Kinematic Analysis of Behavior of Large Earth Dams

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Key words: deformation measurement, engineering survey, earth dams

Summary: The most critical factor in the assessment of the safety threshold value of any structure is the acceleration of its deformation. Therefore, the designed accuracy of monitoring surveys must fulfill requirements of detecting accelerations at critical locations of the investigated object. As an example, time dependant behavior of a large embankment dam during filling up the reservoirs has been analyzed and verified by comparing monitoring results with the deterministic (prediction) model of the deformation. Modeling 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 foundation 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 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. In addition, with properly designed monitoring surveys, one may also determine the actual deformation mechanism. The finite element method may be useful tool in the proper design of the monitoring scheme by providing information on the locations and magnitude of the expected maximum displacements and velocites of movements. The discussed problems are illustrated by three types of earth dams located in California, U.S.A. and in Quebec, Canada.

Résumé: La sécurité des barrages en remblai ne dépend pas seulement d’une conception appropriée et d’une construction adéquate, mais aussi de la surveillance du comportement réel, non seulement, pendant la construction et pendant la mise en eau, mais tout au long de l’exploitation des barrages. La surveillance à l’aide de l’instrumentation géotechnique et géodésique appropriée, permet d’avoir un système d'avertissement en cas d'un comportement anormal de ces barrages en rembai. Ces systèmes peuvent aussi servir d’outil pour une vérification des paramètres géotechniques qui ont été utilisés pour la conception. La comparaison des valeurs de déformations calculées lors de la conception avec les déformations mesurées à l’aide des instruments de surveillance, permet de valider ou de faire une réévaluation des paramètres utilisées dans les analyses. La modélisation du comportement des barrages en remblai est un processus complexe dans lequel il faut considérer le comportement non-linéaire des matériaux de construction, l'interaction entre le barrage et le sol de fondation et/ou le substratum rocheux, l'influence de la charge hydraulique sur le barrage et sur la fondation et, les effets de saturation par l’eau. Le processus de déformation peut être modélisé en employant, par exemple, la méthode des éléments finis. En raison de l'incertitude des paramètres du modèle, la surveillance du barrage et ses abords est nécessaire afin de vérifier et améliorer le modèle. Les problèmes discutés sont illustrés par trois types de barrages en remblai situés en Californie (États-Unis) et au Québec (Canada).

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1. INTRODUCTION

1.1 Safety of the Earth Dams

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. 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 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 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 zones of a dam. That can be caused, for example, by 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.

In case of Concrete Face Rockfill Dams (CFRD), the main concern for the safety 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 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 smaller than the displacements compatible with the structural integrity of the concrete face slab.

Geotechnical parameters of the earth material play significant role in the stability of the dam. The dams located in the seismically active areas are built with material characterised by such geotechnical parameters, which allow for a dam to be more adaptable to the changes of loading conditions.

In the design of earth dams, deterministic modeling using the finite element method (FEM) is frequently used. 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 the construction and filling up the reservoir giving additional information on the actual behaviour of the structure, boundary conditions, and unexpected loads.

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

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 (Kondner, 1963) and (Kondner and Zelasko, 1963).

In this presentation, authors give examples of 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

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 (Chrzanowski, 1993):

- 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 area of 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 the 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.

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). 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 (Szostak-Chrzanowski et. al., 2002).

This paper presents results of numerical modeling of deformations of three dams:

- West Dam of Diamond Valley Lake (DVL) Project in California, U.S.A.,
- La Grande 4 (LG-4) main dam of La Grande Hydroelectric Complex located in northern Quebec, Canada, and
- Toulnustouc Main Dam (Concrete Face Rockfill Dam) located in Northern Quebec, Canada.

2 MONITORING OF EARTH AND ROCKFILL DAMS

Monitoring of the embankment dams may be divided into: 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, and 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, and 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. The main limiting factors of geodetic accuracy are environmental effects such as atmospheric refraction (Chrzanowski and Wilkins, 2006). Recently, a fully automated ALERT system for data collection, data processing, and displacement analysis has been developed at the Canadian Centre for Geodetic Engineering (Lutes et. al., 2001) and (Wilkins et. al., 2003). The system has already been implemented in monitoring of earth dams of DVL project (Duffy et. al., 2001) and in open pit mines in Canada, USA, and Chile (Wilkins et. al., 2003).

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 instruments are combined with the geodetic techniques.

3 EXAMPLES OF EARTH/ROCKFIL DAMS

3.1 Embankment Dams

3.1.1 Diamond Valley Lake Project

Recently completed Diamond Valley Lake (DVL) project, consists of three dams; West, East, and Saddle Dam (Arita et. al., 2000). The DVL dams have been constructed from soil and rock. Figure 1 shows a typical cross-section of the West Dam with height of 88 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 (Bock et. al., 1997) 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 (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).

3.1.2 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 (Paré et. al., 1984). LG-4 main dam is a zoned embankment and has maximum height of 125 m and is 3.8 km long. The dam is constructed almost entirely on bedrock. During the construction, following instruments were installed: 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 (Verma et. al., 1985).

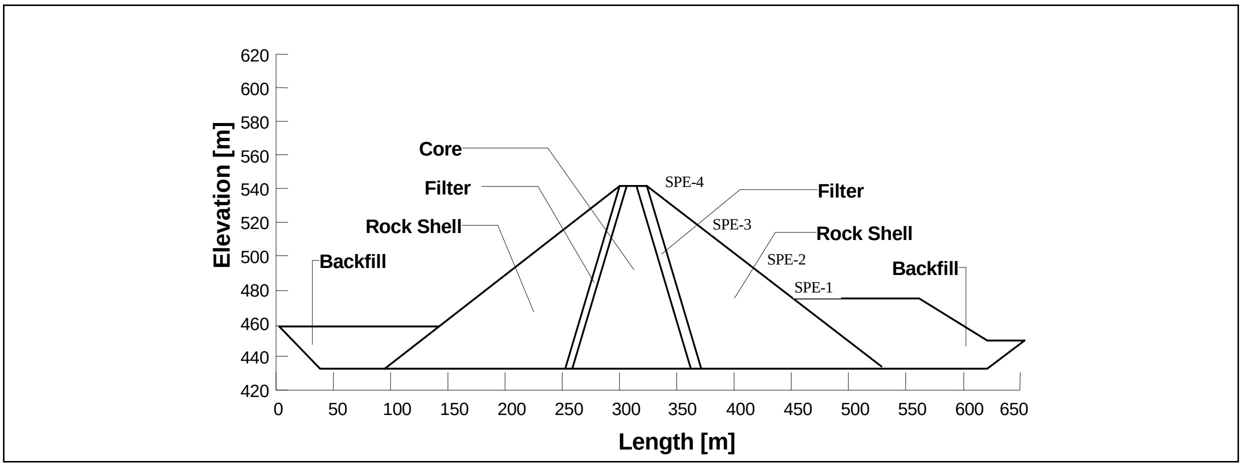

Figure 1. Schematic cross-section of the West Dam

3.2 Concrete Face Rockfil Dam (CFRD): Toulnustouc Main Dam

The Toulnustouc main dam is a concrete face rockfill dam and is located north of the city of Baie-Comeau on the Toulnustouc River in Northern Quebec, Canada. The existing dam has 75 m height 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 included 13 submersible tiltmeters, 1 measuring wire, 22 fissurometers (crack meters), 2 accelerometers, one measuring weir, and 16 survey markers.

There was a requirenment for design of 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 on Figure 2.

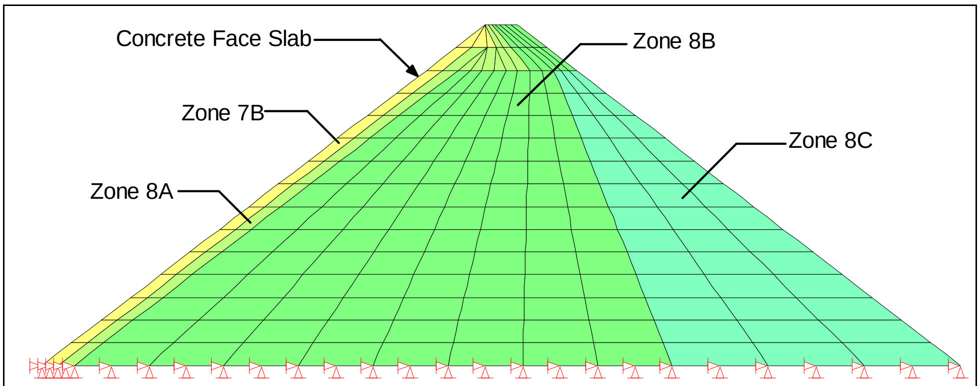

Figure 2. CFRD of 75 m of height resting on bed rock

3.3 Geotechnical Parameters of the Earth and Rockfill

The geotechnical parameters used in the design of DVL dams differ quite significantly from the parameters used in LGC project (Szostak-Chrzanowski et. al., 2000). The values of the geotechnical parameters of the LGC and DVL dams are given in (Massiéra and Szostak-Chrzanowski, 2003) and (Szostak-Chrzanowski et. al., 2000) respectively. The geotechnical parameters data for the CFRD dam and the foundation used in the analysis are given in (Massiéra et. al., 2004).

3.4 Summary of Deformation Analysis using FEM

The presented three types of dams were analysed using finite element method and SIGMA/W software (Krahn, 2004). The behavior of the earth/rockfill dams was analyzed in two stages: during the construction and during the filling of the reservoir. 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 West Dam was performed for the 88 m height of the dam with the assumption that the dam was resting on non-deformable bedrock. Two models of CFRD Toulnustouc main dam with height 75 m 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).

Figure 3 shows the calculated settlements in the center of the West Dam and LG-4 main dams during the construction. The settlements are much larger for West Dam than for LG4 main dam. The maximum settlement in the center of West Dam (height 88 m is 0.23 m and is located at the 54 m elevation. For the LG4 main dam (height 84 m) the maximum settlement in the center of the dam is 0.12 m and is located at 36 m elevation. One should note that the dams were designed to have zero settlement an their crests at the end of construction and before filling the reservoir.

Figure 4 shows designed settlements at the crest of West Dam and CFRD Toulnustouc main dam during the filling of reservoir. The West Dam has larger vertical displacements of crest (-175 mm vs. -60 mm) 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 because of the larger acceleration of the movements than in the case of CFRD dam.

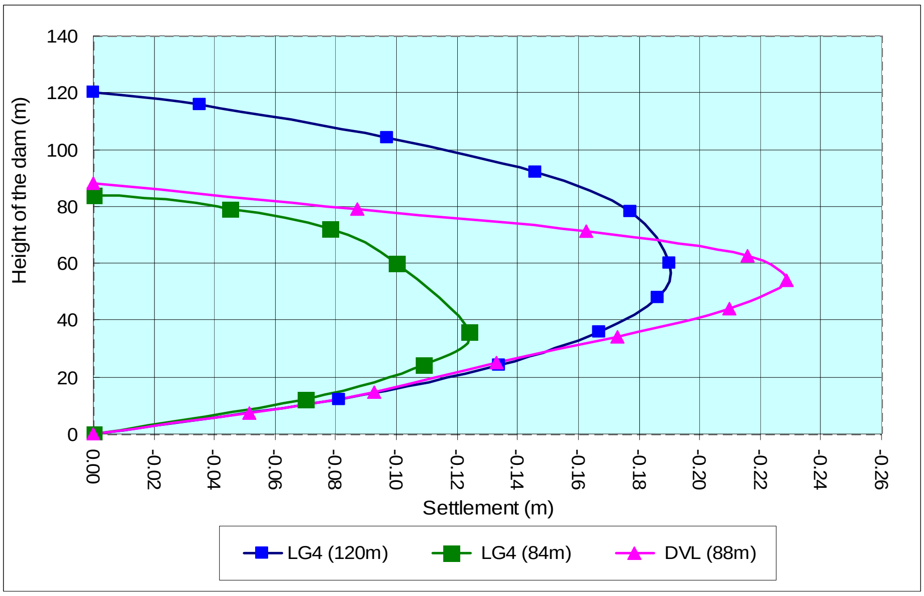

Figure 3. The calculated settlements at the end of construction of DVL and LGC dams

In case of the CFRD dam, the maximum total displacements (220 mm) are expected to occur on upstream face of the dam (Figure 5), where classical geodetic surveys cannot be implemented. Thus, in this case permanently installed geotechnical instruments (e.g., tiltmeters, 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 are reaching 220 mm for the dam resting on bedrock. The maximum displacements of the concrete face slab are 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 a reservoir are shown on Figure 5. The displacements are larger when the dam is resting on 60 m of till.

Change of water level during filling up the DVL reservoir and the settlement of the crest of the West Dam during filling up the reservoir are shown on Figure 6. The rate of settlement is significantly larger in the beginning of the filling up. The velocity of the settlement of West Dam and the velocity of water level change during filling up are shown on figure 7.

4. CONCLUSIONS

The geotechnical parameters of the construction material play a significant role in the stability of earthen dams. The dams located in the seismically stable areas are built with the material, which allows for the dam to be more adaptable to the changing loading conditions caused by the tectonic activity. The dams built on stable (hard) bedrock are more stiff structures. As shown by the examples of three dams, the predicted deformations of each dam and, particularly, the location of the maximum expected displacements significantly differ in each case. Therefore, one cannot develop detailed technical specifications for dam monitoring, which could serve as a standard for any type of the earth dam. In each case, a multidisciplinary approach is needed through a close cooperation between the structural, geotechnical, and geodetic engineers at the design stage of the monitoring surveys. Theoretically, this last conclusion seems to be very obvious. In practice, however, geodetic monitoring surveys are usually designed without any regard to the deterministic model of the expected deformations.

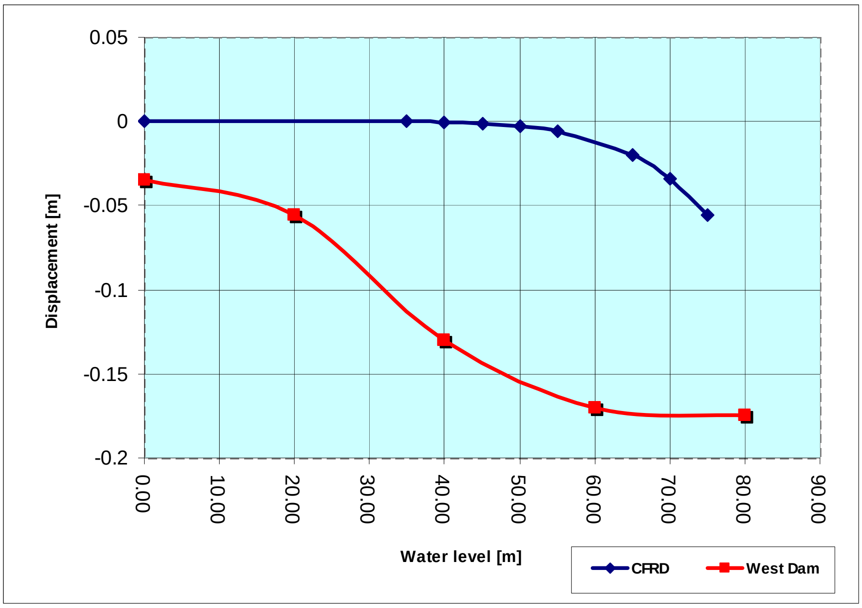

Figure 4. Settlement of crest during filing up a reservoir

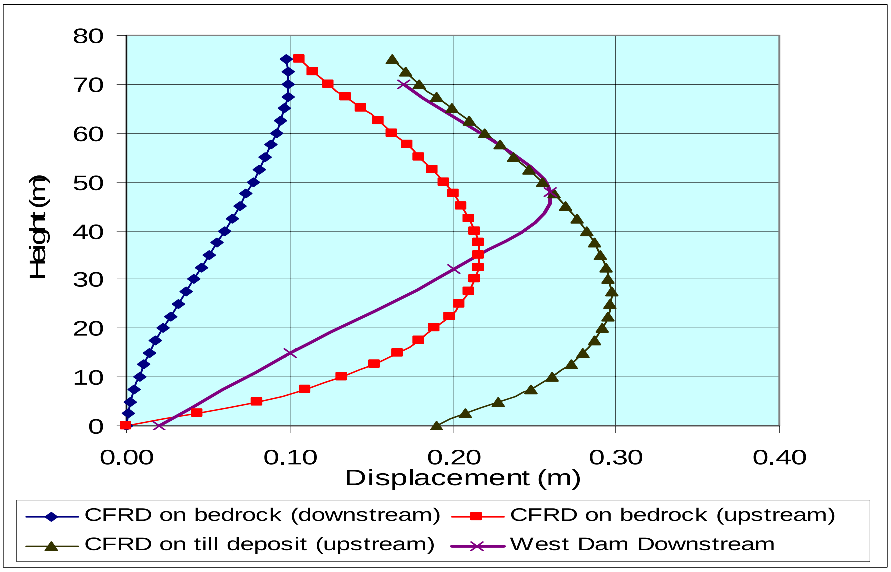

Figure 5. Total displacements of CFRD and West Dam at the end of filling up a reservoir

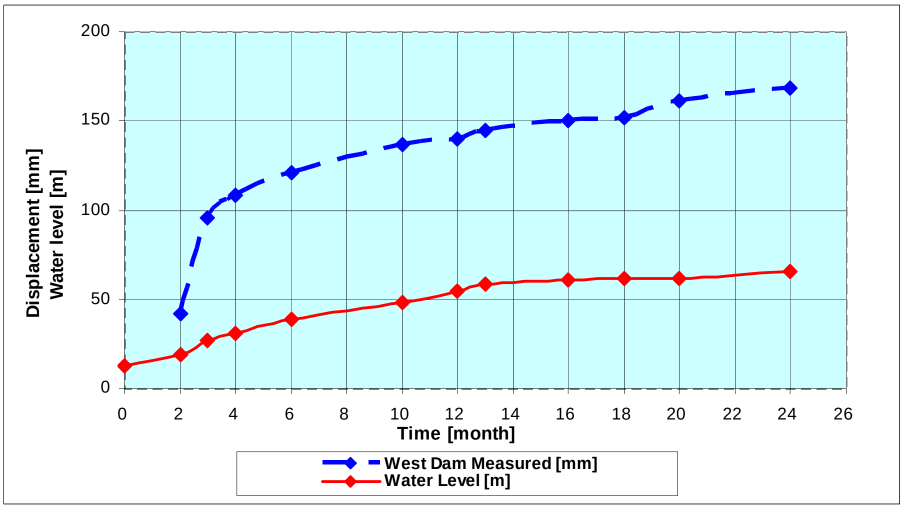

Figure 6. Settlement of the crest of theWest Dam during filling up a reservoir as a function of time

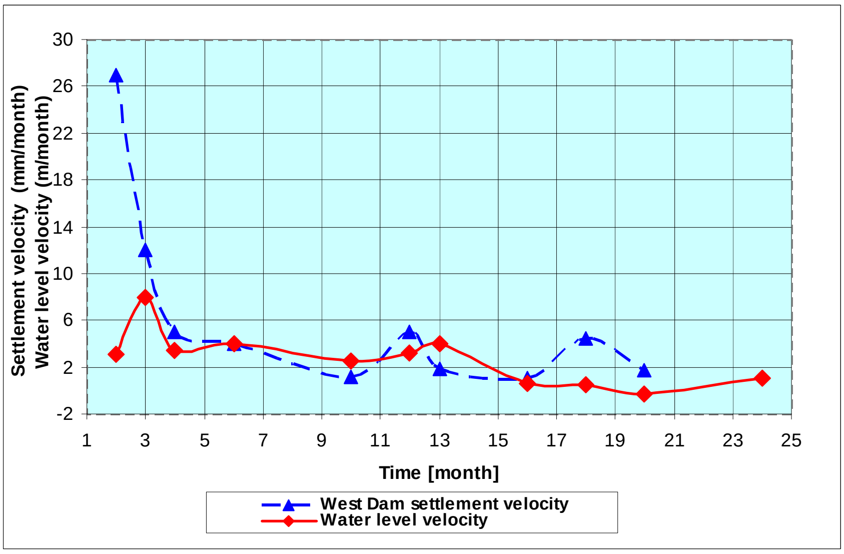

Figure 7. Velocity of the crest settlement of West Dam during filling up a reservoir

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BIOGRAPHICAL NOTES

Prof. Anna Szostak-Chrzanowski, Ph.D., P.Eng. holds M.Sc. degree (1976) in Precision Mechanics from the Technical University of Warsaw, Poland; M.Eng. degree (1979) in Mechanical Engineering from the University of New Brunswick, Canada, and Ph.D. degree (1989) in Mining Geomechanics from the Technical University of Mining and Metallurgy in Krakow, Poland. Since 1998 she holds an honorary appointment as an Adjunct Professor at

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Prof. Dr. Adam Chrzanowski, P.Eng., holds B.Sc., M.Sc. and Ph.D. degrees in engineering and mining surveying from the Technical University of Mining and Metallurgy in Krakow, Poland. He holds four honorary titles/degrees: *Doctor honoris causa* University of Warmia and Mazury, Poland, *Doctor honoris causa* Technical University of Mining and Metallurgy, Poland, Professor Emeritus (*Doctor honoris causa)* University of New Brunswick and *Professor honoris causa* Wuhan Technical University, P.R.CH. He is Professor Emeritus and since 1998 he serves as a director to the Canadian Centre for Geodetic Engineering at the University of New Brunswick (UNB) in Canada. He is also a president and principal consultant to A. Chrzanowski & Associates Ltd. Between 1966 and 1998 he was a professor and chairman (1991-1995) of Geodesy and Geomatics Engineering Department at UNB. He is a Foreign Member of the Polish Academy of Sciences (PAN), Warsaw, Poland, (2005), Foreign Member of the Polish Academy of Arts and Sciences (PAU), Author of over 300 scientific publications on geodetic, engineering, and mining surveys, consultant to numerous international engineering and mining projects, chairman of the International Working Group of FIG on Deformation Measurements and co-founder of the International Society for Mine Surveying. His expertise is in: geodetic control surveys, engineering surveys of high precision, mining and tunnelling surveys, industrial metrology, monitoring and analysis of deformations in engineering and geoscience projects, geodetic and rock mechanics instrumentation, ground subsidence in mining areas. He was awarded Knight's Cross of the Order of Merit by the President of RP for contributions to the scientific exchange and cooperation between Canadian and Polish universities, (1995);

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