Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-340

ECSMGE 24
XVIII EUROPEAN CONFERENCE
ON SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

Influence of permeability on the behaviour of tailings storage facilities by hydromechanical numerical analysis

Influence de la perméabilité sur le comportement des installations de stockage de résidus par analyse numérique hydromécanique

C. Midão
Faculdade de Engenharia da Universidade do Porto, Porto, Portugal

A. Viana da Fonseca, S. Rios*
CONSTRUCT – GEO - Faculdade de Engenharia da Universidade do Porto, Porto, Portugal

**sara.rios@fe.up.pt*

ABSTRACT: Given the catastrophic accidents seen in the last decade at tailings storage facilities (TSF's), there is a growing consensus that a better understanding of the behaviour of these structures is needed including different approaches to analyse their stability. In that sense, the use of numerical tools allowing coupled hydromechanical stress-strain analysis has been encouraged. This paper presents the results of PLAXIS 2D® numerical analysis conducted on a simple slope where the water head was increased in the upstream boundary and a seepage flow was established. A parametric study was developed for different slope heights, water heights, and soil permeability, where the minimum time required for a steady-state seepage flow stabilization was identified. A mathematical formulation is proposed that relates the normalized water height, the soil permeability, and the steady-state time.

RÉSUMÉ: Compte tenu des accidents catastrophiques observés au cours de la dernière décennie dans les installations de stockage de résidus (TSF), il existe un consensus croissant selon lequel une meilleure compréhension du comportement de ces structures est nécessaire, notamment différentes approches pour analyser leur stabilité. En ce sens, l'utilisation d'outils numériques permettant une analyse couplée hydromécanique contrainte-déformation est nécessaire. Cet article présente les résultats de l'analyse numérique PLAXIS 2D® menée sur une pente simple où la hauteur d'eau a été augmentée dans la frontière amont et un écoulement d'infiltration a été établi. Une étude paramétrique a été développée pour différentes hauteurs de pente, hauteurs d'eau et permeabilité du sol, où le temps minimum requis pour une stabilisation à l'état stable d'un écoulement d'infiltration à travers la pente a été identifié. Une formulation mathématique est proposée qui relie la hauteur d'eau normalisée, la perméabilité du sol et le temps d'équilibre.

Keywords: Tailings; PLAXIS 2D®; liquefaction; seepage flow; permeability.

1 INTRODUCTION

Advances in mining technology allowed the exploitation of lower-quality deposits, leading to the generation of more tailings, the discarded material after ore extraction. This has created an increasing pressure on tailings storage facilities which need to be larger in a shorter time. Moreover, the rupture of these structures often involves the release of material downstream, with catastrophic consequences for populations, the environment, and the economy. The triggering causes of failure in these structures are numerous which can be summarized in the following: the existence of defects in the structure, problems in the foundation, unusual weather events, seismic events, overtopping, subsidence, and lack of maintenance during operation and after its closure.

The analysis of several case studies identified static liquefaction and cyclic liquefaction in most cases (Mánica et al., 2022). In practice, static liquefaction phenomena occur much less frequently than cyclic liquefaction phenomena, but their effects are generally much more serious.

The term liquefaction, which was originally created by Mogami and Kubo (1953), has historically been used with a variety of phenomena involving soil deformations caused by monotonic, transient, or repeated disturbances of saturated, cohesionless soils under undrained conditions. The generation of excess pore pressures under undrained loading conditions is common to all liquefaction phenomena. When cohesionless soils are saturated, however, rapid loading occurs under undrained conditions, so that the tendency toward densification causes excess pore pressure to increase and effective stresses to decrease.

Ledesma et al. (2022) presented a procedure to assess the vulnerability of a tailings dam due to flow liquefaction. The procedure required the development of a numerical model with the complete definition of the contour boundaries of the dam under study, where the tailings had to be modeled using a constitutive model capable of capturing the onset of liquefaction and the subsequent loss of strength for complex stress values and the ability to change from drained to undrained loading or fully coupled flow deformation loading without changing material parameters.

This requires a thorough characterization of the tailing material for the proper identification of critical state and instability locus (Viana da Fonseca and Cordeiro, 2022) as well as the influence of stress induced anisotropy (Viana da Fonseca et al., 2023). Delgado et al. (2023) highlighted that this geomechanical characterization needs to be performed up to high stress levels to simulate the stress state at the bottom of large embankments. In some cases, the embankments need to be reinforced with cemented berms (Meneses et al., 2023) where more sustainable binders may be used (Caetano et al., 2023).

This paper aims to summarize the main conclusions drawn from a parametric study with hydromechanical stress-strain numerical analysis in tailings storage facilities to assess their stability with the progressive rise of water. For the analysis, the PLAXIS 2D® software and the Mohr-Coulomb constitutive model were used to evaluate which parameters influence the stability of the water flow. Subsequently, a correlation was established to determine the time necessary to promote a stable/permanent flow regime in tailings storage facilities (TSFs).

2 NUMERICAL ANALYSIS

2.1 Model geometry

In the developed study, two types of embankment sections were used. The first one consists of a 30º slope with a height of 35 m in the upstream boundary and 8 m in the downstream boundary. The second model has the same slope but twice the dimensions of the first one. A larger embankment was used to evaluate the effect of embankment dimensions on the steady-state seepage flow stabilization time. The geometry of the first model can be seen in Figure 1.

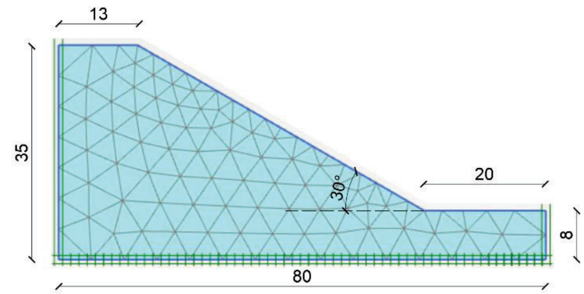

Figure 1. Geometry and dimensions of the first numerical model.

2.2 Material parameters

The constitutive model used was the linear elastic perfectly plastic Mohr-Coulomb model. The parameters for the material were determined through a significant set of monotonic compression triaxial tests, conducted in the Geotechnical Laboratory of FEUP (Table 1).

Table 1. Soil parameters (Mohr-Coulomb).

Parameter		Value	Unit
Unit weights	γ_{sat}	18.00	kN/m^3
	γ_{unsat}	20.00	kN/m^3
Initial void ratio	e	0.800	-
Young Modulus	E	44 000	kN/m^2
Poisson ratio	ν	0.30	-
Friction angle	ϕ'	33.40	º
Cohesion	c'	2	kN/m^2
Coef. earth pressure at rest	K_0	0.45	-
Permeability	k_x=k_y	10^{-5} to 10^{-8}	m/s

2.3 Mesh and boundary conditions

The PLAXIS® plane strain numerical model has finite elements with triangular 15-node elements. The generated mesh comprises 1493 nodes in 174 triangular elements.

In terms of mechanical boundary conditions, the bottom boundary was fixed in both directions, while the left and right boundaries were only fixed horizontally. As for hydraulic boundary conditions during the hydromechanical analysis, a constant head was imposed in the left boundary (which changes depending on the analysis), and on the right bottom border a null head was imposed to simulate downstream drainage.

The numerical analysis comprises two consecutive phases: i) an initial phase to activate the stress state (Gravity Loading); ii) a second stage where the hydraulic boundaries were activated and a hydromechanical numerical analysis (fully coupled flow-deformation analysis) was developed.

These analyses were repeated for the two model heights (H=35 m and 70 m), seven water heads on the left boundary (H_w=5m, 10m, 15m, 20m, 25m, 30m to 35m), four soil permeabilities (k=10^{-5}, 10^{-6}, 10^{-7}, and 10^{-8} m/s), and different seepage times (from a couple of months to several years). The seepage time is imposed as the time factor of the fully coupled flow-deformation analysis.

3 RESULTS

3.1 Identification of steady-state flow condition

For all the analyses where the stability of the embankment was assured, the maximum groundwater flow was recorded for each seepage time, water height, and soil permeability, as illustrated in Figure 2. Therefore, it was possible to plot the relation between water flow and seepage time. Figure 3 shows an example of such graph, where it's clear that after some time the seepage flow stabilises. The minimum time to the groundwater flow stabilization was considered the time to steady-state.

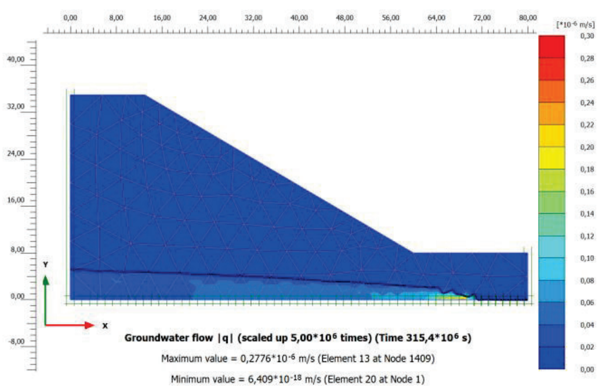

Figure 2. Groundwater flow (m/s) for the first embankment section, with Hw=5m, k=10-6 m/s and seepage time=10years.

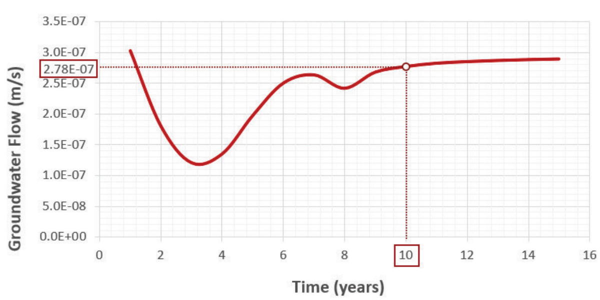

Figure 3. Groundwater flow recorded for each seepage time, and minimum flow time obtained (First embankment section with H_w=5m and k=10^{-6} m/s).

For water heights of 25m, 30m, and 35m in the first embankment section of 35 m, and for water heights of 50m, 60m, and 70m in the second model of 70 m, the slope collapsed without groundwater flow stabilization.

3.2 Results of the parametric study

To compare all the analyses performed in the two model geometries, the water weight was normalized by the slope height (H_w/H) leading to the following ratios: 0.143, 0.286, 0.429, and 0.571. Figure 4 presents the minimum flow time obtained for each height ratio (H_w/H), demonstrating that it does not change much with the height ratio but it varies significantly with soil permeability.

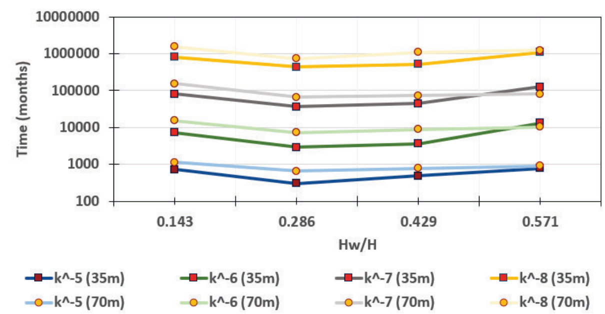

Figure 4. Minimum flow time for each height ratio (H_w/H) and soil permeability for the two model geometries.

3.3 Proposed interpretation model

Considering all the 32 data points obtained, a relation was pursued between the three variables: height ratio, soil permeability, and minimum flow time. Figure 5 shows the 3D graph obtained with the data points used for its generation. To improve the visualisation of the data, logarithms were applied to the two variables: soil permeability and minimum flow time. So, instead of a permeability of 10^{-5} m/s it only appears -5.

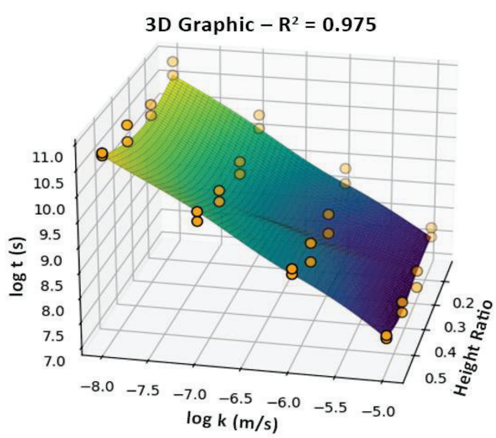

Figure 5. 3D Graphic, with the variables Time (log t (s)), Permeability (log k(m/s)), and Height Ratio.

After creating the 3D graph relating the three variables, a mathematical function that could represent that graph was formulated – equation (1)

$$t = a + b(\frac{H_w}{H}) + c(k) + d\left(\frac{H_w}{H}\right)^2 + e(k)^2 + f(\frac{H_w}{H})(k) \quad (1)$$

where t is the flow time, k is the soil permeability, H_w is the water height, H is the embankment height, and a, b, c, d, e, and f are correlation coefficients. For these later, the following values provided the best adjustment to the data points: a = 3.1639, b = -4.8535, c = -0.9772, d = 6.7779, e = 0.0038, f = -0.0116.

Including the coefficient values in equation (1) the following complete function was obtained, for which a correlation coefficient (R^2) of 0.975 was obtained:

$$t = 3.164 - 4.853(\frac{H_w}{H}) - 0.977(k) + 6.778\left(\frac{H_w}{H}\right)^2 + 0.004(k)^2 - 0{,}012(\frac{H_w}{H})(k) \quad (2)$$

4 CONCLUSIONS

A numerical study was performed to demonstrate the influence of soil permeability, embankment height, and water head on the minimum time for the stabilization of seepage flow. For this purpose, hydromechanical stress-strain numerical analysis were performed in PLAXIS 2D® with Mohr-Coulomb constitutive model. For higher water heads the slope was unstable, but for the other conditions, it was possible to identify the minimum flow time for each case. It was concluded that for a certain soil permeability (k) there is not much variation in the minimum flow time with the height ratio (ratio of water head by embankment height, H_W/H). The paper finishes with a mathematical expression to obtain the minimum flow time depending on the given variables (k and H_W/H).

ACKNOWLEDGEMENTS

This work was financially supported by national funds through the FCT/MCTES (PIDDAC), namely the CONSTRUCT - Instituto de I&D em Estruturas e Construções, Base Funding UIDB/04708/2020 https://doi.org/10.54499/UIDB/04708/2020, the research project INPROVE-2022.02638.PTDC (https://doi.org/10.54499/2022.02638.PTDC), and by scholarship of the last author CEECIND/04583/2017 (https://doi.org/10.54499/CEECIND/04583/2017/CP1399/CT0003).

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