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VOLUME 2

GEOTECHNICAL HAZARDS AND RISKS: EXPERIENCES AND PRACTICES

GEOTECHNISCHE GEFAHREN UND RISIKEN: ERFAHRUNGEN UND PRAXIS

Ernst & Sohn

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5 CONCLUSION

The presented results contribute to the progressive elucidation of the effects of partial saturation on strength and deformability of soils, a phenomenon that constantly puzzles engineers. Namely, in accordance with the standards, strength-deformability properties are tested at saturated conditions that are valid below the filtration line, but are also applied above it: thus, designing is for pessimistic scenario. They will undoubtedly occur in unfavourable conditions, but until then, the tailing dam will function according to parameters in conditions of partial saturation, which can be significantly higher than the standard. Surely, this also requires increased efforts from the employees, and does not exclude the need for traditional tests to carry out the typical analyses.

It can be noted that the parameters tested for different levels of saturation allow for a more realistic modelling of the problems and indicate a solid reserve in the reliability of the tailings dam which will last for most of the duration of exploitation, as described in another paper published in this Proceedings. It is exactly what needs to be applied and used when there is a need for repairs, interventions in the downstream slope etc., where commonly present is also the vegetation which stimulates the partial saturation.

Although the results presented above are in the range of comparative, the experienced also indicates that there is room and need for more precise correlating of results from different laboratory tests which will allow furthering of the knowledge on unsaturated soils, which will also emphasize the need for more precise definition of the parameters of unsaturated soil that sometimes provides for safety, but it can also be a limiting element in analyses and criteria fulfilment. Until then, the experiences described can be used in the design, optimization, or temporary activities of tailings dams in the R. Macedonia. The simple approach and obtained results presented throughout should encourage the engineers to put the unsaturated soil theories to practice, as well as to stimulate further investigations for proposing simple techniques for interpreting the properties of unsaturated soils.

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Impact of unsaturated strength-deformability properties on stress-deformation condition and stability of tailing dams

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Abstract. Tailing dams are large structures whose downstream slope is made from wet fine sand without applying compaction energy. They are always designed with parameters determined in saturated condition, but since the draining reduces the saturation degree, it favourably influences the behaviour of the dam. Having in mind the dedicated laboratory tests conducted in unsaturated condition, those determined strength and deformability parameters were applied in numerical analysis for the calculation of stress and strain condition and the stability of tailing dam. The results of these calculations are commented below since they contribute to the clarification of the role and influence of partial saturation on the slope stability and deformability of tailing sand.

Keywords: Tailing dam, unsaturated condition, stress-strain analyses, slope stability

1 INTRODUCTION

Tailing dams are objects of capital importance where the downstream slope is made of fine sand in wet condition without compaction. The draining reduces the saturation degree, which favourably influences the behaviour of the dam. However, these aspects are routinely calculated in saturated condition, so there always remains the dilemma of "reserves" and arises the interest to study the properties of tailing sand in different conditions of saturation and their further application. Such dedicated tests for determination of shearing strength and deformability parameters under different saturation degree and in large load span were carried out during 2016 in two laboratories at the University "Ss. Cyril and Methodius" (these are described in other paper submitted for publication at this conference), and applied in numerical analyses for calculation of stress-strain condition and stability. In light of such defined characteristics, it is possible to execute optimization of the tailing dams, thanks to numerical modelling where it is possible to apply these laboratory parameters.

2 SLOPE STABILITY OF UNSATURATED SOIL

The analysis of natural or artificial slopes determines the safety factor. This requires the use of some of the numerous limit equilibrium methods with which two-dimensional stability calculations are carried out. When analyses are performed in saturated soil, the calculations use effective parameters of shear strength, while the increase in shear strength that results from the existence of negative pore pressure above the water level is usually overlooked. This is due to difficulties in measuring the values of negative pore pressure and its introduction in the stability calculation. However, if the groundwater level is at a greater depth or if shallow sliding surfaces are involved, the stability calculations should also include the impact of negative pore pressure when shear strength parameters for effective stress are to be determined, as well as the total cohesion c. In order to determine the total cohesion it is necessary to determine the magnitude of the angle φ^b and the magnitude of the matric suction on site. The introduction of matric suction and its contribution to the increase in strength is shown in the expressions of the general limit equilibrium methods suggested by Fredlund et al. (1981).

3 NUMERICAL ANALYSIS OF SLOPE STABILITY

The elements described above are applied to an active tailing dam using results from dedicated laboratory tests given in the literature (Jovanov 2017). The objective is to control the stability of the downstream slope of the tailing dam including changes in the degree of saturation along the depth of the cross-section. Since the tailing dam is monitored regularly by a network of piezometers and inclinometers, the position of the first flow line is known, and between it and the downstream slope of the tailing dam two more lines are interpolated arbitrarily, thus forming domains in which physical-mechanical parameters can be added in function of the degree of saturation.

By zoning the cross-section of the tailing dam, the stability analysis is carried out in three variants:

1. With saturation of 100% of the whole cross-section (effective parameters of shear strength).
2. By varying of the degree of saturation in the zones from the top to down (25/50/75/100%).
3. By including the impact of the matric suction, which has a maximum value of 180 kPa at the surface of the downstream slope, while with the increase in the degree of saturation up to the first flow line, where the matric suction would be 0 kPa (linear distribution is assumed).

In the analyses, the impact of the matric suction is taken into account with the total cohesion. This means that for the manner of zoning of the cross-section given in the third variant, for the domains above the flow line, the total cohesion for each domain is calculated and entered into the input parameters. The analyses are carried out in SLIDE and PLAXIS softwares.

3.1 Limit equilibrium method

The results obtained from the direct shear tests are applied in SLIDE, in which general limit equilibrium method is selected and where, in the first case, the shear strength parameters are entered directly, as interpreted from linear failure envelope and as given in the table below for each of the variants, while in the second case the coordinates of the failure envelope are entered, thus simulating the non-linear behaviour.

Table 3.1 Input data for variant 1

	Model	γ [kN/m³]	c[kPa]	φ [°]
Zone 1	Mohr-Coulomb	22.00	1.0	37
Zone 2	Mohr-Coulomb	20.00	5.0	15
Zone 3	Mohr-Coulomb	19.18	11.0	30

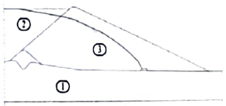
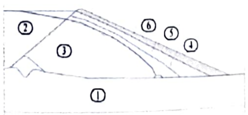


Table 3.2 Input data for variant 2

	Model	γ [kN/m³]	c[kPa]	φ [°]
Zone 1	Mohr-Coulomb	22.00	1.0	37
Zone 2	Mohr-Coulomb	20.00	5.0	15
Zone 3	Mohr-Coulomb	19.18	11.0	30
Zone 4	Mohr-Coulomb	18.90	22.8	32.1
Zone 5	Mohr-Coulomb	17.71	13.0	31.6
Zone 6	Mohr-Coulomb	16.92	17.5	31.3



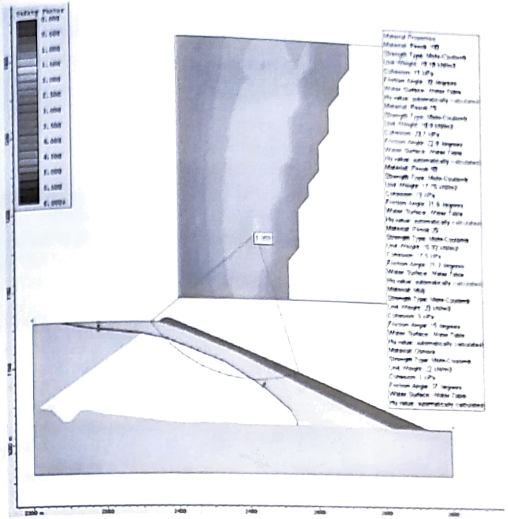


Figure 3.1. Shear surface with the lowest safety coefficient $F_S = 1.969$ (Variant 2, linear failure envelope)

Although the matric suction is taken with a linear distribution along the depth, the calculations are carried out with its mean value in the specified zone. Furthermore, first the total cohesion for each layer is determined, for which the following expression is used:

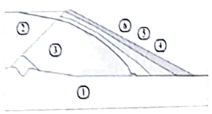
$$c = c' + (u_a - u_w) tg\varphi^b$$

Table 3.3 Calculated total cohesion for a specified matric suction

	Zone 4	Zone 5	Zone 6
Matric suction [kPa]	45	112.5	157.5
Total cohesion [kPa]	15.40	16.30	16.52

Table 3.4 Input data for variant 3

	Model	γ [kN/m³]	c[kPa]	φ [°]
Zone 1	Mohr-Coulomb	22.00	1.0	37
Zone 2	Mohr-Coulomb	20.00	5.0	15
Zone 3	Mohr-Coulomb	19.18	11.0	30
Zone 4	Mohr-Coulomb	19.18	15.40	30
Zone 5	Mohr-Coulomb	19.18	16.30	30
Zone 6	Mohr-Coulomb	19.18	16.52	30



The slope failure safety coefficients are given in Table 3.5.

Table 3.5 Slope failure safety coefficients obtained for the analyzed three variants

Cross-section analysis	Variant 1	Variant 2	Variant 3
Linear envelope used	1.937	1.969	2.015
Nonlinear envelope used	1.941	2.042	2.047

As can be seen, in the particular analyzed case of an inclination of a downstream slope and type of tailing sand, there is no significant difference between the obtained slope stability safety coefficients when linear or nonlinear envelope is used under conditions of total saturation of the profile. However, these coefficients are lower than the ones calculated with the profile in which materials zoned according to different levels of saturation are applied. These numerical analyses also show other differences, more deeply elaborated in Jovanov et al. (2017). One of them depends on whether shear strength parameters determined by linear or nonlinear failure envelope or parameters of matric suction are applied. As can be expected, the use of nonlinear envelope and matric suction parameters results in an objective increase in safety, as well as notably deeper critical slide surface that is connected to the level of first flow line i.e. material with a saturation of 100%!

3.2 Finite elements method

In the analysis using the PLAXIS software, two material models were used: the Mohr-Coulomb model (MC), and the Hardening Soil model (HS), by means of phi/c reduction. In addition, when defining the input parameters, it is necessary to predict the thickness of the considered zone, whose layers above the first flow line are approximately 15 m thick.

The output results are presented in the next figure, followed by the tabular overview of obtained slope failure safety coefficients.

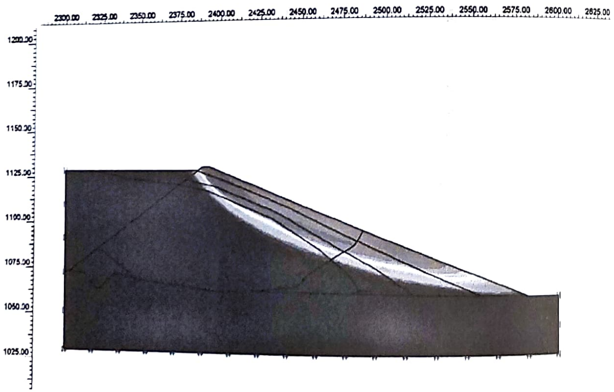


Figure 3.2. Shear surface with lowest safety coefficient $\sum M_{sf} = 1.805$ (variant 1, MS model)

Table 3.4 Slope failure safety coefficients obtained for the three variants of analysis

Model	Variant 1	Variant 2	Variant 3
Mohr - Coulomb	1.805	1.830	1.858
Hardening Soil model	1.813	1.838	1.860

As can be observed, in the particular analyzed case there is no significant difference between the obtained slope stability safety coefficients in the three considered variants. However, it is noticeable that the coefficients under conditions of total saturation are lower than those calculated with the profile in which materials zoned according to different level of saturation are applied or than the third variant, in which matric suction is involved. It can also be seen that by using the Hardening Soil model close but higher values are obtained than the ones where the Mohr-Coulomb model is used. The small difference is probably due to the input data and the supposition that the described dependencies of the rigidities hold for this type of soil as well. Other calculations (Jovanov, 2017) indicate that the values of safety coefficients obtained with residual parameters of shear strength follow the same trend as the values obtained by peak parameters.

Apart from stability control, a comparison of the stress-strain condition for all three variants in the cross-sections A-A and B-B is made, where A-A passes through the top (crown) of the tailing dam, whereas B-B is set through the middle of the downstream slope. The use of more advanced models and data points to a more real simulation of the problem considering that the stresses are reduced, with a relatively small difference in the values, but precisely those routinely used in design practice deviate: when the cross-section is considered as completely saturated. In that case the stresses are greater than those calculated by analysis including matric suction for around 5%, which corresponds to previous findings. Undoubtedly, the small difference is due to the fact that, objectively, most of the cross-section is saturated.

Further, the differences between maximum displacements calculated for the three variants are generally higher than 10%, and can even amount to more than 50%! As can be expected, highest displacements are calculated at the variant with saturated cross-section.

4 ANALYSIS OF THE OBTAINED RESULTS

The presented results of the analyses performed in different software based on the limit equilibrium method and the finite element method, albeit different in nature, point to a similarity both from a graphic aspect, as when the critical slide surfaces have a similar shape and depth, and in terms of the amount, because the obtained values and their differences are comparable and close, which confirms the validity of the calculations. However, from all that was presented previously regarding the analyzed material and geometry of the tailing dam, it seems that there is a relatively small difference in the values obtained for safety coefficients between the three variants, and it is notable that the largest difference occurs between the variants in which the cross-section is considered as completely saturated, and the ones that include matric suction in the analysis, in which case it amounts around 5-50% (for slope stability and for displacements, accordingly), for all cases of numerical analyses and shear strength parameters. At the same time it can be noticed that there is practically no difference between the results obtained through zoning of materials with different saturation, i.e. assignment of parameters from a direct shear test and an oedometer test conducted under conditions of partial saturation, and those obtained with the use of matric suction. Additionally, as an absolute amount, the difference between the obtained slope safety factors for the considered modeling variants is around 0.10, which can be crucial, above all in mining projects and analyses, in determining whether a slope or an object is to be classified as stable or not, and especially in situations when remedial measures and an evaluation of their effectiveness are required!

It is also considered that there are several factors on the side of safety i.e. factors that positively contribute to the increase in the difference in the interest of slope stability or stress/deformations during analysis with partial saturation and matric suction, such as certain assumptions made during data input for numerical analysis, as well as the material itself through the granulometric composition, the substantial water permeability, porosity and other material aspects mentioned in the paper. In this context, it should be emphasized that the shear strength parameters determined for different levels of saturation provide a more realistic modeling of the problem, whether with the use of nonlinear failure envelope or with matric suction.

5 CONCLUSION

The results presented contribute to the gradual clarification of the role of partial saturation in the strength and deformability of soils, a phenomenon that constantly puzzles engineers. Namely, in accordance with the standards, strength-deformable characteristics are tested at saturated conditions that are valid below the filtration line, but are also applied above it, and thus the designing of the structures presents a pessimistic scenario. They will undoubtedly occur in certain unfavorable conditions, but until then, the tailing dam will function according to parameters in conditions of partial saturation, which can be significantly higher than the standard. As for the particular sand and geometry of the tailing dam tested, based on a comparison of the absolute amounts of the obtained values, the misconception may arise that the contribution of the parameters obtained in unsaturated conditions is not at the expected high level, but taking into account that for some analyses the difference in the results reaches over 50%, and is usually 5-10%, it is clear that such experiments are also needed. To be sure, this requires increased commitment from the staff, which does not exclude the need for traditional testing in order to carry out the typical analyses. The experiences described above can be used in designing, optimization or temporary activities of the tailings dams in the Republic of Macedonia.

Hence, it can be observed that the use of nonlinear failure envelope, parameters tested at different levels of saturation and matric suction parameters provide a more realistic modeling of the problem and point to a solid reserve in the form of safety of the tailing dam that will remain for most of the exploitation period. Having in mind that the results obtained with partial saturation and matric suction lead do similar findings, in the absence of laboratory data acquired for the "moisture-matric suction" dependence, the approach of zoning of the material and assignment of parameters according to the expected degree of saturation can be used as a solid alternative method in engineering practice of tailing dams design. It is precisely the one to be used in case of remediation, interventions in the downstream slope, and it is also stimulated by the presence of vegetation, that is regularly found at the downstream slopes of tailing dams.

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Comparison of determination of oedometric modulus based on CPT and laboratory testing in case of pleistocene sand layers

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Abstract. The reliability of geotechnical design results is direct implication of input soil parameters. Hence one of the most crucial parts of geotechnical design is to define strength and deformation parameters. According to Eurocode 7, the statistical analysis of the available data is necessary. Unfortunately, in many cases there is no possibility to fulfill the analysis due to the low number of measurements. In case of major projects there are numerous measurements which provide a sufficient set of data to determine characteristic values based on statistical methods. Oedometric modulus as a deformation parameter has a role in estimation of settlements. Based on oedometer tests the oedometric modulus of deformation can be calculated as a secant modulus linked to a certain stress interval selected on the stress-strain diagram. There are also several recommendations to derive E_{oed} from CPT tip resistance values. The comparison and evaluation of these different methods are described in the paper. Based on the results a best-fit curve is offerred in case of Pleistocene sand layers.

Keywords: Oedometric modulus; CPT; Tip resistance; Coefficient of variation; Correlation

1 INTRODUCTION

The mechanical behaviour of soils can be modelled at various degrees of accuracy (Brinkgreve, 2005). From the simplest isotropic, linear elastic models to the latest, more sophisticated ones there is a wide range of choice. The model's degree of accuracy depends on the scale of the project and on the amount of field investigations and laboratory testing from which the sufficient parameters can be derived. Settlement calculation methods use different stiffness moduli of soils which can be obtained primarily from laboratory testing. Cone penetration test (CPT) data also can be used to estimate modulus in soils for subsequent use in elastic or semi-empirical settlement prediction methods. However, correlations between tip resistance and different stiffness moduli (E) are sensitive to stress and strain history, aging and soil mineralogy (Robertson 2015). The comparison and evaluation of these different methods (oedometer tests and estimation based on CPT) are described in the paper.

1.1 Test area, soil samples and in-situ testing

The set of data analysed in current work is ensured by a major project in South-Central Hungary (Geotechnical Report 2016). Numerous in-situ and laboratory tests were carried out in order to get a comprehensive view about the subsoil conditions. Present research focuses on the relation between CPT tip resistance (q_c) and oedometric modulus (E_{oed}) values.
Therefore 25 field investigation points were chosen where both boreholes (with oedometer tests) and CPT data are available. The average distance between the test spots is approximately 100m and the total exploration area is 100 hectares. The typical soil layers with the average layer thicknesses are landfill (5.2m), organic topsoil (0.7m), grey clay (0.9m), eolian sand (5.0m), fluvial sand (5.4m), gravel terrace (10.0m) and then Pannonian layers. The two sand layers are involved in current research work and described in 2.1 section in details. The boreholes and CPTu measurements were carried out in 2015.