Dam Deformation Surveying

John HAMILTON, United States

Key words: Deformation Surveys, Engineering Surveys

SUMMARY

The Pittsburgh District of the US Army Corps of Engineers owns and operates 16 flood control dams and 23 navigation locks in the northeastern United States. These structures are subject to external loads that cause deformation of the structure. Periodic monitoring surveys are undertaken to quantify the deformations and to ensure that any abnormal behavior can be addressed in a timely manner. Prior to 2005, the deformation surveys were performed using a Wild T2 optical theodolite and a tripod mounted moveable target with micrometer to measure deflections of alignment marks from a monumented reference line. This methodology had several deficiencies, including the detection of movement in one direction only, and was seriously affected by atmospheric refraction (heat waves, or shimmer). Beginning in 2005 and continuing to the present, new methods utilizing modern high accuracy total stations, dual frequency GNSS equipment, and digital levels with invar rods were introduced, as well as new computational methods employing least squares.

This paper discusses the methods developed to monitor these important structures, explains the computations performed, and presents results and experiences experienced over the past seven years.

Dam Deformation Surveying

John HAMILTON, United States

1. INTRODUCTION

The US Army Corps of Engineers (USACE) is a U.S. federal agency under the Department of Defense made up of approximately 34,600 civilian and 650 military personnel, making it the world's largest public engineering, design, and construction management agency. Although generally associated with dams, canals and flood protection in the United States, USACE is involved in a wide range of public works throughout the world. The Corps of Engineers provides outdoor recreation opportunities to the public, and provides 24% of U.S. hydropower capacity. In addition to providing design and construction management of military facilities for the various military branches, two of the Corps main missions in the United States are the planning, design, building, and operation of navigation locks and dams and flood control projects, including reservoirs, dams, flood control channels, and levees.

The mandate to maintain and improve navigation channels was issued in 1824. Today the Corps maintains 19,000 km of inland waterways and operates 235 locks. The flood control act of 1936 gave the Corps the additional mission to provide flood protection to the nation. The Corps is organized into eight divisions, and each division has several districts whose geographical limits are defined by watershed boundaries.

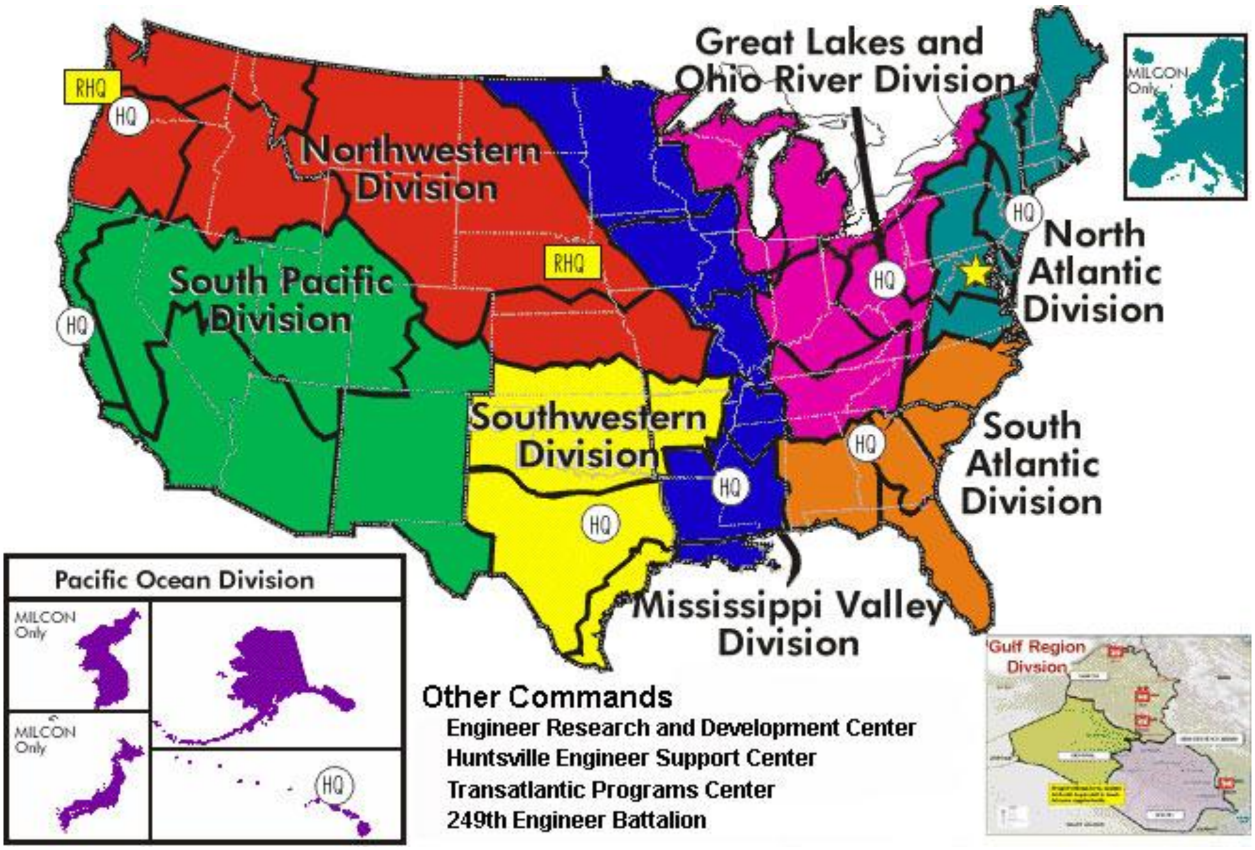

Figure 1 - USACE Divisions

The Great Lakes and Ohio River division includes seven districts: Buffalo, Chicago, Detroit, Huntingdon, Louisville, Nashville, and Pittsburgh. This paper presents the current methodologies employed in the Pittsburgh District to monitor the 39 major structures which the USACE owns and operates.

2. PITTSBURGH DISTRICT

The Pittsburgh District of the US Army Corps of Engineers, is a civil works district with over 600 civilian employees, and has a US Army Colonel assigned as district engineer. The district covers over 67,000 km^2 in western Pennsylvania, southwestern New York, northern West Virginia, western Maryland, and eastern Ohio. There are 23 locks and dams on 383 km of navigable waterways, and 16 multi-purpose flood damage reduction reservoirs, as well as 40 local flood damage reduction projects. The Port of Pittsburgh, where the Allegheny and Monongahela Rivers meet to form the Ohio River, is the second largest inland port (by tonnage) in the United States. The cost to move a ton of cargo one mile (1.61 km) is between $0.005 and $0.01 by barge, $0.05 by rail, and $0.10 by truck. Coal is the main commodity shipped by barge, accounting for 75% of the 34 million tons shipped through Pittsburgh in 2010.

Terrasurv, Inc of Pittsburgh, PA is part of a team lead by Photo Science of Lexington, KY that is under contract with the Pittsburgh District to provide Surveying and Mapping services, and has been performing alignment and settlement surveys for the 39 projects since 2005. .

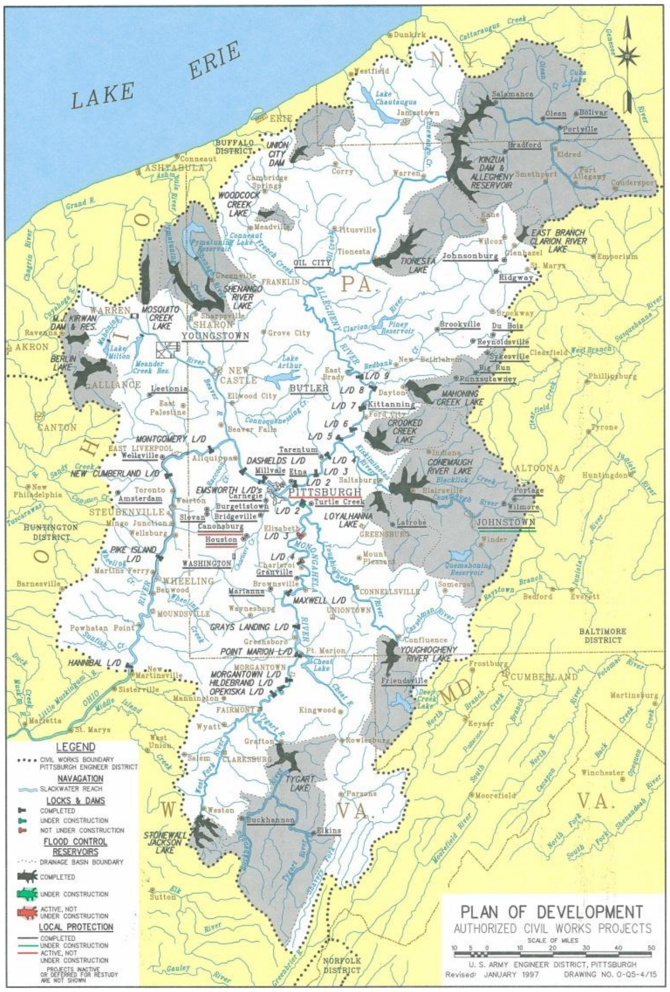

Figure 2 - Pittsburgh District

3. SPECIFICATIONS

The US Army Corps of Engineers publishes a wide variety of Engineer Manuals (http://publications.usace.army.mil/publications/eng-manuals/). Structural Deformation Surveying (EM 1110-2-1009) "*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 standards are defined for monitoring displacements in hydraulic structures*."

Table 2-1. Accuracy Requirements for Structure Target Points (95% RMS)

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

To summarize the above table, from EM 1110-2-1009, the required accuracy for concrete structures is ±5-10 mm horizontally, and ±2 mm vertically, while the required accuracy for embankment structures is ±20-30 mm horizontally and ±10 mm vertically. Based on these criteria, the monitoring surveys performed in the USACE Pittsburgh District are designed to meet the following accuracies (least squares adjustment, station confidence regions at 95% confidence):

- Concrete (navigation locks and dams, concrete gravity dams)
    - Horizontal: ±3 mm (total station)
- Vertical: ±1 mm (invar rods)Embankment structures (earth and rock fill dams):
    - Horizontal: 10 mm (GNSS Static)
    - Vertical: 5 mm (invar or fiberglass rods)

The equipment used to meet these accuracies by Terrasurv includes:

- Trimble S6 high accuracy total station
  - 1” angular accuracy
  - 1 mm ± 1 ppm
- Zeiss S10 total station (limited use on select projects)
  - Same angular and distance accuracy as Trimble S6
- Trimble Dini 12 digital level
  - 2 m and 3 m invar rods
  - 1 m and 4 m fiberglass rods
- Trimble dual frequency GNSS receivers (4400, 4700, 5700, and R8 models)

4. HISTORIC METHODS

Deformation surveys began on most of the structures in the Pittsburgh District in the early 1970’s. The method for horizontal deformation surveys utilized fixed reference points and a series of alignment pins nominally placed online between the reference points. For flood control dams, the reference points typically consisted of instrument pedestals set 1 to 2 meters in the ground, protruding about 1.3 meters above ground.

Figure 3 - Reference Monument pedestal

Additional pedestals were established off structure to be used for verification of the reference network.

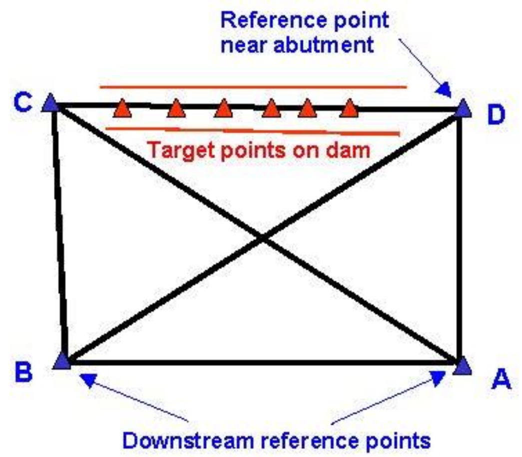

Figure 4 - Reservoir reference network

The reference monuments on the navigation locks typically consisted of disks set in gate monoliths, which were usually constructed down to bedrock.

Figure 5 - Gate Monoliths to bedrock

Off structure pedestals were also used at the locks to verify the gate monolith monuments.

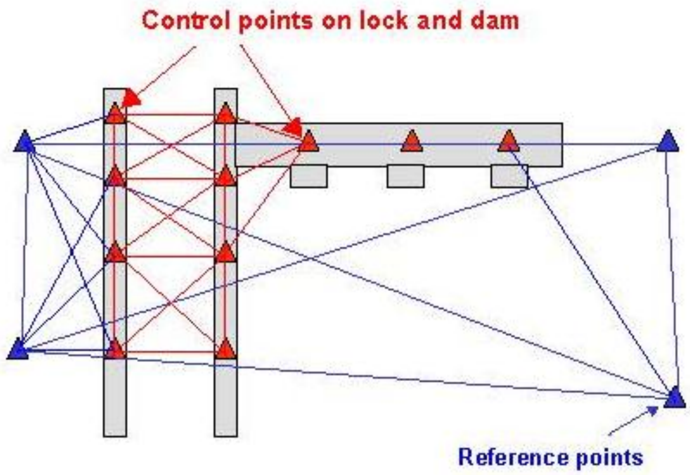

Figure 6 - Locks reference network

A Wild T2 theodolite was used to measure the offset of each alignment pin from the alignment line. For lines that run parallel to the direction of flow (i.e. lock wall), the displacement is recorded as riverward-landward, and for lines that are perpendicular to the flow (dam), the displacement is recorded as upstream-downstream. The advantage of this system is that it directly measures the parameter of interest to the structural engineer. For example, a lock guide wall, constructed similar to a retaining wall, would be expected to move in a direction perpendicular to flow, and movement riverward would be of most concern. Similarly, on a gravity dam the direction downstream would be of most interest. The disadvantage is that as the distance from the instrument increases, it becomes more difficult to discern the cross hairs intersecting the moveable target due to shimmer and heat waves.

5. NEW PROCEDURES FOR EMBANKMENT STRUCTURES

Static GPS procedures are used on embankment structures due to the lesser accuracy required as compared to concrete structures. In this method, a base receiver is setup off the structure. Two or more rover units are deployed to occupy each of the existing alignment pins. Observations are scheduled as follows:

- Minimum observation time (with base): 20 minutes
- Minimum observation time with adjacent alignment pins: 15 minutes

The data is post processed using manufacturer supplied software (currently Trimble Business Center). In addition to processing the baselines from the base to each of the monitoring points, baselines are also processed from the base to surrounding Continuously Operating Reference Stations (CORS). After processing, the data (occupation information, vector components, covariance matrix, etc) is loaded into a database. After thorough data checking, an input file is created for a least squares adjustment using Geolab. A minimally constrained adjustment is performed, holding fixed the previously determined base coordinates. The misclosure is checked at each of the CORS to determine if any movement of the base point has occurred since the previous survey.

The resulting coordinates for each of the monitored points are then loaded into a spreadsheet as UTM Zone 17 coordinates. The coordinates are differenced with respect to a reference epoch (initial survey), and the ΔN and ΔE components are rotated to a system with the X axis parallel to the dam axis (as defined by the reference line). The Y component then represents displacement upstream-downstream.

The aerial image below in figure 7 shows a typical embankment dam. The yellow X's represent the four pedestals, none of which are occupiable with GPS due to trees. The red X's represent the thirteen alignment pins set nominally online. The red and white circle at the north end of the dam, just upstream of the axis, represents the primary project control station, which is in the National Spatial Reference System (NSRS) database maintained by the National Geodetic Survey. This latter station served as the base point. The results of the survey are presented in graphical format in figure 7:

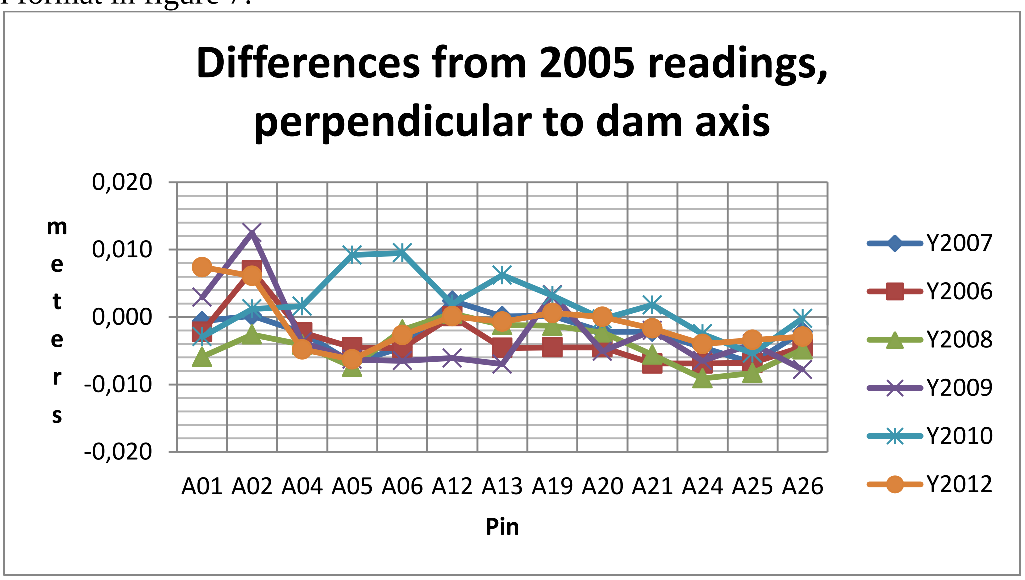

Figure 7 Alignment Results

Note that the required accuracy is 20 to 30 mm, and the largest difference in the data presented above is approximately +13 mm. Therefore, it can be said that the movement of the alignment pins is under the threshold.

6. NEW PROCEDURES FOR CONCRETE GRAVITY DAMS

The monitoring network for the reservoir dams consist of two pedestals defining the alignment reference line, and pins set in each monolith.

Figure 8 -Concrete Gravity Dam network

In figure 8, the alignment pins are shown as red X's, and the reference monuments are shown as yellow X's. Figure 9, below, shows the lines observed in the network using a Trimble S6 total station. The alignment pins are observed from both ends of the reference line.

Figure 9 - Observed lines

As described above, the data is adjusted using least squares. However, in the case of the concrete gravity dams a routine is run which computes the offset of each pin from the reference line. The results are shown below in figure 10, along with error bars on the 2012 data showing the computed 95% confidence region (0.002 m).

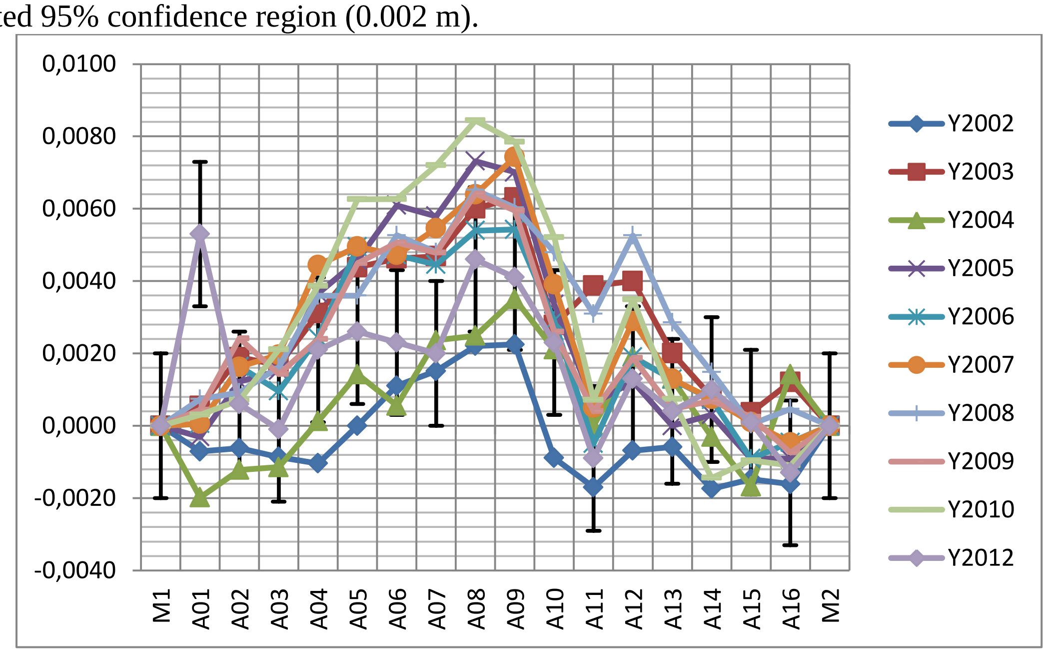

Figure 10 - alignment results

7. NEW PROCEDURES FOR NAVIGATION LOCK(S) AND DAM

The navigation locks present a different type of monitoring problem, as there are several walls to monitor, and typically the reference points are located ON the structure rather than off of the structure. Figure 11 presents an example of this type of project. The lock has two chambers, and therefore six gate monoliths. There are also three pedestals landward of the structure. There are ten separate alignment lines for the structure, nine of which are designed to detect riverward-landward movement and one, across the dam piers, to detect upstream-downstream movement. Each end of the land wall is also constrained for the alignment lines, but the end monoliths are, like the rest of the monoliths, built on pilings, whereas the gate monoliths are anchored to bedrock. Therefore a separate network is first run to determine coordinates for these endpoints. Each of the alignment pins being monitored is observed from two separate setups, preferably resulting in a near 90° angle at the observed pin.

Figure 11 - Navigation Lock

Figure 12 shows the reference stations (Red X's) and alignment pins (yellow X's). A stakeout prism (figure 13) is used to rapidly occupy each point.

Figure 12 - monitoring network

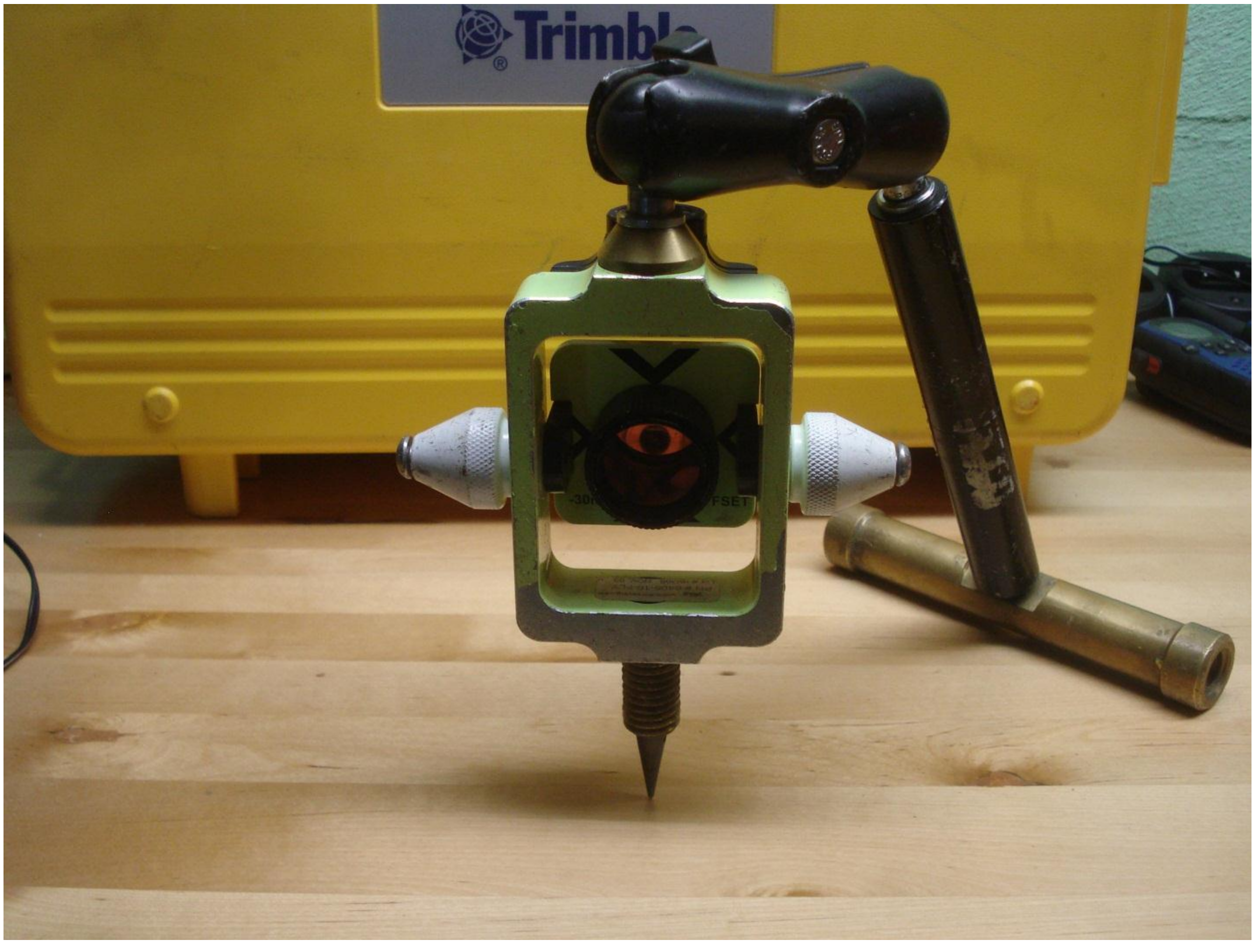

Figure 13 - mini prism with monopole

8. SETTLEMENT SURVEYS

The settlement surveys are done in the same manner for all three types of structures, using a Trimble Dini 12 digital level and either invar rods (for concrete structures) or a fiberglass rod (for embankment structures). The only difference from previous methods is the use of a digital level rather than an optical level. Each project has one primary benchmark and two secondary benchmarks. The primary project benchmark is located off of the structure, while the secondary marls may be on or off. The same alignment pins are used for the settlement survey. Once the data is adjusted, a comparison is made to the initial values.

9. RELATIVE MOVEMENT GROUPS

Several projects have cracks developing, either in the structure itself or at joints between monoliths. The distances between punch marks on three bolts are measured using calipers.

REFERENCES

Structural Deformation Surveying; US Army Corps of Engineers; Engineer Manual EM1110-2-1009

BIOGRAPHICAL NOTES

John Hamilton is a Professional Land Surveyor registered in Pennsylvania. He graduated from Purdue University with a Bachelor of Science degree in Civil Engineering, with a major in Geodesy and minors in Transportation and Geotechnical Engineering. Since 1997 he has been the president of Terrasurv, a small firm which specializes in Engineering Surveying. He has performed geodetic surveys in all fifty of the United States, and has worked in a number of countries in Asia, Africa and South America.

CONTACTS

John Hamilton
Terrasurv
561 Clifton Road
15102 Bethel Park
Pennsylvania
UNITED STATES
Tel. 1 + 412 341 5620
Fax 1 + 412 360 8440
Email: hamilton@terrasurv.com