Deformation Surveying

STRUCTURAL DEFORMATION SURVEYING

(Lecture Notebook)

Doç. Dr. Yunus KALKAN

Doç.Dr. Yunus Kalkan

İTÜ İnşaat Fakültesi

Jeodezi ve Fotogrametri Mühendisliği Bölümü

Ölçme Tekniği Anabilim Dalı

Görüşme Saati:	Çarşamba 11:00-15:00
Oda No:	INB-407
Tel:	0212 285 38 18
Faks:	0212 285 34 14
E-posta:	kalkany@itu.edu.tr

Web sayfası: http://www.ins.itu.edu.tr/olcme/indextr.htm

REFERENCES

- **Engineering And Design Structural Deformation Surveying** US Army Corps of Engineers EM 1110-2-1009

- **W.F. Caspary, J.M. Rüeger, Concepts of Network and Deformation Analyses,** National Library of Australia, 1987

- **Engineering surveying technology / edited by T.J.M. Kennie and G. Petrie** Merkez Küt.Ders Kitapları -- TA562 .E54 1990

- **Surveying : with construction applications / Barry F. Kavanagh** Merkez Küt.Ders Kitapları -- TA625 .K38 2004

Başarı Değerlendirme Ölçütleri

Mid-term Not

Mid-term Exam %60 + Quiz %15 + Homework % 25
Minimum Devam: %70

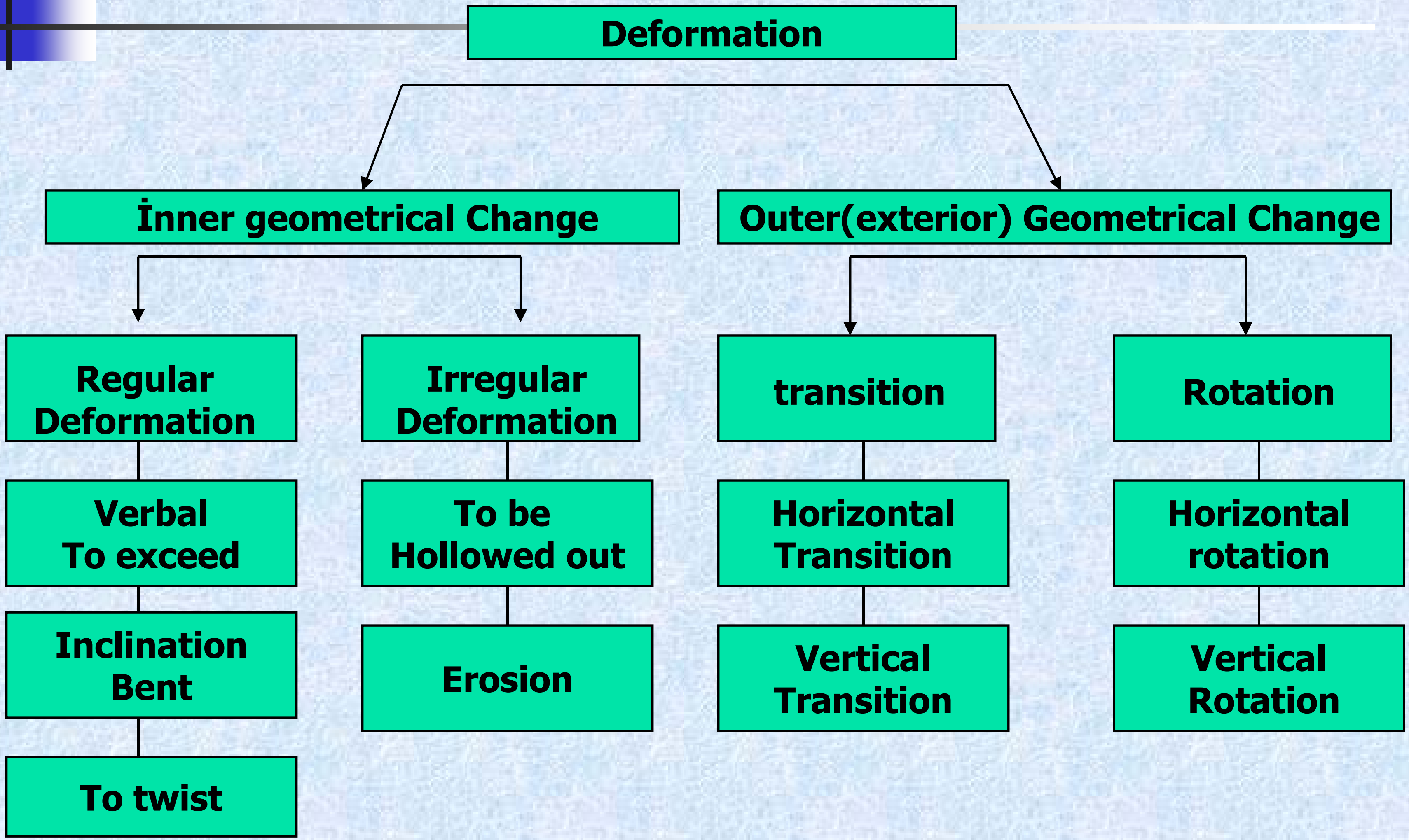
Mid-term Exam	:	1	% 24
Quiz	:	1	% 6
Homework	:	1	% 10

Final Not

Mid-term Not %**40** + Final Exam Not %**60**

Contents

Deformation: **Deformation is a geometrical changing in the objects (material, body,...)**



EM 1110-2-1009
1 June 2002

US Army Corps
of Engineers

ENGINEERING AND DESIGN

Structural Deformation Surveying

ENGINEER MANUAL

Structural Deformation Surveying

Chapter 1- Backround, Structural deformation, Deformation Survey Techniques,

1- Purpose

This Manual provides technical guidance for performing precise structural deformation surveys of locks, dams, and other hydraulic flood control or navigation structures. Accuracy, procedural, and quality control standarts are defined for monitoring displacements in hydraulic structures.

2- Background

The Crops of Engineers has constructed hundereds of dams,locks, levees, and other flood control structures that require periodic surveys to monitor long-term movements and settlements, or to monitor short-term deflections and deformation.

Structural Deformation Surveying

a. Structural deformation

Dams, locks, levees, embankments, and other flood control structures are subject to external loads that cause deformation and permeation of the structure itself, as well as its foundations.

Any indication of abnormal behavior may threaten the safety of the structure. Carefull monitoring of the loads on a structure and its response to them can aid in determining abnormal behavior of that structure.

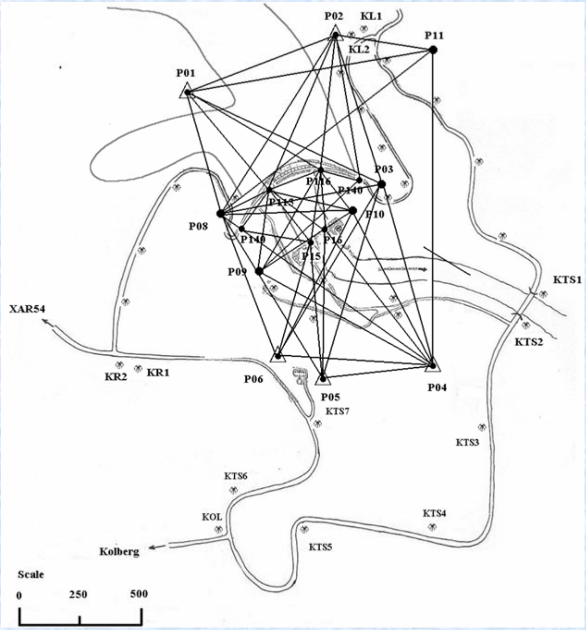
Structural Deformation Surveying

In general, monitoring consists of both measurements and visual inspections.

To facilitate the monitoring of hydraulic structures, they should be permanently equipped with proper instrumentation and/or monitoring points according to the goals of the observation, structure type and size, and site conditions.

Structural Deformation Surveying

b. Concrete structures

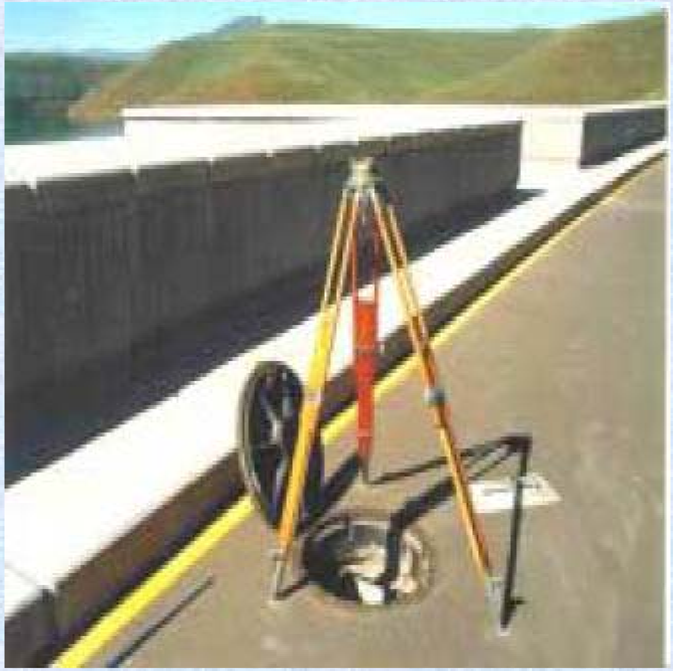


Differences in construction materials are one of the larger influences on how a structure deforms. For example; concrete dams deform differently than earthen or embankment dams. For concrete dams and other concrete flood control devices, deformation is mainly elastic and highly dependent on reservoir water pressure and temperature variations.

Structural Deformation Surveying

b. Concrete structures

Conventional geodetic survey methods from external points and of centimeter-level accuracy are sufficient to monitor these long-term trends. Highly accurate, short-term deflections or relative movements between monoliths due to varying temperature or hydraulic loading are more rarely required.



Structural Deformation Surveying

c. Earthen or Embankment Structures.

<u>Earthen or embankment dams</u> and levees obviously will deform altogether differently than concrete ones. With earthen dams, the deformation is largely characterized as more permanent. The reservoir water pressure also causes permanent horizontal deformation perpendicular to the embankment centerline. With earthen dams, elastic behavior is slight.

Structural Deformation Surveying

c. Earthen embankment structures.

Deformation survey accuracy requirements are less rigid for earthen. embankments, and traditional construction survey methods will usually provide sufficient accuracy. Typical surveys include periodic measurement of embankment crest elevations and slopes to monitor settlements and slope stability.

Structural Deformation Surveying

d. Long-term deformation monitoring.

Depending on the type and condition of structure, monitoring systems may need to be capable of measuring both long-term movement trends and short-term loading deformations. Long-term measurements are far more common and somewhat more complex given their external nature. Long-term monitoring of a structure's movement typically requires observations to monitoring points on the structure from external reference points. These external reference points are inter-connected and termed the "reference network." The reference network must also be monitored at less-frequent intervals to ensure these reference points have not themselves moved.

Structural Deformation Surveying

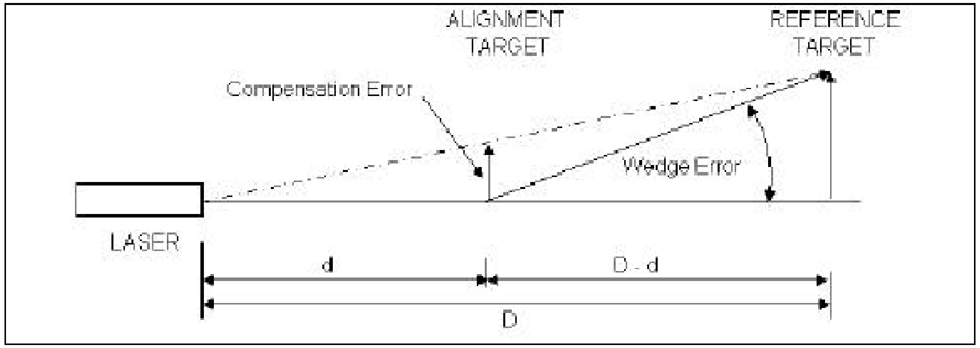
Deformation Survey Techniques

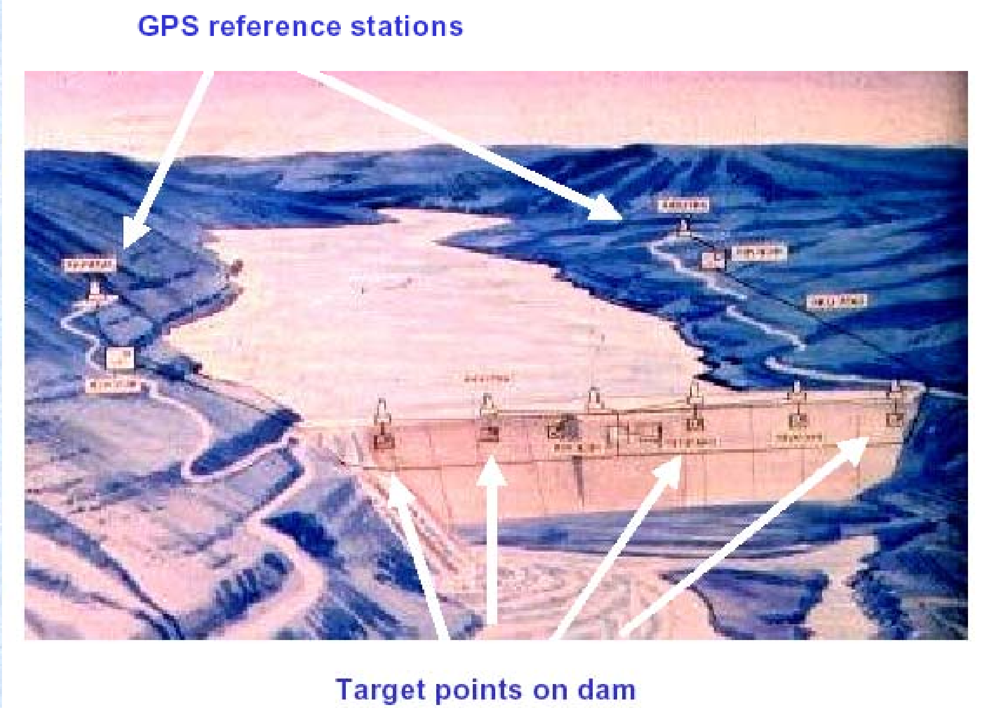
a. Reference and target points

The general procedures to monitor the deformation of a structure and its foundation involve measuring the spatial displacement of selected object points (i.e., target points) from external reference points that are fixed in position. Both terrestrial and satellite methods are used to measure these geo spatial displacements.

1-7. Deformation Survey Techniques

When the reference points are located in the structure, only relative deformation is determined-e.g., micrometer joint measurements are relative observations. Absolute deformation or displacement is possible if the reference points are located outside the actual structure, in the foundation or surrounding terrain and beyond the area that may be affected by the dam or reservoir.

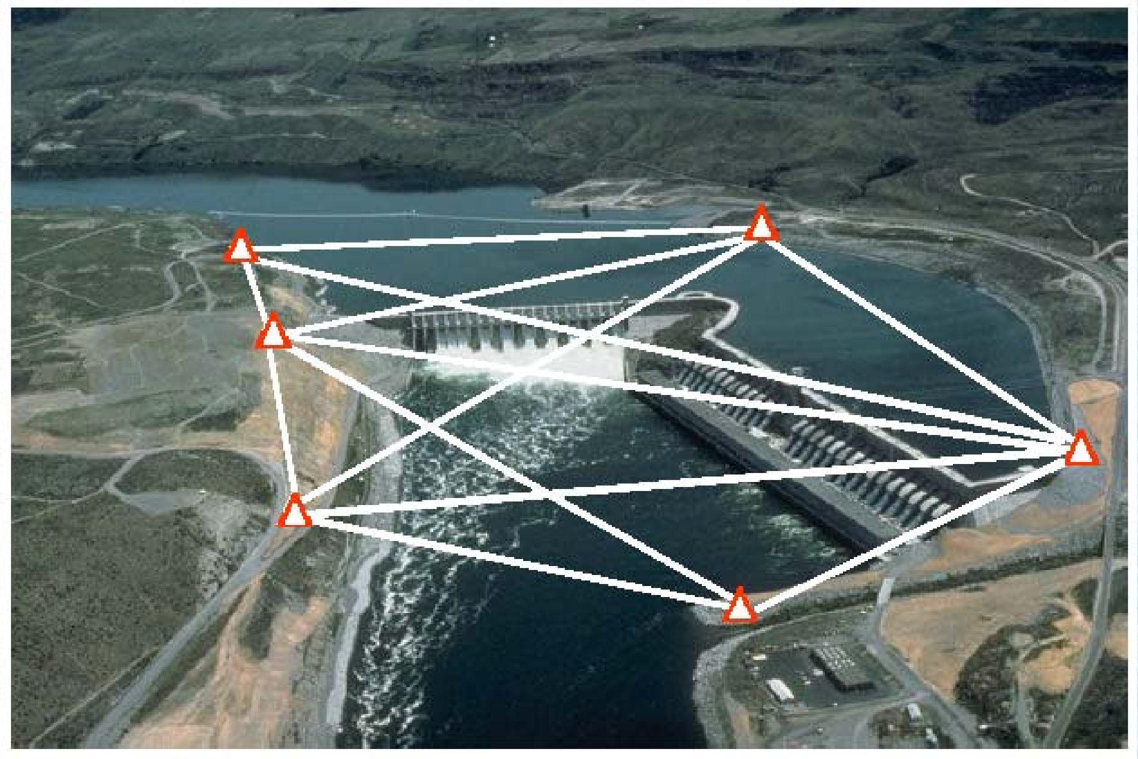




Structural Deformation Surveying

b. Reference point network.

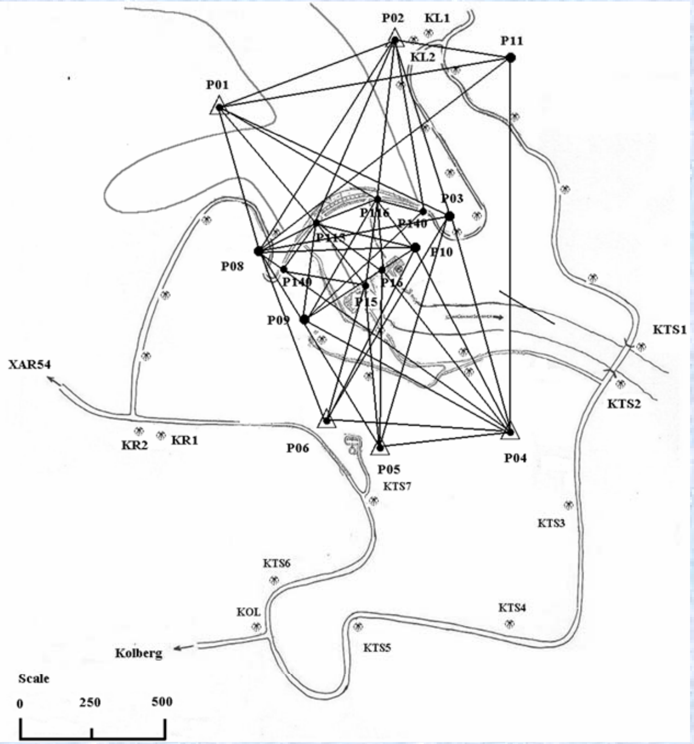
In general, for concrete dams it is ideal to place the reference points in a rock foundation at a depth unaffected by the reservoir.



These reference points can be easily accessed to perform deformation surveys with simple measurement devices.

Structural Deformation Surveying

c. Monitoring techniques



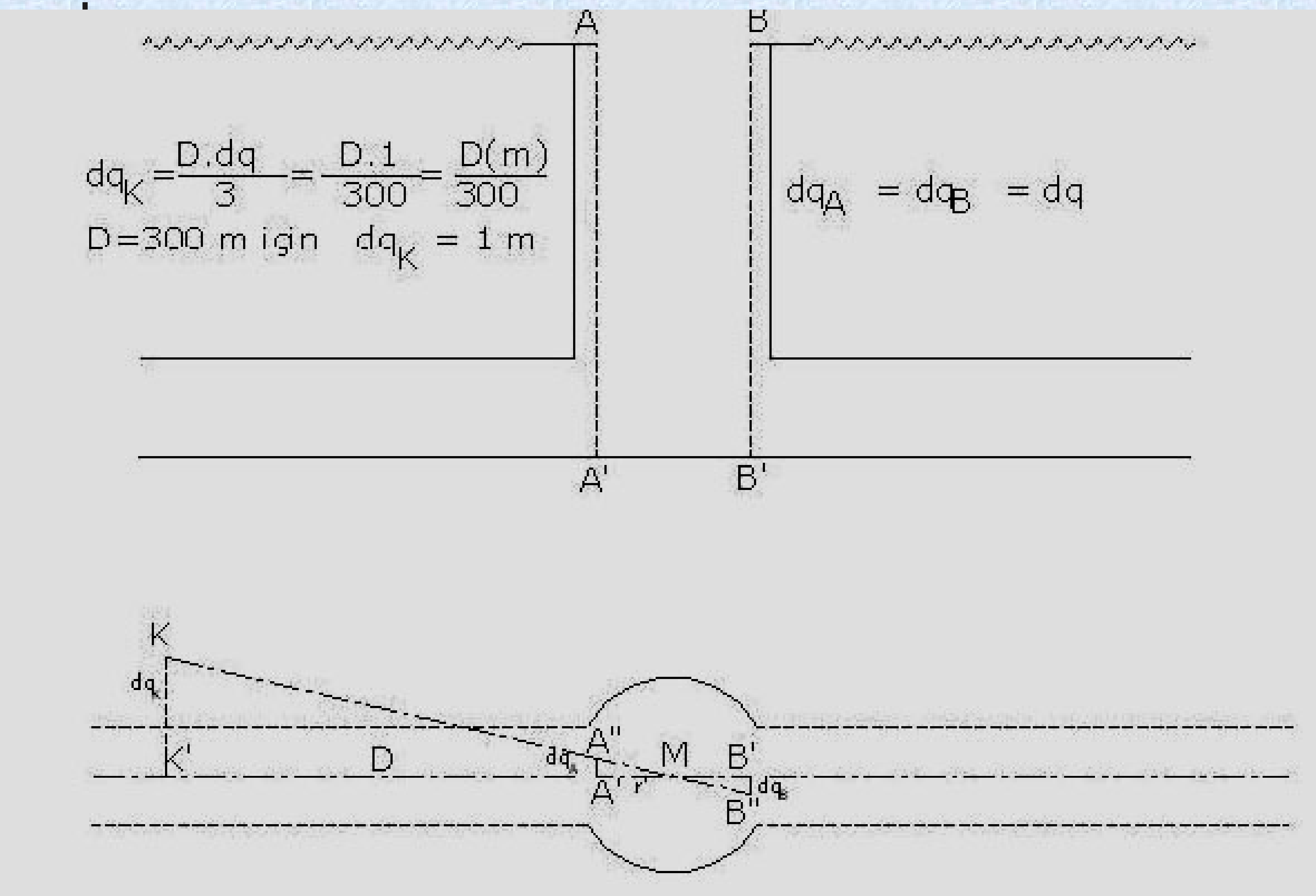
The monitoring of dam or foundation deformation must be done in a manner such that the displacement is measured both horizontally and vertically. Such measurements must include the foundation and extend as far as possible into it. Redundancy is essential in this form of deformation monitoring and is achieved through measuring at the points intersecting the orthogonal lines of the deformation network.

Structural Deformation Surveying

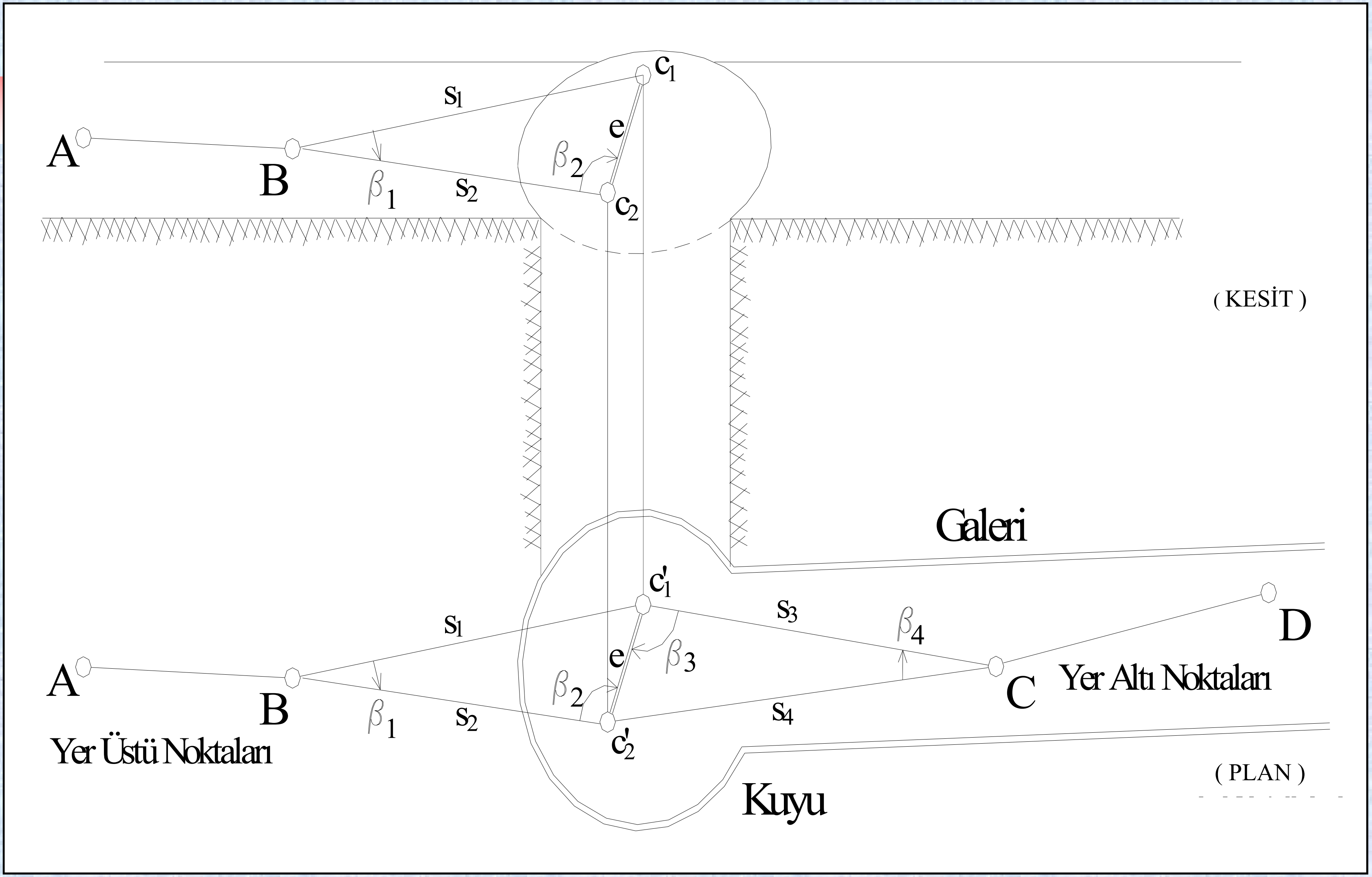
c. Monitoring techniques

If a dam includes inspection galleries and shafts, deformation values along vertical lines can be obtained by using hanging and/or inverted plumb lines and along horizontal lines by traverses—both of these methods are standard practice for deformation monitoring. Where there are no galleries or shafts (e.g., embankment dams, thin arch dams, or small gravity dams), the same result can be achieved by an orthogonal network of survey targets on the downstream face.

Structural Deformation Surveying

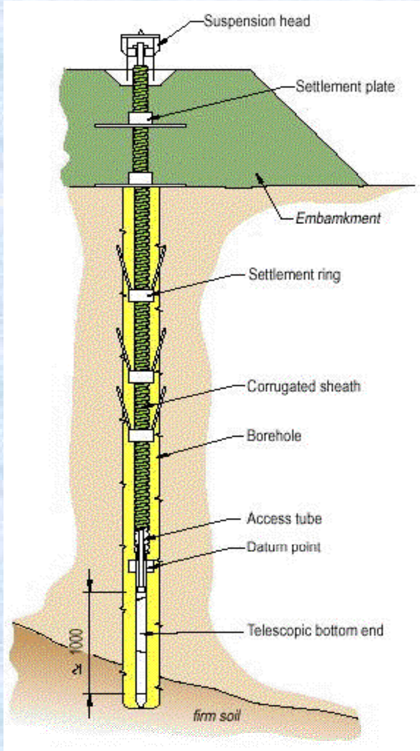


Structural Deformation Surveying



Structural Deformation Surveying

d. Relative displacement observation



A more routine, less costly, and more frequent monitoring process can be employed to monitor the short term behavior of dams by simply confining observation to trends at selected points along the crest and sometimes vertical lines. Such procedures typically involve simple angle measurement or alignment (supplementing the measuring installation) along the crest to determine horizontal displacement, and elevation determination by leveling to determine vertical displacement (i.e., settlement). Even with this monitoring process, it is essential to extend leveling to some distance beyond the abutments. Alternative methods to that described include settlement gauges, hose leveling devices, or extensometers.

Chapter 2- Planning, Design, and Accuracy Requirements

2-1. Standards for Deformation Surveys

a. General. **This chapter provides guidance for planning and implementing structural deformation surveys**

b. Dam safety. **US Army Corps of Engineers owns and operates a wide range of large engineering structures, including major infrastructure facilities for navigation, flood protection, and large dams.**

c. Engineer regulations. **Standards for conducting instrumentation surveys and for periodic inspections. Guidance for Civil Works projects provides for an adequate level of instrumentation to enable designers to monitor and evaluate the safety of the structures.**

d. Specialized standards. **Specialized standards for conducting deformation surveys are justified as long as products are consistent with effective government wide coordination and efficient.**

Planning, Designe and Acuracy Requiretments

Deformation monitoring often requires

specialized surveying methods that are planned and executed according to

specialized techniques and procedures.

Structural Deformation Surveying

2-2. Accuracy Requirements for Performing Deformation Surveys

Table 2-1. Accuracy Requirements for Structure Target Points

Concrete Structures Dams, Outlet Works, Locks, Intake Structures:

Long-Term Movement	+ : 5-10 mm
Relative Short-Term Deflections	
Crack/Joint movements	
Monolith Alignment	+ 0.2 mm
Vertical Stability/Settlement	+ 2 mm

Embankment Structures Earth-Rockfill Dams, Levees:

Slope/crest Stability	+ 20-30 mm
Crest Alignment	+ 20-30 mm
Settlement measurements	+ 10 mm

Control Structures Spillways, Stilling Basins, Approach/Outlet Channels, Reservoirs

Scour/Erosion/Silting	+ 0.2 to 0.5 foot- 10-15 cm

2-3. Overview of Deformation Surveying Design

Monitoring plan. Each monitored structure should have a technical report or design memorandum published for the instrumentation and/or surveying scheme to document the monitoring plan and its intended performance.

A project specific measurement scheme and its operating procedures should be developed for the monitoring system (Figure 2-1).

Separate designs should be completed for the instrumentation plan and for the proposed measurement scheme.

Monitoring Plan

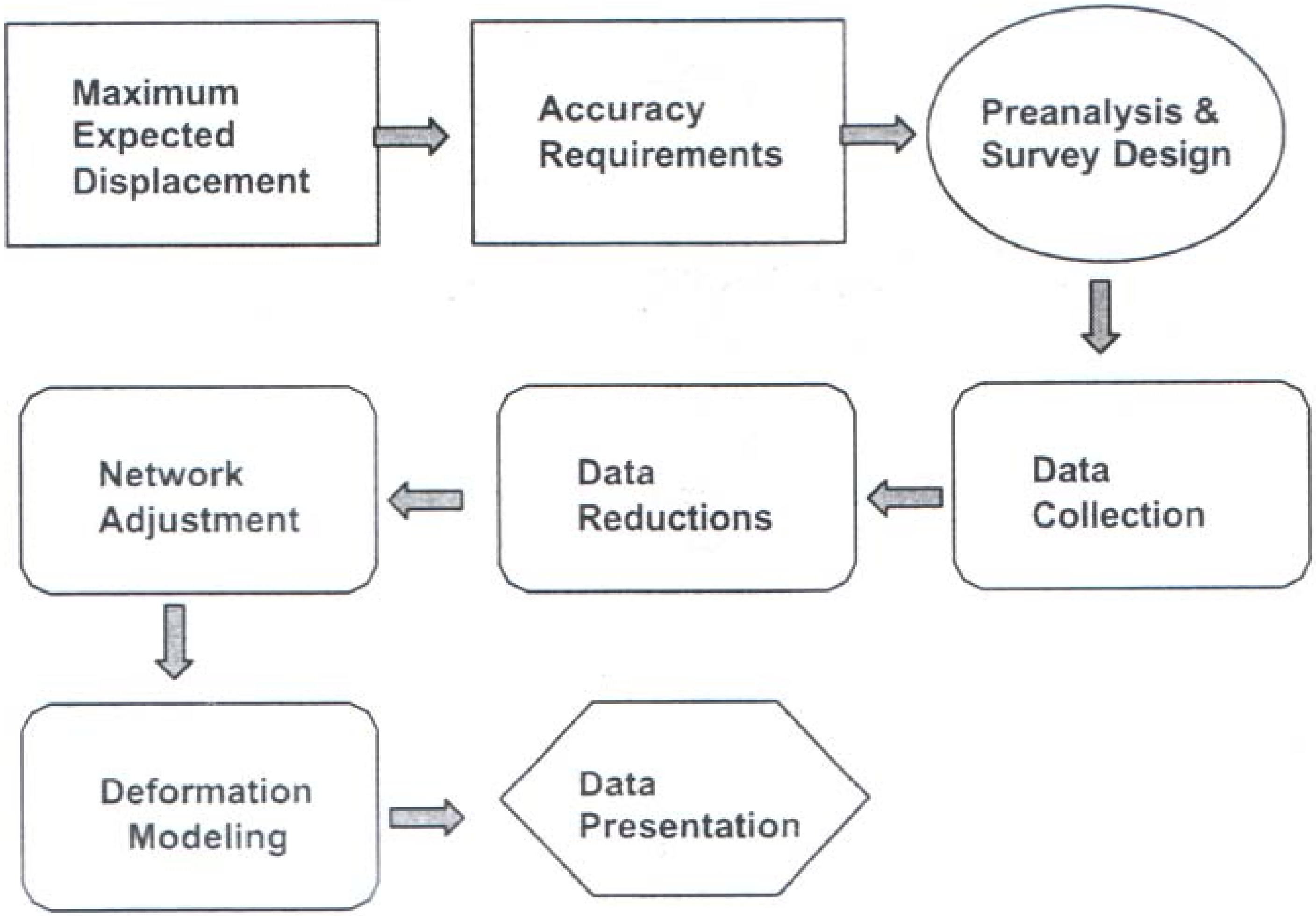
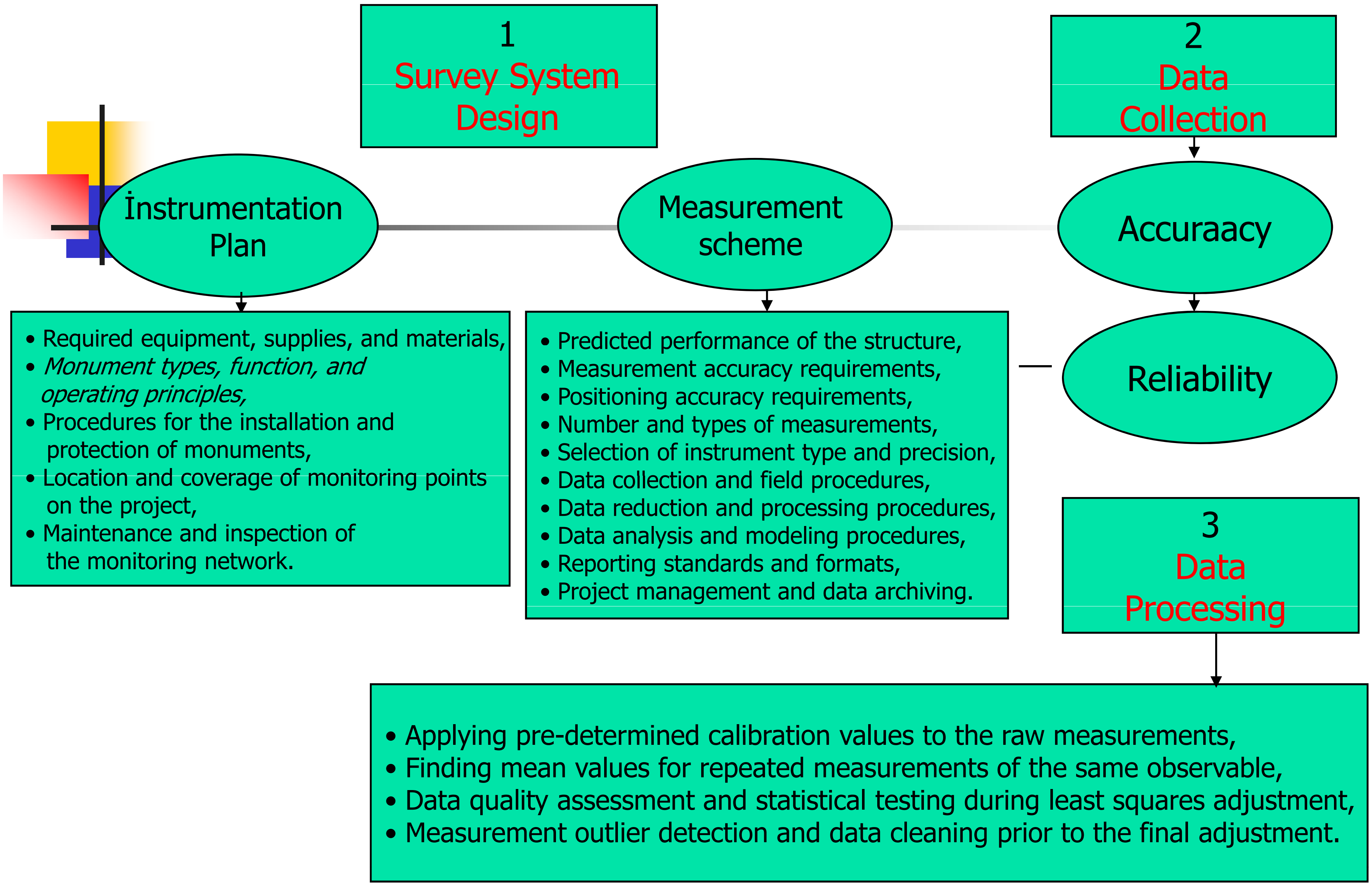


Figure 2-1. Deformation Survey Data Flow


1
Survey System Design
Instrumentation Plan
• Required equipment, supplies, and materials,
• *Monument types, function, and operating principles,*
• Procedures for the installation and protection of monuments,
• Location and coverage of monitoring points on the project,
• Maintenance and inspection of the monitoring network.
Measurement scheme
• Predicted performance of the structure,
• Measurement accuracy requirements,
• Positioning accuracy requirements,
• Number and types of measurements,
• Selection of instrument type and precision,
• Data collection and field procedures,
• Data reduction and processing procedures,
• Data analysis and modeling procedures,
• Reporting standards and formats,
• Project management and data archiving.
2
Data Collection
Accuraacy
Reliability
3
Data Processing
• Applying pre-determined calibration values to the raw measurements,
• Finding mean values for repeated measurements of the same observable,
• Data quality assessment and statistical testing during least squares adjustment,
• Measurement outlier detection and data cleaning prior to the final adjustment.

4
Data Analyses

5
Data presentation

6
Data management

1. *Survey System Design.*

Although accuracy and sensitivity criteria may differ considerably between various monitoring applications, the basic principles of the design of monitoring schemes and their geometrical analysis remain the same. For example, a study on the stability of magnets in a nuclear accelerator may require determination of relative displacements with an accuracy of +0.05 mm while a settlement study of a rock-fill dam may require only +10 mm accuracy. Although in both cases, the monitoring techniques and instrumentation may differ, the same basic methodology applies to the design and analysis of the deformation measurements.

Structural Deformation Surveying

a. Instrumentation plan (design)

The instrumentation plan is mainly concerned with building or installing the physical network of surface movement points for a monitoring project. Contained in the instrumentation plan are specifications, procedures, and descriptions for:

- **Procedures for the installation and protection of monuments,**
- **Required equipment, supplies, and materials,**
- ***Monument types, function, and operating principles,***
- **Location and coverage of monitoring points on the project,**
- **Maintenance and inspection of the monitoring network.**

The plan contains drawings, product specifications, and other documents that completely describe the proposed instrumentation, and methods for fabrication; testing; installation; and protection and maintenance of instruments and monuments.

b. Measurement scheme (design).

The design of the survey measurement scheme should include analysis and specifications for:

- **Predicted performance of the structure,**
- **Measurement accuracy requirements,**
- **Positioning accuracy requirements,**
- **Number and types of measurements,**
- **Selection of instrument type and precision,**
- **Data collection and field procedures,**
- **Data reduction and processing procedures,**
- **Data analysis and modeling procedures,**
- **Reporting standards and formats,**
- **Project management and data archiving.**

The main technique used to design and evaluate measurement schemes for accuracy is known as "network pre-analysis." Software applications specially written for pre-analysis and adjustment are used to compute expected error and positioning confidence for all surveyed points in the monitoring network (see Chapter 9).

2. Data collection.

The data collection required on a project survey is specifically prescribed by the results of network pre-analysis. The data collection scheme must provide built-in levels of both accuracy and reliability to ensure acceptance of the raw data.

a. Accuracy.

Achieving the required accuracy for monitoring surveys is based on
instrument performance,
observing procedures.

Minimum instrument resolution, data collection options, and proper operating instructions are determined from manufacturer specifications. The actual data collection is executed according to the results of network pre-analysis so that the quality of the results can be verified during data processing and post-analysis of the network adjustment.

Structural Deformation Surveying

b. Reliability.

Reliability in the raw measurements requires a system of

- redundant measurements,
- sufficient geometric closure,
- and strength in the network configuration.

Geodetic surveying methods can yield high redundancy in the design of the data collection scheme..

3. Data processing.

Raw survey data must be converted into meaningful engineering values during the data processing stage. Several major categories of data reductions are:

- **Applying pre-determined calibration values to the raw measurements,**
- **Finding mean values for repeated measurements of the same observable,**
- **Data quality assessment and statistical testing during least squares adjustment,**
- **Measurement outlier detection and data cleaning prior to the final adjustment.**

4. Data analysis

Geometric modeling is used to analyze spatial displacements.

General movement trends are described using a sufficient number of discrete point displacements (d_n):

$d_n(\Delta x, \Delta y, \Delta z)$ for *n =* point number

Point displacements are calculated by differencing the adjusted coordinates for the most recent survey campaign (f), from the coordinates obtained at some reference time (i), for example coordinate displacement

$\Delta x = x_f - x_i$ is the x coordinate displacement

$\Delta y = y_f - y_i$ is the y coordinate displacement

$\Delta z = z_f - z_i$ is the z coordinate displacement

$\Delta t = t_f - t_i$ is the t time difference between surveys.

Each movement vector has magnitude and direction expressed as point displacement coordinate differences. Collectively, these vectors describe the displacement field over a given time interval.

Structural Deformation Surveying

Comparison of the magnitude of the calculated displacement and its associated survey accuracy indicates whether the reported movement is more likely due to survey error:

d_n | < (e_n) where,

| d_n | = sqrt ($\Delta x^2 + \Delta y^2 + \Delta z^2$) is the magnitude of the displacement (for point *n*), (e_n) = max dimension of combined 95% confidence ellipse for point n = (1.96) sqrt ($\sigma_f{}^2 + \sigma_i{}^2$), and σ_f is the standard error in position for the (final) or most recent survey, σ_i is the standard error in position for the (initial) or reference survey.

For example

For example, if the adjusted coordinates for point *n* in the initial survey were:

x_i = 1000.000 m

y_i = 1000.000 m

z_i = 1000.000 m

and the adjusted coordinates for the same point in the final survey were:

x_f = 1000.006 m

y_f = 1000.002 m

z_f = 1000.002 m

then the calculated displacement components for point *n* would be:

Δx = 6 mm

Δy = 2 mm

Δz = 2 mm

Structural Deformation Surveying

Assuming that the horizontal position has a standard deviation of $\sigma_h = 1.5$ mm for both surveys, and similarly the vertical position has a standard deviation of $\sigma_v = 2.0$ mm, as reported from the adjustment results, then the combined (95 percent) confidence in the horizontal displacement would be:

$e_n = (1.96)\ \mathrm{sqrt}\ (\sigma_f^{\,2} + \sigma_i^2) = (1.96)\ \mathrm{sqrt}\ (2.25 + 2.25) \sim 4.2$ mm at 95% confidence

The magnitude of the horizontal displacement is:

$|dh|_n = \mathrm{sqrt}\ (\Delta x^2 + \Delta y^2) = \mathrm{sqrt}\ (36 + 4) = 6.3$ mm

$$|dh|_n > (e_n) \Rightarrow 6.3 \text{ mm} > 4.2 \text{ mm}$$

These results show that the horizontal component exceeds the expected survey error margin and is likely due to actual movement of point *n* in the horizontal plane.

Confidence in the vertical displacement would be:

$(e_n) = (1.96)\ \text{sqrt}\ (\sigma_{vf}^{\ 2} + \sigma_{vi}^{\ 2}) = (1.96)\ \text{sqrt}\ (4 + 4) \sim 5.5$ mm at 95% confidence

The magnitude of the vertical displacement is:

$|dv| = 2.0$ mm

$|dv| < (e_n) \Rightarrow 2.0 \text{ mm} < 5.5 \text{ mm}$

5. Data presentation

Survey reports for monitoring projects should have a standardized format.

6. Data management

Survey personnel should produce hardcopy survey reports and complete electronic copies of these reports.

Management plan. All participants should have a general understanding of requirements for the complete evaluation process.

- General Engineering for planning and monitoring requests, preparation/presentation of data and results, and quality assurance measures,
- Surveying for data collection (in-house or contract requirements), data reduction, processing, network adjustment, quality assurance, and preparing survey reports,
- Geotechnical and Structural Engineering for analysis and evaluation of results and preparation of findings and recommendations,
- Technical Support for data management, archiving, computer resources, archiving final reports, and electronic information support.

Structural Deformation Surveying

2-4. Professional Associations

Many professional groups at national and international levels.

Organizations. Within the most active international organizations that are involved in deformation studies one should list:

- International Federation of Surveyors (FIG) Commission 6 which has significantly contributed to the recent development of new methods for the design and geometrical analysis of integrated deformation surveys and new concepts for analyses and modeling of deformations;
- International Commission on Large Dams (ICOLD) with its Committee on Monitoring of Dams and their Foundations;
- International Association of Geodesy (IAG) Commission on Recent Crustal Movements, concerning geodynamics, tectonic plate movement, and modeling of regional earth crust deformation.
- International Society for Mine Surveying (ISM) Commission 4 on Ground Subsidence and Surface Protection in mining areas;

2-5. Causes of Dam Failure

a. Concrete structures.

Deformation in concrete structures is mainly elastic and for large dams highly dependent on reservoir water pressure and temperature variations. Permanent deformation of the structure can sometimes occur as the subsoil adapts to new loads, concrete aging, or foundation rock fatigue. Such deformation is not considered unsafe if it does not go beyond a pre-determined critical value. Monitoring is typically configured to observing relatively long-term movement trends, including, abnormal settlements, heaving, or lateral movements. Some ways concrete dams can fail are:

- **Uplift at the base of gravity dams leading to overturning and downstream creep**
- **Foundation failure or buttress collapse in single or multiple arched dams**
- **Surrounding embankments that are susceptible to internal erosion.**

b. Embankment structures

Deformation is largely inelastic with earthen dams characterized by permanent changes in shape. Self-weight of the embankment and the hydrostatic pressure of the reservoir water force the fill material and the foundation (if it consists of soil) to consolidate resulting in vertical settlement of the structure. Reservoir water pressure also causes permanent horizontal deformation mostly perpendicular to the embankment centerline. Some causes of damage to earthen dams are:

- **Construction defects that cause the structure to take on anisotropic characteristics over time,**
- **Internal pressures and paths of seepage resulting in inadequately controlled interstitial water.**

Usually these changes are slow and not readily discerned by visual examination. Other well-known causes of failure in earthen dams are overtopping at extreme flood stage and liquefaction due to ground motion during earthquakes.

Structural Deformation Surveying

c. Structural distress

The following warning signs are evidence for the potential failure of dams.

· Significant sloughs, settlement, or slides in embankments such as in earth or rockfill dams

· Movement in levees, bridge abutments or slopes of spillway channels, locks, and abutments,

· Unusual vertical or horizontal movement or cracking of embankments or abutments,

· Sinkholes or localized subsidence in the foundation or adjacent to embankments and structures,

· Excessive deflection, displacement, or vibration of concrete structures

· Tilting or sliding of intake towers, bridge piers, lock wall, floodwalls),

· Erratic movement, binding, excessive deflection, or vibration of outlet and spillway gates,

· Significant damage or changes in structures, foundations, reservoir levels, groundwater conditions and adjacent terrain as a result of seismic events of local or regional areas,

· Other indications of distress or potential failure that could inhibit the operation of a project or endanger life and property.

Structural Deformation Surveying

2-6. Foundation Problems in Dams

a. General.

Differential settlement, sliding, high piezometric pressures, and uncontrolled seepage(sızıntı) are common evidences of foundation distress. Cracks in the dam, even minor ones, can indicate a foundation problem.

b. Consolidation.

Pumping from underground can cause foundation settlement as the supporting water pressure is removed or the gradient changed. Loading and wetting will also cause the pressure gradient to change, and may also cause settlement or shifting. Settlement in rockfill dams can be significantly reduced if the rockfill is mechanically compacted. In some ways, a compacted earth core is superior to a concrete slab as the impervious(geçirimsiz) element of a rockfill dam.

Structural Deformation Surveying

c. Seepage(sızıntı)

Water movement through a dam or through its foundation is one of the important indicators of the condition of the structure and may be a serious source of trouble. Seeping water can chemically attack the components of the dam foundation, and constant attention must be focused on any changes, such as in the rate of seepage, settlement, or in the character of the escaping water. Any leakage at an earth embankment is potentially dangerous, as rapid erosion may quickly enlarge an initially minor defect.

d. Erosion

Embankments may be susceptible to erosion unless protected from wave action on the upstream face and surface runoff on the downstream face. This deficiency usually can be detected and corrected before serious damage occurs.

Structural Deformation Surveying

e. Liquefaction(**sıvılaşma**)

Hydraulic fill dams are particularly susceptible to earthquake damage.

Liquefaction is a potential problem for any embankment that has continuous layers of soil with uniform gradation and of fine grain size. The Fort Peck Dam experienced a massive slide on the upstream side in 1938, which brought the hydraulic fill dam under suspicion. The investigation at the time focused blame on an incompetent foundation, but few hydraulic fills were built after the 1930's. Heavy compaction equipment became available in the 1940's, and the rolled embankment dam became the competitive(*rakip*) alternative.

f. Concrete deterioration(bozulma)

Chemical and physical factors can age concrete. Visible clues to the deterioration include expansion, cracking, gelatinous discharge, and chalky surfaces.

Structural Deformation Surveying

2-8. Deformation Parameters

General

The main purpose for monitoring and analysis of structural deformations is:

- **To check whether the behavior of the investigated object and its environment follow the predicted pattern so that any unpredicted deformations could be detected at an early stage.**
- **In the case of abnormal behavior, to describe as accurately as possible the actual deformation status that could be used for the determination of causative factors which trigger the deformation.**

Coordinate differencing and observation differencing **are the two principal methods used to determine structural displacements from surveying data. Coordinate differencing methods are recommended for most applications that require long-term periodic monitoring. Observation differencing is mainly used for short-term monitoring projects or as a quick field check on the raw data as it is collected.**

Structural Deformation Surveying

1. Coordinate differencing. Monitoring point positions from two independent surveys are required to determine displacements by coordinate differencing. The final adjusted Cartesian coordinates (i.e., the coordinate components) from these two surveys are arithmetically differenced to determine point displacements. A major advantage of the coordinate differencing method is that each survey campaign can be independently analyzed for blunders and for data adjustment quality. However, great care must be taken to remove any systematic errors in the measurements, for example by applying all instrument calibration corrections, and by rigorously following standard data reduction procedures.

2. Observation differencing. The method of observation differencing involves tracking changes in measurements between two time epochs. Measurements are compared to previous surveys to reveal any observed change in the position of monitoring points. Although observation differencing is efficient, and does not rely on solving for station coordinates, it has the drawback that the surveyor must collect data in an identical configuration, and with the same instrument types each time a survey is conducted.

Structural Deformation Surveying

a. Absolute displacements.

Displacements of monumented points represent the behavior of the dam, its foundation, and abutments, with respect to a stable framework of points established by an external reference network.

1. Horizontal displacements. Two-dimensional (2D) displacements are measured in a critical direction, usually perpendicular to the longitudinal axis of dam, at the crest, and other important points of embankments (abutments, toes, etc.) using conventional geodetic methods. Alignment techniques for alignment-offset measurements are made in relation to a pair of control points having well-known coordinates. Horizontal movement can also be determined with respect to plumblines having a stable anchor point (see EM 1110-2-4300, Instrumentation for Concrete Structures).

Structural Deformation Surveying

2. Vertical displacements

Vertical displacements are measured in relation to stable project benchmarks, such as deeply anchored vertical borehole extensometers, or alternatively, to deep benchmarks located near the dam using geodetic methods (differential leveling). Hydrostatic leveling is also sometimes used to determine settlements. Settlement gauges are used to detect settlements of the foundation, or of interior structural parts which are not readily accessible (core, foundation contact). Settlements of individual layers of embankments should be monitored through settlement gauges installed in the different layers (refer to EM 1110-2-2300, Earth and Rock-Fill Dams General Design and Construction Consideration).

Structural Deformation Surveying

b. Relative displacements

These measurements are intended to determine small differential movements of points representative of the behavior of the dam, its foundation, and abutments with respect to other points on the structure, or even on the same structural element.

1. Deflections

Relative deflections (inclinations) of a concrete dam are measured by direct or inverted plumblines. Alignment survey techniques are used in the interior galleries of dams to determine the relative movements between monoliths with respect to a horizontal reference line set along the longitudinal axis of the dam. Relative horizontal displacements of points inside embankments are detected by means of inclinometer probes sent through tubes set in drilled shafts. Foundation subsidence and tilts are measured with geodetic leveling, hydrostatic leveling, and tiltmeters. The last two are usually permanently installed in galleries.

Structural Deformation Surveying

2. Extensions

Combinations of geodetic leveling with suspended invar wires equipped with short reading scales at different levels of the dam and connected to borehole extensometers can supply information on the relative vertical movements as well as on the absolute vertical displacements and relative tilts. Extensometers have become important instruments for measuring differential foundation movements. Strain gauges are embedded in the concrete during construction, installed on the faces of the dam after completion, or embedded in foundation boreholes. Joint measurements are justified in the case of joints separating two unsealed structures or to check grouting in dome or arch-gravity dams. Cracks are measured by the same methods with the instruments being installed on the surface.

2-9. Location of Monitoring Points

a. Normal conditions

Monitoring schemes include survey stations at the points where maximum deformations have been predicted plus a few observables at the points which, depending on previous experience, could signal any potential unpredictable behavior, particularly at the interface between the monitored structure and the surrounding material.

b. Unusual conditions

Once any abnormal deformations are noticed, then additional observables are added at the locations indicated by the preliminary analysis of the monitoring surveys as being the most sensitive to identification of causative factors.

Structural Deformation Surveying

c. Long-term monitoring.

The spatial distribution of survey monuments should provide complete coverage of the structure, extending to stable areas of the project if possible. A minimum of four (4)monitoring points are recommended to model behavior in a plane section (tilts, subsidence, etc.). For linear structures, monuments are placed at intervals that provide coverage along the structure's total length, and generally not more than 100 meters apart, when using conventional instruments, to allow for measurement check ties to nearby monuments. The following are suggested guidelines for the location of survey monuments for long-term monitoring applications listed according to the type of structure. Refer also to the generalized monitoring schemes shown in Figures 2-2 through 2-6.

2-10. Design of Reference Networks

a. General: Having multiple control stations in the reference network is critical for improving the reliability of deformation surveys, and for investigating the stability of reference monuments over time. Each control station in the reference network should be intervisible to a maximum number of structural monitoring points (placed on the structure) and to at least two other reference monuments. The number of reference points for vertical control should be not less than three (3), and preferably four (4) benchmarks. For horizontal control the minimum number of reference points should be at least four (4), preferably six (6). Reference stations are usually located at both ends of the dam, along its longitudinal axis, at the elevation of the dam crest. Geometry and reliability of the reference network can be improved by adding control stations either upstream or downstream from the crest or on the structure itself.

b. Project datum selection

A project datum defines the relative positions and coordinates established on the reference network. Coordinates of monitoring points are also calculated with respect to the project datum.

The project datum for large monitoring projects should be based on geodetic TUD-54, ED-50 (or WGS84) coordinates.

A geodetic coordinate system is recommended because positioning can be directly related to a standard reference ellipsoid. Network adjustment processing software often requires definition of the project datum in geodetic coordinates.

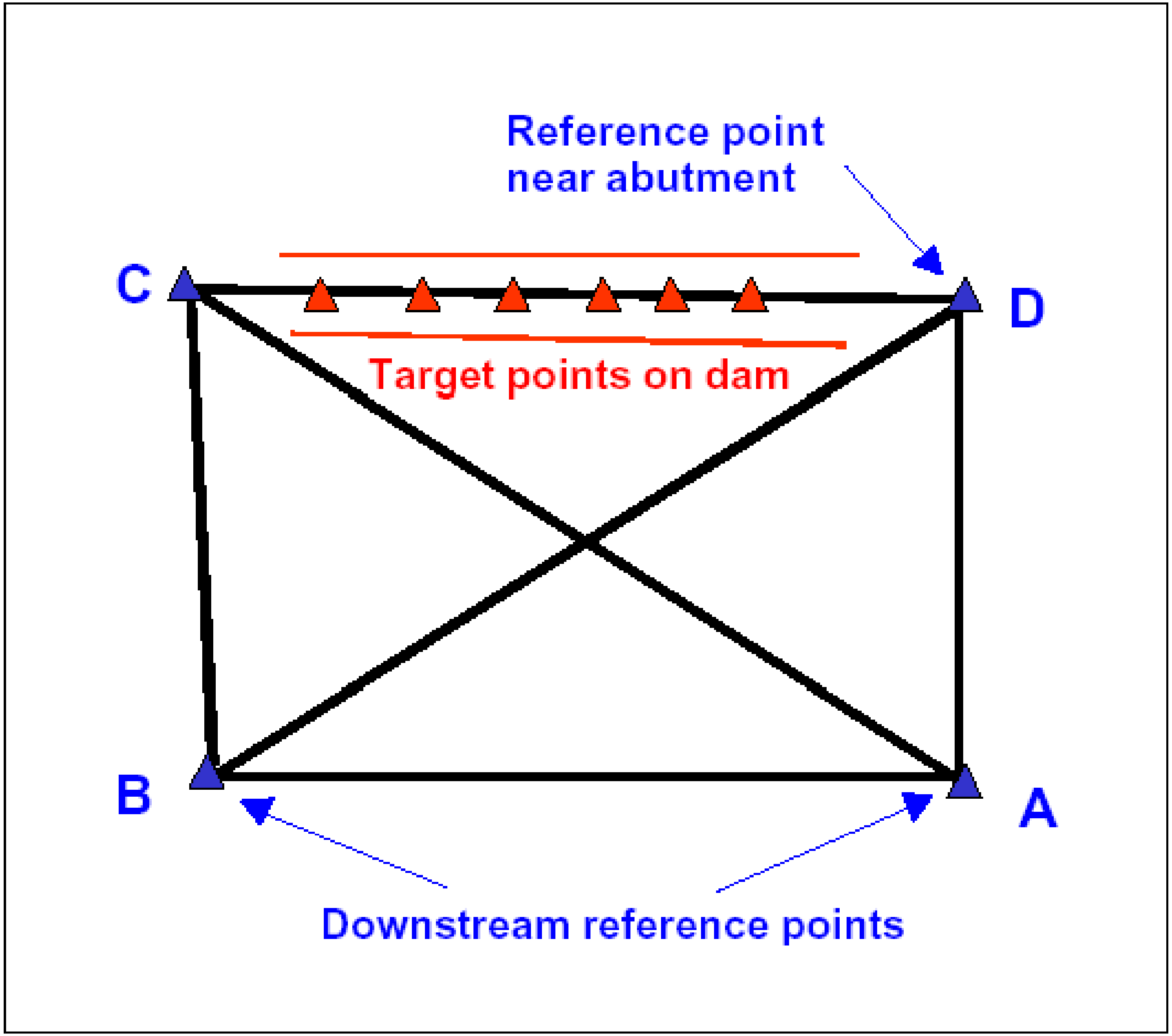


Figure 2-2. Strong monitoring scheme for a concrete or earth/rockfill dam

Figure 2-3. Reference network configuration for a concrete dam depicting reference points near abutments and at downstream locations

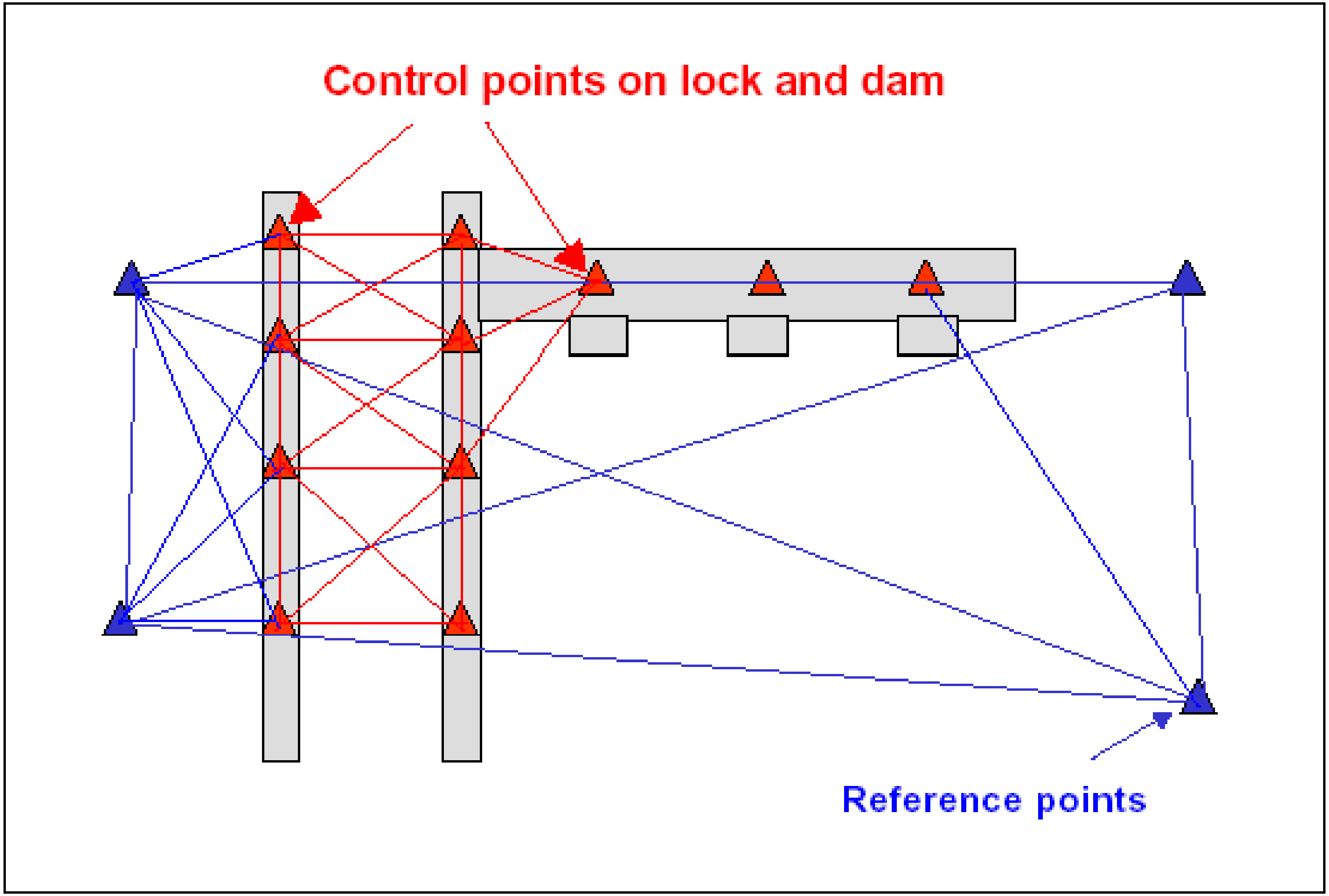


Figure 2-4. Strong monitoring scheme for a lock and dam

Figure 2-5. Idealized monitoring scheme for controlling target points on the lock and dam

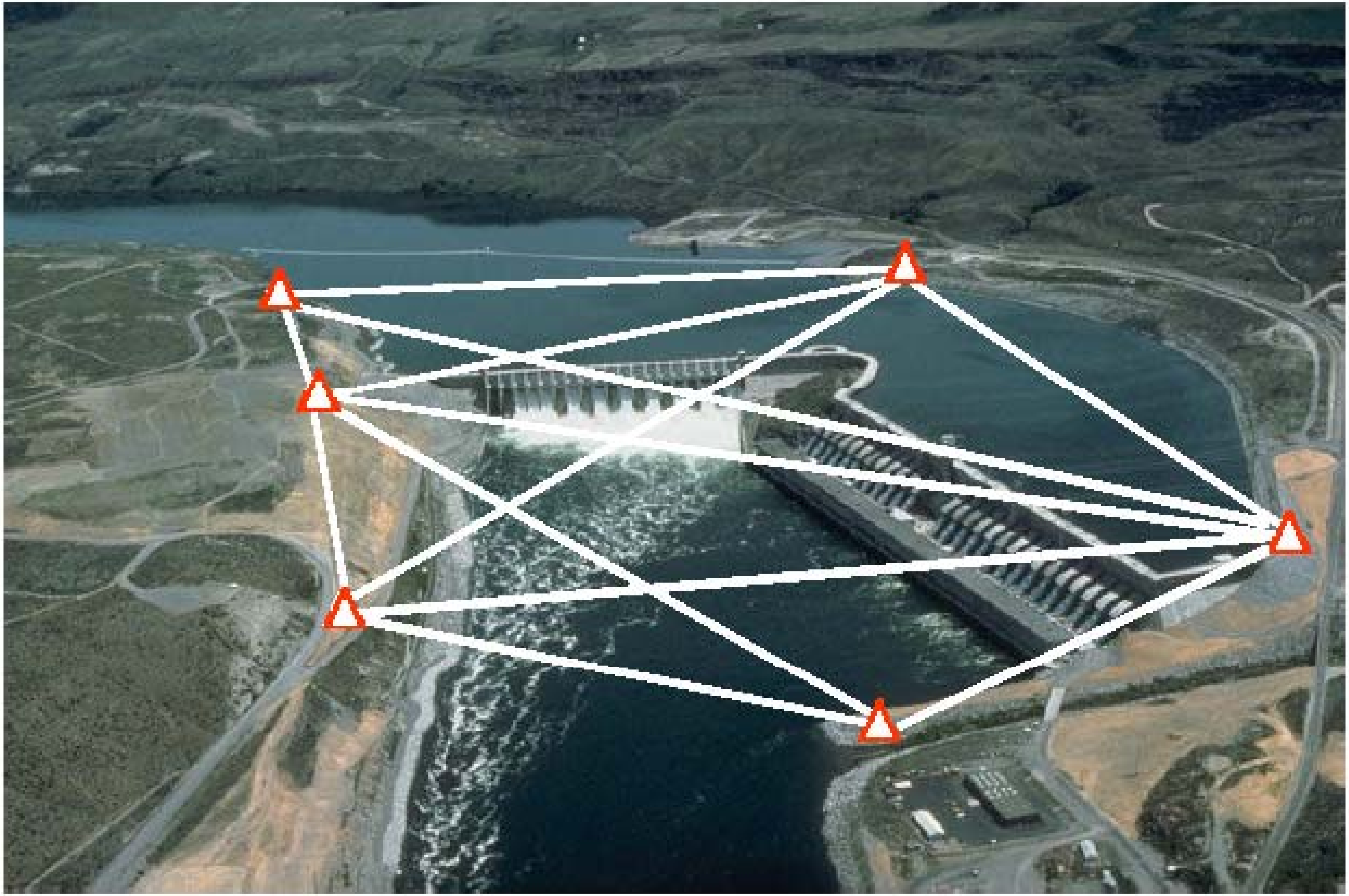


Figure 2-6. Idealized reference network surrounding a hydroelectric dam. External reference points are established at downstream points and on reservoir to provide strong geodetic network

2-11. Reference Point Monumentation

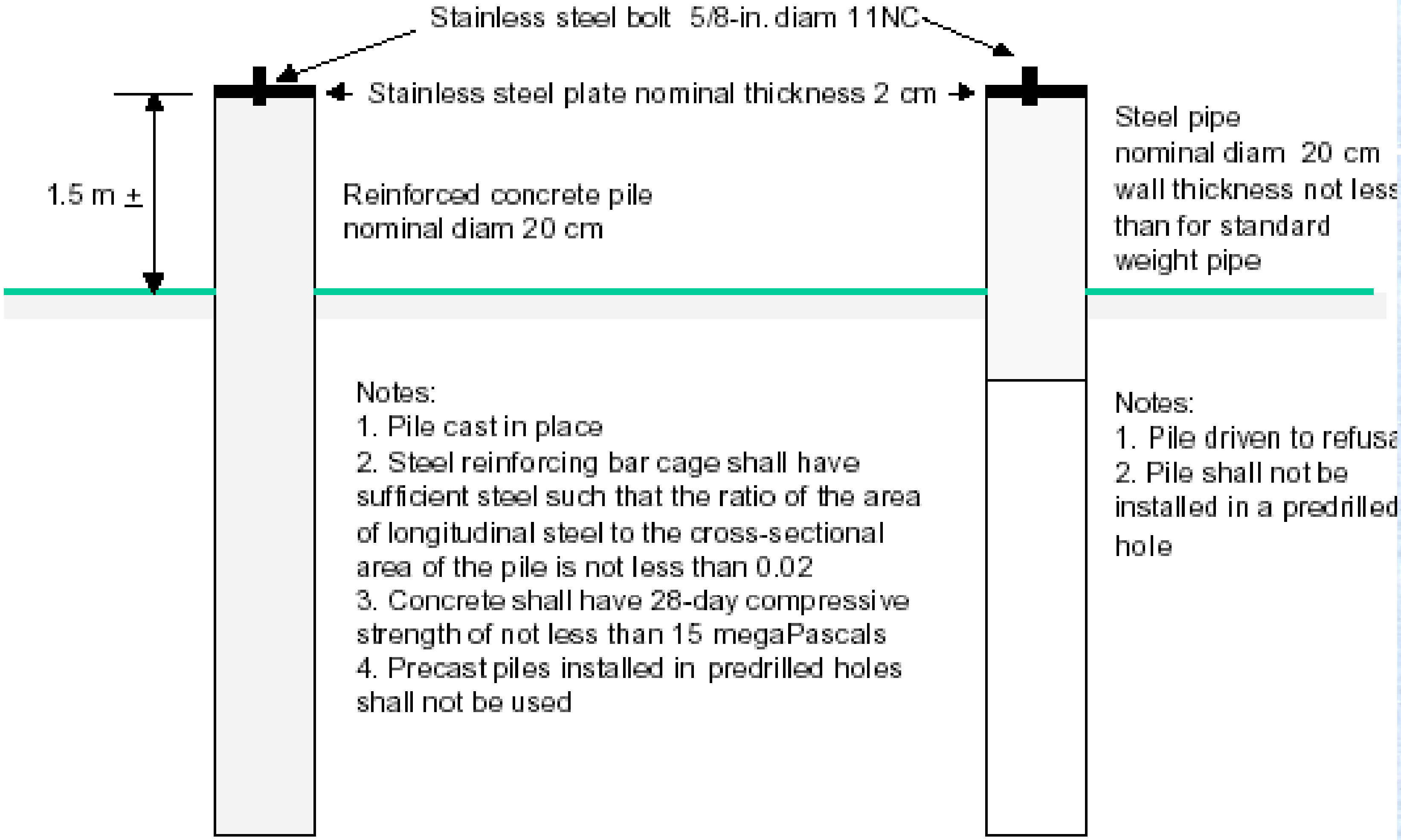
Reference point monuments:

Reference points can be either a steel pipe pile or cast-in-place reinforced concrete pile--Figure 2-7.

If a steel pipe pile is used, the nominal diameter will be no less than 20 cm, while the wall thickness will be no less than that for standard weight pipe. If using a cast-in-place reinforced concrete pile, the nominal diameter will also be no less than 20 cm (Figure 2-8).

Figure 2-7. Reference point monumentation. Concrete pier construction vicinity of a hurricane gate structure. Forced centering plug set into concrete pier.

Reference Points



a. Reinforced concrete pile reference point

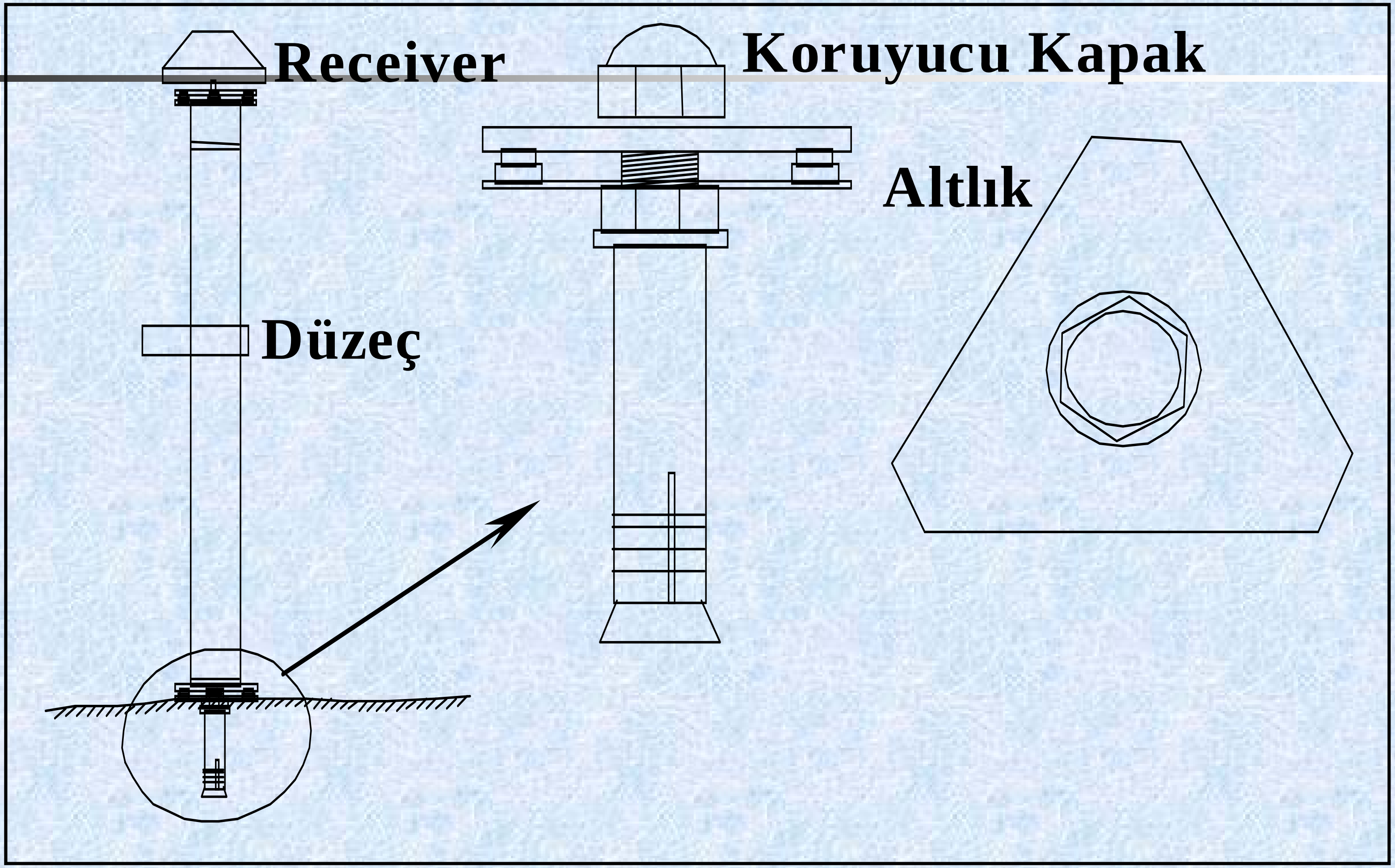
b. Steel pile reference point

Monitoring Points

Monitoring point installation.

Monitoring points set directly in rock or concrete may be either a steel bolt or a steel insert into which survey equipment is force centered-see Figure 2-9.

Monitoring Points



Monitoring Points

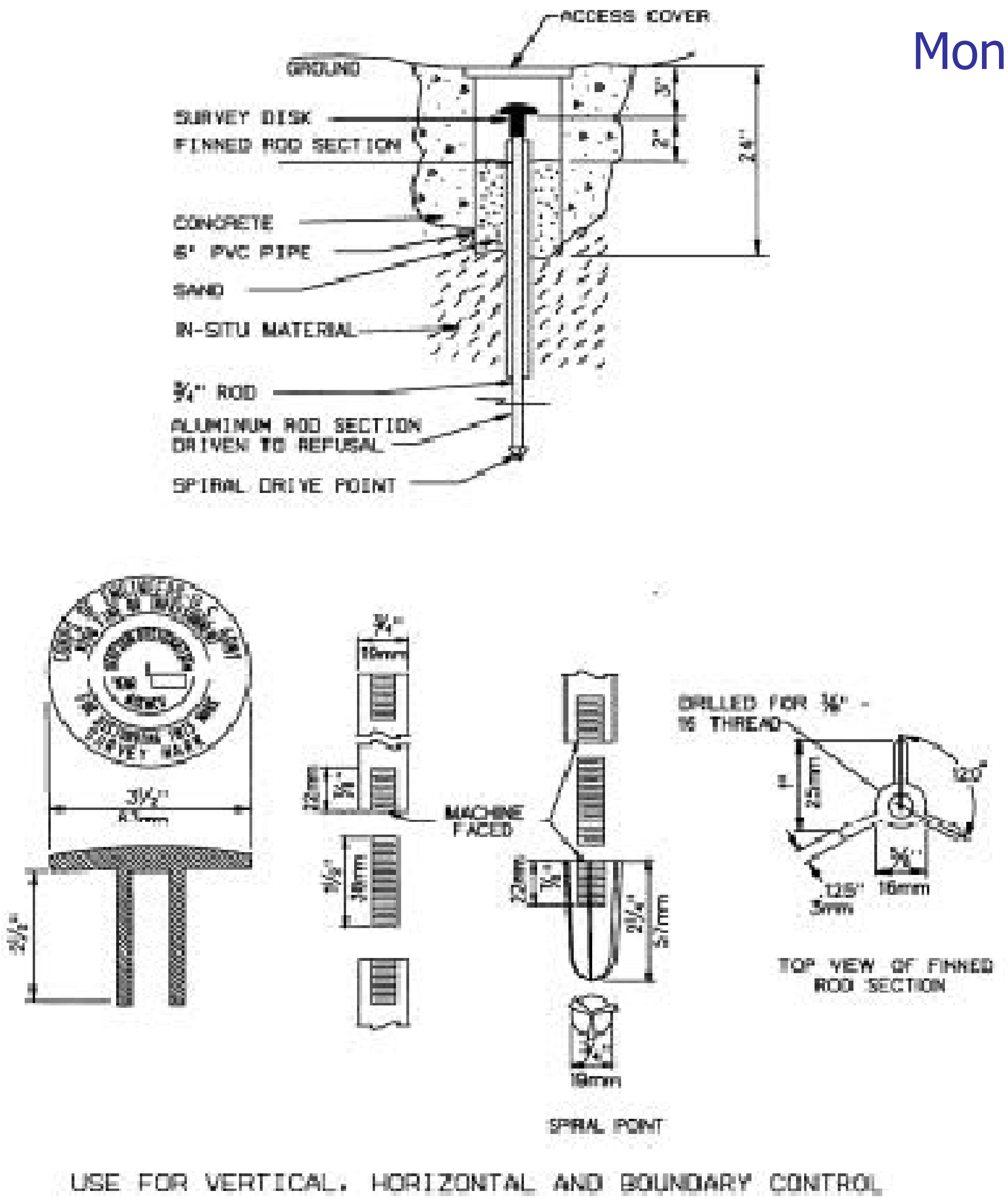
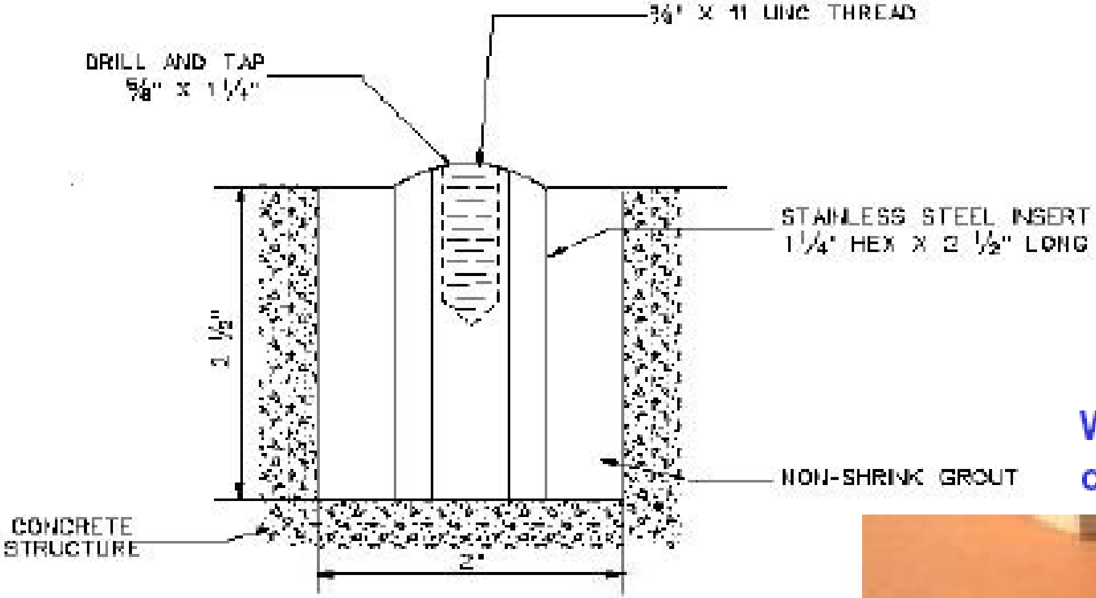


Figure 2-10. External deep-driven benchmark design--for vertical control only

Monitoring Points



5/8-inch forced centering plug set into concrete structure

Wild tribrach with forced centering device

Figure 2-9. Target plug set on concrete structure. Forced centering device on tribrach shown upside down

Monitoring Points

Monitoring point targets

- Optical theodolites. Force-centered, standard target sets
- Electronic total station. Force-centered, standard target set/prism combination
- EDM prisms. EDM targets will be the reflectors included with the EDM unit.
- Chaining points. Targets for taped distances will be the monuments themselves.
- Leveling points. Targets for leveled height difference measurements will be the monuments themselves
- Panel points. Photogrammetric survey targets will consist of a high contrast,
- GPS reference marks. Targets for GPS surveys shall be the monuments themselves.

Optimal Design Methods

- **The optimization of geodetic positioning networks is concerned with accuracy, reliability, and economy of the survey scheme as the design criteria.**
- **Design of deformation monitoring schemes is more complex and differs in many respects from the design of simple positioning networks.**

Accuracy requirements.

- **Positioning accuracy** required for each monitored point is directly related to the maximum expected displacement occurring under normal operating conditions.

- **Accuracy requirements** are computed by equating the maximum allowable positioning error to some portion of the total magnitude of movement that is expected at each point. Specifically, the positioning accuracy (at the 95% probability level) should be equal to one fourth (0.25 times) the predicted value of the maximum displacement for the given span of time between the repeated measurements.

Accuracy requirements.

Survey error budget.

- **Accuracy** should be less than one-third of the predicted value for the maximum expected displacement (D max) over the given span of time between two surveys.

$$P\ error < (1/3)\ D\ max$$

P error = allowed positioning error
D max = maximum expected displacement

- **Displacements** are calculated by differencing coordinates obtained from two monitoring surveys.

$$\sigma_d = sqrt\ (\sigma_1 + \sigma_2)$$

σ_1 = positioning uncertainty of initial survey
σ_2 = positioning uncertainty of final survey

Accuracy requirements.

Survey error budget.

$\sigma_0^2 = \sigma_1^2 = \sigma_2^2$

$\sigma_d = \text{sqrt}\,(2\,\sigma_0^2\,)$

$P_{error} = (\sigma_d\,)/\,\text{sqrt}\,(2)$

2-14. Measurement Reliability

Reliability addresses **the geometric strength of the observation scheme, measurement redundancy, and techniques for minimizing measurement biases**. Statistical methods can determine the maximum level of undetected systematic error using outlier detection.

Some reliability factors

- Redundant measurements,
- External checks on the validity of the data,
- Instrument calibrations,
- Reference network stability analysis,
- Rigorous data processing techniques,
- Multiple connections between stations.

2-15. Frequency of Measurements

Geodetic monitoring surveys (for periodic inspections) are conducted at regular time intervals rather than by continuous measurements that are more typical of automated structural or geotechnical instrumentation.

The time interval between deformation surveys will vary according to the purpose for monitoring, but is generally correlated to condition of the structure.

Continuous monitoring

Guidelines for the frequency for conducting monitoring surveys

(1) Pre-construction.

(2) Initial filling.

(3) Stabilizing phase.

(4) Normal operation.

(5) Remedial phase.

Chapter 3

Deformation Measurement and Alignment Instrumentation

This chapter describes the different techniques and equipment that are used in measuring external structural deformations.

•Geodetic and Geotechnical Measurements

-**Geodetic surveys** include conventional (terrestrial), photogrammetric satellite, and some special techniques (interferometry, hydrostatic leveling, alignment, etc.)

-**Geotechnical measurements** are local deformations using lasers, tiltmeters, strainmeters, extensometers, joint-meters, plumb lines, micrometers, etc.

Comparison of measurement methods

•Geodetic surveys, through a network of points interconnected by angle and/or distance measurements, usually supply a sufficient redundancy of observations for the statistical evaluation of their quality and for a detection of errors.

•Geotechnical instruments are easier to adapt for automatic and continuous monitoring than conventional geodetic instruments They give very localized and, very frequently, locally disturbed information without any check unless compared with some other independent measurements..

Accuracy of the Geodetic surveys

Geodetic surveys with optical and electro-magnetic instruments (including satellite techniques) have positioning accuracy to about ±1 ppm to ±2 ppm (at the standard deviation level) of the distance.

•***Extensometers*** in relative deformation surveys have accuracies of ±0.3 mm

•***Geodetic leveling***, with an achievable accuracy of better than ±0.1 mm over distances of 20 m

•*New developments in three-dimensional coordinating systems* may provide relative positioning in almost real-time to an accuracy of ±0.05 mm over distances of several meters.

3.2- Angle and Distance Measurements

- ***Electronic theodolites.***

The angle measurements has been mainly in the automation of the readout systems of the horizontal and vertical circles of the theodolites.

- ***Three-dimensional coordinating systems***

Two or more electronic theodolites linked to a microcomputer create a three-dimensional (3D) coordinating (positioning) system with real-time calculations of the coordinates. The systems are used for the highest precision positioning and deformation monitoring surveys over small areas.

- ***Electronic Distance Measurements (EDM)***

Short range (several kilometers), electro-optical EDM instruments with visible or near infrared continuous radiation are used widely in engineering surveys.

Angle and Distance Measurements

Leica TCA 2003

Leica TM 5100

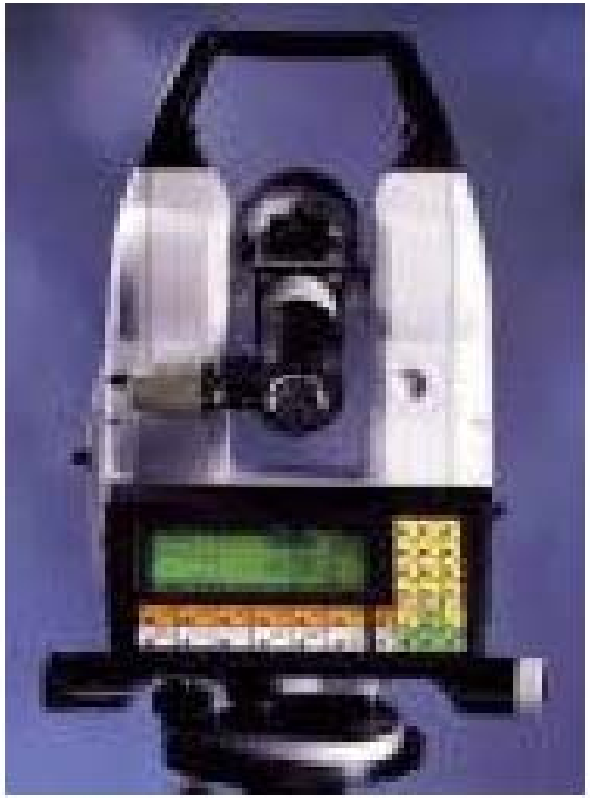


Figure 3-1. Lieca TCA 2003 and TM 5100 electronic total stations used for high precision machine alignment and deformation measurements. Accuracy specified at 1.0 mm (distance) and 0.5 sec (angular)

Angle and Distance Measurements

- ***Pulse type measurement***

These instruments, having a high energy transmitted signal, may be used without reflectors to measure short distances (up to 200 m) directly to walls or natural flat surfaces with an accuracy of about 10 millimeters(**Figure 3-2).**

- ***Dual frequency instruments***

Only a few units of a dual frequency instrument (Terrameter LDM2 by Terra Technology) are available around the world. They are bulky and capricious in use but one may achieve with them a standard deviation of ± 0.1 mm ± 0.1 ppm.

- ***Total stations***

Any electronic theodolite linked to an EDM instrument and to a computer creates a total surveying station. It allows for a simultaneous measurement of the three basic positioning parameters, distance, horizontal direction, and vertical angle, from which relative horizontal and vertical positions of the observed points can be determined directly in the field.

Pulse type measurement.

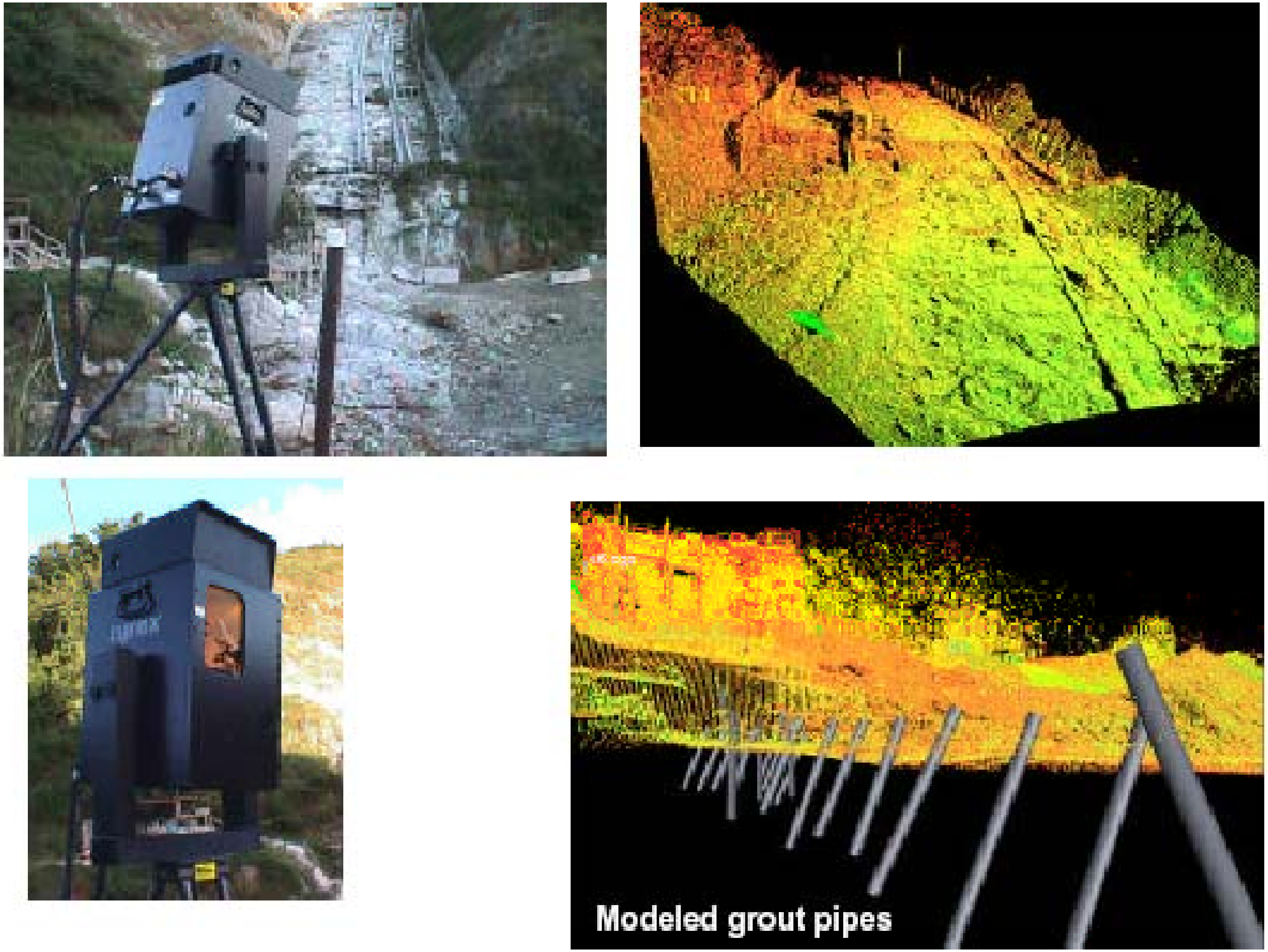


Figure 3-2. Real-time laser modeling during 1999 construction of Portugues Dam near Ponce, Puerto Rico--Cyrax Model 2400

Angle and Distance Measurements

- ***Theomat Coaxial Automated Total Station (TCA)***

It is designed for conducting deformation monitoring surveys.

The EDM system specifications are 0.6 mm resolution at 120 meters and for 1 mm and 1 ppm precision to a single prism at a range of 2500 feet

- ***Automatic Target Recognition (ATR)***

Early automated vision systems were installed in precision theodolites by the 1980's. Its operating components consisted of an external video camera imaging system and a separate servomotor drive.

- ***Survey robots***.

For continuous or frequent deformation measurements, a fully automatic system based on computerized and motorized total stations has recently been developed.

3-3. Differential Leveling

Differential leveling provides height difference measurements between a series of benchmarks. Vertical positions are determined to very high accuracy (±1 mm) over short distances (10-100's of meters) using precision levels.

- ***Automatic levels***

The old method of geometrical leveling with horizontal lines of sight (using spirit or compensated levels) is still the most reliable and accurate, though slow, surveying method. It has a standard deviation smaller than 0.1 mm per set-up

- ***Digital levels***

The recently developed digital automatic leveling systems with height and distance readout from encoded leveling rods (Figure 3-3). It has considerably increased the speed of leveling (by about 30%) and decreased the number of personnel needed on the survey crew.

Differential Leveling

Figure 3-3. Lieca NA 2002 automated digital level and section from bar-coded invar level rod

Differential Leveling

- ***Tilt measurements by leveling***

Monolith tilt on dams can be determined from leveling observations using the dimensions and tilting axis of the object.

3-4. Total Station Trigonometric Elevations

- ***Zenith angle methods***

High precision electronic theodolites and EDM equipment allow for the replacement of geodetic leveling with more economical trigonometric height measurements. An accuracy better than **1 mm** may be achieved in height difference determination between two targets **200 m** apart using precision electronic theodolites for vertical angle measurements and an EDM instrument.

Measurement accuracy: Trigonometric height traversing (reciprocal or with balanced lines of sight) with precision theodolites and with the lines of sight not exceeding **250 m** can give a standard deviation smaller than **2 mm per km.**

3-5. Global Positioning System (GPS)

- The satellite Global Positioning System (shown in Figures 3-4 and 3-5) offers advantages over conventional terrestrial methods.

Figure 3-4. GPS equipment setup on a concrete hydropower dam - spillway and intake structure

Global Positioning System (GPS)

- ***GPS positioning accuracy:*** Experience with the use of GPS in various deformation studies indicate that with the available technology the accuracy of GPS relative positioning over areas of up to 50 km in diameter can be expressed in terms of the variance of the horizontal components of the GPS baselines over a distance (S):

$$\sigma^2 = (3\text{mm})^2 + (10^{-6} \cdot S_{km})^2$$

The accuracy of vertical components of the baselines is **1.5 to 2.5 times** worse than the horizontal components. Systematic measurement errors over short distances (up to a few hundred meters) are usually negligible and the horizontal components of the GPS baselines can be determined with a standard deviation of 3 mm or even smaller.

Global Positioning System (GPS)

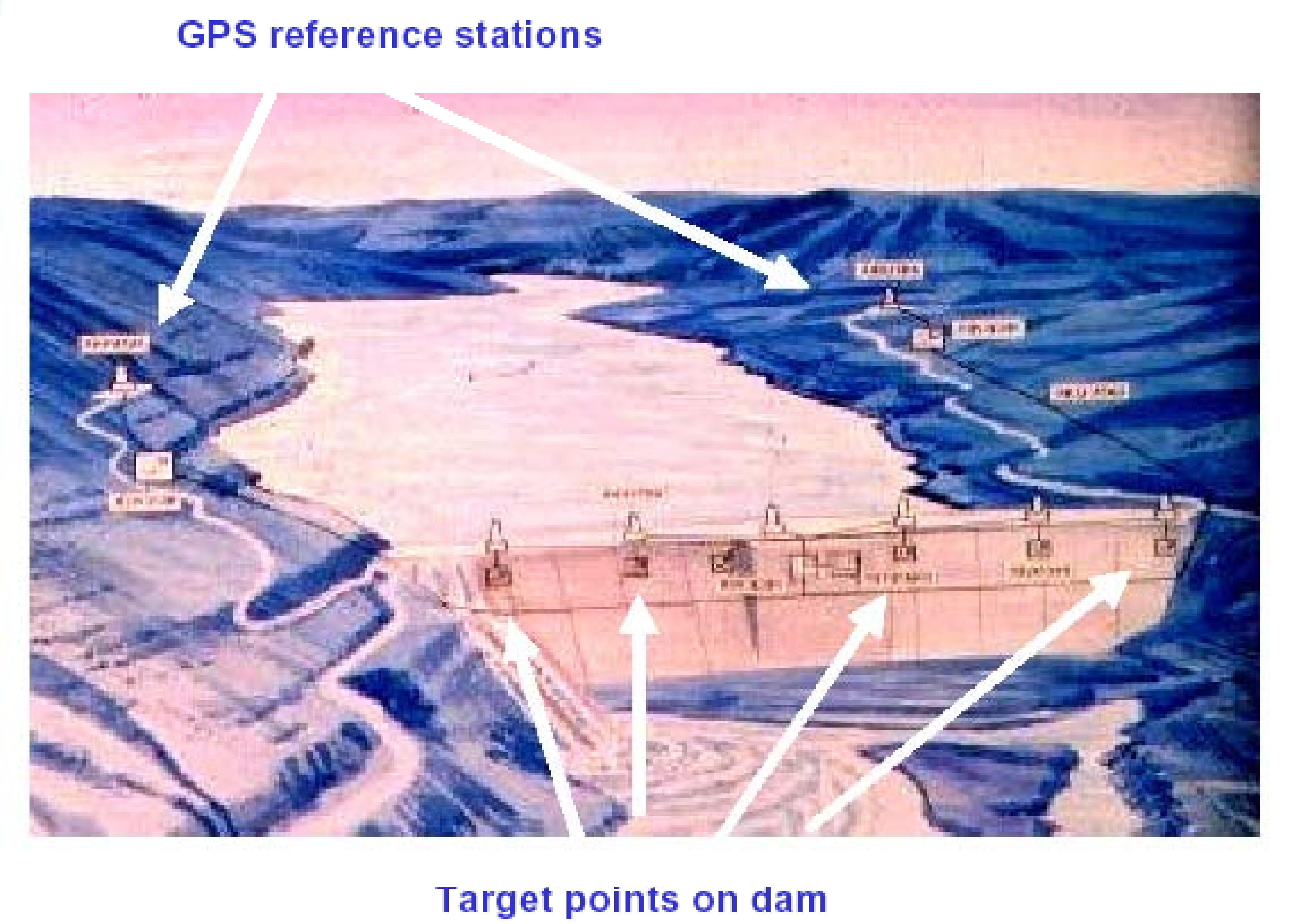


Figure 3-6. GPS deformation monitoring surveys on a dam. GPS monitoring was first applied at Dworshak Dam,

3-6. Photogrammetric Techniques

- Using a camera with f = 100 mm, at a distance S = 100 m, with the accuracy of the image coordinates of 10 μm, the coordinates of the object points can be determined with the accuracy of 10 mm.

- Special large format cameras with long focal length are used in close range industrial applications of high precision. For instance, the model CRC-1 (Geodetic Services, Inc.) **camera with f = 240 mm, can give sub-millimeter accuracy in 'mapping' objects up to a few tens of meters away.**

- Continuous monitoring with real time photogrammetry becomes possible with the new developments in CCD cameras and digital image processing techniques.

3-7. Alignment Measurements

Alignment surveys cover an extremely wide spectrum of engineering applications from the tooling industry, through measurements of amplitude of vibrations of engineering structures, to deformation monitoring of nuclear accelerometers several kilometers long.

Each application may require different specialized equipment.

The methods used in practice may be classified according to the method of establishing the reference line:

• **Mechanical method** in which stretched wire (e.g., steel, nylon) establishes the reference line,

• **Direct optical method** (collimation) with optical line of sight or a laser beam to mark the line,

• **Diffraction method** where a reference line is created by projecting a pattern of diffraction slits.

Alignment Measurements

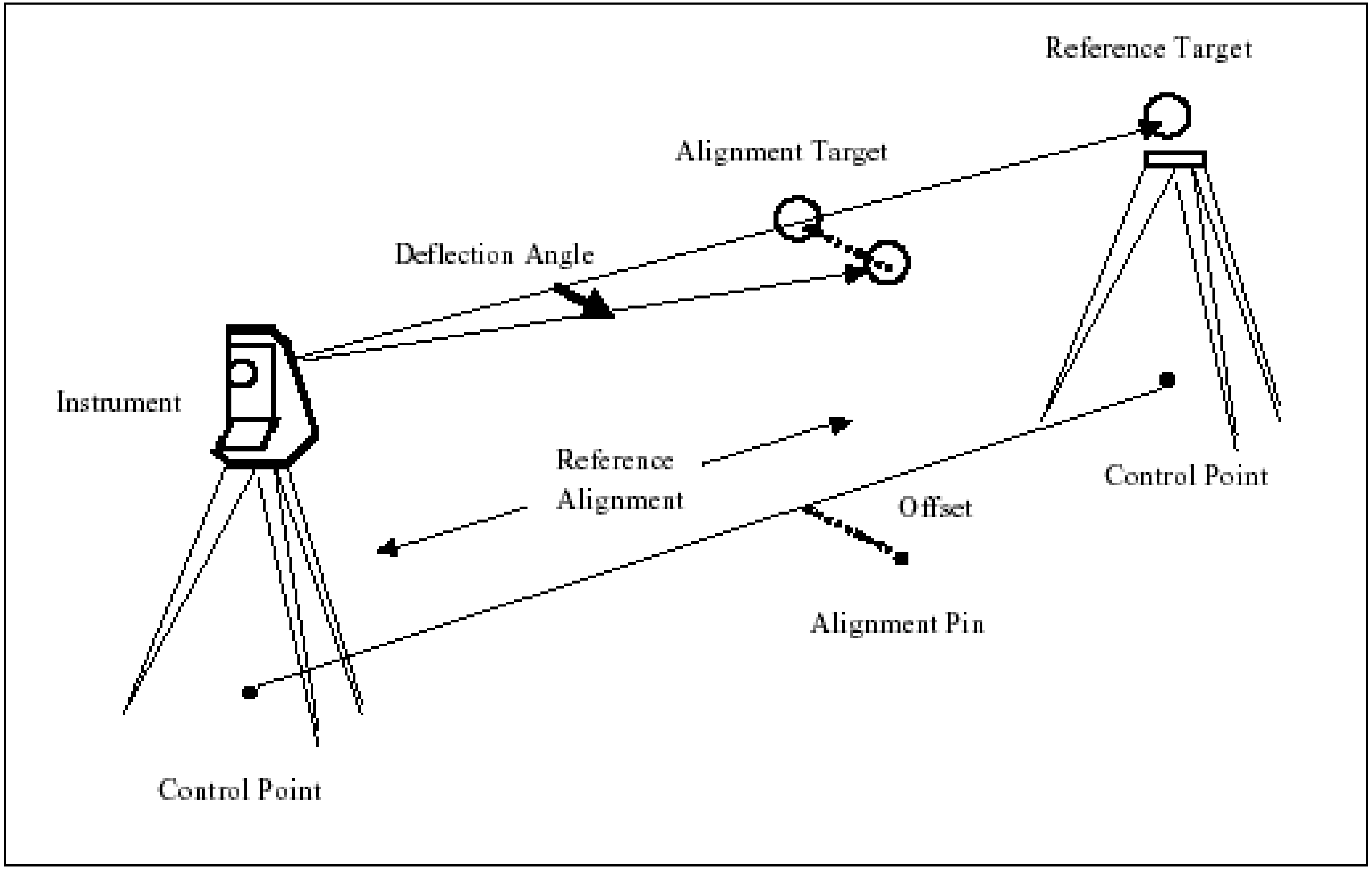


Figure 3-7. Direct optical alignment technique. Deflection angle method used to measure baseline offsets in conventional alignment surveys

3-8. Extension and Strain Measurements

- ***Types of extensometers***

Various types of instruments, mainly

Mechanical and Electromechanical,

are used to **measure changes in distance** in order to

- **Determine compaction or upheaval(yükselme) of soil,**
- **Convergence of walls in engineering structures and**
- **Underground excavations,**
- **Strain in rocks and in man-made materials,**
- **Separation between rock layers around driven tunnels,**
- **Slope stability, and**
- **Movements of structures with respect to the foundation rocks.**

3-8. Extension and Strain Measurements

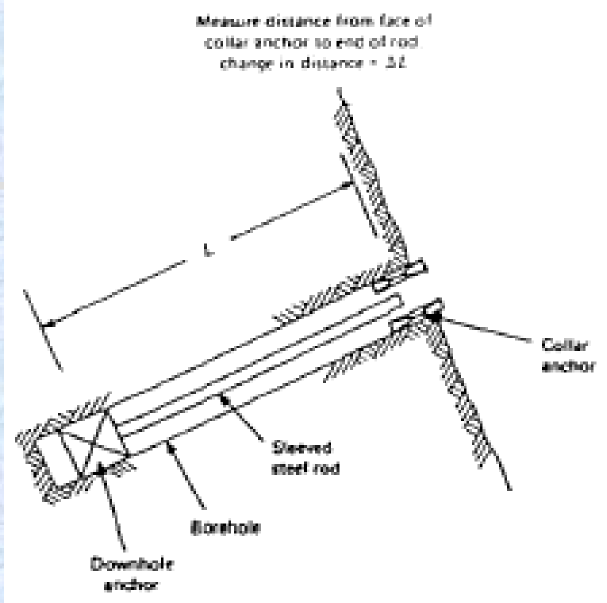
Same Instrument may be named

Extensometer,

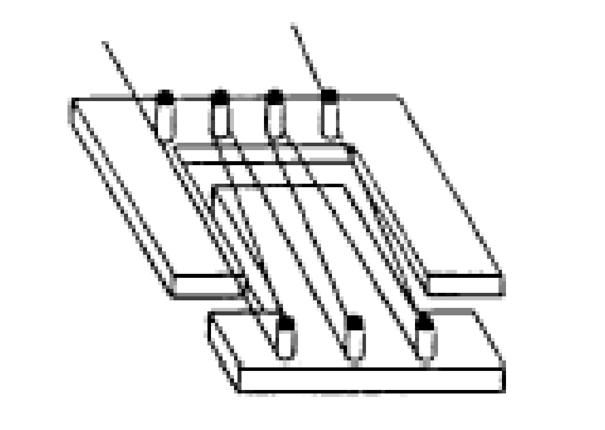
Strainmeter,

Convergencemeter,

Fissuremeter, Cracmeter



Borehole extesometer



wire resistance strain gage

3-8. Extension and Strain Measurements

- ***Types of extensometers***

- **Wire and tape extensometers**
- **Rod, tube, and torpedo extensometers**
- **Interferometric measurements of linear displacements**
- **Use of optical fiber sensors**
- **Precise concrete crack measurements**

Wire and tape extensometers

Both instruments use invar wires and special constant tensioning devices which, if properly calibrated and used, can give accuracies of 0.05 mm or better in measurements of changes of distances over lengths from about 1 m to about 20 meters. When only small changes in temperature are expected or a smaller precision (0.1 mm to 1 mm) is required, then steel wires or steel tapes are more comfortable to use.

Extension and Strain Measurements

Rod, tube, and torpedo extensometers

Steel, invar, aluminum, or fiberglass rods of various lengths, together with sensors of their movements, may be used depending on the application. A typical accuracy of 0.1 mm to 0.5 mm may be achieved up to a total length of 200 m (usually in segments of 3 m to 6 m).

Interferometric measurements of linear displacements

Various kinds of interferometers using lasers as a source of monochromatic radiation are becoming common tools in precision displacement measurements. A linear resolution of 0.01 μm, or even better, is achievable.

Extension and Strain Measurements

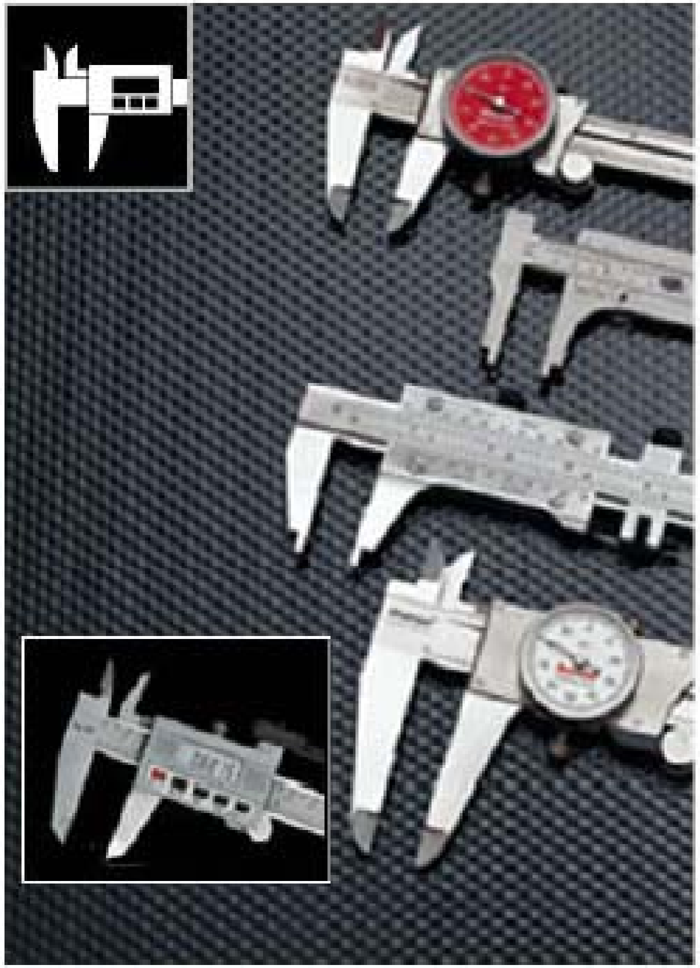
- **Use of optical fiber sensors**

A new development in the measurements of extensions and changes in crack-width employs a fully automatic extensometer that utilizes the principle of electro-optical distance measurements within fiber optic conduits. The change in length of the fiber optic sensors are sensed electro-optically and are computer controlled.

- **Precise concrete crack measurements**

Distances between cracks in concrete structures are typically measured using precision micrometers or calipers, such as those as shown in Figure 3-8.

Extension and Strain Measurements



Various slide and vernier calipers

Inside & outside micrometers

Figure 3-8. Micrometers and calipers that can be used for measuring short distances in concrete structures to an accuracy of 0.0005 inch or better

3-9. Tilt and Inclination Measurements

Methods of tilt measurement

The measurement of tilt is usually understood as the determination of a deviation from the **horizontal plane**, while **inclination** is interpreted as a deviation from the **vertical**. The same instrument that measures tilt at a point can be called either a tiltmeter or an inclinometer depending on the interpretation of the results. Geodetic leveling techniques can achieve an accuracy of 0.1 mm over a distance of 20 m, which would be equivalent to about 1.0 inch of angular tilt.

- **Engineering Tiltmeters and Inclinometers**
- **Suspended and Inverted Plumb Lines**
- **Hydrostatic Levels**

3-9. Tilt and Inclination Measurements

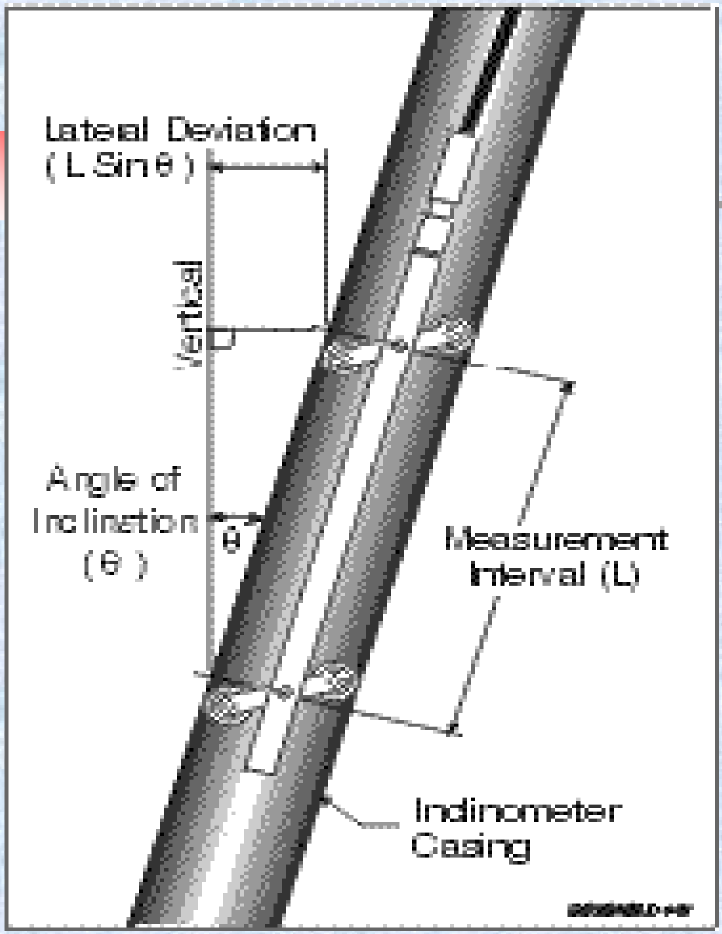
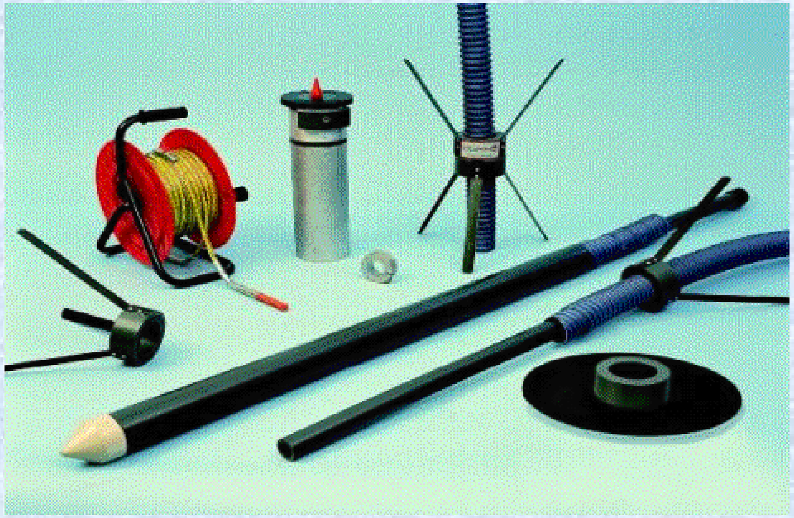


Figure: Inclinometer



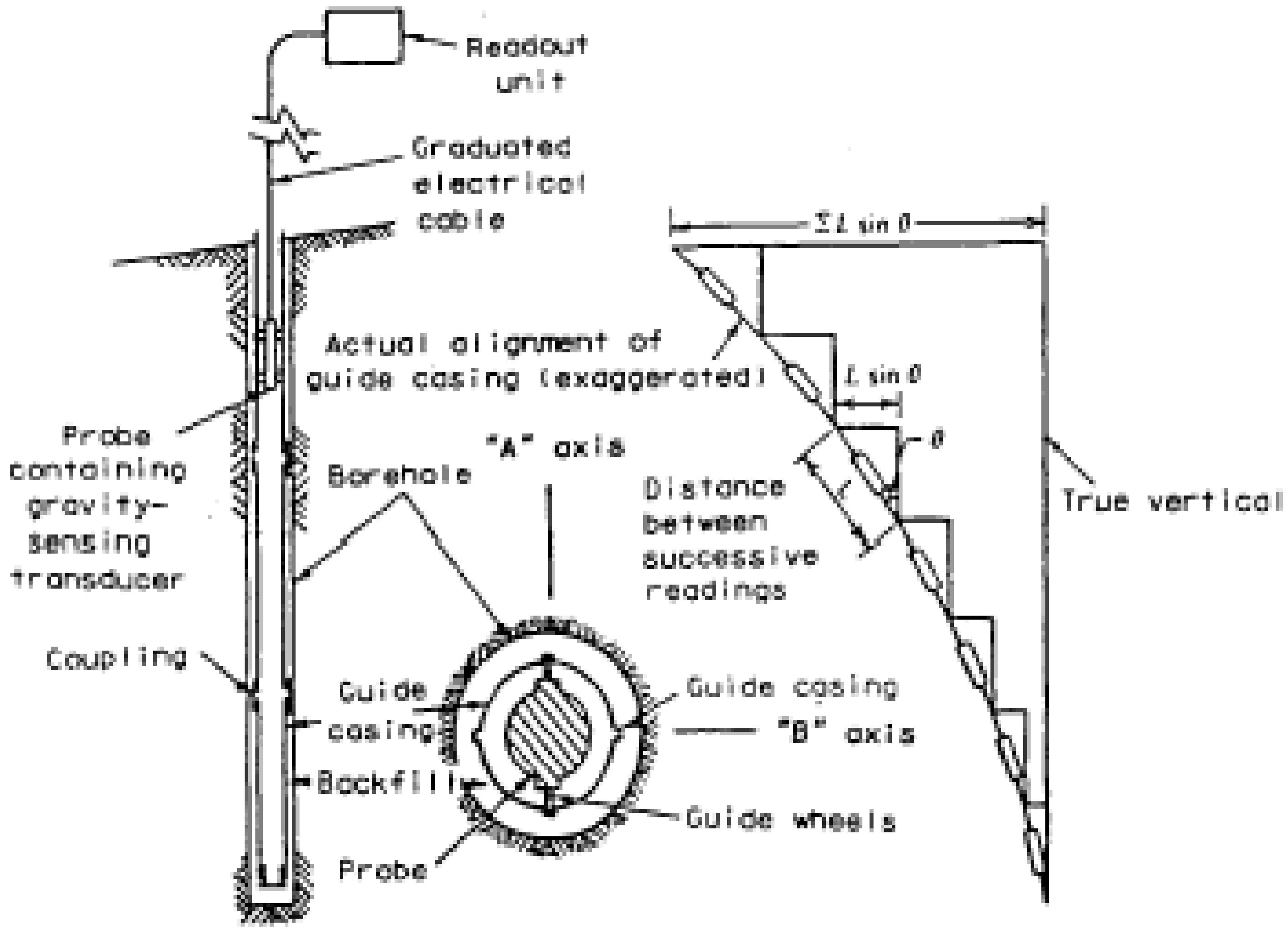
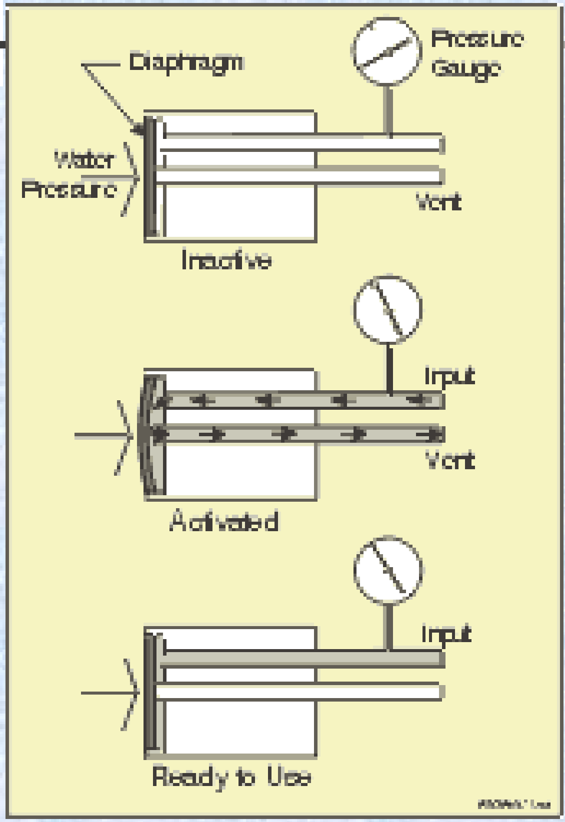


Figure: Principle of Inclinometer Operation



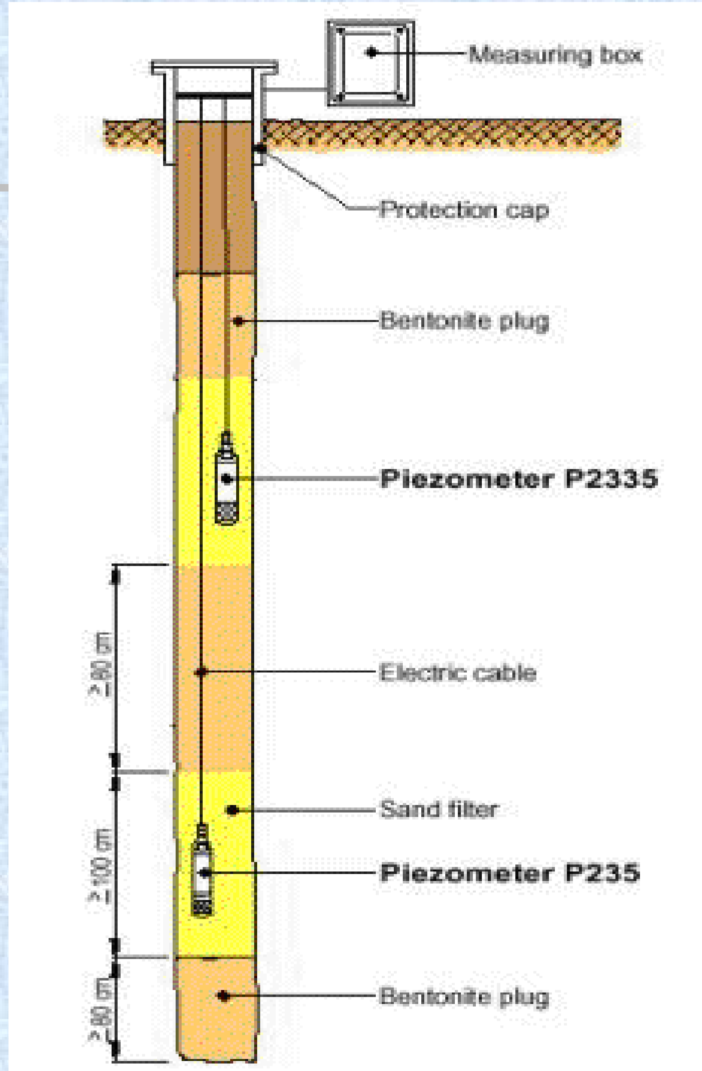
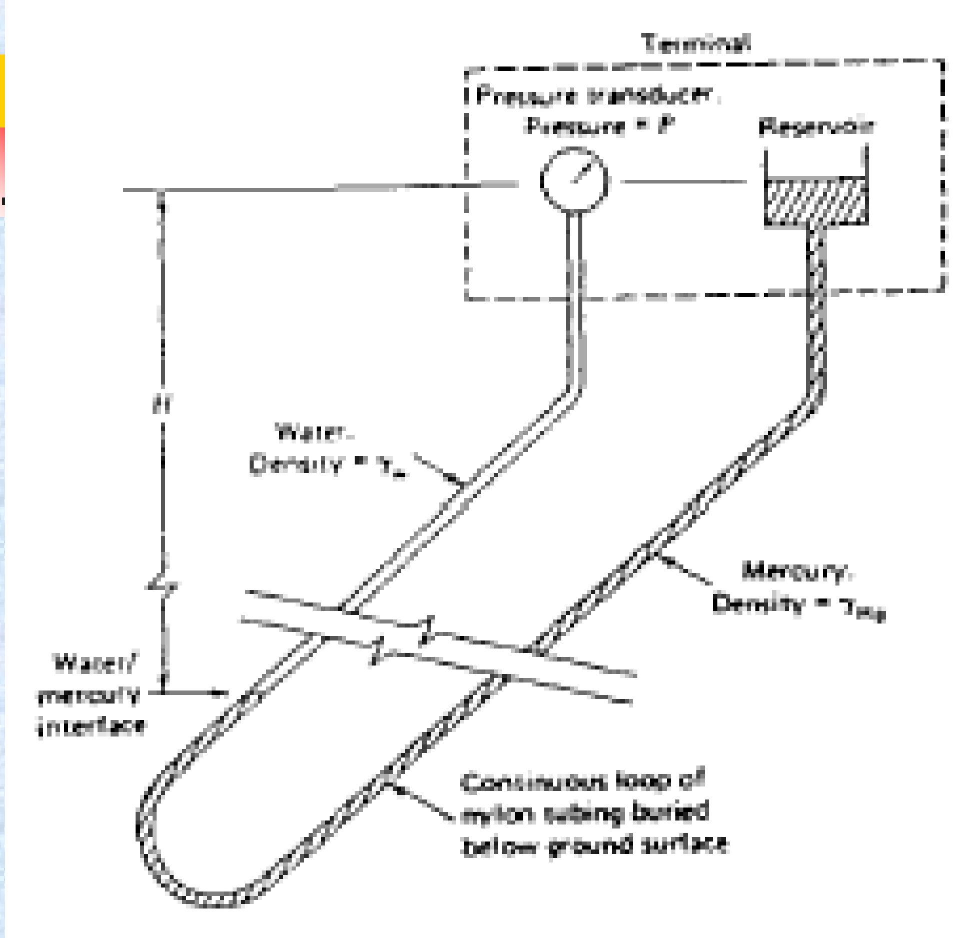


Figure: Piezometer



Schematic of double fluid settlement gage

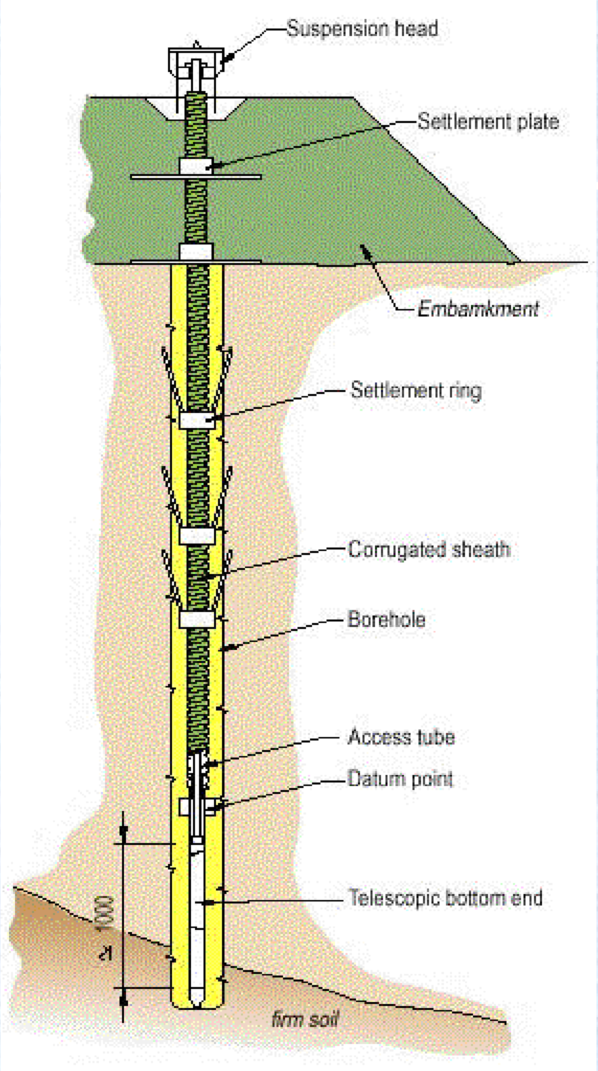


Figure: Settlement gage

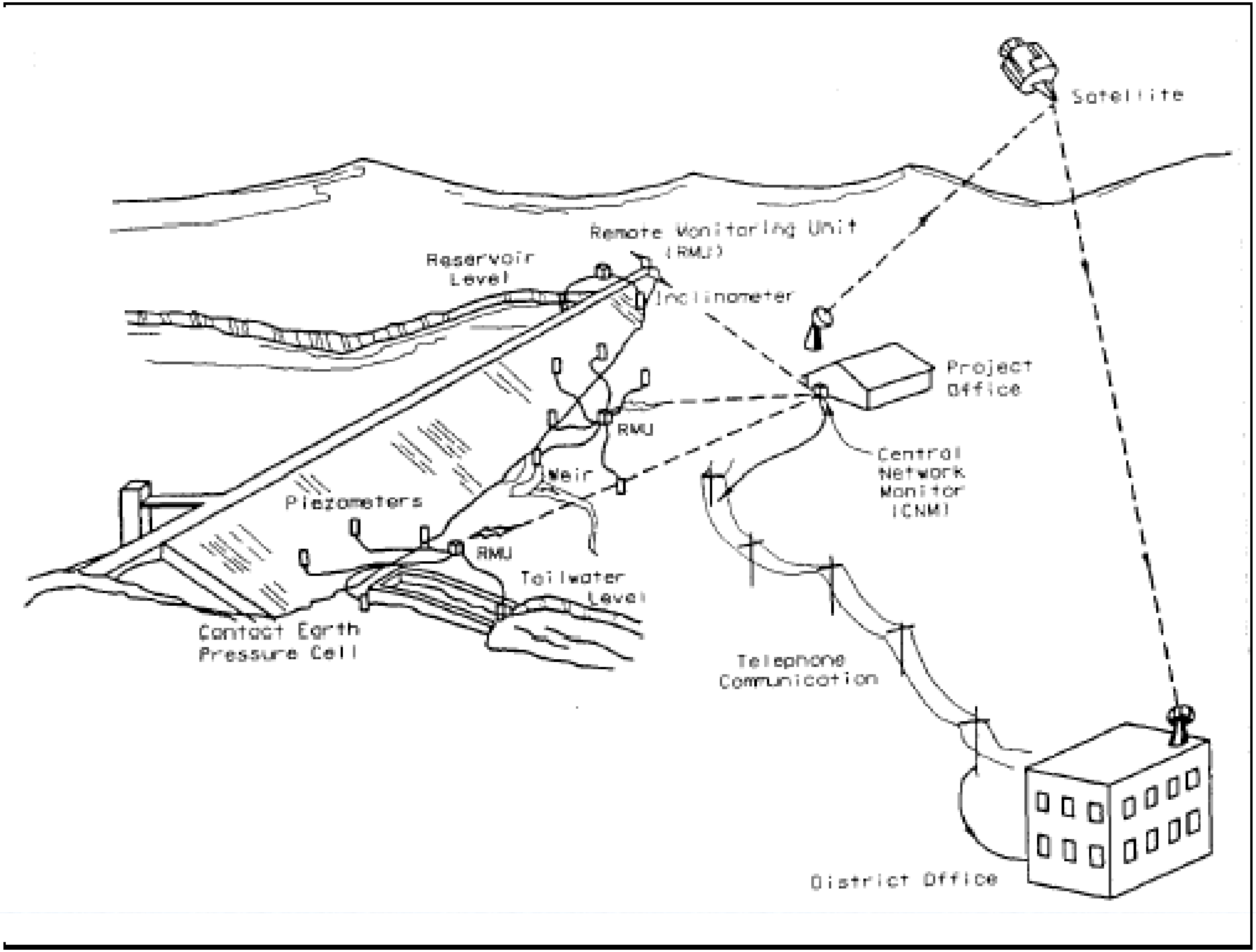
Tilt and Inclination Measurements

***Tiltmeters and inclinometers*.**

There are many reasonably priced models of various **liquid, electrolytic, vibrating wire, and pendulum type tiltmeters** that satisfy most of the needs of engineering surveys.

Tiltmeters have a wide range of applications.

- A series of tiltmeters if arranged along a terrain profile may replace geodetic leveling in the determination of ground subsidence.
- Deformation profiles of tall structures may be determined by placing a series of tiltmeters at different levels of the structure.
- A popular application of tiltmeters in geomechanical engineering is in slope stability studies and in monitoring embankment dams using the torpedo (scanning) type borehole inclinometers (usually the servo-accelerometer type tiltmeters).



Automatic data acquisition system geotechnical instrumentation

3-9. Tilt and Inclination Measurements

Suspended and inverted plumb lines

Two kinds of mechanical plumbing are used in controlling the stability of vertical structures:

(1) Suspended Plumb Lines,

(2) Floating or Inverted Plumb Lines.

- Generaly, invar wire is used for the inverted plumb line, vertical movements of the investigated structure with respect to the bedrock can also be determined.

- The plumb wire can be positioned with respect to reference lines of a recording (coordinating) table to an accuracy of ±0.1 mm or better.

Tilt and Inclination Measurements

Optical plummets

High precision optical plummets (e.g., Leica ZL (zenith) and NL (nadir) plummets) offer accuracy of up to 1/200,000 for precise centering, and both can be equipped with laser. Atmospheric refraction remains as a major source of error for optical instruments.

Hydrostatic leveling

If two connected containers are partially filled with a liquid, then the heights h1 and h2 of the liquid in the containers are related through the hydrostatic equation

$$h_1 + P_1 / (g_1 r_1) = h_2 + P_2 / (g_2 r_2) = \text{constant} \qquad \text{(Eq 3-5)}$$

where ***P*** is the barometric pressure, ***g*** is gravity, and ***r*** is the density of the liquid which is a function of temperature. The accuracy ranges from 0.1 mm to 0.01 mm over a few tens of meters depending on the types of instruments.

3-10. Non-Geodetic Measurements

Deformation of large structures (e.g., dams) is caused mainly by reservoir loads, temperature, self-weight of the dam, and earth pressure. A monitoring system should therefore include regular measurements of the reservoir level and temperature and pressure data.

- **Reservoir level measurement**
- **Temperature measurement**
- **Precipitation measurement**
- **Seepage rate**
- **Chemical property analysis**
- **Pore-water pressure measurement**
- **Uplift pressure**
- **Discharge measurement**

3-11. Optical Tooling Technology

Optical tooling uses the principle that light travels in straight lines so as to enable precise measurements and level lines with every point is perpendicular to the force of gravity (e.g., plumb lines can be set to a given level datum).

Four basic alignment elements are used.

- straightness
- flatness
- squareness
- plumb

Straightness:

A tight wire is often used as a reference line.

Laser alignment

The Line of Sight

Optical Tooling Technology

Flatness(düzlük):

Conventional bubble levels and "laser levels," offer a way to produce a level datum over a wide area. This high degree of levelness is accomplished by horizontally sweeping the laser beam manually or via a motor driven rotary stage. This revolving line of laser light becomes a horizontal "plane of sight," giving a precise horizontal reference datum, sometimes called a waterline.

Squareness:

Perfect squareness implies that one plane forms a 90 degree angle with another intersecting plane.

Plumb:

A plumbline and pendulum are used to establish a single vertical reference line. This reference line is accomplished by a line of sight or laser beam.

3-12. Laser Tooling Method

- **Straightness alignment**
- ***Alignment transfer***
- **Oriented alignment**
- **Alignment plane**

3-14. Laser Alignment Techniques

- **Single target laser alignment**
- **Two target laser alignment**

Laser Alignment Techniques

Two target laser alignment

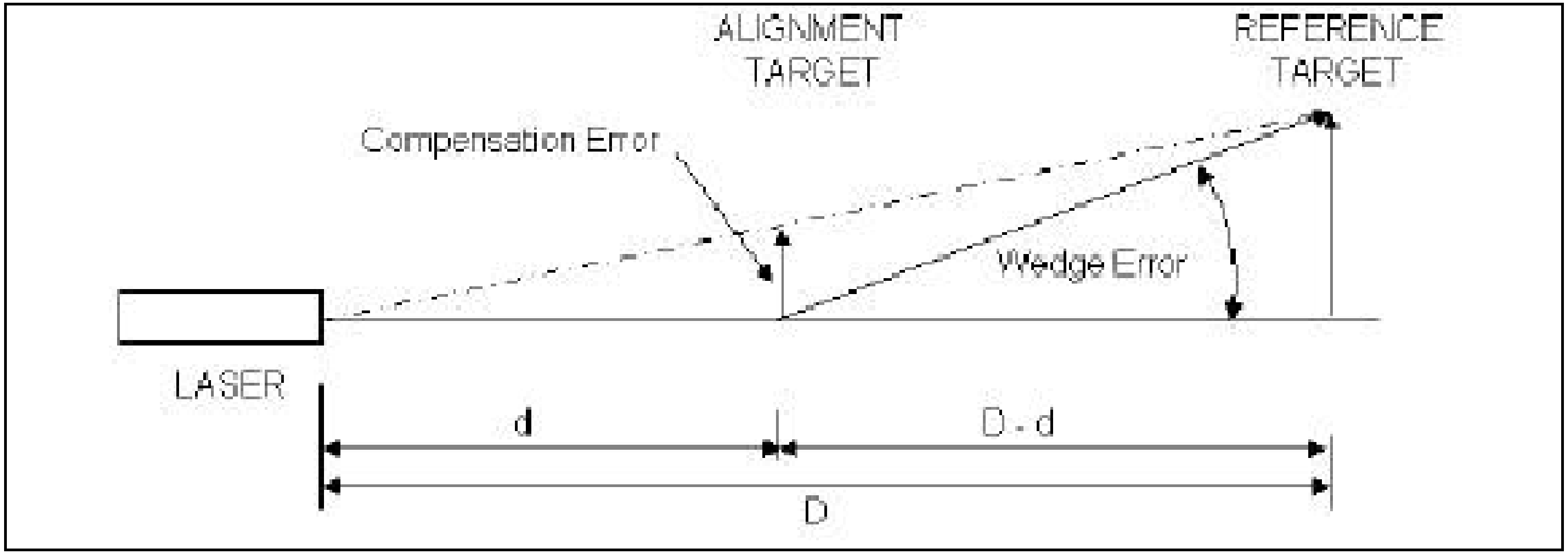


Figure 3-9. Geometry of a two target laser alignment.

Laser Beam Propagation

Table 3-3. Depth of Field for Different Laser Beam Diameters

Initial Diameter	Depth of Field (m)	Depth of Field (feet)
1 mm	1.2	4
4 mm	20	64
10 mm	123	403
20 mm	492	1614
25 mm	769	2522

Table 3-5. AGL laser system beam diameter and range.

Range (meters)	Beam diameter (mm)
0	9.4
213	20
427	45
609	66

Laser Alignment Equipment

This section describes some laser alignment equipment(Figure 3-11).

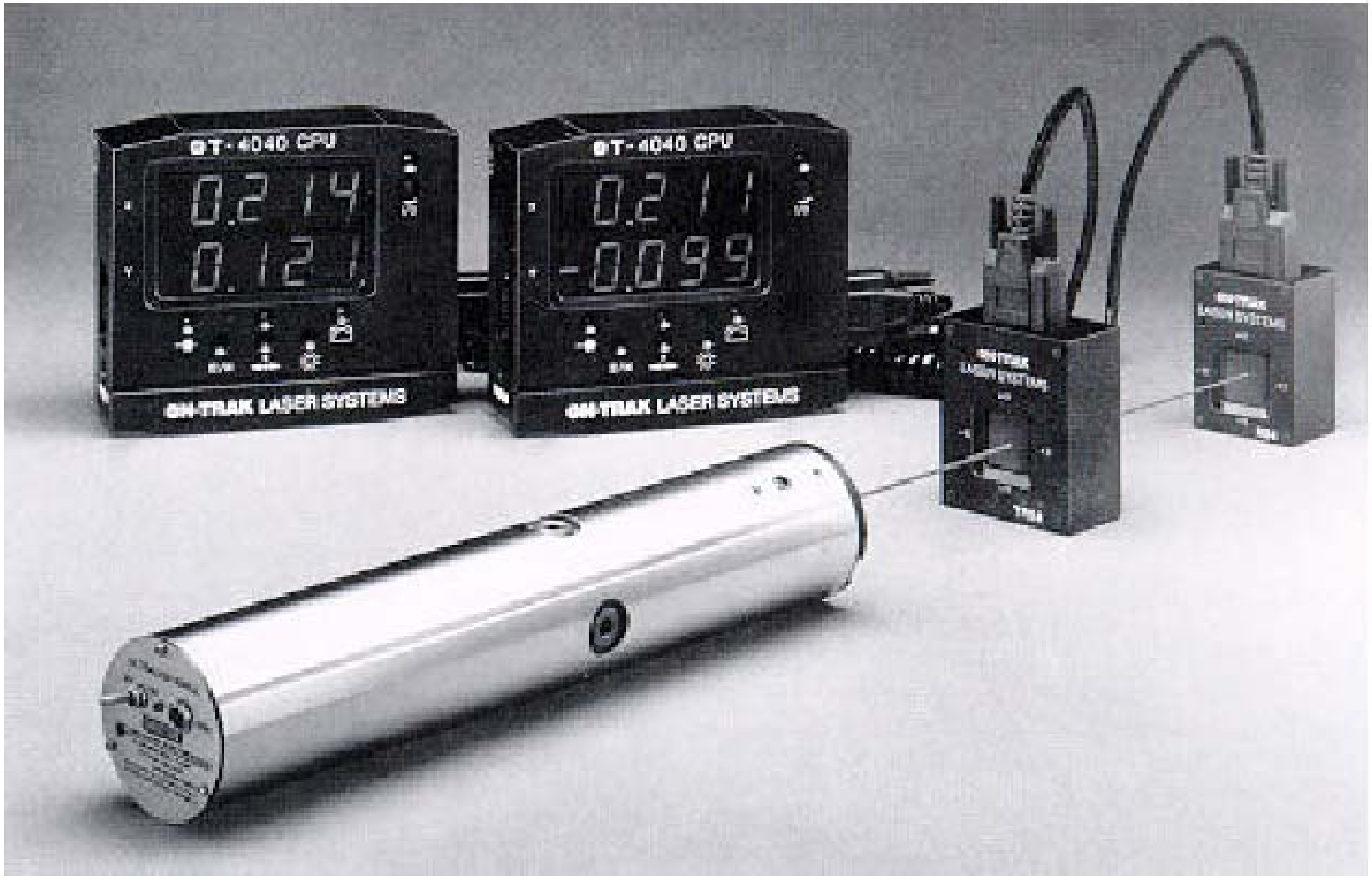


Figure 3-11. Laser alignment system from ON-TRAK Photonics, Inc.

Laser Alignment and Scanning Systems

Table 3-4 contains a partial list of manufacturers of laser alignment and scanning systems with tabulated measurement ranges, target capture areas, accuracies, and product data such as whether the vendor can design scanning, alignment, and custom systems.

Table 3-4. Laser system manufacturers and performance

Manufacture	Scan	Align	Custom	Range	Area in.	Accuracy in.
On-Trak	Y	Y	Y	2700 ft.	0.500	0.001
Hamar	Y	Y	Y	100 ft.	0.075	0.001
Pruf-Tecnik		Y		30 ft.	0.100	0.001
PinPoint		Y		30 ft.	0.250	0.010

Construction Lasers and Machine Control Systems

produces a commercial laser alignment and digital laser theodolite package used for tunneling, mining, and alignment control.

Components of the system are:

- **Laser transmitter**
- **Alignment Base Plate**
- **Digital laser theodolite**

Table 3-5. AGL laser system beam diameter and range.

Range (meters)	Beam diameter (mm)
0	9.4
213	20
427	45
609	66

Laser survey accuracy evaluation.

$\sigma = + 0.042$ inches (1.07 mm),

meaning that the derived deflections would have a 95% confidence value of:

(1.07) (sqrt (2)) (1.96) = 2.97 mm.

3-19. Suspended and Inverted Plumblines

Plumbline readings since 1991 indicate that both monoliths are stable within

+0.25 mm (0.01 inch) in the U/D direction and within
+1mm (0.04 inch) along the axis of the dam.

Suspended and Inverted Plumblines

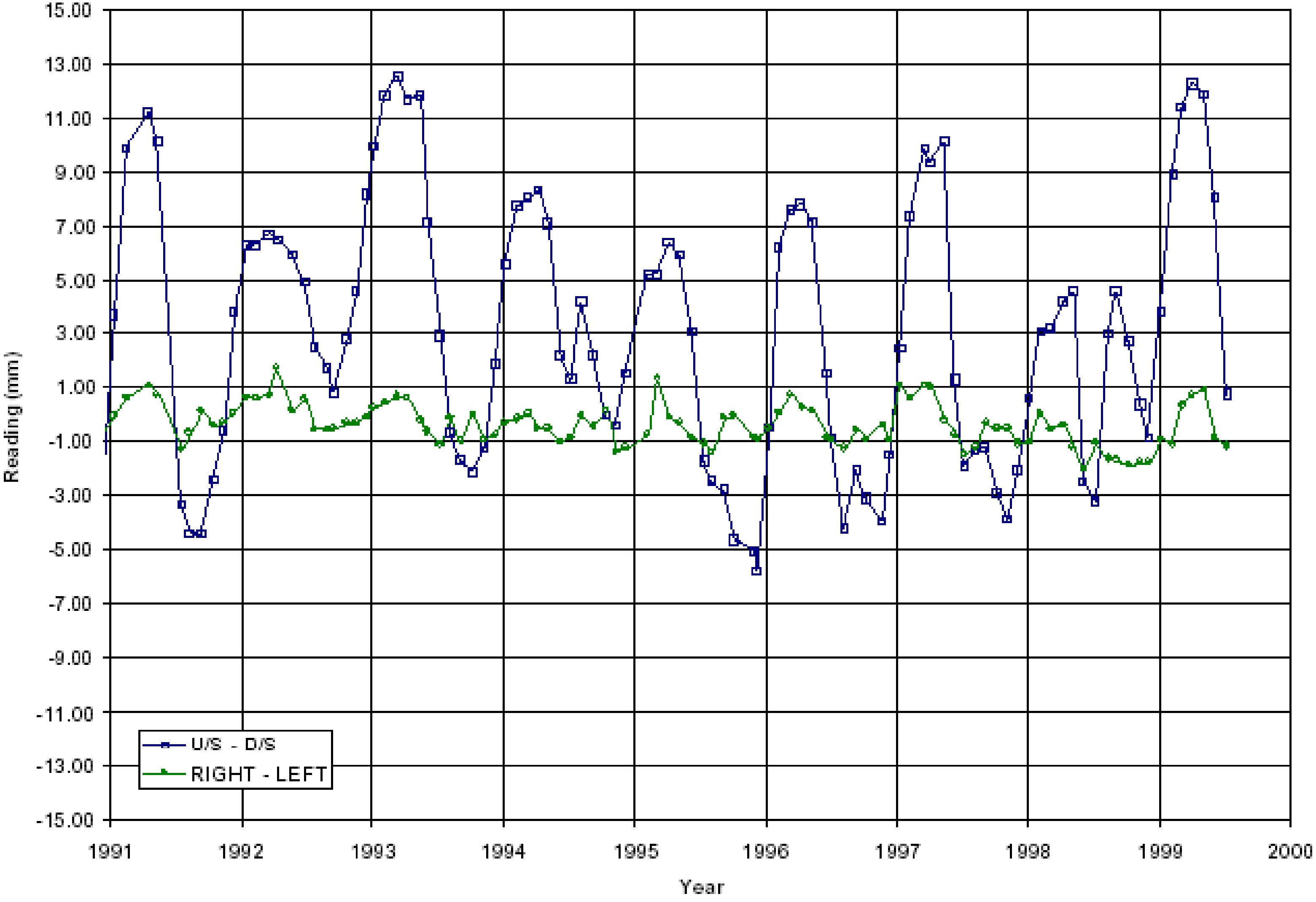


Figure 3-14. Combined readouts from suspended and inverted plumblines at Monolith 23, Libby Dam

Comparison of Alignment System

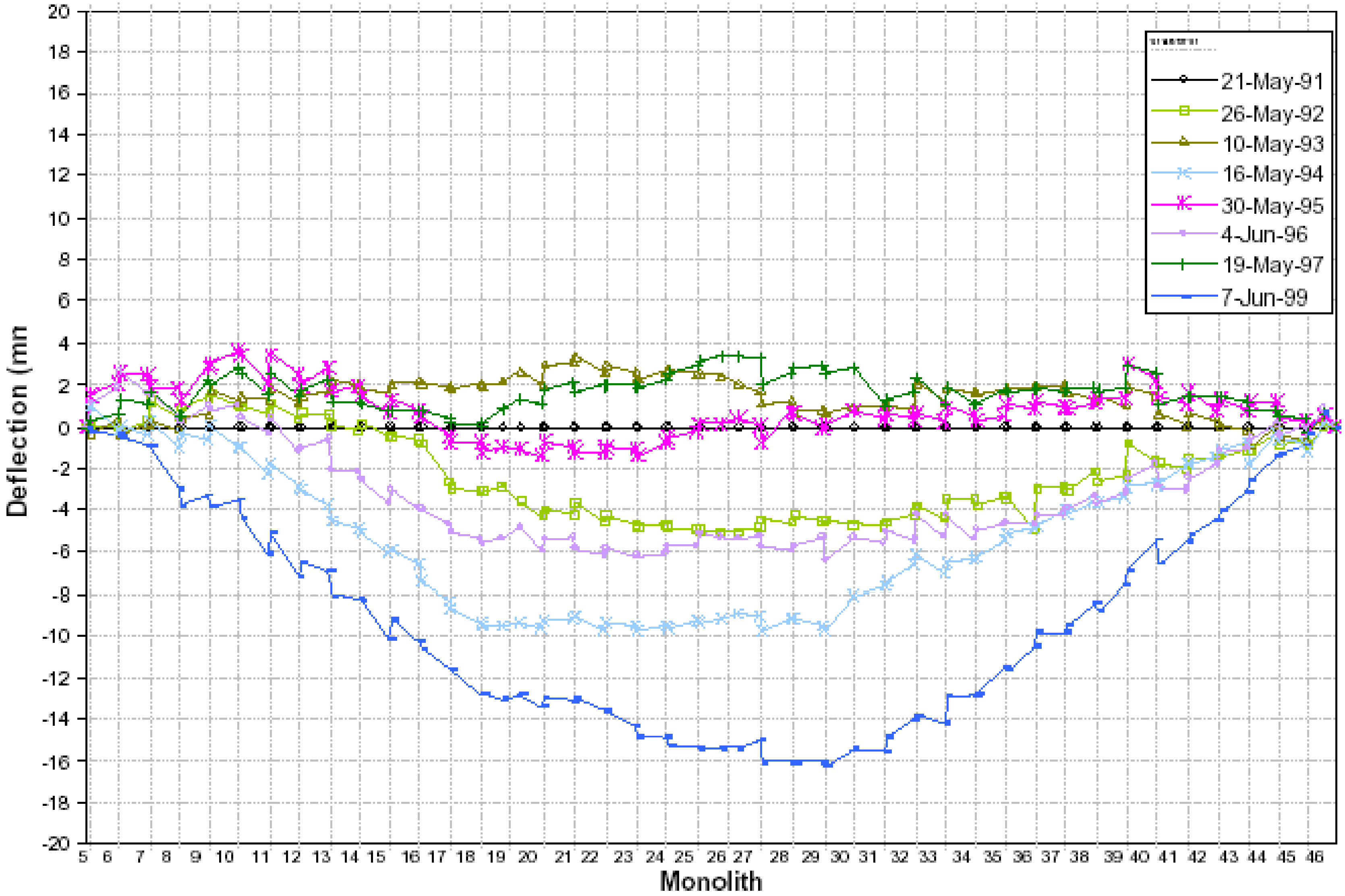


Figure 3-15. May results of Libby laser alignment (1991 base)

Comparison of Alignment System

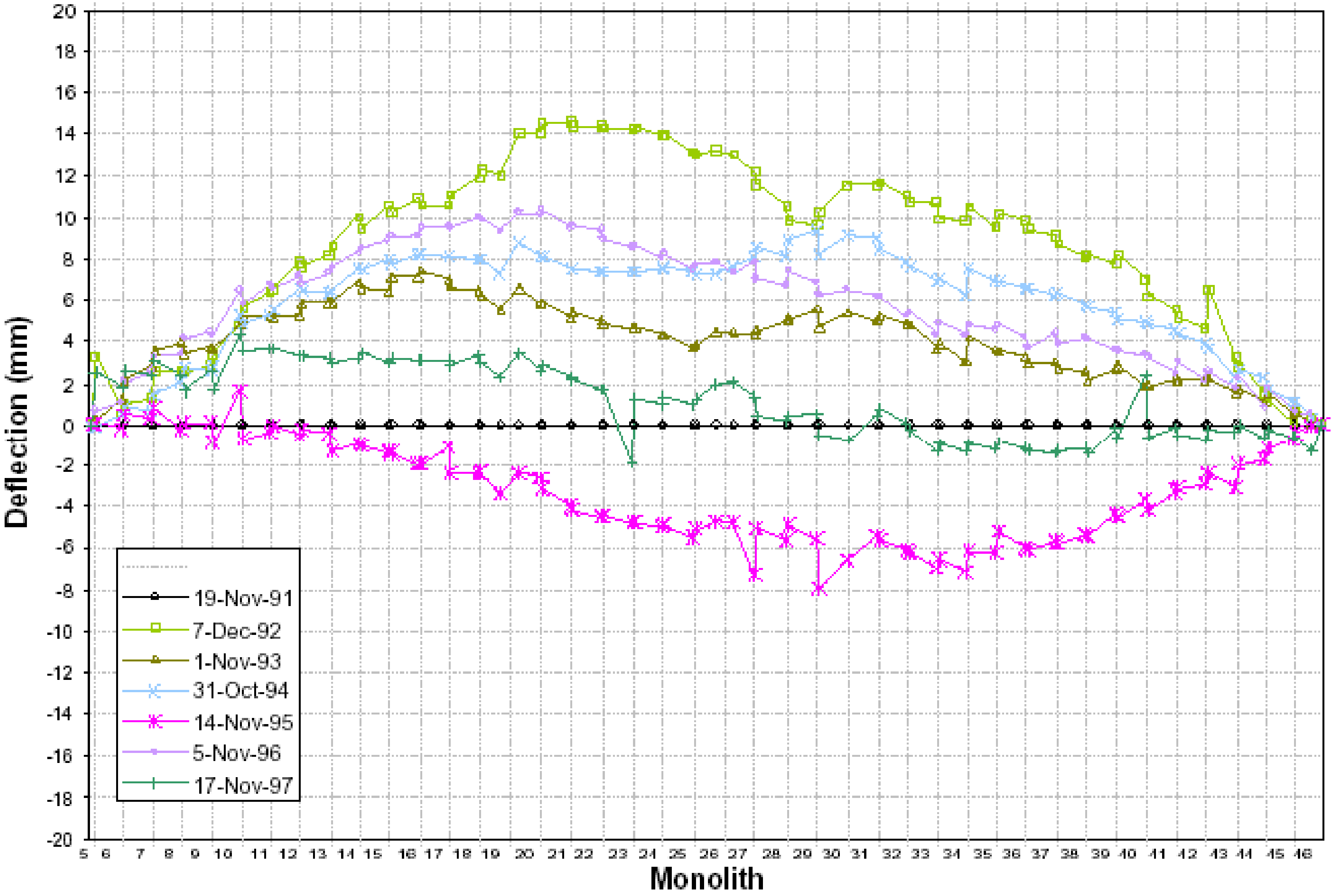


Figure 3-16. November results of laser alignment (1991 base)

Comparison of Alignment and Plumbline Systems

Table 3-6. Comparison of laser alignment with plumbline data

Date	Plumb (mm)	Reduced (1991)	Laser (mm)	Diff Δ (mm)	Temp (°C)	ΔT/Δy (°C/m)
1991-05-21	6.9	0.0	0.0	0.0	13	
1992-05-26	5.8	-1.1	-4.6	-3.5	14	-0.05
1993-05-10	11.8	4.9	2.5	-2.4	11	-0.03
1994-05-16	5.2	-1.7	-9.4	-7.7	14	-0.11
1995-05-30	3.7	-3.2	-1.0	2.2	18	0.03
1996-06-04	3.5	-3.4	-6.1	-2.7	14	-0.04
1991-11-19	0.4	0.0	0.0	0.0	8	
1992-12-07	7.1	6.7	14.2	7.5	3	0.10
1993-11-01	-1.3	-1.7	4.6	6.3	12	0.09
1994-10-31	-0.3	-0.7	7.4	8.1	12	0.12
1995-11-14	-5.0	-5.4	-4.3	1.1	8	0.02

Sources of Measurement Error and Instrument Calibrations

Surveying Measurement Errors

Random error

- pointing error
- centering error
- leveling error
- reading error

Systematic error

- EDM/prism zero error
- EDM scale error
- EDM signal refraction error
- EDM cyclic error

Settlement Surveys
(Vertical deformation Surveying)

Vertical settlement determined by precision differential leveling is performed using compensatory autocollimation or sprit leveling instruments with fixed or attached parallel plate micrometers, and observing invar double (offset) scale metric rods with supporting struts.

Settlement Surveys

Precise Differential Leveling Observations

Precise Level

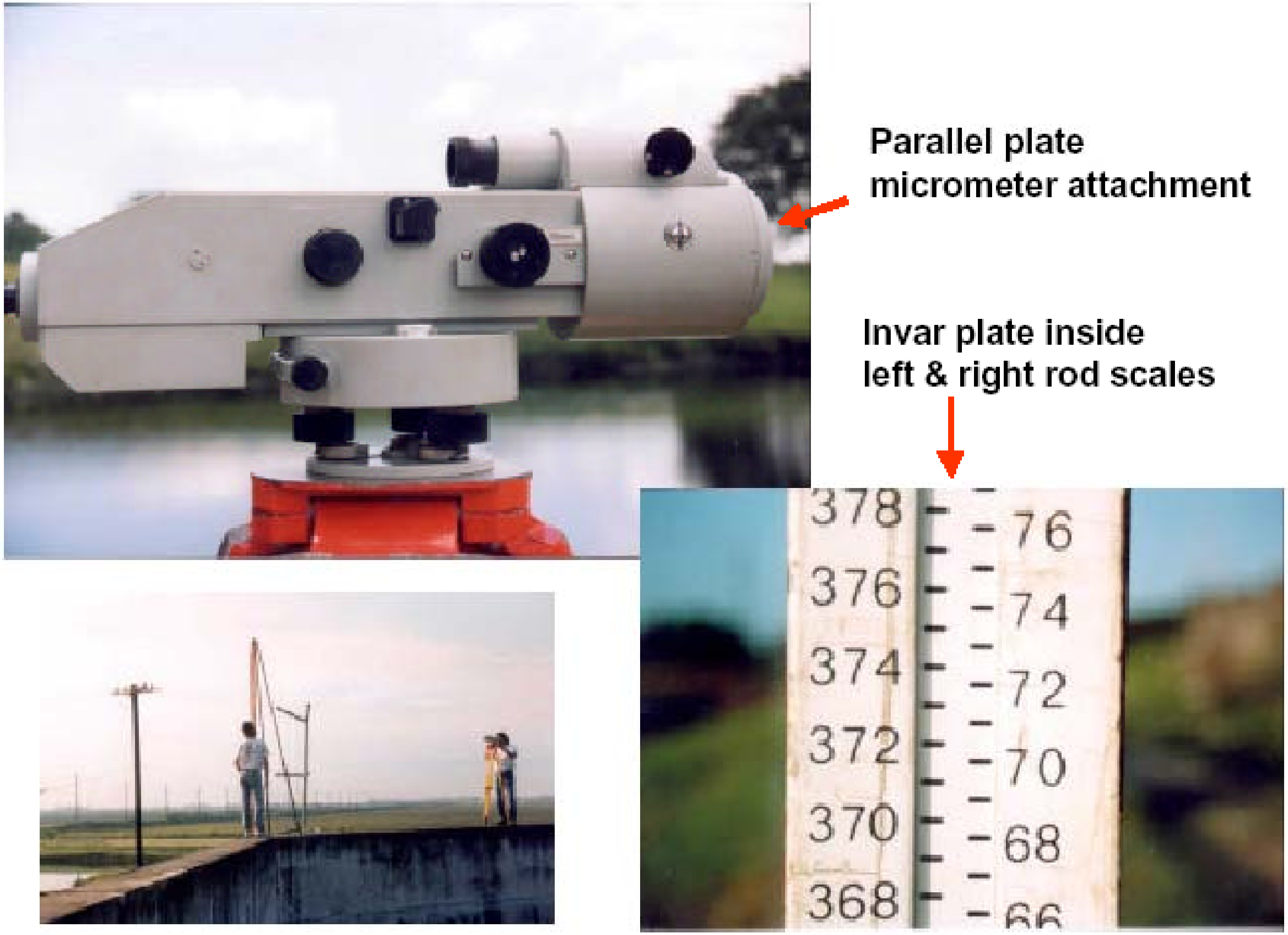


Figure 6-2. Zeiss Ni1 automatic level with parallel plate micrometer attached. Double-scale Invar rod with constant 3.01550 meter difference in left and right scales

Precise Differential (Geometrical) Leveling

When determining elevation by precise spirit leveling, the following guidelines will be followed.

1. *Double-run level section*
2. *Sighting convention.*
3. *Rod readings.*
4. *Stadia distance.*
5. *Foresight sideshots.*
6. *Rod settlement.*
7. *Rod index error.*
8. *Ground refraction.*

Alignment, Deflection, and Crack Measurement Surveys --Micrometer Observations

This chapter describes micrometer observation methods for accurately measuring small relative deflections or absolute deformations in hydraulic structures.

Figure 7-1. Alignment micrometer measurements relative to fixed baseline

Relative Alignment Deflections from Fixed Baseline

Deflections of points along structural sections can be monitored by observing their offset from an alignment established by two baseline control points. The deflection of a point relative to a fixed baseline is observed either by micrometer target methods

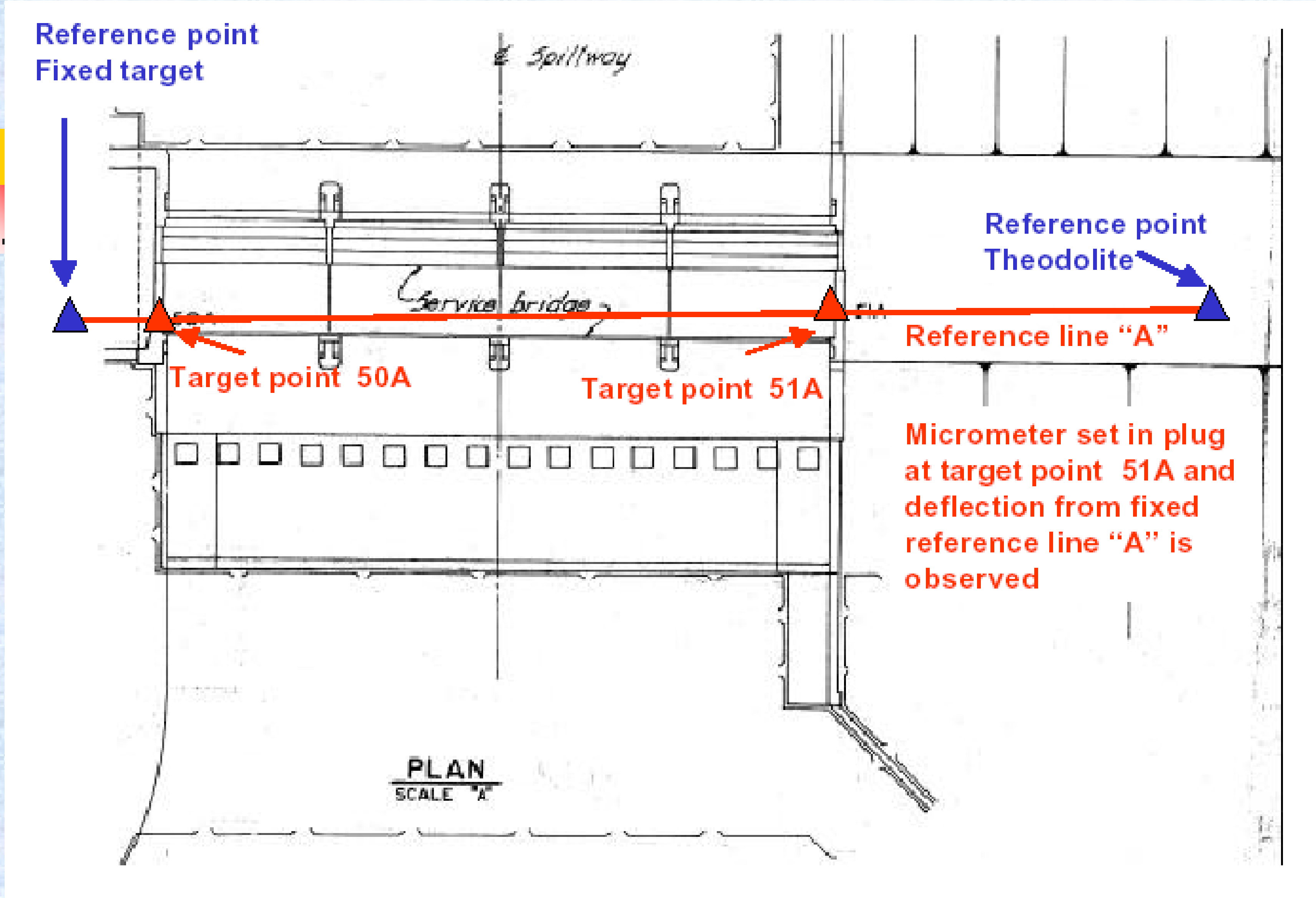


Figure 7-2. Typical relative alignment deflection measurements of concrete structures relative to fixed baseline.

Micrometer Crack Measurement Observations

This section describes absolute micrometer joint or crack measurement procedures using micrometers.

Expected short-term accuracy is on the order of

± 0.0005 inch,

relative to the fixed calibration reference bar.

Estimated long-term crack measurement accuracy is at the

± 0.005 to 0.010 inch level;

Micrometer Crack Measurement Observations

Figure 7-5. Starrett vernier caliper crack measurements between monoliths.

GPS

GLOBAL POSİTİONİNG SYSTEM

Monitoring Structural Deformations Using the Global Positioning System

This chapter provides technical guidance on the use of the Global Positioning System (GPS) for monitoring and measuring three-dimensional (3D) displacements on large engineering structures.

Applications of GPS for the determination of long-term stability and movement on dams, navigation locks, and other similar types of construction projects are described.

- ***Monitoring Structural Deformations with GPS***
- ***GPS Performance on Monitoring Networks***
- ***Data Quality Assessment for Precise GPS Surveying***
- ***Mitigation of Multipath Signals.***

Global Positioning System

1. Purpose
2. Background
3. Scope of Chapter
4. Surveying Requirements
5. Surveying Procedures
6. Data Processing Procedures
7. GPS Monitoring Applications
8. GPS Survey Reporting and Results
9. GPS Performance on Monitoring Networks

GPS Performance on Monitoring Networks

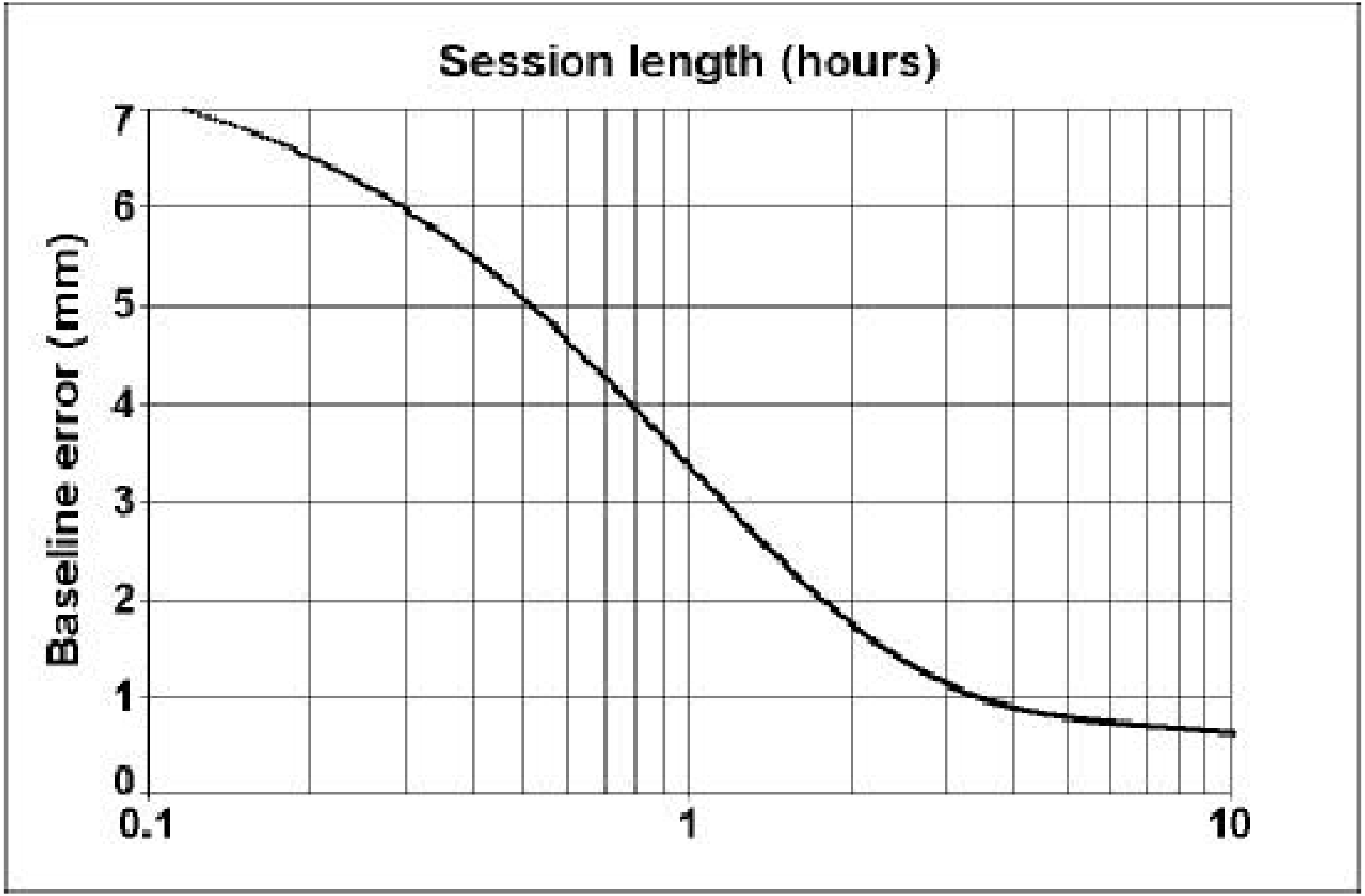


Figure 8-3. Accuracy convergence time plotted as log session length needed to exceed average baseline position error.

GPS Performance on Monitoring Networks

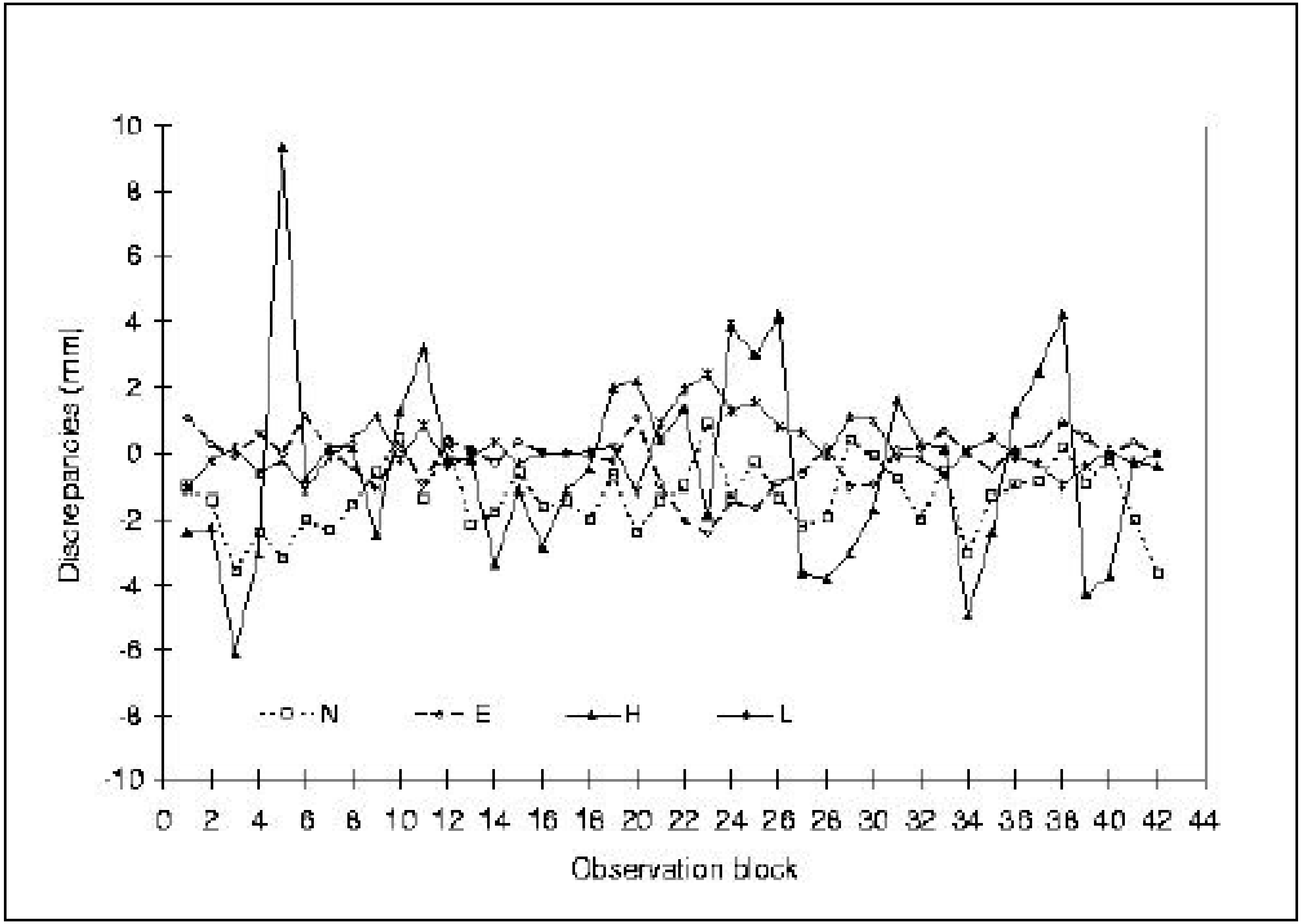


Figure 8-2. GPS coordinate component repeatability from 15-minute sessions over short baselines.

GPS Surveying Session length.

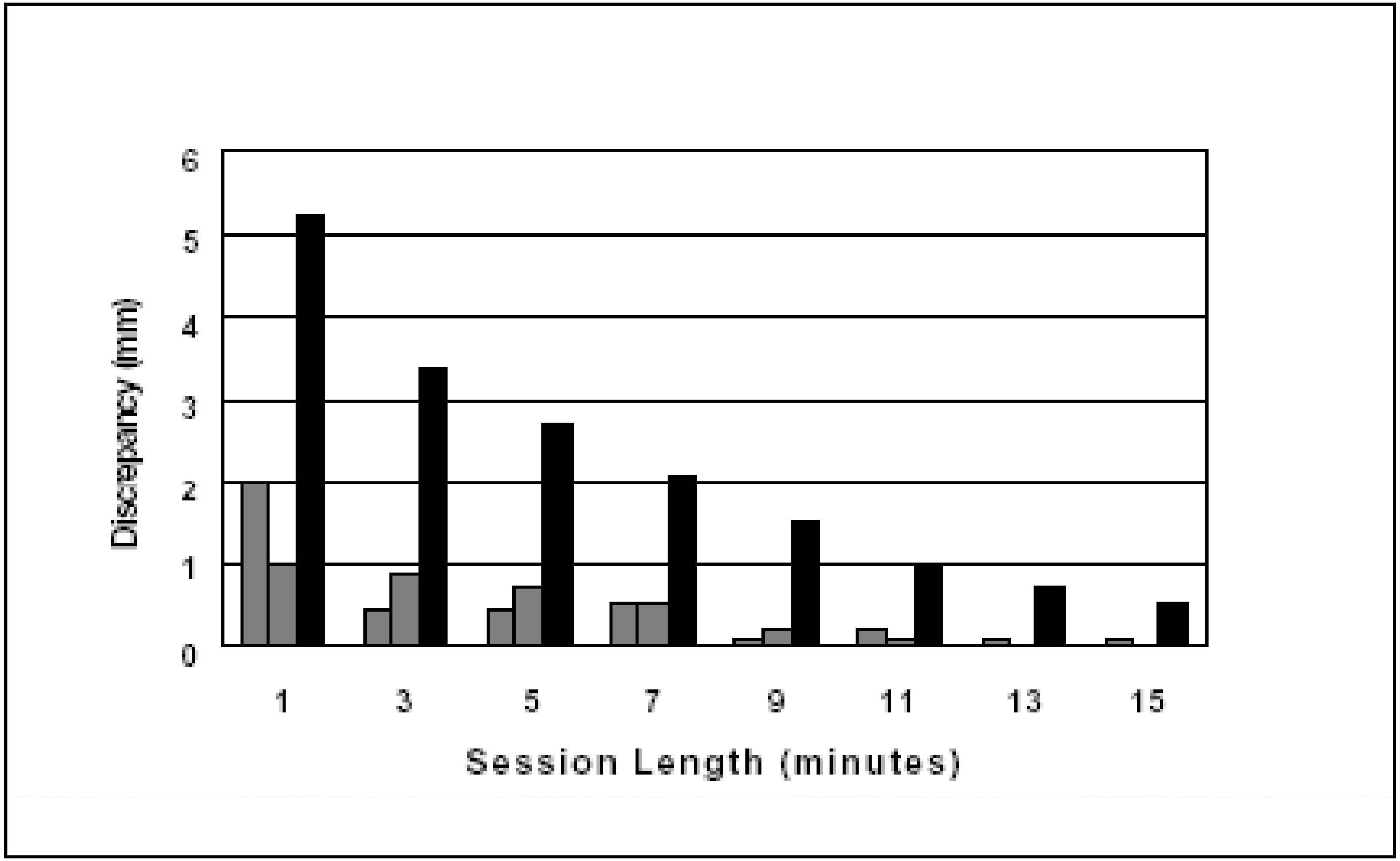


Figure 8-6. Convergence of coordinate component discrepancies to the true position with a simulated displacement of 2.5 mm. For each session the components are plotted north, east, height respectively.

Global Positioning System

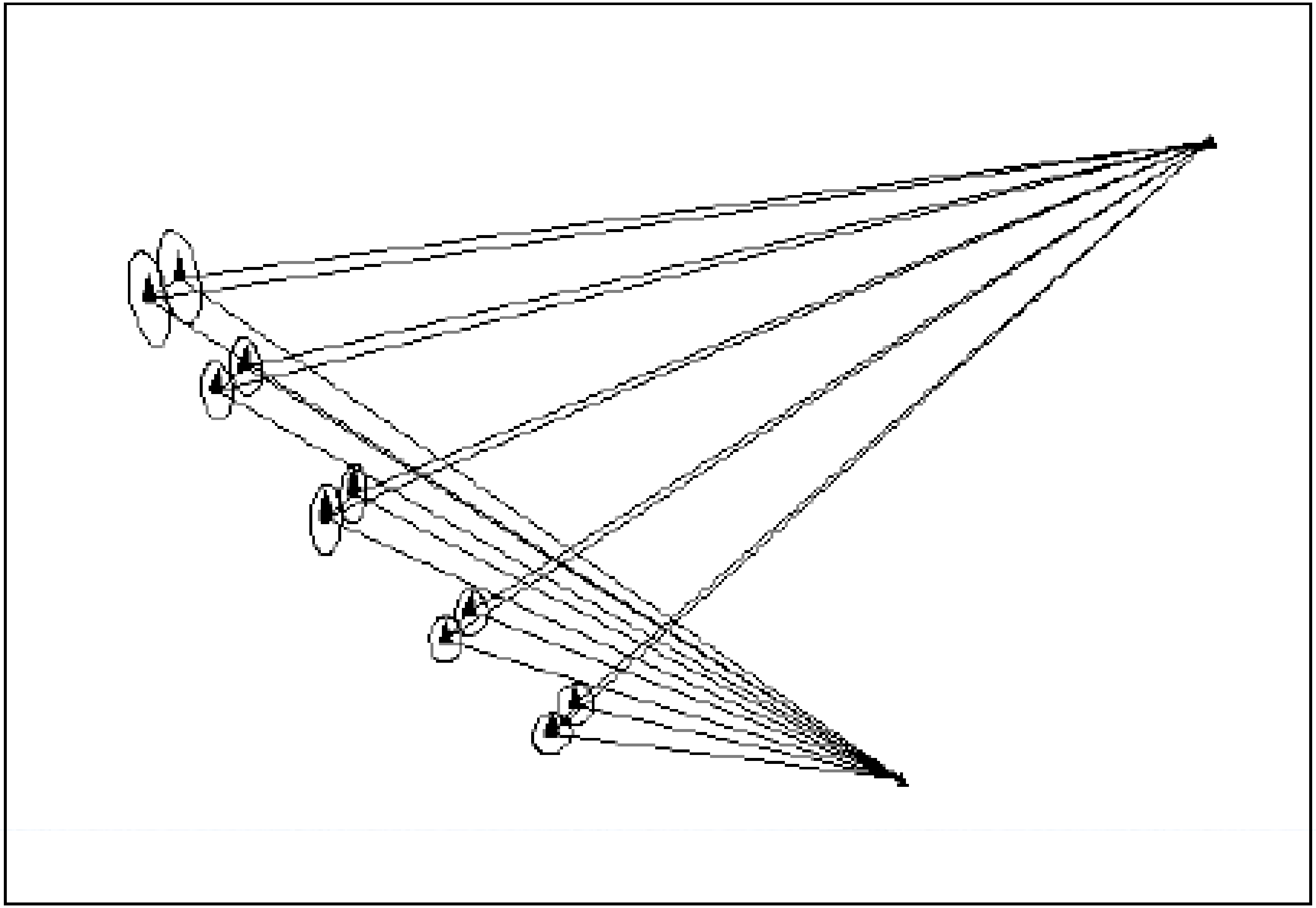


Figure 8-7. Network map of 10 monitoring points compared between GPS and precise conventional surveying results. Error ellipses are plotted at ten times actual size. Overall differences are less than 2-3 mm in all cases.

Adjustment Output Parameters

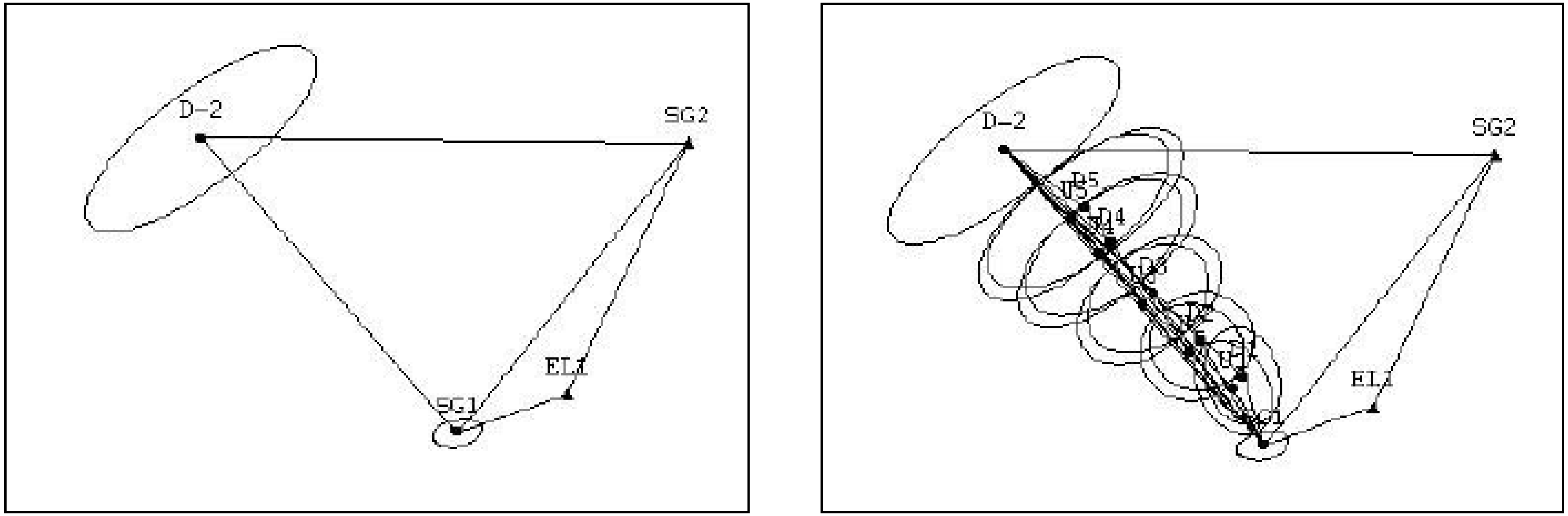


Figure 9.5. Adjustment output plots showing the reference network and monitoring network. The left-hand plot shows only the reference network stations with their error ellipses. The right-hand plot shows both the reference stations and the structure monitoring points with their error ellipses.

Network Maps
connections between points

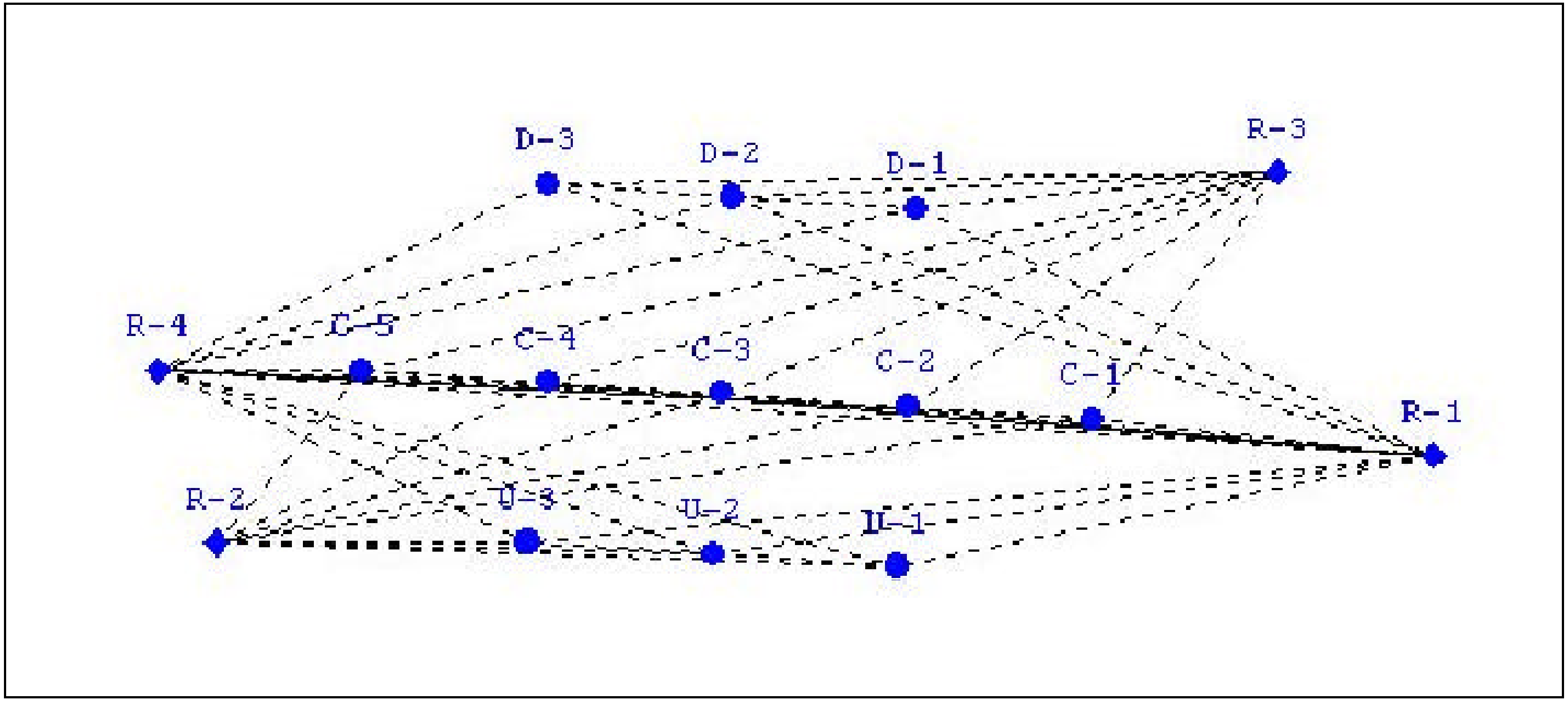


Figure 9. 13. Adjustment network map showing station names and connections between points based on observations made during data collection. R-1 thru R-4 are reference stations, C-1 thru C-5 are centerline monitoring points, U-1 thru U-3 are upstream monitoring points at the base of the structure, D-1 thru D-3 are downstream monitoring points at the base of the structure.

Network Maps

Network Points and Confidence Ellipses

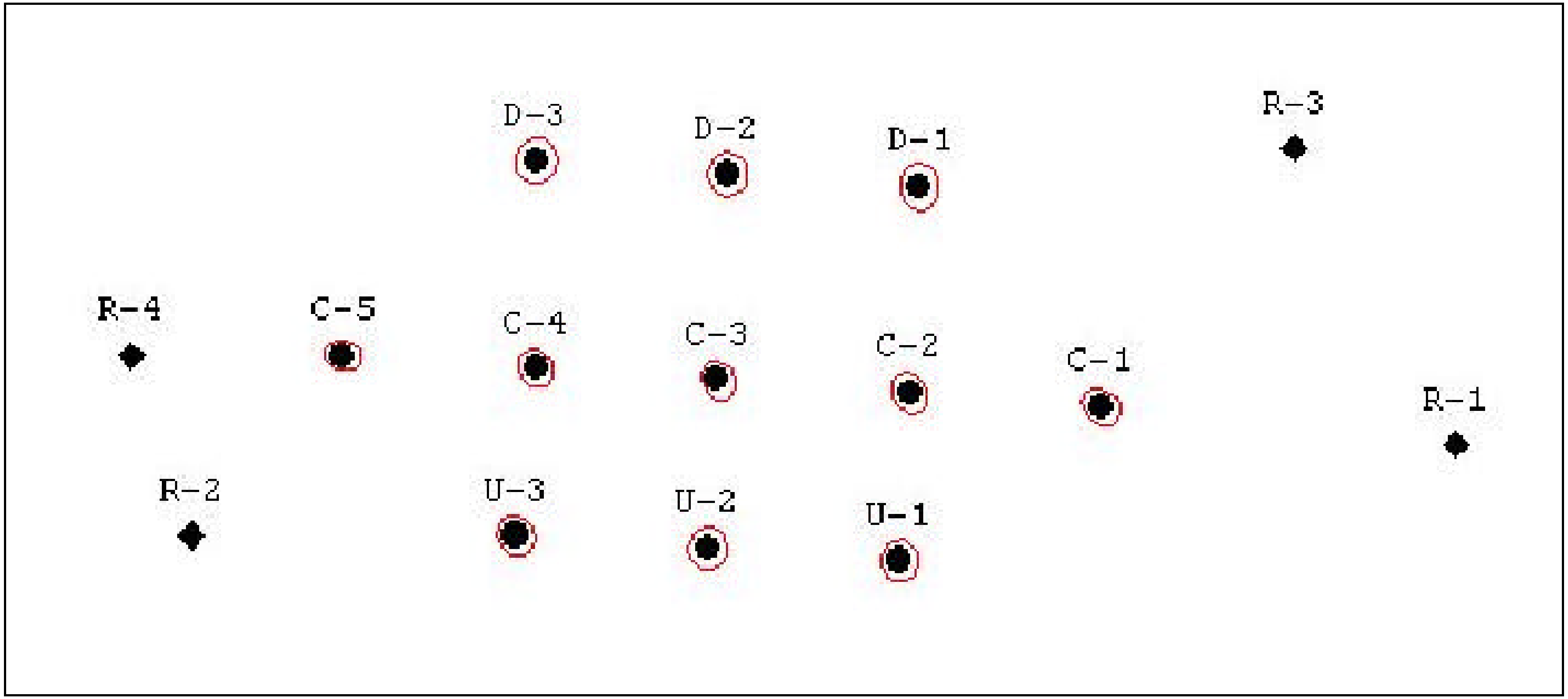


Figure 9.12. Adjustment network map (plan view) showing station names, relative locations, and the point confidence ellipse (95 percent) for horizontal positioning plotted around each point. Network map and confidence ellipses are plotted at different scales. Circles indicate monitoring points and diamonds represent reference stations.

Deformation Monitoring Using Ratio Methods

This section provides guidance on performing deformation surveys using EDM ratio difference techniques. These surveys are done using an EDM or total station. Standard trilateration techniques are used to compute movements. This process requires measurement of the reference control network and the structure itself.

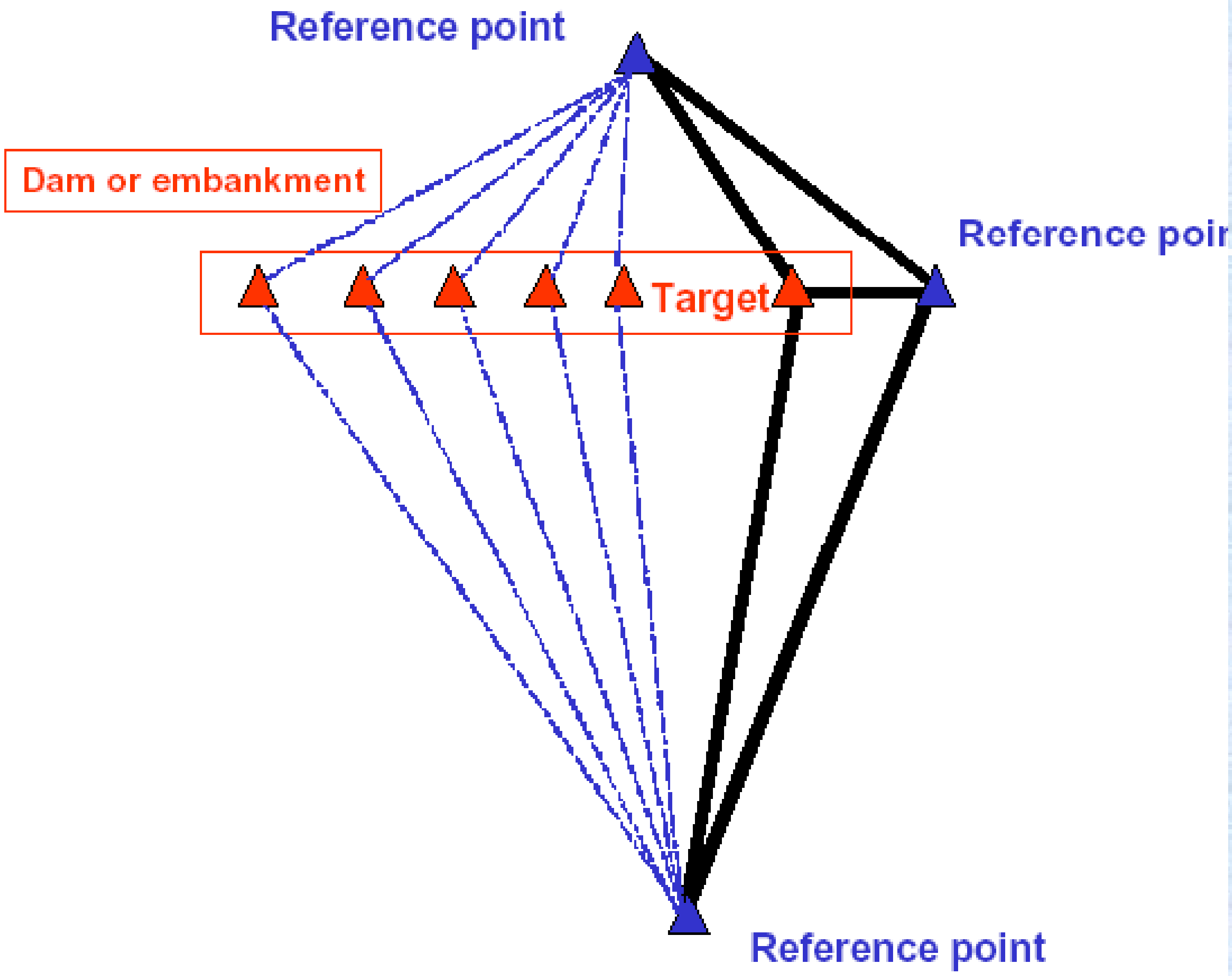


Figure 10-3. Control Monuments for a Dam

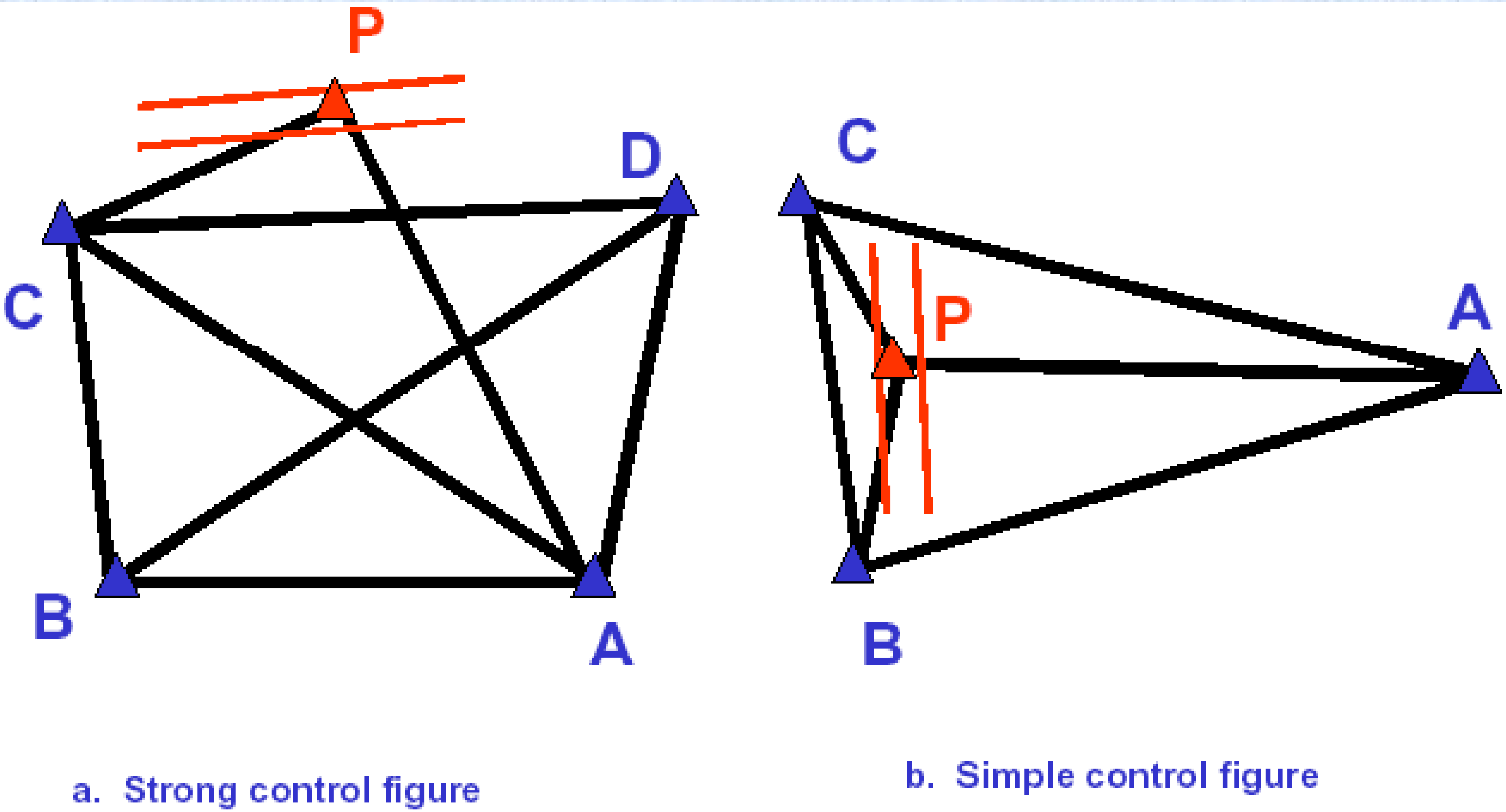


Figure 10-4. Strong and simple control figures around a structure

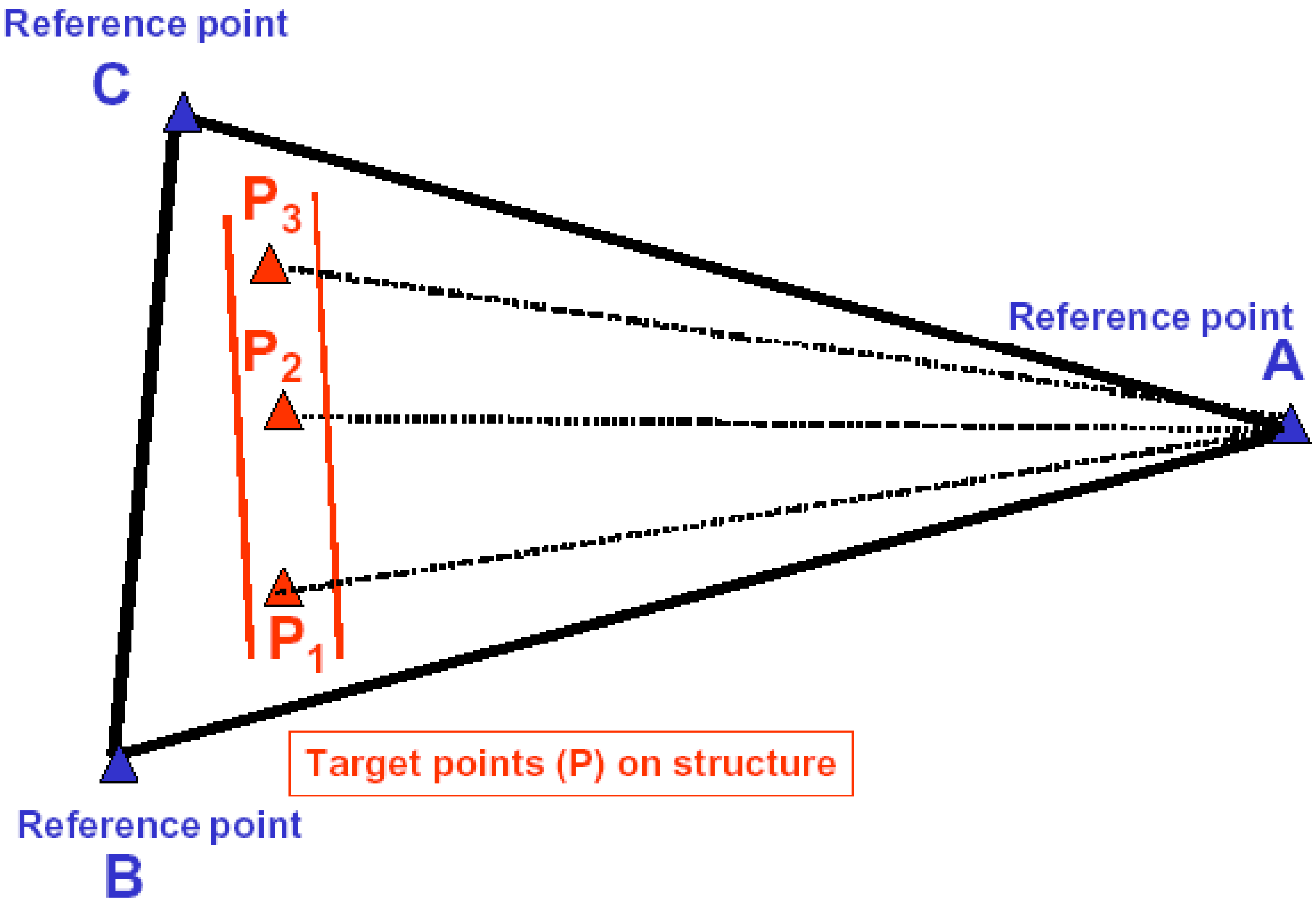


Figure 10-5. Use of a Reference Line

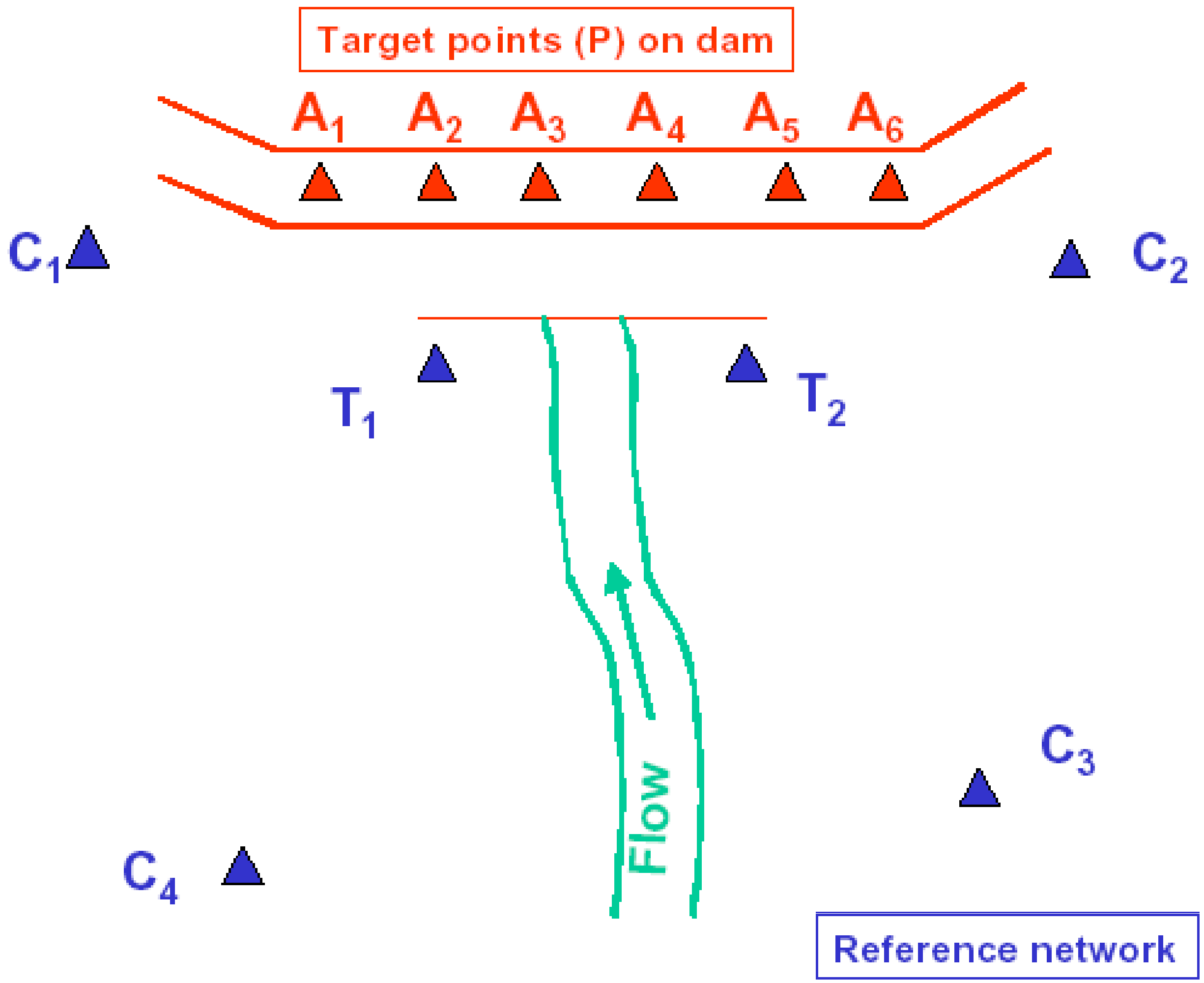


Figure 10-6. Example survey scheme on a concrete dam.