RELATION BETWEEN MONITORING AND DESIGN ASPECTS OF LARGE EARTH DAMS

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Abstract: 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. The geotechnical and geodetic monitoring 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 where geotechnical parameters are of the highest importance. By comparing results of monitoring measurements with a prediction (deterministic) model of deformation, one may determine and explain causes of deformation in a case of unexpected behaviour of the investigated object and its surrounding. Modelling of deformation of earth dams is a complex process in which one should consider the nonlinear behaviour of the construction material, interaction between the structure and the underlying soil and rock strata, influence of water load on the structure and on the foundation bedrock, and the effects of water saturation. The deformation process can be simulated (predicted) using, for example, the finite element method with the hyperbolic model of the nonlinear behaviour of the material. 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. Thus, the role of monitoring becomes much broader than just the conventional determination of the status of the deformable object. 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

1.1. Safety of the Earth Dams

The most common causes of failure of the embankment dams are internal erosion of fine-grained soils from the embankments, erosion under the foundation or abutment, stability problems resulting from the high pore pressures, hydraulic gradients, and overtopping of the dam or spillway. A less common cause of failure is the development of high water pressures and possible liquefaction either in the foundation or embankment during earthquakes.

Deformations of an earth or rockfill 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 material. Deformations are also influenced by the deformations of the foundation, the transfer of stresses between the various zones of the dam and the other factors. After the construction 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 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. Variations of stresses may occur at different elevations and in different zone of a dam. That can be caused by e.g. differential settlements between the core and the upstream and downstream filter zones. If the core is more compressible than the upstream and downstream filter zones, it settles more under its weight than the filter zone and, by the effect of arching, core mass leans on stiffer filter zones. This causes the reduction of vertical stresses and consequently the lateral stresses develop towards the base of the core. The phenomena can cause a hydraulic fracturing and a risk of erosion of the fine particles of the core.

The main concern for the safety of Concrete Face Rockfill Dams (CFRD) is the deformation of the concrete face slab. During the reservoir filling, the load of water and deformations of the rockfill produce a deformation of the concrete 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. In a classic CFRD where the concrete face slab is constructed after the completion of construction of the rockfill embankment, it is very important to estimate the displacements of the concrete face slab during a filling of the reservoir. Furthermore, it is important to verify if these displacements are lower than the displacements compatible with the structural integrity of the concrete face slab.

The geotechnical parameters of the earth material play significant role in the stability of the dam. The dams located in the seismically stable areas are built with material characterised by the geotechnical parameters, which allow for a dam to be more adaptable to the changes. 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. In the design of the earth dams, the finite element method (FEM) is used very often. 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 from FEM may be compared with measured values during construction and filing up a reservoir giving additional information on the actual behaviour of the structure, boundary conditions and unexpected loads.

The above criteria should be based on the prediction (design) model of the expected deformations. In this presentation, authors give examples of the predicted deformations for various earth dams and discuss the effect of the prediction results on the proper design of the monitoring surveys.

1.2. Role of Monitoring

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 [1]. The determination of geotechnical parameters may be done in situ or in the laboratory. In laboratory testing the selected samples may differ from one location to another, they may be disturbed during the collection, or the laboratory loading conditions may differ from natural conditions. Therefore, the comparison of the monitored data with the predicted data obtained during the design may give very important information concerning the geotechnical parameters [2].

One of the major tasks of the monitoring surveys is to verify that the behaviour of the investigated dam follows the designed (predicted) pattern in space and time domains.
The design of the monitoring surveys must include [3]:

- 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, which depends on expected rates and magnitudes of the deformations.
- accuracy requirements.

In case when the area of a 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 numerical analysis of the deformations of the West and East embankment Dams of Diamond Valley Lake (DVL) Project in California, the La Grande 4 main dam of La Grande Hydroelectric Complex located in northern Quebec, Canada, and analysis of the behavior of a Concrete Face Rockfill Dams 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 or on supports, etc.). The number and the distribution of measuring instruments depend on specific problems foreseen in the training of the conception which, sometimes, control the schedule of due dates of construction. Dunnicliff [4] presented in detail the various measuring instruments used in embankments and in earth and rockfill dams.

Monitoring of the embankment dams may be divided into following groups: environmental, geotechnical, geodetic, and visual inspection. Geotechnical monitoring may be divided into two groups; physical and geometric measurements. The physical measurements are: pore pressure measurements using piezometers, measurements of seepage through the dam, the foundation, and the abutments, using V-notch weirs, measurement of stresses within the selected locations in the dam using earth pressure cells. The geometric measurements are: tilt monitoring using plumblines or inclinometers, foundation displacements using rod extensometers, foundation movements using inclinometers. 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. Recently, a fully automated system ALERT for data collection, data processing and displacement analysis has been developed at the Canadian Centre for Geodetic Engineering [5] and [6]. The system has already been implemented in the monitoring of earth dams of DVL project [7] and in open pit mines in Canada, USA, and in Chile [8].

From the point of view of the achievable instrumental accuracy and automation, the distinction between the geodetic and geotechnical techniques does not apply any more. 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 and possibility of the statistical evaluation of the data quality provide reliable results. In most cases, however, it is recommended to use integrated monitoring systems in which geotechnical measurements are checked by comparing them with the geodetic data.

3. DEFORMATION MODELING USING FINITE ELEMENT METHOD

Finite element method (FEM) is used very often in the design or in the verification of the behaviour of earth dams. The FEM is used in the analyses of behaviour through calculation of displacements, strains, and stresses in the structure caused by changeable loading or boundary conditions. The values calculated from FEM may be compared with measured values giving information on the actual behavior of the structure. The differences between predicted and measured values may be arising from the selection of geotechnical parameters or assumed loading and boundary conditions in the FEM model. In order to find the cause of the differences, several models may have to be analyzed for different loading conditions with verified parameters.

In order to perform the finite element analysis of a dam the following steps must be specified:

1. Selection of the model for the analysis (geometry, loading and boundary conditions)
2. Selection of the material model (linear elastic, non-linear),
3. Selection of geotechnical parameters of the materials.

The behaviour of the earth material may be determined using hyperbolic non-linear model([9] and [10]).

4. EXAMPLES OF EARTH/ROCKFILL DAMS

4.1. Embankment Dams

4.1.1. Diamond Valley Lake Project

Recently completed Diamond Valley Lake (DVL) project, consists of three dams [11]. The DVL dams have been constructed from soil and rock. Figure 1 shows a typical cross-section of the West Dam with height of 87 m. 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 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 [12] which monitor the earth crust movements.

A fully automated monitoring scheme with a telemetric data acquisition was designed using both geotechnical and geodetic instrumentation. Geotechnical instrumentation was designed independently of the geodetic portion of the monitoring plan. It includes a total of 262 piezometers, 7 inclinometers, 74 settlement sensors, 6 fixed embankment extensometers, 14 weirs and 18 strong motion accelerographs. The automated geodetic monitoring system consists of 8 robotic total stations (Leica TCA1800) with the automatic target recognition and electronic measurements of angles and distances. In addition, 5 continuously working GPS receivers were permanently installed on the crests of the dams to provide a warning system that "wake up" the robotic total stations in case of abnormally large displacements [7]. The accuracy of the geodetic measurements was designed to detect displacements larger than 10 mm at 95% confidence level [13].

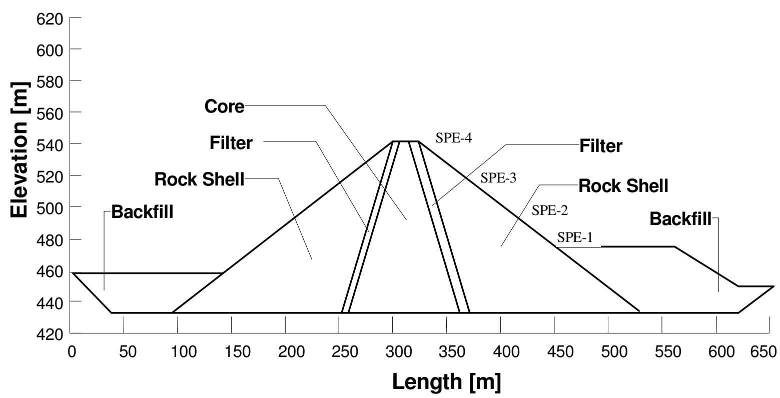


Figure 1. Schematic cross-section of the West Dam

4.1.2. La Grande 4 (LG-4) Project

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, [14]. LG-4 main dam has maximum height of 125 m and is 3.8 km long. LG-4 main dam is a zoned embankment. 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, settlement cells, and linear extensometers, surface movements, hydraulic and electrical piezometers, electrical vibrating wire and pneumatic total pressure cells, and weirs [15]. It allowed for checking the behaviour of the embankment during the construction and during the filling up the reservoir.

4.2 Concrete Face Rockfill Dam (CFRD): Toulnustouc Main Dam

The Toulnustouc main dam is located north of the city of Baie-Comeau on the Toulnustouc River in Northern Quebec. The existing dam has height of 75 m and is 0. 575 km long and it is built on bedrock foundation. The thickness of the concrete face slabs is 0.3 m. Instrumentation installed in the structure includes 13 submersible tilt meters, 22 fissurometers (crack meters), 2 accelerometers, one measuring weir, and 16 survey markers.
There was a long-term monitoring of slab deflection, which is caused by the dominant hydrostatic load moving the concrete face gradually in the downstream direction. Each instrument had to withstand a maximum of 75 m head of water and be sufficiently accurate to measure small deformations (mm scale).The analyzed cross-section of the dam is shown in Figure 2.

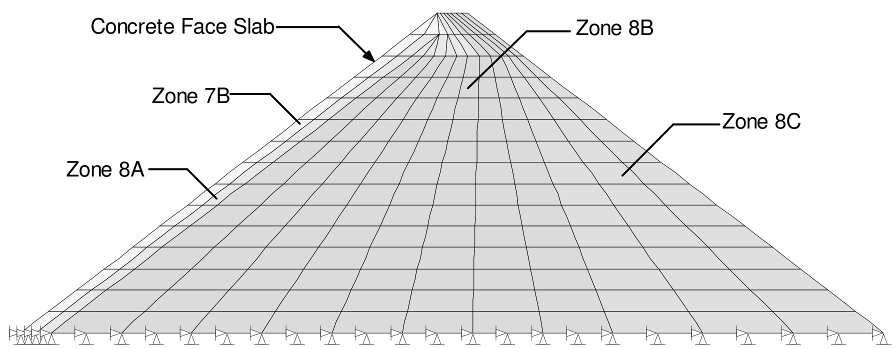


Figure 2: CFRD of 75 m of height resting on bed rock

4.3 Geotechnical Parameters of the Earth and Rock Fill

The geotechnical parameters used in the design of DVL dams differ quite significantly from the parameters used in LGC project [16]. Loading modulus number K and bulk modulus number Kb for LGB dam are larger than for DVL dam. The exponent for loading behaviour n and modulus exponent m for LGB dam are larger than for DVL dam. The geotechnical parameters of the LGC and DVL dams are given in [17] and [16] respectively. The geotechnical parameters data for the CFRD dam and the foundation used in the analysis are given in [18].

4.4 Summary of Deterministic Modeling (Prediction) of Deformations using FEM

The presented three cases of dams listed above were analysed using finite element method and SIGMA /W software [19]. The behavior of the earth/rockfill dams was analyzed in two stages. First stage was an analysis of the behavior during construction of a dam. The second stage was an analysis of a response of the constructed structure to the filling of the reservoir with water. The analysis of settlements during construction of LG4 main dam was performed for two assumed heights: 84 m and 120 m. The dam was assumed to rest on non-deformable bedrock. The analysis of DVL dam was performed for West Dam with the assumption that the dam was resting on non-deformable bedrock. Two models of CFRD -Toulnustouc main dam were analysed. The first model of the dam followed the real foundation conditions and the dam was resting on bedrock foundation. The second model was a simulation of the dam structure resting on a 60 m high foundation of dense till (moraine).

The calculated settlements in the centre during the construction are much larger for DVL dam than for LG4 main dam. The maximum settlement in the center of West Dam (height 88m) is 0.23m and is located at the 54m elevation. For the LG4 main dam (height 84m) the maximum settlement in the centre of the dam is 0.12m and is located at 36m elevation (Figure 3). The calculated horizontal displacements of West Dam using DVL parameters are larger than when using LGC parameters.

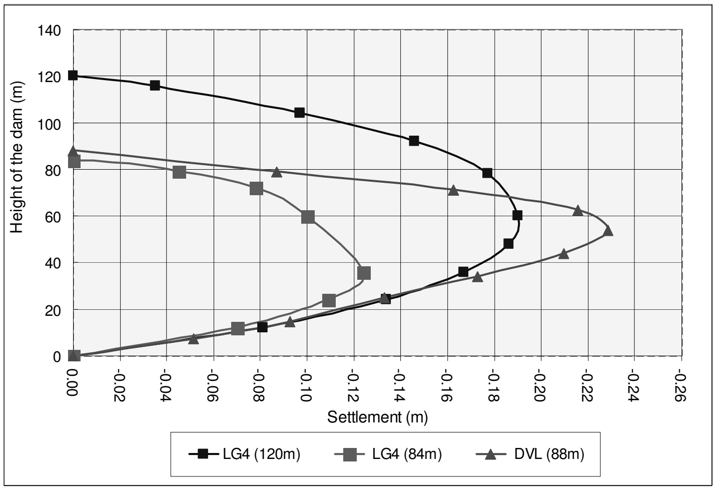


Figure 3: The calculated settlements at the end of construction of DVL and LGC dams

The comparison of vertical displacements at the crest of West Dam and CFRD Toulnustouc main dam during the filling of reservoir with water are shown on Figure 4. The West Dam has larger vertical displacements at the crest at the end of filling the reservoir. The deformation rates are also different for each case. As one can see from the comparison of predicted rates of the displacements expected at DVL dam and CFRD dam, the DVL dam will require more frequent observations at the beginning of the filling of the reservoir because of the larger acceleration of the movements than in the case of CFRD dam. The CFRD dam will have larger acceleration of the movement at the end of filling of the reservoir.

In case of the CFRD dam, the maximum displacements are expected to occur on upstream face of the dam, where classical geodetic surveys cannot be implemented (see Figure 5). Thus, in this case permanently installed geotechnical instruments (e.g., inclinometers, extensometers) should be used on the upstream face while geodetic surveys could be utilized on the crest and the downstream face. Here one should note that the maximum displacements of the upstream (concrete) face are expected to take place 40 metres below the crest and is reaching 0.22 m for the dam resting on bedrock. This is very often overlooked by geodetic engineers, who tend to install their points along the crest due to the easiest access.The maximum displacements of the concrete face slab were function also of the height of the dam during the filling of the reservoir. The calculated settlements for CFRD dam at the end of filling up the reservoir are shown on Figure 5. The displacements are larger when the dam is resting on 60 m of till deposit (Figure 5). The magnitude of horizontal displacements is larger than magnitude of settlements. The calculated horizontal displacements are larger for CFRD resting on 60 m till deposit (Figure 6).

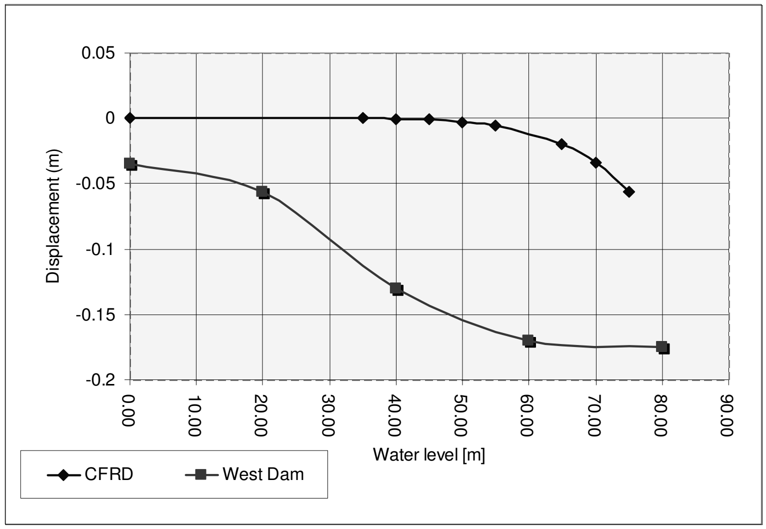


Figure 4: Vertical displacement of crest during filing up a reservoir

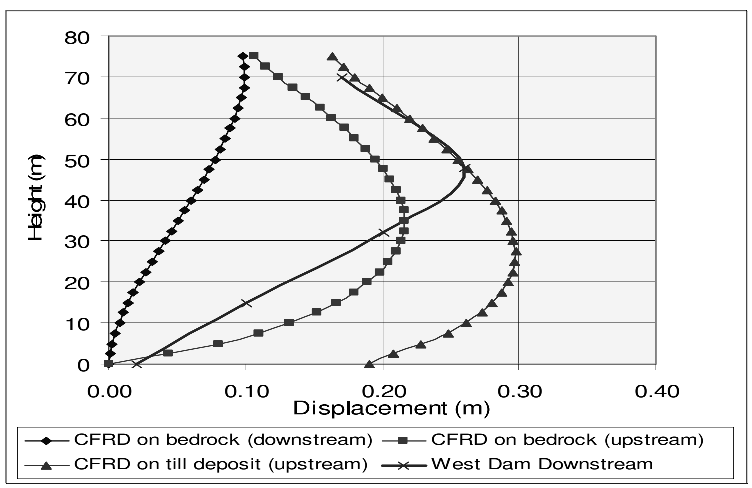
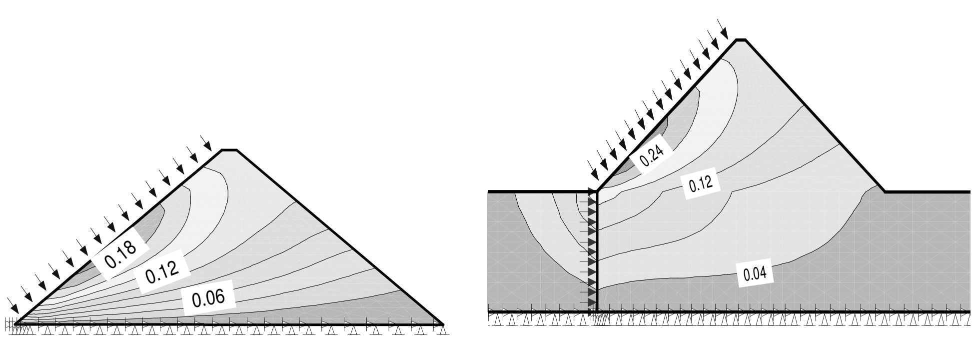


Figure 5: Displacements of CFRD and West Dam at the end of filling up a reservoir



a) b)

Figure 6: Calculated horizontal displacements (in metres) 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).

5. CONCLUSIONS

A-priori estimation (prediction) of the magnitude and localisation of maximum displacements and deformations is essential for the proper design of monitoring surveys. Responses to the loading conditions are different for each dam. Therefore, the design of the monitoring surveys cannot be standardized. 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 (hard) bedrock are more stiff structures. In case of CFRD dams, the maximum displacements are expected to occur on upstream face of the dam. The type of geotechnical parameters of the earth dam construction material play significant role in the stability of the dam. By comparing results of properly designed monitoring measurements with a prediction model of deformation, one can verify the design parameters of the investigated dam and may determine and explain causes of deformation in a case of the unexpected behaviour. Thus, the role of monitoring surveys becomes much broader than just the conventional determination of the status of the deformable object.

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