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RELIABILITY AND EFFICIENCY OF DAM DEFORMATION MONITORING SCHEMES

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ABSTRACT:

New technological developments in geotechnical and geodetic monitoring sensors and new methods of integrated analysis require a new approach to the design and integrated analysis of the monitoring schemes. The optimal design must be based on a good understanding of the expected mechanism of deformations, expected magnitude and localization of the maximum deformations, and required accuracy and sources of errors. A poorly designed monitoring scheme may lead to false decisions concerning mitigation measures. These issues are addressed in a recently developed concept of Integrated System (IS) for monitoring, modeling, and predicting deformations, which consists of five interacting components of the deformation monitoring process, namely: deterministic (*a-priori*) modeling of deformations, design of the monitoring scheme, collection of the monitoring data, geometrical analysis, and physical interpretation. The individual components of IS are discussed on examples of concrete, embankment, and concrete face rock fill dams.

RESUMÉ:

De nouveaux développements technologiques dans les capteurs de surveillance géotechnique et géodésique et de nouvelles méthodes d'analyse intégrée nécessitentune nouvelle approche pour la conception et l'analyse intégrée des systèmes desurveillance. La conception optimale doit être basée sur une bonne compréhension du mécanisme prévu de déformations, de l'ampleur attendue et la localisation des déformations maximales, et la précision requise et sources d'erreurs. Un système de surveillance mal conçu peut conduire à des décisions fausses concernant les mesures d'atténuation. Ces questions sont abordées dans un concept récemment développé de système intégré (IS) pour la surveillance, la modélisation et la prédiction des déformations, qui se compose de cinq éléments interdépendants du processus desurveillance de la déformation, à savoir: déterministe (a priori) la modélisation des déformations, la conception de le système de surveillance, la collecte des données de surveillance, l'analyse géométrique, et l'interprétation physique. Les composantes individuelles de l'IS sont discutés sur des exemples de béton, remblais, barrages et concrètes face à enrochement.

1 INTRODUCTION

Deformation monitoring of large dams and their surroundings has always been recognized as an important tool in providing information on the stability and integrity of the dams, surrounding slopes and utility structures. Recent developments of new monitoring technologies and methods for the integrated analysis and modelling of dam deformations expand the role of monitoring surveys beyond being just a warning system. Results of fully automated and continuous monitoring surveys, when subjected to proper analysis, may also be used in verifying design parameters (Szostak-Chrzanowski et al. 2002), explain the causes and mechanism of deformation (Chrzanowski and Szostak-Chrzanowski, 1995) and provide information for improvements in the design of future dams.

New technological developments in geotechnical and geodetic monitoring sensors and new methods of integrated analysis of deformations require a new approach to the design and integrated analysis of the monitoring schemes. In order to take full advantage of the new developments, the design of the monitoring schemes must be based on a good understanding of the expected mechanism of deformations, expected magnitude and localization of the maximum deformations, and sources of errors of the new technologies. A poorly designed monitoring scheme may lead to false decisions concerning mitigation measures. These issues are addressed in a recently developed concept of an Integrated System (IS) for monitoring, modeling, and predicting deformations (Chrzanowski and Szostak-Chrzanowski, 2010). This presentation reviews some key issues in monitoring surveys and their analysis, which may help those in charge of monitoring systems in selecting the monitoring techniques, their optimal implementation, and interpretation of the results.

2 REQUIREMENTS OF DEFORMATION MONITORING SCHEMES

2.1 Accuracy Requirements

As a general rule, the accuracy, at a 95% confidence level, of estimated rates of monitored displacements should be at least 3 times smaller than the maximum expected displacements over the observation time interval (Chrzanowski, 1993). Each dam requires different monitoring accuracy depending on the dam dimensions, material type, interaction with foundation bedrock, etc. Generally, concrete dams and structures of hydro-electric power plants require monitoring measurements that are about 5 times more accurate than do embankment dams and slopes surrounding reservoirs. Table 1 lists typical accuracies and the recommended types of monitoring technologies (geodetic and/or geotechnical) to be used during the normal behaviour of the structures. However, once any irregularities in the behaviour are observed, there is no limit, other than economic, to the desired accuracy. The higher the accuracy of the measurements, the easier it will be to explain the causes and mechanism of the unpredicted deformations.

2.2 Reliability

Reliability is a key requirement in any monitoring survey. A non-reliable and poorly designed monitoring system may lead to false conclusions and misinterpretation. To achieve good reliability, the design of the monitoring system must be based on:

- A good understanding of the physical process leading to the deformation;
- The sources of errors in monitoring measurements and their mitigation;
- A sufficient redundancy of observables; and
- A sufficient robustness to harsh environmental conditions.

Proper calibration and frequent checks of the instrumentation during their performance are key factors. Here, special attention must be paid to geotechnical/structural instruments, which are very often embedded in the investigated structures and left in situ over prolonged periods of time (months or even years). Some new technologies, such as laser scanners (Alba et al. 2008,; Schneider, 2006), ground based radar interferometry (Alba et al. 2006), MEMS accelerometers/tiltmeters (Danish et al. 2008), and area distributed fibre-optics strainmeters still require more research on their optimal use, calibration, and environmental effects on their performance, before they become reliable, particularly in long term monitoring.

Table 1: Accuracy requirements of monitoring schemes

Type of structure	**Typical ranges of required accuracy [mm] of displacements at 95% confidence level**	**Recommended Type of Monitoring Technology**
Concrete dams and other concrete utility structures	0,2 - 5	Geotechnical instrumentation supplemented by geodetic techniques
Embankment dams and slopes surrounding the reservoir	10 – 15	Geodetic techniques supplemented by geotechnical instrumentation
Concrete face rock fill dams (CFRFD)	Concrete face: 3 – 5	Geotechnical instrumentation embedded in concrete face
	Downstream face: 10 – 15	Geodetic techniques supplemented by geotechnical sensors

2.3 Three-Dimensional (3-D) Information

The monitoring results are supposed to help in identifying the causes and actual mechanism of deformation. In complex conditions of multiple causes of deformation, 3-D monitoring information is essential in separating various causes. This is of particular importance when the monitoring results show significant discrepancies from predicted values. This aspect of deformation monitoring is very often underestimated by those responsible for the design of the monitoring scheme.

2.4 Identification of Unstable Reference Points

In deformation surveys, the definition of the datum is adversely affected by the use of reference points that are erroneously assumed stable. This in turn gives a biased displacement pattern that can easily lead to a misinterpretation of what is really happening to the deformable object. Thus, the monitoring scheme must provide for the identification of unstable reference points.

A methodology utilizing an iterative weighted similarity transformation (IWST) of displacements for the identification of unstable reference points was developed (Chen et al., 1990) in Canada in the early 1980s. The methodology is based on using a similarity transformation of displacement components d_i with the condition that $\sum|d_i|$ = min. The weights of individual displacement components are inversely proportional to the absolute value of the component itself. The transformation is an iterative process that is repeated until subsequent iterations reach a preselected convergence criterion. One should point out that the problem of instability of reference points is very often underestimated in practice.

This methodology has been implemented in the world-respected GeoLab network adjustment and analysis software package. This will make adjusted network data immediately available to the built-in IWST module, making it easier than ever to identify unstable reference points.

2.5 Automation and Continuity

Full automation, telemetric data acquisition, as well as the spatial and temporal continuity of deformation measurements are desired and become essential when abnormal deformation pattern occurs.

2.6 Cost Effectiveness

Theoretically, with the current advancements in monitoring technologies, at a cost one can achieve high precision, full automation, and almost real-time processing of deformation measurements. Practically, however, monitoring systems must compromise between the requirements and the available resources and one should aim at having the simplest possible monitoring system as long as it satisfies the accuracy and reliability criteria.

3 REVIEW OF MONITORING TECHNIQUES

The sensors used in monitoring measurements are generally grouped into geodetic/remote sensing techniques (terrestrial and space) and geotechnical/structural instruments (e.g. tiltmeters, extensometers, and strainmeters). Geodetic methods supply information on the absolute and relative displacements (changes in coordinates) from which displacement and strain fields for the monitored object may be derived. Thus, geodetic surveys supply global information on the behavior of the investigated object. In some cases, however, the use of geodetic techniques alone may be uneconomical and may have inadequate accuracy, particularly in case of concrete dams and utility structures.

There are many geotechnical instruments equipped with electro-mechanical transducers which may be easily adapted for continuous monitoring and telemetric data acquisition. Usually, geotechnical instruments are embedded in the investigated object for the duration of the monitoring project. These instruments supply only very localized information on a selected component of the deformation, for example, only local tilt or local extension when using a tiltmeter or an extensometer, respectively. In addition to the sensors of deformations, various sensors of physical quantities must be used, for example, piezometers, load cells, stress cells, seepage gauges and others - these are not discussed in this presentation.

Among the available geodetic and geotechnical/structural technologies, there are very few, if any, sensors that can fully satisfy the monitoring criteria as a stand-alone system. Therefore, in most cases, various techniques must be combined into an *integrated monitoring system*.

3.1 Comments on Geodetic Monitoring Systems

Among geodetic techniques that provide continuous and reliable 3-D results at sub-centimetre accuracy are the Global Positioning System (GPS) and robotic total stations (RTS) equipped with the automatic target recognition. Other geodetic techniques which may satisfy the criteria of the sub-centimetre accuracy, includes laser scanners and radar interferometry including the satellite borne synthetic aperture radar (InSAR) and ground based radar interferometry either with real or synthetic aperture radar (GB-InSAR) systems. They have, however, some limitations in using them as stand alone systems. For example, InSAR and GB-InSAR, provide only 1-D information on displacement components along the line of sight. Alba et al. (2008) describe results of deformation monitoring of a concrete dam using the ground based radar interferometry with the Italian built IBIS-L model(http://www.idscompany.it). The experiment was conducted only over a 37 hour period without any consideration to connecting the measurements to reference stable points and re-orientation of the instrument, which are a must in long term monitoring surveys. Both laser scanners and radar interferometry instruments are strongly affected by changeable atmospheric conditions and must be supplemented, for example, by GPS and/or RTS to provide check on the stability of the survey stations and provide re-orientation parameters in case of repeated set-ups of the instruments over a long period of time (Alba, 2006; Schneider, 2006).

Table 2 summarizes advantages and disadvantages of various geodetic methods.

3.2 Comments on the Use of Robotic Total Stations (RTS)

Robotic total stations supplemented by GPS are still the most recommended geodetic techniques to be used in monitoring large embankment dams and steep slopes. There are a few available software packages supporting use of RTSs to provide for a fully automated data gathering, processing, alarming, and graphical display of displacements. DIMONS and ALERT (enhanced version of DIMONS) software packages, developed at the Canadian Centre for Geodetic Engineering (Lutes et al. 2001; Chrzanowski and Szostak-Chrzanowski, 2010), include the aforementioned identification of unstable points and automatic removal of their effects.

Table 2: Advantages and disadvantages of selected geodetic techniques

Technology	**Advantages**	**Disadvantages**
Robotic Total Stations (RTS)	- 3D reliable information - cost effective - sub-cm accuracy for distances < 1 km - available in a fully automated mode	- spatial resolution limited to the number of targets used - affected by atmospheric refraction
Global Navigation Satellite Systems (GPS, Glonass, etc.)	- 3D reliable information - line of sight not required between stations - accuracy of a few mm for short baselines (a few km) - available in a fully automated mode	- expensive when a large number of points must be monitored - spatial resolution limited to the number of targets used - environment dictates achievable accuracy - requires open visibility to the sky
Satellite-borne radar interferometry (InSAR)	- continuous spatial resolution - sub-centimetre accuracy	- displacement detection limited to the line-of-sight direction - not presently available in fully automated mode - sensitive to changes of atmospheric humidity and surface moisture, which may cause temporal de-correlation of radar images
Ground based Radar Interferometry	- continuous spatial and temporal resolution - sub-mm repeatability over short time interval - semi-automated mode	- displacement detection limited to the line-of-sight direction - actual accuracy requires more research - not suitable as a stand-alone system in long term monitoring
Laser Scanners	- continuous spatial resolution (clouds of points) - sub-centimetre accuracy over short (<200 m) distances - 3D information	- not suitable as a stand alone system in long term monitoring - not fully automated mode - achievable accuracy depends upon surface reflectivity
Leveling	- Sub-millimetre accuracy, reliable	- only vertical component - only manual operation

Typically, the RTS/ALERT system is applied in a stationary mode with continuous data gathering and processing over prolonged periods of time. In these cases, the robotic total stations are placed in protective shelters with glass observation windows (Figure1). In cases, where continuous monitoring is not required, the RTS/ALERT can be used in a portable mode. During the first epoch of monitoring observations the data are automatically stored in the database. Upon revisiting the same monitoring site, the RTS must be pointed manually only to one of the reference prisms and the rest of the measurements are done automatically using the approximate orientation to each target retrieved from the database. After completing the preselected number of observation sets, ALERT processes the data, compares it with the data of any preselected former epoch, and displays, in almost-real time, displacements of individual or groups of points. This way, the evaluation of the deformation is done in the field immediately after completing the observations.

Currently, the DIMONS and ALERT software packages are being interfaced with the aforementioned GeoLab network adjustment and analysis software package to facilitate the fully automated processing of data from multi-RTS monitoring networks.

So far, a number of stationary and portable RTS/ALERT have been deployed world-wide in monitoring large dams, dikes, and steep slopes. Among the largest projects one should mention the Diamond Valley Lake (DVL) project in California where the RTS/ALERT system consisting of 8 Leica TCA1800 RTSs and 9 active GPS stations (Fig.2) continuously monitor about 300 prisms on three large earthen dams since October 2000 (Duffy et al., 2001). The accuracy of the geodetic measurements was designed to detect displacements larger than 10 mm at 95% confidence level.

The monitoring system has continuously worked since October 2000 without any major problems providing verification of the design parameters at the construction stage (Szostak-Chrzanowski et al. 2001), during filling of the reservoir (Szostak-Chrzanowski, 2002 as well as during the post-construction operation (Szostak-Chrzanowski et al., 2008) over the last eleven years.

Figure 1: Typical RTS shelter at the Diamond Valley Lake project in California.

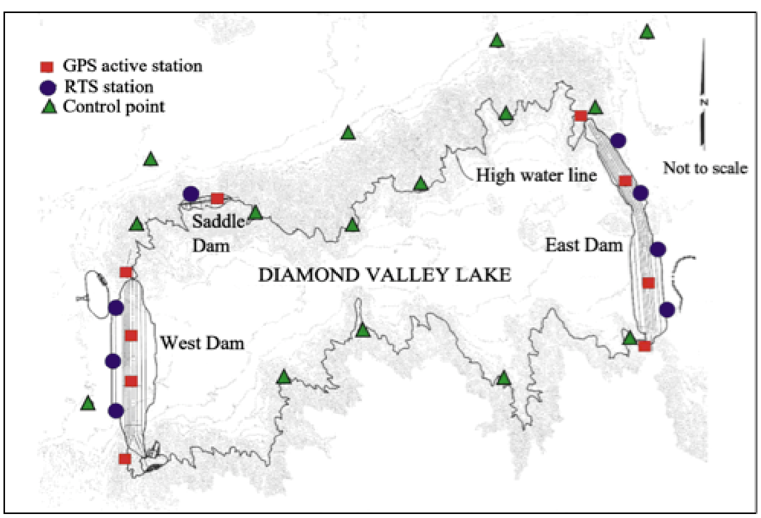


Figure 2: RTS/GPS monitoring system at the DVL project

3.3 Effects of Atmospheric Refraction

The major weakness of all geodetic methods is their vulnerability to the effects of atmospheric refraction and delay of electromagnetic signal (e.g. tropospheric delay in GPS measurements).
The pointing error, *e*, caused by refraction is a function of the gradient of temperature dT/dL occurring across the line of sight. It can be derived from the basic theory of refraction that the approximate relationship between *e* and temperature gradient can be expressed as in equation (1):

$$e = (3.9Ps^2 10^{-5}/T^2)\ dT/dL \qquad (1)$$

Where:

s	distance to the target in [m]
P	barometric pressure in [mb]
T	absolute temperature [^{o}K]
dT/dL	temperature gradient [^{o}C/m] perpendicular to the line of sight

For example, in atmospheric conditions of 1013 mb of barometric pressure and temperature of 20^{o}C, over a 500 m sight length, a uniform change in the temperature gradient across the line of sight from night-time to daytime of only 0.2^{o}C/m would cause more than a 2 cm change in the determined position of the target. In many cases, the effects of refraction may reach much larger values. Figure 3 shows a comparison of vertical displacements of a target at West Dam of the Diamond Valley Lake project in California (Duffy et al. 2002) between the night-time (4 am) and at noon using a robotic total station. The distance to the target was 340 m and the line of site was about 1.5 m above the ground, along the face of the dam. The observations at 4 am show a systematic shift of about 40 mm in comparison with the observations at noon. The effects of refraction can be significantly minimized or even completely removed by daily averaging of the continuous monitoring results. In case of the DVL project, several cycles of observations are taken daily over evenly distributed time intervals and weakly averages are used in the deformation analysis. The accuracy (standard deviations) of the averaged displacements are smaller than 5 mm.

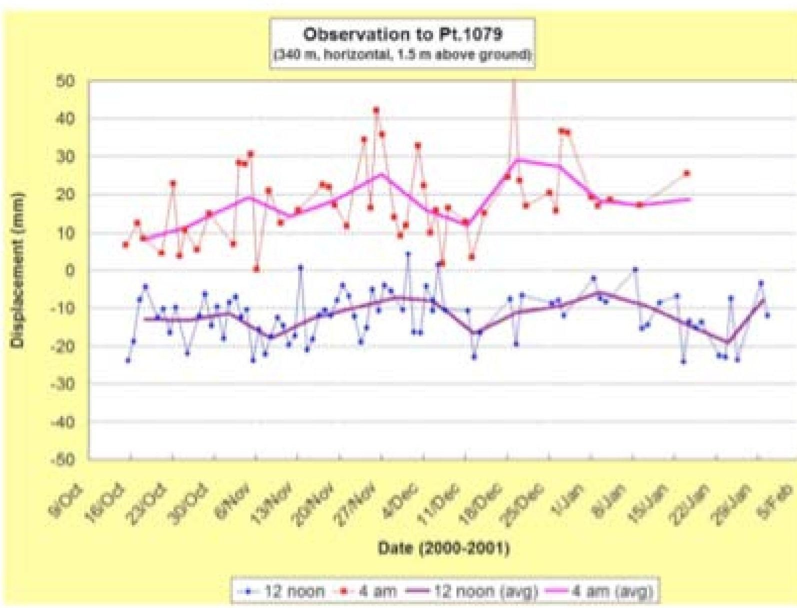


Figure 3: Comparison of effects of refraction at 4 am and at noon

Because the effect of refraction on direction measurements increases proportionally to the square of the distance, it follows that the location of the observing instruments should be as close as possible to the targets being monitored and the lines of sight should be as high as possible above the ground surface and as far as possible from surfaces with heat radiation, e.g., walls exposed to the sun radiation. This should be considered at the stage of designing the locations of instruments and the targets.

Changes in atmospheric conditions also affect electro-optical distance measurements but the effect is much smaller than in the case of direction observations. For example, a 1^{o}C change in air temperature along the line of sight causes approximately only a 10^{-6}S change in the distance S. This can be further reduced by introducing corrections to the observed distances using meteorological observations. Thus, the radial components of displacements, observed with geodetic distance measuring techniques, are generally of a higher accuracy than the transverse components obtained from direction measurements.

3.4 Comments on the Use of Geotechnical Instruments

Concerning geotechnical sensors, there are many instruments (extensometers, strain meters, tiltmeters) of high precision that can provide useful information on ground surface deformations. Recent developments are based on nanotechnology and micro electro-mechanical sensors (MEMS), which permit the miniaturization of sensors and reduction of their cost. Table 3 summarizes the achievable accuracies of some basic geotechnical sensors.

Table 3: Geotechnical Sensors

Type of Sensor	**Achievable accuracy**	**Comments**
Extensometers (rods, wires, tapes)	0.05mm / 10m	Rod extensometers are among the most reliable instruments
Strainmeters (vibrating wire, fibre-optics)	10^{-5}	Long fibre optics strainmeters require good experience in their installation
Torpedo-type borehole inclinometers (uni-axial or bi-axial)	3mm/ 10m	Very useful information in slope stability studies, particularly when combined with GPS or RTS. Manual operation.
MEMS strings of tiltmeters in boreholes or in conduits	1 mm/10m	Require more research on their long-term reliability.
Tiltmeters	0.2" (0.06 mgon)	Due to the very small base, the observed structural tilts may be biased by very local instabilities. Should be complemented by leveling tilt measurements.
Plumb-lines (suspended or inverted)	0.05mm / 10 m	Both are strongly recommended. However, inverted plumblines require a good experience in their installation

Among the geotechnical instruments, rod extensometers (in boreholes or in conduits along the structural elements) with electro-mechanical transducers, suspended plumblines, and various mechanical and electro-mechanical joint-meters are the most reliable and robust instruments. Tiltmeters, vibrating wire and fibre-optic strainmeters, and inverted plumblines require very careful installation, thorough calibration, and good experience in their use. Among the least reliable instruments are wire and tape extensometers.

All geotechnical instruments require thorough calibration for the effects of environmental temperature, drift of the readout, and conversion constant of the readout. Once embedded within the structure, however, the geotechnical/structural instruments cannot be rechecked or re-calibrated. Because of this, it is not uncommon that geotechnical instruments provide unreliable data or even fail during the life of the structure. Since geodetic measurements allow for redundancy and the possibility of statistical evaluation of the quality of the data, they generally provide more reliable results. Geodetic and geotechnical measurements complement each other and, ideally, should be used together creating an *integrated monitoring scheme.*

4 DESIGN AND INTEGRATED ANALYSIS OF DAM DEFORMATIONS

Integrated analysis of deformations of any type of a deformable body combines geometrical analysis of monitoring surveys and physical interpretation. Geometrical analysis describes the change in shape and dimensions of the monitored object, as well as its rigid body movements (Chrzanowski et al., 1990). The ultimate goal of the geometrical analysis is to determine the displacement and strain fields in the deformable object in space and time domains (Chen, 1983; Chrzanowski et al., 1986). Physical interpretation establishes the relationship between the causative factors (loads) and the deformations (Chen and Chrzanowski, 1986). This can be determined either by a statistical method, which analyses the correlation between the observed deformations and loads, or a deterministic method, which utilizes information on the loads, properties of the material, and physical laws governing the stress-strain relationship according to the principles of continuum mechanics. Fig.4 shows schematically the concept of the integrated analysis.

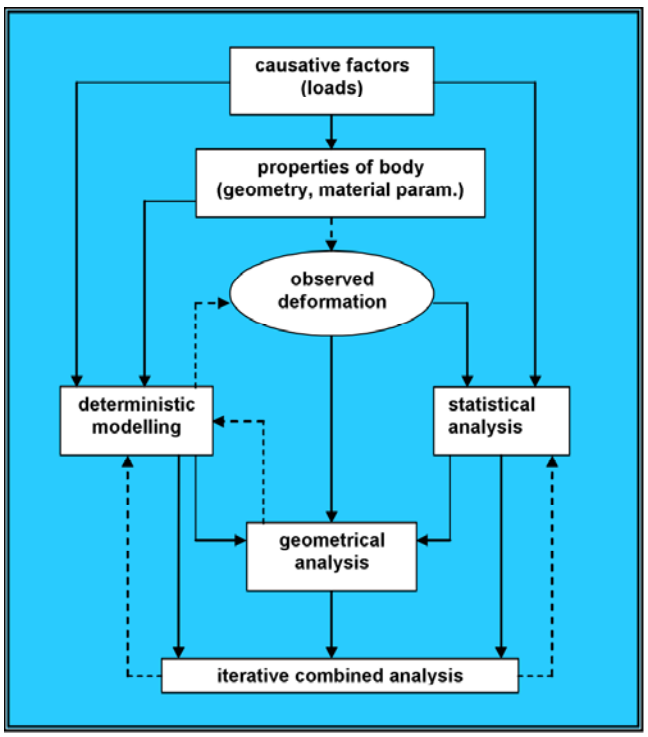


Figure 4: Concept of integrated analysis of deformations

Generally, any deformation study consists of the following steps:
Step 1: Deterministic (*a-priori)* modeling of the expected deformation;
Step 2: Design of the monitoring scheme;
Step 3: Installation of the monitoring scheme and data collection;
Step 4: Geometrical analysis of monitoring measurements;
Step 5: Integrated analysis and physical interpretation.

If no agreement is reached between the deterministic (Step 1) and geometrical (Step 4) models of the deformation, the above five steps may have to be repeated using either an updated deterministic model or updated monitoring scheme. The interaction between the individual five steps of the deformation study is shown in Fig.5 as a basis of a concept of Integrated System for monitoring and analysis of deformations.

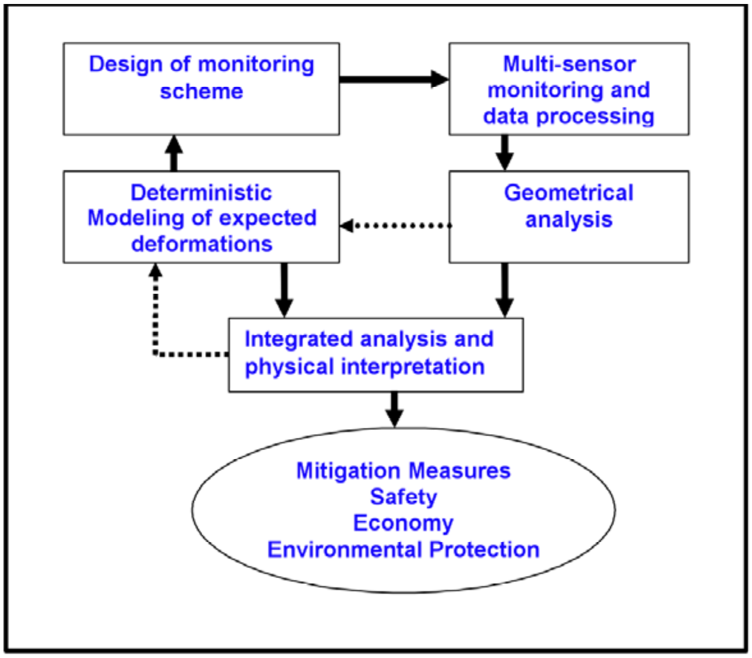


Figure 5: Interaction between components of the Integrated System of deformation monitoring and analysis

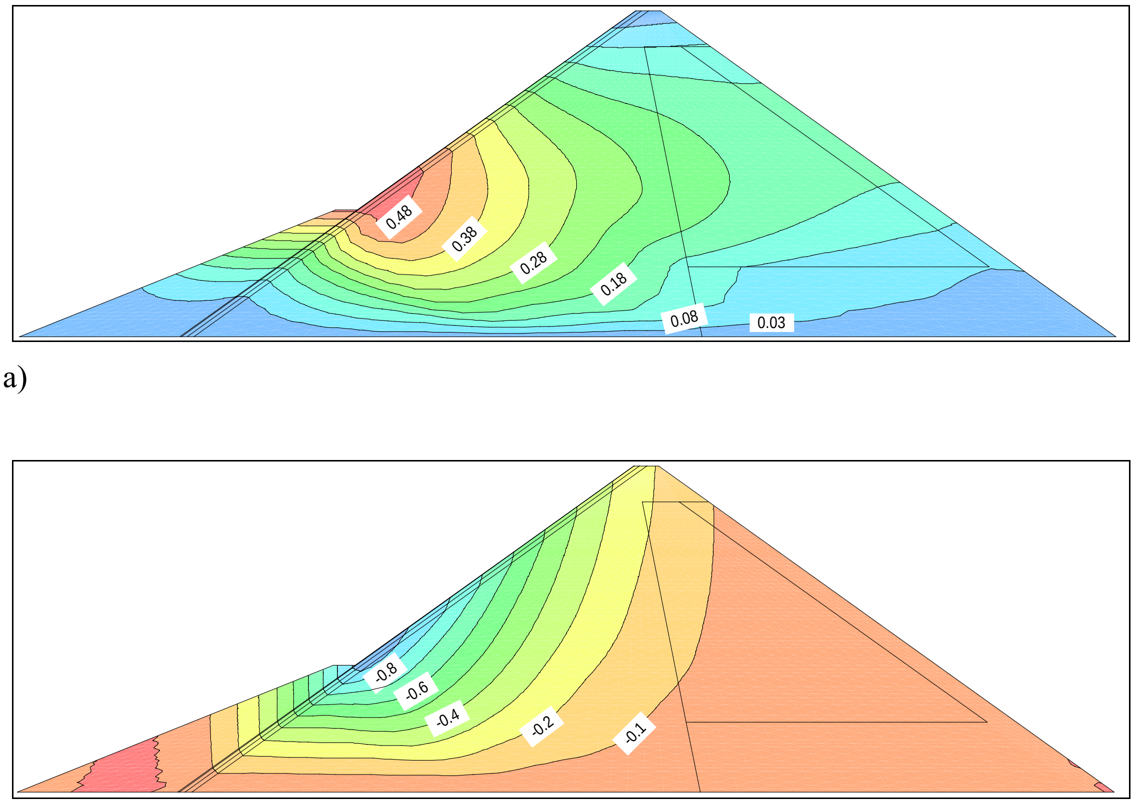
4.1 Use of Deterministic Modeling in the Design and Analysis of Monitoring Schemes

Deterministic modeling of deformations is a core of the Integrated System. The deterministic method establishes relation between the causative factors (loads) and the deformation based on equations of equilibrium, kinematic relation between strain and displacement, and using relation between strain and stress through constitutive matrix. The ultimate goal of the deterministic modeling of deformations is to develop a prediction model for the given type of the investigated object, given properties of the material, and assumed mathematical model of stress-strain relation. Once the prediction model is developed, it may be used in designing the monitoring scheme. On the other hand, using the back analysis, the results of the properly designed monitoring observations may be used to enhance the deterministic model (e.g. by correcting the material parameters of the observed object). In addition, by combining results of properly designed monitoring surveys with the results of deterministic model one may determine the actual deformation mechanism (Chrzanowski and Szostak-Chrzanowski, 1993; Chrzanowski and Szostak-Chrzanowski, 1995) and explain the causes of deformation in case of an abnormal behavior of the investigated object.

As an example, the deterministic modeling of expected deformations has been applied at Shuibuya Concrete Face Rockfill Dam (CFRD) in China using the finite element method (Szostak-Chrzanowski et al., 2008). Shuibuya CFRD is presently the highest of its kind in the world. It is 233 m high and 608 m long, and is resting on bedrock. Fig. 5 shows expected horizontal and vertical displacements during the filling of the reservoir.

As one can see from the modelled displacements, the largest displacements are expected to occur at the upstream face of the dam, which is covered by a concrete slab. It is the most crucial area for monitoring the deformation at CFRDs. Since the upstream face is under water, the monitoring scheme should utilize geotechnical instruments such as fibre-optic strainmeters, built-in rod extensometers and arrays of micro-machined tilt sensors based on

MEMS technology (Danish et al., 2008) embedded in the concrete slab. The rest of the dam could be monitored by geodetic methods using, for example, robotic total stations and GPS. Final details of the design including the density of the instrumentation, accuracy requirements and frequency of observations require additional information. For example, by modelling the expected deformation at various water levels in the reservoir, one can obtain information on the velocity of deformations. This would aid in determining the required frequency of repeat surveys.



b)

Figure 6: Predicted displacements [metres] after filling the reservoir (215m water level) at Shuibuya CFRD

a) horizontal displacements, b) vertical displacements

4.2 Geometrical Analysis of Multi-sensor Monitoring Results

The goal of the geometrical analysis is to determine the displacement and strain fields in the space and time domains for the whole deformable object from observed deformations at discrete points. A generalized method of geometrical analysis was developed in early 1980s (Chen 1983; Chrzanowski et al. 1983) in Canada. It permits to use any type of deformation observations (geodetic and geotechnical) in a simultaneous analysis.

The generalized method of the geometrical analysis accepts from the principles of continuum mechanics that the deformation of an investigated object (change in shape and dimensions) is fully described if 6 strain components (3 normal strains and 3 shearing strains) of the strain tensor and 3 differential rotations at every point of the body are determined. These deformation parameters can be calculated from strain-displacement relations if a displacement function representing the deformation of the object is known. Since, in general, deformation surveys are performed at discrete points, the displacement function must be approximated through some selected deformation model which fits the observed displacements, or any other types of observables, in the statistically best way. For example, the displacement function $d(x,y,z,t) = [u(x,y,z,t), v(x,y,z,t), w(x,y,z,t)]^T$ with u, v, and w being components of the displacement in x-, y-, and z-directions, respectively, may be determined through a polynomial (or other functions) approximation of the displacement field. The displacement function can be written in matrix form as:

$$\mathbf{d}(x, y, z, t) = \mathbf{B}(x, y, z, t)\,\mathbf{c} \;, \qquad (2)$$

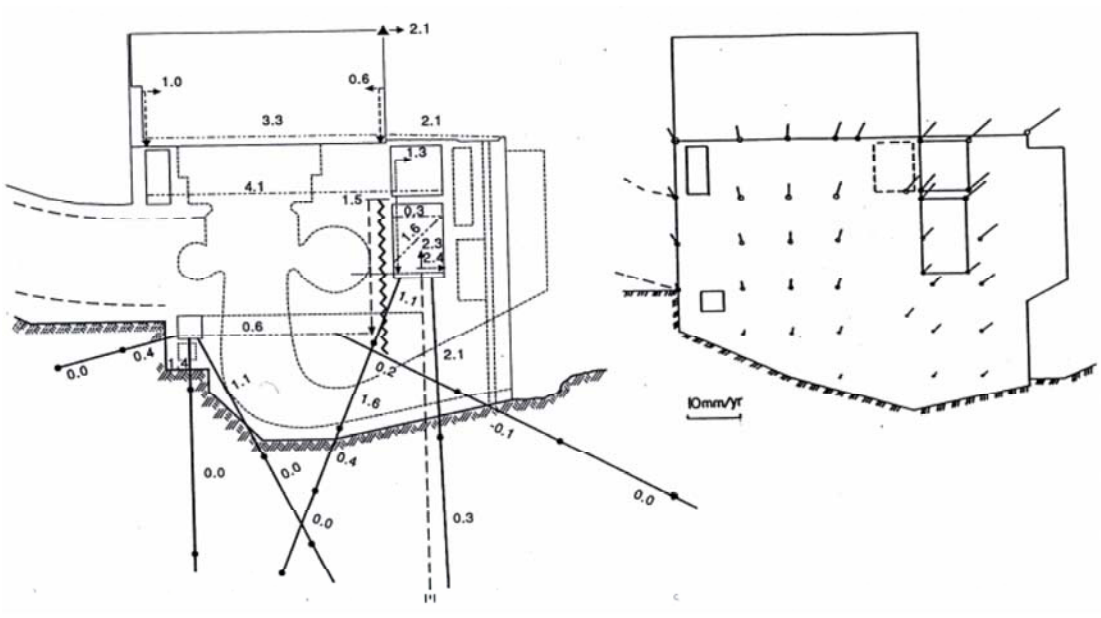
where **B**(x, y, z, t) is the deformation matrix with its elements being some selected base functions, and **c** is the vector of unknown coefficients. A vector **Δl** of changes in any type of deformation observations, for instance, changes in tilts, in distances, or in strain, can always be expressed in terms of the displacement function (Chen 1983). In matrix form, the relationship is written as:

$$\Delta\mathbf{l} = \mathbf{A}\mathbf{B}\Delta l\ \mathbf{c} \qquad (3)$$

where **A** is the transformation matrix relating the observations to the displacements of points at which the observations are made, and **B**Δl is constructed from the above matrix **B**(x, y, z, t) and is related to the points included in the observables. If redundant observations are made, the elements of the vector ***c*** and their variances and covariances are determined through the least-squares approximation, and their statistical significance can be calculated. One tries to find the simplest possible displacement function that would fit to the observations in the statistically best way.

The generalized geometrical analysis has been successfully implemented in a number of deformation projects including, among others, monitoring of the Mactaquac hydro-electric power station near Fredericton, N.B., Canada. The station, constructed in 1960s, started showing significant deformations and fracturing of concrete structures in the mid-70s. Geodetic techniques and dozens of various geotechnical instruments (borehole extensometers, plumb-lines, tape extensometers and jointmeters) have been used to explain the mechanism and cause of deformations.

Figure 7a shows a sample of observed rates (mm/y) of absolute and relative displacements in a cross-section of the power house structure (Chrzanowski and Secord, 1990).



(a) (b)

Figure 7: Application of the generalized method of geometrical analysis (after Chrzanowski 1993) at the Mactaquac hydro-electric power station: a) observed rates of deformations (mm/y), b) derived displacement field.

A full explanation of the causes of deformation came only after applying the generalized method of geometrical analysis. Several different functions (full or partial polynomials) were attempted in fitting the observation data, including relative rotations and translations between the structural blocks and different deformations in each block. After eliminating all the statistically insignificant coefficients of the selected displacement functions, the final displacement field (Figure 7b) appeared to be quite simple with the whole cross-section of the power house undergoing the deformation described by the horizontal (dx) and vertical (dy) displacement functions (rates per year):

$$u(x,y) = dx = a_1x + a_3xy + a_4x^2$$

$$w(x,y) = dy = b_2y \qquad (4)$$

in which the values of the a_i and b_i coefficients and their accuracies were determined through the least squares fitting to the observed deformations.

The derived displacement field indicated a volumetric expansion of the whole structure. This finding confirmed the postulated earlier hypothesis about swelling of concrete due to the alkali-aggregate reactivity.

5 CONCLUSIONS

In order to take the full advantage of the new developments in monitoring techniques, one has to have a good understanding of the advantages and limitations of the new monitoring techniques, sources of errors, and monitoring requirements.

Deterministic modeling of expected deformations at all stages of the dam construction and during filling the reservoir should be used as a tool in designing deformation monitoring schemes. By combining results of deterministic model with the results of geometrical analysis of monitoring measurements, one may perform the physical interpretation and explain causes of deformation.

Recently developed concepts of integrated monitoring and analysis of deformations help in the design, analysis, and physical interpretation of dam deformations.

More research is needed on the optimal integration of various monitoring techniques and on the optimal fusion of software packages such as, e.g., DIMONS and GEOLAB for fully automated collection and processing of the monitoring data.

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