STUDY OF A LONG-TERM BEHAVIOR OF LARGE EARTH DAM COMBINING MONITORING AND FINITE ELEMENT ANALYSIS RESULTS

Anna SZOSTAK-CHRZANOWSKI[1], Adam CHRZANOWSKI[1], Michel MASSIÉRA[2], Maciej BAZANOWSKI[1], and Cecilia WHITAKER[3]

[1]*Canadian Centre for Geodetic Engineering, University of New Brunswick*[1]
[2]*Faculté d'ingénierie (génie civil), Université de Moncton*[2]
[3]*Metropolitan Water District of Southern California, U.S.A.*[3]

Abstract: Sensitive structures such as large earth dams require continuous and real time information on their stability, particularly when they are located in tectonically active zones. The results from automated monitoring surveys, when compared with the predicted regular behavior of the structures, give information on the effects of seismic disturbances and may trigger a warning alarm if irregular behavior exceeding a threshold value is detected. Deformations of an earth or rockfill dam start occurring during the construction of the dam. After the construction of the dam is completed, the considerable movements of the crest and the body of the dam can develop during the first filling of the reservoir. Later, the rate of deformations decreases in time, with the exception of variations associated with the periodic variations of the level of the reservoir and, in seismic zones, with the tectonic activity. The dams located in the seismically active areas are built with the material, which allow for a dam to be more adaptable to the changes of loading conditions. The deformation process can be simulated using, for example, the finite element method. Due to the uncertainty of the model parameters, careful monitoring of the dam and its surroundings are required in order to verify and enhance the model. This paper presents an analysis of long term deformations of West Dam of Diamond Valley Lake (DVL) Project in California, U.S.A.

1. INTRODUCTION

Safety of earth dams depends on the proper design, construction, and monitoring of actual behaviour during the construction and during the operation of the structure. Deformation monitoring of large dams and their surroundings supplies information on the behaviour of the structure and its interaction with the bedrock. Monitoring results may also be used in verifying design parameters where the geotechnical parameters are of the highest importance. Therefore, monitoring of the deformations is one of the main tools to asses the stability and safety of the dam. The comparison of the monitored data with the predicted data, obtained during the design, may give important information concerning the quality of the accepted geotechnical parameters.

From the safety point of view, the most important stage in the construction of large water reservoirs is the first filling of the reservoir. At the stage of the first filling the main two effects to be considered are pressure of water and effect of wetting. During the process of wetting, the values of geotechnical parameters and the derived values of Young modulus (E) decrease. Young modulus of the material in the submerged sections of the structure becomes smaller and buoyancy force is developed producing dam deformation.

After the filing of the reservoir is completed, the dam undergoes long-term deformations caused by a creep of material. A good review of the long-term behaviour of earth dams, based on an earlier evaluation of monitoring data from 15 dams, is given by Dascal (1987). If a dam is subjected to changeable loading conditions by fluctuating water level in the reservoir, it may undergo additional deformations. This is a topic of the study presented in this paper. The study has used 6 years of monitoring data available from three large earth dams of the Diamond Valley Lake (DVL) project in South California.

The construction of the three dams at the Diamond Valley Lake (DVL) was completed by the Metropolitan Water District (MWD) of Southern California in 2000. 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 large earth/rock filled dams (Figure 1):

- 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 filling of the reservoir began in November 1999 and took 38 months. Due to the dimensions of the project and its location within the earthquake prone area, an extensive monitoring program has been developed in order to provide a warning system and confirm that the dams and foundations are functioning as intended. The monitoring instrumentation includes an extended array of geotechnical instrumentation for seepage and internal deformation measurements, strong motion accelerographs, active GPS stations connected to the California continuously operating reference system (CORS) and a fully automated terrestrial geodetic system for Dam Deformation Monitoring (DDM) (Duffy et al., 200; Lutes et al., 2001).

This paper gives only a limited review of the automated geodetic DDM system followed by a discussion of the monitoring results and the results of numerical modeling of deformations during the initial filling of the reservoir and long term deformation (after the initial filling was completed). The numerical modeling has been performed by using a methodology developed as a collaborative project between the Canadian Centre for Geodetic Engineering (CCGE) at the University of New Brunswick and Faculté d'ingénierie at Université de Moncton (Szostak-Chrzanowski et al., 2002).

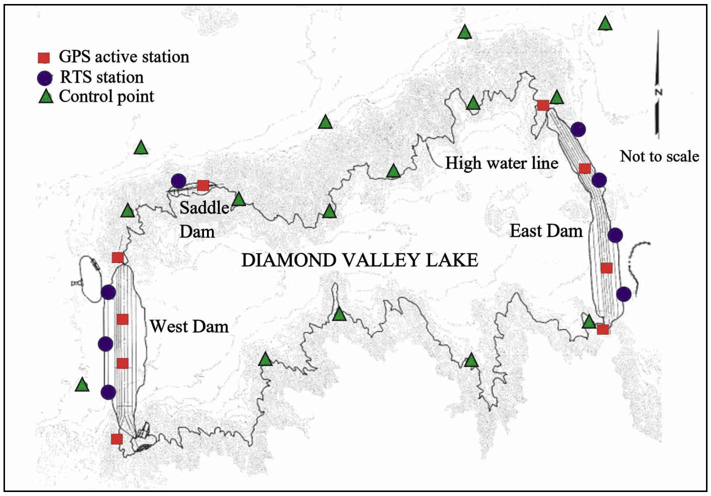

Figure 1 - Geodetic monitoring scheme at the DVL project

2. REVIEW OF THE DAM DEFORMATION MONITORING SYSTEM

A fully automated monitoring scheme with a telemetric data acquisition has been designed using both geotechnical and geodetic instrumentation. 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.

Until October 2000, the geodetic monitoring surveys with about 300 survey markers were performed manually, using geodetic levelling and four roving GPS receivers. In October 2000 a fully automated system with a capability of the continuous monitoring of the behaviour of the dams was implemented (Duffy et al., 2001). The accuracy of the geodetic measurements was designed to detect displacements larger than 10 mm at 95% confidence level (Whitaker et al., 1999).

The automated system consists of 8 robotic total stations (Leica TCA1800S) with the automatic target recognition and electronic measurements of angles and distances to a total of 232 retro-reflecting prisms. The prisms are mounted on concrete pillars installed along the crests and on the downstream faces of the dams. Fig. 2 shows the West Dam with the visible rows of target pillars.

Each RTS with its computer equipment, meteorological sensors, communication radio, and power supply are housed in an observation shelter (Fig. 3). Due to the remote locations of the structures, all equipment is run by DC power from solar panels located adjacent to the shelters.In addition, 5 continuously working GPS receivers, linked to CORS have been permanently installed on the crests of the dams (Fig. 1) to provide a warning system that will "wake up" the robotic total stations in case of abnormally large displacements. The monitoring data is automatically collected at preselected time intervals and is controlled by an office computer located about 100 km away. All the data collection and automatic data processing are controlled by DIMONS software developed at CCGE (Lutes et al., 2001). The software controls all functions of the robotic total stations (RTS) and automatic data collection at pre-scheduled time intervals. It performs an automatic data reduction (station adjustments, EDM corrections), identification of unstable reference or RTS points using the iterative similarity weighted transformation (Chen et al., 1990), and automatically updates and displays the coordinates of the targets after each cycle of observations.

Figure 2 - The West Dam equipped with the target pillars

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 (Chrzanowski, 1999). Therefore, in designing the survey procedures, minimization and randomization of the refraction effects was a major concern. The randomization of refraction effects has been designed to collect 10 cycles of observations at 8 hours intervals over 4 days every week and average out the results for the weekly reporting of displacements. Error analysis of the monitoring scheme led to a conclusion that in order to satisfy the 10 mm displacement detection criterion, maximum distances from RTS to object targets (prisms) should not exceed 500 m.

3. EVALUATION OF MONITORING RESULTS

Since all three dams of the DVL project have indicated a similar deformation trend, the presented results are limited to only one cross-section in the middle of the West Dam (Fig. 4). The dam of the average height of 85m and total length of 2.9 km was constructed from soil and rock. Total collected surveying data covers 82 months after the dam was constructed. The analysis included changes of displacements of four survey points: SP1 at the toe, SP2 and SP3 on the downstream face and SP4 on the crest of the dam (Fig. 4).

Figure 2 - Typical RTS observation shelter

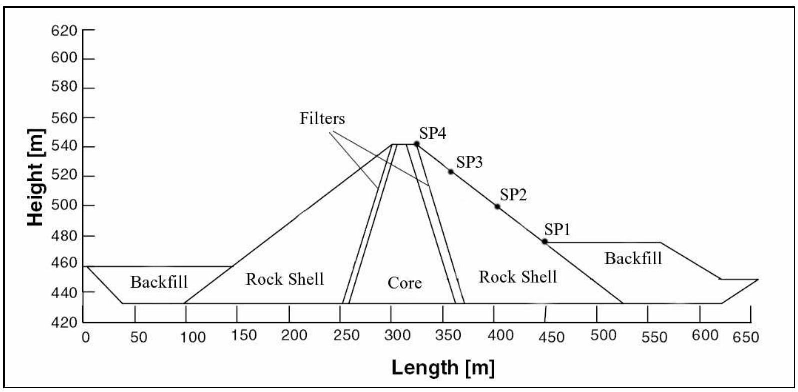

Figure 3 - West Dam cross section

Filling of the reservoir started in November 1999 and it reached maximum height of 75m above the upstream toe of the dam after 37 months. Figure 5a shows changes in water level since the beginning of the filling process. Between 36th and 56th month (marked by the arrows 1 and 2), the water level slowly decreased to 60m and started slowly rising again, reaching another maximum (arrow 3) of 78m in the 73rd month (6 years from the beginning).

The effect of the changeable water level on the changes of the observed displacements is shown in Figures 5b and 5c for vertical and horizontal displacements respectively. Figure 6 shows total vertical displacements of SP4 (crest) as a function of time. To check whether the displacements follow a regular consolidation pattern, which is supposed to follow the logarithmic function of time (Dascal, 1987), Fig.7 shows the displacements of SP4 as a function of [log(time)] where the time is in months. The plot indeed resembles the expected soil-consolidation curve (Dascal, 1987) despite the changes in the water level. The obtained curve shows the expected three stages of the displacements, a slow settlement in the beginning, followed by the major part of settlement which occurred in 37 months and the linear trend in the third stage.

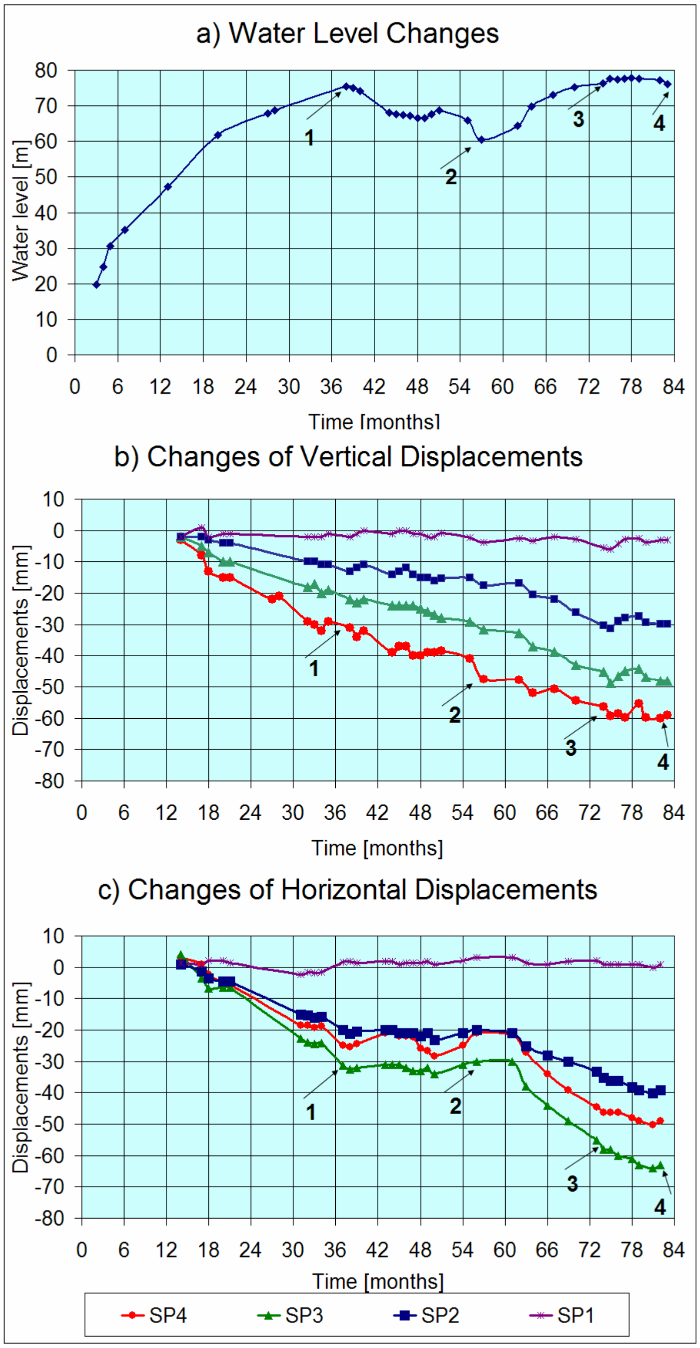

Figure 5 - Water level and displacement changes as a function of time

The results indicate that the change in the water level by about 20% does not affect settlement trend when the dam is already at the third stage of consolidation. This is also shown in Fig. 5b that the settlement pattern for all other points on the face of the dam is not affected by the water level change. However, the horizontal movements (Fig, 5c), which are of the same magnitude as the settlement values, show a significant sensitivity to the water level changes. During the period of decreasing water level, the horizontal displacements stabilized and started increasing again when the water level started increasing. One should also note that the maximum horizontal displacements take place at point SP3, which is about 20 m below the crest. This should be taken under consideration when designing the monitoring scheme.

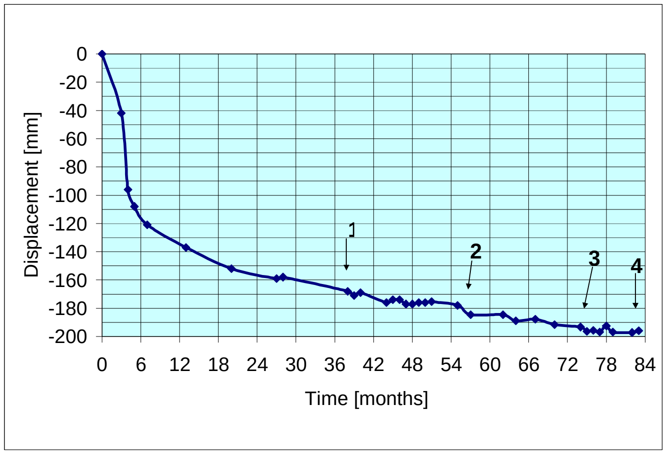

Figure 4 - Measured settlement of point SP4 as a function of time

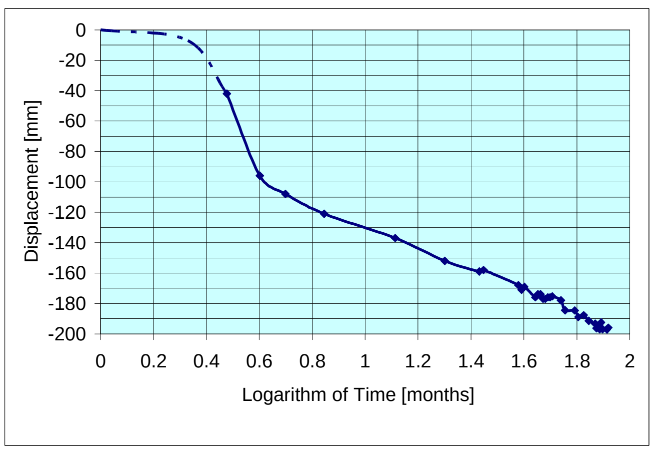

Figure 5 - Measured settlement of point SP4 as a function of log (time)

4. ANALYSIS OF DAM BEHAVIOUR USING FEM

A preliminary deterministic modeling for verifying geotechnical parameters of the dam material was performed at the stage of the dam construction in dry condition (Szostak-Chrzanowski et al., 2000). In the analysis of construction process, the dam was assumed to have non-linear material characteristics and was modelled using the hyperbolic model (Duncan and Chang, 1970). In the hyperbolic model, the non-linear stress- strain curve is a hyperbola in $\sigma_1 - \sigma_3$ versus axial strain plane. Table 1 lists geotechnical parameters used in the analysis. In Table 1, ϕ is an angle of friction, γ is unit weight, K is loading modulus number, and n is exponent for loading behaviour. K_b is bulk modulus number, m is bulk modulus exponent, K_o is the earth's pressure ratio, and R_f is the failure ratio.

Parameters	Core	Filters	Rockfill shell
γ (kN/m^3)	22	20.42	22
ϕ	38°	47°	45°
K_o	0.5	0.5	0.5
K	500	560	560
K_b	210	330	330
n	0.55	0.48	0.48
m	0.4	0.33	0.33
R_f	0.7	0.65	0.65

Table 1 - Geotechnical Parameters for the West Dam.

The analysis of the first filling of the reservoir was performed with the effects of pressure of water, buoyancy force, and effect of wetting. During the process of wetting, the values of geotechnical parameters and the derived values of Young modulus (E) decrease (Touileb et al. 2000). Young modulus of the material in the submerged sections of the structure becomes smaller and buoyancy force is developed producing dam deformation. The values of geotechnical parameters in case of wet conditions differed through the structure and were given in Szostak-Chrzanowski et al., 2002. Young modulus significantly varied through the structure and has been discussed in Szostak-Chrzanowski et al., (2002). The modlled settlement during the first filing of the reservoir is shown in fig.8.

Next, the long term behaviour of the West Dam was analyzed including the effect of water level changes on the settlement. In order to simulate response of the dam to the loading conditions, the dam in the analysed cross section was assumed to be on the bed rock. In order to follow the ob served progress of settlement, the values of Young modulus used in the analysis were decreased (scaled). The values of Young modulus used for the decreased water level to 60m are shown in Table 2. The calculated changes of settlement as a function of change of water level are shown in Fig.8. The horizontal monitored displacements are shown in Fig. 9. FEM modeling of the horizontal displacements requires further research because the mechanism of horizontal displacements follows a different mechanism of deformation than the mechanism of consolidation.

Average E_{dry} [MPa]								
Water level [m]	Core		Filters		Upstream face		Downstream face	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
60	30	20	32.5	27	41.25	38.75	41.5	38.78

Table 2 - Values of Young modulus for dry and wet material

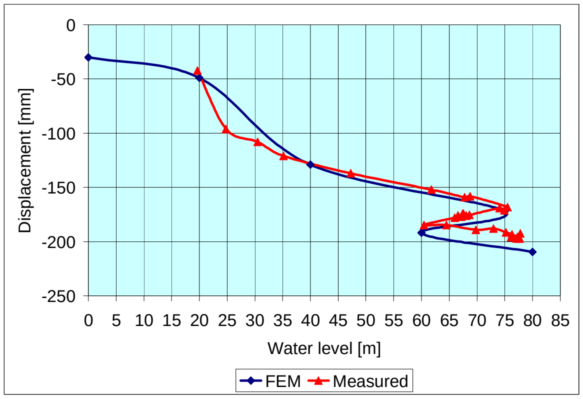

Figure 6 - Modeled and measured settlement of pt. SP4 as a function of water level

5. CONCLUSIONS

The deformation of the West Dam continued for seven years after the end of construction. The after construction settlement reached 200 mm it means 0,24% of the height of the dam. It is as expected for this type of dams. Generally, the deformation of the earth/rockfill dams are considered as stabilized when the settlement becomes smaller than 0.02% of the height of the dam per year. In case of the West Dam the average settlement over the last five years reached only 0.014% per year. It means that the dam can be considered as stable. The change of the water level by 20% has not affected the consolidation rate of the dam. However the horizontal displacements, which follow a different mechanism of deformation than the mechanism of consolidation, require further study. One should note that the maximum horizontal displacements do not take place at the crest but much below (at about 2/3 of the height) on the downstream face. This should be taken under consideration when designing the monitoring scheme.

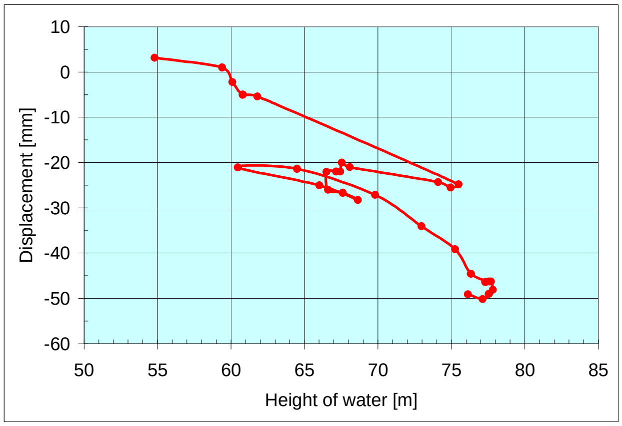

Figure 7 - Measured changes of horizontal displacements of pt. SP4

A very good agreement has been obtained between the calculated (modelled) displacements and geodetic monitoring data on the crests of the dams in the process of filling the reservoir. This agreement confirms that the geotechnical parameters and the values of Young modulus, as used in the FEM analysis, as well as the presented method of modelling the dam behaviour, are correct. This is an important conclusion for a possible use of the verified parameters in future analyses of possible effects of additional loads arising, for example, from tectonic movements.

Acknowledgements

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Corresponding author contacts
Anna SZOSTAK-CHRZANOWSKI
amc@unb.ca
Canadian Centre for Geodetic Engineering, University of New Brunswick; Canada