INTERCONNECTION BETWEEN MONITORING AND DETERMINISTIC MODELING OF THE BEHAVIOR OF LARGE EARTH DAMS

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ABSTRACT

Monitoring of deformations, whether using geodetic or geotechnical instrumentation, besides providing a warning system in case of an abnormal behaviour of the dam, may be used as a tool for a verification of design parameters. By comparing results of monitoring measurements with a deterministic (*a-priori*) model of deformation, one may determine and explain causes of deformation in a case of unexpected behaviour of the investigated object and its surrounding. Thus, the role of monitoring becomes much broader than just the conventional determination of the status of the deformable object. On the other hand, a predicted behaviour of the dam may be used in designing the monitoring scheme, giving information on the magnitude and location of the expected maximum deformation parameters. In addition, with properly designed monitoring surveys, one may also determine the actual deformation mechanism. The discussed problems are illustrated by three types of earth dams located in California, USA, and in Quebec, Canada.

1. INTRODUCTION

Deformations of an earth or rock filled dam start occurring during the construction of the dam. These deformations are caused by the increase of effective stresses during the construction by the consecutive layers of earth material and also by effects of creep of the material. Deformations are also influenced by the deformations of the foundation and by the transfer of stresses between the various zones of the dam. Once the construction of a 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 generally in time, with the exception of variations associated with the periodic variations of the water level of the reservoir and, in seismically active zones, with the earthquakes. Intensity, rate, and direction of movements, in a specific point of the body of the dam or its crest, can vary during the various phases of the construction and the operation of the reservoir.

In the design of the earth dams, usually the finite element method (FEM) is employed. The FEM is used in the analyses of expected displacements, strains, and stresses in the structure caused by changeable loading or boundary conditions. The values calculated

using FEM may be compared with measured values during the construction, during the filing up the reservoir, and during the life of the structure giving additional information on the actual behaviour of the structure, boundary conditions and unexpected loads.

Monitoring is important for a better and safer design of the future dams through the verification of the design parameters where the geotechnical parameters are of the highest importance (Szostak-Chrzanowski et al., 2003). A comparison of the monitored data with the predicted data obtained during the design may give very important information concerning the quality of the accepted geotechnical parameters (Szostak-Chrzanowski et al., 2002).

One of the major tasks of the monitoring surveys is to verify that the behavior of the investigated dam follows the designed (predicted) pattern in space and time domains. The design of the monitoring surveys must include:

- **determination of the minimum number (density) and locations of the monitored points, (the monitoring scheme should include points where the maximum displacements are expected);**
- **frequency of the repeated measurements, the frequency of measurements depends on expected rates and magnitudes of the deformations;**
- **accuracy requirements.**

In case when the reservoir is located within the influence of active tectonic plates, the design of the monitoring surveys has to consider not only loading effects of the reservoir and gravitational settlement of the dams but also effects of earth crustal movements. 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 geodetic control of the whole area of the reservoir to control the stability of the ridge lines above the reservoir and must be connected to the existing regional network of monitoring of the earth crustal movements.

This paper presents the discussion of the results of FEM analysis of the deformations of the embankment dams of Diamond Valley Lake (DVL) Project in California, the La Grande 4 main of La Grande Hydroelectric Complex located in northern Quebec, Canada, and analysis of the behavior of a Concrete Face Rockfill Dam (CFRD) located in Northern Quebec.

2. MONITORING OF EARTH AND ROCKFILL DAMS

Type, number, and distribution of monitoring equipment depend on characteristics of the site of the dam (narrow valley with steep banks, rough variation of the geometry of foundations, soft or permeable deposits in the bed of the river, etc.). Typically, the monitoring schemes consist of geodetic and geotechnical instrumentation. Geotechnical monitoring may be divided into two groups; physical and geometric measurements. Geodetic monitoring determines vertical and horizontal displacements of selected (targeted) surface points with respect to reference points located in a stable area using terrestrial and satellite positioning techniques. With current geodetic technology which utilises robotic total stations with automatic target recognition, GPS, and other sensors one may achieve almost any, practically needed, instrumental resolution and precision, full automation and real-time data processing. The only limitations are imposed by environmental effects, for example, effects of atmospheric refraction. Recently, a fully

automated system ALERT for data collection, data processing and displacement analysis has been developed at the Canadian Centre for Geodetic Engineering (Lutes et al., 2001; Wilkins et al., 2003 a). The system has already been implemented in the monitoring of earth dams of DVL project (Duffy et al., 2001) and in open pit mines in Canada, USA, and in Chile (Wilkins et al., 2003 b).

Geotechnical instruments once placed within the structure mass can not be rechecked or calibrated. Therefore, very often the geotechnical instrumentation provides unreliable data or even fails during life of the structure. The geodetic measurements, through redundant measurements, provide a possibility for a statistical evaluation of the accuracy of the gathered data. In most cases, it is recommended to use integrated monitoring systems in which geotechnical measurements are checked by comparing them with the geodetic data.

3. EXAMPLES OF EARTH/ROCKFILL DAMS

Diamond Valley Lake (DVL) reservoir was created by enclosing the valley by three dams (MWD, 2000). The largest is the West Dam, which is a zone embankment dam and is 87 m high and 2.7 km long. The area of the DVL is located within the interaction zone between the North American and Pacific tectonic plates. The San Jacinto and San Andreas faults are located about 10 km and 30 km, respectively, from the reservoir. 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 crust movements in this seismically active area that is prone to frequent earthquakes. The local monitoring network was connected to the existing GPS regional network of the continuously operating reference stations (CORS) of Southern California which monitor the earth crust movements. A fully automated geodetic monitoring scheme with a telemetric data acquisition was designed using the ALERT system (Duffy et al., 2001) and 8 robotic total stations with the automatic target recognition. Fig.1 shows the schematic cross-section of the West Dam.

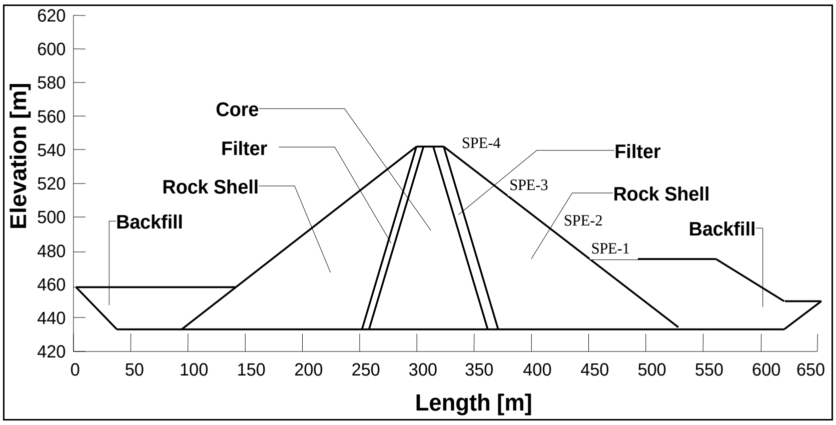


Fig. 1. Schematic cross-section of the West Dam.

La Grande 4 (LG-4) main dam is the second largest structure of the La Grande Complex (LGC) of James Bay hydroelectric development located in northern Quebec, Canada (Paré et al., 1984). LG-4 main dam is a zone embankment dam and is 125 m high and 3.8 km long. The dam is constructed almost entirely on bedrock. During the construction of the La Grande Complex, the main installed instruments were

inclinometers with tubes with telescopic joints, the settlement cells, and the linear extensometers, levelling, hydraulic and electrical piezometers, electrical vibrating wire and pneumatic total pressure cells, and wires (Verma et al., 1985).

The Toulnustouc dam is a Concrete Face Rockfill Dam (CFRD) and is located north of the city of Baie-Comeau on the Toulnustouc River in Northern Quebec. The existing dam is 75 m heigh and 0. 575 km long and it is built on bedrock foundation. The main concern for the safety of Concrete Face Rockfill Dams (CFRD) is the deformation of the concrete face slab. The concrete slab acts as an impervious membrane and any development of cracks in the slab would allow for the water to penetrate the rockfill of the dam and cause the structure to weaken or even loose its stability. The thickness of the concrete face slabs is 0,3 m. Toulnustouc dam uses state-of-art geotechnical instrumentation including submersible tiltmeters for monitoring settlement of the concrete slabs. The analyzed cross-section of the dam is shown in Fig.2.

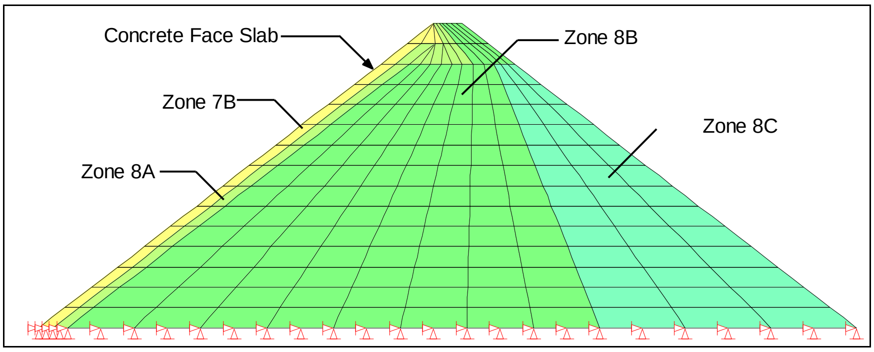


Fig. 2. CFRD of 75 m of height resting on bed rock.

4. RESULTS OF THE ANALYSIS

The presented below analyses of the above listed dams were performed using finite element method and SIGMA /W software (Krahn, 2004). The behaviour of the earth material was determined using hyperbolic non-linear model (Kondner, 1963; Kondner and Zelasko (1963). The geotechnical parameters of the LG-4 and DVL dams are given in (Massiéra and Szostak-Chrzanowski, 2003) and (Massiéra et al., 2001) respectively. The geotechnical parameters data for the CFRD dam are given in (Massiéra et al., 2004).

The analyses of LG-4 dam and DVL West Dam were performed assuming that the dams were resting on bedrock. LG-4 dam was analysed for two different heights of 80m and 120m. The CFRD -Toulnustouc dam was analysed for the two cases: 1) dam resting on bedrock (real case); 2) dam structure resting on a 60 m high foundation of dense till moraine (simulated case). Fig. 3 shows the expected settlements along the centre lines of the DVL West Dam and LG-4 dam at the end of construction as a function of height. The settlements of the West Dam are much larger than of the LG-4 dam (84m). The maximum settlement in the center of West Dam (height 88m) is 0.23m and is located at the 54m elevation. For the LG-4 dam (height 84m) the maximum settlement in the center of the dam is 0.12m and is located at 36m elevation.

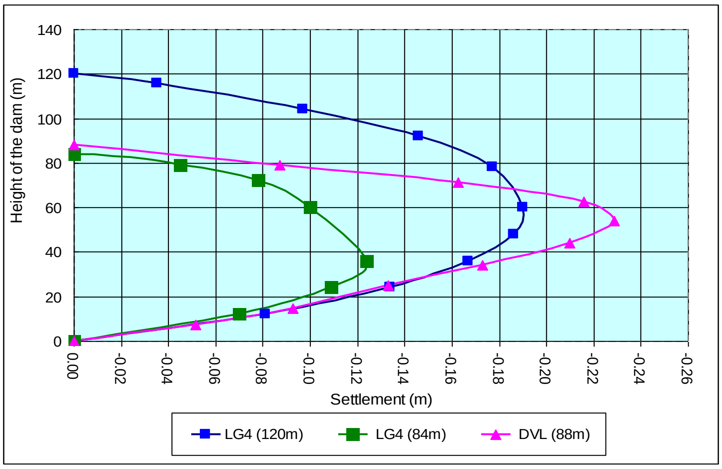
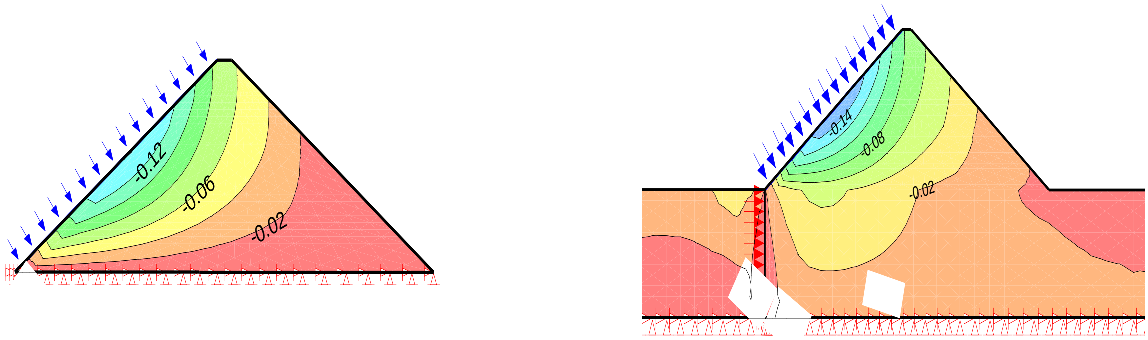


Fig. 3. The calculated settlements at the end of construction of DVL and LGC dams.

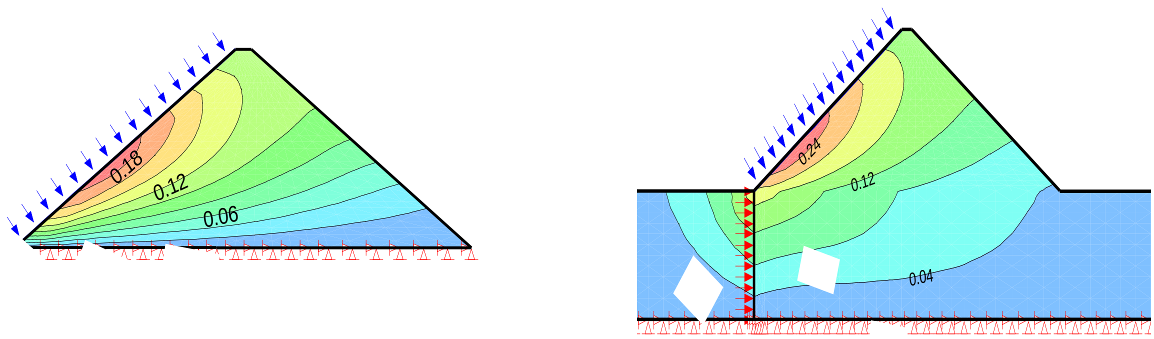
In case of the CFRD dam, the maximum settlements at the end of the filling of the reservoir (Fig.4) are expected to occur on upstream face of the dam, where classical geodetic surveys cannot be implemented. The displacements are larger when the dam is resting on 60 m of till (moraine). The maximum horizontal displacements (Fig.5) of the upstream (concrete) face are expected to take place 43 m below the crest and are reaching 0.24m.



a)

b)

Fig. 4. Calculated settlements (m) at the end of the filling of the reservoir for a CFRD of 75 m of height resting on: a) rock; b) 60 m of till (moraine).



a)

b)

Fig. 5. Calculated horizontal displacements (m) at the end of the filling of the reservoir for a CFRD of 75 m of height resting on: a) rock; b) 60 m of till (moraine).

The deformation of the West Dam continued for seven years after the end of construction. Fig. 6 shows long term changes of water level and long term vertical and horizontal displacements. 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.

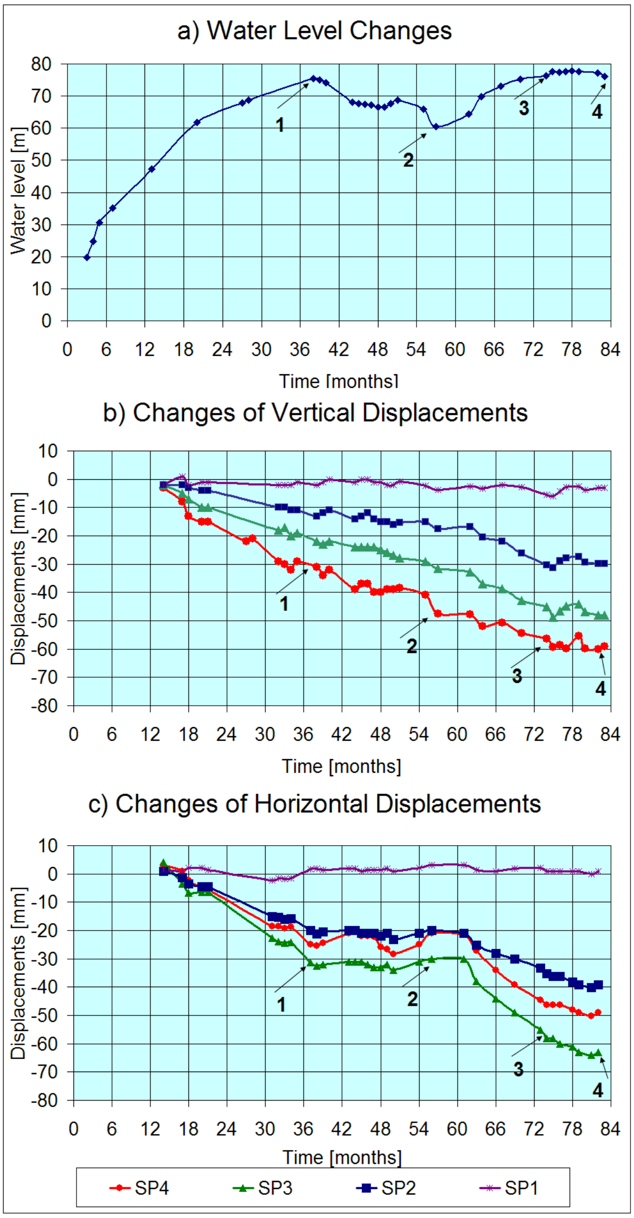


Fig. 6. Water level changes and long term displacements at the West Dam.

5. CONCLUSIONS

The geotechnical parameters of the earth dam construction material play significant role in the stability of the dam. The dams located in the seismically stable areas are built with earth's material which allows for a dam to be more adaptable to the changing loading conditions caused by tectonic activity. The dams built on stable bedrock are more stiff structures.

In case of the CFRD dam, the maximum displacements are expected to occur on upstream face of the dam. The long term monitoring results at the West Dam indicated that changes in water level up to 20% do not affect the pattern of long term settlement. However, horizontal displacements are more sensitive to the water level changes. This requires further investigation using results of long term continuous monitoring.

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