Reliability assessment of the earth embankment

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1 Abstract

An earthfill dam is defined as a permanent or temporary geotechnical facility built out of soil materials with water retention or water level elevation as its primary function. A correctly designed dam provides for a safe and reliable structure, which serves its purpose during construction period and throughout its lifetime, even in the case of the most critical situations predicted in the designing phase of a project. The paper discusses a dike built of slightly permeable mixture of gravel and silty soils, located in the area of demanding geologic and seismic conditions. The report features integral technology of a vertical and surface sealing system in order to prevent dam leaking and consequential water losses. Moreover, the results of laboratory tests proving adequate impermeability and stability of embankment dam are given and interpreted for the implementation of a thin cut-off wall and appropriate mixture of natural materials. Water losses assessments in combination with static, pseudostatic and dynamic analyses at given maximal expected and submitted design seismic loadings have been made for the analysed structure.

2 Introduction

In the field of dam engineering, geotechnical experts see the main challenge in stability of the structure along with its impermeability and water losses prevention. Combined with other factors, such as geomechanical data, climatic conditions, flood risk, geotechnical category or the importance of the facility, the lifetime of the construction and its placement into the space, the design of such a structure creates a complex and multilayered problem. A detailed analysis and engineering approach lead to solutions that combine stable and reliable structure with an optimal way of sealing, enabling to achieve project requirements in terms of water losses and stability.

The paper deals with a hypothetical earth embankment, earth levee or dike, respectively, which main purpose is to retain water for the needs of accumulation. Data for the analysis are chosen on the basis of the experiences and characteristics of the earth materials located in different areas with demanding geological and seismic conditions. Construction and sealing of the embankment was executed as an integral method of vertical and sector sealing system in the form of a cutoff wall (Schmallwand) and a sealant mixture of soils (Einmischdichtung), which was implemented by following the modelling of the projects in neighbouring Austria (see literature).

The finite element method based software, Plaxis 2D, with complex elasto-plastic soil model, i.e. "Hardening Soil – Small model", was used to perform geomechanical analysis of the cross section on the selected earth dam. Water losses with analysed stability conditions of embankment and materials that could potentially be used for the construction were studied together with their response to the impact of seismic loads using quasi-static calculations in accordance with the Eurocode standards and dynamic analyses based on the load of standardized El Centro earthquake spectrum.

3 Key elements of ensuring the reliability of earthfill dams

Loads and factors acting on the levee can be permanent, variable and temporary. Permanent action is the weight of the structure, whereas variable actions include the pressure of the accumulated water, the buoyancy, the hydrodynamic pressure in the area of seepage and the pore pressure.

Properly designed dam provides for a safe and reliable structure, serving its purpose during construction period and throughout its lifetime, predicting the most critical situations in the designing phase of a project. In order to be stable, an earth dam must meet three stability requirements, functioning as static or mechanical, hydrodynamic and dynamic stability. In all the principles, the main safety parameter is represented as sufficient shear strength which is changing, mostly decreasing, mainly under the influence of various (especially hydrodynamic and dynamic) effects. Considering earth embankments, with water retention as its primary function, the soil permeability plays a key role, which, among the prevention of water losses, directly affects the most common reasons of the structure failure, internal erosion and piping, hydraulic heave and regressive erosion.

Reduction of water losses is considered as the main function of an accumulation dike.

In Slovenia, the use of the standard SIST EN 1997: 2005 (EC-7) is obligatory for geotechnical design of demanding facilities; whereas standard EC-8 is required for the design of facilities subjected to seismic loading. These standards (EC-7, EC-8) do not apply to the most demanding hydrotechnical facilities among which large dams and earth embankments belong. In most cases, more rigorous alternative regulations and recommendations of ICOLD (International Comission on Large Dams) are considered for designing and proving the mechanical stability of structures.

4 Sealing of the earth embankment with the use of a low permeable mixture and a cut-off wall

In the construction of earth embankments and accumulation dikes, a number of types and sealing methods can be used to reduce water losses, to achieve the necessary hydraulic and mechanical resistance while sustaining the reliability of the constructed facilities during the time of the execution of their primary function, which is mainly water retention.

Considered sealing system is represented as the combination of the out of so-called sealing mixture built embankment body with a transition to vertical sealing implemented as a thin cut-off wall.

1.1 Sealing mixture

Sealing mixture (SMix) from the original (EINMISCHDICHTUNG) is a natural sealing material that practically completely prevents the seepage of accumulated water through the body of the embankment. It is composed mostly from a natural soil of gravel (GP) and from fine or silty sand (SM) containing up to 30% of the silt fraction D <0.06 mm. The principle of sealing or the prevention of water flow represents the concomitant effect of very fine pores in the material conditioned by the granulometric composition and the very good compaction of the mixture at 98% of the achieved maximum density determined by the “Modified Proctor” test (MPT). Because of the high density, the fine-grained fraction D <2.0 mm completely fills the empty spaces between the individual pebbles and the karst, as a result of wide range of acceptable granulation of materials, D = 0.02-100 mm (Škrabl et al., 2015).

1.2 Laboratory tests of the soil mixture

The main goal of the laboratory tests was to confirm the thesis that by carefully selecting a mixture of coarse gravel and silty sand, compacted with the Modified Proctor test, the required low permeability k = 1.0 · 10-6 m/s can be achieved with the corresponding shear strength and specific gravity.

In his study, Škrabl et al. (2015) proved and stated: "We can estimate that through the compaction of sandy gravel soil, according to MPT, their permeability is reduced to approx. 3% of their initial value or for ca. 33 times, ... "This principle, while ensuring that soil is well graded, was the main guide for designing a low level permeability mixture of gravel and sand.

For the purposes of the above-mentioned study, numerous types of mixtures were compiled and mixed, which differed in most ways from the basic or basic coarse grain material (GP-GW) to which different proportions of coarse, medium and fine grain (silty) sands were added and then investigated in the Laboratory for Soil Mechanics at the Faculty of Civil Engineering, Traffic Engineering and Architecture, University of Maribor.

The density was determined by the MPP procedure in cells of 15x12 cm and 25x20 cm (diameter x height). Measurements of the permeability of the compacted material were carried out with a permeameter (compaction permeameter), where the measurements were performed using methods with constant and variable hydraulic head. Deformability of compacted mixtures was tested in triaxial cells on specimens with dimensions of 10 cm in diameter and 20 cm in height. During triaxial testing, measurements of permeability were also carried out. We are convinced of the high accuracy of calculated permeability coefficients, since significant intensities of lateral tensions (measurements were performed at $\sigma = 25$, 50, and 100 kPa) with a rubber membrane almost completely seal the peripheral surface of the cylindrical samples. All our laboratory tests aimed to achieve a density of 98% of the maximum density according to MPT.

Based on results and foreign literature (Semprich, Scharner, Jauk, & Fürst, 2012), we determined the range of granulometric diagrams that defines the grain structure of the mixtures which correspond to the requirements for sufficiently low permeability and sufficient shear strength. The trends are shown in Figure 1.

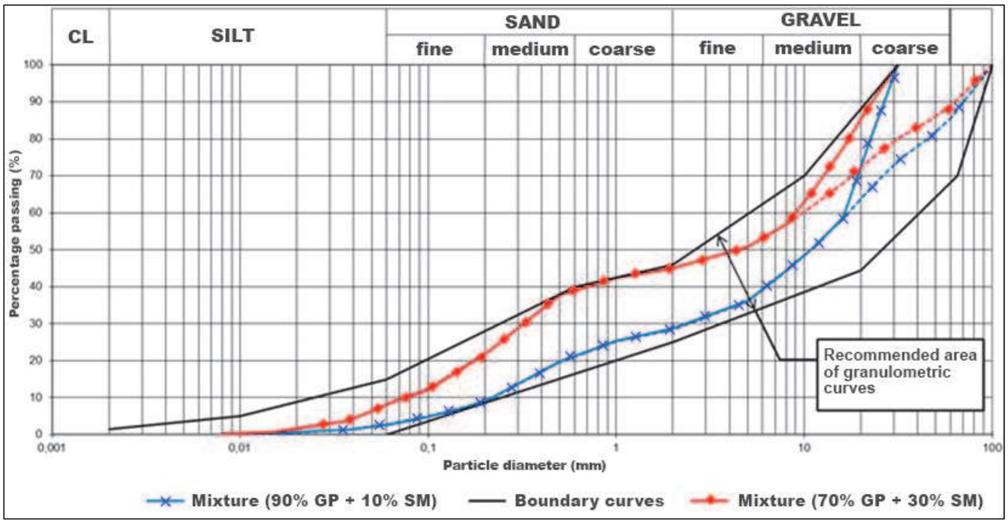

Fig. 1: Suitable range of granulometric diagrams for SMix that fulfill the design requirements with curves of the most suitable tested specimens.

The analysis of the shear strength estimates that obtained results (Figure 2) can be realistic for tested material, especially considering the high density and the high degree of interlocking (despite a smaller proportion of larger fractions); however, in reality highly compacted soils can be fragile and therefore the total shear strength is not entirely acceptable for the demonstration of all limit states for long-term project situations in buildings with a lifetime of 100 years.

In particular, the obtained value of cohesion strength, the majority of which certainly results from the mechanical energy of compaction (in the form of interlocking), is therefore questionable and as such unreliable and unacceptable for the calculation of ultimate limit states of critical infrastructures with a long lifetime. The triaxial testing of low-density mixtures (86% MPT) leads to the conclusion that for a parameter of the characteristic shear strength of the sealing mixture it is reasonable to take into account the following values: c'=1.0 kPa (to eliminate shallow slip surfaces in the embankment) and φ'= 38°.

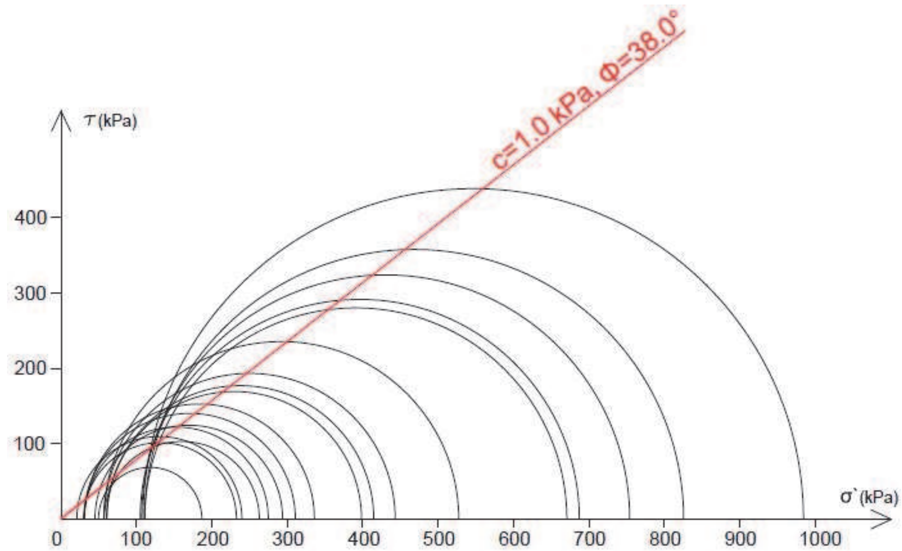

Fig. 2: The shear strength of all samples of mineral aggregates according to the study "Interpretation of possible ways of sealing and implementation of energy embankments of HPP Hrastje – Mota (Škrabl, et al., 2015).

1.3 Cut-off wall

A thin diaphragm wall, originally named ″schmalwand″, provides for practically impermeable grout curtain, formed in the ground by injecting a specialized injectable mass, consisting of an expansion cement, sodium bentonite, filler and water, shown in Figure 3b. The design principle bases on the hydraulic and vibratory embedding of a special tool in the soil (HEB 100 or HEB 50). When pulling backwards, instantly controlled discontinuity is injected in the soil and in materials along it, providing a thin barrier in the soil that completely prevents the flow of accumulated water. In laboratory conditions, the cut-off wall`s coefficient of permeability reached the value k = (1-10) · 10-9 m/s (Fross, Reiser, Schremser, & Semprich, 2009).

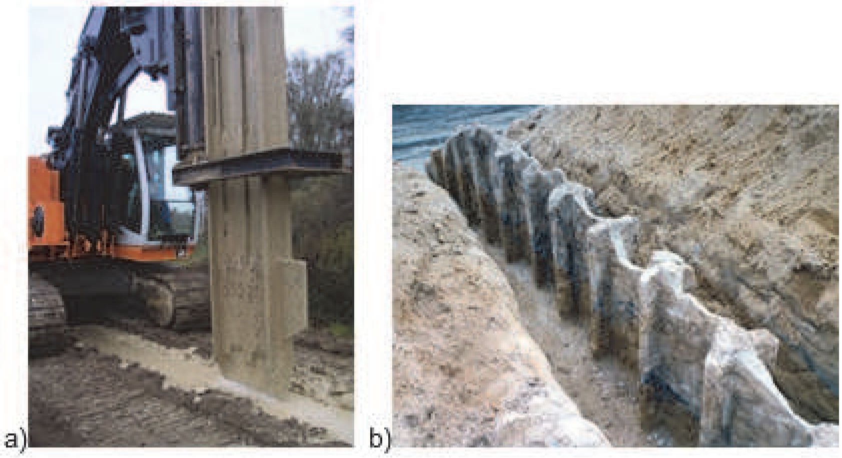

Fig. 3: The design and construction principle of a Cut-Off wall.

Sources (all available on 20. 4. 2018):
a) http://www.dyckerhoff-bohrtechnik.de/online/download.jsp?idDocument=5396&instance=5

b)http://www.hansgruener.de/docs_d/kanal_mdk_wsa/dietfurt_schleuse_df_8403_3.htm

5 Geomechanical reliability assessment of the selected profile

The studied profile of the accumulation dike is located in the area where the basic foundation material is a 90 m thick layer of young, heavily clayed gravel deposits (PL/Q) from the period of the plioquaternar, above which the main hydrogeological structure, the aquifer, is formed out of quaternary sediments (Q) in a thickness of 10 m. On the surface above them, a 2 m thick layer of silty sand is placed, which has low compaction and represents a high liquefaction potential and therefore it must be removed before the construction starts. The characteristic cross section of the embankment in the selected profile is shown in Figure 4.

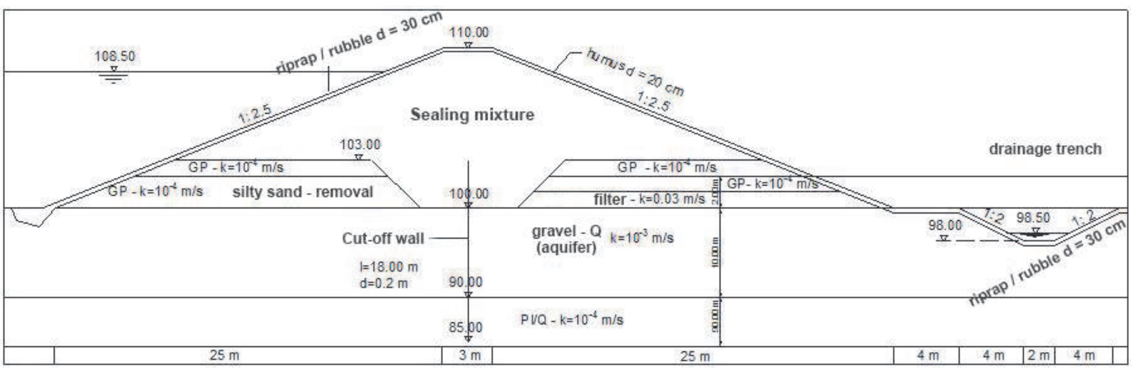

Fig. 4: Cross section of the selected profile.

Classification of our construction follows the ICOLD criteria for a large dam due to the height of the embankment and the geomechanical complexity of the area; consequently, as alternative regulations the ICOLD's more rigorous recommendations were used.

The Plaxis 2D software with its numerical procedures based on the finite element method was used to analyse the static stability in combination with water losses and to assess the behaviour of the dam under the earthquake load. 240 m wide and 110 m high model consisted of a mesh of 970 finite elements and calculated using "The Hardening Soil with Small-Strain Stiffness" material model (Hardening Soil – Small). HS – Small implemented in PLAXIS bases on the Hardening Soil model and uses almost entirely the same parameters. In fact, only two additional parameters are needed to describe the variation of stiffness with strain:

- the initial of very small-strain shear modulus G_0,
- the shear strain level $\gamma_{0.7}$ at which the secant shear modulus G_s is reduced to about 70% of G_0 (PLAXIS, 2018).

1.4 Stability assessments during construction and at the rising of water level

In the case of stability assessment, the following project criterion will be taken into account:

- The stability of all parts of the accumulation embankment must be entirely demonstrated while considering the impact of groundwater seepage during the design situation of the upper operating water level of hydropower plant at 108.50 m with a safety factor Fs = 1.5 (recommendation of ICOLD, considered as an alternative regulation).

The analysis of the structure and the estimation of water losses must be carried out in a sufficiently large area and not only within the external dimensions of the embankment. The necessary reliability for the ultimate limit state conditions of piping and hydraulic heave of the soil must also be ensured.

The displacements of completed construction were 9.31 cm and after the raise of water to the operating level (108.5 m) 1.89 cm, which is expected and within acceptable limits. The safety factor after shear strength reduction was 1.63, which provides a sufficient degree of global stability based on our project criteria (Fs = 1.5). Water losses reach q=165 m3/day/m. The water flow through the embankment and cut-off wall is shown in Figure 5.

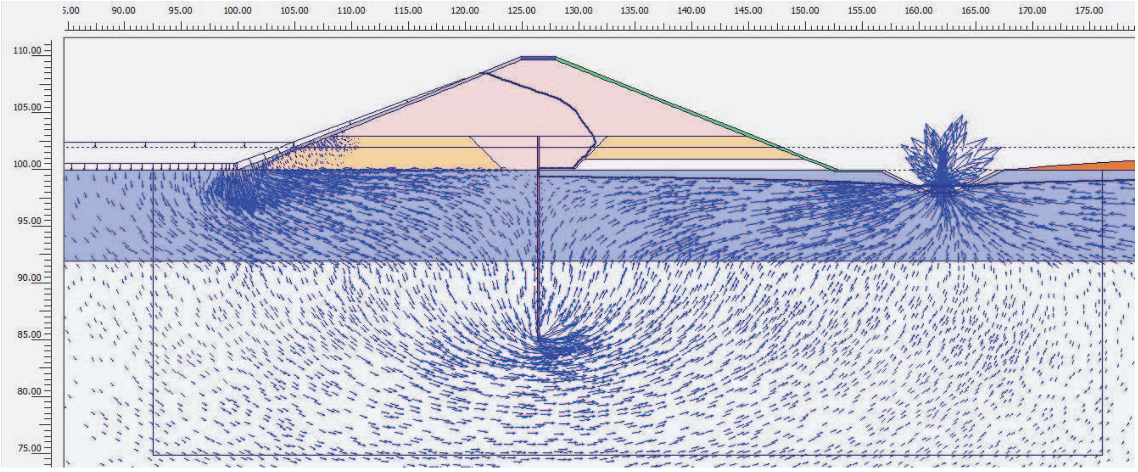

Fig. 5: Water table and flow lines through the dike and around the cut-off wall (flow lines are seen even 100 m below the surface).

1.5 Analysis of seismic load according to Eurocode (EC-8) standards

Considering the data of the peak ground acceleration (PGA) and including improvised water movement during the earthquake, we checked the following project situations:

- The embankment and sealing system must remain intact during the impact of the project earthquake (OBE – Operating Base Earthquake), furthermore the safety of $Fs \geq 1.1$ must be ensured.
- The safety of dikes, $Fs \geq 1.0$, must be ensured while maximum expected earthquake (SEE - Safety Evaluation Earthquake) is acting on the structure. Minor damages of the embankment and sealing system are permitted, but the facility should not instantly collapse, neither uncontrolled water losses are allowed to occur.

A simplified quasistatic (pseudostatic) method for assessing the impact of expected earthquakes was used in the calculation, results of which are shown in Table 1. For the analysis of the maximum earthquake we used PGA values corresponding to the medium high acceleration of ground in the Slovenian territory at 1000 annual return, namely $\alpha_{max}=0.4\cdot g$, and for a 200-year projectile earthquake with $\alpha_{proj}=0.3\cdot g$. According to EC-8, the values of used ground accelerations are:

- OBE: $a_h = 0.15\cdot g,\ a_v = 0.022\cdot g$
- SEE: $a_h = 0.2\cdot g,\ a_v = 0.03\cdot g$.

Hydrodynamic pressure on the outer face of the bank, $q(z)$, may be evaluated as $q(z)=\pm 7/8\cdot k_h\cdot\gamma_w\cdot(h\cdot z)^{1/2}$, as described in EC – 8, part 5, where k_h, h and z are the horizontal seismic coefficient, the free water height and the vertical downward coordinate with the origin at the surface of water.

Tab. 1: Results of pseudostatic analysis

Directions of accelerations	OBE		SEE	
	Fs	|u|	Fs	|u|
Y= +, X= -	1.11	17 cm	1.01	33 cm
Y= +, X= +	1.29	16 cm	1.14	28 cm
Y= -, X= -	1.11	14 cm	1.01	31 cm
Y= -, X= +	1.33	18 cm	1.17	30 cm

1.6 Dynamic analysis with seismic load

The control calculation was carried out using the record of accelerations, speeds and soil movements describing the earthquake that occurred in the past, more precisely, the El Centro accelerogram, which was normalized to the expected value of the acceleration of the ground at the maximum earthquake.

Dynamic analysis was performed for the earthquake time period of 10 seconds. The accelerations (Figure 6) and displacement values are the most critical at the crest of the structure, a_{max}=5.26m/s^2 with maximum displacement of 13 cm.

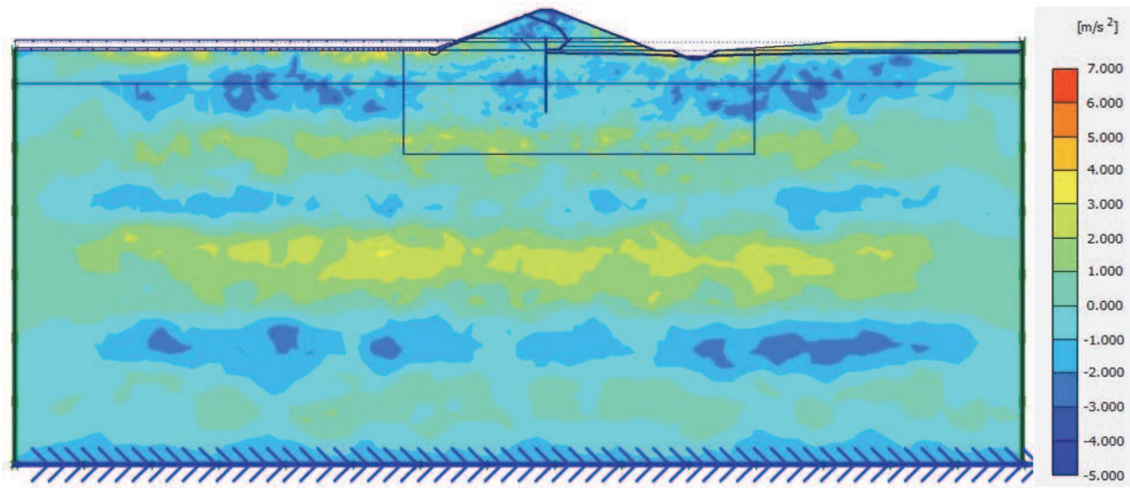

Fig. 6: Horizontal acceleration distribution in the analyzed model (t=4.00s, a_{max}=5.26 m/s^2).

6 Conclusion

The article presents some of the results for a comprehensive geomechanical assessment of the reliability of the earth embankment, located in relatively demanding geological and seismic conditions. The implementation of the dike was carried out with the technology of integral sealing system, less known in the RS area, with carefully chosen and tested soil mixture and cut-off wall. The calculations were performed with the complex elastoplastic model HS – Small, proving the sufficient safety of structure.

7 References

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