Proceedings, 11th FIG Symposium on Deformation Measurements, Santorini, Greece, 2003.

UTILIZATION OF CONTINUOUS OPERATING REFERENCE STATIONS (CORS) IN SOUTHERN CALIFORNIA FOR DEFORMATION MONITORING

Michael A. Duffy and Cecilia Whitaker

Geometronics Team, Infrastructure Protection Unit
Metropolitan Water District of Southern California, USA
700 Moreno Avenue, La Verne, CA, 91750

Abstract

The Metropolitan Water District (MWD) of Southern California currently has 33 facilities with structures (including concrete dams, earthen dams, reservoirs, power plants, control structures and water filtration basins) that require structural deformation monitoring of some kind. For more than 20 of these facilities, three dimensional data (X,Y and Z) is collected on a twice yearly schedule to fulfill a requirement by the State of California, Division of Safety of Dams to report on the structural health of our facilities under their jurisdiction.

An economical method (a reduction in both personnel and equipment) was developed to utilize the free, static GPS data from the network of Continuous Operating Reference Stations (CORS) that are installed over Southern California for crustal motion studies. Using two CORS stations as fixed base stations (or one CORS and one on-site receiver used as a base), two vectors are measured to each deformation monument. These two vectors are processed with the precise ephemeris and analyzed to determine the relative position of the monument. This relative position is re-measured every six months and compared to the previously established positions to study trends in the structural deformation. Utilizing two vectors from two fixed CORS stations, instead of creating a typical survey network, prevents contamination of data from possible errors at neighboring monuments. Also, these surveys incorporated the use of fixed height tripods to prevent height errors and choke ring antennas to reduce multipath.

This method has resulted in excellent repeatability of the horizontal position for deformation trend analysis; however, the vertical position is still being obtained with electronic leveling methods at this time. MWD has realized a 50% reduction in personnel and equipment needed to obtain the horizontal positions on eleven facilities, several of which are discussed.

1. Introduction

The Metropolitan Water District wholesales water for the six counties (5,200 sq. mi.) of southern California. The complete water distribution system includes the 242 mile long Colorado River Aqueduct, 775 miles of pipeline for water distribution, five pumping plants, nine reservoirs (ranging from 261,000 m^3 to 987 million m^3 capacity), five water filtration plants each encompassing an average of eight settling and mixing basins and one or two finished water reservoirs, and 16 hydroelectric plants (MWD, 2002).

MWD has an active, ongoing structural surveillance program to monitor the condition of its facilities. Since the St. Francis dam failure (north of Los Angeles, 1928) and the Baldwin Hills off-stream reservoir failure (Los Angeles, 1963), the State of California Department of Water Resources (through their Division of Safety of Dams (DSOD)) requires that all dams and reservoirs that reach certain height and volume criteria (DWR, 1993) be monitored for structural integrity to insure the safety of the public. MWD currently has 20 facilities that meet the DSOD height and capacity criteria for State required monitoring and reporting. Currently, we also monitor fifteen of our facilities that are not under State jurisdiction as part of our ongoing dam/structural surveillance program.

2. MWD Deformation Monitoring Program

MWD has expanded its deformation-monitoring program substantially in the last few years, adding several large scale projects with a static labor force of three people. The Diamond Valley Lake project has been completed and added a substantial amount of monitoring to the program. As we have previously reported, this project is a fully automated, X,Y,Z displacement monitoring system using robotic total stations (Duffy, et al, 2001; 2002). In addition to this large project, we have two new projects that require monitoring large (15 and 40 sq. mi., respectively), remote desert areas for X,Y,Z displacements caused by groundwater aquifer pumping and withdrawal. These two large projects are labor intensive, requiring a two-person crew to remain in the field for several weeks to complete the required monitoring. This is due to a combination of a long drive time to the sites, and once at the site, rugged access to the widespread area of monitoring points.

In 1999, we reported at the Institute of Navigation (ION) (Duffy, 1999) about our method of incorporating continuously operating reference stations (CORS) (Figure No. 1) into our static GPS surveys for deformation monitoring. The use of these CORS in our monitoring projects has economically increased our efficiency without sacrificing accuracy and precision. (For all of our monitoring surveys, our accuracy criteria is the detection of horizontal and vertical displacements larger than 10 mm at the 95% confidence level for earthen dams and 5 mm for concrete structures per guidelines given in Chrzanowski (1992).) As stated in Duffy (1999), we started utilizing the CORS as control stations on our monitoring projects. We typically utilize two CORS for each project and we measure one vector from each CORS to each onsite deformation monitoring point. We have been able to reduce from a four to a two-person crew. Each crewmember utilizes two receivers, setting up each receiver independently of the others. This conversion from a network solution to a minimum vector solution greatly increased the accuracy, precision and economy of our horizontal surveys. We also improved our equipment to utilize choke ring antennas, fixed height tripods and improved GPS receivers.

Figure No. 1. Typical SCIGN CORS
A drilled, braced monument with choke ring antenna and radome, equipment box with receiver and radio, and solar panels.

3. The CORS Network

The CORS are part of a network that was installed by the Southern California Integrated GPS Network (SCIGN), a group of scientists that use the CORS as a crustal motion-monitoring network (Hudnut et al, 2001). This network is now (since July 2001) fully operational with approximately 250 stations reporting in daily, many of which are located on or in close proximity to our facilities. The GPS data (RINEX file format) from all these

CORS (and others worldwide) are downloaded and archived daily and are available free of charge from the Scripps Institution of Oceanography's Orbit and Permanent Array Center (SOPAC). These stations are also maintained and repositioned after seismic events by these organizations. This is an indirect cost savings for our program because now someone else is maintaining our control network, which as we discussed in Duffy (1999), was almost as time consuming and costly as the monitoring.

4. Project Conditions

MWD uses this GPS minimum vector method on fifteen sites on a regular basis. Two of our sites are earth-fill dams that are on-stream dams with a large reservoir behind them, Lake Mathews and Lake Skinner. Many of the other sites are off-stream, earth-fill reservoirs located in urban areas around southern California. (Most of our facilities are older, well established structures, with long-term stability histories.) We also monitor two large groundwater aquifer water storage projects in the Mohave Desert. We will review four reservoir projects and one groundwater project to show the advantages of this method.

Lake Mathews has a main dam (Figure No. 2) and two dikes that have to be monitored with a total of 90 monitoring points. This facility was particularly difficult to monitor using more conventional methods due to long structures and desert climate. This facility has a SCIGN CORS (MAT2; Figure No. 1) installed at the bedrock abutment separating the two dikes. For our second "CORS" we set up a base station on a historic control monument that is in the bedrock on the north abutment of the main dam. These two CORS provide our two vectors for monitoring the horizontal displacements.

Figure No. 2. Lake Mathews Main Dam Concrete lined upstream; rock on downstream face (almost 1.2 km. long)

Figure No. 3. SCIGN station "BILL" Lake Skinner dam in background

At Lake Skinner, we monitor a 1.6 km. dam and a finished water reservoir at the adjoining filtration plant with a total of 70 monitoring points. Lake Skinner has a SCIGN CORS (Figure No. 3) on site and for our second CORS, we use a CORS from the Diamond Valley Lake facility located a few kilometers north of Lake Skinner.

Garvey Reservoir and Live Oak Reservoir are both earth-fill, off-stream reservoirs located in urban areas of southern California. Both sites have a SCIGN CORS installed near the reservoir. At Garvey we set up a temporary CORS on a historic control monument for the second station. At Live Oak we are fortunate to have a second SCIGN CORS nearby that we are able to utilize. Both sites have approximately 40 monitoring points each.

Hinds Pumping Plant and the nearby dry lake that is used for water storage are located in the Mohave Desert, east of the Palm Springs area. Geological studies performed in this dry lake area showed the capability of storing (and then pumping) water in the groundwater aquifer that is under the dry lake. MWD has started to use this aquifer as a “water storage” facility instead of building a reservoir. Due to the storage and pumping of water, we must monitor the effects this has on nearby structures, including power transmission lines, Interstate Highway 10, the pumping plant and probably most importantly the flow of the Colorado River Aqueduct (CRA). Hinds Plant is the fifth pumping plant along the CRA that brings the water into southern California. The CRA is a gravity-feed canal (with minimal grade) that runs between the five pumping plants from the Colorado River, westward to Lake Mathews, for 390 kilometers. An important aspect of the Hinds deformation project is assuring that the water being pumped into the groundwater aquifer for storage does not disrupt the flow of the aqueduct by raising or lowering the canal structure. We have approximately 50 monitoring points spread over the project. The monitoring points along the highway, the transmission lines (Figure No. 5) and the dry lake are monitored using the GPS minimum vector method both for horizontal (±1-2cm) and vertical position (±3-4cm). Although we are not economically able to follow the rigorous guidelines that the US National Geodetic Survey (NGS) has published (Zilkoski, 1997) regarding using GPS to determine 2 centimeter vertical, we have had fairly good results with monitoring the ground settlement, in addition to the horizontal displacements. Although the vertical monitoring is beyond the scope of this paper, it is important to note that the vertical monitoring of the canal is done with electronic differential leveling equipment due to the importance of knowing the changes in this structure very precisely (≤1 cm).

Figure No. 4. The Colorado River Aqueduct Hinds Pumping Plant is at the base of the mountain in the background

Figure No. 5 Monitoring the electrical transmission towers in the dry lakebed

5. Results

The repeatability of the measurements using this method is shown to be very good. Comparisons of current survey results to surveys completed six months prior and 12 months (Table No. 1) prior show that the displacements generally fall within the 95% (2 sigma) error ellipse generated by the least squares adjustment.

Garvey Reservoir shows no significant displacement in the east-west direction (the dam alignment) and shows only minor to insignificant change in the northerly, downstream direction, possibly due to a little thermo-elastic effect.

Live Oak Reservoir displacements all fall within the 95% error ellipse, showing no significant variation with the exception of point 8004. This point shows sort of an anomalous result in this survey as compared with 12 months prior. The displacements show the point moving laterally on the dam, which is probably incorrect. Since other nearby points did not show this type of displacement, we watch this point (and the others nearby) in future surveys for a correction or a new trend.

Garvey Reservoir (E-W dam alignment)

Station 45+50 cross section: mid-dam (N34°03'03", W118°06'57")

Point ID Number	October 2002 6 month comparison		October 2002 12 month comparison		95% ellipse major axis	95% ellipse minor axis
	Delta Northing	Delta Easting	Delta Northing	Delta Easting		
1030 (crest)	-0.004	0.005	-0.005	0.002	±0.004	±0.004
1008 (berm)	0.004	0.002	-0.003	0.003	±0.004	±0.003
1012 (berm)	-0.001	0.002	-0.005	0.000	±0.004	±0.003

Live Oak Reservoir (NW-SE dam alignment)

Station 8+50 cross section: mid-dam (N34°08'06", W117°45'17")

Point ID Number	November 2002 6 month comparison		November 2002 12 month comparison		95% ellipse major axis	95% ellipse minor axis
	Delta Northing	Delta Easting	Delta Northing	Delta Easting		
8013 (crest)	-0.002	0.000	-0.005	0.004	±0.005	±0.004
8004 (toe)	-0.006	0.003	-0.015	0.008	±0.006	±0.005

Lake Mathews Reservoir Dam (N-S dam alignment)

Station 33+50 cross section: mid-dam (N33°50'09", W117°27'41")

Point ID Number	January 2003 6 month comparison		January 2003 12 month comparison		95% ellipse major axis	95% ellipse minor axis
	Delta Northing	Delta Easting	Delta Northing	Delta Easting		
6032 (crest)	0.004	0.010	0.004	0.006	±0.007	±0.006
6156 (berm)	0.007	0.011	0.007	0.007	±0.006	±0.006
6163 (toe)	-0.003	-0.002	0.004	0.003	±0.007	±0.006

Lake Skinner Reservoir Dam (N-S dam alignment)

Station 25+00 cross section: mid-dam (N33°35'14", W117°04'20")

Point ID Number	March 2003 6 month comparison		March 2003 12 month comparison		95% ellipse major axis	95% ellipse minor axis
	Delta Northing	Delta Easting	Delta Northing	Delta Easting		
5036 (crest)	-0.006	0.004	0.002	-0.005	±0.002	±0.002
5025 (berm)	0.002	-0.002	0.001	0.001	±0.002	±0.002
5017 (berm)	0.004	-0.004	0.000	0.001	±0.002	±0.002
5013 (toe)	0.004	0.000	0.004	-0.002	±0.002	±0.002

Table No. 1 Displacement value comparisons to prior six months and prior year.

Hinds Pumping Plant & Groundwater Aquifer/Dry Lake (N33°41'18", W115°37'44")						
Point ID Number	January 2003 6 month comparison		January 2003 12 month comparison		95% ellipse major axis	95% ellipse minor axis
	Delta Northing	Delta Easting	Delta Northing	Delta Easting		
1021 (canal)	0.000	-0.001	0.013	0.001	±0.005	±0.005
1035 (road)	0.001	-0.006	0.009	-0.013	±0.007	±0.006
1026 (lines)	0.013	0.008	0.009	-0.020	±0.017	±0.010
1039 (dry lake)	0.003	-0.005	0.010	-0.010	±0.006	±0.005
1040 (dry lake)	-0.009	0.009	0.012	-0.012	±0.006	±0.004
1041 (dry lake)	0.019	0.006	0.031	-0.023	±0.010	±0.006

Table No. 2 Displacement value comparisons to prior six months and prior year.

Lake Mathews shows good repeatability in both directions and also shows a little rebound in the east-west direction due to the record draw -down of water in the reservoir that occurred during this time frame.

Lake Skinner Dam shows seasonal variation in its displacements, which are easily tracked using this method. This dam is in a desert region with large temperature changes between the summer and winter monitoring cycles.

Hinds Pumping Plant is not as easy to analyze as the reservoirs since different structures and areas are being subjected to differing pore water pressure. On Table No. 2, the values for the comparison to six months prior show little significant variation. The two points in the very middle of the dry lake, Points 1040 and 1041, and Point 1039 on the westerly edge of the dry lake, show a little more variation than the other points which are farther away from the pumping area. The dry lake at this time frame (6 months ago) was not actively being filled with water, nor is it currently being filled. Comparing the current survey to the prior twelve months does show some variation in comparison because the aquifer was being pumped into twelve months ago. Two of the three dry lakebed points show a little variation, as does the transmission line point on the northerly edge of the lakebed. All three show that displacement had occurred twelve months ago and that the point rebounded six months later. Point 1041 had more displacement and less rebound than the other two. This is possibly because it is in a location with residual water. The canal, which is northerly of the lakebed and the pumping area, shows a slight variation in the northing. This could have indicated some pressure on the canal from the water. The differential leveling (settlement) of this monument is used to verify that any horizontal displacement is not affecting the flow of the aqueduct.

6. Conclusions

Using the CORS as control monuments on our various facilities has provided an economical and labor saving method to determine the horizontal displacements on our monitoring points. Since we no longer have to maintain a control network, we save the labor hours usually devoted to that task. Each crewmember is now more efficient, since each one can run two receivers and does not have to be synchronized with the other member. We are able to repeat these displacement positions consistently so that we can track any horizontal trends over time. The reduction in personnel and time spent at each facility has allowed us to incorporate more projects into our program with no increase in personnel, while still maintaining precise measurements.

References

Chrzanowski, A., Saverio Avella, Y. Q. Chen, J. M. Second (1992). "Existing Resources, Standards, and Procedures for Precise Monitoring and Analysis of Structural Deformations - Volume 1." U.S. Army Corps of Engineers, TEC-0025.

Department of Water Resources (DWR), Division of Safety of Dams (DSOD), State of California (1993). "Statutes and Regulations Pertaining to Supervision of Dams and Reservoirs". State of California Water Code, Division 3, Part 1.

Duffy, Michael A., Cecilia Whitaker, Adam Chrzanowski and James Lutes (2002). "Interpretation of First Results from the Automated and Integrated Monitoring Scheme at Diamond Valley Lake in California." *Proceedings of the International Federation of Surveyors, XX11 International Congress*, *TS6.3 Deformation Measurements and Analysis I*. Washington, D.C., USA. April 19-26, 2002.

Duffy, Michael A., Chris Hill, Cecilia Whitaker, Adam Chrzanowski, James Lutes and Geoffrey Bastin (2001). "An automated and Integrated Monitoring Program for Diamond Valley Lake in California." *Proceedings of Commission 6, of the International Federation of Surveyors, Deformation Working Group, 10th International Symposium on Deformation Measurements*, Orange, California, USA, pp. K-1 to K-23.

Duffy, Michael A. and Cecilia Whitaker (1999). "Deformation Monitoring Scheme using Static GPS and Continuous Operating Reference Stations (CORS) in California." Proceedings of the Institute of Navigation (ION), ION GPS '99, Nashville, Tennessee, USA. September 14-17, 1999, pp. 63 -70.

Hudnut, Kenneth W., Yehuda Bock, John E. Galetzka, Frank H. Webb, and William H. Young (2001). "The Southern California Integrated GPS Network (SCIGN)." *Proceedings of Commission 6, of the International Federation of Surveyors, Deformation Working Group, 10th International Symposium on Deformation Measurements*, Orange, California, USA, pp. 129 to 148.

MWD Public Affairs Division (2002). "The District at a Glance". Metropolitan Water District (MWD) of Southern California, Los Angeles, California, USA.

Zilkoski, David B., Joseph D. D'Onofrio and Stephen J. Frakes (Nov 1997). "Guidelines for Establishing GPS Derived Ellipsoid Heights, 2 cm and 5 cm Standards, Version 4.3". NOAA Technical Memorandum, NOS NGS-58, Silver Springs, Maryland, USA. http://www.ngs.noaa.gov/PUBS_LIB/NGS-58.html

Web Site References

NGS Web Site: http://www.noaa.ngs.gov/

SCIGN Web Site: http://www.scign.org/

SOPAC Web Site: http://sopac.ucsd.edu/