning system in the form of a failure detector. According to the 1965 guidelines the minimum instrumentation for a public warning system should include at least three separate cables securely attached to the dam as signal carrying loops such that in the event of a total or partial failure the wires will physically rupture resulting in an open circuit of the loops (ICOLD, 1989).

The Norwegian approach to instrumentation is twofold: dams are either extensively or routinely instrumented. Extensive instrumentation systems are installed in a dam that falls within one or more of the following conditions: (1) has an unusual problem, (2) has design features that are significantly different from existing dams, or (3) it is the first new class or type of dam being constructed. A list of the most extensively instrumented Norwegian embankment dams is given in Table I.17. Alternatively the routine instrumentation program includes three basic types of measurements, namely (Nilsen et al., 1982): (1) measurement of seepage to evaluate the long term performance of the completed structure, (2) geodetic measurements to determine deformations of the dam during construction, and on a long-term basis, and (3) the measurements of pore water pressure in the core material to verify the embankment is being constructed at a safe rate. As explained earlier, the first two types of measurements are mandatory by the regulations but, whether or not the pore water pressure is monitored will usually depend on the situation.

The reason for this conservative approach to dam monitoring is that most new dams in Norway are a carbon copy of an already well proven design for which the performance is well documented. Consequently, the number of embankment dams that have been extensively instrumented are relatively small (ICOLD, 1989).

Table I.17
Most Extensive Instrumented Embankment Dams in Norway
(from ICOLD, [1989, p. 210])

Name of Dam	Type and Number of Instruments							
	LM	SM	IC	E	PE	PF	TS	T
Essand					22			
Møsvatn					7			
Stradevatn					18			
Bordal	3	41			33	11		16
Lille Mänika	1					11		
Hyttejuvet	1	30			28		1	
Sønstevann	1	30			6	19		
Valslivatn	1					8		
Kalvatn	1	11			10		10	
Akersvann	1				7		5	
Mandøla	3	17				8		
Muravatn	1	54				9		6
Follsjø Gråjø Trial	4	17			8			
Dam	1	9		6	7			
Løpet	1					10		
Svartevann	1	160	8	28	30		60	8
Nyhellern	1	277	2	30	16			6
Innerdalen	1	82			9			
Nerskogen	6	138				27		
Vatnedalsvatn S.	2	76		13	12	3	27	4
Vatnedalsvatn M.	1	186	4	38	29		40	5

Name of Dam	Type and Number of Instruments							
	LM	SM	IC	E	PE	PF	TS	T
Oddatjørn	1	247		41	32	8		6
Storvassdamen	3	284	12	30			10	

Note: LM = Leakage Measurements SM = Survey Monuments
IC = Inclinometer Casings E = Extensometers
PE = Piezometers in Embankment PF = Piezometers in Foundation
TS = Total Stress T = Temperature

Surface deformations (horizontal and vertical displacements) are determined by triangulation or by a combination of angle and distance from a network consisting of series geodetic monuments near the dam and object points on the crest and slopes of the dam. The equipment used are precision theodolites and levels, and EDMIs. The remaining measurements which include leakage, internal deformation, strain, pore water pressure and earth pressure, are taken using standard equipment: V-notch weirs, borehole inclinometers (vertically or inclined), extensometers (or long base strain meters), piezometers (hydraulic or vibrating wire type) and pressure sensor cells respectively (ICOLD, 1989).

Norwegian data acquisition equipment and methods vary depending on the scale of the project. For instance, for small projects with a small number of instruments the data is often recorded manually with the aid of a portable instrument. For larger projects and those in remote locations, data is recorded automatically by small microprocessors base data loggers (Dibiagio and Myrvoll, 1985).

The duration of the monitoring programs normally includes the first two cycles of the reservoir filling and draw-down. Afterwards only leakage and surface deformation are measured systematically on a long-term basis. Typical performance data consists of plots of the measured parameters as a function of time or scaled drawings of the dam with the deformation parameters illustrating how the dam is behaving (ICOLD, 1989).

I.22 Portugal

Portugal has 81 large dams of which 71 of these dams are monitored using geodetic and/or geotechnical/structural methods (*World Register of Dams,* 1988; Florentino, 1992). Concrete and masonry dams make up approximately 70% of the total dams, namely gravity, arch, buttress and multiple arch (Pedro et al., 1991).

The dam safety programme in Portugal is governed by the *Dam Safety Regulations 1990 (Decree - Law n° 11/90 6th January, Lisbon)*, and the *Codes of Practice* concerning design, construction, operation and monitoring of dams which is now in the process of being approved by the Portuguese government. These regulations and codes reflect the practice of safety control of Portuguese dams over the past forty years. The regulations assign the responsibility for dam safety to the dam owner and the State Authority the Director General of Natural Resources (Direcçäo-Geral de Recursos Naturais - DGRN). Furthermore, the regulations stipulate that DGRN, when required, is to be technically assisted by other organizations such as the National Laboratory of Civil Engineering (Laboratório Nacional de Engenharia Civil - LNEC), National Service of Civil Defence (SNPC) and Committee on Dam Safety (ICOLD, 1988; Pedro et al., 1991; Florentino, 1992). For example, LNEC may be called upon by DGRN to assist them by preparing or revising the monitoring plans, preparing reports as defined by the monitoring plans and implementing the monitoring data in order to have a continuous representation of the dam's behaviour (ICOLD, 1989). Some of the principal issues of the *Safety Regulations 1990*, primarily those relating to dam monitoring, are discussed in the following paragraphs. However, for a more comprehensive review of the regulations the reader is referred to the Portuguese National Committee on Large Dams' report in ICOLD (1989).

The regulations stipulate that a monitoring program will contain plans for:

(1) visual inspections (e.g., frequency of visits, types of inspections, qualifications of the inspecting agents, main quantities to be observed, format of the report),

(2) installation and operation of the monitoring scheme (e.g., physical quantities to be assessed, specifications of instrument and of their installation and use, frequency of measurements during the construction, filling and operation phases, qualification of agents charged with the installation and operation of the monitoring scheme, methods of data collecting and processing), and

(3) the methods used to analyze the data and evaluate safety (e.g., behaviour models used to determine the most hazardous scenarios).

The physical quantities monitored and the instrumentation used to monitor Portuguese dams are not significantly different than those practised by other countries. The quantities monitored and the monitoring schemes are summarized in Tables I.18 - I.21. Table I.18 illustrates the quantities measured in concrete and fill dams. Table I.19 gives information on the placement of the instruments common to concrete and fill dams whereas Tables I.20 and I.21 provides information on the placement of the instruments depending on the type of dam (e.g., gravity dam, homogeneous fill dam). Furthermore, the frequency of the measurements are given in Table I.22. All of the tables reflect the *Dam Safety Regulations* 1990 described in the Portuguese International Committee on Large Dams' report published in ICOLD (1989).

Table I.18
Summary of Quantities Monitored in Portuguese Dams
(after ICOLD, [1989, pp. 229-234])

Category of Quantities	Physical Quantities	Methods/Instruments Used
	CONCRETE DAMS	
External Actions	* Reservoir levels * Air temperature * Water temperature * Ground motion	 * Thermometer * Thermometer
Structural Effects	* Displacements	* Geodetic methods (triangulation, precision traverse and levelling), direct or inverted plumb line, borehole extensometers
	* Rotations * Joint movements * Crack movements	* Electric joint meters, deformeters, electric resistance clinometers
	* Strain * Stress	* Strain meters, no-stress meters * Stress meters, relief methods (bore hole device with stress tension tubes), compensation methods for surface stress (flat jack)
	* Concrete temp. (inside) * Uplift * Seepage	* Thermocouple
Dynamic Effects	* Displacement Velocities Accelerations	* Velocity transducers, microsiesmographs
	FILL DAMS	
External Actions	* Reservoir levels	Not instrumented

Category of Quantities	Physical Quantities	Methods/Instruments Used
Structural Effects	* Internal/external displacements * Pore pressure * Total pressure * Total flows	* Triangulation methods, precision levelling, USBR cross-arms, slope indicators * Hydraulic piezometers, pore pressure cells * Total pressure cells (Glotzl type hydraulic cells or Maihak type diaphragm cells) * V-notch cells, standard cells
Dynamic Effects	Currently no instruments have been installed to observe dynamic phenomena.	

Table I.19
Portuguese Monitoring Schemes Common to Concrete and Earthfill Dams (after ICOLD, [1989, pp. 229-235])

Phases	Common to Concrete Dams		Common to Fill Dams	
	Methods and Instruments Used		Methods and Instruments Used	
Construction	* Thermometer (or other electric resistance instruments)	* Provide info to possibly correct construction procedures (lift heights, concrete intervals, artificial cooling).	* Piezometers	* In the foundation and earth zones.
	* Rockmeters	* Placed under concrete block to allow the assessing of the foundation deformability.	* Total pressure	* In the interface zones between materials of different deformabilities.
	* Creep cells	* Placed inside concrete to provide the evolution of the deformability of the concrete and data to determine the stress for the strain meters.		
	* Embedded strain and stress meters	* Provide the reference state of stress of the dam foundation and structure at the end of the construction period.		

Phases	Common to Concrete Dams		Common to Fill Dams
First Filling	* Horizontal displacement	* By means of plumb lines and at certain reservoir levels by geodetic methods.	They are similar, however it depends upon the type of fill dam (see Table 3.21).
	* Vertical displacement	* Precision levelling or rockmeters.	
	* Joint movements	* Deformeters.	
	* Displacement of dam foundation	* Rockmeters.	
	* Seepage and uplift		
Operation	Measure quantities related to safety and those mentioned in the construction and filling phases.		

Table I.20
Portuguese Monitoring Schemes Particular to the Major Types of Concrete Dams (after ICOLD, [1989, pp. 229-234])

Quantities	Instruments and Method Used	
Arch Dams		
* External Actions & Ground Motion		* No permanent instrumentation has yet been installed. Studies have been made to install them in existing and future dams.
* Planimetric Displacement	* Triangulation	* Targets placed over the body of the dam to obtain a good representation of the global movement. Along arches usually at two levels (one near the crest and other at mid height or even at more levels when justified). Along cantilevers (one along the cantilever or three or more distributed on the downstream side of the dam body). Precision traverse (as mentioned in Table I.18).
	* Plumb Lines	* Installed with geodetic targets as a check.

Quantities	Instruments and Method Used	
	* Borehole Extensometers	* To obtain absolute displacements of the intermediate anchored points and the rotations of the corresponding sections. In the vicinity of coordimeters near the foundation to obtain the vertical component of the movement of these points. Also crossing significant foundation cracks or faults where movement may effect the behaviour of the dam.
* Altimetric Displacement	* Precision Levelling	* Points located at dam crest and when feasible at inspection galleries and downstream surroundings.
	* Invar Wires and Rockmeters	* Connecting galleries by means of connecting invar wires with rockmeters anchored to deep point installed galleries near the abutments.
* Hydraulic Behaviour	* Piezometers and Drain Curtains	* To measure seepage and uplift pressures.
* Joint Movements	* Deformeters	* Practically in all joints in accessible zones (e.g., on the crest, near dam face, inside inspection and drainage galleries).
* Movement of Points Inside the Body of Dam	* Jointmeters	* In the medium zones of the block or at a distance of about one meter to the dam face and according to the information needed.
* Rotations	* Electric Clinometers	* Scarcely measured but there is a trend to measure them again.
* Concrete Temperature	* Thermometers	* As all other electric resistance instruments (stress and strain meters) give values of temperature, resistance thermometers are installed in a supplementary way. To obtain the information about the mean temperature and the thermal gradient variations along some strategic selected sections.
* Strain/Stress	* Strain/Stress Meters	* Placed in zones where the highest stress is anticipated (i.e., along the arch crest and the main cantilever and near the foundation haunches).
Gravity Dams		
* Planimetric Displacement	* Triangulation	* targets over the body to obtain movements of the different blocks, especially higher ones and those located at different deformability zones. Where possible at each block at least one near the crest and the other near the foundation. Also depending on the dam height one or more intermediate markings may have to be installed.
	* Precision Traverse	* Installed in some horizontal galleries.
	* Plumb Lines	* Installed in one or more blocks.
* Vertical Displacement	* Precision Levelling	* At the dam crest, in some cases in horizontal galleries and drainage galleries and in galleries near the foundation.

Quantities	Instruments and Method Used	
* Joint Movements	* Deformeters	* Used to monitor relative movements between adjacent blocks usually installed in places similar to those of arch dams.
	* Electric Joint Meters	* Inside joints.
* Uplift Pressures		* More important then arch dams. Special attention is given to the drained water turbidity.
* Rotations	* Electric Clinometers	* Like the arch dams these measurements are just being measured again.
* Temperature	* Thermometer	* Internal temperature in sections distributed along the height of the block. One or a small number of blocks need to be instrumented because thick concrete has a very high thermal inertia.
* Stress/Strain	* Strain Meters	* Usually installed in high dams only. The usual low stress developed inside gravity dams in most cases does not justify its measurement.
Buttress Dams		
* External Actions & Ground Motion		* When justified. Only one dam (Aguieira Dam) has been installed with permanent equipment to monitor this phenomena.
* Planimetric Displacement	* Special Triangulation Networks	* The geometric characteristics of the buttress dam calls for a special network. Targets are distributed over the body of the dam buttress and arches at different levels.
	* Plumb Lines	* To measure displacements of points near the foundation and of points of the arches and buttresses. Special installation may be required, for instance plumb lines incased in external devices.
* Vertical Displacement	* Precision Levelling	* Bench marks placed at the crest of the dam and along inspection galleries and downstream zones.
	* Rockmeters	* They may be required to measure foundation movements in some particular zones.
* Internal Joint Movements	* Carlson Apparatus	* In joints of the arches and, at several elevations, in some joints near the dam faces.
	* Deformeters	* Surface joint movement in accessible zones.
* Hydraulic Foundation Behaviour	* Piezometers and Drainage Curtains	* Their placement depends upon the foundation characteristic and the development of water tightness and drainage works during the construction phase.
* Temperature	* Thermometers	* Due to the small thickness of the arches the temperature variations are considerable.

Quantities	Instruments and Method Used	
Strain/Stress	* Strain/Stress Meters and Creep Cells	* Installed in the most typical zones.
Solid Buttress Dams		
* Planimetric Displacement	* Triangulation Networks	* Targets placed over the body of the dam namely near the crest and at one or more levels on the buttresses downstream faces.
	* Plumb Lines	* To measure displacements of some points near the crest or of points near the foundation. Plumb lines encased in external devices are used to measure the displacement of points that cannot be monitored using solely plumb lines.
* Vertical Displacement	* Precision Levelling	* Bench marks placed at the dam crest and sometime at the downstream zones.
	* Rockmeters	* They have just recently been considered.
* Internal Joint Movement	* Joint Meters	* Installed at half-thickness between the heads of the blocks.
	* Surface Joint Deformeters	* Measure opening and sliding movements of joints at accessible zones.
* Concrete Temperature	* Thermometer	* The differences in thickness between the head and the web of the buttress may cause peculiarities in the temperature pattern inside the concrete.
* Strain/Stress	* Strain/Stress Meters	* Groups of each together placed in the most typical zones of the body of the dam may be very useful in the behaviour analysis.

Table I.21
Portuguese Monitoring Schemes Particular to the Major Types of Earthfill Dams (after ICOLD, [1989, pp. 234-235])

Quantities	Instruments and Method Used	
Homogeneous Dams		
* Surface Displacement	* Triangulation * Precision Levelling	* Surface monuments are distributed such that they can be used to model the entire surface of the dam. * Bench marks are usually placed at the crest (if vertical movements are measured) or sometimes at the berm.
* Internal Displacement		* Used to determine the distribution of the horizontal and vertical displacement.

Quantities	Instruments and Method Used	
* Pore Pressure		* Measured in one or more sections usually the highest section. In the transition Zones between the body of the dam and the abutments.
* Water Seepage		* Where drainage galleries exit or when devices collection total or partial that of water are available.
Zoned Dams		
* Surface/Internal Displacement		* Identical to those of homogeneous dams. Some internal displacement devices are placed in the transition zones between different material.
* Pore Pressure	* Pore Pressure Cells and Piezometers	* In clay cores, they are placed in one or more of the highest sections. Further to these sections piezometers may be placed in other sections that are considered important for the dam safety. They are also placed in transition zones between the dam and the abutments.
* Total Pressure	* Piezometers	* Placed in clay cores and in transition zones between different materials. Their distribution is important in the safety evaluation with respect to hydraulic fracturing.
* Seepage		* Same consideration as for homogeneous dams.
Rockfill Dams With Upstream Impervious Face		
* Displacements	* Triangulation and Precision Levelling Methods	* Survey monuments and bench marks are placed on the crest and on the downstream face. Consideration should be made to measure displacement of points on the upstream face in some sections by means of slope indicators and measurement of displacement along transverse and longitudinal lines.
* Flows	* Pressure Cells and Piezometers	* Partial and total flows at the upstream face since the impermeability is only guaranteed at the upstream face.
Note: The remaining of the quantities measured are similar to those of the other dams described in this table.		

Table I.22
Frequency of Measurement of Portuguese Dams
(after ICOLD, [1989, pp. 235-236])

Phases	Instruments and/or Quantities Measured	Frequency of Measurements
		Concrete Dams
During Constructions	* Electrically Embedded Apparatus	* During installation - every 4 hrs until 12 hrs after. After installation (24 hrs after) - every day at on the same hour for the first week. After one month of installation - every 2 weeks. Following period - once a week.
During Filling	* Visual Inspection * Measurements of Displacement by Geodetic Methods	* Continuous. * To achieve a rapid safety assessment especially when the water reaches certain levels of the reservoir, at such time an analysis must determine a thorough understanding of the behaviour of the dam.
After First Filling	* For the first 5 years * For the subsequent years	* For essential quantities - weekly Displacements by geodetic methods - annually For the remaining quantities - fortnightly * The frequency of the measurements usually decrease, however displacements by means of plumb lines and borehole extensometers and seepage and uplifts are still measured once a week.
		Fill Dams
During Construction	* Pore/Internal Pressure	* Measurements are made immediately after installation of the instruments as soon as conditions allow it and their frequency depends on the construction development.
First Filling		* As stipulate in the specifications in the monitoring plans.
After First Filling	* Measurements and Visual Inspections	* Under normal circumstances (dam behaves as expected) the measurement are conducted every 2 years. This will be changed by the new Dam Safety Regulations.

In the field of automation, Portugal has long recognized the need for continuous data recording for certain instruments like plumb lines, thus some recording instruments have been used in concrete dams. However, owing that Portuguese dams are accessible throughout the year and that the necessary automation equipment is readily available off-the-shelf, the priority for the development of electronics has been to fulfil rapid data processing and efficient behaviour analysis. With respect to fill dams automatic data acquisition has not yet been considered, but the automatic processing for data analysis is similar to that used for concrete dams (ICOLD, 1989). An example of a typical data processing and analysis system is given by Florentino et al. (1985).

The analysis of the data is performed in stages. In the first stage the data is inputted into the computer where it is checked for major errors and converted into the geometrical and physical investigated quantities (stress, strain and deflection). These quantities are further validated by means of a model analysis and then plotted by subroutines in tabular or graphical forms in order to interpret the behaviour of the dam (e.g., diagrams of the distribution of displacements, stresses, uplifts, seepage and temperatures). In the second stage these results combined with the information gathered from visual inspections and existing documents are further classified by either a qualitative or quantitative method. The qualitative method consists of detecting the correlation between the actions, mainly water level and temperature, and the corresponding physical quantities as those given by the diagrams. In some cases the correlation is tempted using mathematical models such as hydraulic, thermal and structural models (Pedro et al., 1979; ICOLD, 1989). On the other hand, the quantitative method consists of setting up a quantitative model (statistical, deterministic or hybrid type) which describes the functional relationship between the observed effects and the corresponding actions. The model attempts to predict the values of some physical quantities, taking into account factors including material properties, geometric characteristics and previous behaviour of the dam (Gomes and Matos, 1985; ICOLD, 1989). Some examples of the different types of quantitative models that have been applied to existing dams are given by Gomes and Matos (1985).

Additional information regarding the different types of monitoring systems and data analysis addressed above, complete with case studies, can be found in articles by Pedro et al. (1979), Casaca (1984), Florentino et al. (1985), Gomes and Matos (1985), Ramos and Soares de Pinho (1985), Ferreira de Silva et al. (1991) and Pedro et al. (1991).

I.23 South Africa

The first dam constructed in South Africa (SA) was a large (h = 15 m) U-shape embankment dam in 1652 (Olwage and Oosthuizen, 1984). Today, three centuries later, there are over 452 large dams registered in SA: 257 (57%) embankment dams and 199 (43%) concrete dams (*World Register of Dams*, 1988).

In SA, most large dams are owned and engineered by or on the behalf of the SA Department of Water Affairs (DWA). Dam safety in SA originated with DWA in 1978 when safety inspections of dams owned by DWA were conducted every 5 years by a competent team of engineers. A giant leap towards the implementation of safety regulations occurred in 1982 when a Dam Safety Directorate was established in the department of DWA to develop a dam safety programme (Oosthuizen, 1984). However, it was not until recently, in 1986, that the South African Government introduced Dam Safety Regulations. The regulations insure that plans for monitoring systems for new dams are approved by the appropriate authority and that the adequacy of monitoring systems of existing dams are evaluated every 5 years (ICOLD, 1989).

The majority of the documents related to dam safety in SA have been written by the DWA personnel who are also active members of the South African National Committee on Large Dams (SANCOLD). Consequently, the facts reported in this discussion reflect solely the views, practices and experiences of DWA.

There are no specifications for dam monitoring in SA. Attempts by DWA to write specifications failed due to the multiple restrictions and limitations associated with existing dams and the requirements of a monitoring system peculiar to a site with new dams (ICOLD, 1989). As an alternative to specifications, DWA has developed an underlining philosophy for the design of a monitoring system for a particular site. This philosophy dictates the basic factors which DWA believers should be considered when designing an optimum monitoring system. These include:

(1) the function of the instrument system,
(2) the phase in the life of the dam for which the system is required (pre-construction, construction, initial filling, normal operation, etc.),
(3) the physical conditions of the dam (geology, design assumptions, hazard potential, etc.), and
(4) the particular operational conditions (e.g., the ability and attitude of the observer).

On the basis of this philosophy, DWA recommends a series of steps that should be followed during the design of a monitoring system (see Table I.23). Furthermore, DWA often refers to ICOLD Bulletin N° 41 as a guide for determining the initial parameters to be measured and the required frequencies of the measurements (ICOLD, 1989).

Table I.23
Steps for the Design and Installation of a Monitoring System as Suggested by the South African Department of Water Affairs (after ICOLD, [1989, p. 252])

1. Determine Function(s) and Monitoring Phases	• Determine site conditions	Study the expected behaviour of the structure by determining: • the loads acting on it • its capacity to resist these loads • other factors influencing the response of the structure (design redundancies, etc.)
2. Study Similar Systems	• Identify critical and key aspects	
3. Preliminary Design	• Identify parameter to be measured. • Select location and number of instruments. • Select read-out frequencies. • Determine required accuracy, measuring range, sensitivity, repeatability of the various instruments. • Select types of instruments, sensor read-out units, etc. • Tailor lay-out to acceptable limits. • Prepare preliminary drawings and documentation.	
4. Intermediate Evaluation	• Consult Designer, Dam Safety Specialists, Suppliers, Construction Team. • Perform a cost-benefit analysis based on the alternatives. Aspects such as installation cost, and costs (and convenience) for taking readings and processing the data in the long term, should also be included.	
5. Final Design	• Prepare scenarios for instrumentation failures and design and specify defensive back-up systems. • Finalize design (simplest arrangement of devices suitable for the purpose). • Write specifications (tenders, installation, etc.)	
6. Installation	• Obtain co-operation of construction staff on site. • Plan the installation procedure in detail. • Make final preparations for installation (logistics, re-calibration, etc.) • Install or supervise installation. • Keep good photographic records. • Record design adjustments. • Do performance checks.	

7. Final Report	Prepare an installation report containing: • As-built drawings. • Zero readings. • Records (photographs). • Instructions and manual to the observer and analyst. • An evaluation of the installation.

The monitoring instruments and practices preferred by DWA are summarized in Table I.24. SA has taken a rather simplistic approach to dam monitoring. In SA, most dams are situated in remote areas hundreds of kilometers away from the organization responsible for dam safety evaluation and therefore, authorities do not considered it feasible to have sophisticated equipment on site which requires specialized technicians to operate and maintain. Overall, DWA prefers geodetic methods to monitor external absolute displacements, and geotechnical/structural techniques for relative internal deformations. Where applicable, in the case of concrete dams, traverse methods through galleries and drainage tunnels are preferred over triangulation of points on the external surface of the dam (ICOLD, 1989). This decision was based on the results of a case study by Roberts et al. (1985). Roberts et al. (1985) compared the triangulation method with the traverse method on the bases of accuracy, man power requirements, time and cost constraints, and suitability under all operational and weather conditions. The case study concluded that the advantages of the traverse method far outweighs those of the triangulation (see Roberts, 1985).

As part of the monitoring program, DWA considers site inspection by a trained inspector to be indispensable in the process of establishing the complete behaviour of the dam. DWA conducts quarterly inspections in additional to the frequent inspections by local dam owners and periodic dam safety inspections by experienced personnel (Croucamp, 1985). DWA has also been involved in the design of new monitoring equipment: for example, it developed what is known as the borehole stress meter. The meter is a vibrating wire instrument installed in a borehole to measure stress variations in concrete (ICOLD, 1989).

Table I.24
South Africa's Preferred Instrumentation and Methods for Monitoring Dams
(after ICOLD, [1989, pp. 245-247])

Dam Type	**Quantity Measured**	**Methods Instruments**	**Remarks**
Displacements			
Concrete	Relative	• 3-D displacement crack monitoring devices (e.g., Wexham crack width meter accurate to ± 0.02 mm or ID crack width meter accurate to ± 0.1 mm • mechanical type pendulums with optical reading • tiltmeters	• the ID crack meter was developed by DWA, designed primarily for use during inspections
	Absolute	• geodetic surveys (precise levelling and triangulation, traverse in galleries and drainage tunnels)	• for many existing dams this method is the only practical solution
Embankment	Internal Settl.	• along lines in transverse directions a group of hydraulic settlement cells are used • along the vertical axis magnetic rings are installed around inclinometer tubes at fixed levels	• (i.e. along cross-sections) • these are installed during constr.
	External (on embank. or berm)	• levelling and triangulation	• for measuring settlements and other relative movements
	Inclin.	• inclinometers with torpedo- shaped sensors containing sensitive sensors	
Pressure			

Dam Type	**Quantity Measured**	**Methods Instruments**	**Remarks**
All Types of Dams	Pore Pressure	• stand pipes and twin tube hydraulic piezometers	• used to measure piezometric level
		• resistance and piezo-electrical types • hydraulic membrane type of piezometers	• are recommended for short term measurements
	Earth Pressure	• Bourdon type of pressure meters	• for use with the hydraulic type piezometers
		• hydraulic type cell with transducers	• most favoured (can be calibrated in situ)
	Strain and Stress		
	Strain	• sliding micrometers	• preferred over any other borehole extensometers • has an accuracy of better than 10^{-3} mm/m
	Stress	• small diameter uniaxial stress meters • smaller bi-axial version of a similar stress meter as the uniaxial one	• it was still being tested by DWA at the time this table was published

Regarding data analysis, DWA has a central data processing and evaluation center for most of its dams. DWA fully recognizes the disadvantages of this method and has taken steps to equip some of its personnel with programmable pocket calculators to take the readings and compare them with those obtained from the behaviour model at the central processing station. In addition, DWA's goal is to have a semi-automated system using a microcomputer at the dam site so that local observers can process the readings and make a reasonable interpretation of the behaviour of the dam expediently and without having to wait for the results from the central office. As with the pocket calculator, these results can then be compared to those of the behaviour model (ICOLD, 1989).

With regards to dam monitoring DWA professes that it has gained a considerable amount of experience and therefore, has taken a number of precautionary steps (referred to as the *golden rules)*. Some of these include:

1. When designing an instrumentation system it is necessary to consider all of the possible mode of failure and malfunctions of the system.
2. It is not only good practice to use a back-up system but it is also advisable to install a *new* type of instrument of unknown performance along side a proven instrument in order to gain experience and confidence of the new instrument.
3. All instruments must be re-calibrated, preferably at the same altitude and under the same conditions as those where the instruments are to be used.
4. It is a good practice to study the operating principles and design of each instruments carefully.
5. It is a good practice to use instruments with a good performance record.
6. Lightning protection must be considered (this is something which is often neglected).
7. Inspections by local operators and his staff, apart from the other inspections, is one the most valuable method of monitoring the behaviour and condition of the dam.

Additional examples reflecting the types of monitoring systems and data analysis used in SA can be found in a number of case studies reported by members of the SANCOLD at the ICOLD Fifteenth International Congress on Large Dams, Q56, (e.g., Croucamp, 1985; Melvill, 1985; O'Connor, 1985; Van Der Spuy et al., 1985).

I.24 Spain

As of December 1991 Spain registered 1,031 large dams. An accurate account of the number of dams being monitored in Spain is not yet available. However, the Spanish Committee on Large Dams (SPANCOLD) is currently processing data from a questionnaire which will provide this information. SPANCOLD is also preparing general specifications for dam monitoring. A draft of the specification will be available some time in 1992, in Spanish (Yagüe, 1992).

In 1979, dam experts in Spain conducted a review of 52 Spanish dams that had suffered damage or even failed. This study revealed that in almost every case, pore pressure in the structure and foundation played a decisive role, thus underlining the importance of hydraulic monitoring (Laa et al., 1979). Since then, the standard practice in Spain has been to insure that all dams are instrumented with equipment that monitor hydraulic related quantities such as seepage, uplift, and pore pressures, in the structure and foundation (Laa and Gonzalez, 1985). In fact, in Spain, hydraulic monitoring is regarded as a way of analyzing the safety of a dam. Laa and Gonzalez (1985) provide a formulation and examples of the application of a proposed deterministic hydraulic model, developed by the University of Santander. The model is based primarily on uplifts and seepage. Laa and Gonzalez (1985) also show that the reliability of the model is increased when the model is complemented with the displacement at the base of the dam, measured from pendulums (direct and inverted) and extensometers. An interesting method for localizing water seepage across a concrete surface or any cracked deteriorated concrete or bituminous slab is a recent one proposed by Malmcrona and Diaz-Ambrona (1991). The method consists of placing a special designed cloth over the area of interest. Any seepage water will tarnish the cloth indicating the shape of the infiltrated zone, and to some extent an approximate rate of the seepage.

Baltar and Garcia (1985) claim that one of the contributions to safety is an exhaustive revision of all the installations by a *team of experts* and that a responsible engineer must be aware of his own limitations and should ask for the cooperation of specialists as deemed necessary.

The typical instrumentation systems and the frequency used to monitor Spanish dams (constructed between 1934-1975) are listed in Table I.25. This table illustrates that Spanish dams are monitored using conventional geodetic and geotechnical techniques and it reflects the importance of the aforementioned hydraulic monitoring. All of the 22 dams in the table are supervised by a permanent staff, referred to as a Technical Service. Note that the term *geodesic blanks* and the frequency designation of *S* listed in Table I.25 are not clarified. For additional examples of the type of monitoring systems applied to Spanish dams, the reader is referred to Guerreiro and Hoyo (1985) page 947.

In areas of high seismic activity Spanish dams are instrumented with basically two types of instruments: (1) seismographs to record earthquakes near the reservoir area, and (2) strong motion accellerographs to record the actual shaking at the ground level and at different points on the dam structure. Examples of these types of instruments, along with their output data and how they have been applied to existing dams are given by Adrover

Table I.25
Instrumentation and Measurement Frequency of Spanish Dams
(from Baltar and Garcia, [1985, p. 1238])

Dam (Type)	Displacement				Joint Movement		Hydraulic State			Concrete State			Terrain Movements		
	P (Type)	CR	GB	NL	EB	JM	DM	FD	P	TC	STM	SM	TM	CSM	NL (in slope)
S. Pedro (G)		5 M													
S. Esteban (AG)	$1_{(D)}$F	20 F	33 S	26 Q	33 M		F	18 F	13 M				10 F		69 Q
Sequeiros (G)		14 M													
S. Martin (G)		7 M													
Pumares (G)		9 M			15 M		M	38 M	9 M						
Casoyo (AG)		3 M					M	20 M							
Sta. Eulalia (A)	$1_{(OP)}$F	2 F	32 S			14 F	F	114 F	24 M	27 M			2 M		
Santiago (G)		6 M													
Montefurado (G)		10 M					F	28 F	12 F						
Bao (G)		13 M	51 S				F	76 F	56 M						
Giustolas (G)		9 M					F								
Chandreja (B)		13 M					F	48 F	24 M						

Dam (Type)	Displacement				Joint Movement		Hydraulic State			Concrete State			Terrain Movements		
	P (Type)	CR	GB	NL	EB	JM	DM	FD	P	TC	STM	SM	TM	CSM	NL (in slope)
Edrada (A)		2 M					F	27 F							
Las Portas (A)	$5_{(CB)}$W	9 F	62 S	26 Q	135 S	22 F	F	413 F	51 M	134 M	78 M		6 F		26 Q
Cernadilla (G)	$2_{(I)}$F	20 M		18 S	37 M	8 M	F	81 F	62 F	60 M	42 M			12 M	77 S
Ricobayo (G)		8 M					F	29 F	12 F						
Villalcampo (G)		16 M		14 S	28 M		F	43 F	17 F						20 S
Castro-Dam (G)		5 M		7 S	13 M		F	21F	13 F						7 S
Castro-Dike (G)		9 M		10 S	9 M		F	10 F	13 F						11 S
Aldeadávila (AG)	$3_{(D)}$F				30 M	4 M	F	53 F	3 F	13 M	144M	5 M			
Saucelle (G)		6 M		7 S			F	46 F	14 F						23 S
Almendra (A)	$5_{(CB)}$W		31 S	40 S	105 S	184 M	F	269 F	135 M	161 M	134M			48 M	278 S

Table Definitions

1. Instrumentation

P - Pendulum
DM - Dam Leakage
TM - Telerock Meters
CR - Crest Reference
FD - Foundation Drains
CSM - Contact Strain Meters
GB - Geodesic Blanks
P - Piezometer
NL - Nails Levelment
TC - Thermoelectric Couples
EB - Elongameter Bases
STM - Strain-Meters
JM - Joint Meter
SM - Stress Meters

2. Dam Types

G - Gravity
A - Arch
AG - Arch Gravity
B - Buttress

3. Frequency

W - Weekly
F - Fortnightly
M - Monthly
Q - Quarterly

4. Pendulum Type

D - Direct
I - Inverted
CB - Combined
OP - Optical Plummet

3. Notes

a. The water level registration, precipitation and ambient temperatures is daily.
b. The temperatures in the water are taken simultaneously with the displacement measurements in the dam.
c. Usually a complete survey is carried out monthly going to a fortnightly frequency for the most significant instruments in the most important dams.

and Saiz (1985).

I.25 Sri Lanka

Sri Lanka reported to have registered a total of 79 large dams. Of the 79 large dams only 10 are monitored: 5 are monitored by geodetic and geotechnical/structural methods (in Kotmale, Victoria, Randenigala, Rantembe and Maduru Oya) and 5 are monitored solely by geotechnical/structural techniques (in Kotmale, Victoria, Randenigala, Rantambe and Kalawewa) (de Silva, 1992). A complete list of these dams is given in the Sri Lanka National Committee on Large Dams (SLNCOLD) Bulletin N° 2 (SLNCOLD, 1987). Details of the types of techniques used to monitor their dams have been published in the SLNCOLD Bulletin N° 2 (SLNCOLD, 1991). There is no legislation for monitoring dams in Sri Lanka however, Bulletin N° 2 is considered the be foundation for establishing dam safety legislation in the country. All dams and reservoirs in Sri Lanka are state owned. The concern that dams will eventually fall into the hands of private owners has given rise to the need for some form of legislation which insures the safety of the people living downstream (SLNCOLD, 1991).

As a developing country, it is not economical for Sri Lanka to use extensive instrumentation except in the highest dams and in those that are classified as high risk dams. As a result, dam monitoring is primarily reverted to conventional visual methods and basic observations by experienced engineers and technical staff. There is a shortage of trained personnel and a need to establish surveillance units who could inspect dams at least every five years (SLNCOLD, 1987). Currently, the major types of methods and instruments used to monitor Sri Lanka's major dams are: survey targets, inclinometers, strain meters, stress meters, extensometers, transducers (for measuring pore pressure in impervious core, bottom water pressure in downstream foundation, and total pressure of the core and rockfill), telepress meters (for measuring total earth pressure on spillway wall), measuring weir, observation well, and seismic equipment (e.g., seismographs). Inspection of dams is taken very seriously. An inspection program consists of: (1) informal inspection by the technical staff as directed by the weekly diary, (2) monthly inspections by senior staff on selected projects, (3) formal inspections by an outside party of experienced persons in the areas of geology, geotechnical, hydrology, etc., and (4) special inspections which are carried out following unusual events such as major floods, unexpected weather patterns and earthquakes (SLNCOLD, 1991).

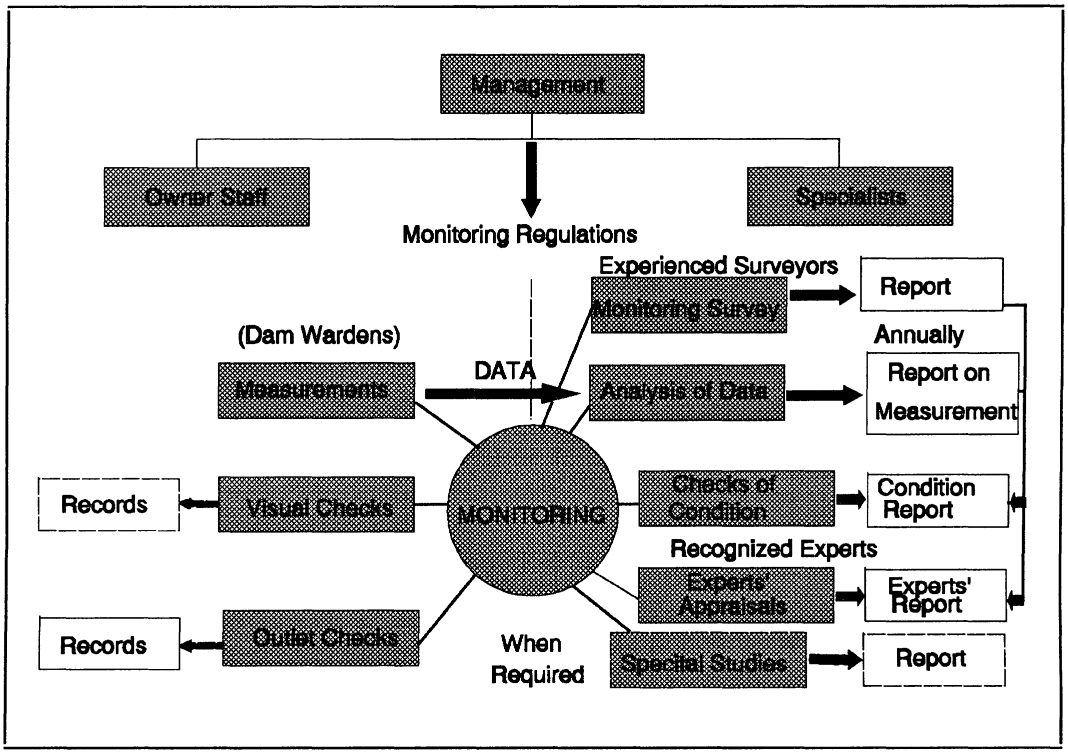
I.26 Switzerland

Switzerland has officially listed approximately 144 large dams, 95% of which are monitored using geodetic instrumentation and 100% are monitored using geodetic and/or geotechnical/structural instrumentation (Bischof, 1992). In Switzerland there are no detailed national specifications defining the monitoring of dams, the types of instruments required and the frequency of measurements (ICOLD, 1989). The safety of dams is governed by the federal law through the *Dam Regulations Act* enacted on July 9, 1957. These regulations contain precise procedural rules and not technical requirements and thus guarantee a high degree of flexibility, allowing the supervising authority to decide and enforce the safety standards according to the current technology and the specific circumstances (Biedermann, 1985). A copy of the legislations can be found in *Swiss Dams: Monitoring and Maintenance* (SNCOLD, 1985). The specifications (Biedermann et al., 1988) were provided by the Swiss National Committee on Large Dams (SNCOLD) at the Fifteenth International Congress on Large Dams (Biedermann, 1985).

As a result of this policy, the safety of dams is the responsibility of their owners. They are free to select what they consider to be the most suitable equipment and monitoring methods, all of which is subject to approval by the Swiss Federal Surveillance Authorities (ICOLD, 1989). The reader is referred to ICOLD (1989) for a list of duties and responsibilities of the dam owners to the surveillance authorities. The Swiss Federal Surveillance Authorities supervise the execution of monitoring and carry out critical analysis of reports submitted to them on the condition and behaviour of the dam. These authorities also participate every two-to-three years in annual inspection visits and always attend the five yearly inspections undertaken by experts.

The methodology used in monitoring Swiss dams is illustrated in Figure I.1 (Biedermann, 1985). One of the essential ingredients of Switzerland's dam safety program is a monitoring system comprised of suitable instrumentation, rapid analysis, and interpretation of readings (ICOLD, 1989). Monitoring itself consists of measurements from the instrumentation system and visual inspection, neither being sufficient on their own. Like Argentineans, the Swiss also believe that a monitoring system should be sufficiently redundant. The Swiss try to achieve redundancy by maintaining parallel but separate sets of instruments and, in addition, facilities for evaluating data by double-checking and by using alternative measurement methods (e.g., plumb line & traverse, alignment & triangulation, and settlement gauge & levelling) (Biedermann et al, 1988).

Figure I.1 Monitoring of Swiss Dams
(after SNCOLD, [1985, p. 35])



Switzerland is one of the few countries in the world that believe or admit that supervision of large structures such as dams is today an interdisciplinary task of Civil Engineers, Surveying Engineers, and Geologists, and that a mutual understanding amongst them is essential (Gilg et al, 1985). All Swiss dams are monitored using either geodetic or both geodetic and geotechnical/structural instrumentations. When compared to other countries, Switzerland places more importance on geodetic measurements. Geodetic systems are regarded as complementary control tools. They are based on a horizontal network (angular alignments, triangulation, traverse, optical alignment, EDM) connected to a vertical network (pendulum, levelling). Geodetic schemes are closely coordinated by specialists such as Civil and Surveying Engineers. The Civil Engineer specifies which deformations at which points should be measured and the Surveying Engineer specifies how to best coordinate the various geodetic methods. These methods are used for both short- and long-term monitoring. A new method which is also under consideration for determining the absolute displacements is the Global Positioning System (GPS) (Egger and Schneider, 1988).

Throughout the surveying world, for many years, the Swiss have been known for their ingenuity and exceptional talents for developing high precision surveying equipment (including photogrammetric equipment). Some of the most recent developments published in a number of company brochures, particularly by WILD, are listed in Table I.26

Table I.26
Recent Monitoring Surveying Equipment Developed in Switzerland (information gathered from company brochures)

Equipment		Description
Electronic Theodolites	Leica (WILD) T2002 Leica (WILD) T3000	Equipped with microprocessor controlled biaxial sensors (electronic tiltmeters) which ca sense the mislevelling of the theodolite to an accuracy better than 0.5" and automatically corrects both vertical and horizontal direction readouts.
Three Dimension Coordinate Systems	Leica (WILD) TMS	Two or more electronic theodolites linked to a microcomputer creating a 3-D positioning system with on line calculations of the coordinates.
Electronic Distance Measurements (EDM) Devices	Leica (WILD) DI2002	Offers a standard deviation of ±1 mm over short distances (up to 200 m).

Equipment		Description
	Terrameter LDM2 (by Terra Technology)	A dual frequency instrument which can give an accuracy of better than 1 ppm.
	Leica (WILD) DIOR 3002	It uses a high frequency transmitted signal which makes it capable of measuring short distances (up to 200 m) directly from the observer to natural flat surfaces without the use of reflectors with an accuracy or 10 mm.
Total Station	Leica (WILD) TC2002 (combination of Theodolite Leica (WILD) T2002 and EDM Leica (WILD) DI2002)	An electronic theodolite linked to an EDM and to a computer creating a total survey station which allows for a simultaneous measurement of distances and horizontal and vertical angles from which relative horizontal an vertical positioning of the observed points can be determined directly in the field.
	Leica (WILD) APS	Used for continuous or frequent monitoring of deformations (fully automatic monitoring systems based on computerized and motorized total station.
	Georobot III	
Levelling	Leica (WILD) N2000	Digital automatic levelling systems with height and distance readout from encoded levelling rods.
	Leica (WILD) NA3000	
Optical Plummet	Leica (WILD) ZL (Zenith)	Offer accuracy of 1/200,000. Both can be equipped with laser.
	Leica (WILD) NL (Nadir)	

Automated monitoring systems are not considered imperative but are somewhat convenient. They are often used when the dam site is not readily accessible (e.g., dams located in high mountainous regions which are not always accessible in winter) or simply as an extension to the surveillance system. The Swiss strongly believe that one cannot depend completely on the reliability of the data from an automated measuring system.

An automated system must never replace the classical monitoring methods (Biedermann, 1985; ICOLD, 1989).

ICOLD (1989), SNCOLD (1985) and other publications published by SNCOLD/ICOLD show that the geotechnical/structural instrumentation installed in Swiss dams are not unlike those installed in dams of other countries. The major difference is that Switzerland's Safety Regulations force dam owners and authorities to ensure that the dams are monitored and analyzed with the most recent equipment and methods available. Examples of the types of instrumentation used to monitor and analyze both concrete and embankment dams are provided in the sample specifications (Biedermann et al., 1988).

The methods of analysis consist of graphical representations including one or more of the following: (1) a graph of the results in a chronological representation (used when the seasons have a much greater influence than reservoir levels); (2) a graphical representation of variables such as displacement and seepage as a function of the reservoir level (used when the water levels have a predominant influence); and (3) a graphical representation based on "equal conditions" (used when the measured results are corrected for hydrostatic and seasonal effects). The latter method, known as the "compensated displacement" method, is applied above all of the rest for determining upstream-downstream displacements of concrete dam crest and sometimes for other points on vertical dam profiles (ICOLD, 1989). For evaluating geodetic schemes with redundant observations, mathematical models using the least square adjustment are used. If there is doubt as to whether or not the reference points are fixed, a more sophisticated method such as the Helmert transformation is used (Egger and Schneider, 1988).

Deterministic, statistical or combined (hybrid) methods are being increasingly used to calculate the deformations for a standard loading (e.g., water load) or to convert the measured deformations into the deformations that would result from a standard loading. In the first case, the differences in the deformations between those obtained by one of the graphical methods (measured) and those calculated are compared to an acceptable margin of error. In the second case, the measured displacements are used as displacement inputs and if the dam behaves as expected the same deformation values will be obtained (SNCOLD, 1985). An excellent source which provides numerous examples of the surveillance of Swiss dams is entitled *Swiss Dams: Monitoring and Maintenance* (SNCOLD, 1985). More examples of the Swiss approach to dam monitoring are given by Gilg et al. (1985) and Kovari (1985).

I.27 Thailand

In Thailand there are a total of 18 large dams. The Electrical Generating Authority of Thailand (EGAT) is responsible for 13 dams and the Department of Energy Affairs (DEA) is responsible for the remaining 5 dams. Ninety-nine percent of their large dams are monitored using both geodetic and geotechnical/structural instrumentations (Bhadrakom, 1992).

Dam safety in Thailand is somewhat limited. There are no national or local standards, but those responsible for the dams follow the "Dam Safety Code of Practice" and the "Safety Evaluation of Existing Dams" adopted from Finland's National Board of Waters and Environment and the United States Bureau of Reclamation (USBR) respectively

(Bhadrakom, 1992). Furthermore, the EGAT has established a Dam Safety Committee responsible for the inspection, surveillance, and maintenance of the instrumentations and dams under its jurisdiction (Champa, 1984).

The instrumentations and methods used to monitor dams are conventional and in some cases instrumentations are manufactured locally using simple design and construction techniques. A typical geodetic systems for a concrete face rockfill embankment dam will consist of surface settlement targets located on the crest, upstream face, downstream face and supporting base (plinth) gallery of the dam. The geotechnical/structural instrumentation will include foundation settlement gauge, hydrostatic settlement gauge, stress meter, strain meter, weir and motion accelerograph (Mahasandana and Mahatharadol, 1985). Table I.27 illustrates one of Thailand's most extensive monitoring system applied to a dam (i.e., the Khao Laem Dam located on the Quae Noi River 300 km northwest of Bangkok). Table I.27 includes the frequency of measurements for each instrument.

The types of analysis used to determine the deformations are also very simplistic and somewhat orthodox. The measurements from each instrument is plotted over time and then compared to the expected design criteria. For an exclusive description of the types of monitoring systems and analysis exercised on some of Thailand's major dams, the reader is referred to Champa (1984) and Mahasandana and Mahatharadol (1985).

Table I.27
Monitoring System and Frequency of Measurements for the Khao Laem Embankment Dam, Bangkok, Thailand (after Mahasandana and Mahatharadol [1985, p. 8] and Bahadrakom [1992])

DESCRIPTION	QTY.	LOCATION	MEASURED QUANTITY	FREQ.
DAM BODY				
1. Foundation settlement gauge	31	Main dam foundation	Foundation settlement	6/year
2. Hydrostatic settlement gauge	12	Rock fill	Rock fill settlement	6/year
3. Stress meter	12	Back slope of retaining wall & power intake	Rock fill pressure	6/year
4. Surface settlement point	98	Face slab (20), crest (20), D/S slope (34) and plinth gallery (24)	Settlement	6/year
FACE SLAB				
1. Strain meter	57	Embedded in concrete face	Concrete strain Zero load strain	6/year 6/year
2. No-stress strain meter	4	Embedded in concrete face	Joint movement	1-/month
3. Perimetric joint meter	29	Perimetric joint	Joint movement	1-/month
4. Vertical contraction joint meter	4	Contraction joint	Face slab deflection	1/year
5. Inclinometer	4	On concrete face slab		
SEEPAGE MEASUREMENT				

DESCRIPTION	QTY.	LOCATION	MEASURED QUANTITY	FREQ.
1. Seepage detection system	89 prs.	Plinth gallery (19) & right abutment galleries (70)	Located in area of seepage	4/month
- Micro flow meter	1	Ditto	Seepage flow	4/month
- Temp. probe	1	Ditto	Water temp. logging	
- Bourdon gauge	14	Ditto	Water press.	4/month
2. Seepage measuring				
- Weir	14	Right abutment galleries (11), D/S toe (2), & permanent bridge (1)	Seepage	4/month
- Gauging station	1	2.5 km D/S of dam	Seepage	
3. Ground water observation hole	39	16 in galleries & 23 D/S	Ground water level	
SEISMIC MONITORING SYSTEM				
1. Short period seismograph (SPS-1)	1	Right abutment	Hypocentral distance	
2. Strong motion accelerograph (SMA-1)	4	Gallery A, crest, D/S toe and spillway gallery	Acceleration	

I.28 UK

Great Britain is one of the first country to enforce government regulations concerning dam safety. The current act is the *Reservoir Act (RA) of 1975*. This act surpasses the initial act, the *Reservoir (Safety Provisions) Act of 1930,* in that it is much more stringent and effective (Penman, 1982). The 1975 RA does not apply to the province of Ireland (Millmore and Charles, 1988). The current legislation applies to reservoirs which hold or capable of holding 25,000 cubic meters of water above the natural level of any part of the land adjoining the reservoir (Charles and Tedd, 1991). There are about 2,450 dams that come within the scope of the 1975 RA (Hinks and Charles, 1992). However, in accordance with the ICOLD definition of "large dams" only about 529 of the 2,450 dams in the UK are considered to be large dams. Furthermore, of these 529 large dams approximately 408 are embankment type dams and the remaining 121 are concrete type dams (World Register of Dams, 1984).

The provisions of the 1975 RA are described by Johnson et al. (1979). In summary, under the act:

(1) there is a requirement for all reservoirs to be registered and kept under continual supervision by a qualified Civil Engineer,

(2) the power of supervision is assigned to the Secretary of State,

(3) there is a provision for establishing enforcement authorities, and

(4) conditions are outlined for criminal liabilities and other administrative procedures (e.g., remedial measures are taken if the owner fails to respond to the deficiencies of the inspecting engineer's report).

The 1975 RA was not implemented until 1986. Before the act was implemented it was amended by the Scottish Hydro-Electric Board. One significant change was converting the reservoir surveillance and instrumentation policy from a system of manual recording and monitoring to one with more automated equipment and computer software.

Another notable change was the addition of the clause stating that every large reservoirs has to have a Supervisor Engineer with the appropriate experience and who is a member of the Supervising Engineering Panel (Beak, 1992).

The responsibility for implementing the reservoir safety legislation act has been given to the Department of the Environment (DOE). Within the scope of the act, DOE organizes research programmes dealing with the safety of reservoirs. Furthermore, the Building Research Establishment (BRE), a sub-department of DOE, conducts research into the safety of embankment dams (Charles and Tedd, 1991).

Some of the outcomes of BRE's research has been the development of new types of instruments and methods for monitoring and analyzing embankment dams. One development has been the so called settlement index (Eq I.1). The index is used to interpret the results of crest settlements in order to assess the performance of embankment dams. In equation I.1, s is the crest settlement in millimetres measured between time t_1 and t_2 after the completion of the embankment construction, and H is the height of the dam in meters. Some of the findings suggested from a review of the settlement indices calculated for a number of British dams, based on the data collected over a period of eight to ten years, are that the settlement pattern is affected by reservoir operation and in particular by major draw downs. Another major development has been the simple index ratio $(\sigma_{ha}/\gamma_w h_w)$ which can be used as an indicator of the susceptibility to hydraulic

$$S_I = \frac{s}{1000.H.\log(t_2/t_1)} \tag{I.1}$$

fracture. The numerator of the index ratio, σ_{ha} ,is the total horizontal stress acting in the direction along the axis of the dam and the denominator, $\gamma_w h_w$,is the full reservoir pressure at the depth of the measurement. If the index ratio is greater than unity then hydraulic fracture is unlikely to occur (Charles and Tedd, 1991). Other examples of such developments are given by Charles and Tedd (1991).

BRE's work is often published for use by engineers in carrying out safety evaluations under the 1975 RA. For example, BRE is the author of the UK *Engineering Guide to the Safety of Embankment Dams (Building Research Establishment Report BR 171),* published in 1990, and the co-author of the *Engineering Guide to Seismic Risk to Dams in the United Kingdom* (Charles and Tedd, 1991; Hinks and Charles, 1992).

British dam experts believe that the continuing safety of an embankment dam largely depends on visual surveillance supplemented by the installation and monitoring of instrumentation. These experts also consider pore pressures, seepage and settlements to be the most helpful indicators of the behaviour of embankment dams (Charles et al., 1992).

A sample of the types of instruments and frequency adopted by the UK are shown in Table I.28. Table I.28 illustrates the policy developed and adopted by the Northern Scotland Hydro-Electric Board.

The current policy for instrumenting and monitoring dams in the UK is well described by Beak (1992). Generally, Beak (1992) indicates that the trend in the UK has been to replace the typical geodetic, geotechnical/structural instrumentations (e.g., crest levelling, alignment using a collimator, pendulums, crack and joint measurements using callipers, temperature sensors cast into the concrete, piezometers) with new techniques that are more adaptable to automation (e.g., automatic pendulums to measure movement in both directions, displacement transducers to measure cracks and joints, thermocuples for concrete temperatures, invar wires to monitor longitudinal movements in dam galleries, vibrating wire strain gauges attached to concrete surfaces to enable strain measurements in a plane). The goal is to have all of the readings recorded and the information transmitted through a land line to a remote computer. Articles written by Penman (1982), Penman and Kennard (1982), Beak (1992) and Charles et al. (1992) give excellent examples of the types of instruments and monitoring systems applied to dams in the UK. Included in some of the articles are detailed descriptions and drawings of the instruments used, as well, the advantages and disadvantages of each instrument.

Table I.28
Types of Monitoring and Frequency
Adopted by Scotland Hydro-Electric Board (UK)
(from Johnson et al., [1979, p. 251])

Type of Dam	Condition and Behaviour	Age of Dam	Type of Monitoring and Frequency
Arch	Normal	First five years	Full instrumentation quarterly
	Normal	After five years	Full instrumentation twice a year
Gravity and Buttress	Normal	First five years	Full instrumentation twice a year
	Normal	After five years	Full instrumentation for one cycle every fifth year

Type of Dam	Condition and Behaviour	Age of Dam	Type of Monitoring and Frequency
Embankment (Earth or Rockfill)	Normal	First five years	Levelling twice a year. Pore pressure monthly (earthfill only).
	Normal	After five years	Levelling once a year. Pore pressure twice a year (earthfill only).
Gravity and Buttress	Unexpected or uncertain behaviour or where special circumstances apply	First five years	Full instrumentation twice a year. Pendulums four times a year (if installed).
	As above	After five years	Full instrumentation for one cycle every 3-5 years or as considered necessary. Pendulums four times a year (if installed) otherwise instrumentation of key stations twice a year.
Embankment (Earth or Rockfill)	As above	All ages	Levelling twice a year. Pore pressures monthly (earthfill only)

Notes:

(1) As the dam becomes older or deteriorates, the frequency of the measurements may be required to increase.

(2) If the dam is built in doubtful conditions or with abnormal behaviour, more extensive instrumentation is installed and the frequency of the readings are increased.

(3) For arch dams, and large dams subject to large variations in water levels, more frequent cycles are carried out.

(4) Supervisory inspections and monitoring are undertaken after major floods, seismic activity or unusual events.

Overall, the UK's experience and knowledge in the design and behaviour of dams have been primarily with embankment type dams. This stems from the fact that the majority of the dams within the scope of the reservoir legislation act are embankment type dams (some 2,000 dams). In particular, UK engineers have acquired experience in monitoring embankment dams with very wet clay cores known as puddle clay cores (Charles and Tedd, 1991). A UK survey of embankment dams concluded that the majority of the 2,000 embankment dams (i.e., approximately 1,300 dams) have puddle clay cores (Millmore and Charles, 1988).

The types of data analysis applied to British dams are traditional in the sense that they are very simple and straight forward. In most cases the results are presented in tabular or graphical form. For example, the deflections of embankment dams may be graphed as a function of the reservoir level and those for concrete dams as a function of time. If the reader is interested in some examples of the types of instruments and survey techniques used to monitoring existing concrete and embankment dams and their associate problems, he or she is referred to the case studies cited by Davie and Tripp (1991), Gosschalk et al. (1991), Johnson et al. (1979) and Ferguson et al. (1979).

I.29 USA

There are as many as 5,469 large dams registered in the USA (Sharma, 1992). According to Sharma (1992), current information regarding how many dams listed in the United States Committee on Large Dams (USCOLD) Database are instrumented is not available. However, there are a total or 764 dams owned by the Federal Government that are being monitored: 475 by the US Army Corps of Engineers (COE); 265 by the US Bureau of Reclamation (USBR); and 24 by the Tennessee Valley Authority. Whether or not these structures are being properly maintained and monitored is an ongoing concern of organizations such as the USBR, Association of State Dam Safety Officials (ASDSO), Interagency Committee on Dam Safety (ICODS), Federal Emergency Management Agency (FEMA), USCOLD and COE.

Sharma (1992) suggests that the monitoring instrumentation design is entirely system dependant (i.e., the expected behaviour of the dam largely depends on the dam-type and its interaction with foundation and surrounding geological environment). Therefore, there cannot be rigid standards that are applicable to all dams for monitoring their performance; there can be only guidelines and considerations. Also, in 1978 a team of experts within the USBR set out to study the question of minimum instrumentation of dams. The study concluded a number of factors that were important when considering the installation of instrumentation in new and existing dams, but it was not successful in arriving to a conclusion on the minimum number of instruments required for monitoring the deformation of a certain type of dam (Bartholomew et al., 1987). Some of the guidelines and manuals that are currently used in the US are:

1. USCOLD Publication, *General Considerations Applicable to Performance Monitoring of Dams*, December 1986
2. *Concrete Dam Instrumentation Manual*, US Bureau of Reclamation (1987), Denver, Colorado
3. *Embankment Dam Instrumentation Manual*, US Bureau of Reclamation (1987), Denver, Colorado
4. *Instrumentation for Concrete Structures* (September 1980). Engineer Manual, EM 1110-2-4300, US Corps of Engineers, Washington, D.C.
5. Instrumentation of Earth and Rockfill Dams: Part 1 of 2, *Groundwater and Pore Pressure Observations*, (31 August 1971) and Part 2 of 2, *Earth Movement and Pressure Measuring Devices*, (19 November 1976), Engineer Manual, EM 1110-2-1908, US Army Corps of Engineers, Office, Chief of

Engineers, Washington, D.C.

6. *General Considerations on Reservoir Instrumentation*, report by USCOLD Committee on Measurements, 1979/1981
7. *Seismic Instrumentation in Dams*, USCOLD Committee on Earthquakes, April 1975
8. Dunnicliff, J. (1988). *Geotechnical Instrumentation for Monitoring Field Performance*. John Wiley & Sons, New York.

In the USA, the concern for the aging of dams by some federal agencies dates back to the mid 1960s. The concerned agencies established a periodic inspection program to evaluate the conditions of their dams which has contributed to the current active, continuing program of dam safety evaluation in the federal department. However it was not until after a number of tragic dam failures that Congress passed legislation in 1972, known as the *National Dam Inspection Act.* This act called for the inventory and inspection of all non-federal dams. Furthermore, it was not until another tragic event, the Teton Dam failure in 1976, that funds were actually allotted to perform the inspections under the 1972 Act. Immediately following the Teton Dam disaster the Federal Government convened a team of specialists to develop guidelines known as the "Federal Guidelines for Dam Safety." In 1979 the President of the USA implemented these guidelines and FEMA was charged with monitoring conformance to these guidelines. At approximately the same time, after the failure of the Teton Dam, the President directed the COE to up-date the dam inventory and inspect about 9,000 non-federal large and small dams classified as being hazards (Duscha, 1984). To date the COE National Dam

Inspection Program has been one of the most significant development in dam safety efforts. Another survey of a review of state dam safety programs conducted in 1982-1984 by the University of Tennessee disclosed that over half (26) of the states still did not have adequate dam safety legislation and adequate resources and personnel to conduct effective and sustainable dam safety programs. An informal survey concluded that these statistics were still viable in 1989 (Ellam, 1990). The newest act that is in effect in the USA is the *Dam Safety Act of 1986* (Title XII of P.L. 99-662) (ASDSO Newsletter, 1989).

At the Fourteenth International Congress on Large Dams in 1982 in Rio de Janeiro, A.W. Wahler of the USA expressed that one of the problems in his country is that earth dams are often delegated to junior engineers because senior developers consider them to be simple. He also added that a number of government agencies in the USA were responsible for designing earth dams without being specialist in the subject (IWP & DC, 1982). With approximately 86% of the 5459 large dams in the USA being embankment type dams one may conclude that W.A. Wahler's statement is a valid explanation as to why such an exuberant number of American dams (9,000) are considered unsafe by the COE's guidelines.

According to Leps (1985), history of dam failures in the USA has demonstrated that the instrumentation provided in each case was not selected, installed, observed, or evaluated in a sufficiently timely manner, or with the skill judgment required, to permit adequate forecasts of, and offsetting measures against inadequate safety. Leps (1985) supports this statement by citing a number of cases where this is a fact, one being the Teton Dam in Idaho. The only instrumentation at the time of Teton Dam failure consisted of nine surface bench marks on the dam and nineteen deep observation wells in bedrock in the region adjacent to the dam and reservoir. There were no piezometers, no internal settlement or deformation devices and no provision for monitoring leakage except visually (Leps, 1985).

Despite these statistics there has been encouraging developments in dam safety within the past few years. In 1984 a constitution and by-laws were adopted by several states to form ASDSO. With respect to dam safety, ASDSO's mandate is to provide information and assistance to state dam safety programs and to improve the efficiency and effectiveness of the programs. Since its establishment, ASDSO has expanded to include 48 States and two territories. The association has sponsored national meetings on an annual basis where the use of innovative ideas and technology in dam rehabilitation projects is presented and exchanged. In addition, organizations such as FEMA has supported several projects aimed at enhancing the state dam safety programs including the development of a Model State Program for dam safety and the establishment of technical groups to consider special issues (Ellam, 1990). Another important event that is worth noting is the signing of a Memorandum of Understanding (MOU) in 1989 between COE and FEMA to transfer funds authorized in the *Dam Safety Act of 1986* to update the National Inventory of Dams. Under the MOU, FEMA's goal is to eventually establish a National Database consisting of both federal and non-federal owned dams (ASDSO Newsletter, 1989).

As the concern for dam safety in America grew it became apparent that there was little comprehensive dam safety training available. Recognizing this predicament, an ad hoc steering committee comprising of USBR, COE, FEMA, ASDSO and USCOLD was established in 1985 to explore innovative solutions to the training needs problem. The ideal solution adopted by the steering committee was to design a self-instructional training package. It was argued that self-instructional training is capable of reaching a very large and broad audience and can be readily tailored to the needs of the individual learner. The newly established dam safety training program was given the name Training Aids for Dam Safety (TADS) and obtained the support of fourteen US Federal agencies within ICODS (Veesaert, 1990).

The TADS program consists of three components comprising of a series of modules with workbook and texts, supplemented with videotapes. The first component is entitled "Safety Inspection of Dams" which includes modules on how to prepare for, conduct, and document the inspection of different types of embankment and concrete dams. Included in this component is also a module on the instrumentation of embankment and concrete dams. The second component, "Dam Safety Awareness, Organization and Implementation," consists of a series of modules on the importance of dam safety, dam ownership responsibilities and liabilities, and how to organizing dam safety and operation and maintenance programs, and emergency action planning. The third and last component, "Data Review, Investigation and Analysis, and Remedial Action for Dam Safety," outlines the dam safety process and, how to evaluate hydrologic and hydraulic accuracy, concrete and embankment dam stability, and deformation and seepage conditions. These modules are available through the supporting US Federal agencies or through USBR (Veesaert, 1990).

In the USA, the monitoring of the performance of dams for their structural safety by means of external and internal structural measuring instrumentation dates back to 1930, as exemplified by the Hoover Dam (1936) monitoring system. However, for the reasons stated earlier, it is apparent that this approach was not applied to the majority of the existing dams in the USA. The need for the surveillance of dams and the consideration applicable to monitoring and assessing the structural safety of the dam and its foundation are presented in the USCOLD publication entitled "General Considerations on Reservoir Instrumentation", written by the USCOLD Committee on Measurements 1979-1981 (ICOLD, 1989). The aim of the publication is to provide federal and non-federal agencies with a monitoring program that will ensure that the dam is safe and operating as expected. A summary of the publication was presented to the ICOLD Committee on Monitoring of Dams and their Foundations and has been published in the ICOLD (1989) as part of the Committee's report. The following discussion will outlined some of the major considerations of the USCOLD's report.

Overall, the USCOLD's report includes the following (ICOLD, 1989):

1. The purpose and need for dam surveillance
2. For embankment and concrete dams, it recommends the quantities to be measured and the instruments and measuring methods to be used to measure those quantities (see Table I.29)
3. The procedures to observe when designing a surveillance system (e.g., the need to establish the purpose of the instrumentation, the steps required when selecting instruments, and listing the purpose of each instruments)

4. Recommendations of the monitoring frequencies at the different phases of the project (see Table I.31 of this report)
5. Considerations concerning data acquisition, processing and presentation of results, including requirements for the personnel responsible for these readings
6. An example of the principles, process and situations which should be considered in the evaluation of any data set to determine the structural performance of the dam
7. A guide to some of the factors that should be considered when selecting an automated system for a dam.

The types of instrumentations and monitoring techniques for both embankment and concrete dams recommended by USCOLD are listed in Table I.29. In Table I.29, the USCOLD suggests that a surveillance system for all dams should comprise of a combination of geodetic, geotechnical/structural monitoring instrumentation. Moreover, Tables I.30a and I.30b illustrate that a number of these instruments have already been installed in some of USA's existing dams. With respect to geodetic methods, particularly when performing precision measurements with Electronic Distance Measuring Equipment (EDME), the USCOLD strongly stresses the need for a qualified person to make the measurements. Some of the new monitoring methods developed in the USA include new EDME equipment, the Streaming Potential Method and the Subsurface Temperature Monitoring (Thermotic Monitoring) for monitoring seepage (ICOLD, 1989).

Another development which was initiated in 1984 by the COE is the Continuous

Deformation Monitoring System (CDSM). This is a fully automated deformation monitoring system that uses GPS to perform high precision surveys of structures. It was designed particularly to monitor dam deformation. In 1989, the system was installed at the Dworshak Dam in Idaho for three months for field verification. The results showed that CDMS is capable of measuring displacements within an accuracy of ± 3 mm root mean square (rms). Further tests of this systems are planned for 1992 (Frodge, 1992b).

Table I.29
Instrumentation and Monitoring Techniques
Recommended by USCOLD
(after ICOLD, [1989, pp. 287-292])

Quantities Measured	Instruments	E	CG	RCCG	CA	CB	C/E
1. MOVEMENTS							
Horizontal and vertical translation	Precision theodolite, EDM, inclinometer	x	x	x	x	x	
Rotation	Tiltmeters	x	x		x	x	x
Relative	Strain detection devices including joint meters, extensometer and a variety of crack monitoring devices	x	x	x	x	x	x
Strain	Strain meters (e.g., Carlson elastic wire type)		x	x	x	x	
Differential between zones		x					
At joints or at cracks in concrete			x	x	x	x	
2. STRESS							

Quantities Measured	Instruments	E	CG	RCCG	CA	CB	C/E
	Gloetzl flat plate, carlson stressmeter, Goodman flat jack, (strain meters converted into stress)	x	x	x	x	x	
3.GROUND WATER AND WATER PRESSURE							
Pore water pressure	Open stand pipes or wells or by piezometers systems of either the open or closed pipe. Closed system piezometers include hydraulic or pneumatic type.	x					
Uplift pressure		x	x	x	x	x	x
Ground water elevation		x	x	x	x	x	
Seepage Movements	Weirs (90° V-notch, rectangular or trapezoidal type), flowmeter, parshall flumes, calibrated containers, thermatic surveys and self potential measurements.						
* Phreatic surface		x					
* Discharge amounts		x	x	x	x	x	x
Analysis of Collected Seepage							
* For solids		x					
* For chemical compounds		x	x	x	x		
Detection of seepage paths		x	x	x	x	x	x
4. TEMPERATURE							
Of the water (at various levels, in the reservoir and below the dam)	Thermometers	x	x	x	x	x	
Of concrete at various depths at the mass	Carlson type resistance thermometers, face thermometers		x	x	x	x	
Of atmosphere	Thermometers	x	x	x	x	x	x
Of soil or foundation mass	Carlson type resistance thermometers	x	x	x	x	x	

Quantities Measured	Instruments	E	CG	RCCG	CA	CB	C/E
5.SEISMIC EFFECTS							
Accelerations	Seismographs and strong motion accelerographs	x	x	x	x	x	x
Displacement		x	x	x	x	x	x

E = Earth
RCCG = Roller Compacted Concrete Gravity
CB = Concrete Buttress
CG = Concrete Gravity
CA = Concrete Arch
C/E = Concrete and Earth

Table I.30a
Dam Monitoring Instrumentation Applied to Existing Concrete Dams in the USA (from ICOLD, [1989, p. 316])

Name (year)	H/L (m)	INSTRUMENT TYPE							
		Plumbl.	**Uplift Press**	**Collim.**	**Found. def.**	**Embd. Instr. (strain /temp)**	**Drain Flows**	**Seepage Meas.**	**Others**
Crystal (1976)	98/194	16	-	3	16	28	54	13	Slide meas. strain gauges
East Canyon (1966)	79/133	-	-	4	10	-	-	-	Triangul.
Flaming Gorge (1964)	153-/392	24	13	8	-	1,078	-	15	16 Therm.
Grand Coulee Forebay (1974)	55/357	24	33	11	10	23	37	-	Whittemore pts; deflectometers; therm.
Glen Canyon (1964)	216-/476	25	38	-	12	1,800 +	16	-	Triangul; climatological

Name (year)	H/L (m)	INSTRUMENT TYPE							
		Plumbl.	**Uplift Press**	**Collim.**	**Found. def.**	**Embd. Instr. (strain /temp)**	**Drain Flows**	**Seepage Meas.**	**Others**
Hungry Horse (1953)	172-/645	12	50	-	-	464	139	-	Climatological
Monticello (1957)	93/312	6	-	-	-	162	-	-	EDM; triangul.
Morrow Point (1968)	143-/221	26	-	5	3	1,118	36	-	Power plant monuments; slide monitoring
Nambe Falls (1976)	46/98	-	10	6	-	60	21	11	Embedded meas: flat jack press. (12)
Pueblo (1975)	58/-3109	6	10	6	6	-	8	-	Buttress movement (12), EDM-20 embedded meas.
Yellowtail (1966)	160-/451	9	23	3	9	1,650 +	-	193	Obs. wells 45
Clarance Canon (1984)	138/-1940	2	42	-	-	47	-	-	Trilat. 43 pts
Dworshak (1973)	218/-1000	2	55	52	9	790	-	4	Seismograph (4)

Name (year)	**H/L (m)**	**INSTRUMENT TYPE**							
		Plumbl.	**Uplift Press**	**Collim.**	**Found. def.**	**Embd. Instr. (strain /temp)**	**Drain Flows**	**Seepage Meas.**	**Others**
New Bullards Bar (1-969)	193-/716	4	18	-	39	518	-	15	Triangul. 13 pts; jointmeters 172

Table I.30b
Dam Monitoring Instrumentation
Applied to Existing Embankment Dams in the USA
(from ICOLD, [1989, p. 317])

Name (year)	**H/L (m)**	**INSTRUMENT TYPE**						
		Pnuem. Piezom.	**Standpipe Piezom.**	**Inclin.**	**Vibr.-Wire Piezom.**	**Meas. Pts**	**Seepage Meas.**	**Others**
Calamus (1985)	29.3/2195	48	106	3	16	66	25	Baseplate 12; pneumatic settl. sensors 48; thermistor 111
Choke Canyon (1982)	43.1/56-31.4	none	53	none	-	96	none	Baseplate 7
McGee Creek (*)	50.0/6000	77	41	7	-	57	none	Pneumatic settlement sensors 8; total press. cells 24
McPhee (1984)	82.3-/396.3	96	22	7	-	40	none	Pneumatic settlement sensors 64; extensometers 2; strong motion 5

Name (year)	H/L (m)	INSTRUMENT TYPE						
		Pnuem. Piezom.	**Stand-pipe Piezom.**	**Inclin.**	**Vibr.-Wire Piezom.**	**Meas. Pts**	**Seepage Meas.**	**Others**
Navajo (1963)	123/1112	none	48	none	-	60	7	Hydraulic piezometers 40; internal vert. movements 2; water analysis 11; horizontal drain 3
Palmetto Bend (1980)	21/13,904	none	60	4	-	3	128	
Red Fleet (1980)	44/518	27	38	9	-	70	2	Horizontal drains 100; tunnel drains 30
Ridgeway (*)	69.2-/740.9	68	53	14	8	86	2	Total pressure cells 13; extensometers 16; strong motion 6
San Justo (*)	43/220.1	none	30	23	32	100	15	
San Luts (1967)	115/5669	none	61	19	70	250	13	Hydraulic piezometers 119; internal vert. movements 4; baseplate 3

Name (year)	**H/L (m)**	**INSTRUMENT TYPE**						
		Pnuem. Piezom.	**Standpipe Piezom.**	**Inclin.**	**Vibr.-Wire Piezom.**	**Meas. Pts**	**Seepage Meas.**	**Others**
Sugar Pine (1980)	58/183	21	4	5	-	20	1	Hydraulic piezometers 30; total pressure cells 29; extensometers 12; internal vertical movements 1
Clarence Canon		62	20	9	21	28	-	Carlson soil pressure cell 1; Carlson electrical piezometers 5

(*) Signifies that it the dam was under construction at the time the table was published.

Although it may seem elementary, a significant point with respect to the instrumentation system design is that the personnel selected to be responsible for the instrumentation should be able to answer the question: "Is the instrument functioning correctly?" In doing so, they should be capable of checking for gross error by a simple visual means or if required by more extensive means, and periodically calibrate and maintain the instrumentation. Furthermore, these persons should be thoroughly experienced, and capable of fully understanding the purpose and importance of the instrumentation. The USCOLD's report continues on to suggests that this group be headed by a senior Civil Engineer who is intimately familiar with the instrumentation system, the dam and its structural behaviour (ICOLD, 1989). It would appear that the USCOLD is trying to avoid the situation that transpired with the Waco Dam failure in Texas from reoccurring. Waco Dam is an example of a failure where significant movements were noted from a review of the construction survey data, but at the time was ignored and explained away as being a survey error. Later, investigations revealed that the failure was caused by a slippage in the foundation clay shale about 15 meters below the ground (Stroman and Karbs, 1985).

The USCOLD's recommended observation schedule from which a basic framework can be formulated for a specific monitoring schedule compatible with the types of instruments installed in the project are listed at Table I.31. The observation schedule indicates the monitoring frequencies to be observed over the four basic stages of the life of a dam; during construction, first filling, initial holding (if applicable), during the first year and after the dam attains a stabilized pattern of behaviour. Also included, as a note, are the measurements that should be observed before construction begins (ICOLD, 1989). For comparison an actual observation schedule that is being implemented on Monticello earth dams in South Carolina is provided in Table I.32.

To enable a better assessment of instrument performance and to increase the confidence in the readings, USCOLD suggests that the monitoring system should have some redundancy. This may be accomplished by installing instruments with different types of sensors close to each other (e.g., in the case of piezometer installations, flushable hydraulic cells can be installed beside vibrating wire instruments). The necessary data for the safety evaluation of the dam should be presented in tabular or graphical form and compared with the predicted behaviour. Measured values of response patterns (deflection, seepage, uplift) plotted against time is considered be one of the key end product of data processing. If dam owners do not have the expertise to perform the data processing and analysis, they are encouraged to seek the guidance of federal agencies such as USBR, COE and other larger agencies. Generally, according to the US National Report (ICOLD, 1989), these agencies own and operate many dams and have well established in-house instrumentation and dam performance evaluation groups staffed with experienced engineering personnel. There is, however, some doubt whether this statement represents the true situation, particularly in the area of geodetic monitoring.

Table I.31
USCOLD Instrument Monitoring Schedule
(from ICOLD, [1989, p. 325])

PERIOD	TYPE OF MEASUREMENT		
	DEFLECTION & DEFORMATION	STRESS, STRAIN & TEMPERATURE	SEEPAGE, PIEZOMETER LEVELS
During Construction	PL - weekly SL - prior to filling FD - weekly MP - weekly	SS - weekly SM - weekly T - weekly	U - weekly D - weekly P - weekly

PERIOD	TYPE OF MEASUREMENT		
	DEFLECTION & DEFORMATION	STRESS, STRAIN & TEMPERATURE	SEEPAGE, PIEZOMETER LEVELS
First Filling	PL - daily during fill or each specified rise SL - once after reservoir reaches level to be maintained FD - daily during fill or each specified rise MP - daily during fill or each specified rise	SS - once each specified rise SM - once after reservoir reaches level to be maintained T - once after reservoir reaches level to be maintained	U - following filling D - following filling unless un-anticipated flow is encountered P - daily during fill or once each specified rise
Initial Holding (if applicable)	PL - daily for first week, weekly thereafter SL - monthly FD - weekly MP - weekly unless creep is indicated	SS - weekly SM - weekly T - weekly	U - daily for first week, weekly thereafter D - weekly P - daily for first week, weekly thereafter
Subsequent First Year's Operation	PL - bi-monthly SL - quarterly FD - monthly MP - monthly	SS - bi-monthly SM - bi-monthly T - bi-monthly	U - weekly D - weekly P - weekly
After Dam Attains Stabilized Pattern of Behaviour	PL - monthly SL - annually at high reservoir FD - monthly MP - monthly	SS - monthly SM - monthly T - monthly	U - weekly D - weekly P - weekly

Note:

Pre-construction Observation
* Geodetic - once before start of construction

* Groundwater levels - once before start of construction
* Seismic activity - early before construction to establish ref base

PL - Plumblines
SL - Survey Transverse, Triangulation
FD - Foundation Deformation Meters
MP - Multiple Position Extensometer
SS - Stressmeters
SM - Strainmeters
T - Thermometers
U - Uplift Pressure
D - Seepage
P - Piezometers

Table I.32
Frequency of Instrument Readings and Dam Surveillance of the Earth Dams of Fairfield Pumped Storage Facility South Carolina (USA) (from Massey, [1982, p. 1155])

Instrument	Before Filling	During Filling	After Filling	Remarks
Accelerometer			Automatically signals powerhouse following earthquake larger than .0045g.	
Water level recorder piezometers			weekly or within one hour following the triggering of the accelerometer	
Permanent piezometers and observation Wells (a)	bi-weekly	twice/week with reservoir below El. 400 daily with reservoir above El. 400	bi-weekly: continue for 2 months after reservoir is first tilled weekly thereafter (b)	
Horizontal drains, intake structure, vertical pipe drains, springs, flow at all toe drainage weirs, downstream weirs and drains, and relief wells	bi-weekly	daily	same frequency as tabulated above for permanent piezometers (c)	reservoir perimeter springs & wells are read monthly
Turbidity measurements	bi-weekly	daily	monthly	

Instrument	Before Filling	During Filling	After Filling	Remarks
Settlement plates and borros anchor points	bi-weekly	twice/week	bi-weekly: continue for 2 months after reservoir is first filled monthly thereafter	
Crest monuments, intake monuments, and penstock slope monuments and targets	bi-weekly	weekly	bi-weekly: continue for 2 months after reservoir is first filled monthly: after 2nd full reservoir month	
Slope indicator	bi-weekly	weekly	bi-weekly: continue for 2 months after reservoir is first filled quarterly thereafter	readings were discontinued in 1980 because of damage to pipe
Lake level and rainfall	daily	daily	daily	
Slope targets	bi-weekly	weekly	bi-weekly: continue for 2 months after reservoir is first filled	penstock slope targets continued monthly
Surveillance of reservoir shoreline	N/A	daily	quarterly (d)	
Surveillance of crest, u/s face, d/s face and area d/s of toes	after completion of construction	weekly: with reservoir below El. 400 daily: with reservoir above El. 400	concurrent with readings of the permanent piezometers	
General routine inspection of all Monticello Dams	after completion of construction	daily	daily	

(a) The number of permanent piezometers being monitored during the life of the facility may change.

(b) If an earthquake causes the accelerometer to trigger and the permanent and continuous water level recorders of Dam B indicate a water level change equal to or greater than one foot compared with the previous reading, frequency of the readings will increase to daily or as requested by the engineer.

(c) If an earthquake causes the accelerometer to trigger and the flow or turbidity changes are noticed, frequency of readings or observations will change to daily or as requested by the engineer.

(d) Frequency may be adjusted depending on rate of erosion.

Automation of data collection in American dams is increasingly being used primarily because of: (1) the decrease in cost of the technology, (2) the increased reliability of the systems, (3) the greater availability of electronic sensors for making measurements, and (4) the increased cost of labour for monitoring. The USCOLD provides a lists of instruments which they consider can be readily automated, and a list of dams owned by USBR and others that have been installed with an automated data acquisition system (ICOLD, 1989). The reader is referred to Walz (1989) for additional information on the automation of data management in the USA. Walz (1989) includes the types of system components, hardware and software requirements that need to be considered when implementing such a system. He also provides a table suggesting the types of instruments that can and cannot be easily automated.

In addition to the information provided by USCOLD's report in ICOLD (1989), there are a number of articles related to dam safety and monitoring that have been published by different experts and members of other organizations in the USA. These include reports on the implementation of monitoring instruments (Leps, 1985; Lytle, 1985), monitoring systems and instrumentation used on existing dams (Massey, 1982; Moore and Kleber, 1985; Stroman and Karbs, 1985) and case studies of some of the problems encountered with embankment and concrete dams (Abraham and Sloan, 1979; Fetzer, 1979; Murray and Browning, 1984; Davis et al., 1991; Fiedler et al., 1991; Kelly, 1991; Thompson et al., 1991).

Other excellent sources of information are the aforementioned USBR guides on the instrumentation of concrete and embankment dams entitled, *Concrete Dam Instrumentation Manual* and *Embankment Dam Instrumentation Manual* (Bartholomew and Haverland, 1987; Bartholomew et al., 1987). The manuals not only provide information on the types of instruments and monitoring techniques currently used by USBR but for each instrument the manuals include: their advantages and limitations, samples of data and analysis from existing dams, a list of sample specifications, and guidelines on the frequency of the measurements. The frequency guidelines have bee reproduce in Tables I.33 and I.34. These manuals have been prepared primarily for USBR personnel to provide them with information on the installation, operation, and analysis of instrumentation systems of USBR dams, however designers, engineers, surveillance staff, dam owners, and dam safety personnel within the USA or abroad may also use this information (Bartholomew et al., 1987).

Table I.33
USBR Suggested Minimum Frequency of Readings for Instruments Used to Monitor Concrete Dams (from Bartholomew and Haverland [1987, p. 9])

Type of Instrument	During Construction		Initial Filling	Operation		
	Constr.	Shut-down		1st Year	2-3 Years	Reg.
Vibrating Wire Piezometer	W	M	W	BW	M	M
Hydrostatic Uplift Pressure Pipes	W	M	W	W	BW	M
Porous-tube Piezometers	M	M	W	W	M	M

Type of Instrument	During Construction		Initial Filling	Operation		
	Constr.	Shut-down		1st Year	2-3 Years	Reg.
Slotted-pipe Piezometers	W	M	W	W	BW	M
Observation Wells	W	M	W	W	BW	M
Water Levels	W	M	W	W	M	M
Seepage Measurements (weirs, flumes,etc.)	-	-	W	W	BW	M
Visual Seepage Monitoring	W	W	W	W	BW	M
Resistance Thermometers	TW	M	W	W	M	M
Thermocouples	D	M	W	W	M	M
Carlson Strain Meters	W	W	W	BW	M	M
Joint Meters	W	W	W	BW	M	M
Stress Meters	W	M	W	BW	M	M
Reinforcement Meters	W	M	M	M	M	M
Penstock Meters	W	M	M	M	M	M
Deflectometers	W	M	W	W	M	M
Vibrating-wire Strain Gauges	W	M	M	M	M	M
Vibrating-wire Total Pressure Cells	W	M	M	M	M	M
Load Cells	W	M	W	BW	M	M
Pore Pressure Meters	W	W	W	BW	M	M
No-stress Strain Meters	W	W	W	BW	M	M
Foundation Deformation Meters	W	W	W	BW	M	M
Flat jacks	D	W	W	BW	M	M

Type of Instrument	During Construction		Initial Filling	Operation		
	Constr.	Shut-down		1st Year	2-3 Years	Reg.
Tape Gauges (tunnel)	W	W	W	BW	M	M
Whittemore Gauges	-	-	BW	BW	M	M
Avongard Crack Monitor	W	M	W	W	M	M
Wire Gauges	-	-	M	M	M	Q
Abutment Deformation Gauges	W	M	W	W	M	M
Ames Dial Meter	W	M	W	W	M	M
Differential Buttress Gauges	W	M	W	W	M	M
Plumblines	D	W	D	W	BW	M
Inclinometers	W	W	W	W	BW	M
Collimation	EOD	M	W	BW	M	M
Embankment Settlement Points	-	-	M	BM	Q	SA
Level Points	M	Q	M	M	BM	BM
Multipoint Extensometers	W	M	W	M	M	Q
Triangulation	-	-	M	M	Q	SA
Trilateration (EDM)	-	-	BW	M	Q	Q
Reservoir Slide Monitoring System	-	-	M	M	M	Q
Power Plant Movement	-	-	W	M	M	M
Rock Movement	W	M	W	M	M	M

Note:

A - Annually AR - As Required BM - Bimonthly BW - Biweekly CR - Continuous Reading
D - Daily EOD - Every other day for a month I - At time of installation
Q - Quarterly M - Monthly SA - Semi-annually TM - Twice Monthly TW - Twice Weekly

1 - Daily during curtain grouting
2 - May be discontinued after 3 years unless anomalies are noted.

These are suggested minimums: however, anomalies or unusual occurrences such as earthquake or flood will require additional readings.

Table I.34
USBR Suggested Minimum Frequency of Readings for Instruments Used to Monitor Embankment Dams (from Bartholomew et al., [1987, p. 10])

Type of Instrument	During Construction		Initial Filling	Operation	
	Constr.	Shut-down		1st Year	Reg.
Vibrating Wire Piezometers	TM	M	TW	M	M
Pneumatic Piezometers	TM	M	TW	M	M
Carlson Pore-Pressure Cells	TM	M	W	M	M
Total Pressure Cells (vibrating-wire, pneumatic, other)	M	M	W	M	Q
Porous-tube Piezometers	TM	M	TW	M	M
Slotted-pipe Piezometers	TM	M	TW	M	M
Seepage Measurements (weirs, flumes,etc.)	M	M	3/W	M	M
Observation Wells	TM	M	TW	M	M
Geophysical Seepage Measurements (thermotic surveying)	AR	AR	AR	AR	AR
Internal Vertical Movements Devices	1	M	M	2	3
Foundation Baseplate Settlement	1	M	M	2	A

Type of Instrument	During Construction		Initial Filling	Operation	
	Constr.	Shut-down		1st Year	Reg.
Pneumatic Settlement Sensors	M	M	M	4	A
Vibrating Wire Settlement Sensors	M	M	M	4	A
Inclinometers (horizontal and vertical)	1	M	M	M	SA
Multi-point Extensometers	M	M	M	4	M
Shear Strips	M	M	M	5	A
Radiosonde Methods	M	M	M	2	A
Tiltmeters	M	M	M	5	M
Embankment Measurement Points	I	SA	M	2	6
Structural Measurement Points	M	M	M	2	6
Vibrating Measuring Devices	CR	CR	CR	CR	CR
Water Quality Testing	M	M	M	M	M

Note: 1 - Complete set of readings each time a unit or an extension is installed.
2 - Six months after completion.
3 - Six year interval.
4 - One month after completion.
5 - Three months after completion.
6 - Three to six years interval.

All entries are recommended frequency of readings. Readings may be required more frequently (even daily) for certain installations.

I.30 Uruguay

Uruguay has only 6 large dams officially registered. At least four of the 6 dams are being monitored using geodetic and geotechnical instrumentation. Uruguay has no national standards or specifications for dam monitoring (Buschieazzo, 1992). According to Mr. Buschieazzo, the Secretary of the Uruguay Committee on Large Dams, the last time that Uruguay published some form of technical notes on its dams was in the Proceedings of the Sixth International Congress on Large Dams, New York, 1958, Question 21, R21. Unfortunately Mr. Buschieazzo could not provide any information regarding the status of the instrumentations and the monitoring systems being used on Uruguay's dams. Furthermore, no additional information was found from any other sources.