Verification of Material Parameters of Earthen Dams at Diamond Valley Lake Using Geodetic Measurements

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Key words: Deformation modelling, earth dam, geotechnical parameters.

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. 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. 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 important information concerning the quality of the accepted geotechnical parameters. This paper presents a method, using finite element analysis, for modeling effects of saturation of the dam materials in order to determine expected displacements during the reservoir filling.

Two large earthen dams of the recently built Diamond Valley Lake (DVL), the largest water storage reservoir in South California, have been used as an example in verifying geotechnical parameters through a comparison of modelled and observed displacements. The DVL reservoir, constructed by Metropolitan Water District (MWD) of Southern California, is located about 160 km south-east of Los Angeles. It has been created by enclosing the Domenigoni/Diamond valleys by three large earth/rock filled dams.
This largest in the United States earthfill dam project consists of:
•West Dam, about 85 m high and 2.7 km long, volume 49.7 10^6 m^3,
•East Dam, about 55 m high and 3.2 km long, volume 32.9 $10^6 m^3$, and
•Saddle Dam, about 40 m high and 0.7 km long, volume 1.9 10^6 m^3.
Construction of the dams was finished in 1999 and filling of the reservoir started in December 1999. At the time of writing this paper (January 2002) the reservoir, of a capacity of almost one billion cubic metres, has been 67% filled. It is estimated that filling will be completed in 2-3 more years

In October 2000 a fully automated system with a capability of the continuous monitoring of the behaviour of the dams was implemented. The automated system consists of 8 robotic total stations (Leica TCA1800S) with the automatic target recognition and electronic measurements of angles and distances. In addition, 5 continuously working GPS receivers,

have been permanently installed on the crests of the dams 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 the University of New Brunswick.

The main objective of the presented study has been to verify whether the behaviour of the West Dam and East Dam during the filling of the reservoir follows a pattern derived from a numerical model using the finite element analysis. In the analysis, the main two effects were considered at the stage of filling the reservoir: pressure of water and effect of wetting. During the process of wetting, the values of geotechnical material parameters and the derived values of Young modulus (E) decrease. Young modulus of the wet material in the submerged sections of the structure becomes smaller and buoyancy force is developed producing dam deformation.

The determination of deformation of the dams due to wetting was performed assuming the behaviour of earth dam and the bedrock as linear elastic materials. Values of the Young modulus in the investigated cross-sections of the dams were obtained from the non-linear analysis in dry conditions (Szostak-Chrzanowski et al. 2000). The determined values shown a large variation of the Young modulus through the structure. In the analysis in wet conditions, the values of Young modulus were decreased according to known empirical formulae and averaged over selected zones.

In the presented example, modeling of the dam deformation due to wetting shows that the predicted displacements, at the crest and at the downstream face, are of the magnitude that can easily be detected by the automated geodetic monitoring system at DVL project. 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 filing 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.

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1. INTRODUCTION

Diamond Valley Lake (DVL), located about 160 km south-east of Los Angeles, when filled up, will be the largest water storage reservoir in Southern Califonia of a capacity of nearly one billion cubic metres. It has been created by Metropolitan Water District (MWD) of Southern California by enclosing the Domenigoni/Diamond valleys by three large earth/rock filled dams (Fig.1). This largest in the United States earthfill dam project consists of:

•West Dam, about 85 m high and 2.7 km long, volume 49.7 10^6 m^3,
•East Dam, about 55 m high and 3.2 km long, volume 32.9 $10^6 m^3$, and
•Saddle Dam, about 40 m high and 0.7 km long, volume 1.9 10^6 m^3.

Filling of the reservoir started in December 1999. At the time of writing this paper (January 2002) the reservoir, of a capacity of almost one billion cubic metres, has been 67% filled. It is estimated that the complete filling will take 2-3 more years, depending on the water availability.

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. 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 important information concerning the quality of the accepted geotechnical parameters.

In October 2000, a fully automated system with a capability of the continuous monitoring of the behaviour of the dams was implemented at DVL (Whitaker et al. 1999, Duffy et al. 2001). The automated system consists of an array of geotechnical instrumentation with the automatic data acquisition and a geodetic system consisting of 8 robotic total stations (Leica TCA1800S) with the automatic target recognition and electronic measurements of angles and distances to about 300 targets (prisms) located on the crests and faces of the dams. In addition, 5 continuously working GPS receivers, have been permanently installed on the crests of the dams to provide a warning system that will “wake up” the robotic total stations in case of abnormally large displacements. All functions of the robotic total stations, automatic data collection at preselected time intervals, and automatic processing of the geodetic data are controlled by an office computer located about 100 km away, using

DIMONS software developed at the University of New Brunswick (Duffy et al., 2001, Lutes et al., 2001).

At the design stage of the DVL Project, MWD performed a thorough analysis of the expected dam deformations during and after the construction including, among others, analyses of gravitational consolidation and settlement, effects of seepage, and earthquake- induced deformations. As a result of the analysis, post-construction threshold values of observed deformation have been established for the normal behaviour of the structures as listed in (MWD, 1997). Based on those values, the overall accuracy of the monitoring surveys has been designed to detect displacements with the accuracy of 0.01m at the 95% confidence level.

A preliminary study on the use of geodetic monitoring data in verifying geotechnical parameters of the dam material was performed at the stage of dam construction in dry condition (Szostak-Chrzanowski et al., 2000). In the process of filling the reservoir, the wetting of the dam material may cause significant changes to the material parameters. The main objective of the study presented in this paper has been to verify whether the behaviour of the West Dam and East Dam during the filling of the reservoir follows a pattern derived from a numerical model using the finite element analysis.

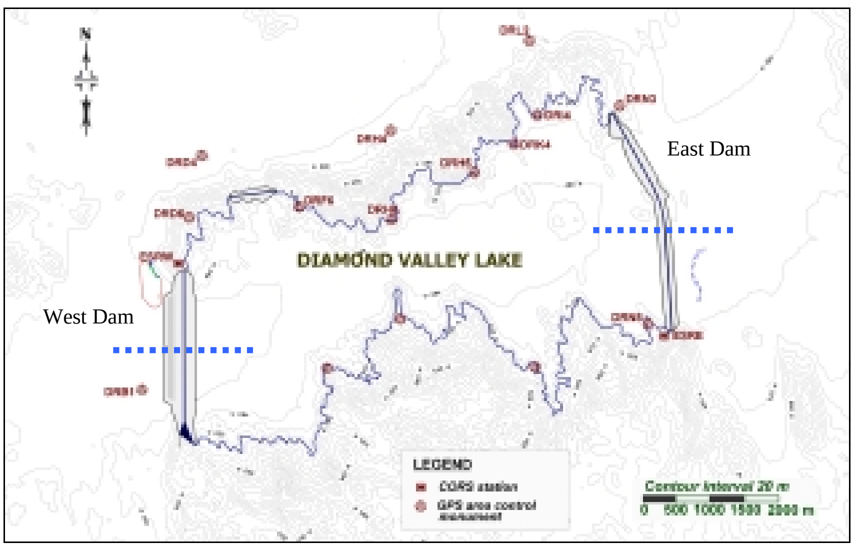

Fig. 1. Diamond Valley Lake Reservoir in California

3. METHODOLOGY OF DEFORMATION ANALYSIS DUE TO WETTING

Effects of wetting have been analysed and compared with monitoring data at selected cross-sections of the West and East dams (Fig.1). The determination of deformation of the dams due to wetting was performed assuming the behaviour of earth dam and the bedrock as linear elastic materials. The initial values of Young modulus in the investigated cross-sections of the dams were obtained from the non-linear construction analysis in dry conditions (Szostak-

Chrzanowski et al. 2000). The determined values shown a large variation of the Young modulus through the structure. In the analysis in wet conditions, the values of Young modulus were averaged over selected zones.

At the stage of filling the reservoir, the main two effects were considered: pressure of water and effect of wetting. During the process of wetting, the values of geotechnical material 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.

In the process of the calculation of displacements, one has to determine the change of E between dry and wet conditions. Thus, the analysis of the effects of wetting has been performed in the following steps.
1. Determination of Young modulus for dry conditions (E_{dry}) of the dam and foundation using non-linear analysis of the dam construction.
2. Determination of Young modulus for partially wet conditions (E_{sat}) of the dam structure using non-linear analysis. The wet conditions are function of the reservoir water level.
3. Determination of the displacements of the dam structure caused by the difference between E_{dry} and E_{sat} using linear elastic analysis.

In the analysis of construction process (step 1 and step 2), the dams were assumed to have non-linear material characteristics and were 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.

During the construction of the dam, the non-linear behaviour of the soil was modelled by successive increments of loading. Within each increment of the load, the soil behaviour was assumed to be linear, with the re-evaluated values of Young modulus. After achieving full compaction, the material of the embankment dam was modelled as a linear-elastic material.

The rock mass on which the embankment dam is located has been assumed to behave as a linear-elastic material under the load of the weight of the dam and the weight of water in the reservoir.

4. GEOTECHNICAL PARAMETERS OF THE DAM MATERIAL

The DVL dams have been constructed from soil and rock. The core materials are silty and clayey sandy alluviums obtained from the floor of the reservoir and the rock fill was obtained from bedrock hills of the reservoir. Fig. 2 shows as an example a typical cross-section of the West Dam. Table 1 lists geotechnical parameters used in the analysis of West and East Dams.

Table 1. Geotechnical Parameters for the West and East Dams.

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

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. The wet parameters are smaller than dry parameters for the same soil. The wet parameters were obtained using the relations shown in Table 2 for filter and shell (Touileb et al. 2000). For core, the wet parameters are given for the 0 m, 20m, 40m, 60m, and 80m height of water at the West Dam in Table 3 and for the 0 m, 14.25m, 28.5m, 42.75m, and 52.25m height of water at the East Dam in Table 4.

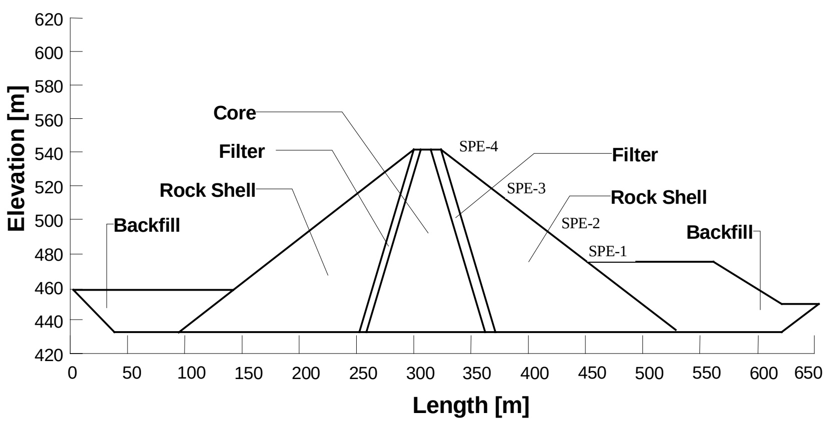

Fig.2 Schematic cross-section of the West Dam

Table 2.Geotechnical parameters for saturated conditions at West and East Dams.

Zone	K_{sat}	$K_{b\ sat}$
Filter	K_{sat} = 0.85 K = 476	$K_{b\ sat}$ = 0.85 K_b = 280.5
Rockfill shell	K_{sat} = 0.60 K = 336	$K_{b\ sat}$ = 0.60 K_b= 198.0

Table 3. Geotechnical parameters for core in saturated conditions as a function of the height of the water at the West Dam.

Height of water (m)	$\mathbf{K_{sat}}$	$\mathbf{K_{b\ sat}}$
0	$K_{sat} = 0.9\ K = 450$	$K_{b\ sat} = 0.9\ K_b = 189$
20	$K_{sat} = 0.8\ K = 400$	$K_{b\ sat} = 0.8\ K_b = 168$
40	$K_{sat} = 0.8\ K = 400$	$K_{b\ sat} = 0.8\ K_b = 168$
60	$K_{sat} = 0.7\ K = 350$	$K_{b\ sat} = 0.7\ K_b = 147$
80	$K_{sat} = 0.6\ K = 300$	$K_{b\ sat} = 0.6\ K_b = 126$

Table 4. Geotechnical parameters for core in saturated conditions as a function of the height of the water at the East Dam.

Height of water(m)	$\mathbf{K_{sat}}$	$\mathbf{K_{b\ sat}}$
0	$K_{sat} = 0.9\ K = 450$	$K_{b\ sat} = 0.9\ K_b = 189$
14.25	$K_{sat} = 0.8\ K = 400$	$K_{b\ sat} = 0.8\ K_b = 168$
28.5	$K_{sat} = 0.7\ K = 350$	$K_{b\ sat} = 0.7\ K_b = 147$
42.75	$K_{sat} = 0.6\ K = 300$	$K_{b\ sat} = 0.6\ K_b = 126$
52.25	$K_{sat} = 0.6\ K = 300$	$K_{b\ sat} = 0.6\ K_b = 126$

5. DETERMINATION OF YOUNG MODULUS

The values of Young modulus were obtained from the construction analysis using geotechnical parameters for dry and wet conditions. Figure 3 shows the investigated cross-section of the West Dam with the delineated wet (saturated) zones during filling of the reservoir. The obtained values of Young modulus significantly vary through the structure. Table 5 and Table 6 list average values of E_{dry} and E_{sat} for different zones of dry and wet material in the West Dam and East Dam respectively.

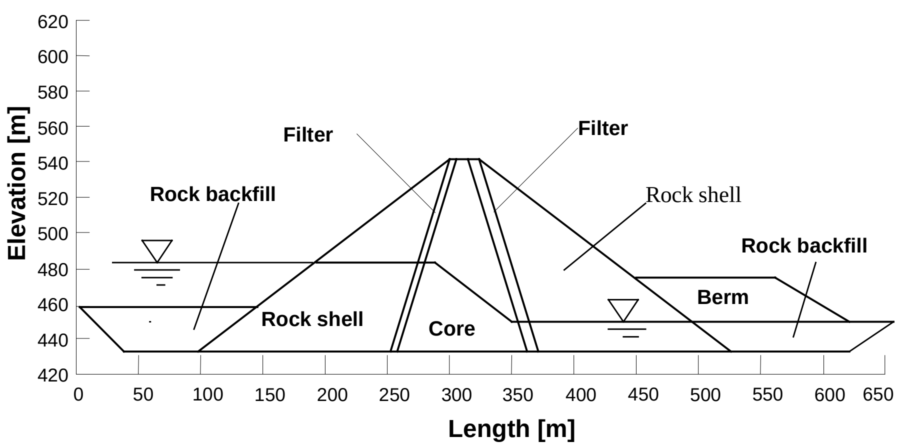

Fig 3. Schematic cross-section of the West Dam with dry and wet zones.

Table 5. Calculated values of E at selected heights for dry and saturated conditions at the West Dam.

	Dry Materials – E, MPa				**Saturated Materials – E_{sat}, MPa**			
			Rockfill Shell				Rockfill Shell	
	Core	Filters	Upstream	Downstream	Core	Filters	Upstream	Downstream
Construction	44	53	56	54				
Water Level (m)								
0	43	53	48	55	42	54	40	
20	44	55	47	44	39	53	37	62
40	43	51	43	45	32	50	33	55
60	35	41	32	44	28	49	30	50
80	34	40	32	44	23	45	27	50

Table 6. Calculated values of E at selected heights for dry and saturated conditions at the East Dam.

	Dry Materials – E, MPa				**Saturated Materials – E_{sat}, MPa**			
			Rockfill Shell				Rockfill Shell	
	Core	Filters	Upstream	Downstream	Core	Filters	Upstream	Downstream
Construction	42	50	47	47				
Water Level (m)								
0	40	47	44	47	39	46	38	
14.25	40	47	43	46	34	45	34	42
28.50	37	45	36	42	32	43	30	39
42.75	37	45	36	41	25	43	28	39
52.25	37	45	36	41	23	43	26	38

The Young modulus of the rock backfill in West Dam and East Dam is E = 45 MPa and E_{sat} = 40 MPa.

6. MODELLING OF DISPLACEMENTS DURING FILLING OF RESERVOIR

6.1. Determination of Vertical Displacements at the West Dam

The investigated cross-section of West Dam is located in the middle of the dam. At this location the dam is 843 m high. The cross-section of the model is shown in Fig. 3. The calculated values of Young modulus for dry and wet conditions are given in Table 5. The analysis was performed for the water level reaching toe of the dam, and 20 m, 40 m, 60 m, and 80 m above the toe of the dam. The calculated vertical displacements are shown in Fig 4.

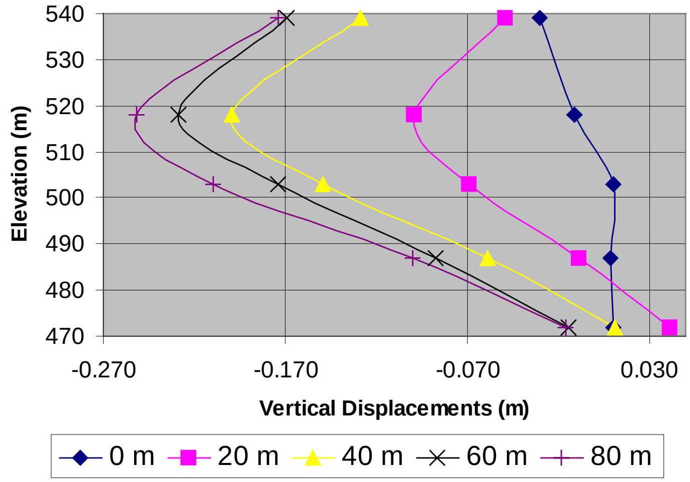

Fig. 4. Vertical displacements of the West Dam at the pt (SPE-1 to SPE-3) and at the crest (SPE-4)

The FEM calculated displacements could be compared only with one measured value obtained to a point on the crest of the dam (Fig. 5) because the manual surveys (prior to the commencement of automated measurements in December 2000) did not include points on the downstream face. At the end of December of 2001 the calculated vertical displacement was 0.172 m and measured was 0.173 m. The predicted vertical displacement at the end of the filling of reservoir is 0.174m.

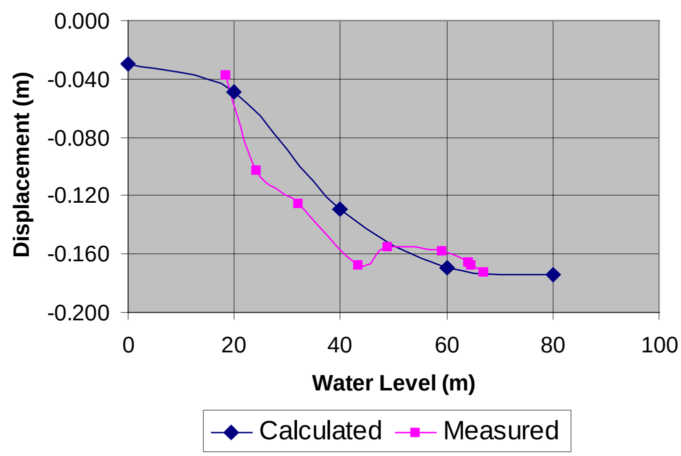

Fig. 5. Calculated and measured displacements at the crest of the West Dam

6.2 Determination of Vertical Displacements at the East Dam

The investigated cross-section of East Dam is located in the middle of the dam. At this location the dam is 56.3 m high. The calculated values of Young modulus for dry and wet conditions are given in Table 6. The analysis was performed for the water level reaching toe of the dam, and 14.25m, 28.5m, 42.75m, and 52.25m height of water above the toe of the dam. The calculated vertical displacements are shown in Fig 6. At the end of December of 2001 the calculated vertical displacement was 0.048m and measured was 0.046m This comparison gave a very good agreement indicating that the behaviour of the dam is as expected. The calculated maximum vertical displacement of the crest is 0.074m.

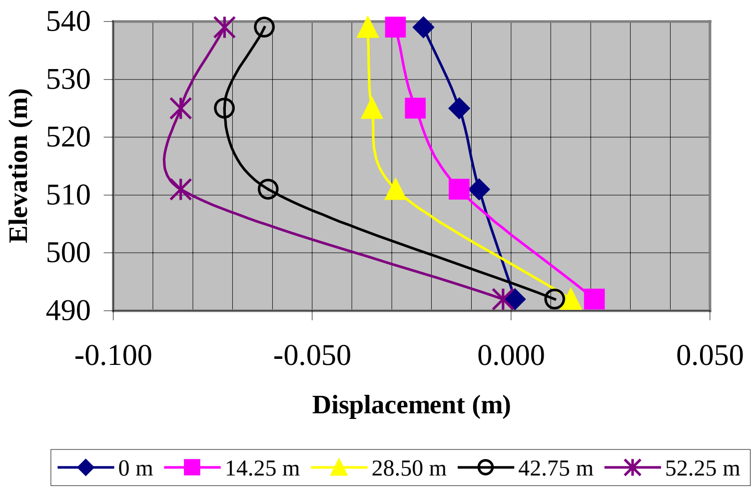

Fig. 6. Vertical displacements of the East Dam at the pt (SPE-1 to SPE-3) and at the crest (SPE-4)

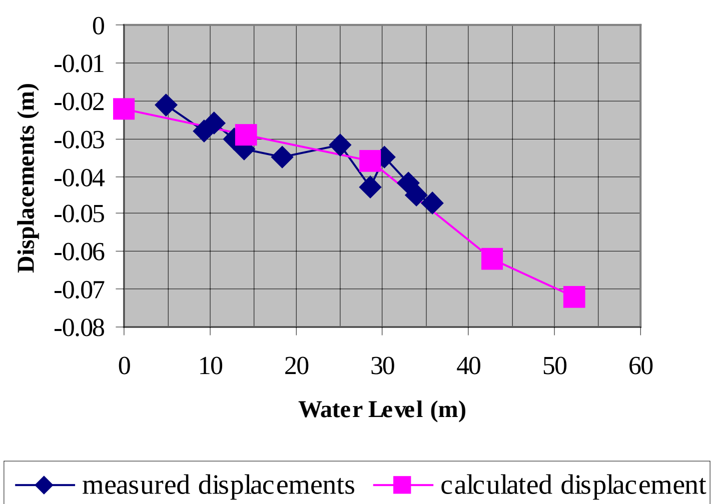

Fig.7. Calculated and measured displacements at the crest of the East Dam.

7. CONCLUSIONS

Due to possible uncertainties of the values of geotechnical parameters of the construction material, one may expect large uncertainties in the determined post-construction Young modulus. This affects the determination of the expected deformations of the embankment dams. The developed method for modelling effects of the saturation of the dam material gives displacement results comparable to the observed values. The presented examples of modeling the dam deformation due to wetting shows that the predicted displacements, at the crest and at the downstream face, are of the magnitude that can easily be detected by geodetic measurements. 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 filing 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.

The research is in progress and additional modeling of the DVL dams will be performed when filling of the reservoir will be completed and when more geodetic data will become available for the verification of the results.

8. ACKNOWLEDGEMENTS

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BIOGRAPHICAL NOTES

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