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AN AUTOMATED AND INTEGRATED MONITORING PROGRAM FOR DIAMOND VALLEY LAKE IN CALIFORNIA

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Abstract

The Metropolitan Water District of Southern California has constructed a new reservoir, Diamond Valley Lake, near Hemet, California. This project includes three large earth/rock dams of 2.9 km, 3.2 km and 0.8 km lengths, up to 85 m high, enclosing a valley approximately 7.2 km long and 3.2 km wide. When filling is complete, the reservoir will hold over 986 million cubic metres of water.

A plan was developed to monitor the effects of reservoir and dam loads on the dams and their foundations to ensure that any adverse conditions that develop during operation, and especially during initial filling, are detected as soon as possible. Since Diamond Valley Lake is located in a seismically active area, the dam deformation monitoring (DDM) program is supplemented by an on-site GPS area monitoring network that is connected to the continuously operating (GPS) reference stations (CORS) of Southern California crustal motion monitoring system.

The DDM plan, in addition to routine visual inspection, consists of:

- geotechnical monitoring instrumentation consisting of piezometers, strong motion accelerographs, weirs, inclinometers, and extensometers, supported by the Automated Data Acquisition System (ADAS);
- a real-time GPS monitoring system; and,
- an automated terrestrial geodetic monitoring system consisting of eight permanently installed robotic total stations and an array of 228 prisms mounted on the faces of the monitored structures.

The geodetic DDM system detects displacements larger than 10 mm at the 95% confidence level. The total stations are remotely operated and automatically collect three-dimensional positioning data on a set time schedule from which displacements are determined and plotted. The collection and analysis of the geodetic data is accomplished in a fully automatic mode by DIMONS software developed at the University of New Brunswick.

The automatic monitoring system has been fully operational since October 2000.

1. Introduction

1.1 Overview of the Project

In 1996 the Metropolitan Water District of Southern California (Metropolitan) began construction of Diamond Valley Lake, Southern California's largest water storage reservoir, with a capacity of nearly one billion cubic metres of water (986.8 million m^3). This $2-billion project, located near Hemet, California (about 160 km southeast of Los Angeles), was designed to secure six months of emergency water supply [Metropolitan, 1997] for about 16 million inhabitants. It was created by enclosing the Domenigoni and Diamond Valleys at an elevation of about 500 metres with the construction of three earth/rock filled dams (Figure 1 and Figure 2). The reservoir, about 7.2 km long and more than 3 km wide, covers over 4500 acres of land. The reservoir project consists of:

- the West Dam, 85 m high and 2.9 km long;
- the East Dam, 55 m high and 3.2 km long; and,
- the Saddle Dam, 40 m high and 0.8 km long.

The dams have clay cores and rock fill shells with internal filter and drain zones. Aside from one dam founded partly on dense alluvium, the foundations consist of sound bedrock. The project also included construction of a storage forebay at the West Dam, a detention basin, and a pumping plant. The storage water is currently supplied from the Colorado River through a 387 km aqueduct. A second water source comes via the California State Water Project through an existing 710 km aqueduct from northern California; it will be transported by the 72 km long, 3.7 m diameter Inland Feeder Pipeline to Diamond Valley Lake by 2004. The filling of the reservoir began in December 1999 and is estimated to take between two and five years, depending on the availability of water throughout the western United States. At the time of writing this paper (February 2001), the filling was about 60 % complete.

Figure 1. Oblique view of the Diamond Valley Lake.

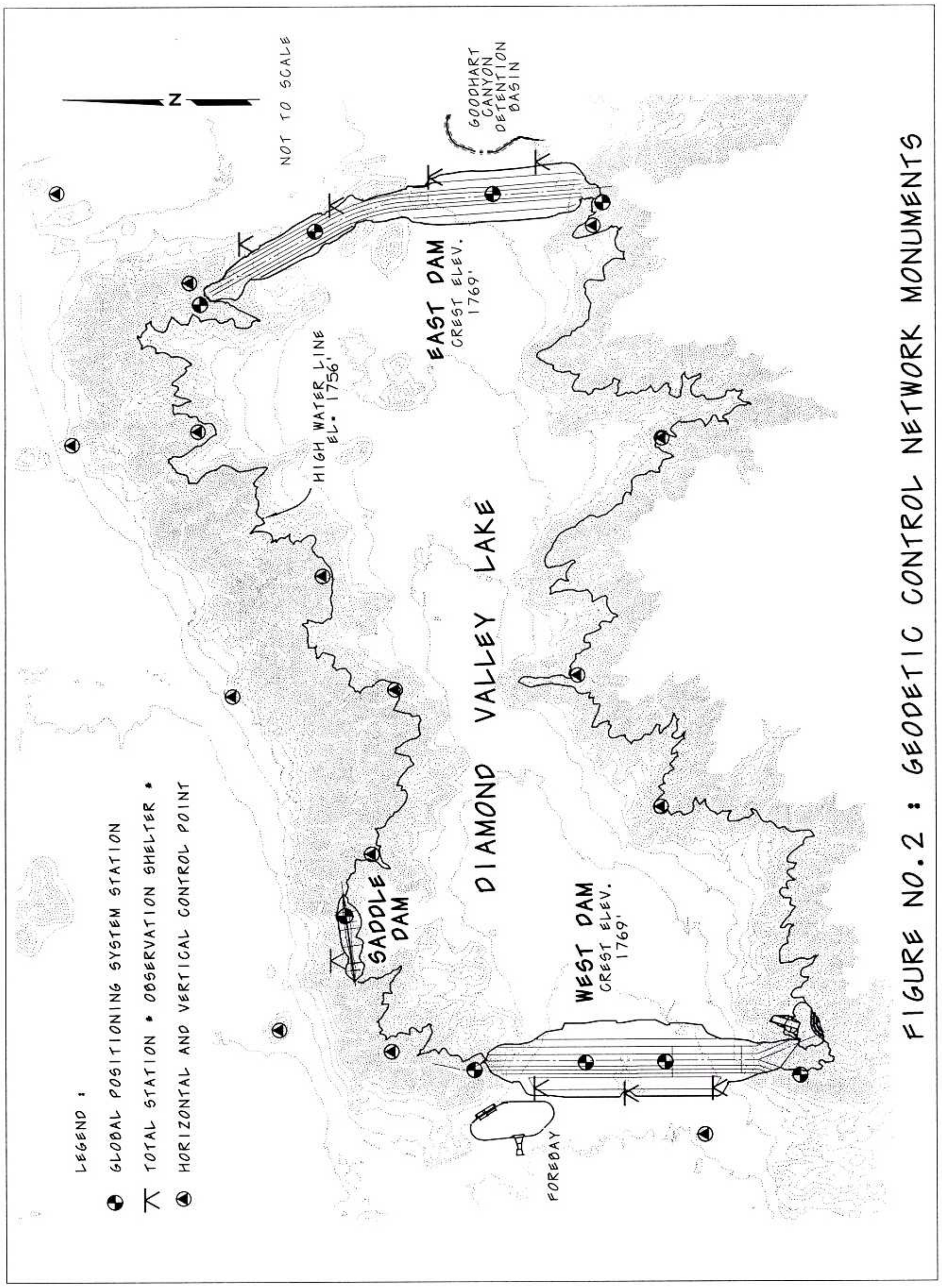

Figure 2. Plan view of the project area.

1.2 Performance Monitoring Program

A program of performance monitoring has been established in order to confirm that the dams and foundations are functioning as intended. The principal aspects to this are the seepage performance and deformation of the dams, as a result of the water load on the structures. The seepage performance of the dams is monitored using piezometers, which measure water pressure inside the structure and with seepage weirs, which measure seepage water at certain points downstream of the structures. The deformation performance of the dams and foundations is measured using settlement gages, inclinometers, and survey monuments on the surface of the structures. The response of the dams to earthquake loading will be measured using accelerographs located on natural ground downstream of the dams, and on abutments and crests of the dams.

1.3 Geotechnical Monitoring Program

The geotechnical instrumentation includes the seepage monitoring instruments (piezometers and seepage weirs), and local deformation instruments (settlement gages, inclinometers, and accelerographs).

Vibrating wire type piezometers were embedded in the fine-grained core zone of the dam to measure pore water pressures in this zone. The levels of pore water pressures in the core zone can be critical to embankment stability during construction, when pore water pressure builds up as embankment fill is placed above. In addition, pressures in the alluvial foundation were measured to assure that high pore pressures in this zone would not create slope instability for the partially constructed dams.

Open well and Casagrande piezometers were installed in the coarser pervious zones downstream of the core. These piezometers allow monitoring of the performance of the impervious zones and foundation cutoffs, as well as the performance of the free-draining downstream zones. Anomalous behavior of these piezometers might be indicative either of an unexpected increase in seepage quantity through the impervious zones, or of the inability of the drainage zones to carry the seepage, either of which may be an indication of developing problems.

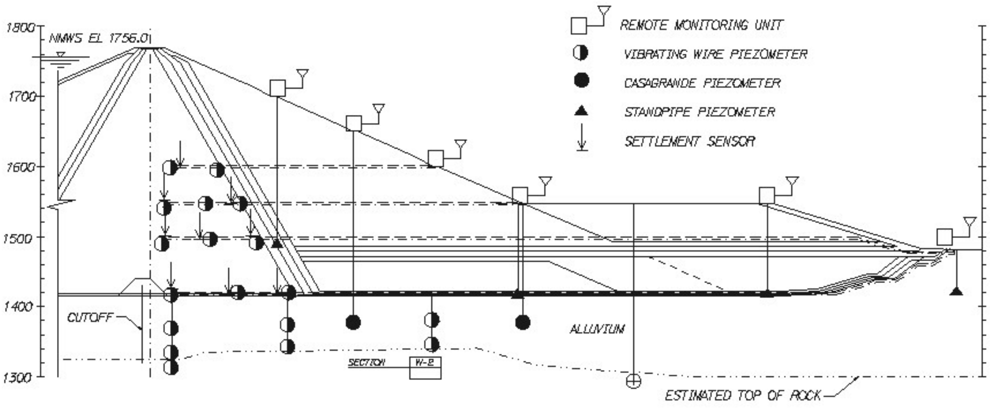

Figure 3. Typical distribution of the instruments in one of the dam cross-

Seepage weirs have been installed downstream of the dams. The seepage weirs do not measure all the seepage that passes through the dams or foundation, but the quantity of seepage measured in the weirs, and the rate of change of the seepage quantity, provides an indicator whether the dams and foundations are performing properly. In addition, the weirs are fitted with turbidimeters that measure the seepage turbidity. Turbid seepage is an indicator that fine-grained particles are showing up in the seepage, and would be an indicator of potential problems developing internally.

The geotechnical instrumentation array includes 189 piezometers, 15 strong motion accelerographs, 3 inclinometers, 74 settlement sensors, 4 fixed embankment extensometers and 16 weirs. The instruments have been grouped mainly along selected cross-sections of the three dams. Figure 3 shows a typical distribution of the instruments in one of the dam cross-sections.

1.4 Geodetic Monitoring Program

The geodetic monitoring plan was developed to monitor the response of the dams and foundations to the gravitational load of the dam and reservoir to ensure that any adverse conditions that develop during operation, and especially during initial filling, are detected as soon as possible.

The area of Diamond Valley Lake is located only a few miles south of the San Jacinto fault, a tributary fault to the San Andreas fault, within the interaction zone between the North American and Pacific tectonic plates. Therefore, in designing the dam deformation monitoring 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. Thus, in order to be able to discriminate between various factors affecting the integrity of the dams, the local dam monitoring schemes must be supplemented by a geodetic network to monitor the stability of the ridgelines and mountain slopes around the reservoir. The area geodetic control network has been connected to the existing regional GPS network of continuously operating reference stations (CORS) of the Southern California Integrated GPS Network (SCIGN), which monitors the earth crust movements [Bock et al., 1997]. Thus the monitoring scheme comprises:

1. The local Dam Deformation Monitoring (DDM) system (the local geotechnical DDM system and the local geodetic DDM system).
2. The on-site GPS area control network for monitoring the stability of the area surrounding the reservoir and for checking and updating positions of DDM reference stations.
3. The regional GPS control network connecting DDM and on-site area geodetic monitoring systems with the CORS stations of SCIGN.

The local geodetic DDM information is required as a part of a Metropolitan 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 Diamond Valley Lake structures have been monitored weekly, beginning with the construction of the first berm and continued throughout the duration of the earthen dam construction period. The same monitoring frequency will continue during the initial filling period of the reservoir over the course of several years. Monitoring will then be reduced to quarterly surveys for a period of 5 years, or until the structures are stabilized, and then probably reduced to twice yearly in accordance with a State approved monitoring program for these facilities.

This paper, after a general overview of the monitoring scheme, gives details on the design, installation, and evaluation of a fully automated geodetic DDM system.

2. Overview of the Deformation Monitoring Scheme

2.1 Regional and On-site Area Monitoring Networks

The regional control network of the monitoring scheme includes four continuously operating GPS stations that are part of the CORS system of 250 such stations monitoring crustal motion of the continental plates in southern California. Two of the CORS stations are located on the project site, one near the northwest quadrant and one at the southeast quadrant of the reservoir (Figure 2). The two remaining stations are several kilometres away. These continuously operating GPS receivers are administered by SCIGN, a collaboration of scientists (from Scripps Institution of Oceanography's Orbit and Permanent Array Center (SOPAC) in La Jolla, California; the United States Geological Survey's (USGS) Pasadena Office; and the Jet Propulsion Laboratory in La Canada, California) studying crustal motion and earthquakes. SCIGN handles all data processing and analysis of the system and posts daily geodetic positions for all stations on the Internet. By utilizing this CORS system for the regional control, one is able to discriminate between the effects of regional crustal motion and on-site area deformation due to local causes.

The on-site area control network consists of sixteen standard survey monuments situated on the two ridgelines surrounding the reservoir (Figure 2). These monuments were initially tied horizontally to California's High Precision Geodetic Network (HPGN) NAD83, Zone 6, Epoch 1991.35, and have National Geodetic Survey (NGS) first order elevations established with respect to the North American Vertical Datum of 1988 (NAVD88). These monuments act both as a network to monitor stability of the surrounding hills that may be affected by the increasing load as the water level rises in the enclosed valley, and as area control points for monitoring the stability of the reference stations of the local geodetic DDM system from which displacements of object points on the faces of the dams are determined. Utilizing these methods to monitor the reference monuments of the DDM will avoid contamination of the local dam displacement measurements with non-structurally related settlement or movement such as regional slipping and creep.

Table 1. Accuracy of initial GPS positioning of RTS points

RTS Point	Location	95% Error Ellipses	
		a [mm]	b [mm]
RTS2 (pt.1760)	West Dam	5	4
RTS3 (pt. 1740)	West Dam	4	3
RTS4 (pt. 1720)	West Dam	5	4
RTS5 (pt. 2720)	Saddle Dam	7	5
RTS7 (pt. 3720)	East Dam	10	6
RTS8 (pt. 3740)	East Dam	5	3
RTS9 (pt. 3760)	East Dam	5	3
RTS10 (pt. 3780)	East Dam	5	3

The initial horizontal positioning of the area control points (HPGN monuments) was performed with dual frequency GPS receivers (Trimble 4000Sse and Trimble 4000Ssi) in a static mode using 30 to 60 minute sessions. The duration of the observation sessions was designed to give relative error ellipses smaller than 10 mm at the 95% confidence level. These static sessions were processed together with data downloaded from the four CORS stations. A least squares network adjustment was performed to obtain geodetic positions for the sixteen control monuments and for about 30 reference stations of the local geodetic DDM system. The network will be measured every year, or after any major seismic event. Relative displacements between the two ridgelines that encircle the reservoir, and stability of observing stations and reference points of the local geodetic DDM system, will be determined from the network analysis. The accuracy of the GPS positioning of the RTS points is summarized in Table 1.

2.2 Local Geodetic

Optimization of accuracy and cost of the geodetic DDM system has been paramount in the design of the monitoring scheme. Detection of horizontal and vertical displacements larger than 10 mm at the 95% confidence level, with respect to local reference points, was accepted as the accuracy criterion in designing the DDM scheme. Thus the maximum semi-axes of the standard error ellipses of a single horizontal positioning should not exceed 2.9 mm (calculated as $10/2.45\sqrt{2}$) and standard deviation of a single vertical positioning should not exceed 3.6 mm (calculated as $10/1.96\sqrt{2}$). To achieve this accuracy in a reasonably economical way is not a trivial task. Various geodetic techniques and various configurations of the monitoring scheme were compared and analyzed for their accuracy and cost. The use of manually operated precision total stations was compared to the use of robotic total stations (RTS), and the use of GPS with both manual static and real-time kinematic (RTK) modes of operation. Use of active GPS stations in a continuous mode of operation, use of laser alignment systems, and various combinations of the above techniques have also been analyzed. Aside from monitoring techniques, other factors had to be considered as well, namely: the restriction of human access to the dams after an earthquake, the need for continuous monitoring in emergency situations, and assurance to the public that the dams are continuously monitored for safety.

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 automatic target recognition and passive prisms permanently installed on the crests and downstream faces of the dams. This system has been combined with five continuously operating RTK GPS monitoring stations on the dam crests, which act as a real-time alarm, and the aforementioned geotechnical instrumentation. The only data that is collected manually by field survey personnel is from surveys on the upstream side of the three dams, performed only immediately prior to water inundation. After the reservoir is full, these monuments will be monitored only as the water level and schedules allow. Despite the comparatively high initial investment for a system based on robotic total stations ($1.3-million), about $1.5-million total cost savings over the first five years of operation will be experienced by Metropolitan. This does not include the number of other safety advantages previously mentioned.

Leica TCA1800S total stations with automatic target recognition and with a specially calibrated EDM component were 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) of 1.5" [Leica, 1996]. In order to meet the positioning accuracy criteria, the maximum distances to the object prisms and number of repeated surveys in each survey campaign had to be optimized as discussed in more detail in the following sections.

3. Design and Installation of the Geodetic DDM System

3.1 Effect of the Accuracy Criteria on the Design

Selecting the total number of robotic total stations and object prisms was a compromise between required accuracy and cost. The maximum spacing between the total stations is limited by the above mentioned accuracy criteria. For example, an 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 error (e.g., atmospheric refraction) could be eliminated. To meet the requirement of obtaining standard error ellipses smaller than 2.9 mm, it was decided to keep the maximum distances from the total stations to the object prisms at less than 500 m. The angles were to be observed in a minimum of two sets of direct and reverse measurements to obtain a standard deviation of observations of 1.1". As far as the distance measurements were concerned, the specified EDM instrument accuracy easily satisfied the positional accuracy criteria. These two components resulted in the desired horizontal positioning error of 2.7 mm at 500 m distances. Even if the average air temperature would be known only to ±5°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 a distance of 500 m. Therefore, from the point of view of random observation errors, the maximum distances from the total station to the object prisms could be 500 m.

3.2 Effects of Atmospheric Refraction

It was realized that in the semi-arid and generally very hot climate conditions at Diamond Valley Lake, systematic errors of atmospheric refraction could produce unacceptably large positioning errors. For example, a constant gradient of temperature across the line of sight of only 0.1°C/m could produce a positioning error of 10 mm over a distance of 500 m [Chrzanowski, 1989; Chrzanowski, 1999]. Therefore, in designing the survey procedures, minimization and randomization of the refraction effects was a major concern.

It was thought, during the design phase of the project, that the minimization of the refraction effects could be achieved by designing the total station location as high above the ground as possible (a minimum of 1.5 m) and far from any side obstacles. Observations were also scheduled to be made during the time of day with the least refraction effects.

In the summer of 1996, Metropolitan performed extensive test surveys with a Leica TCA total station in similar environmental conditions as those expected at Diamond Valley Lake. Systematic effects of atmospheric refraction became quite obvious. It was originally thought that if the surveys were always conducted in the early morning hours, between 3 a.m. and 5 a.m., the effects of refraction on the determination of displacements could become negligibly small. If those effects became significant at Diamond Valley Lake, the only economical option would be to randomize the refraction effects by re-observing the vertical and horizontal angles over two or three nights, in several sets that would be spread each night over 3-4 hours.

A possibility of installing instrumentation for measurements of gradients of temperature and applying corrections to the observed directions was also considered [Chrzanowski, 1999] but would have significantly increased the cost of the project.

Another possible way to reduce atmospheric refraction effects on angle measurements was 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, one could reduce the refraction effect by a factor of four.

This option, however, was discarded due to its high cost. It was finally decided to keep the maximum distances to the targets less than 500 m. The actual results of the monitoring surveys would be evaluated after two to three months of system operation, with the possibility of introducing modifications to the observation scheme.

3.3 Design of the Configuration of the Monitoring Network

By accepting 500 m as the maximum allowable distance between an RTS and its targets on a dam face, the monitoring scheme includes eight permanently mounted RTSs (Figure 2), 228 object targets (prisms) mounted on concrete pillar monuments (Figure 4), and five continuously operational GPS monitoring stations on the crests of the dams (Figure 2). The DDM station array has been designed to keep all distance measurements at 500 m or less. Three reference back sight targets were installed and included into the observation scheme at each RTS. One of the reference targets serves as the main orientation reference and the others are used as control points for monitoring the stability of the RTS station and the main reference target. Some of the reference points are common for two neighboring RTSs. Figure 5 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.

Figure 4. Pillar monuments with the target prisms.

The West Dam and East Dam have three and four permanently mounted robotic total stations, respectively, and two GPS monitoring stations each. The Saddle Dam has one permanently mounted robotic total station and one GPS monitoring station. The fill portion of the detention basin is monitored by the two southerly East Dam RTSs. The forebay is monitored using the northerly West Dam total station. The target monument spacing is 152 m (500 ft) 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 monument spacing is 76 m (250 ft) on the crest of the dams.

All 360 upstream and downstream survey monuments were installed by January 2000. The radio communication and computer systems were installed and operating by mid-September 2000. With the completion of all eight total station shelters, the three dams, forebay and detention basin have been automatically monitored since mid-October 2000.

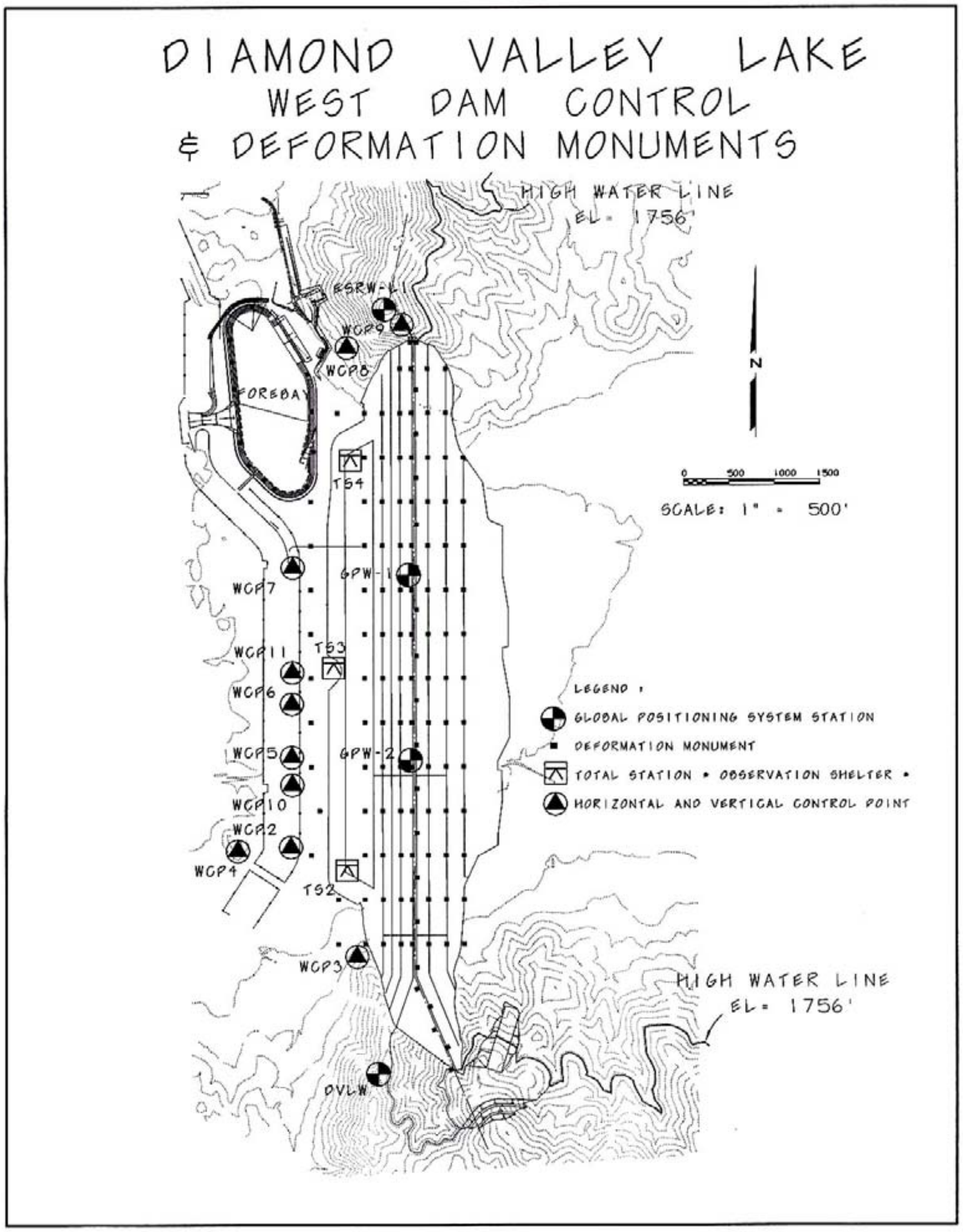

Figure 5. **Observation scheme at the West Dam.**

3.4 Meteorological Equipment

The meteorological sensor module ENV-50-HUM from Sensor/Metrics, Inc. was selected for measurements of temperature, barometric pressure, and relative humidity for the reduction of EDM data at each RTS location. The module has a durable weatherproof case that is easily mounted on poles, beams, or rooftops. It provides temperature measurements between –40°C and +50°C with an accuracy of ±0.5°C, barometric pressure between 930 mb and 1070 mb with ±2 mb accuracy, and humidity between 0% and 100% RH with ±5% accuracy. It can be connected to any PC or modem to collect and display real-time data. The module sensors were tested and calibrated at the University of New Brunswick (UNB). The software to interface with the meteorological sensors was developed by UNB. For this project, the modules have been equipped with two temperature sensors, one for measurement of the internal temperature of the RTS shelter, and another for measurement of the outside air temperature for distance reductions.

3.5 Design and Construction of Observation Shelters

Each RTS with its computer equipment, meteorological sensors, communication radio, and power supply are housed in an observation shelter (Figure 6). The observation shelters were designed to be small (10 ft x 10 ft) square buildings with windows on all sides. The configuration of the windows provides a view of all the monuments to be observed from each total station. The windows are dual pane glass with a 14% gray tint to help reduce the heat inside the structures. A heat conveyance fan on the insulated roof of the structures draws cooler air in from vents at the bottom of the structure. Windows are approximately 6 ft high to allow for a line of sight to points on top of the dam.

Figure 6. RTS observation shelter.

Calculations and laboratory tests at UNB have shown that distance measurements at Diamond Valley Lake will have errors of +6.4 mm to +7.8 mm, depending on the incidence angle of the electromagnetic signal on the glass panel, while the line of sight in direction measurements will be shifted from 0 mm at an incidence angle of 0° to 3 mm at an incidence angle of 40°. Since the glass errors are constant for repeated sightings to object prisms, their effect cancels out in the determination of target displacements.

Due to the remote locations of the structures, all equipment is run by DC power from solar panels located adjacent to the shelters. The solar panels charge three batteries that can supply power to all the equipment for five days without recharging. Solar power allows for an independent station and communication network that does not rely on other utilities in times of emergency.

The foundation of the shelters was designed according to the geology of each location to provide good structural stability. The pillar that each RTS is mounted on is monolithic with the foundation of the structure. A GPS antenna can be mounted to a structural support on the roof of each shelter (Figure 7), directly above the center of the instrument using an optical plummet so that the stability of the foundation/pillar can be monitored by the annual area GPS control surveys (see Section 2.1 above). In addition, three levelling benchmarks are installed on each foundation slab to monitor vertical stability and tilting, if needed.

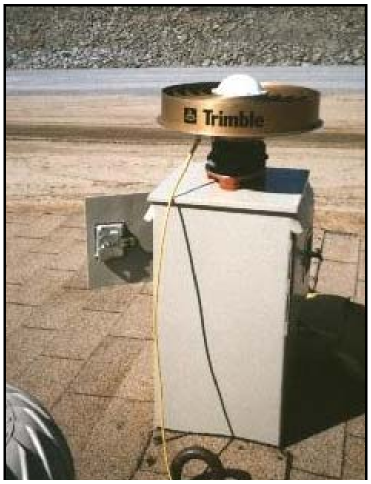

Figure 7. Choke ring antenna on observation shelter roof.

3.6 Geodetic Data Communication Network

Each total station requires a dedicated computer for the remote access capability, for controlling functions of the total station, and for data storage. This computer configuration consists of an industrial computer (capable of operating at 55°C), an Ethernet card, surge protection, external rebooter, and remote monitoring and accessing software. The computer is a Pentium 233Mhz computer sealed from dust and insects in a metallic case with two internal cooling fans. The computers are mounted to the southerly, shaded, wall of each shelter to protect them from direct sunlight. The computer has multiple serial ports for directly connecting both the total station and the meteorological sensors. A Compaq server was installed on-site at a small air-conditioned building just south of the new pumping plant known as the Radial Gate Structure (RadGat) to act as the data backup and processing hub. This is the entry point to and from the Metropolitan Wide Area Network.

Data communication and remote access between the on-site PCs running the total stations and the Metropolitan computer network has been accomplished using 17 BreezeCom spread spectrum radios, creating a wireless LAN system covering over 15 square miles at the site. Each shelter has one Station Adapter (SA) radio with a small antenna aimed at the closest Access Point (AP) radio using a whip antenna. The five AP radios are situated on the three dam crests to act as wireless hubs and perform relay functions between the eight shelter radios and the four Workgroup Bridge (WB) radios. The four WB radios provide connectivity for the longer distance data transfers (from two to six miles) that require larger parabolic grid antennas.

3.7 DIMONS Software for Automatic Data Collection and Processing

All functions of RTSs, remote data collection, and automatic processing are controlled by DIMONS (Displacement Monitoring System) software developed at UNB in cooperation with A. Chrzanowski & Associates, a consulting company in Canada. Details on DIMONS are given in another paper of this symposium [Lutes at al., 2001]. Here, only the main characteristics of DIMONS and its application to the Diamond Valley Lake project are given.

1. DIMONS is made up of several key components, each handling specific tasks related to project management, data collection, and analysis. Every component must be set up on all computers which will be used in the monitoring surveys.

2. Every RTS and meteorological sensor module must be controlled by a host computer. Each host computer may be accessed directly or via a network connection.

3. DIMONS can handle the collection and processing of data collected by any number of RTSs. Each RTS, set up on a survey point, makes observations of distances, horizontal directions and vertical angles to a set of survey points with target prisms. These target points include object stations (which are expected to possibly move over time) and reference stations (which are expected to remain stable over time).

4. The core of the system is the database, where most defining parameters of a monitoring project are stored. A separate database is maintained for each project defined on the system. The Windows system registry is used by DIMONS to store settings required to access the databases

5. Observation sequences, as stored in the database, may be initiated manually by a user at any time, or programmed to execute at any time. The Windows task scheduling service is used to trigger all automated observations.

6. Data collected during observation sessions is stored on the host that controls the data collection. This data may be transferred to a central computer, again manually or by a predefined schedule.

7. All observations are processed for direction station adjustments, EDM meteorological corrections, and calculation of survey point coordinates. In addition, DIMONS will perform an iterative weighted similarity transformation (IWST) to detect any instabilities in the fixed reference survey points [Chen et al., 1990].

4. Automated Collection and Processing of the DDM Data

4.1 Initial Positioning of RTSs and Reference Points

Horizontal positions of all 8 RTS stations and their main reference points were obtained from the initial survey campaign (October 2000) of the on-site area GPS network as described in Section 2.1 above. The coordinates of each RTS were obtained by including into the on-site area network GPS receivers centered above the RTS pillars. They will be checked once each year or after any significant seismic event. Determination of the absolute vertical elevations, initially needed on the DDM system, was accomplished by geodetic levelling from the first order benchmarks located along two highways at the east and west ends of the project.

4.2 Monitoring Surveys

Though initial coordinates of all RTSs have been determined in the coordinate system of the on-site area network, each RTS survey point with its set of observed object and reference survey points are treated in the displacement monitoring process as an independent local network in its own local coordinate system. The displacements of any object target point are computed based on its movement with respect to the RTS point and the reference target points. Because of the distorting effects of the glass windows on the lines of sight, a rigorous relationship between the local coordinate systems of individual RTS sub-networks is difficult. Nevertheless, the differences are negligibly small in calculating displacements of the targets, which may be observed from two different RTS stations.

The eight total stations are linked to a computer system network that automatically and remotely controls all functions using the DIMONS software. This allows for remote power-up (especially useful in emergencies), remote download, and real-time measurement as needed.

The system operates on a set time schedule (currently, two cycles of observation sets per day, at 4 am and 12 noon) that automatically activates the RTS and the observation process. The total stations are programmed to collect a prescribed number of sets of observed horizontal and vertical directions and distances to all or selected sub-group of reference and object targets. Measurements of air temperature (both internal and external), barometric pressure and humidity at each total station are automatically recorded and used for distance reductions. When collection of the observation data in the given cycle is complete, the system automatically shuts down and is basically “on-call” until the next scheduled power-up. In the case of emergency, the DDM can be activated by designated Safety of Dams or Survey personnel via the Metropolitan Wide-Area Network or any of the automated monitoring systems within the aforementioned ADAS.

All RTS procedures can be controlled from a Metropolitan office that is connected to the Metropolitan Wide Area Network by a remote link through pcAnywhere. The remote controls include scheduling the remote power-up, giving commands for the measurements of selected angles and distances, and establishing the number of sets of measurements in a given cycle of observations. The data collection, downloading of raw data, backup of files, and processing of raw data is performed automatically within the DIMONS software.

A set of tolerance criteria must be defined. This includes the minimum and maximum number of sets to perform, and the maximum allowable value of residuals from the station adjustments. Currently, a minimum of two sets of observations are collected in each cycle. If any of the residuals of the station adjusted directions exceeds 3″, additional sets are taken.

4.3 Data Processing

After a full cycle of data has been collected, the raw distances are first corrected for the RTS and target additive constants, and for any RTS scale bias. Next, the measured atmospheric conditions are used to perform a velocity correction on the distances. After this, the sets of observations are combined using a least squares set adjustment. Finally, the combined observations are corrected for the effect of instrument and target heights above the survey points. The field observations are now reduced mark-to-mark and ready for use in coordinate calculations.

Mark-to-mark reduced observations are used to calculate coordinates for all of the observed points. The coordinates of one fixed point and the azimuth to one of the targets are used to define the coordinate system. These computed coordinates are considered *preliminary coordinates* because they have not been screened for the possible effect of any unstable reference points.

A subset of the observed points is indicated to be a set of *reference* (stable) points by the user. The computed preliminary coordinates are then compared to the coordinates obtained from a specified *base cycle*, and a check is performed to determine whether any of the reference points show significant movement. This step is known as *unstable point detection*, and is an important part of the overall computations. The IWST of displacements [Chen et al. 1990] is used in the identification of the unstable reference points.

Finally, coordinates of all stable reference points (including the RTS point if identified as being stable) are treated as constrained stations in the calculation of the final coordinates of the object points.

After final point coordinates have been computed for an observation cycle, it is useful to generate a displacement plot. The displacement plot can reveal deformation trends, and is a useful diagnostic tool to determine whether the computed displacements are significant in a statistical sense.

There may be locations where observations are made from more than one RTS. In this case, the location is denoted by more than one survey point and target. In this manner, a named target point has its position determined in more than one coordinate system. The displacements of the location as computed from a pair of measurement cycles may be compared for the purpose of accuracy evaluation of the monitoring system (see Section 6.1)

5. Emergency Response Plan

The on-site CORS, the GPS object stations and the RTSs are linked to an Automatic Data Acquisition System (ADAS), designed by consultants for Metropolitan, 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 are programmed to automatically turn on and start monitoring the dams. This provides near instantaneous response time, particularly important in case of a seismic event.

The emergency power-up may occur in several ways. There are four methods of alarming built into the operations of the instrumentation of the dams. ADAS has 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, linked to the ADAS system and capable of receiving these alarm notifications, will be automatically powered up upon receipt of notification. The total stations of the DDM system can also be remotely powered on by Metropolitan staff using any PC on the Metropolitan computer network, through the data communication system, or from home with proper access privileges.

Within the first day after an event, a GPS static survey will be started to verify positions of the eight RTSs and their back sight reference points. This survey will be completed with eight geodetic receivers, utilizing the four CORS stations, five active GPS object stations, and manually collected GPS data on the RTSs and reference points of the DDM system. Receivers will be connected to the antennas on the observation shelters, while special brackets have been designed to attach GPS antennas above the prisms located on the main back sight reference points. RTS observations to the back sight 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 (ridgelines) control 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 RTSs and reference back sights with the previous positions very precisely.

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 RTSs and back sights, 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 ridgeline points and perform deformation trend analysis using the IWST of the displacements [Chen et al., 1990]. The trend analysis will be followed by integrated deformation modelling [Chrzanowski et al., 1991] of the dams and surrounding area using both geodetic and geotechnical data.

6. Preliminary Evaluation of the RTS Monitoring Results

6.1 Overall Accuracy of RTS Monitored Displacements

The automatic DDM system has been fully operational since October 9, 2000. At the time of writing this report, about three months of data became available. During that time, no irregular behaviour of the three dams has been noticed. This preliminary evaluation of the accuracy of the DDM system is limited to data collected by the eight RTSs.

In order to randomise effects of atmospheric refraction, the observation cycles have been separated by several hours, to occur during both day and night. Initially, the system was programmed to perform observations in three cycles per day (4 am, 12 noon, 8 pm), three days per week. Since January 15, 2001, after initial evaluation of refraction effects, the program of observations has been changed to collect data in two cycles per day (4 am, 12 noon), 5 days per week. For reporting purposes, weekly averages of the coordinates of each point are computed from the results of individual cycles. It is planned to revise the schedule after a full evaluation of the system during the summer of 2001, when the performance will be tested in the hot weather conditions.

The preliminary accuracy evaluation of the DDM system has been based on comparing displacements of those points that are observed simultaneously from two neighbouring RTSs. There are 4 double-observed targets at the West Dam and 6 at the East Dam. Figure 8 shows the West Dam point with targets 1079 and 7079, observed from TS3 and TS2.

The differences of double-observed displacements may be treated as true errors. By taking a sufficiently large sample of the true errors of differences, one may estimate standard deviation of the single (in our case the weekly averaged) observation from:

$$\sigma = \sqrt{\textstyle\sum(D_i^2)/2n} \qquad (1)$$

where n is the total number of examined pairs of observations, and D_i are differences of individual double observations.

A sample of 8 weeks of observations of ten double points taken between December 4, 2000 and January 29, 2001 has been used in the evaluation. Following the tolerance requirement of detecting displacements of 10 mm or larger, the tolerance for the difference of two independently determined displacements is 14 mm (calculated as $10\sqrt{2}$). Analysis of the behaviour of dN, dE, and dH components (based on weekly averages) for ten double points has shown that:

1. Of 216 double observations, three differences (all dH components) exceeded the 14 mm tolerance.
2. Three dH components exceeded, with differences of 15 mm, 19 mm, and 21mm.
3. 98% of determined displacements fall within the designed tolerance.

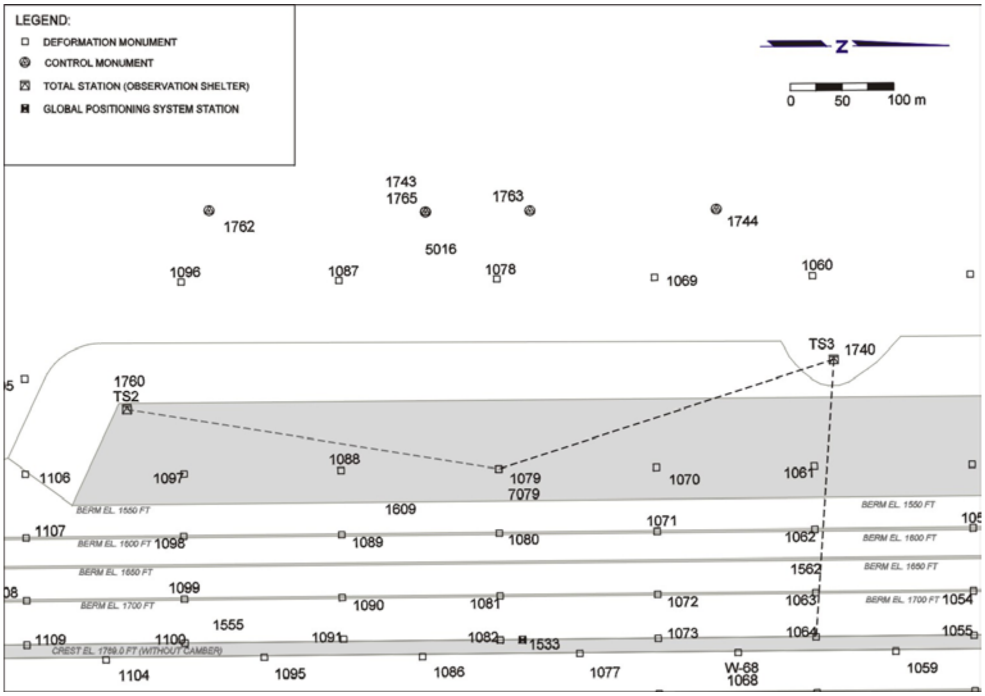

Figure 8. Example of a double-observed point.

Following from Equation (1) and the 216 available observations to double points, the standard deviations of single displacement components (based on weekly averages), became:

$$\sigma_{dN} = 1.3 \text{ mm}; \quad \sigma_{dE} = 2.5 \text{ mm}; \quad \sigma_{dH} = 4.5 \text{ mm}.$$

This is a very good result, considering that the double observed points are located at the marginal distances (340 m to 500 m from RTSs) of the networks. Since the double targets are located either at the toes or at the crests of the dams, the lines of sight to those points are either close to the ground or along the faces of the dams, thus being maximally exposed to large gradients of temperature. One may expect, therefore, that the overall accuracy of displacements of all other points should be either equal to or better than the accuracy of the double-observed points.

Since the lines of sight to the double points at both dams are oriented more or less in the south-north direction, the accuracy of dN components of displacements is affected mainly by errors of distance measurements, dE is affected mainly by errors of horizontal angle measurements, and dH is affected mainly by errors of vertical angles. Since distances are much less affected by varying gradients of temperature than angles, the standard deviation of dN components is the smallest, and σ_{dH} is the largest, as expected. This is illustrated by an example in Figure 9 showing displacements of the double point 1079/7079, as obtained from observations (weekly averages) from RTS3 and RTS2 between October 16, 2000 and January 29, 2001.

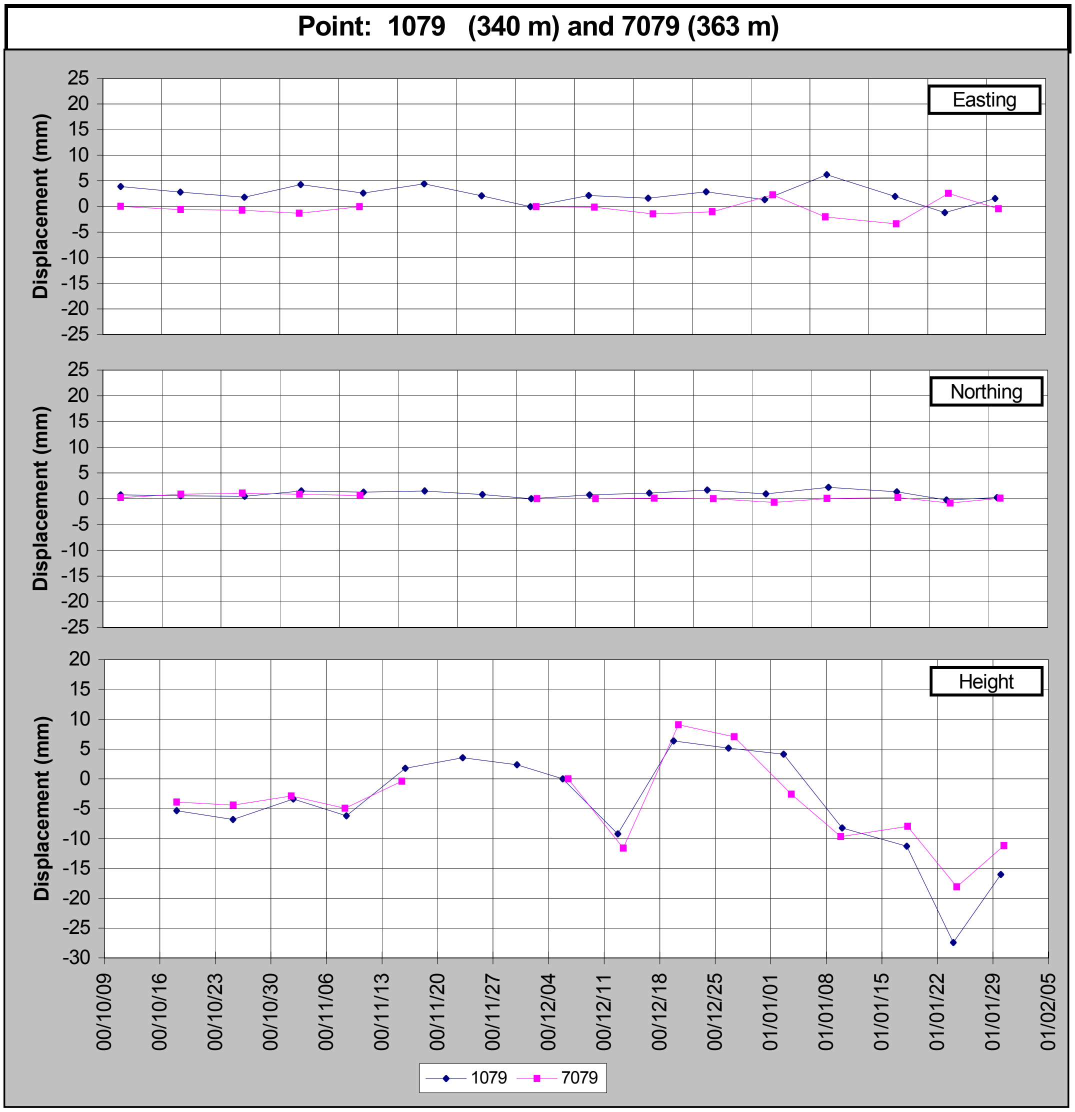

Figure 9. **Displacement components for double point 1079/7079.**

6.2 Evaluation of the Refraction Effects

The above discussion on the overall accuracy of displacement determination has proven that the required tolerance of 10 mm in detecting the displacements is being satisfied if 10 cycles of early morning and noon observations per week are averaged. Preliminary results show, however, that the accuracy of individual cycles is strongly affected by systematic errors caused by varying temperature gradients. Estimation of the accuracy of individual cycles of observations may be of importance in the emergency case when one would be interested in a determination of the displacements immediately after an unusual event such as earthquake or after an unscheduled cycle of observations triggered by the alarm system of the Emergency Response Plan.

As expected, the strongest refraction effects occur along the lines of sight that are low to the ground or along the dam face. The smallest effect is on the lines of sight from RTSs to the top of the dam. The lines from RTS3 to 1079 and from RTS3 to1064 (see Figure 8) have been used as an illustration of the two extreme cases. The line RTS3-1079, of a total length of 340 m, runs almost horizontally about 1.5 m above ground. The line RTS3-1064, of a total length of 276 m, goes steeply up to the top of the dam with a height difference of 70 m, thus having the average vertical clearance above the face of the dam of several metres. Figures 10 and 11 show the time series of daily changes of height at 4 am and 12 noon for points 1079 and 1064 respectively. The two examples indicate that:

1. In both cases, the noon observations seem to give more consistent results than the observations at 4 am.
2. The height changes of point 1079 may reach 50 mm over a few days time interval (assuming that no actual deformation takes place) when observing at 4 am and 20 mm when observing at noon, while the maximum height changes at point 1064 may reach 20 mm during the 4 am observations and 8 mm during the noon observations.
3. The weekly averages of 4 am vs. 12 noon observations to point 1079 show a systematic bias of about 30 mm. There is no significant bias between 4 am and 12 noon results at pt. 1064.

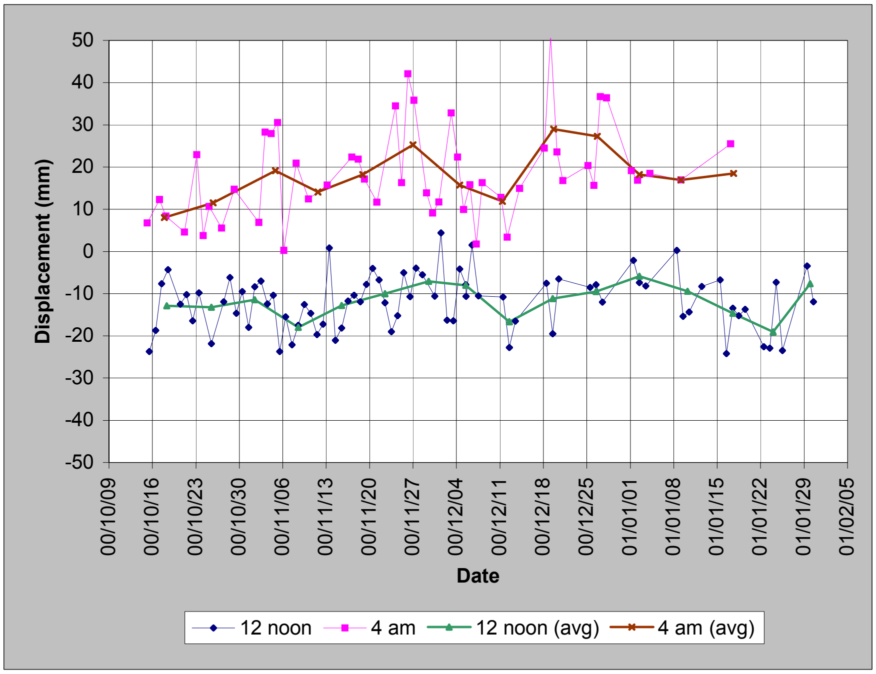

Figure 10. Comparison of 4 am and 12 noon height determinations for point 1079.

One may conclude from Figure 10 that in extreme conditions, the atmospheric refraction may introduce errors of up to 50 mm in the determination of displacements from a single cycle of observations taken always at the same time of the day, and up to 70 mm difference between displacements determined at noon and at 4 am. In the case of point 1079, one may show that the systematic bias of 30 mm over the distance of 340 m corresponds to a change in the vertical gradient of temperature (dT/dH) of 0.6°C/m between 4 am and 12 noon. This is a realistic value and agrees very well with results of investigations conducted some years ago at UNB [Chrzanowski, 1989]. One should emphasize that the given results correspond to the cool months at Diamond Valley Lake. During that time, the temperatures at noon ranged from 25°C in October to 13°C in January, and the temperatures at 4 am ranged from 12°C in October to 5°C in January. One may expect significantly larger effects during the summer months. For the time being, one may accept that, in the emergency situation, the displacements determined from only one cycle of observations will have errors ranging between 10 mm to 70 mm depending on the location of the point with respect to the observing RTS and depending on the time of the day.

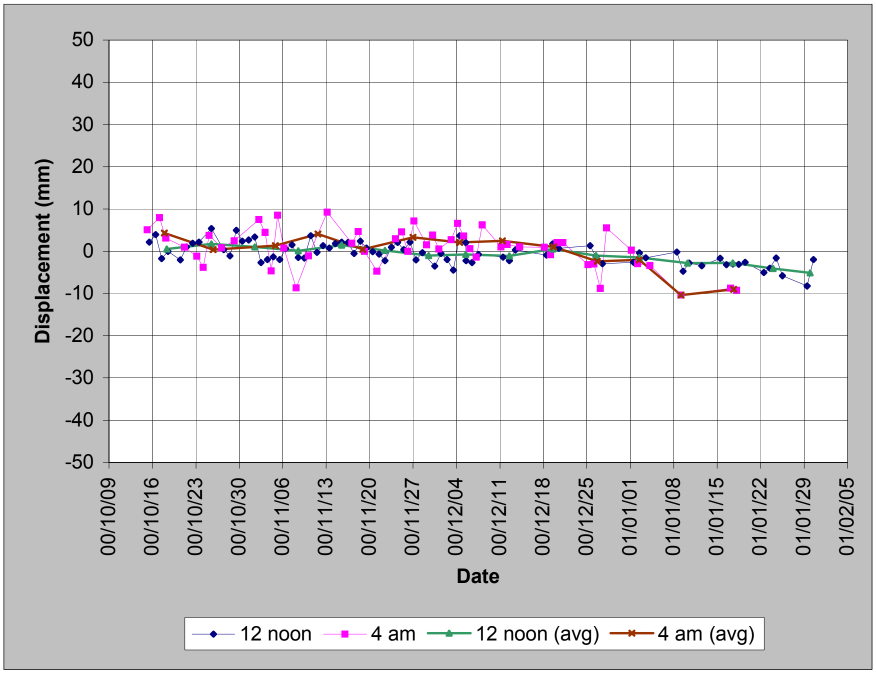

Figure 11. Comparison of 4 am and 12 noon height determinations for point 1064.

The DDM system with its daily observations supplies a wealth of material for studies of atmospheric refraction effects. Additional evaluation and optimization of the DDM system will be performed during the summer of 2001.

7. Conclusions

In October, 2000, the fully automated system for monitoring structural dam deformations at Diamond Valley Lake has been successfully implemented and supplies reliable weekly information on the displacements of targeted points within the required tolerance of 10 mm at the 95% confidence level.

The selected instrumentation and DIMONS software have met all the requirements and expectations of the project.

Effects of atmospheric refraction are being randomized and well controlled by taking observations at 4 am and 12 noon and by averaging 10 cycles of weekly observations for the final determination of displacements. Optimal scheduling of observations will be reviewed during the summer months when final evaluation of the effects of refraction will be made.

Acknowledgment

We would like to thank all the Metropolitan field staff for their dedicated effort at monitoring the reservoir during its construction and early filling prior to implementation of the automated system. Your months of precise field work to accurately define base line measurements for this new system will not soon be forgotten.

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