# Design of an Automated Dam Deformation Monitoring System: A Case Study

**Cecilia Whitaker** [1], **Michael A. Duffy** [1] **and Adam Chrzanowski** [2]

[1] Metropolitan Water District of Southern California
California, USA

[2] University of New Brunswick
Fredericton, N.B., Canada

## Abstract

A large water reservoir is being constructed by the Metropolitan Water District of Southern California about 160 km south east from Los Angeles. This project encompasses building 3 earthen dams of 2.9 km, 3.2 km and 0.8 km length to enclose a valley of approximately 7.2 km long and 3.2 km wide. A fully automatic survey system has been designed to monitor the stability of the dams and of the surrounding area. There will be over 360 deformation monuments to be monitored continuously or, at least, monthly starting from completion of structures (end of 1999) through to the complete filling of the reservoir, estimated to take at least 5 years. A geodetic surveying system was designed to detect displacements of points larger than 10 mm at 95% confidence level using multiple, permanently installed, robotic total stations and an array of permanently mounted prisms to provide an economically feasible way to monitor such a large site. The total stations will be remotely operated and will automatically collect three dimensional data on a set time schedule. These total stations will also be linked to an active GPS system which will be programmed to turn on the total stations whenever a preset tolerance level of deformation is exceeded due to, for instance, an earthquake or abrupt settlement.

## 1. Introduction

In 1996, the Metropolitan Water District (MWD) of Southern California, started construction of Southern California's largest water storage reservoir with a capacity of nearly one billion cubic metres of water. The reservoir, located near Hemet, California, about 160 km southeast of Los Angeles, was designed to secure six months of emergency water supply (MWD, 1997) to about 16 million inhabitants. It is being created by enclosing the Domenigoni/Diamond valleys at an elevation of about 500m by three earth/rock filled dams (Fig.1):

a) the West Dam which will be about 85 m high and 2.9 km long;
b) the East Dam which will be 55 m high and 3.2 km long; and
c) the Saddle Dam which will be 40 m high and 0.8 km long.

This is the largest earthfill dam project in the U.S. The reservoir, about 7.2 km long and more than 3 km wide, will cover over 1800 hectares of land. This $1.8 billion project includes construction of a storage forebay at the West Dam, a detention basin at the east end and a pumping plant. The storage water will be supplied from the Colorado River (by a 387 km aqueduct) and from the California State Water Project (by a 710 km aqueduct) to Lake Silverwood Reservoir. From Lake Silverwood the water is transported by a 72 km long and

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3.7 m diameter Inland Feeder Pipeline to the Eastside Reservoir. The construction work started in 1996 and it is planned to be finished by the end of 1999. The initial filling of the reservoir could take over 5 years. Figure 2 shows the construction site at the East Dam as of December 1998.

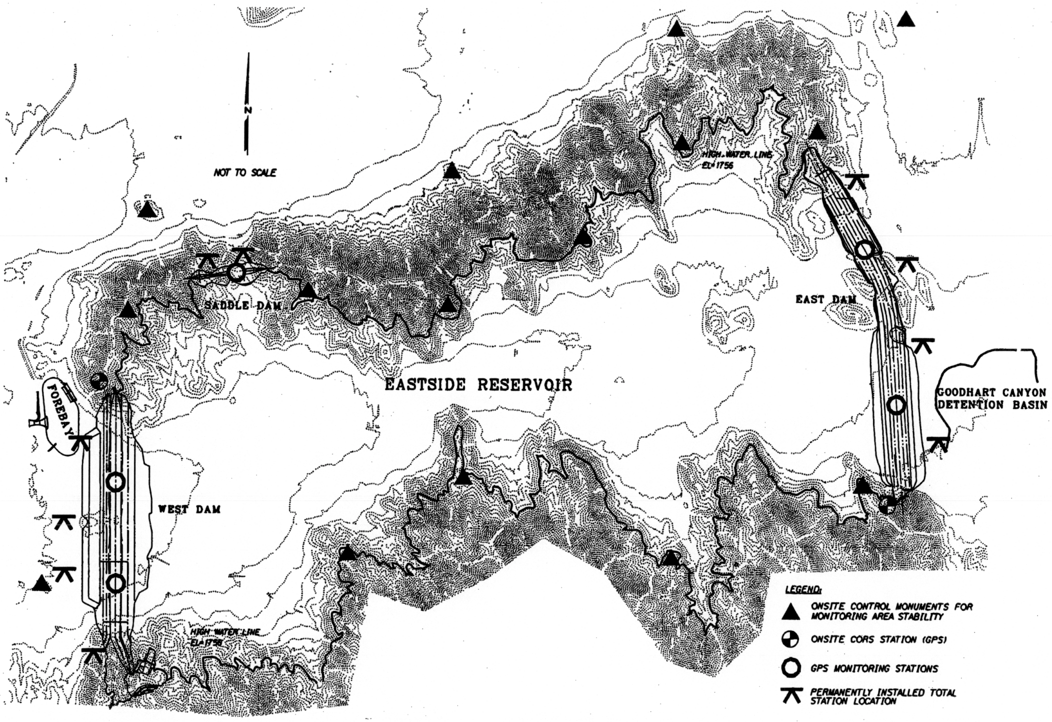

**Figure 1.** Geodetic control network monuments

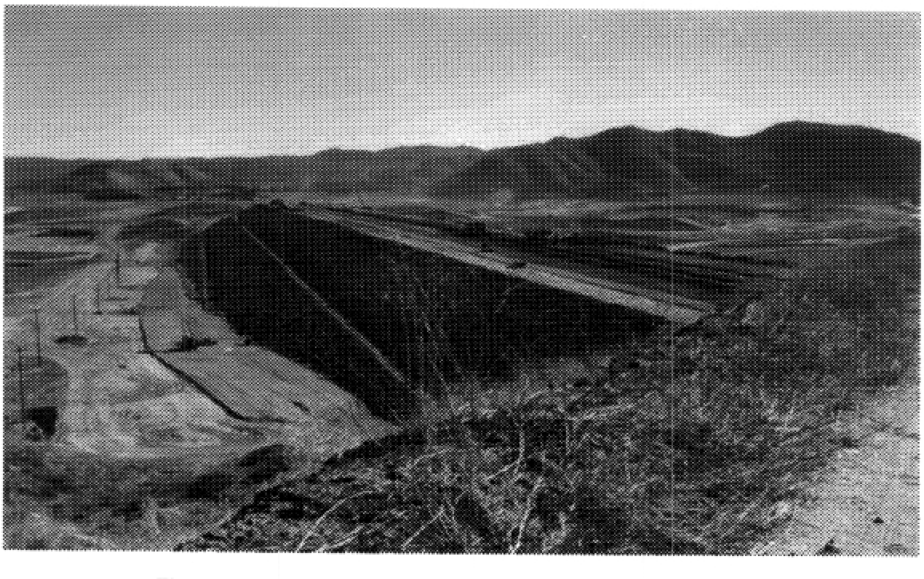

**Figure 2.** Construction site at the East Dam (December 1998)

Due to the dimensions of the project and due to the seismicity and frequent earthquakes in the area, a considerable effort has been put into designing an efficient and reliable system for monitoring deformations of the dams and of the surrounding area. Special attention has been paid to monitoring the behavior of the dams during the initial filling of the reservoir. During that period of time, preferably continuous or, at least, monthly monitoring surveys will be required. The monitoring information will be included as a part of a MWD Safety of Dams report to the California Division of Safety of Dams (DSOD) within the Department of Water Resources. The DSOD requires monitoring of all facilities that are under their jurisdiction. According to the existing state approved programs, the Eastside Reservoir structures should be monitored at least monthly starting as soon as construction of the first berm is completed throughout the rest of the construction period and then during the initial filling period of the reservoir, which could be over the course of many years. Monitoring will then be reduced to quarterly surveys for a period of 5 years or until the structures are stabilized and then reduced to twice yearly, in accordance with a State approved monitoring program for these facilities.

Both geodetic and geotechnical instrumentation will be used in the monitoring scheme. Geotechnical instrumentation has been designed independently of the geodetic portion of the monitoring plan. The geotechnical instrumentation will include 262 piezometers (various types), 18 strong motion accelerographs, 7 inclinometers, 74 settlement sensors, 6 fixed embankment extensometers and 14 weirs. The collected geotechnical information will be integrated with the geodetic information for structural analysis and physical interpretation of deformation. This paper discusses the design of the geodetic monitoring surveys which are in hands of the Geometronics Section of the Survey Engineering Branch at MWD.

## 2. Components of the Monitoring Survey Scheme

The area of the Eastside Reservoir is located within the interaction zone between the North American and Pacific tectonic plates. Therefore, in designing the dam deformation monitoring (DDM) surveys one had to consider not only loading effects of the reservoir and gravitational settlement of the dams but also effects of earth crustal movements in this seismically active area that is prone to frequent earthquakes. Thus, in order to be able to discriminate between various factors affecting the integrity of the dams, the local dam monitoring schemes have to be supplemented by an on-site geodetic control of the whole area of the reservoir to measure the stability of the ridge lines surrounding the reservoir and must be connected to the existing regional GPS network of continuously operating reference stations (CORS) of Southern California which monitor the earth crust movements (Bock et al. 1997). Thus the monitoring scheme will comprise:

a) Dam Deformation Monitoring (DDM) system which includes a number of monitored object points on the dams and a network of local reference stations with respect to which displacements of the object points are to be determined
b) on-site GPS geodetic control network for monitoring the stability of the area surrounding the reservoir (ridge lines) and for checking and updating positions of DDM reference stations
c) regional GPS geodetic control network connecting DDM and on-site geodetic monitoring systems with the Southern California crustal motion monitoring CORS network.

The regional control that will be utilized in the monitoring scheme includes four continuously operating (GPS) reference stations (CORS) that are part of a growing system of 250 such stations that monitor crustal motion of the continental plates in southern California. Two of the CORS stations are located on the construction site (Fig.1), one near the west end and one at the east end of the reservoir. Figure 3 shows the CORS station at the east end. Two other which will be utilized in the monitoring scheme are several kilometres away. These continuously operating GPS receivers are administered by a collaboration of scientists (Southern California Integrated GPS Network; SCIGN) studying crustal motion and earthquakes. They handle all data processing and analysis of the system and then post geodetic positions for all stations on the Internet. By connecting the on-site GPS network to the CORS system, one should be able to discriminate between the effects of regional crustal motion and on-site area deformation due to local (reservoir) causes.

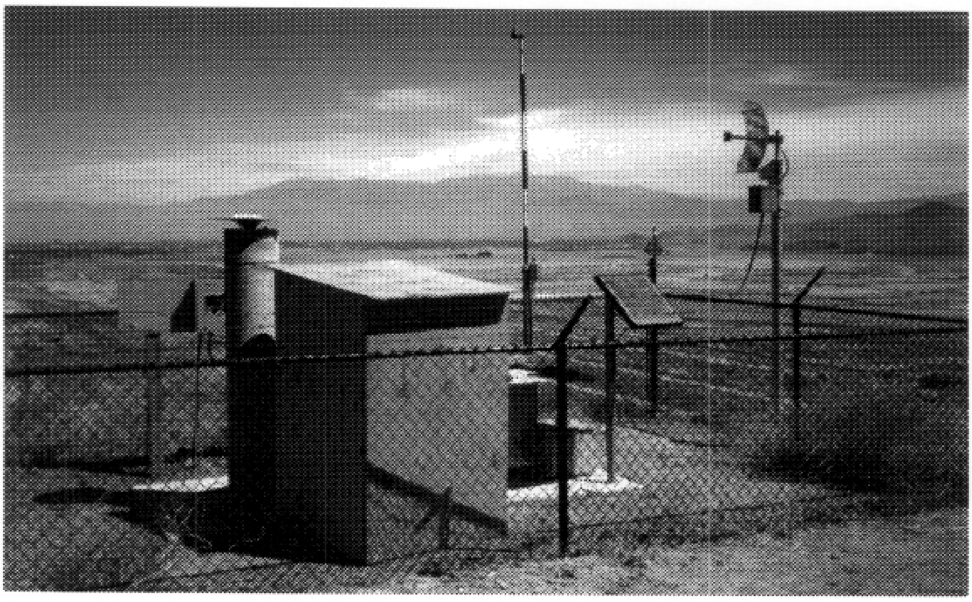

**Figure 3.** GPS CORS station at the east end

The on-site GPS control network consists of sixteen standard survey monuments situated on the two ridge lines surrounding the reservoir (Fig. 1). These monuments have currently been tied to California's High Precision Geodetic Network (HPGN) horizontally and have National Geodetic Survey (NGS) first order elevations established with respect to the North American Vertical Datum of 1988 (NAVD88). These monuments will act both as on-site control for the reference stations of the local DDM system and as a monitor of the effects of increasing the load on the hills around the reservoir as the water level rises in the enclosed valley. Utilizing these methods to monitor the reference monuments of DDM will avoid contamination of the local dam displacement measurements with non-structurally related settlement or movement such as regional slipping and creep.

At the time of writing this paper (February, 1999), both the regional and on-site area GPS networks are in place and have been incorporated into the monitoring scheme. A fully automatic Dam Deformation Monitoring (DDM), which is the main subject of this presentation, has been designed and is being implemented.

## 3. Dam Deformation Monitoring (DDM) Network

### 3.1. Accuracy Criteria

Optimization of accuracy and cost of the DDM system has been the crucial aspect of the design of the whole monitoring scheme. Detection of horizontal and vertical displacements larger than 10 mm at the 95% confidence level with respect to local reference control points has been accepted as the accuracy criterion in designing the DDM scheme for monitoring the aforementioned 5 structures, i.e., the 3 dams, the forebay and the detention basin. Thus the maximum semi-axes of the standard error ellipses of a single horizontal positioning should not exceed $10/\ 2.45\sqrt{2} = 2.9$ mm and standard deviation of a single vertical positioning should not exceed $10/1.96\sqrt{2} = 3.6$ mm.

### 3.2. Instrumentation and Configuration of the DDM Networks

To achieve the aforementioned positional accuracy in a reasonably economical way is not an easy task. Therefore, various geodetic techniques and various configurations of the monitoring scheme were compared and analyzed for their accuracy and cost. Use of total stations of high precision with manual operation has been compared with the use of robotics total stations and use of GPS with both manual static and real-time kinematic modes of operation. Use of active GPS stations with continuous mode of operation, use of laser alignment systems, and various combinations of the above techniques have also been analyzed. Other factors, not only monitoring techniques, had to be considered as well, namely, restrictions of human access to the dams after an earthquake, a need for continuous monitoring in emergency situations and safety assurance to the public that the dams are continuously monitored.

The analysis led to a conclusion that the optimal monitoring scheme should be based mainly on the use of permanently installed robotic total stations with the automatic target recognition and permanently installed object prisms on the crests and downstream faces of the dams in combination with a few continuously operating GPS monitoring stations on the dam crests and the aforementioned geotechnical instrumentation. The only data that will have to be collected manually by field survey personnel will be on the upstream side of the three dams (after the reservoir is full, these monuments will be monitored only as the water level allows). This combination of instrumentation, despite the comparatively high cost of the initial investment, brings about $1.7 million total cost savings over the first five years of operation and a number of other advantages in comparison with a system that would be based mainly on manually operated total stations.

Leica TCA2003 total stations with the automatic target recognition and with a specially calibrated EDM component have been selected as the robotic total stations for the project. They offer standard deviation of distance measurements of $\sqrt{(1\text{mm})^2 + (2\text{ppm})^2}$ and angle measurements (one set in average atmospheric conditions) with a standard deviation of 1.5" or better.

The total number of the robotic total stations and the object prisms had to be compromised between the required accuracy and cost. The maximum spacing between the total stations is limited by the above mentioned accuracy criteria. For example, the angle error of 1.5" will produce a linear positioning error of 7.2 mm at a distance of 1000 m even if all other sources of errors (e.g. atmospheric refraction) could be eliminated. Therefore, to meet the accuracy requirements, it was decided to keep the maximum distances from the total stations to the object prisms not longer than 500 m and to observe horizontal and vertical angles in at least four sets. As far as the distance measurements are concerned, the specified EDM measurement accuracy should easily satisfy the positional accuracy criteria. Even if the average air temperature would be known only to ± 5$^{o}$C (producing an error of 5 ppm in the observed distance) the positional error in the direction of the observed distance would be only 2.5 mm over the distance of 500 m.

Possible effects of atmospheric refraction have been of a major concern in designing the DDM system. For example, a constant gradient of temperature across the line of sight of only 0.1$^{o}$C/m could produce a positioning error of 10 mm over the distance of 500 m on an average summer day. Therefore, in designing the survey procedures, minimization and randomization of the refraction effects has been of a major concern. The minimization of the refraction effects can be achieved by designing the total station locations as high above the ground as possible, far away from any side obstacles and performing the measurements during the time of the day with the least refraction effects. In the summer of 1996, MWD performed extensive test surveys with a Leica TCA total station in similar environmental conditions as those expected at the Eastside Reservoir. Systematic effects of atmospheric refraction became quite obvious. It was concluded, however, that if the surveys would always be conducted in the early hours, between 3 am and 5 am, the effects of refraction on the determination of displacements could become negligibly small. This is in agreement with some earlier studies conducted at the University of New Brunswick in Canada (Kharagani, 1987; Chrzanowski, 1989).

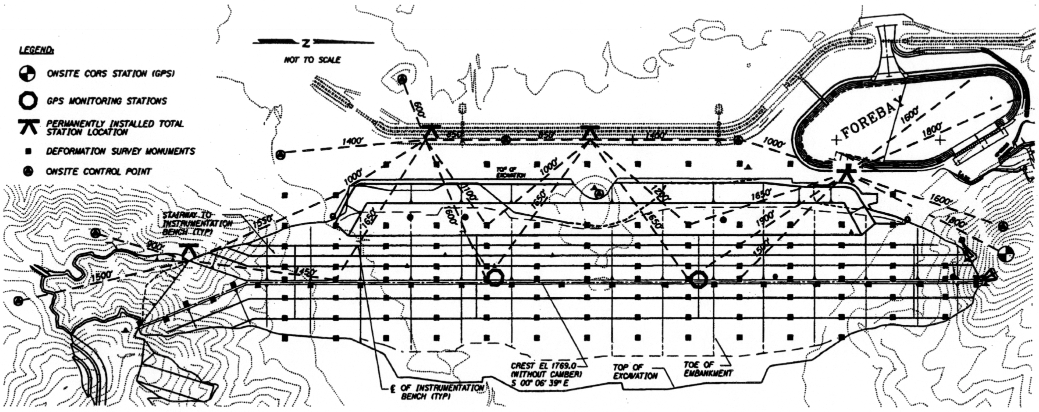

Figure 4. West Dam deformation monitoring configuration

If those effects would become significant at the Eastside Reservoir, the only economical option would be to randomize the refraction effects by reobserving the vertical and horizontal angles over two or three nights in several sets that would be spread over 3-4 hours (say, two hours after the sunset and two hours before the sunrise). The final decision on the observation schedule will be made after additional tests on the site, including measurements of gradients of temperature are performed when the system becomes operational (December,1999). Another possibility would be to add more total stations to the observation scheme to shorten the maximum observation distances. Since the error of refraction is proportional to the square of the distance, by shortening the distances to 250 m would reduce the refraction effect by a factor of four. This option, however, has been discarded as being uneconomical.

According to the final design, the DDM system will have a total of ten permanently mounted robotic total stations (Fig. 1), 360 object targets (EDM prisms) mounted on a pillar type monuments and five continuously operational GPS monitoring stations on the crests of the dams. The total station array has been designed to keep all distance measurements at 500 m or less. At least three reference backsight targets will be installed and included in the observation scheme at each robotic total station. Figure 4 shows, as an example, locations of total stations, reference targets and object prisms at the West Dam. Similar configurations were designed at the other structures.

The West Dam and East Dam will each have four permanently mounted robotic total stations and two GPS monitoring stations. The Saddle Dam will have two permanently mounted robotic total stations and one GPS monitoring station. The Goodhart Canyon Detention Basin will have one “roving” robotic total station and will also use two of the East Dam total stations. The Forebay will be monitored using the northerly West Dam total station. The monument spacing will be about 150 m apart on each of the dam berms, at the toe of the dams, on the crest of the forebay, and on the crest of the detention basin. The monuments will be about 75 m apart on the crest of the dams.

Each permanently mounted robotic total station will be equipped with a dedicated field computer with modem, network card, surge protection and remote monitoring and accessing software. The computers will have multiple serial ports for connecting the theodolite and the meteorological sensors. There will be a parallel port connection to allow a zip drive to be installed. The computers will be of an “environmentally protected” type - one that is meant to withstand dust, insects, outdoor use, etc. Communication between the field computers and a master computer at the MWD office (located 120 km away) will be provided by a wireless communication system that is described in section 4 below.

### 3.3. Design of Observation Shelters

Each total station will be housed in an “observation shelter” (Figure 5). The windows will be constructed of several large glass panels joined in a faceted and tilted arrangement, similar to a control tower window at an airport. Windows will be 6mm thick sodalime float glass. This glass has a 91% transmission of light due to a low iron content. The windows will be installed at a slight angle. This is to prevent having the theodolite line of sight perpendicular to the glass panel.

The foundation of each shelter has been designed according to the geology of each location to provide as stable a structure as possible. The pillar that the total station will be mounted on will be monolithic with the foundation of the structure. A holder for GPS antenna will be permanently mounted to a structural support on the roof of the shelter, directly above the center of the instrument (to be checked by a zenith optical plummet) so that, whenever needed, the stability of the foundation/pillar can be monitored by the GPS control surveys connected to the on-site geodetic control network. The block walls and structural supports will be embedded in the foundation so that movement of the foundation/pillar will be translated to the GPS point. Three leveling benchmarks will be installed in the foundation concrete slab for checking its vertical stability whenever any tilts would be suspected.

Initially, the power supply to each total station will be provided by solar cells. Eventually, the stations will be connected to 110V electric power lines. The emergency backup system for power for the total stations will be through internal batteries which can run the equipment for up to eight hours. The shelters will be ventilated and eventually (when connected to the electric power lines) will be air-conditioned.

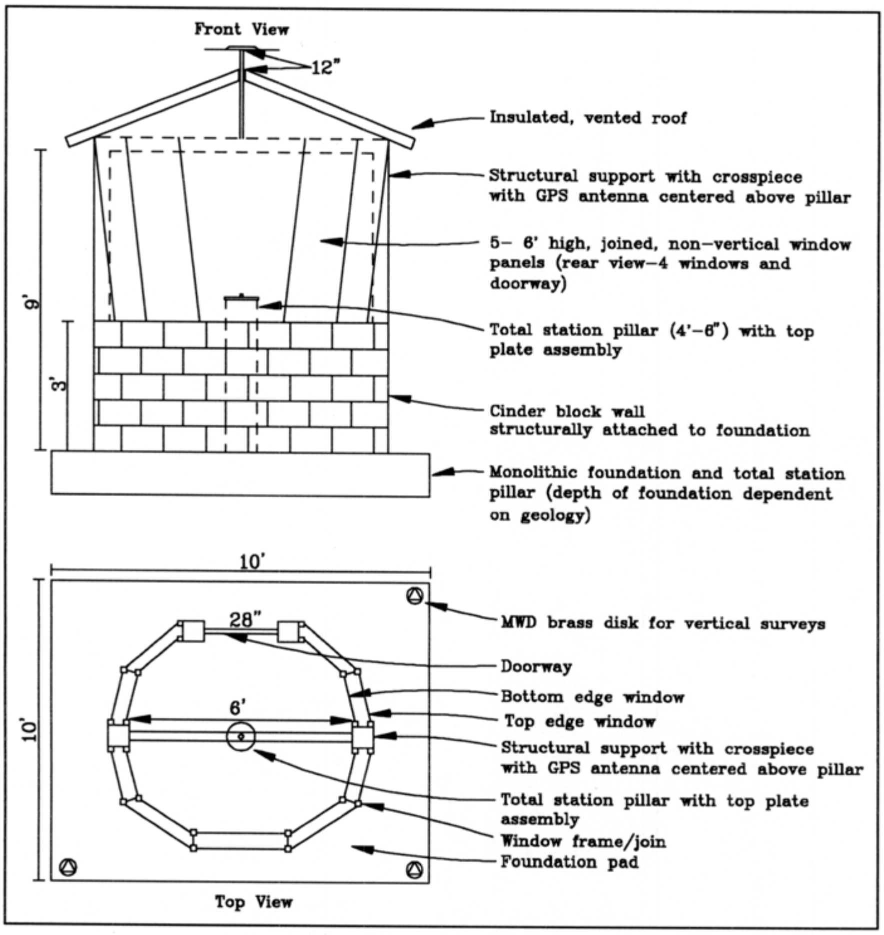

**Figure 5.** DDM observation shelter

## 4. Geodetic Data Collection and Transmission

### 4.1. Data Collection

The survey of object points will be accomplished by taking radial shots in direct and reverse mode to all the object prisms and to three or more reference points. The total stations will be monitoring horizontal and vertical directions, and slope distances. One of the reference stations (presumably the most stable one) will be assigned as the main reference backsight for direction measurements. Each total station with its subset of reference and object points will be treated as an independent sub-network in the subsequent data processing and analysis of displacements (see section 5 below).

The total stations will be linked to a computer system that will automatically and remotely control all functions. This will allow for remote power-up (especially useful in emergencies), remote download, and real-time measurement as needed. The system will operate on a set time schedule that will automatically turn on at the correct time and start direction (horizontal and vertical) and distance measurement sets. The total stations will also be programmed to collect a prescribed number of sets of angles at predetermined time intervals to achieve a preset level of accuracy. Sensors of air temperature and barometric pressure at each total station will automatically feed the information for distance reductions. When collection of all the prescribed sets of the observation data will be completed, the data will be transmitted to the main office computer for its evaluation, processing and deformation analysis (see section 5 below). After each epoch of observations, the system will be automatically shut down and will be basically "on-call" until the next scheduled power-up, or in the case of emergency, until someone remotely powers-up the system. Leica's APSWin software will be used in controlling all functions of the TCA2003 total stations and collecting observation data.

### 4.2. Communication System

Data communication and remote access between the onsite PCs running the total stations and the survey office will be accomplished using a spread spectrum wireless LAN system. This system utilizes Mavric™ Explorer wireless data communication networking controllers which have been developed by Metric Systems Corporation (Brown 1997). There will be one network controller at each total station location, one on the crest of each dam and one at the "host PC" in the onsite pumping plant communication room. The three network controllers on the crest of the dams will act as control points in the data flow and will also provide redundant communication links between the dams and "host PC" in emergency situations. For data access, this host PC will be programmed (pcANYWHERE™ script file) to call up the ten total stations via the network controllers and have all data download to the host PC. The data on this PC will then be accessible from remote locations utilizing pcANYWHERE™ software. This host PC will be able to transmit the data by a connection on the MWD computer network and by modem.

The onsite CORS and GPS object stations, along with the DDM total stations, will also be linked to an Automatic Data Acquisition System (ADAS) designed by consultants for MWD for the geotechnical instrumentation data collection. If a movement over a certain tolerance is picked up by the GPS monitoring system, or if any of the geotechnical instruments monitored through the ADAS exceeded expected limits, the DDM total stations would be programmed to automatically turn on and start monitoring the dams. This provides near instantaneous response time.

## 5. Geodetic Data Processing and Analysis

### 5.1. Absolute Positioning

Once the automatic DDM system becomes operational (end of 1999), absolute horizontal and vertical positions of all the robotic total stations and their main reference points will be determined in order to maintain the deformation analysis in one coordinate system and draw conclusions on the global stability of the whole area. The determination of horizontal positions will be performed together with the positioning survey of the on-site area control (16 monuments on the ridges surrounding the reservoir) using GPS in a static mode. The duration and number of the observation sessions will be designed to give relative error ellipses smaller than 5 mm at 95% confidence level. These static sessions will be processed along with data downloaded from the four CORS stations. A least squares network adjustment will be done to obtain geodetic positions for the 16 monuments of the area network and for all robotic total stations and the main backsight reference stations of the

DDM networks. A determination of the initial absolute vertical elevations will be accomplished by geodetic leveling of the first order accuracy from deep benchmarks located along two highways at the east and west ends of the project to the benchmarks at the shelters of the total stations and at main reference points. The absolute positioning surveys will be repeated at least annually and after each major seismic event (see section 6 below).

### 5.2. Processing and Evaluation of DDM Surveys

The ultimate goal of the DDM surveys is to determine x, y, and z components of displacements of the marked object points (pillars with EDM prisms) on the 3 dams and on other investigated structures with respect to stable reference points.

As it was mentioned earlier, after the initial determination of absolute positions, each total station with its sub-set of object targets on the dams and the reference stations will be treated as an independent sub-network for the determination of displacements of the object points. The only link between the neighboring total stations and the respective sub-networks will be through observations made from two neighboring total stations to a set of common object points belonging to both subnetworks (Fig. 4). Differences between the independently calculated displacements of those common points will serve as the final check on the quality of observations and stability of the reference system. Therefore, no adjustment will be performed on those redundant observations.

Raw observation data obtained from each total station will undergo an automatic evaluation and displacement analysis at the central office computer. The following steps will be performed:

*Step 1: Quality check of observations.* This step includes station adjustment of the collected sets of horizontal directions (a minimum of four sets), averaging of vertical directions and slope distances, and estimation of variances and residuals (internal accuracy parameters) of the observations. The variances and residuals are compared with the preset tolerances using statistical testing. If the test passes, go to Step 2. If the test fails, a command is given to the total station to measure an additional set and the Step 1 is repeated.

*Step 2: Correction of observation data*. Meteorological and calibration corrections are applied to the averaged directions and distances.

Step 3: *Epoch comparison of observations to reference points*. In this step, the averaged and corrected directions and distances to reference stations are compared with the values of the initial epoch of observations. If the differences are within the preset tolerances, go to Step 4. If the differences fail the statistical test, a warning signal is given (for a possible interpretation in Step 7).

Step 4: *Epoch comparison of coordinates of reference and object points*. In this step, coordinates of all observed points are calculated (using minimum constraints) with their variances and covariances and compared with the initial epoch to yield displacements of the points. If displacements of any reference points exceed the tolerance value, go to step 5. If the displacements of reference points pass the statistical test, go to Step 6.

Step 5: *Iterative Weighted Similarity Transformation of displacements of reference points*. In order to identify the unstable reference points (including the total station), the displacements of reference points and their variance-covariance sub-matrix obtained in Step 4 undergo the Iterative Weighted Similarity Transformation (Chen et al., 1990). The reference points which show displacements larger than their confidence region at 95% confidence level are flagged as being unstable.

Step 6: *Final calculation of displacements of object points.* The final determination of displacements of object points (including the unstable reference points) is obtained through least squares fitting of a displacement model into the observed displacements in which all the stable points are modeled as having zero displacements with their appropriate variances and covariances (Chrzanowski et al., 1983). The final displacements and their error ellipses are plotted

*Step 7: Consistency check* . In this step, differences in calculated displacements for points observed from two theodolite stations are tested. If differences are within a prest tolerance, mean values of the two determinations will be taken as the final displecemnts. If differences exceed preset tolerances, a manual intervention is necessary.

## 6. Design of Emergency Response Plan

An emergency response plan (to be implemented after the reservoir is operational) was developed to obtain verification of monument positions in a timely fashion after an event, with the most important measurements (those needed to verify structural integrity) obtained first. Within the first hour after an event, all the total stations will be powered on, obtaining the subset of deformation measurements specific to each total station, and transmitting the data to the office computer. After the automatic data processing and displacement analysis, a check on the status of the dams will be obtained within few hours after the event. The geodetic displacements when viewed in conjunction with the real-time geotechnical data obtained, will give a basis for the physical interpretation of integrity of the structures (Chrzanowski et al., 1991).

The “power up” may occur in several ways. There will be four methods of alarming built into the operations of the geotechnical instrumentation of the dams. The instrumentation is all connected by the aforementioned ADAS that will have the capability to send an alarm if a preset tolerance for any of the designated instruments is exceeded. The instrument types integrated into the alarming system will be the five GPS object stations on the crests of the dams, strong motion accelerographs, seepage flow meters, and the facility operators system known as SCADA. The DDM system of total stations will be linked to this ADAS system and will be capable of receiving these alarm notifications and will be automatically powered on upon receipt of notification. The total stations of the DDM system can also be remotely powered on by MWD staff using any PC on the MWD computer network with pcANYWHERE™ remote accessing software.

Within the first day after an event, a GPS static survey will be started to verify positions of the ten total stations and their backsight reference points. This survey will be completed utilizing the four CORS stations, five active GPS object stations, and manually collecting GPS data on the total stations and reference points of the DDM system. Receivers will be hooked up to the antennas on the observation shelters and antennas will temporarily replace the prisms on the main backsight reference points. Total station observations to the backsight reference points can also be added to the analysis of the network stability.

The second day after an event, GPS measurements will be manually collected on the sixteen onsite (ridge lines) control (HPGN monuments) along with the four CORS stations. By the second day after an event new coordinates of the CORS stations (as determined and posted by SCIGN) will be available and analysis of the first day of GPS will be completed. At this point in time, one will be able to compare new positions of the total stations and reference backsights with the previous positions.

By the third day after an event, one should be able to complete the analysis that will verify the geodetic positions of all the DDM total stations and backsights, the HPGN onsite monuments and the GPS object stations. This information will be compared with previous positions to determine if there are any significant displacements of any of these monuments. This information will then be used to identify any unstable reference and onsite ridge line points and perform deformation trend analysis using the aforementioned iterative weighted similarity transformation of the displacements (Chen et al. 1990). The trend analysis will be followed by integrated deformation modeling (Chrzanowski et al. 1986) of the dams and surrounding area using both geodetic and geotechnical data.

## 7. Concluding Remarks

The continuous monitoring system presented here was designed to provide adequate geodetic information over a large number of points for a long period of time with as little human intervention as possible. It also was designed to provide timely information after a major event, such as an earthquake, to help protect the public health and safety of the residents located near the reservoir. The system pays for itself in less than two years and provides all the geodetic information needed for reporting to the State of California in a timely fashion without requiring additional labor costs. It can analyze a good portion of the downstream surface area of all three dams in a few hours, including analysis and reporting time.

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