# Chapter 11
# Analysis and Assessment of Results

## 11-1. General

This chapter provides guidance on the interpretation of results from periodic monitoring surveys of hydraulic structures.

*a*. *Concept of the integrated analysis.* Even the most precise monitoring surveys will not fully serve their purpose if they are not properly evaluated and utilized in a global integrated analysis. The analysis of deformation surveys includes:

- *Geometrical Analysis:* describes the geometrical status of the deformable body, its change in shape and dimensions, as well as rigid body movements (translations and rotations) of the whole deformable body with respect to a stable reference frame, or of a block of the body with respect to other blocks, and

- *Physical Interpretation:* which consists of:

  Stochastic Interpretation: a statistical (stochastic) method that analyzes (through a regression analysis) the correlations between observed deformations and observed loads (external and internal causes producing the deformation),

  Deterministic Interpretation: a method utilizing information on the loads, properties of the materials, and physical laws governing the stress-strain relationship; which describes the state of internal stresses and the relationship between the causative effects (loads) and deformations.

Once the load-deformation relationship is established, the results of the physical interpretation may be used for the development of prediction models. Through a comparison of predicted deformation with the results of the geometrical analysis of the actual deformations, a better understanding of the mechanism of the deformations is achieved. On the other hand, the prediction models supply information on the expected deformation, facilitating the design of the monitoring scheme as well as the selection of the deformation model in the geometrical analysis. Thus, the expression "integrated analysis" means a determination of the deformation by combining all types of measurements, geodetic and geotechnical, even if scattered in time and space, in the simultaneous geometrical analysis of the deformation, comparing it with the prediction models, enhancing the prediction models; which in turn, may be used in enhancing the monitoring scheme. The process is iteratively repeated until the mechanism of deformation is well understood and any discrepancies between the prediction models and actual deformations are properly explained.

*b*. *Deformation modeling.* Recently, the concept of integration has been developed in which all three--the geometrical analysis of deformation and both methods of the physical interpretation--are combined into a simultaneous solution for all the parameters to be sought. Implementation of the method still requires further development. The deterministic and statistical modeling of deformations have been used in the analysis of dam deformations, at least in some countries, for many years. As aforementioned, the geometrical analysis has been done so far in a rather primitive way, with geotechnical/structural engineers analyzing separately the geotechnical observation data and surveyors taking care of the geodetic survey observations. The geotechnical analyses have usually resulted only in a graphical display of temporal trends for individual observables and the geodetic analysis would result in a plot of displacements obtained from repeated surveys that may not even be properly adjusted and analyzed for the stability of the reference points. Over the past ten years, an intensive study by the FIG working group has resulted in the development of proper methods for the analysis of geodetic surveys and has led to the development of the so-called "UNB Generalized Method" of the geometrical deformation analysis, which can combine any type of observations (geotechnical and geodetic) into one simultaneous analysis.

## 11-2. Geometrical Analysis

*a. Identification of unstable reference points*. In most deformation studies, the information on absolute movements of object points with respect to some stable reference points is crucial. One problem that is frequently encountered in practice in the reference networks is the instability of the reference points. This may be caused either by wrong monumentation of the survey markers or by the points being located too close to the deformation zone (wrong assumption in the design about the stability of the surrounding area). Any unstable reference points must be identified first, and before absolute displacements of the object points are calculated. Otherwise, the calculated displacements of the object points and subsequent analysis and interpretation of the deformation of the structure may be significantly distorted. Given a situation where points A, B, C, and D are reference points used to monitor a number of object points on a structure; if point B has moved (but this is not recognized) and it is used with point A to identify the common datum for two survey campaigns, then all the object points and reference points C and D will show significant changes in their coordinates even when, in reality, all but point B are truly stable.

*b. Iterative Weighted Similarity Transformation (IWST).* A method to detect unstable reference points has been developed which is based on a special similarity transformation that minimizes the first norm (absolute value) of the observed vector of displacements of the reference points. The IWST approach to stability monitoring can be performed easily for one-dimensional reference networks and by an iterative weighting scheme for multi-dimensional reference networks until all the components of the displacement vectors ($d_i$) satisfy the condition:

$$\sum \| d_i \| = \text{minimum} \qquad \text{(Eq 11-1)}$$

In each iterative solution, the weights ($p_i$) of each displacement are changed to be:

$$p_i = 1 / d_i$$

After the last iteration (convergence), any transformed displacement vectors that exceed their transformed point error ellipses (at 95% probability) are identified as unstable reference points. The displacements obtained from the transformation are, practically, datum independent, i.e., that whatever minimum constraints have been used in the least squares adjustment of the survey campaigns, the display of the transformed displacements will always be the same. Thus, the obtained results represents the actual deformation trend which is used later on in selecting the best fitting deformation model.

*c. Stable point analysis.* Quality control for reference networks requires analysis of the stability of each reference station, for example by the Iterative Weighted Similarity Transformation (IWST).

(1) Data processing setup. Software routines must be coded for automated data processing. The input data for IWST processing consists of the adjusted station coordinates for the reference network (for both the current and previous monitoring survey), and each associated covariance matrix of parameters. Both data sets are available from network adjustment post-processing results. Test statistic critical values,

degrees of freedom, and the pooled adjustment variance factor are also required for post-processed statistical assessment.

(2) IWST processing algorithm. The following matrix equation is solved iteratively until the solution converges on a fixed transformation value (e.g., to less than 0.01 mm).

$$(d)' = [\mathbf{I\text{-}H(H^T W\, H)^{-1} H^T W}](d) = [\mathbf{S}](d) \tag{Eq 11-2}$$

where

d' = transformed displacement vector
d = initial displacement vector
**I** = Identity matrix
**H** = datum defect matrix
**W** = weight matrix

The identity matrix is a matrix with ones along the diagonal and zeroes elsewhere. The datum defect matrix (**H**) is designed for the particular type of survey datum used. For example, for GPS surveys it has a block diagonal structure with a 3 by 3 identity matrix in each block representing the union of datum defects from each survey (i.e., 3D translations only). The weight matrix (**W**) is a diagonal matrix with the entries equal to the inverse of each coordinate component displacement. The displacement vector contains the displacements between the two surveys for each point. The dimensions of each matrix must be compatible with $n$ as the number of stations, for example if (d) is $3n \times 1$, then **H**, **W**, and **I** are $3n \times 3n$. The transformation covariance matrix is initially the sum of each adjustment covariance matrix, where the covariance matrix (**Q**) is also modified at each iteration by:

$$\mathbf{Q' = S\, Q\, S^T} \tag{Eq 11-3}$$

with **S** defined above.

*d*. *Geometrical deformation analysis*. In order to be able to use any type of geodetic and geotechnical observations in a simultaneous deformation analysis, the UNB Generalized Method of the geometrical analysis has been developed. The method is applicable to any type of geometrical analysis, both in space and in time, including the detection of unstable reference points and the determination of strain components and relative rigid body motion within a deformable body. It permits using different types of surveying data (conventional, GPS, and geotechnical/structural measurements. It can be applied to any configuration of the monitoring scheme as long as approximate coordinates of all the observation points are known with sufficient accuracy. The approach consists of three basic processes:

- identification of deformation models;
- estimation of deformation parameters;
- diagnostic checking of the models and final selection of the "best" model.

A brief description of the approach is given below.

(1) Deformation parameters. The change in shape and dimensions of a 3D deformable body is fully described if 6 strain components (3 normal and 3 shearing strains) and 3 differential rotations at every point of the body are determined. These deformation parameters can be calculated from the well-known strain-displacement relations if a displacement function representing the deformation of the object is known. Since, deformation surveys involve only discrete points, the displacement function must be approximated through some selected deformation model which fits the observed changes in

coordinates (displacements), or any other types of observables, in the statistically best way. The displacement function may be determined, for example, through a polynomial approximation of the displacement field.

(2) Displacement function. A displacement function can be expressed in matrix form in terms of a deformation model **B c** as:

$$\mathbf{d}\,(x,y,z,t-t_o) = (u,v,w)^T = \mathbf{B}\,(x,y,z,t-t_o)\;\mathbf{c} \qquad \text{(Eq 11-4)}$$

where

**d** = displacement of a point (x,y,z) at time t (with respect to a reference time $t_o$ )
u, v, w = components of the displacement function in the x,y,z directions, respectively,
**B** = deformation matrix with its elements being some selected base functions,
**c** = vector of unknown coefficients (deformation parameters).

(3) Deformation models. Examples of typical deformation models (displacement functions) for a two-dimensional analysis are given below.

*(a)* Single point displacement or a rigid body displacement of a group of points, say, block B with respect to block A. The deformation model is expressed by the following displacement functions:

$$u_A = 0, \qquad v_A = 0$$

$$u_B = a_o, \qquad v_B = b_o$$

where the subscripts represent all the points in the indicated blocks, and $a_o$ and $b_o$ are constants.

*(b)* Homogeneous strain in the whole body and differential rotation. The deformation model is linear and it may be expressed directly in terms of the strain components ($\epsilon_x$, $\epsilon_y$, $\epsilon_{xy}$ ) and differential rotation, $\omega$, as:

$$u = \epsilon_x\, x + \epsilon_{xy}\, y - \omega y$$

$$v = \epsilon_{xy}\, x + \epsilon_y\, y + \omega x \qquad \text{(Eq 11-5)}$$

*(c)* A deformable body with one discontinuity, say, between blocks A and B, and with different linear deformations in each block plus a rigid body displacement of B with respect to A. Then the deformation model is written as:

$$u_A = \epsilon_{xA}\, x + \epsilon_{xyA}\, y - \omega_A\, y$$

$$v_A = \epsilon_{xyA}\, x + \epsilon_{yA}\, y + \omega_A\, x \qquad \text{(Eq 11-6)}$$

and

$$u_B = a_0 + \epsilon_{x\,B}\,(x - x_0) + \epsilon_{xy\,B}\,(y - y_0) - \omega_B\,(y - y_0)$$

$$v_B = b_0 + \epsilon_{xy\,B}\,(x - x_0) + \epsilon_{y\,B}\,(y - y_0) + \omega_B\,(x - x_0) \qquad \text{(Eq 11-7)}$$

where $x_0$, $y_0$ are the coordinates of any point in block B.

(4) Combined models. Usually, the actual deformation model is a combination of the above simple models or, if more complicated, it is expressed by non-linear displacement functions which require fitting of higher-order polynomials or other suitable functions. If time dependent deformation parameters are sought, then the above deformation models will contain time variables.

(5) Displacement function. A vector $\boldsymbol{\delta l}$ of changes in any type of observations, for instance, changes in tilts, in distances, or in observed strain, can always be expressed in terms of the displacement function. For example, the relationship between a displacement function and a change *ds* in the distance observed between two points i and j in two monitoring campaigns may be written as:

$$ds_{ij} = [(x_j - x_i) / s]\, u_j + [(y_j - y_i) / s)]\, v_j - [(x_j - x_i / s)]\, u_i - [(y_j - y_i) / s)]\, v_i \qquad \text{(Eq 11-8)}$$

where

$u_j$ $v_j$
$u_i$ $v_i$

are components of the displacement function at points:

$x_j$ $y_j$
$x_i$ $y_i$

respectively. For example, with a horizontal tiltmeter, the change $d\tau$ of tilt between two survey campaigns may be expressed in terms of the vertical component (w) of the displacement function as:

$$d\tau = (\partial w/\partial x) \sin\alpha + (\partial w/\partial y) \cos\alpha \qquad \text{(Eq 11-9)}$$

where

$\alpha$ = the orientation angle of the tiltmeter.

The functional relationships for any other types of observables and displacement functions are written in matrix form as:

$$\boldsymbol{\delta l} = \mathbf{A}\, \mathbf{B}_{\boldsymbol{\delta l}}\, \mathbf{c} \qquad \text{(Eq 11-10)}$$

where **A** is the transformation matrix (design matrix) relating the observations to the displacements of points at which the observations are made, and $\mathbf{B}_{\boldsymbol{\delta l}}$ is constructed from the above matrix **B** $(x, y, z, t\text{-}t_o)$ and related to the points included in the observables.

(6) Best-fit deformation models. For redundant observations, the elements of the vector **c** and their variances and covariances are determined through 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 search for the 'best' deformation model (displacement function) is based on either *a priori* knowledge of the expected deformations (for instance from the finite element analysis) or a qualitative analysis of the deformation trend deduced from all the observations taken together. In the case of the observables being the relative displacements obtained from geodetic surveys, the iterative weighted transformation of the displacements gives the best picture of the actual deformation trend helping in the spatial trend analysis. In the case of a series of observations taken

over a prolonged period of time, plotting of individual observables versus time helps to establish the deformation trend and the deformation model in the time domain. In the analysis, one has to separate the known deformation trend from the superimposed investigated deformation. For example, in order to distinguish between the cyclic (seasonal) thermal expansion of a structure with a one-year period of oscillation and a superimposed deformation caused by other effects which are, for instance, linear in time, all the measurements can be analyzed through a least-squares fitting of the cyclic function

$$y = a_1 \cos(\omega t) + a_2 \sin(\omega t) + a_3 t + a_4 + a_5 \delta(t_i) + \ldots, \qquad \text{(Eq 11-11)}$$

to the observation data, where $\omega = 2\pi/\mathrm{yr}$, and ($a_3$) is the rate of change of the observation (extension, tilt, inclination, etc.). The amplitude and phase of the sinusoid can be derived from ($a_1$) and ($a_2$). The constant ($a_4$) is the y-intercept and the constants ($a_5$, ...) are possible slips (discontinuities) in the data series where $\delta(t_i)$ is the Kronecker's symbol which is equal to 1 when $t > t_i$, with $t_i$ being the time of the occurrence of the slip, and is equal to 0 when $t < t_i$.

(7) Deformation modeling procedures. Geometrical deformation analysis using the UNB Generalized Method is done in four steps:

*(a)* Trend analysis in space and time domains, and the selection of a few alternative deformation models, seem to match the trend and make physical sense.

*(b)* Least-squares fitting of the model or models into the observation data and statistical testing of the models.

*(c)* Selection of the 'best' model that has as few coefficients as possible with as high a significance as possible (preferably all the coefficients should be significant at probabilities greater than 95%) and which gives as small a quadratic form of the residuals as possible.

*(d)* Graphical presentation of the displacement field and the derived strain field.

The results of the geometrical analysis serve as an input into the physical interpretation and into the development of prediction models as discussed above.

## 11-3. Statistical Modeling

*a*. *General.* The statistical method establishes an empirical model of the load-deformation relationship through regression analysis, which determines the correlations between observed deformations and observed loads (external and internal causes producing the deformation). Using this model, the forecasted deformation can be obtained from the measured causative quantities. A good agreement between the forecasts and the measurements then tell us that the deformable body behaves as in the past. Otherwise, reasons should be found and the model should be refined.

*b*. *Cause-effect model.* Interpretation by the statistical method requires a suitable amount of observations, both of causative quantities and of response effects. Let d (t) be the observed deformation of an object point at time t. For a concrete dam, for example, it can usually be decomposed into three components:

$$d(t) = d_H(t) + d_T(t) + d_r(t) \qquad \text{(Eq 11-12)}$$

where $d_H(t)$, $d_T(t)$, $d_r(t)$ are the hydrostatic pressure component, thermal component, and the irreversible component due to the non-elastic behavior of the dam, respectively. The component $d_H(t)$ is a function of water level in the reservoir, and can be modeled by a simple polynomial:

$$d_H(t) = a_0 + a_1 H(t) + a_2 H(t)^2 + ... + a_m H(t)^m \tag{Eq 11-13}$$

where H (t) is the elevation of the water in the reservoir. The component $d_T(t)$ can be modeled in various ways depending on the information on hand. If some key temperatures $T_i(t)$, for i = 1, 2, ..., k, in the dam are measured, then:

$$d_T(t) = b_1 T_1(t) + b_2 T_2(t) + ... + b_k T_k(t) \tag{Eq 11-14}$$

If air temperature is used, the response delay of concrete dams to the change in air temperature should be considered. If no temperature is measured, the thermal component can be modeled by a trigonometric function.

*c. Elastic deformation.* The irreversible component $d_r(t)$ may originate from a non-elastic phenomena like creep of concrete or creep of rock, etc. Its time-dependent behavior changes from object to object. It may be modeled, for example, with an exponential function. The following function is appropriate for concrete dams:

$$d_r(t) = c_1 t + c_2 \ln(t) \tag{Eq 11-15}$$

Coefficients ($a_i$, $b_i$, $c_i$) in the above equations are determined using the least squares regression analysis. The final model suggests the response behavior of the different causative factors and is used for prediction purposes.

*d. Plastic deformation.* For an earth dam, the thermal effect is immaterial and the irreversible component becomes dominant. It should be mentioned that the statistical method for physical interpretation is applicable not only to observed displacements, but also to other monitored quantities, such as stress, pore water pressure, tilt of the foundation, etc. The only difference is that the response function for each causative quantity may change.

## 11-4. Deterministic Modeling

*a. General.* The deterministic method provides information on the expected deformation from information on the acting forces (loads), properties of the materials, and physical laws governing the stress-strain relationship. Deformation of an object will develop if an external force is applied to it. The external forces may be of two kinds: surface force, i.e., forces distributed over the surface of the body, and body forces, which are distributed over the volume of the body, such as gravitational forces and thermal stress. The relation between the acting forces and displacements is discussed in many textbooks on mechanics. Let **d** be the displacement vector at a point and **f** be the acting force. They are related as:

$$\mathbf{L}^T \mathbf{D} \mathbf{L} \mathbf{d} + \mathbf{f} = 0 \tag{Eq 11-16}$$

where **D** is the constitutive matrix of the material whose elements are functions of the material properties (e.g., Young's modulus and Poisson's ratio) and **L** is a differential operator transforming displacement to strain. If initial strain $\epsilon_0$ and initial stress $\sigma_0$ exist, the above equation becomes:

$$\mathbf{L}^T \mathbf{D} \mathbf{L} \mathbf{d} + ( \mathbf{L}^T \sigma_0 - \mathbf{L}^T \mathbf{D} \sigma_0 ) + \mathbf{f} = 0 \qquad \text{(Eq 11-17)}$$

In principle, when the boundary conditions are given, either in the form of displacements or in the form of acting forces, and the body forces are prescribed, the differential equation can be solved. However, direct solution may be difficult, and numerical methods such as the finite element or boundary element of finite differences methods are used. The finite element method (FEM) is the most commonly used method in structural and geotechnical engineering, particularly in modeling dam deformations.

*b. Finite element method.* The basic concept of the FEM is that the continuum of the body is replaced by an assemblage of small elements which are connected together only at the nodal points of the elements. Within each element a displacement function (shape function) is postulated and the principle of minimum potential is applied, i.e., the difference between the work done by acting forces and the deformation energy is minimized. Therefore, the differential operator **L** is approximated by a linear algebraic operator. Numerous FEM software packages are available in the market ranging significantly in prices depending on their sophistication and adaptability to various types of material behavior. Software packages have been developed for 2D and 3D finite element elastic, visco-elastic, and heat transfer analyses of deformations. FEM has found many practical applications in dam deformation analyses, in tectonic plate movements, in ground subsidence studies and in tunneling deformations.

*c. Deterministic modeling.* In the deterministic modeling of dam deformations, the dam and its foundation are subdivided into a finite element mesh. The thermal component (dT) and hydrostatic pressure component (dH) are calculated separately. Assuming some discrete water level in the reservoir, the corresponding displacements of the points of interest are computed. A displacement function with respect to water level is obtained by least squares fitting of a polynomial to the FEM-computed discrete displacements. Then, the displacements at any water level can be computed from the displacement function. In computation of the thermal components, the temperature distribution inside the structure should first be solved. Again, FEM could be used, based on some measured temperatures (boundary conditions). Both the coefficient of thermal diffusivity and the coefficient of expansion of concrete are required. The thermal components for the points of interest are calculated using FEM with computed temperature at each nodal point. The total deformation is the sum of these two components plus possible action of some other forces, e.g., swelling of concrete due to alkali aggregate reaction which can also be modeled. FEM is certainly a powerful tool in the deterministic modeling of deformations. One has to remember, however, that the output from the FEM analysis is only as good as the quality of the input and as good as the experience of the operator who must have a good understanding of not only the computer operation but, particularly, good knowledge in the mechanics of the deformable bodies.

## 11-5. Hybrid Analysis Method

*a. General.* Interpretation by statistical methods requires a large amount of observations, both of causative quantities and of response effects. The method is not suitable at the early stage of dam operation when only short sets of observation data are available. Some portions of the thermal and hydrostatic pressure effects may not be separated by the statistical modeling if the changes in temperature and in the elevation of water in the reservoir are strongly correlated. The deterministic method proves very advantageous in these aspects. The deterministic method is of an *a priori* (design) nature. It uses the information on geometric shape and material properties of the deformable body and acting loads to calculate deformations. Due to many uncertainties in deterministic modeling, e.g., imperfect knowledge of the material properties, possibly wrong modeling of the behavior of the material (non-elastic behavior), and approximation in calculations, the computed displacements may depart significantly from observed values d(t). With the discrepancy produced by uncertainties in Young's modulus of elasticity, E, and the thermal coefficient of expansion ($\alpha$), the deterministic model can be enhanced by combining it with the statistical method, in the form:

$$d(t) + v(t) = x\, d_H(t) + y\, d_T(t) + c_1 t + c_2 \ln(t) \qquad \text{(Eq 11-18)}$$

where v (t) is the residual, $d_H(t)$ and $d_T(t)$ are the hydrostatic and thermal components, respectively, calculated from the deterministic modeling, and the last two terms take care of the possible irreversible component. The functional model for the irreversible component may vary and can be changed by examining the residuals. The unknowns (x, y, $c_1$, and $c_2$) are estimated from the observations using the least squares estimation. The coefficient x is a function of Young's modulus and y is a function of the thermal expansion coefficient of concrete:

$$x = E_0 / E$$
$$y = \alpha / \alpha_0 \qquad \text{(Eq 11-19)}$$

where $E_0$ and $\alpha_0$ are the values used in the deterministic modeling.

*b. Material properties.* There must be a calibration of the constants of the material properties using the discrepancies between the measured displacements of a point at different epochs and that calculated from FEM. One must be aware, however, that if the real discrepancy comes from other effects than the incorrect values of the constants (e.g., non-elastic behavior), the model may be significantly distorted. A concept of a global integration has been developed, where the geometrical analysis of deformations and both methods of physical interpretation are combined. Using this concept, deformation modeling and understanding of the deformation mechanism can be greatly enhanced.

## 11-6. Automated Data Management

*a. Advantages and limitations of automation.* In the total effort of deformation monitoring, the quality of the analysis of the behavior of the object being monitored depends on the location, frequency, type, and reliability of the data gathered. The data concerned is any geotechnical observable as well as any conventional geodetic observable (angle, distance, height difference, etc.). Apart from the location and type of instrumentation, the frequency and reliability of the data can be enhanced by employing an "automatic" system of data gathering or acquisition and processing (including the deformation analysis). A data management system encompasses everything that happens to the data from the instant at which it is sensed to the time of analysis. Under ordinary circumstances, the interval of time between sensing and analysis may extend over several days or more. Under critical conditions, this may have to be nearly instantaneous in order to provide a warning, if necessary. The volume of data may consist of only several items (in the simplest routine investigation) to many hundreds or thousands (in very complex, critical situations, particularly if vibration behavior is of interest). The rate of sampling may be annually, monthly, weekly, daily, hourly, or even more frequently. The amount of human involvement may range from total (a "manual" system) to virtually none (an "automatic" system). Neither extreme is practical. A manual system is labor intensive and liable to errors or blunders and is less flexible in the re-examination of data. An automatic system is attractive but has some limitations. Although a "data acquisition system" strictly involves the gathering of data, the phrase has been used by many to mean the whole system of data management. Advantages and limitations of an automatic data acquisition system are summarized in the following two lists.

Advantages of an automatic data acquisition system:

- personnel costs for reading instruments and analyzing data are reduced,
- more frequent readings are possible,
- retrieval of data from remote or inaccessible locations is possible,
- instantaneous transmission of data over long distances is possible,
- increased reading accuracy can be achieved,
- increased flexibility in selecting required data can be provided,
- measurement of rapid fluctuations, pulsations, and vibrations is possible,
- recording errors are fewer and immediately recognizable, and
- data can be stored electronically in a format suitable for direct computer analysis.

Limitations of an automatic system:

- a knowledgeable observer is replaced by hardware,
- an excess of data could be generated, leading to a failure in timely response,
- the data may be blindly accepted, possibly leading to a wrong conclusion,
- there could be a high initial cost and, possibly, a high maintenance cost,
- often requires site-specific or custom components that may be initially unproven,
- complexity may require an initial stage of debugging,
- specialized personnel may be required for regular field checks and maintenance,
- a manual method is required as backup,
- a reliable and continuous source of power is required, and
- the system may be susceptible to damage by weather or construction activity.

With an appropriate compromise between manual and automatic functions, a properly designed and working system can minimize the effects of the limitations mentioned above. Therefore, the advantages of an automatic ("semi-automatic") system easily outweigh its disadvantages.

*b. Automated data system.* A data management system with a PC computer or programmed data collector provides for direct connection to (and sometimes control of) instrumentation and for keyboard entry for other equipment. The system should accommodate manually recorded data or data directly acquired from instrumentation. The raw data are contained in observation files, archived for security, and are processed or "reduced" (using calibration, test values, etc.) into data files which are then used by various analysis and display software applications.

(1) Field checks. A check file is required for access either during data collecting or available in hardcopy. The check file contains expected values predicted from stochastic (statistical) analyses of the data files and provides for a warning in the field. A warning is also given in the processing if the currently processed value differs beyond a set tolerance from the most recent value in the data file.

(2) Integrated analysis. Any data or derived data, whether geotechnical or geodetic (repeated in a suitable time series), can be brought together in the integrated deformation analysis of a structure. A time series is analyzed for trends with the separation of seasonal and long term behavior. The method of least squares fitting provides a full statistical analysis of the trend with the detection of outlying or erroneous data. It is possible to derive a new series from two original series or to create a series from repeated geodetic campaigns (e.g., tilt derived from leveling). The system can also show several series of data simultaneously, without fitting, to provide a graphical comparison of the series.

(3) Interpretation of results. Geodetic data is treated traditionally in campaigns for adjustment and spatial trend analysis. Once the observations have been repeated a sufficient number of times, they can be treated as a time series. Geotechnical series are treated in a similar manner (e.g., time series analysis, spatial series analysis, and plots). The trend analyses are automated by command files that are setup to control fitting and automated plotting of several series in succession. All of the data can be used together in simultaneous integrated geometrical analyses following the UNB Generalized Method, or several series can be plotted simultaneously without fitting. With both the observation files and the data files as ASCII text files, they are accessible through any text editor for manual entry or editing and can be input to other software applications.

*c*. *Desirable characteristics of an automated system.* Overall, the desirable characteristics of a data management system for deformation surveys includes:

- Data integrity (offering checks in the field and later processing).
- Data security (automatic archiving and regular data file backup).
- Automated acquisition, processing, and analysis.
- Compatibility and integration with other observables.
- Flexibility in access to the data for possible manual entry and editing.
- Data openness (useable by other software).
- Flexibility to be modified for additional instrumentation or other forms of analysis.
- On-site immediate access to data or any of the forms of analysis.
- Near-real time results of trend or other analyses.
- Testing and calibration is an integral component of the system.

## 11-7. Scope of Deformation Analysis

Over the past 10 years there has been significant progress in the development of new methods for the geometrical and physical analyses of deformation surveys. FIG has been leading in the developments, particularly in the areas of integrated geometrical analysis of structural deformations and combined integrated analysis. However, due to lack of interdisciplinary cooperation and insufficient exchange of information, FIG developments have not yet been widely adapted in practice. General worldwide use of the geometrical analysis methods is still poor, including even the basic analysis of geodetic monitoring networks. The above comments lead to the following:

- The analysis of deformation surveys should be in hands of interdisciplinary teams consisting of geotechnical, structural, and surveying engineers specialized in both geometrical and physical analyses.

- More use should be made of the concepts and developed methodologies for the geometrical integrated analysis and combined deterministic-statistical modeling of deformations.

## 11-8. Mandatory Requirements

There are no mandatory requirements in this chapter.