Prediction of the future behavior of the existing dam, based on the results of auscultation measurements

Dajana Biorac
Enegroprojekt – Hidroinženjering Consulting Engineers Co, Belgrade, Republic of Serbia

ABSTRACT: In this paper, two-dimensional modeling of the existing dam was performed in order to determine the characteristics of the material from which the dam was built and to predict the behavior of the dam in the future. The material characteristics were adopted so that the benchmark movements and groundwater levels in the dam body correspond to the measured in-situ values. The numerical analysis took into account different situations during the operation of the dam and for each of them a stability assessment was provided.

Key words: dam, calibrated material properties, wet strain, slope stability.

1 INTRODUCTION

This paper presents numerical modeling of the behavior of the earth-fill dam, in which signs of wetting appeared on the downstream slope during operation.

Namely, it is a zoned earth-fill dam, whose cross section is displayed in Figure 1.

The dam was built in 1989 for agriculture purposes (irrigation) and flood protection. The dam is founded on an impermeable Eocene flysch. The construction lasted less than a year. The reservoir has been fully filled within about 18 (eighteen) months after construction completion. After 20 (twenty) years of operation, the wet spot was noticed on the dam's downstream slope during regular maintenance.

The main technical data of the dam are:

1. Dam height above foundation: 34.6 m;
2. Elevation of the dam crest: 102.00 m asl;
3. Elevation of the foundation: 67.40 m asl;
4. Crest width: 5 m;
5. Base width: 120 m;
6. Crest length: 174 m;
7. Normal Water Level: 98.8 m asl.

2 NUMERICAL ANALYSIS

The basic monitoring system of the dam was established already during construction and immediately after the construction of the dam was completed. The results of auscultation measurements were used in numerical analysis for model calibration. After calibration, a prediction of the dam's future behavior was made.

All calculations were performed by the finite element method using the Geo-Studio 2018 software package, i.e., its programs: Slope / W (stability calculations), Seep / W (filtration calculations), Sigma / W (stress-strain analysis).

Numerical analysis was performed for the following cases, which will be described individually in the following chapters:

1. case – Dam after construction
2. case – First filling
3. case – Occurrence of the wet spot
4. case – Remedial works

Analyzes were performed on two-dimensional models.

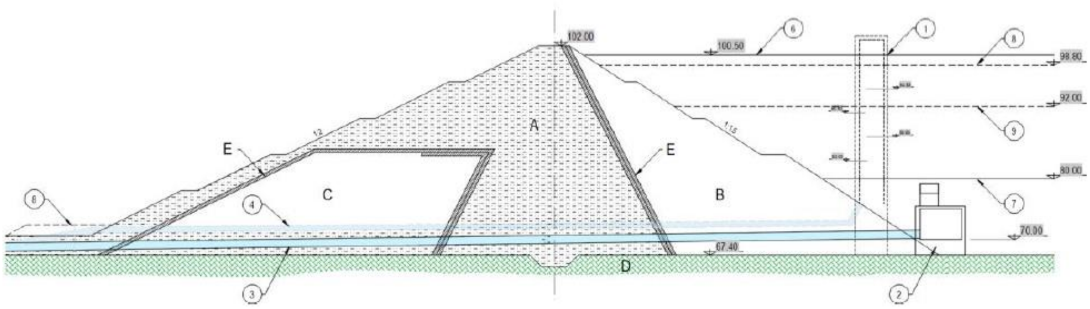

Figure 1. Typical cross-section of the dam, gde je: A – clayey silt material; B – rockfill material; C – limestone and sandstone blocks; D – impermeable rock base; E – filter material; 1 – intake tower; 2 – intake structure; 3 – bottom outlets; 4 – irrigation pipeline; 6 – maximal reservoir level (100.5 m asl); 7 – minimal operating level (80.0 m asl); 8 – normal operating level (98.8 m asl); 9 – depleted operating level (92.0 m asl).

3 DAM AFTER CONSTRUCTION

In this part of the numerical analysis, the calibration of the material parameters, adopted by the design, was performed (Table 1) - so that the displacement values are obtained, which correspond to the measured displacements of geodetic benchmarks immediately after the construction of the dam.

Table 1. Design material properties

Material	w	γ	cu	φ	c	Eoed	E	ν	k
	%	kN/m^3	kPa	°	kPa	MPa	MPa	-	m/s
A’	13	21	-	36	36	15	-	0.4	10^{-6}
A	16	19.5	75	-	-	5	-	0.5	10^{-9}
B	-	24	-	38	-	50	-	0.3	10^{-3}
C	-	24	-	38	-	50	-	0.3	10^{-4}
D	-	25	-	39	32	-	620	0.25	10^{-9}

where w is soil moisture; γ – specific gravity; cu – undrained shear strength; φ – angle of internal friction; c – effective cohesion; Eoed – oedometric modulus; E – elastic modulus; ν – Poisson coefficient; k – permeability

In the numerical analysis, the construction of the dam was simulated in 37 steps in the program GeoStudio - Sigma / W (Figure 2). The “Coupled Stress / PWP” analysis was applied, which can be used to determine, in addition to the primary settlement, consolidation settlement as well.

The following boundary conditions were adopted (Figure 2):
1) the lower limit is a fix in the X and Y directions, 2) the left and right borders are a fix in the X direction, 3) the piezometric level is adopted on the terrain surface. The duration of one step t1 = 9 days was adopted, so that the total duration of the dam embankment is: t = 9 days · 37 steps = 333 days.

The parameters of the material, for which the displacements at the benchmarks closest to the in-situ displacements are obtained, are shown in Table 2.

Table 2. Calibrated material properties

Material	γ	cu	φ	c	E	ν	wc	m_v	k
	kN/m^3	kPa	°	kPa	MPa	-	-	1/kPa	m/s
A1	21	-	36	36	25	0.35	0.10	$4\cdot10^{-5}$	$1\cdot10^{-6}$
A*	19.5	70	-	-	20	0.45	0.20	$5\cdot10^{-5}$	$2\cdot10^{-11}$
A2*	19.5	100	-	-	25	0.37	0.20	$4\cdot10^{-5}$	$2\cdot10^{-11}$
A3*	19.5	150	-	-	30	0.37	0.20	$3.33\cdot10^{-5}$	$2\cdot10^{-11}$
A4*	19.5	100	-	-	20	0.39	0.20	$5\cdot10^{-5}$	$2\cdot10^{-11}$
B	24	-	38	-	50	0.30	-	$2\cdot10^{-5}$	$1\cdot10^{-3}$
C	24	-	38	-	50	0.28	-	$2\cdot10^{-5}$	$1\cdot10^{-4}$
D	25	-	39	32	620	0.25	0.20	$1.6\cdot10^{-6}$	$1\cdot10^{-9}$

where γ - is specific gravity; cu – undrained shear strength; φ – angle of internal friction; c – effective cohesion; E – elastic modulus; ν – Poisson coefficient; wc – saturated volumetric water content; m_v – compressibility; k – permeability
*Zone A (clayey silt material) is divided on to subzones: A, A2, A3 i A4

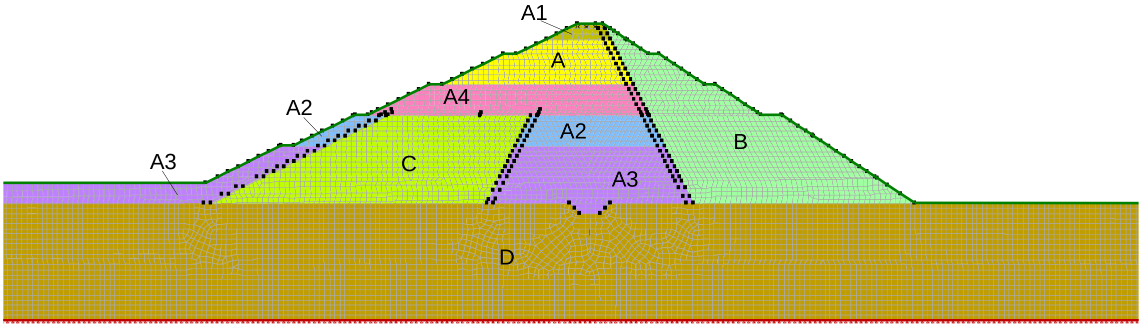

Figure 2. Calculation model, where: A – clayey silt material; B – rockfill material; C – limestone and sandstone blocks; D – impermeable rock base; E – filter material

The comparison of the results of numerical analysis with the values of the displacement of geodetic benchmarks at the end of the dam construction, is shown in Table 3.

Table 3. The displacements of the geodetic benchmarks (mm)*

Bench	Numerical analysis		Readings in-situ 23-01-88	
Mark	Y	Z	Y	Z
BM5	0	0	0	0
BM10	10.52	-22.7	-38	-22
BM14	26.36	-19.3	-28	-20
BM16	15.6	-8.86	-18	-7

* The convention is adopted in the table: Y displacements are horizontal displacements positive in the upstream-downstream direction; With displacement, vertical displacements are positive in the down-up direction.

The calculation of the stability of the slopes was performed by the finite element method, using the program GeoStudio-Slope / W. The minimum safety factors for the upstream and downstream slope, immediately after the completion of the dam construction are as follows:

Table 4. Dam stability after construction completion

Slope	FS
Upstream	1.416
Downstream	2.187

4 FIRST FILLING

The calculation model uses water level fluctuation, based on real measurements. To calibrate the values of the water permeability coefficients of the material in the composition of the dam, water level readings on piezometers K2 and K3 were observed. In Table 2, lower values of water permeability coefficients for clay material were adopted in relation to the projected values (Table 1).

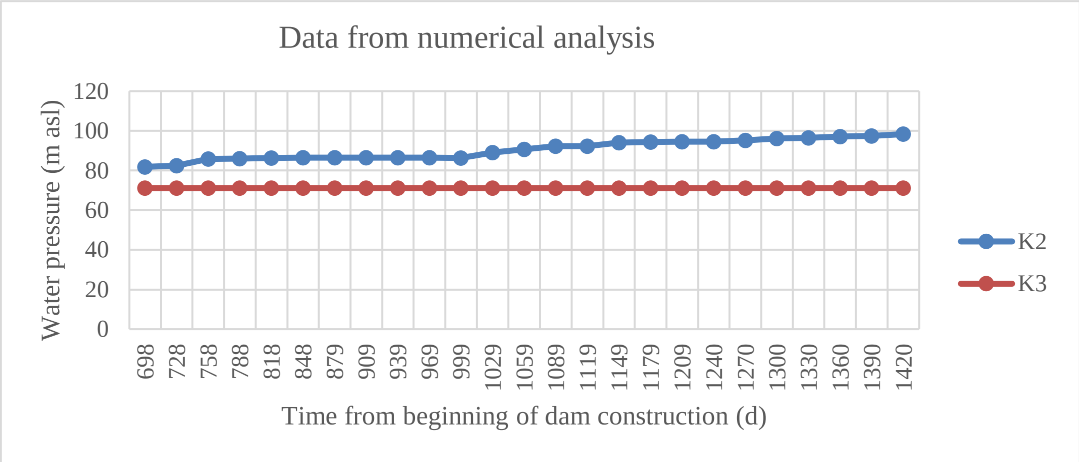

Figure 3. Water level at piezometers K2 and K3 - results obtained by numerical analysis

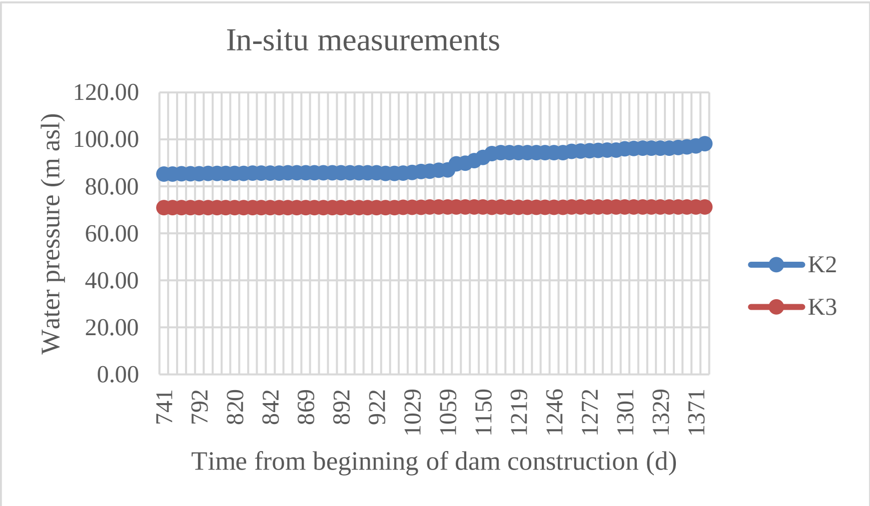

Figure 4. Water level at piezometers K2 and K3 - values obtained by in-situ measurements

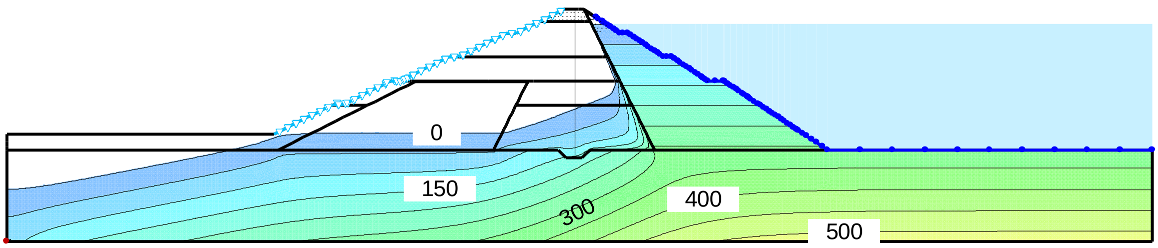

Figure 5. Piezometric line at the end of first filling

Table 5. Dam stability during first filling

Slope	FS
Upstream	1.376
Downstream	2.281

5 OCCURRENCE OF THE WET SPOT

After 20 (twenty) years of operation, the wet spot was noticed on the downstream slope of the dam during regular maintenance. The wet spot was located at the downstream toe of the dam in the central part, close to the axis of the dam. Extensive vegetation on the central part of the embankment dam indicated that the humid zone extends to the downstream slope of the dam above the wet spot. Emergency investigation revealed that excessive water on the downstream slope originates in the reservoir.

The change in the reservoir water level until the moment when the wet strain is noticed, is displayed in Figure 7.

The numerical model shown in Figure 2, displays correspondence of the real field conditions for the period after 20 years of operation, with the application of an upstream hydraulic boundary condition corresponding to real changes in the accumulation levels (Figure 7).

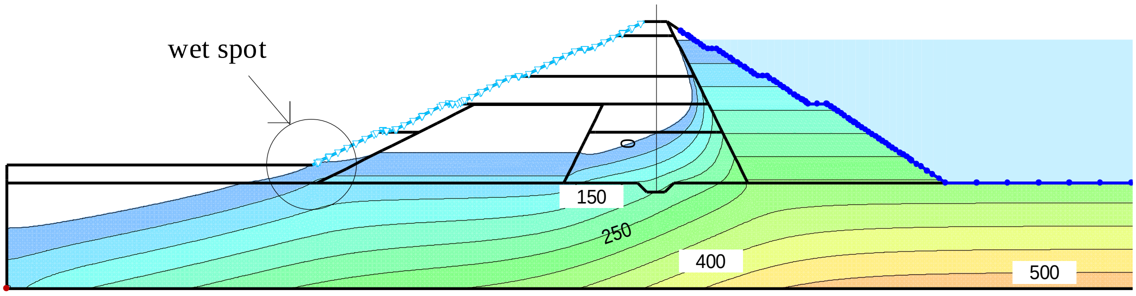

Figure 6. Piezometric line in the dam after 20 years of operation

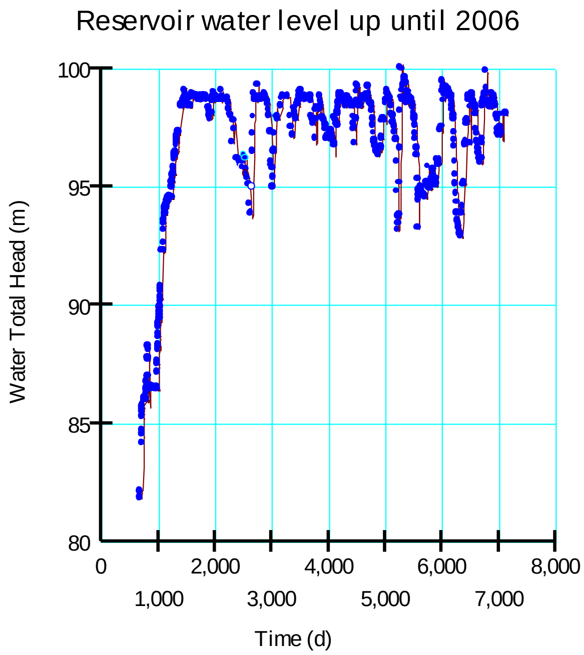

Figure 7. Reservoir water level up until occurrence of the wet spot

The minimum safety factor for the upstream and downstream slopes, for the period up to the wet strain occurrence, is shown in the following table.

Table 6. Dam stability up until the occurrence of the wet strain

Slope	FS
Upstream	1.41
Downstream	2.187

6 REMEDIAL WORKS

In 2008 the reservoir level was lowered to a maximum of 93.6 m asl and the irrigation pipeline was filled with the concrete. The space between the irrigation pipeline and the concrete cover was grouted with the cement grout. After this emergency remediation, the reservoir operational level was additionally lowered to a 92.0 m asl.

It is foreseen to fill all the pipes within the dam body, with concrete during the rehabilitation works, after which the reservoir water level would return to 98.8 m asl.

The value of the water permeability coefficient around the irrigation pipe was increased to $k = 10^{-8}$ m/s in the numerical analysis. This assumption was introduced due to the possible change of the clayey material due to the lowering of the water level in the accumulation, as well as due to the migration of the clayey material particles through the corroded irrigation pipe.

In addition, due to the closure of the irrigation pipe with concrete, as well as due to the grouting of the zone around the pipe - the value of the water permeability coefficient in material C (limestone and sandstone blocks) was reduced to $k = 10^{-8}$ m/s also in the zone around the pipe Figure 8. and Table 7).

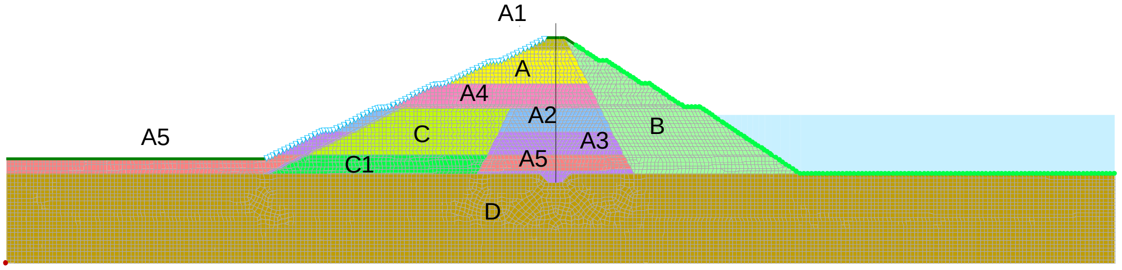

Figure 8. Construction model after remedial works

Table 7. Material properties after remedial works

Material	γ	cu	φ	c	E	ν	wc	m_v	k
	kN/m^3	kPa	°	kPa	MPa	-	-	1/kPa	m/s
A1	21	-	36	36	25	0.35	0.10	$4\cdot10^{-5}$	$1\cdot10^{-6}$
A*	19.5	70	-	-	20	0.45	0.20	$5\cdot10^{-5}$	$2\cdot10^{-11}$
A2*	19.5	100	-	-	25	0.37	0.20	$4\cdot10^{-5}$	$2\cdot10^{-11}$
A3*	19.5	150	-	-	30	0.37	0.20	$3.33\cdot10^{-5}$	$2\cdot10^{-11}$
A4*	19.5	100	-	-	20	0.39	0.20	$5\cdot10^{-5}$	$2\cdot10^{-11}$
A5*	19.5	100	-	-	20	0.39	0.20	$5\cdot10^{-5}$	**$1\cdot10^{-8}$**
B	24	-	38	-	50	0.30	-	$2\cdot10^{-5}$	$1\cdot10^{-3}$
C**	24	-	38	-	50	0.28	-	$2\cdot10^{-5}$	$1\cdot10^{-4}$
C1**	24	-	38	-	50	0.28	-	$2\cdot10^{-5}$	**$1\cdot10^{-8}$**
D	25	-	39	32	620	0.25	0.20	$1.6\cdot10^{-6}$	$1\cdot10^{-9}$

where γ is specific gravity; cu – undrained shear strength; φ – angle of internal friction; c – effective cohesion; E – elastic modulus; ν – Poisson coefficient; wc – saturated volumetric water content; m_v – compressibility; k – permeability

*Zone A (clayey silt material) is divided on to subzones: A, A2, A3, A4 i A5

**Zone C (limestone and sandstone blocks) is divided on to subzones C i C1

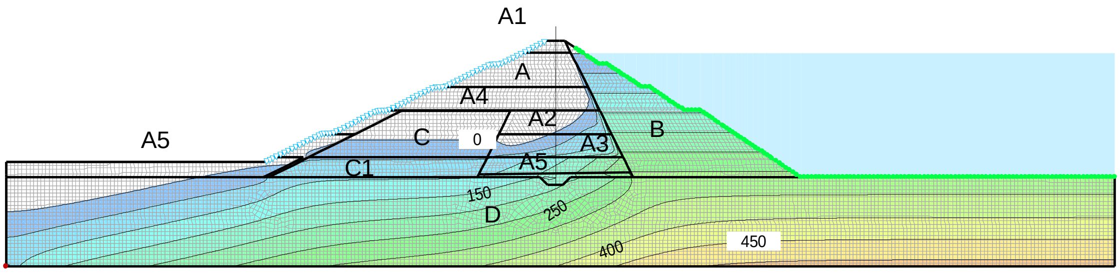

Figure 9. Piezometric line in the dam body after remedial works

The minimum stability factors for the upstream and downstream dam slope, after remedial works, are displayed in Table 8.

Table 8. Dam stability after remedial works

Slope	FS
Upstream	1.144
Downstream	2.033

7 CONCLUSION

This paper treats the two-dimensional modeling of the existing dam. The designed characteristics of the dam materials were calibrated based on the measured values of in-situ displacements.

The values of the vertical displacements are quite similar to the measured in-situ values at the places of reference, while there are significant deviations with the horizontal displacements. This anomaly can be explained by the limited accuracy of the 2D modeling of the objects with a three-axis stress state.

The water permeability coefficients of the dam materials were calibrated so that the water levels at the piezometers K2 and K3 correspond to the measured ones.

Numerical analysis treats the following cases during the exploitation of the dam:
1) Dam after construction, 2) First filling, 3) Occurrence of the wet spot, 4) Remedial works.

Slope safety factors for each case are displayed in Table 9.

Table 9. Dam stability for different calculation cases

Slope	Dam after construction	First filling	Occurrence of the wet spot	Remedial works
Upstream	1.144	1.376	1.41	1.144
Downstream	2.033	2.281	2.187	2.033

Table 9 shows that the stability of the dam slopes is satisfactory for all calculation cases, except for the remediation phase. In order to ensure adequate stability of the upstream slope also during the return of the accumulation to the level of 98.8 m asl, it is necessary to consider slower raising of the water level to the level of 98.8 m asl.

Based on Figure 9, it can be seen that the piezometric line does not cross the downstream slope of the dam (water does not wet the downstream slope), which leads to the conclusion that remedial works had produced the desired effect. A downstream drainage curtain could be introduced as an additional measure. This would further lower the piezometric line at the side of the dam downstream slope.

8 REFERENCES

Geo-Slope International Ltd, 2021. Stability Modeling with GeoStudio
Geo-Slope International Ltd, 2021. Stress-Strain Modeling with GeoStudio
Fell R., MacGregor P., Stapledon D., Bell G., 2005. Geotechnical Engineering of Dams
ICOLD B155, 2012. Guidelines for use of Numerical Models in Dam Engineering