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RELATIONSHIP BETWEEN SOIL PHYSICAL-MECHANICAL PARAMETERS AND EARTH DAM SLOPE STABILITY USING STOCHASTIC AND NUMERICAL MODELING

RELAÇÃO ENTRE PARÂMETROS FÍSICO-MECÂNICOS DO SOLO E A ESTABILIDADE DE TALUDES DE BARRAGENS DE TERRA COM EMPREGO DE MODELAGEM ESTOCÁSTICA E NUMÉRICA

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RESUMO - O objetivo desta pesquisa é obter uma relação matemática para estimar o fator de segurança inicial em barragens de terra, com base em um modelo de regressão linear. Para ampliar a amostra inicial que inclui as propriedades físico-mecânicas dos solos existentes em aterros de barragens de terra construídas, é necessária a aplicação do método de Monte Carlo. Com base na modelagem numérica, a variação do fator de segurança em uma barragem de 30 metros de altura é analisada pelo método Morgenstern-Price, considerando fluxo de água estacionário e incluindo solo não saturado na análise. É realizado um modelo numérico híbrido, que combina o Método dos Elementos Finitos para análise da filtração e o Método do Equilíbrio Limite para obtenção do fator de segurança. Dentre os resultados da modelagem numérica e do projeto experimental proposto, observa-se que a coesão é a variável mecânica predominante no comportamento de estabilidade de taludes de barragens com aterro homogêneo. São propostos ábacos para estimar o fator de segurança inicial no estado insaturado através da fixação do peso específico, para diversos valores de coesão e ângulo de atrito interno; e é estabelecida uma relação matemática para estimar o fator de segurança, que possui coeficiente de determinação igual a 95%.

Palavras-chave. Estabilidade de taludes. Solo não saturado, Modelagem estocástica. Fator de segurança. Regressão linear.

ABSTRACT - The main goal of this research is to obtain a mathematical relationship to estimate the initial safety factor in earthen dams, based on a linear regression model. To expand the initial sample that includes the physical-mechanical properties of existing soils in embankments of built earthen dams, it is necessary to apply the Monte Carlo method. Based on numerical modeling, the variation of the safety factor in a 30-meter-high dam is analyzed using the Morgenstern-Price method, considering steady water flow and including unsaturated soil in the analysis. A hybrid numerical model is carried out, which combines the Finite Element Method for the analysis of the filtration and the Limit Equilibrium Method to obtain the safety factor. Among the results of the numerical modeling and the proposed experimental design, it is observed that cohesion is the predominant mechanical variable in the behavior of slope stability of dams with homogeneous embankment. Abacuses are proposed to estimate the initial safety factor in the unsaturated state, fixing the specific weight, for various values of cohesion and angle of internal friction; and a mathematical relationship is established to estimate the safety factor, which presents a coefficient of determination equal to 95%.

Keywords: Slope stability. Unsaturated soil. Stochastic modeling. Factor of safety. Linear regression.

INTRODUCTION

Slope landslide is the movement of instability that involves the mobility of a considerable amount of material, mainly due to a shear failure through one or more surfaces. Slope stability is described in terms of a factor of safety (FoS), which can be obtained from a certain mathematical analysis (Konig et al., 2022).

The deterministic design method commonly used in geotechnical engineering is characterized by having a large uncertainty of the variables considered. Soil properties vary from one location to another and can also change over time, so the information obtained for one location does not guarantee that this behavior will be extend to the rest of the analyzed area (Fernández et al., 2018).

Earth dams are engineering works built primarily to regulate floods, store and distribute water reserves. The soils that make up the curtains of these structures are subjected to various construction processes to achieve adequate compaction. To relate the suction and the equilibrium humidity present in the compacted soils that make up the curtains of the earthen dams, the characteristic curve is obtained.

There are several procedures to determine the characteristic curve of soils in the laboratory, which are divided into direct and indirect depending on the equipment used, as well as the suction measurement interval and the moisture content present (Tristá, 2015). In the construction of the curtains of earthen dams, clayey soils with high fines contents are mainly used, which present high suction values. On the other hand, data such as the granulometry of the material and the volumetric and gravimetric relationships are essential to determine the characteristic curve of a soil, although the reliability of each procedure depends on the quality and quantity of the data used (Arya & Heitman, 2015; Torres, 2011).

In the present investigation, the method of Aubertin et al. (2003), which is based on the modification of the method proposed by Kovács (1981), expanded to include clayey soils in the analysis.

This method is implemented in GeoSlope (2021), and it is the only one available in the program, which depends on the parameters of the granulometric curve of the soils to obtain their volumetric water content and suction. Additionally, it has been used by several authors, obtaining good results in all cases (Essayad & Aubertin, 2021; Lanoix, Pabst, & Aubertin, 2020; Wu et al., 2017, 2020).

In recent years, investigations related to slope stability have been supported by computational modeling and its solution through various methods. Based on the approaches of Fredlund & Fredlund (2019), and as computational development has allowed, new search routines have been developed that attempt to directly determine the shape and location of the critical slip surface.

To review, under new conditions, the stability of the slopes in built earth dams, it is necessary to obtain a statistically valid sample of representative geotechnical parameters of the soils that make up the curtains of these structures. For all these reasons, stochastic modeling is used to expand the original sample and use these results in the elaboration of numerical models.

The generation of random variables is used in situations in which it is required to know the stochastic behavior of a system through computational simulation. The objective of stochastic generation is to obtain a sample of a variable, whose empirical density function adjusts, as closely as possible, to that given as a probabilistic model of it. To establish a comparison framework, based on the consulted bibliography, it is considered that the geotechnical variables follow normal and log-normal probability density functions (Azevedo et al., 2018; Hernández, 2016; Martínez, 2010; Army Corps of Engineers, 2006). For this, it is necessary to generate many values, to guarantee the stability of the system, which is uneconomical and with a high execution time, for all this, the generations are limited with a given level of uncertainty (Hernández, 2016; Martínez, 2010).

Then, it is necessary to carry out a Simple Random Sampling (SRS) to reduce the size of the resulting population to a smaller sample, since the economic aspect and time restrict any investigation, for which it is required that the samples be as small as possible, also trying to ensure that they are representative of the study population. The SRS is the assignment of the same probability to each unit of the population of being selected to integrate the sample. The larger the size of the sample that is selected in the SRS, the greater efficiencies the subsequent estimates will have.

The importance of incorporating all these elements in the same investigation lies in the possibility of generalizing the results obtained from the extensive statistical study of the geotechnical variables involved in slope stability problems. Obtaining the characteristic curve of the soils from mathematical methods facilitates their incorporation into the review of geotechnical problems where, despite their importance, they are not considered due to the implicit difficulties of obtaining the results of real suction values in the laboratory, associated with economic and time limitations.

MATERIALS AND METHODS

In this investigation, a homogeneous earth dam with a curtain height of 30 meters is considered, with a drainage prism and an impermeable base in a state of operation; whose geometry is shown in figure 1.

The drainage prism is considered a gravel-like material with high permeability with saturated behavior. The waterproof foundation is fixed with non-deformable characteristics for slope stability analysis, since it is not of interest to study its behavior or its influence on the slope factor of safety. However, for the modeling of stationary filtration, parameters are established that, like those of the prism, are shown in table 1.

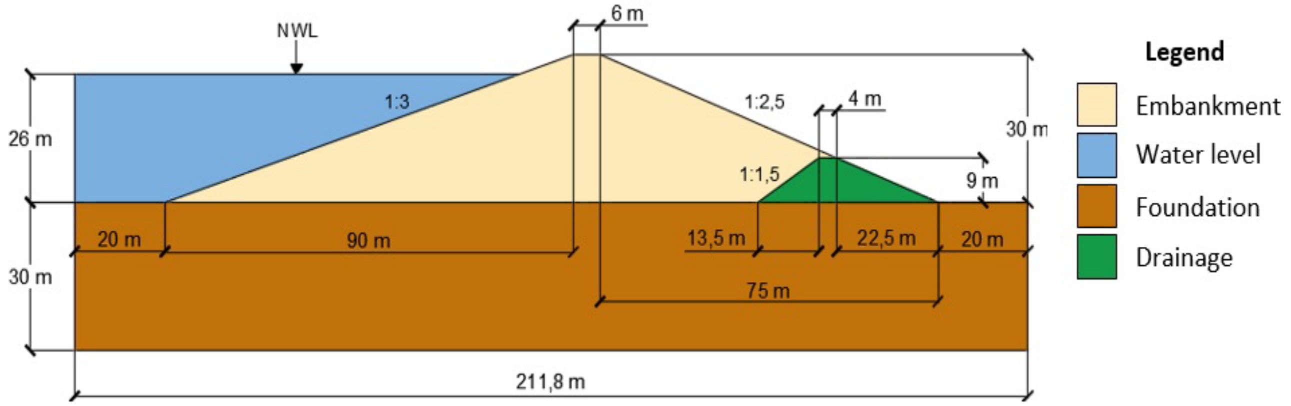

Figure 1 - Dam model 30 meters high.

Table 1 - Geotechnical parameters of the drainage prism and the foundation.

Geotechnical Parameter	Drainage	Foundation
Saturated specific gravity γ_{sat} (kN/m^3)	21	-
Effective internal friction angle φ' (°)	40	-
Effective cohesion c' (kPa)	0	-
Saturated horizontal permeability k_x (m/s)	1,00E-4	1,00E-12
Anisotropy ratio k_y/k_x (dimensionless)	1	1
Volumetric compressibility index m_v (kPa^{-1})	1,00E-5	1,00E-5

To define the soils to be used in the modeling of the dam, a series of engineering-geological reports of built dams and similar typology are compiled, after which, the statistical summary of the data is carried out (Table 2), as a first step to obtain a statistically valid sample of the geotechnical parameters necessary for modeling, which allows the subsequent generalization of the results obtained.

Table 2 includes measures of central tendency, variability, and shape. From their analysis, the variables: modulus of elasticity, specific weight, permeability and percentage of clay, show values of bias and kurtosis outside the expected range (from -2 to 2); therefore, they do not present a normal distribution established from a geometric criterion, so it is necessary to apply other analyzes to the samples.

Table 2(a) - Statistical summary of the populations.

	Modulus of elasticity	Specific weight	Void ratio	Cohesion	Friction angle
Count	18	22	20	20	20
Average	20535,7	18,2	0,885	28,7	17,1
Standard deviation	24052,4	1,4	0,19	13,3	4,6
Coefficient of variation	117,1%	8,1%	22,0%	46,5%	26,6%
Standard error	5669,2	0,3	0,05	2,9	1,0
Standardized bias	6,7	-3,7	0,25	0,8	1,7
Standardized Kurtosis	13,6	5,7	0,15	-0,3	1,0

Table 2(b) - Statistical summary of the populations.

	Permeability	Liquid limit	Plastic limit	% Sand	% Silt	% Clay
Count	19	20	20	19	19	19
Average	3,68E-07	49,6	26,5	34,1	27,7	28,4
Standard deviation	6,32E-07	10,9	6,4	14,1	9,3	12,9
Coefficient of variation	171,9%	22,1%	23,9%	41,2%	33,6%	45,4%
Standard error	1,45E-07	2,4	1,4	3,2	2,1	2,9
Standardized bias	4,0	0,7	0,6	-0,06	-0,4	2,2
Standardized Kurtosis	4,2	-0,7	1,6	-0,2	-0,3	1,3

In order to regularize the data by eliminating the values that are not significant and that produce behavior outside the normal range in the statistical analysis, a statistical cleaning criterion is used (Hernández, 2016; Martínez, 2010). Figure 2 shows the graphs of aberrant values obtained for the variables: modulus of elasticity, specific weight, permeability and percentage of clay.

Figure 2 shows each value of the data together with horizontal lines that represent the relationships between the sample mean and the standard deviation, it is observed that there are extreme points, more than twice the interquartile range away, in the data set. Based on these results, the aberrant data in each case are manually eliminated, obtaining a new statistical summary, shown in table 3.

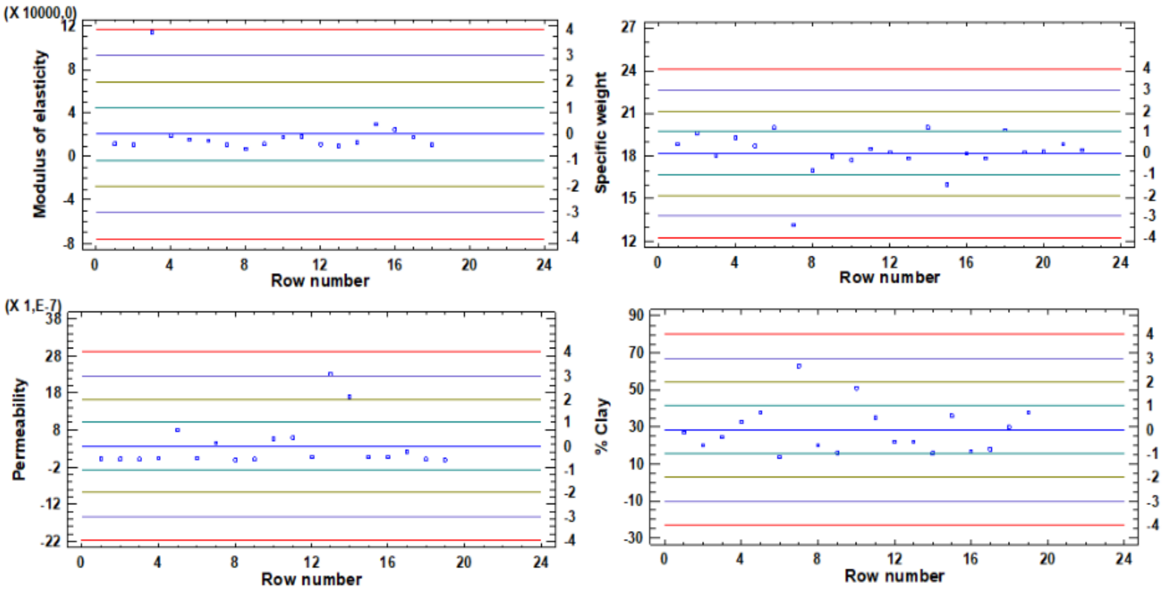

Figure 2 - Graph of aberrations obtained for the variables: modulus of elasticity, specific weight, permeability and percentage of clay.

Table 3 - Statistical summary of the clean populations.

	Modulus of elasticity	**Specific weight**	**% Clay**	**Permeability**
Count	16	20	18	10
Average	14123,4	18,5	26,5	5,64E-07
Standard deviation	4590,8	0,8	10,1	8,17E-07
Coefficient of variation	32,5%	4,4%	38,2%	144,7%
Standard error	1147,7	0,2	2,4	2,58E-07
Standardized bias	1,3	0,6	1,4	1,9
Standardized Kurtosis	0,37	-0,32	0,13	0,7

Table 3 shows that there are significant differences in the mean, standard deviation and coefficient of variation with respect to those obtained in table 2; those that were reduced against to the initial data from the elimination of the distant values of the sample mean. As a consequence, a new range of values was obtained whose bias and kurtosis results are in the expected range (-2 to 2). For the remaining variables: cohesion, friction, liquid limit, plastic limit, percentage of sand and percentage of silt, no aberrant values were found in the analysis.

It is necessary to verify the uniformity of the existing initial population, once it has been cleaned of aberrant data.

To do this, each of the variables will be associated, as appropriate, to a certain probability distribution. The distributions were tested: Gamma, Weibull, Normal and Log-normal (Figure 3); to verify which was the one that best adjusted to the initial populations, performing two goodness-of-fit tests: Kolmogorov-Smirnov and Chi-square, to define if a certain probability function adequately adjusts to the experimental data, the P-Value is evaluated in each case (Table 4).

From figure 3 and table 4, it was obtained that all the variables analyzed in this case were adjusted to the Gamma and Log-normal distributions with 95% confidence. However, for the Weibull distribution, the variables modulus of elasticity, specific weight and friction angle presented P-values lower than 0,05 and for the Normal distribution, the permeability variable presented a P-value lower than the limit. Based on these analyzes and the criteria proposed in the consulted bibliography, the Normal distribution was selected to characterize the variables: modulus of elasticity, specific weight, void ratio, liquid limit, plastic limit, percentage of sand, percentage of silt and percent clay. Meanwhile, for the variables: cohesion, friction angle and permeability, a Log-normal distribution was selected.

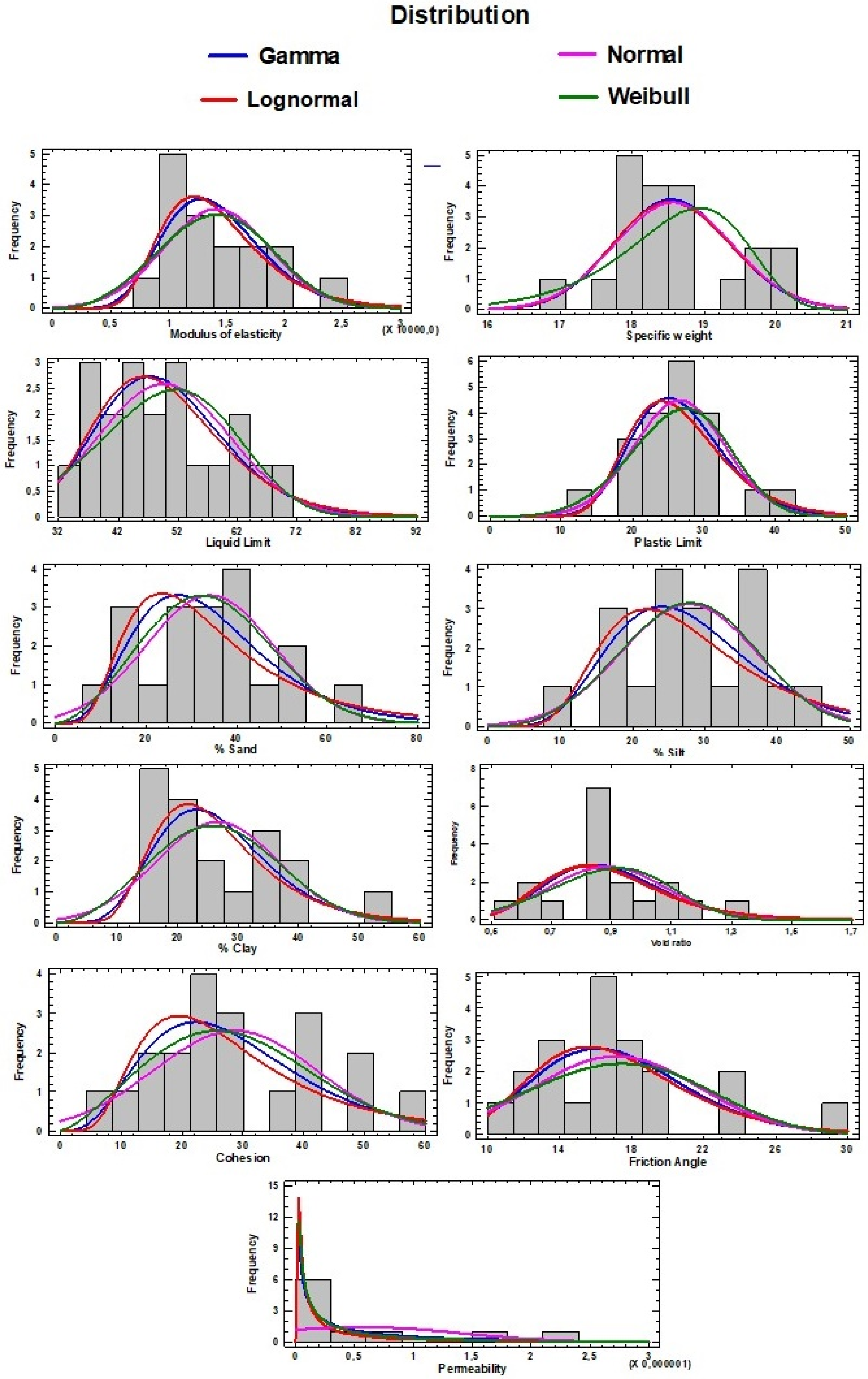

Figure 3 - Probability distributions evaluated for all variables.

Table 4 - P-values obtained for all variables.

Variable	Method	Gamma	Log-normal	Normal	Weibull
Modulus of elasticity	Chi-Square (P-Value)	0,09	0,57	0,12	0,02
	K-S (P-Value)	0,72	0,84	0,62	0,70
Specific weight	Chi-Square (P-Value)	0,45	0,15	0,15	0,04
	K-S (P-Value)	0,94	0,94	0,90	0,55
Void ratio	Chi-Square (P-Value)	0,04	0,04	0,02	0,01
	K-S (P-Value)	0,67	0,55	0,83	0,80
Liquid limit	Chi-Square (P-Value)	0,45	0,72	0,45	0,64
	K-S (P-Value)	0,98	0,99	0,95	0,84
Plastic limit	Chi-Square (P-Value)	0,10	0,13	0,18	0,13
	K-S (P-Value)	0,53	0,40	0,44	0,33
% Sand	Chi-Square (P-Value)	0,43	0,43	0,54	0,43
	K-S (P-Value)	0,87	0,68	0,99	0,98
% Silt	Chi-Square (P-Value)	0,33	0,33	0,54	0,54
	K-S (P-Value)	0,93	0,84	0,94	0,92
% Clay	Chi-Square (P-Value)	0,57	0,57	0,20	0,88
	K-S (P-Value)	0,81	0,93	0,65	0,75
Cohesion	Chi-Square (P-Value)	0,43	0,26	0,33	0,43
	K-S (P-Value)	0,99	0,99	0,89	0,98
Friction angle	Chi-Square (P-Value)	0,10	0,49	0,10	0,03
	K-S (P-Value)	0,83	0,86	0,56	0,50
Permeability	Chi-Square (P-Value)	0,61	0,22	0,004	0,37
	K-S (P-Value)	0,76	0,95	0,50	0,85

Then, random variables are generated in all cases, applying the Monte Carlo method. In order to obtain a sample size for each of the variables, which guarantees the stability of the system, the stopping criterion shown in figure 4 is selected, in this case, corresponding to the variable modulus of elasticity.

As can be seen in figure 4, as the sample size increases, the descriptive statistics become similar to those initially estimated. This study was carried out for all the variables, obtaining similar behaviors in each case analyzed.

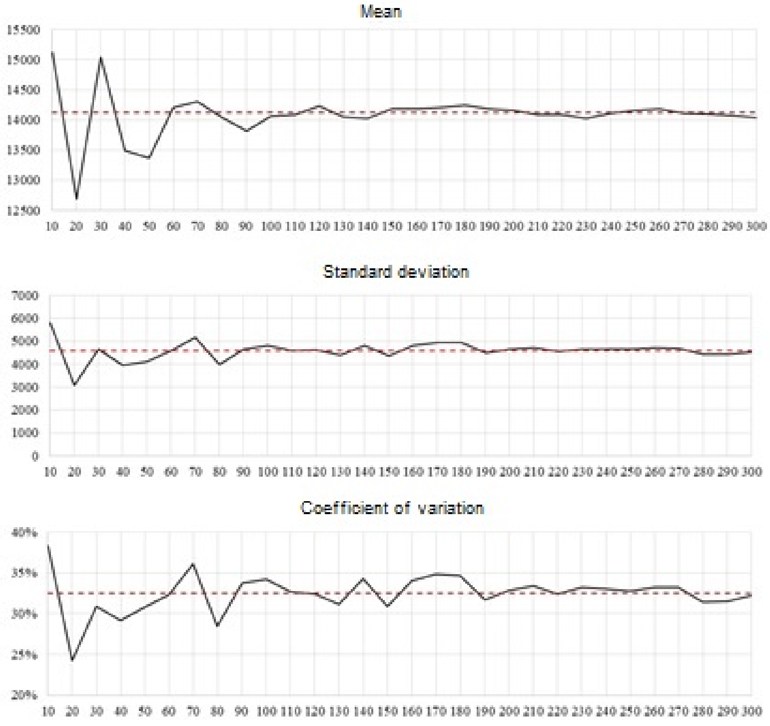

Figure 4 - Behavior of the measures of central tendency of the variable modulus of elasticity when increasing the sample size.

In order to minimize the size of the generated samples, a convergence error with the assumed values equal to 5% is allowed (Hidalgo & Pacheco, 2011). Since each variable was studied individually, the convergence results obtained differ between them. However, the properties of the soils are not independent of each other, on the contrary, there is a relationship between each of them associated with the type of soil analyzed. The summary of these results is shown in figure 5.

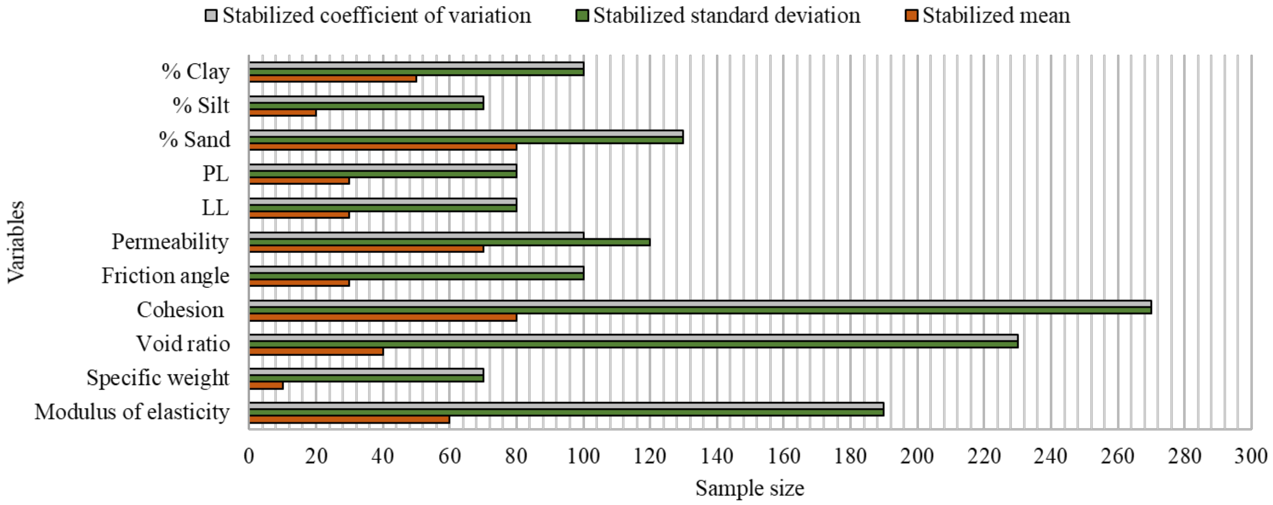

Figure 5 - Summary of stabilization of sample sizes.

As can be seen in figure 5, all the variables do not stabilize for the same values of the central tendency parameters, therefore, the final sample size has been selected equal to 300, greater than the largest number of samples obtained, which for the current data set it would be the cohesion, which stabilizes for 270 values. At this point, it is necessary to check the randomness of the data, from a Run Test, which verifies whether the order of appearance of two values of a variable is random. The results obtained corresponding to this analysis are shown in figure 6.

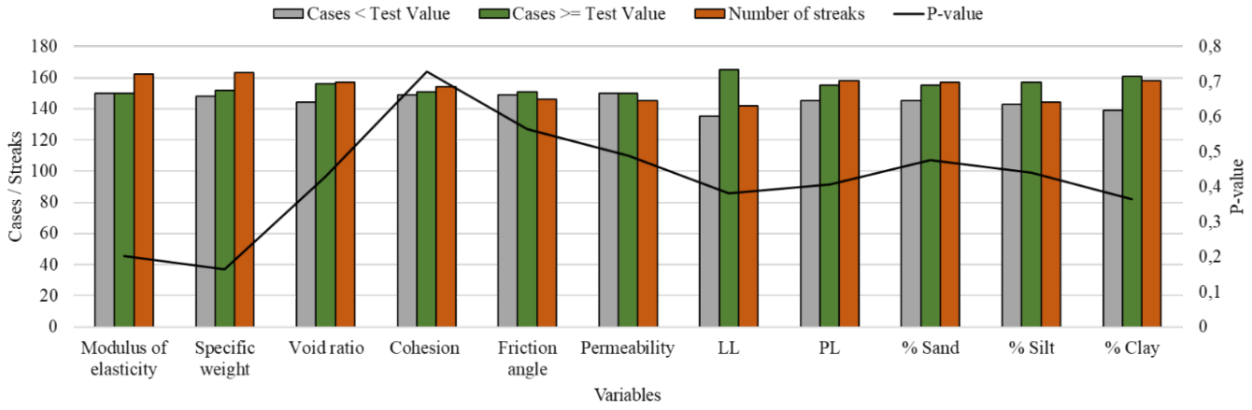

Figure 6 - Results of the runs test considering values above and below the mean.

The results shown in figure 7 show that the lowest P-value resulting from the tests performed is greater than or equal to 0.05 in all cases, therefore, the idea that the samples come from a Normal distribution cannot be rejected. or Log-normal, as appropriate, with 95% confidence. Being the process of generation and computational simulation quite complex for the sample size obtained, it was decided to carry out a resampling of the data generated using the SRS technique, from the implementation of equation 1, which corresponds to the analysis when the size of the original population (Hernández, 2016; Martínez, 2010).

The results of figure 6 indicate that the P-value is greater than 0.05 in all cases, therefore, it can be ensured that the generations are random with a confidence level of 95%. Additionally, it is necessary to verify the uniformity of previously generated random values. To decide if they can be considered as carrying out a simple random sample with normal or log-normal distribution, depending on each case, the normality tests are carried out: Chi-Square, Kolmogorov-Smirnov and Shapiro-Wilk, for a 95 % probability. The results obtained for the variables analyzed are shown in figure 7.

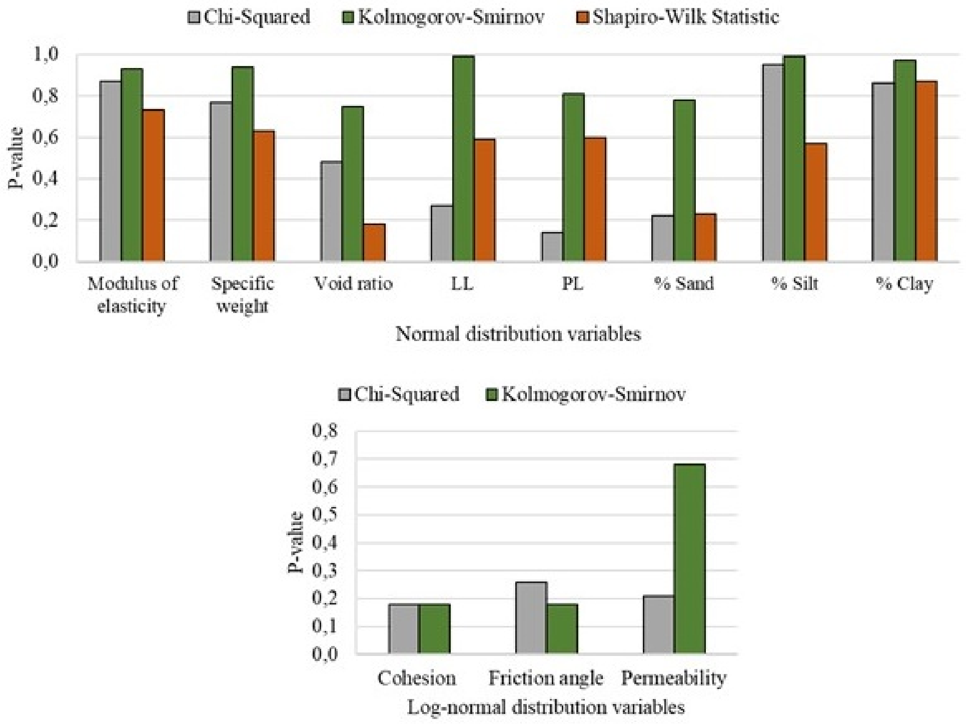

Figure 7 - Results of the P-value obtained for the normality tests performed.

$$n = \frac{Z^2pqN}{NE^2 + Z^2pq} \qquad (1)$$

Where n is the sample size to obtain, Z is the standardized variable of normal distribution, equal to 1,96 for 95% confidence; p is the probability of success, it is considered equal to 0,5; q is the probability of failure, it is considered equal to 0,5; N is the size of the population, 300 for all variables; E is the precision of the study, it is considered equal to 0,15; since the geotechnical properties present a high variation among themselves, even for the same type of soil.

Once equation 1 has been applied, with the previously defined parameters, 40 combinations were obtained, to replace the total maximum defined as the size of the initially generated population.

Then, from the values of the percentage of sand, silt and clay, as well as the percentage of gravel, obtained from the difference between 100% and the sum of the percentages of sand, silt and clay, figure 8 shows show the resulting granulometric curves for the 40 defined soils.

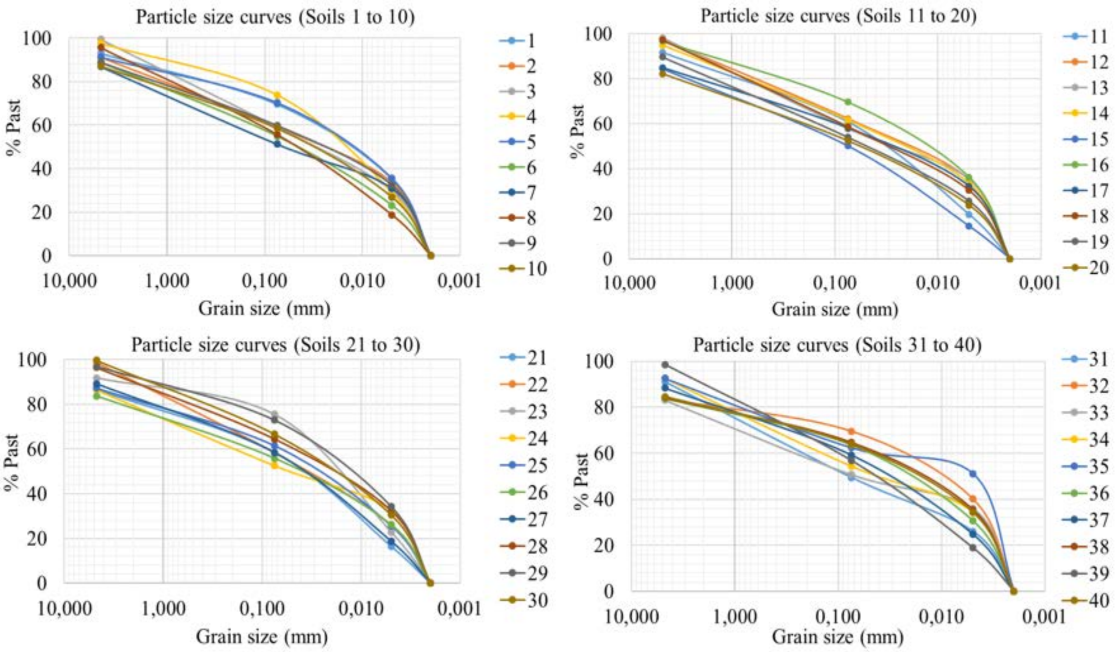

Figure 8 - Granulometric curves of the 40 soils obtained.

Then, table 5 shows the remaining physical-mechanical parameters of the 40 soils resulting from the stochastic modeling, for their subsequent use as materials that will make up the embankment of the investigated earth dam, with the mechanical parameters being cohesion and internal friction effective (corresponding to drained consolidated triaxial tests) since the dam is considered in a state of operation, and there is no component of consolidation of pore pressures.

Table 5 - Physical-mechanical properties of the study soils.

Number	Specific weight (kN/m^3)	Cohesion (kPa)	Friction angle (°)	Permeability (m/s)	Volumetric compressibility index (kPa^{-1})	Liquid limit
1	18,3	30,9	13,5	1,5E-07	5,6E-05	57
2	18,8	56,8	13,4	1,1E-07	1,0E-04	47
3	18,9	18,6	13,2	6,6E-08	5,1E-05	38
4	17,9	29,8	17,6	1,5E-07	9,3E-05	72
5	19,2	42,1	15,4	8,7E-08	7,4E-05	60
6	18,8	32,0	21,3	4,7E-07	6,6E-05	39
7	19,0	22,1	14,3	1,7E-07	6,5E-05	39
8	18,0	43,7	13,2	1,2E-06	8,9E-05	48
9	17,3	40,6	14,9	6,0E-07	1,4E-04	56
10	18,5	57,7	27,1	1,8E-07	6,4E-05	57
11	17,6	18,3	17,4	2,2E-07	6,3E-05	62
12	17,7	18,1	21,2	6,6E-08	9,0E-05	46
13	18,1	22,0	15,0	6,9E-06	9,0E-05	48
14	18,2	25,3	19,0	1,3E-06	7,5E-05	63
15	19,3	42,2	27,3	1,6E-07	1,0E-04	71
16	19,0	37,0	12,6	3,2E-07	9,5E-05	71
17	17,4	17,4	12,8	9,4E-08	7,4E-05	39
18	18,5	34,4	14,6	3,0E-07	1,4E-04	33
19	17,8	25,2	16,1	2,4E-07	6,0E-05	59
20	18,6	32,3	13,8	1,6E-07	6,1E-05	70
21	19,2	22,0	16,6	1,6E-07	4,0E-05	53
22	18,6	39,7	20,1	3,0E-07	1,7E-04	53
23	18,5	17,5	28,3	4,6E-08	8,9E-05	60
24	18,8	17,9	14,1	7,7E-06	1,3E-04	50
25	17,1	23,7	13,2	1,8E-07	9,4E-05	54
26	18,0	31,4	20,2	7,4E-07	8,5E-05	48
27	17,8	36,9	18,1	5,3E-07	5,7E-05	60
28	18,2	33,9	13,1	8,2E-07	5,7E-05	51
29	18,3	22,7	29,5	9,0E-07	8,7E-05	56
30	19,3	67,5	17,7	8,1E-07	6,3E-05	58
31	16,6	28,9	14,8	4,3E-08	7,9E-05	57
32	18,5	13,8	19,8	2,2E-07	1,1E-04	54
33	18,2	66,9	19,8	2,3E-06	1,9E-04	45
34	17,2	30,0	13,8	1,3E-06	8,0E-05	49
35	19,4	24,4	22,7	2,5E-07	1,1E-04	57
36	18,7	23,0	21,7	2,3E-07	4,0E-05	60
37	18,6	31,3	16,3	1,2E-07	9,3E-05	51
38	18,9	26,7	14,6	3,3E-07	7,7E-05	40
39	17,8	23,6	17,2	4,4E-07	7,4E-05	49
40	17,8	19,3	17,7	3,6E-07	8,6E-05	61

To obtain the characteristic curve using the Aubertin method (Aubertin et al., 2003) available in the GeoStudio program (GeoSlope, 2021), the values corresponding to D60 (effective diameter of the particles for 60% past the granulometric curve), D10 (effective diameter of the particles for 10% past the granulometric curve), the liquid limit, the volumetric compressibility index (obtained from the modulus of elasticity of each soil) and the corresponding volumetric water content (CVA). For this last parameter, the relationship established by equation 2 is used, applied considering 100% saturation.

$$CVA = \frac{S \, . \, e}{1 + e} \quad (2)$$

Where e is the void ratio of each soil; S is the degree of saturation, equal to 1 for these cases (100% saturation).

Figure 9 shows the 40 characteristic curves for all the soils obtained using stochastic modeling, which implies the possibility of using mathematical methods, such as the one implemented in the GeoStudio program (GeoSlope, 2021), and reduces the need to carry out expensive and complex laboratory tests. delayed, to include partially saturated soils in the analysis of geotechnical problems.

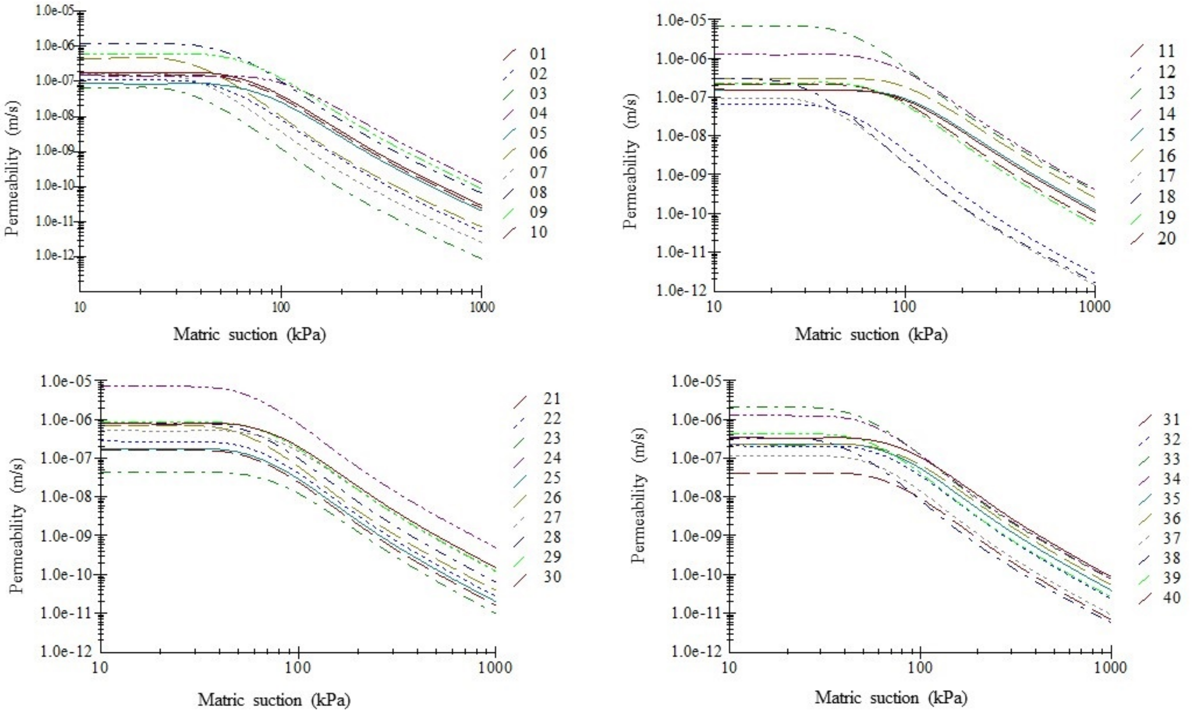

Figure 9 - Characteristic curves of the 40 soils obtained through GeoStudio program (GeoSlope, 2021).

Subsequently, with the use of the characteristic curve generated in each case and the corresponding saturated permeability, the hydraulic conductivity curves for the curtain soils are obtained (Figure 10), by means of the Fredlund et al. (1994) method, also implemented in GeoStudio program (GeoSlope, 2021). For all the soils in the curtain, based on the analysis of the unsaturated stationary seepage, an anisotropy ratio ($\frac{k_y}{k_x}$) of 0,0833 is set (Armas & Horta, 1987; Flores et al., 2020; Haramboure et al., 2021).

RESULTS AND DISCUSSION

Two-dimensional models offer precise results for the analysis of slope stability with simple geometries, such as earth dams. For this reason, in the present investigation the GeoStudio program (GeoSlope, 2021) is used, applying the Morgenstern-Price method to estimate the FoS (Fredlund & Fredlund, 2019). The result corresponding to the pore pressure and the critical failure surface for one of the curtain soils is shown in figure 11.

For each model, a relationship study of the FoS obtained is carried out, with the specific weight, cohesion and friction angle; geotechnical parameters that are used explicitly in the traditional methods of calculating the factor of safety. The results correspond to the numerical modeling of the 30-meter-high dam, with a drainage prism and an impermeable base,

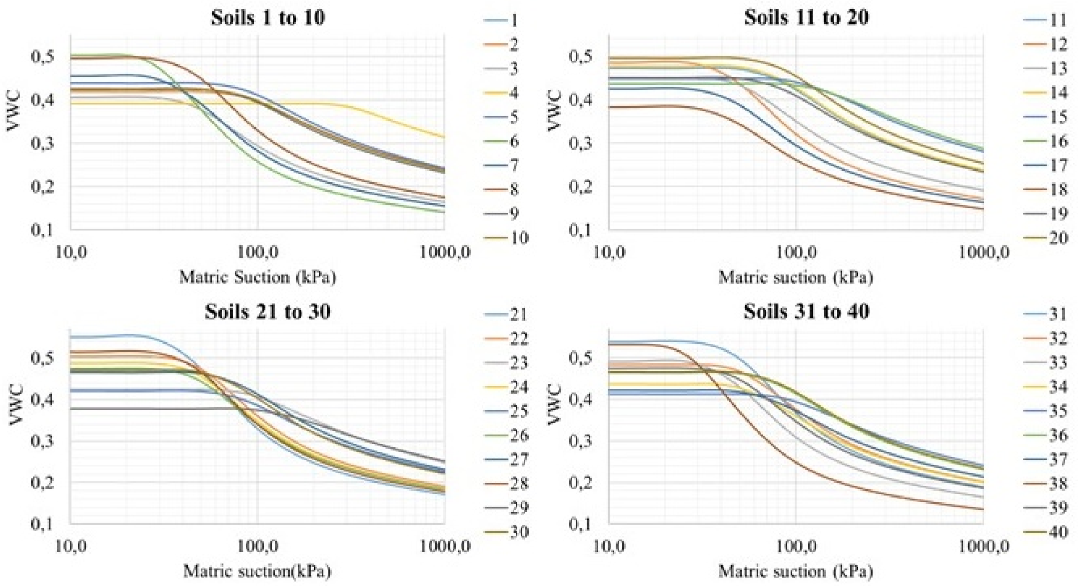

Figure 10 - Hydraulic conductivity curves of the 40 soils obtained through GeoStudio program (GeoSlope, 2021).

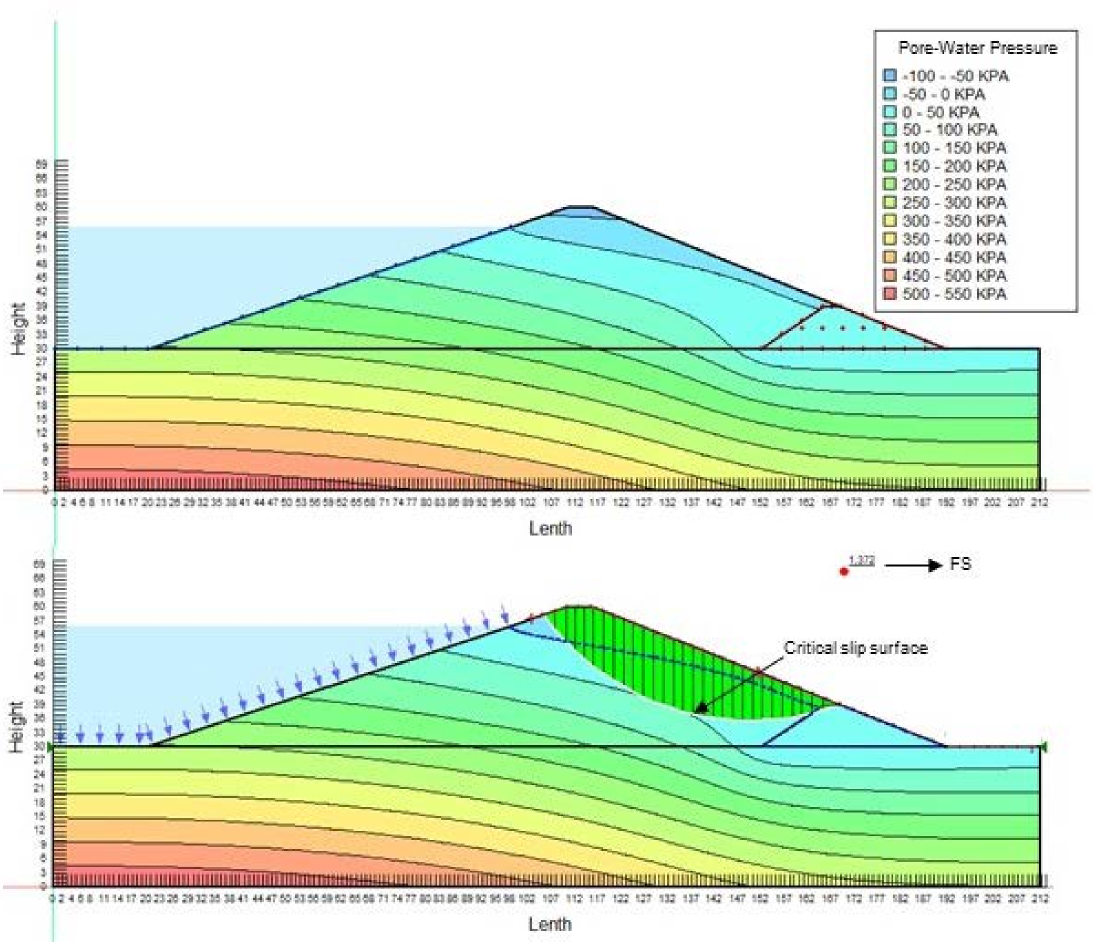

Figure 11 - Numerical model created in GeoStudio program (GeoSlope, 2021).

considering the 40 soils obtained with the use of stochastic modeling in the dam curtain, in a partially saturated state. Figure 12 shows the Pareto diagram corresponding to the results obtained.

Figure 12 shows each of the estimated effects in decreasing order of importance. The vertical line is used to determine which effects are significant. Any bar that extends beyond the vertical line corresponds to a statistically significant effect at the 95% confidence level. The main effects that influence the most are: cohesion (B), the angle of friction (C). As this increase, the value of the FoS increases. The analysis of the normal probability plot for the safety factor is performed, shown in figure 13.

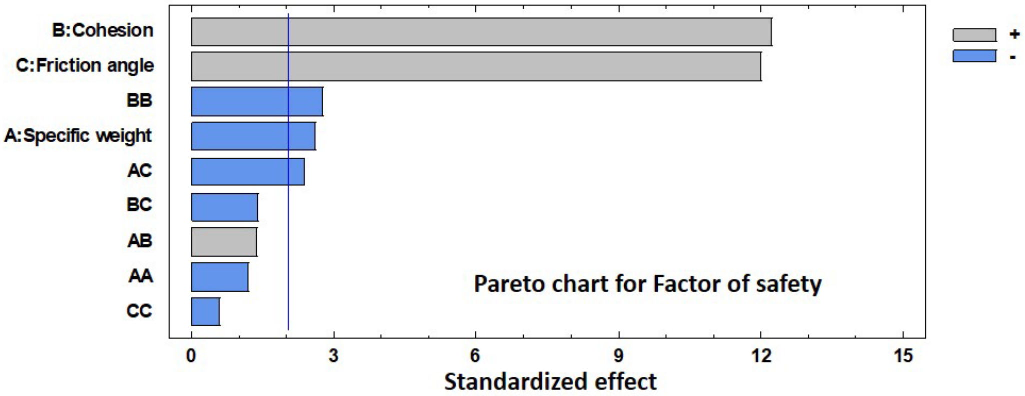

Figure 12 - Pareto diagram for the FoS.

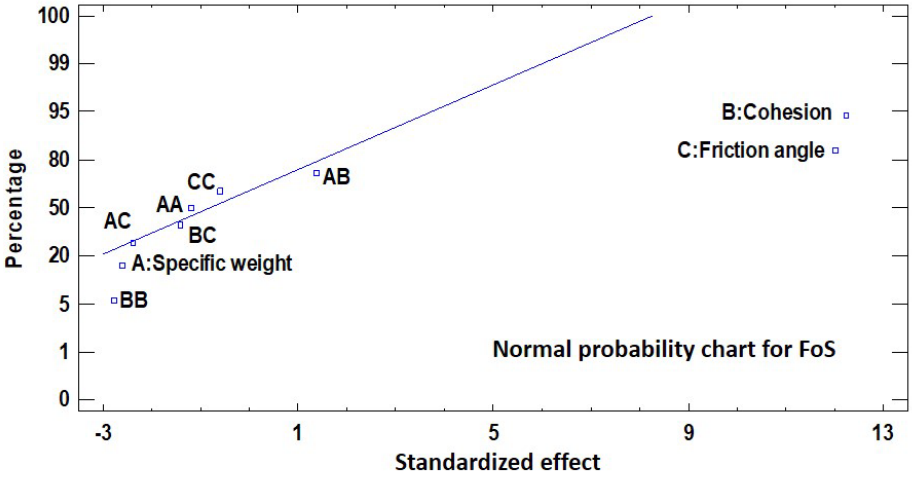

Figure 13 - Normal probability plot for the FoS.

Figure 13 shows all the effects that act on the FoS, of which those that are not real behave as if they came from a normal distribution centered at zero.

This means that they are located close to the straight line, while the real signals will be to the right of the line. It can be seen that the effects with the greatest influence are cohesion and the angle of friction, which corresponds to what is obtained in the Pareto diagram.

Then, to exclude the effects that least influence the analysis, the main effects graph is taken into account, shown in figure 14, from which it can be seen that the main effects are cohesion and friction angle, whose trend is positive, while the specific weight, with less influence, presents a negative trend. From all the results and the excluded effects, the corresponding regression equation is proposed (Equation 3).

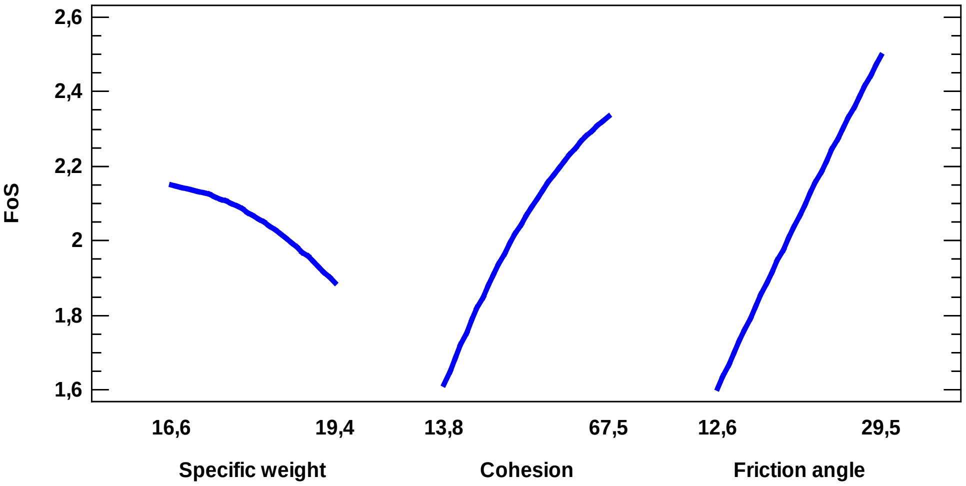

Figure 14 - Main effects plot for the FoS.

$$FoS = 1{,}49835 - 0{,}0626699 * \gamma \ + 0{,}0150395 * c + 0{,}0482634 * \phi \qquad (3)$$

Where FoS is the factor of safety; γ is the specific weight (kN/m^3); c is the cohesion (kPa) and ϕ is the angle of internal friction (°).

The R^2 statistic for this model is 94.9%. Figure 15 shows the estimation of the safety factor as a function of cohesion and friction angle. For this, it is considered that the specific weight will have its minimum, maximum and average values in each case.

Figures 16-18 show the contour graphs for obtaining the safety factor based on the combination of cohesion and friction angle, for the minimum, maximum and average specific weights of the total modeled data.

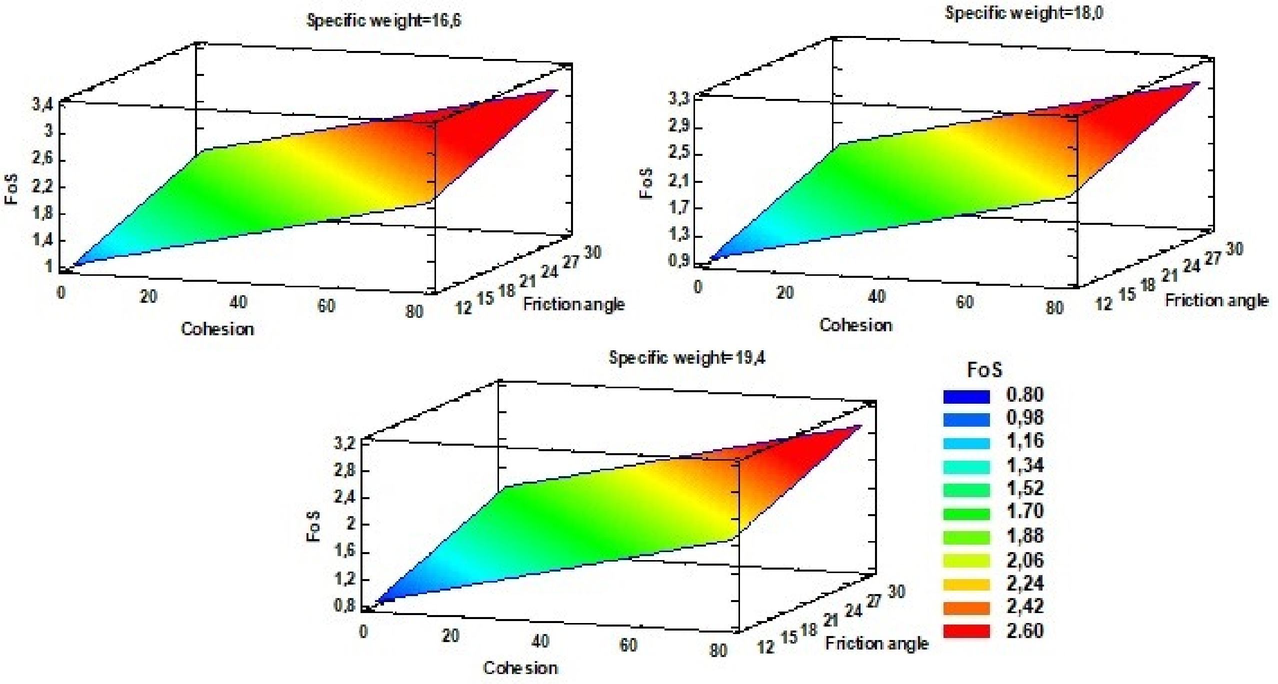

Figure 15 - Response surfaces for the factor of safety.

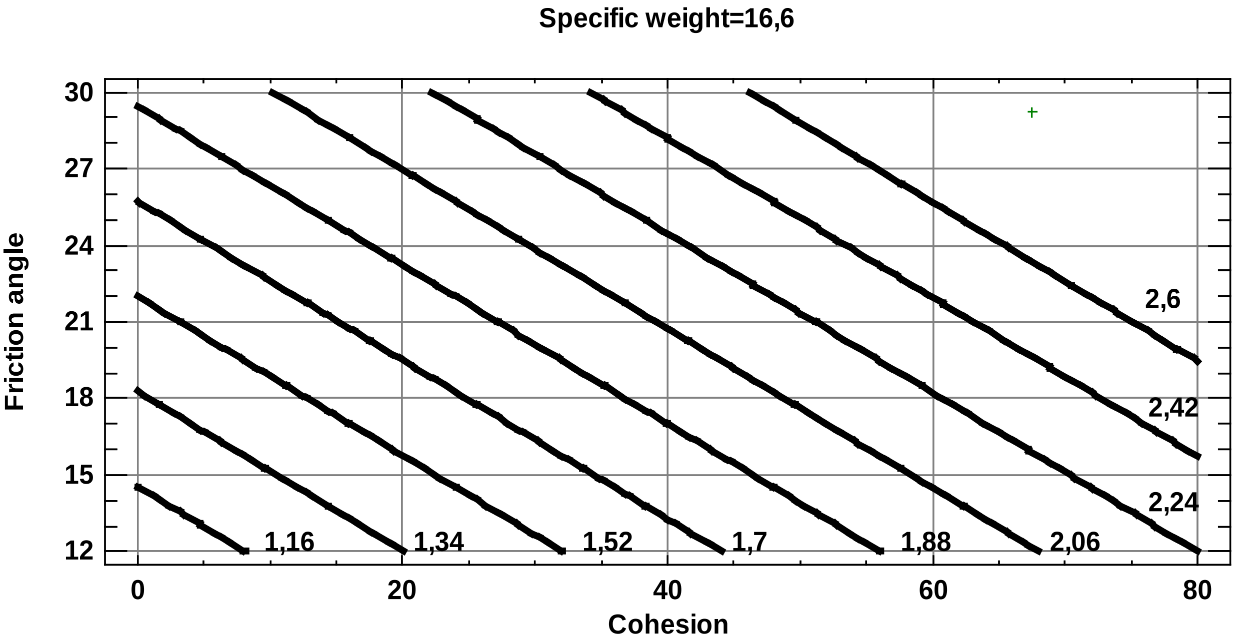

Figure 16 - Contour plot for the safety factor, as a function of cohesion and friction angle; with a specific weight of 16.6 kN/m^3.

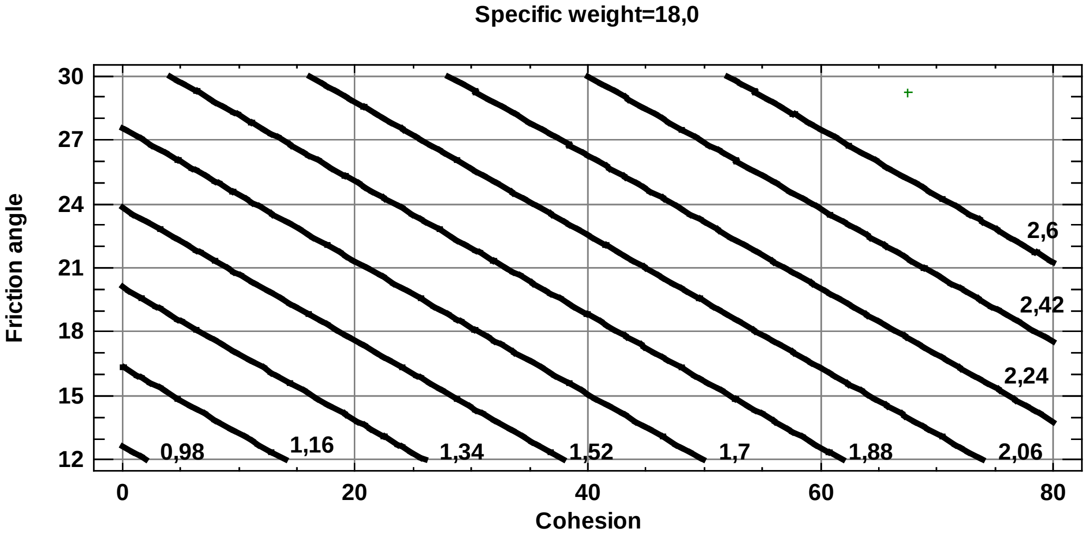

Figure 17 - Contour plot for the safety factor, as a function of cohesion and friction angle; with a specific weight of 18,0 kN/m^3.

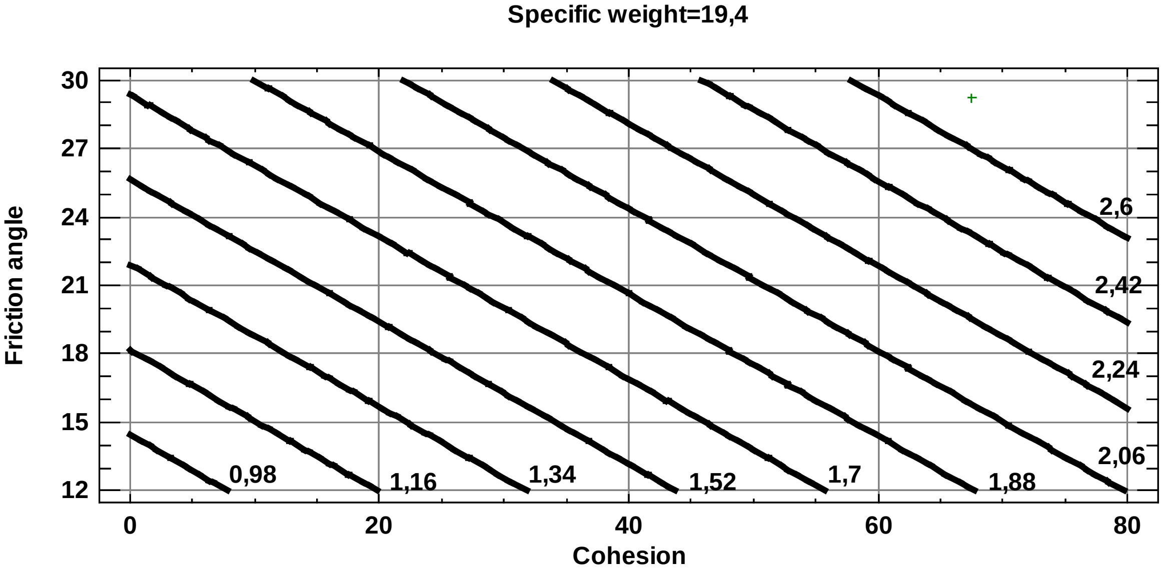

Figure 18 - Contour plot for the safety factor, as a function of cohesion and friction angle; with a specific weight of 19,4 kN/m^3.

Figure 19 lists the safety factor obtained through the numerical model and that calculated by applying the proposed regression equation. Figure 19 also shows that the R^2 statistic is 94.9% and the error is 7%, which can be considered a high precision between the two.

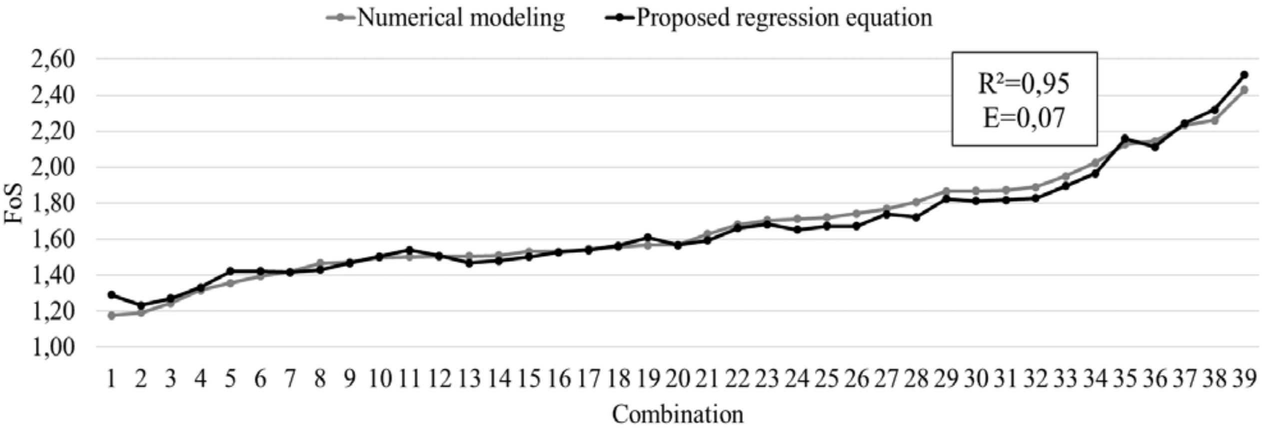

Figure 19 – Relationship between the FoS obtained using numerical modeling and the proposed regression equation.

CONCLUSIONS

Stochastic modeling is used to enlarge a sample, when the initial data is insufficient or does not allow by itself to characterize a study population. It was verified that, for the analyzed data, the variables: modulus of elasticity, specific weight, limits and percentages of material corresponding to the granulometry, present a Normal probability distribution.

Meanwhile, the variables: cohesion, friction and permeability present a Log-normal distribution. All of this is consistent with what is stated in the international bibliography consulted.

The combination of stochastic modeling and the mathematical methods implemented in GeoStudio program (GeoSlope, 2021) allow forecasting factors of safety in slopes made up of different soils with partially saturated behavior based on typifying their behavior, which facilitates the study of the properties and the Effect of the incorporation of partially saturated soils to the study of the slope stability of earthen dams.

From a small set of executed project data, the corresponding calibrations were performed, from which a stabilized resulting population of 300 values data was obtained. Then, using the SRS, this quantity was reduced to obtain a sample of 40 combinations of geotechnical properties for clayey soils. This reduction in the number of combinations makes it possible to save time and resources for the study of slope stability, taking into account the precision required in each study and the error the researcher is willing to commit.

It is observed that cohesion is the fundamental geotechnical variable in stability analysis. Friction intervenes and later, the specific weight. The remaining variables obtained in the stochastic modeling were used to obtain the characteristic curve of the partially saturated soil. Since the mechanical parameters are effective (corresponding to the state of operation of the dam), this result announces that the parameters that define the partially saturated behavior of the soil under normal slope conditions (that is, without external effects such as rain or rapid unpacking).

To estimate the FoS a regression equation with a coefficient of determination equal to 95% is obtained. This equation is applicable for earthen dams such as the one described in this investigation and allows obtaining the initial FoS considering partially saturated soils. Additionally, contour graphs are proposed, which can be used to estimate the interval in which the FoS value is found, taking into account variations between cohesion and friction angle for specific specific weights.

REFERÊNCIAS

ARMAS, R. & HORTA, E. Presas de Tierra (P. R. Fonte (ed.). Editorial ISPJAE. **Ingeniería Hidráulica**, 1987. Instituto Superior Politécnico José Antonio Echeverría (Cujae), La Habana, Cuba. ISBN 978-959-07-1141-1

ARMY CORPS OF ENGINEERS. Reliability Analysis and Risk Assessment for Seepage and Slope Stability Failure Modes for Embankment Dams. **Engineer Technical Letter**, n. 1110-2, v. 561, 2006.

ARYA, L.M. & HEITMAN, J.L. A Non-Empirical Method for Computing Pore Radii and Soil Water Characteristics from Particle-Size Distribution. **Soil Science Society of America Journal,** n. 79, p. 1537–1544, 2015. https://doi.org/10.2136/sssaj2015.04.0145

AUBERTIN, M.; MBONIMPA, M.; BUSSIERE, B.; CHAPUIS, R.P. (2003). A model to predict the water retention curve from basic geotechnical properties. **Canadian Geotechnical Journal**, n. 1122, p. 1104–1122, 2003. https://doi.org/10.1139/T03-054

AZEVEDO, G. F.; CARVAJAL, H. E. M.; SOUZA, N. M. Landslides hazard analysis by use of approach probabilistic applied to a three-dimensional slope stability model. São Paulo, UNESP, **Geociencias**, v. 37, n. 3, p. 655–668, 2018. https://doi.org/10.5016/geociencias.v37i3.11798

ESSAYAD, K. & AUBERTIN, M. Consolidation of hard rock tailings under positive and negative pore water pressures: Testing procedures and experimental results. **Canada Geotechnical Journal**, v. 58, n. 1, p. 49-65, 2021

FERNÁNDEZ, W.; VILLALOBOS, S.; KING, R. Probabilistic analysis of slope stability in completely decomposed granite residual soils. **Revista Ingeniería de Construcción**, v. 33, p. 5–14, 2018.

FLORES, I.; TRISTÁ, J.G.; COBELO, W. Análisis de la estabilidad del talud aguas abajo para el caso de una presa de tierra con suelo parcialmente saturado procedente de la formación Vía Blanca. In: CONVENCIÓN CIENTÍFICA DE INGENIERÍA Y AQUITECTURA, 18, 2018.

FLORES, I.; TRISTÁ, J.G.; HARAMBOURE, Y.G. Estabilidad de taludes durante un desembalse rápido en presas de tierra con suelos parcialmente saturados. **Ingeniería y Desarrollo**, v.; 38, n. 1, p. 13–31, 2020. http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0122-34612020000100013&lng=en&nrm=iso&tlng=es%0Ahttp://www.scielo.org.co/scielo.php?script=sci_abstract&pid=S0122-34612020000100013&lng=en&nrm=iso&tlng=es.

FREDLUND, D.G. & FREDLUND, M.D. **Developments in Landslide Analysis** (Issue November, p. 23), 2019.

FREDLUND, D.G.; XING, A.; HUANG, S. Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. **Canadian Geotechnical Journal,** v. 31, n. 3, p. 521–532, 1994. https://doi.org/10.1139/t94-062

GEO-SLOPE. Stability Modeling ith GeoStudio. 2021. http://www.geo-slope.com

HARAMBOURE, Y.G.; FLORES B.I.; TRISTÁ, J.G. Efecto de desembalse en la estabilidad de presas de tierra : dos casos de estudio en Cuba. **Ingeniería Hidráulica y Ambiental**, XLII, n. 1, p. 42–53, 2021.

HERNÁNDEZ, F.M.. **Procedimiento para el diseño por fatiga de pavimentos de hormigón simple para carreteras en**

Cuba. Cuba. 2016. Tesis (Doctorado en Ciencias Técnicas). Universidad Central "Marta Abreu" de Las Villas;Universidad Tecnológica de La Habana José Antonio Echeverría (CUJAE).

HIDALGO, C.A., & PACHECO, A. Herramientas para análisis por confiabilidad en Geotecnia: la teoría. **Revista Ingenierías Universidad de Medellín**, v. 10, n. 18, p. 69–77, 2011.

KONIG, T.; KUX, H.; CORSI, A. Landslide Risk Management Using the Mathematical Model Trigrs. **Geociencias**, v. 41, n. 1, p. 243–254, 2022. https://doi.org/10.5016/geociencias.v41i1.16290

KOVACS, G. **Seepage Hydraulics**. Developments in water science. Elsevier. 6.519 pp. 1981.

LANOIX, M.B.; PABST, T.; AUBERTIN, M.. Field determination of the hydraulic conductivity of a compacted sand layer controlling water flow on an experimental mine waste rock pile. **Hydrogeology Journal.** v. 28, n. 4, p. 1503-1515, 2020. https://doi.org/10.1007/s10040-020-02129-7.

MARTÍNEZ, A. *Modelación estocástica de problemas de ingeniería geotécnica*. 2010. Tesis (Doctorado en Ciencias Técnicas), Universidad Central de Las Villas.

TORRES, G. **Estimating the Soil–Water Characteristic Curve Using Grain Size Analysis and Plasticity Index.** 2011 [Universidad Estatal de Arizona]. http://medcontent.metapress.com/index/A65RM03P4874243N.pdf%5Cnhttp://repository.asu.edu/attachments/56747/content/TorresHernandez_asu_0010N_10702.pdf.

TRISTÁ, J.G. **Estudio del comportamiento tenso-deformacional de suelos parcialmente saturados en Cuba**. Cuba. 2015. Tesis (Doctorado en Ciencias Técnicas). Universidad Central "Marta Abreu" de las Villas; Instituto Superior Politécnico ¨José Antonio Echeverría¨.

WU, R.; MARTIN, V.; MCKENZIE, J.M.; BRODA, S.; BUSSI, B.; SELKER, J.; AUBERTIN, M. Fiber optic measurements of soil moisture in a waste rock pile. **Groundwater.** v. 59, n. 4, p. 549-561, 2017. https://doi.org/10.1111/gwat.13075.

WU, R.; MARTIN, V.; MCKENZIE, J.; BRODA, S.; BUSSIÈRE, B.; AUBERTIN, M.; KURYLYK, B.L. Laboratory scale assessment of a capillary barrier using fibre optic distributed temperature sensing (FO-DTS). **Canada Geotechnical Journal,** v. 57, n. 1, p 115–126. 2020.

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