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Behavioral evaluation of earth dams built with materials above optimum moisture content in high rainfall areas

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Article

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Wet core

Abstract

South Americas topographic characteristics and available materials have led engineers to select earth or rockfill material for dams construction. However, there are tropical regions with high annual rainfall where the soil compaction above the optimum moisture must be studied in detail. This research presents the results of tests performed on compacted soil samples, with water contents of +2 % and +5 % above the optimum moisture. Such samples were classified as low plasticity sandy silt by the USCS and as sandy lateritic clay by MCT methods. The investigation analyses a seepage, slope stability, and stress-strain numerical analysis conducted on typical hypothetical homogeneous and heterogeneous dams. In general terms, the heterogeneous sections showed adequate behavior for all the modeled soils. However, the slopes of the homogeneous sections exhibited low safety factors during the rapid drawdown of the reservoir water level. The material compacted above the optimum water content presented a superior performance to dissipate pore water pressure along the time than the other soils. Concluding that the use of soil above the optimum can be convenient and economical for dam construction, in the case where no other material is available, and a fast pore water relief is sought.

1. Introduction

A series of accidents during the construction and operation of earthen dams has drawn the scientific community's attention. As an example, the tailings dam failure of the Brumandino dam located in Brazil brought social, economic, and environmental consequences. In detail, hundreds of people died as a consequence of dam failure. Additionally to this social consequence, the Paraopeba river was polluted. High levels of mercury were detected in the water coming from the dam upstream, where iron mines were located (Thompson et al., 2020). Therefore, the need for research about the mechanical performance of these structures is always pertinent. Special attention must be taken in the constitutive materials used in the design or the construction of earthen dams. A particular case of analysis is soil water content's influence on the mechanical performance of the structures.

The soil's mechanical properties used to construct dams are directly dependent on the soil water content at the moment of compaction. Properties such as permeability, compressibility, and ultimate strength are affected by the soil water content. These properties are used to compute the mechanical performance of the structure. As an example, the Young modulus of soils compacted above the optimum water content is lower than in those samples compacted at the optimum water content. It implies that the soil generates low resistance and elevated pore water pressure during the construction phase. Despite these well-known disadvantages of using soils with water content above the optimum, there is no other option than to use these high water content soils in some regions of South and Central America. Techniques of constructions like silt stabilization, air drying, or mixing with dryer granular materials produce delays and increase the construction cost that most of the cases make them inapplicable (Jalili & Jahanandish, 2009). Therefore, professional practitioners need to understand the implications that have the use of soil above the water content in the design, construction, and performance of dams.

On the contrary to what it should be expected, there is a lack of information regarding the design or mechanical

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assessment of dams constructed with water contents above the optimum. In the literature, there are construction descriptions of dams built using soil 2 % to 10 % above the optimum water content (Bernell, 1982; Kerkes, 1988; Morpurgo, 1976; Villegas et al., 1976a, 1976b). To mention one example, Villegas et al. (1976a) describe the experience acquired during the construction of Santa Rita Dam. This region has an average annual precipitation of 6210 mm of water. Consequently, conditioning the soil to its optimum water content was almost impossible, and the contractors decided to use soil above the optimum water content in the construction process. The construction process was done using rigorous control compaction procedures and a long period of construction process between each layer of soil. This project's economic success achieved by using a non-standard material is an example that non-traditional techniques and materials could be used to reduce the building cost. Additionally to this economical benefits, using soil above the optimum water content reduces the time of settlements, and it is reported that around 88 % of the total settlement could be achieved during the construction process (Rashidi & Haeri, 2017). This research seeks to contribute to the understanding of dams' mechanical performance that were built using soil with water content above the optimum.

This research compares the performance of two types of dams built with soil above the optimum water content (i.e. homogenous and heterogeneous dams). A numerical model was developed to assess the pore water pressure during a rapid drawdown of the earthen dams. Moreover, a slope stability analysis was performed using the results of pore water pressure. The mechanical parameters used in the model were experimentally obtained from soil compacted with different water contents. For this research, compaction, microscopy, permeability, consolidation, and triaxial tests were performed on samples compacted at the optimum, 2 %, and 5 % above the optimum water content. The results found in this research showed that this un-standard material could be used with caution in dam projects. Especially when the designer seeks pore water pressure relief.

2. Experimental programme

Laboratory tests were performed by Garcia (2013) on compacted silty sand soil from the Federal District - Brazil. The paper presents the parameters and analysis of the physical, mechanical, and microstructural properties of the material. These results were used in the numerical models of homogeneous and heterogeneous dams with an impermeable core. The purpose is to understand the influence of compaction water continent in dams. Two hypothetical cross-sections were analyzed, and seepage, slope stability, and stress-strain were computed with these parameters.

2.1 Experimental protocol

The soil utilized was collected from the University of Brasilias Geotechnics experimental foundations campus. The samples were extracted by manual digging of a well with an approximate diameter of 1 m and depth of 1,5 m. The extracted samples were disturbed, and different compacted samples were fabricated using this soil. The selected soil is a good representation of the soils of the Federal District of Brazil. These soils are covered by a soil mantle according to Mendonca et al. (1994) cited by Araki (1997). These soils are a result of the chemical weathering associated with lixiviation and lateralization from the quaternary tertiary period.

Conventional tests were performed on the compacted soil specimens. The specimens were constructed with different moisture contents and the standard compaction energy. The tests had the objective of measuring the physical, mechanical, and hydraulic characteristics of the studied samples. These results were used in the numerical simulation to study the effect of soil moisture content on dam behavior. In this research, the conducted tests were natural moisture content, solids specific weight, natural unit weight, grain size analysis, liquid limit, plastic limit, compaction test, scanning electron microscopy, variable head permeability tests, consolidation tests, and CID triaxial tests. The following sections present the results of the material characterization. All tests were performed following the Brazilian Association of Technical Standards (ABNT) procedures.

2.1.1 Physical characterization tests

Table 1 presents the test results obtained of natural moisture, natural unit weight, specific gravity, grain size analysis with and without deflocculates, Atterberg limits, SUCS, and MCT classification.

The results show a considerable alteration when the procedures are performed using dispersant, which presumes that the material presents clay and sand aggregations. The soil matrix is predominantly sandy and silty.

In earth dam projects, the soil aggregation directly influences the infrastructure performance. The most aggregated soils have a greater quantity of macropores, which is directly related to permeability, isotropy, and low resistance. However, the orientation of the particles during the compaction process gives to the sample the following characteristics: less aggregated soils are susceptible to exhibit anisotropic hydraulic and mechanical behaviors.

The classifications exhibited in Table 1 show that USCS classifies the studied soil as ML (low plasticity silt). This classification is not coherent with the material tactile-visual analysis, nor with the grain size analysis. The significant presence of clay and the predominance of sand and silt gives this soil, particular characteristics. On-site, the Federal District soil behaves similarly to clay, which is the reason it is known as the porous clays of Brasilia.

The MCT classification (Cozzolino & Nogami, 1993), catalogs the soil as a LA'-LG' since the soil is located in the interface of both types of soil (i.e., the soil is classified as sandy lateritic and lateritic clay). This classification is coherent with the tactile-visual analysis and with the soil behavior.

2.1.2 Compaction testing

In the compaction curve in Figure 1, the values of optimum moisture content and maximum dry density for the tested soil were 23 % and 15,5 kN/m^3. This point has an approximate saturation degree between 80 % and 90 %.

The shape of the compaction curve shows the influence of the sand and silt fraction. The curve presents a closed format with high dry unit weight.

Table 1. Results from physical characterization tests and soil classification.

Grain size distribution	Distilled water + dispersant	Gravel (%)	0
		Sand (%)	58.9
		Silt (%)	24.4
		Clay (%)	16.7
	Distilled water	Gravel (%)	0
		Sand (%)	74.8
		Silt (%)	24
		Clay (%)	1.2
		Natural unit weight - γ (kN/m^3)	17.5
		Solids specific weight - γ_s (kN/m^3)	26.9
		Natural moisture content - w (%)	27
		Liquid limit - w_l (%)	35
		Plastic limit - w_p (%)	23
		Plasticity index - *IP* (%)	12
		SUCS Classification	ML
		MCT Classification	LA'-LG'

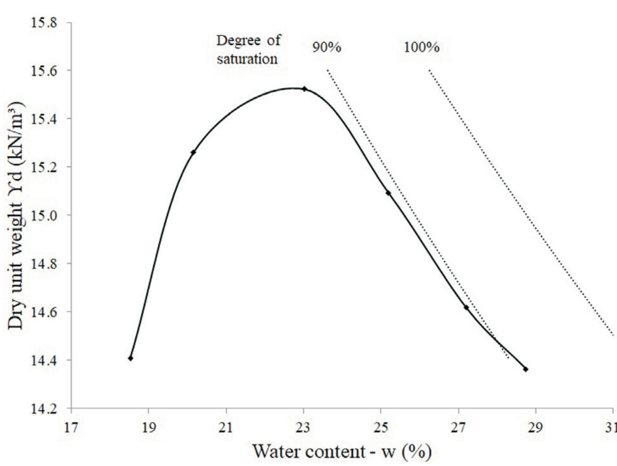

Figure 1. Compaction curve for the UnB experimental site soil.

The samples for consolidation, permeability, and triaxial tests were fabricated using the results of the compaction test. The defined moistures of 23 %, 25 %, and 28 % correspond to the optimum moisture content, optimum moisture content + 2 %, and optimum moisture content + 5 %.

2.1.3 Scanning electron microscopy analysis

The study of the compacted soil microstructure was carried out qualitatively. SEM images were obtained during the compaction process over a range of moisture continents.

Figures 2, 3 and 4, present the images of the surfaces observed during the braking and dehydration of the samples, which were obtained by the SEM for the three test

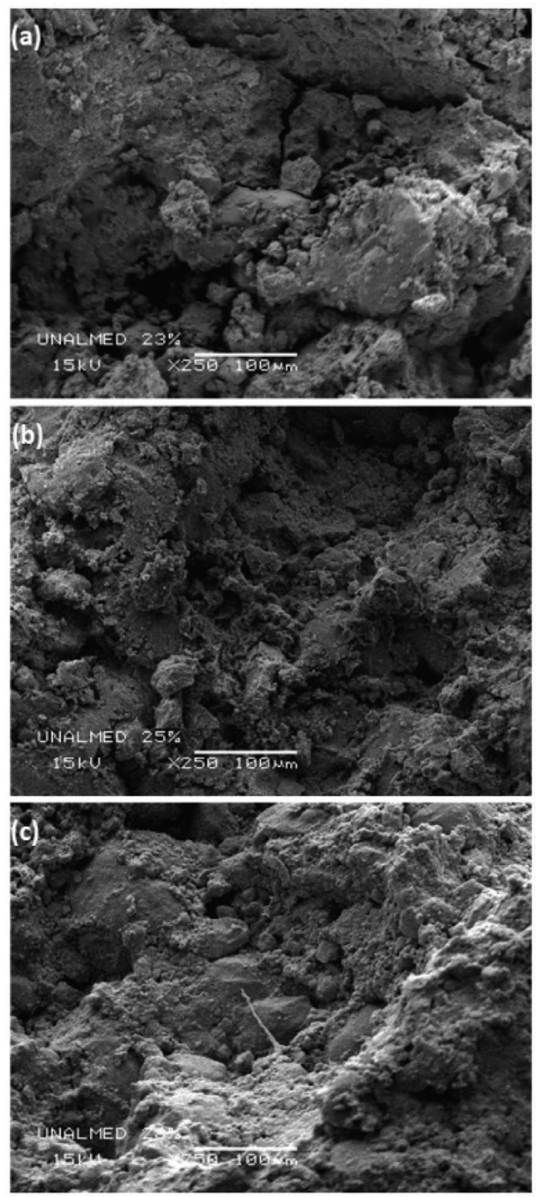

Figure 2. Images obtained by SEM for x250 magnification: (a) Image of compacted soil with 23 % moisture content; (b) Image of compacted soil with 25 % moisture content; (c) Image of compacted soil with 28 % moisture content.

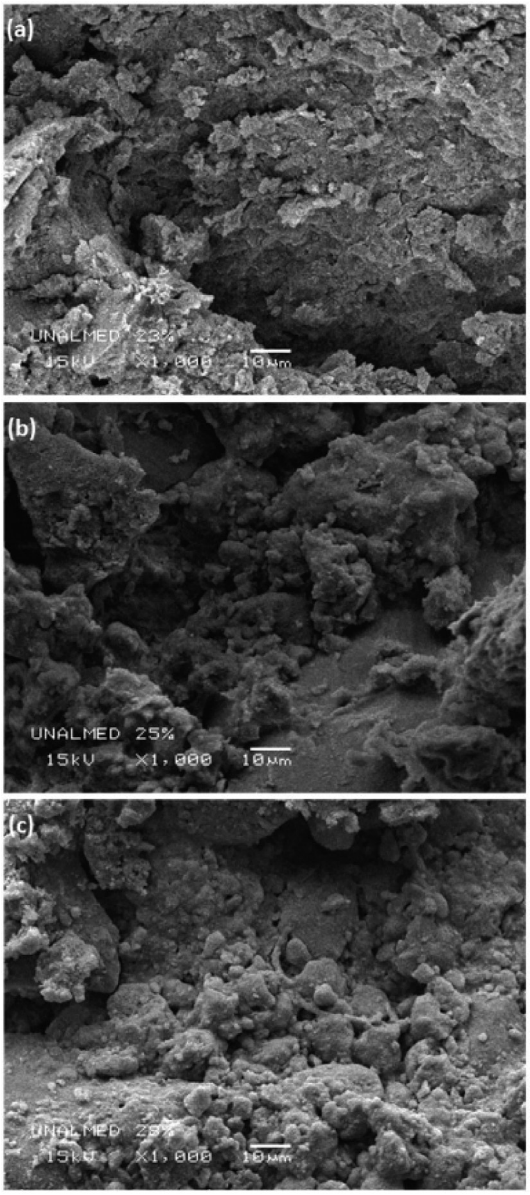

Figure 3. Images obtained by SEM for x1000 magnification: (a) Image of compacted soil with 23 % moisture content; (b) Image of compacted soil with 25 % moisture content; (c) Image of compacted soil with 28 % moisture content.

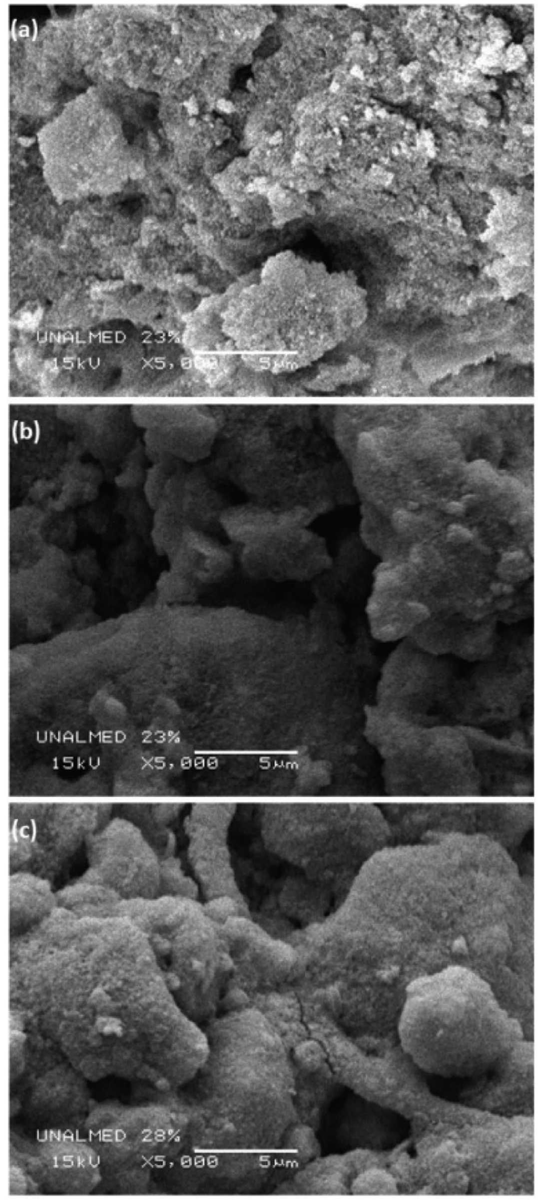

Figure 4. Images obtained by SEM for x5000 magnification: (a) Image of compacted soil with 23 % moisture content; (b) Image of compacted soil with 25 % moisture content; (c) Image of compacted soil with 28 % moisture content.

moisture contents with 250, 1000, and 5000 magnifications. On these images, it is possible to observe that the compacted soils exhibit a highly porous structure.

In Samples with optimum moisture content, the aggregates form a denser and more massive soil structure. The high-density value is achieved due to the low aggregate strength, which deforms and breakdown easily reducing the pores. On the other hand, the samples above the optimum moisture content, particularly samples with 28 % moisture content, the clay matrix wraps the silt grains and closes the micropores.

The most representative shapes exhibit soft vertexes and dimensions that vary between 5 and 20 μm (Figures 3b and 4b) but can reach 30 to 40 μm. On Figures 2a, 3a and 4a are not possible to identify the individual grains, as it happens in compacted samples above optimum moisture content.

In Samples with moisture contents above optimum, it is possible to visualize the cavities generated by the grains during the breakdown process. Additionally, in these figures, it is possible to observe a few micropores with cavities superior to 5 μm.

In the SEM images for 5000x magnification (Figure 4.a, 4.b, and 4.c), it is possible to observe the following features: rectangular aggregations of sand, silt and clay with grain to grain contact, rough superficial texture, and the presence of micropores with openings with diameters smaller than 1 μm. These measured characteristics are bidimensional, which means they are not realistic. However, it still provides a clear idea of the size of the pores and the aggregate shape.

In this type of soil, the phenomenon of aggregation of particles is more important than the colloidal phenomenon suggested by Lambe (1958). In the case of samples with moisture contents above optimum, the soil is not homogeneous and particles are not oriented. As an example, the SEM results show that these soils behave similarly to the soils presented by Cetin et al. (2007) and Mitchell (1993). In these researches, compacted soils bellow optimum moisture content show an aleatory orientation, and the orientation changes as the moisture content increases until it reaches the optimum moisture content. However, the study reveals that that beyond the optimum moisture content, the degree of preferential orientation decreases, opposite to the generally accepted point of view in classic soil mechanics and the previously stated studies.

2.1.4 Variable head permeability test

Table 2 presents the measurements of the variable head permeability test. The tests were carried out on the compacted soil samples, and permeability was measured in the vertical direction. The numerical model assumed isotropy of this parameter.

It is possible to observe that the soil permeability decrease as water content increase. This fact is a consequence of the larger micropores presented in samples with water content above the optimum.

Table 2. Permeability coefficients for different compaction moisture contents.

Moisture content (%)	*K* (m/s)
22.7	1.05E-09
24.7	6.45E-09
27.8	1.34E-08

2.1.5 Oedometric tests

The saturated consolidation tests were performed with the following stresses: 25, 50, 100, 200, 400, 800, and 1600 kPa. Figure 5 presents the normalized compressibility curve of each of the three studied samples. These graphs represent the variation of the void ratio when increasing the pressure over the test soils.

Figure 5 shows that the compressibility increase as moisture increases. As an example, samples with a moisture content of 28 % presents the highest compressibility. The compressibility of samples with 23 % and 24 % of water content is equal. This fact is evidenced in the virgin side of the compressibility curve of these two samples. It is important to point out that even though the test specimens were elaborated with compacted material at different moisture contents, generating different initial void ratios, the final void ratios were similar. This fact can be seen in Figure 5.

2.1.6 CID triaxial tests

The triaxial tests were performed under drained controlled strain and isotropically consolidated (CID triaxial tests). The soils were compacted at different moisture contents by following conventional stress paths (axial load), with effective confining stresses of 50, 100, 200, and

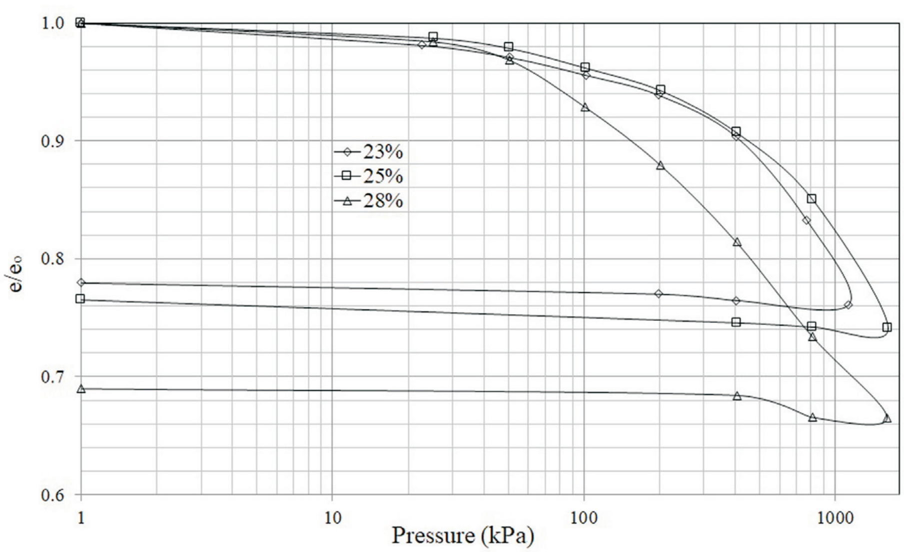

Figure 5. Normalized compressibility curve for the three compaction moisture contents.

400 kPa. Furthermore, back pressure was applied through the drainage tubes at the base and head of the sample to saturate the sample.

The tests performed using samples at optimum moisture content had a degree of saturation ranging between 77 % and 79 %, while for tests performed with samples of +2 % above the optimum had an initial saturation degree of 84 %. On the other hand, samples with a water content of +5 % above the optimum had an initial saturation degree of 85 %. For all the samples, the final degree of saturation was above 98 %.

Figures 6, 7, and 8 show deviatoric stress vs. the axial strain graphs for the samples that were compacted at optimum moisture content, optimum moisture content +2 %, and optimum moisture content +5 %.

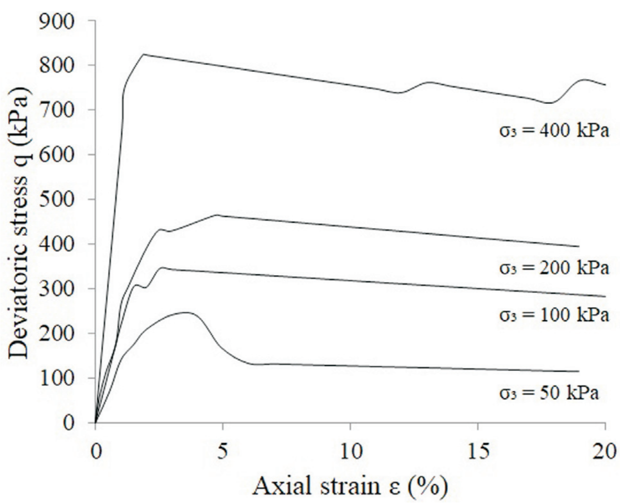

Figure 6. CID triaxial tests result for soil sample compacted at optimum moisture content.

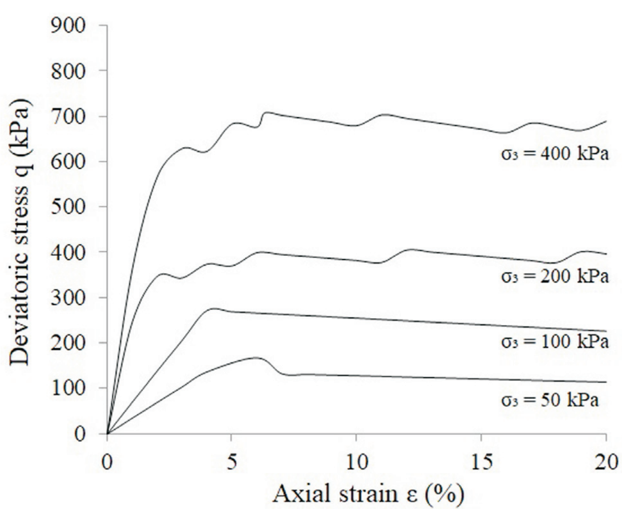

Figure 7. CID triaxial tests result for soil sample compacted at optimum moisture content +2 %.

From Figures 6 to 8, it is possible to observe that for all the samples the soil stiffness increase as the effective confining stress increases. Additionally, it is possible to notice a prominent decrease in the soil maximum peak stress and stiffness as the compaction moisture content increases. The maximum deviatoric stress for the soil compacted at 28 % of the moisture content was approximately 50 % of that for the soil compacted with 23 % of moisture content (i.e., optimum moisture content). Meanwhile, the failure strain for all of the test soils ranged between 4 % and 6 %.

A linear failure envelope was established for each type of tested soil (Figure 9) from the maximum values of effective stress paths in the *p*-*q* plane. The straight line was obtained by the linear regression for the maximum value of *q*, for the four test confining stresses at the different moisture contents analyzed during the investigation.

In Figure 9, it is possible to observe that the envelopes for 23 % and 25 % moisture contents are parallel, which means that the friction angle will be very similar in both cases. However, the interception with the y-axis has a lower value in the case of the soil compacted with 25 % of mois-

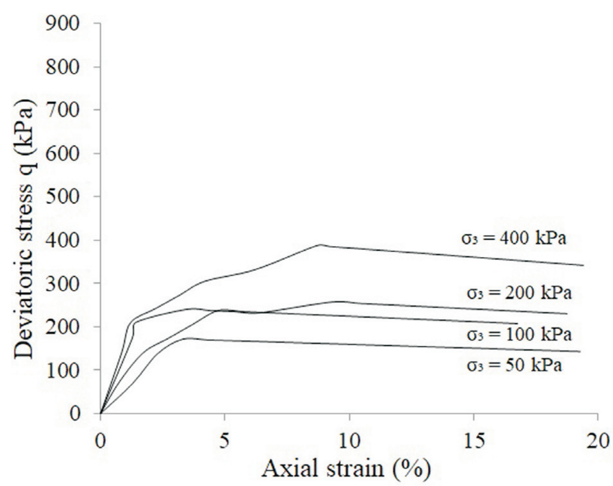

Figure 8. CID triaxial tests result for soil sample compacted at optimum moisture content +5 %.

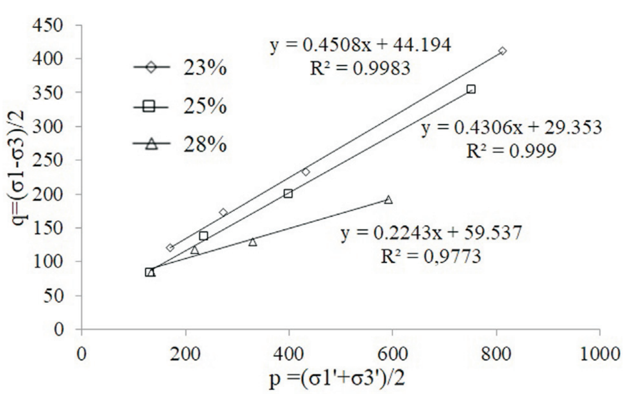

Figure 9. *p* - *q* diagrams for the three compaction moisture contents.

ture content, which means that the cohesion drops with the increase of 2 % of moisture content.

In the case of the soil compacted with 28 % of moisture content, the curve has a lower slope which means that the friction angle decreases considerably. It also presents an increase in the cohesion that can be a result of the structure that the soil forms when it is compacted with moisture contents that considerably surpass the optimum moisture content. This behavior is attributed to the structures formed by the clay and silt aggregations, as observed in the electron microscope scanning images (Figures 3c and 4c).

In general terms, the results were expected, and the strength parameters are better for soils compacted at optimum moisture content. On the contrary, the mechanical parameters were decreased in samples with water content above the optimum.

2.2 Geotechnical parameters of the tested soil

From the experimental setup, strength, consolidation, and permeability parameters of the core material for heterogeneous dams and the filling material for homogeneous dams were obtained.

The constitutive model utilized throughout the analysis was the nonlinear hyperbolic model, which was initially attributed to Kondner (1963) and later modified by Duncan & Chang (1970). The model simulates the non-linearity stress-strain behavior of soils, the stress-strain curve is hyperbolic and the soil stiffness modulus varies with the confining stress.

Tables 3 and 4 present a summary of the selected model's geotechnical parameters for the different compacted samples. Additionally, the parameters for foundation soils, backstraps, transition material, and typical filter materials are presented. These parameters can be found in the literature for projects with similar weather conditions.

From the triaxial modulus results presented in Table 4, it was possible to find a relationship between the Young modulus and the confining stress for each tested soil type. The experimental data were fitted based on the nonlinear hyperbolic model proposed by Duncan & Chang (1970). The equation is presented below:

$$Ei = KP_a\left(\frac{\sigma_3}{P_a}\right)^n \tag{1}$$

where K and n are the parameters of the equation to be fitted, P_a is the atmospheric pressure, assumed as 101.3 kPa

Figure 10 presents the modulus for soils compacted with the three moisture contents used during the investigation. The correlation coefficient of each curve presented in the figure has a value of 1. Table 5 shows the calculated values for the K and n constants of the hyperbolic model.

From the values of K and n, it is possible to establish a relationship with the compaction moisture content for this soil (Figures 11 and 12) and the mentioned parameters. The results were validated with aditional trials.

2.3 Dam behavior analysis using numerical simulations from GeoStudio software

Numerical simulations of seepage flow used SEEP/W software. The slope stability sued SLOPE/W software. Finally, stress-strain was computed using SIGMA/W. The commercial package of this software is named GeoStudio package by Slope International Ltda.

Table 3. Geotechnical parameters of the dam's constituent materials.

Material	E (MPa)	γ (kN/m^3)	ν	f (°)	c (kPa)	k (m/s)	K_o	R_u
Foundation soil	60	18	0.35	28	30	1.00E-11	0.5	0.2
Gravel shell	60	20	0.35	38	10	1.00E-04	0.5	0
Transition filter	100	20	0.35	32	0	1.00E-03	0.5	0.05
Filter	100	20	0.35	30	0	1.00E-03	0.5	0.05
Embankment soil	23 %	19.1	0.4	27	48	1.00E-09	0.55	0.25
	25 %	18.9	0.4	26	30	5.00E-09	0.56	0.3
	28 %	18.5	0.4	14	50	1.00E-08	0.7	0.5

Table 4. Deformability modulus for the three types of soils for various confinement pressure.

Moisture content	E (MPa)			
	σ_c' = 50 kPa	σ_c' = 100 kPa	σ_c' = 200 kPa	σ_c' = 400 kPa
Optimum moisture content	14.2	22.4	27.4	62.5
Optimum moisture content + 2 %	4.7	8.5	25	37.3
Optimum moisture content + 5 %	3.5	5.9	12.9	19.4

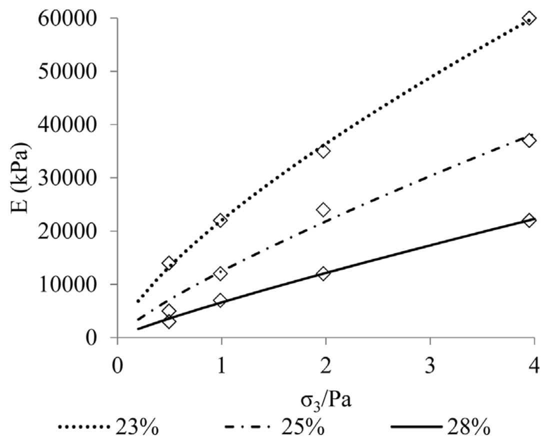

Figure 10. The relation between the deformability modulus and the confinement pressure.

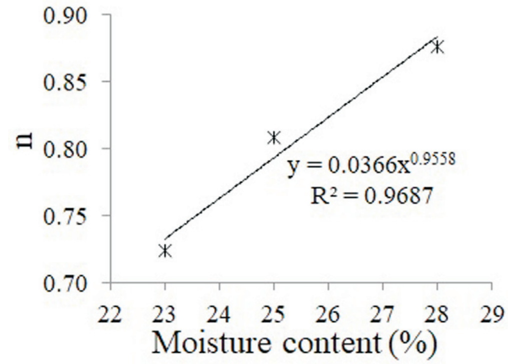

Figure 11. The relation between n and the compaction moisture content.

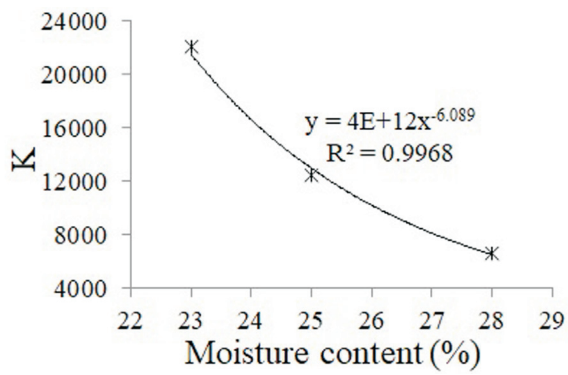

Figure 12. The relation between K and the compaction moisture content.

Table 5. Parameters K and n for the three compaction moisture contents.

w (%)	K	n	R^2
23	22036.4	0.72	0.99
25	12468.3	0.81	0.98
28	6612.1	0.88	0.99

2.3.1 Typical cross-sections adopted for analysis

This research studied two typical cross-sections for dams. One is a homogeneous dam with a vertical filter, and the other a heterogeneous dam (Figures 13 and 14). Computations are presented in meters.

2.3.2 Seepage flow analysis

In dam design, the control of flow through backfill, body dam, and foundations constitutes an essential analysis for the safety of the project (Cruz, 1996). The water seepage, forming *piping*, is one of the most common causes of earth dam failures.

2.3.3 Steady-state operation regime

In the steady-state operation regime, the water level is maximum (level 157 m). The flow values are low due to the low permeability coefficients for compacted soil. These values of flow are represented by a unit length of the dam.

Figure 15 shows the flow Q (m^3/s) values for both cross-sections analyzed using soil with different moisture contents. The lowest flow corresponds to dams compacted with silt clay material with 23 % moisture content. This material exhibits the lowest value of the permeability coefficient.

2.3.4 Rapid drawdown

Rapid drawdown analysis was performed, adopting a drainage time of 15 days (1.296.000 s). The hydraulic head at the beginning was 157 m (maximum reservoir level) and 100 m in the end (dam's foundation).

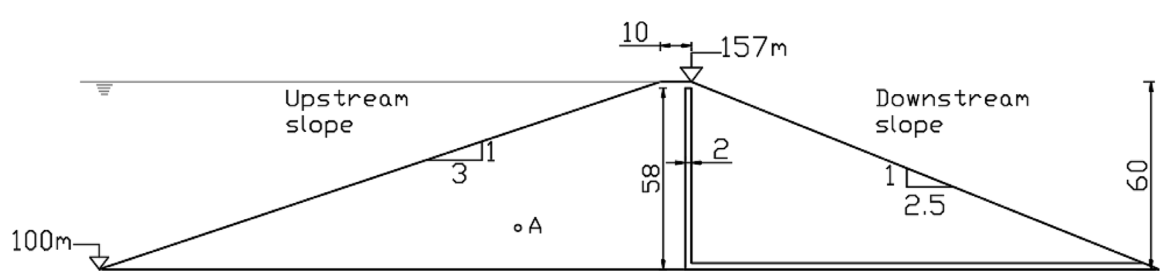

Figure 13. Typical cross-section 1 (homogeneous dam).

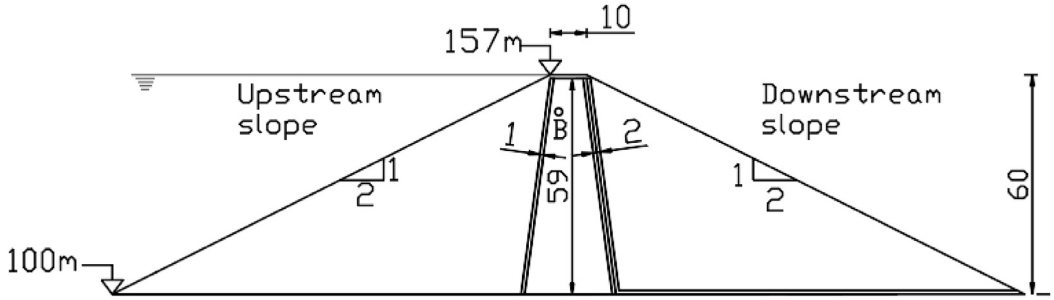

Figure 14. Typical cross-section 2 (heterogeneous dam).

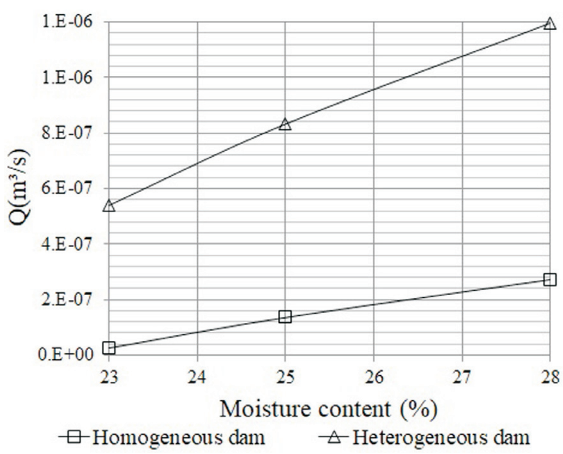

Figure 15. Flow for different compaction moisture contents.

Pore pressures were calculated in tow different points for each dam, a point in the backstrap upstream from the homogeneous dam (point A, Figure 13) and a point in the core of the heterogeneous dam (point B, Figure 14).

Figures 16 and 17 show the pore pressure distribution for those points for the three different water contents. The rapid drawdown process has a higher effect over soils compacted at optimum moisture content since after being compacted the soil structure formed a less permeable structure. This causes a slower pore pressure dissipation.

None of the three types of soils present a good behavior under rapid drawdown. The pore pressure dissipation is slow. This slow rate of dissipation of pressure generates instability in the slopes of the dam. During the 15 days of drainage, the pore pressure decreases slightly (the phreatic line remains stagnant), generating instability problems. In the soils with 25 % and 28 % compaction moisture contents, the soils exhibit a good rate of pore pressure dissipation 50 days after the rapid drawdown initiation.

In the case of the heterogeneous dam, the slow pore pressure dissipation will not have a great influence over the dam backfill stability because these are constructed with gravel, which has a high permeability coefficient, thus a high capacity to dissipate pore pressures. This fact is shown in Figure 17.

2.4 Slope stability analysis

The slope stability analyses were performed for the final stages of construction, operation, and rapid drawdown of the reservoir. For the operation regime, the pore water pressure was imported from the SEEP / W program and the slope stability analyzes were carried out in the SLOPE / W program using the Morgenstern & Price (1965) method. For the rapid drawdown of the reservoir, the coupled pore pressure - stress analysis was performed using the SEEP/W and SIGMA/W programs, determinis-

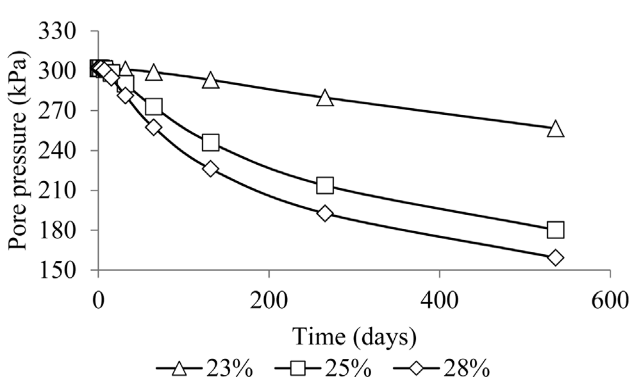

Figure 16. Pore pressures in point A for the three compaction moisture contents, homogeneous dam.

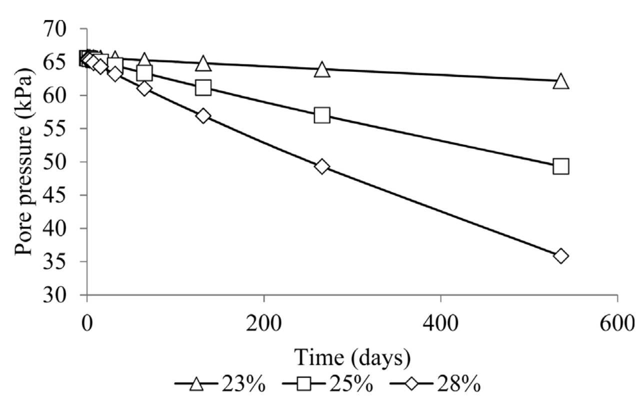

Figure 17. Pore pressures in point B for the three compaction moisture contents, heterogeneous dam.

tic safety factors were obtained using the Morgenster & Price (1965) method.

According to USACE (1970), the minimum suggested value for the factor of safety in the slope stability analysis is 1.3 during the end of the construction phase, 1.5 during the steady-state operation regime and 1.1 during the rapid drawdown of the reservoir.

2.4.1 End of construction

The safety factor evaluation during the final construction stage is performed for the slopes located upstream and downstream of the dam. Table 6 shows the safety factors for the homogeneous and heterogeneous dams, where it is possible to observe that all safety factors are greater than the minimum suggested values.

For the final construction stage, the constructive pore pressure coefficient Ru was used at the dam - foundation soil interface to consider the most critical situation. For both types of dams, the obtained safety factors under the conditions of material compacted at 23 % and 25 % moisture contents are similar.

2.4.2 Steady-state operation regime

It is important to point out that the seepage nets and pore pressures were imported from the seepage analysis performed in Seep/W, which was presented previously. The analysis was only performed for the downstream slope because the water level in the upstream slope acts as a stabilizer agent. The minimum safety factors for the homogeneous and heterogeneous dams in the three moisture contents are presented in Table 7.

Table 6. Safety factors for homogeneous and heterogeneous dams during the final construction stage.

Moisture content	Upstream slope safety factor		Downstream slope safety factor	
	Homogeneous dam	Heterogeneous dam	Homogeneous dam	Heterogeneous dam
23 %	2.2	2.0	2.2	1.9
25 %	2.2	2.0	1.9	2.0
28 %	1.6	1.9	1.6	2.0

Table 7. Safety factors for the homogeneous and heterogeneous dams during the operation phase.

Moisture content	Safety factors for upstream slope (homogeneous dam)	Safety factor for downstream slope (heterogeneous dam)
23 %	1.9	1.7
25 %	1.8	1.7
28 %	1.4	1.6

As shown in Table 7, the safety factors during the construction phase are lower than the values obtained during the final construction stage, due to the formation of the flow network.

In the case of the homogeneous dam, the soil that shows the lowest safety factor is the soil compacted at optimum moisture content +5 %, which means that it would not be acceptable. As a result, it would be necessary to flat the slope geometry or modify the construction material.

On the other hand, in the case of the homogeneous dam, the lowest safety factors are greater than 1.5. Therefore, the homogeneous dam does not present stability problems during this phase due to the core compaction moisture content, as in almost 100 % of the cases the failure surface occurs in the gravel backfill.

In both analyzed cross-sections, the lowest safety factors for optimum moisture content and optimum +2 % moisture content soils are very similar, which agrees with the literature's result, where a range of +/- 2 % of the specified compaction moisture content is accepted worldwide.

2.4.3 Rapid drawdown

The coupled stress - pore pressure analyzes were performed by using Sigma/W and Slope/W software. The flow network and initial pore pressures were imported from the seepage analysis performed in Seep/w.

During the reservoir drawdown, the load imposed by the water over the upstream slope is eliminated, leaving the backfill saturated. The excess of pore pressure can lead to failure, which is the reason it is generally the most critical condition to be analyzed.

The downstream slope did not exhibit variations in the safety factor in relation to the operation condition. Therefore, the only simulations performed were on the critical upstream slope.

Figures 18 and 19 show the time results of minimum safety factors for the homogeneous and heterogeneous dams with the three compaction moisture contents. The total drainage time was 15 days, but the safety factors are pre-

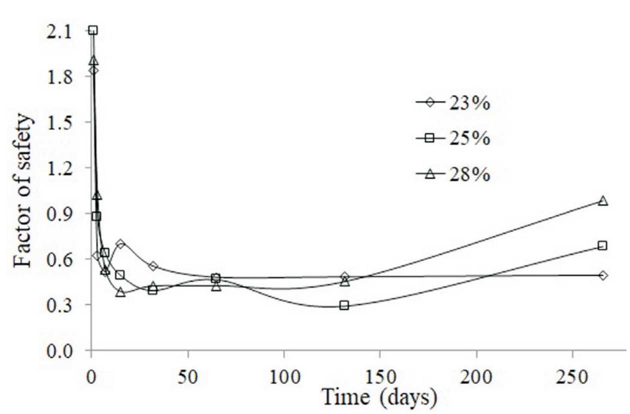

Figure 18. Time variation of the safety factors for the homogeneous dam.

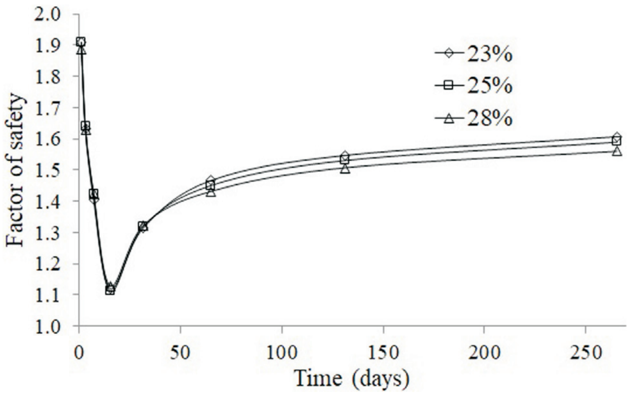

Figure 19. Time variation of the safety factors for the heterogeneous dam.

sented every 266 days, due to the slow pore pressure dissipation by the silt clay material.

In the case of the homogeneous dam, the most critical value occurs approximately at day 15, where the reservoirs drainage is completed. The slow dissipation of pore pressure caused the safety factor to become greater than 1.1 on day 300 after starting the drainage. Opposite to the homogeneous dam, the safety factor for the heterogeneous dam are greater than 1.1 overtime, this result shows an adequate and favorable factor of safety for this type of dam in this critical condition.

Comparing the results for the three soils with different moisture content, it is possible to observe (Figure 18) that for the homogenous dam the soil compacted above optimum moisture content (25 % and 28 % moisture content) showed lower safety factors. However, these soils compacted above optimum moisture content have greater permeability coefficients, thus the dissipation of pore pressure occurs faster over time which improves rapidly the stability. Figures 20 and 21 show the geometry of the potential failure surface in the critical condition that corresponds to the period between the seventh day and the end of the rapid drawdown for the homogeneous and heterogeneous dam.

In all types of stability analysis, the heterogeneous dam showed satisfactory performance. On the other hand, the homogeneous dam showed a critical performance in the rapid drawdown stage. In this case, the factor of safety can increase by building flatter slopes as demonstrated by Garcia et al. (2019). The upper limit of 5 % above the optimum moisture content must be respected to obtain the expected factors of safety.

2.5 Strain-stress analysis

The following analyzes were performed using SIGMA/W software. The results analyzed were expressed in total stresses and strains. According to Silveira (2006), 70 % to 90 % of settlements occur during the construction phase. These results were obtained during the construction of instrumented dams, where settlements were monitored.

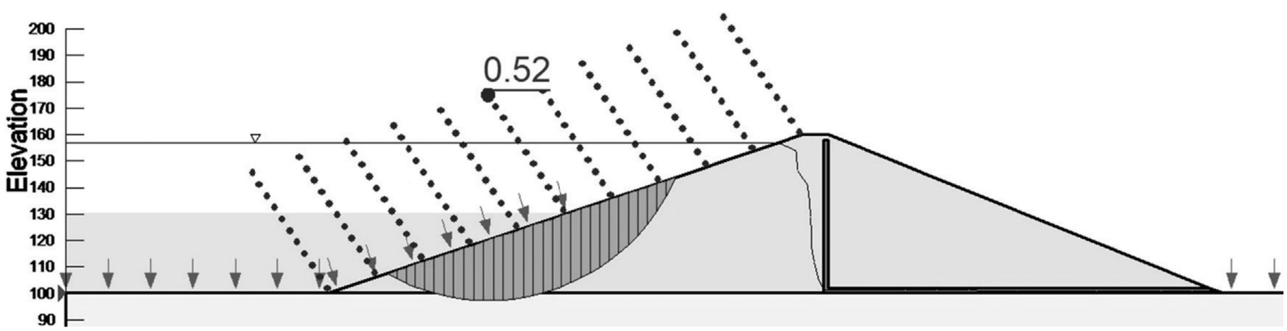

Figure 20. Minimum safety factor for the homogeneous dam (7-15 days - end of the rapid drawdown).

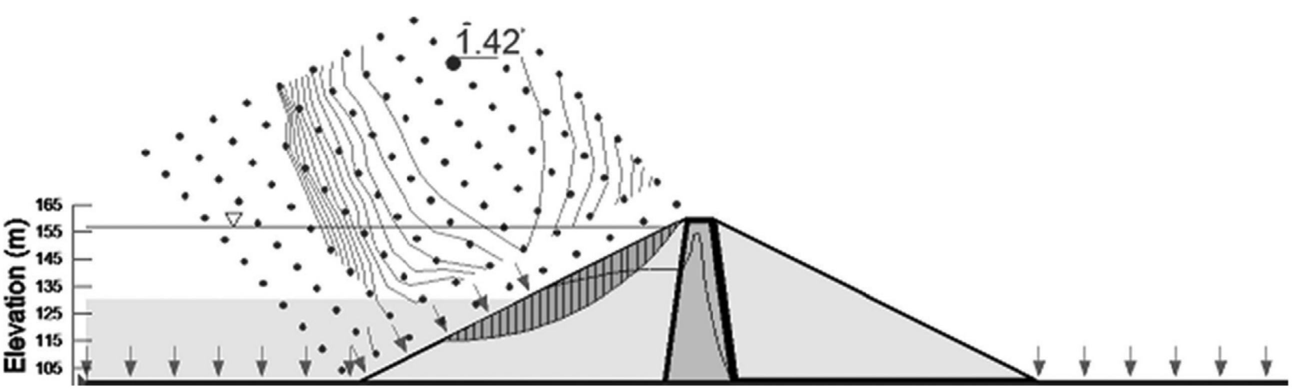

Figure 21. Minimum safety factor for the heterogeneous (7-15 days - end of the rapid drawdown).

2.5.1 End of construction

The maximum stress at the base was approximately 800 kPa for both of the analyzed cross-sections. In the case of the homogeneous dam, in Figure 22 it is possible to observe the phenomenon of concentrated stresses in the filter zone for the dam built +5 % above the optimum. This occurs as a consequence of the stiffness differences between the sand and the filling material. The plastic points did not present evident concentrations, which means that clear signs of failure-zone formations were not observed (Figure 23). On the other hand, in the case of the heterogeneous dam, it is possible to observe the stress arching phenomenon in the transition zone (Figure 24). The plastic points present a slight concentration in the base of the core and the superficial part of the gravel backstraps (Figure 25).

2.5.2 Construction by stages

The numerical simulation was performed in six stages, each step represents a construction of a layer of a thickness of 10 m. For the homogeneous dam, the settlements were computed for the three soils. These settlements were found to be similar. The maximum settlement for the soil compacted at optimum moisture content was 2.26 m, while for the soil compacted with +5 % above optimum moisture content was 2.4 m.

Figures 26 and 27 show the distribution of maximum vertical and horizontal displacements along the dam's central axis in the last compaction stage. It is possible to observe that the maximum settlement is located between the 10 and 30 m from the top o the dam. The maximum horizontal displacements in the homogeneous dam do not exceed 90 cm, which is an acceptable value for large homogeneous earth dams.

These analyses were performed for the heterogeneous dam as well. The maximum settlement for the soil compacted at optimum moisture content was 2.26 m, and 2.31 m for the soil compacted at optimum moisture +5 % content. The settlements for the heterogeneous dam were lower than those computed for homogeneous dams.

Figures 28 and 29 show the distribution of maximum vertical and horizontal displacements along the central axis of the heterogeneous dam for the sixth stage of construction. The maximum horizontal displacements were around 70 cm.

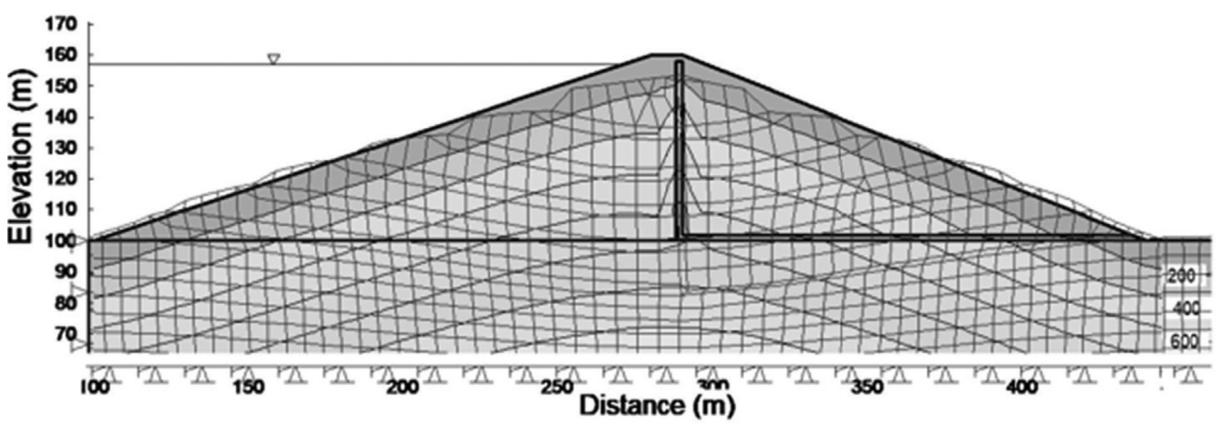

Figure 22. Total stress for the homogeneous dam.

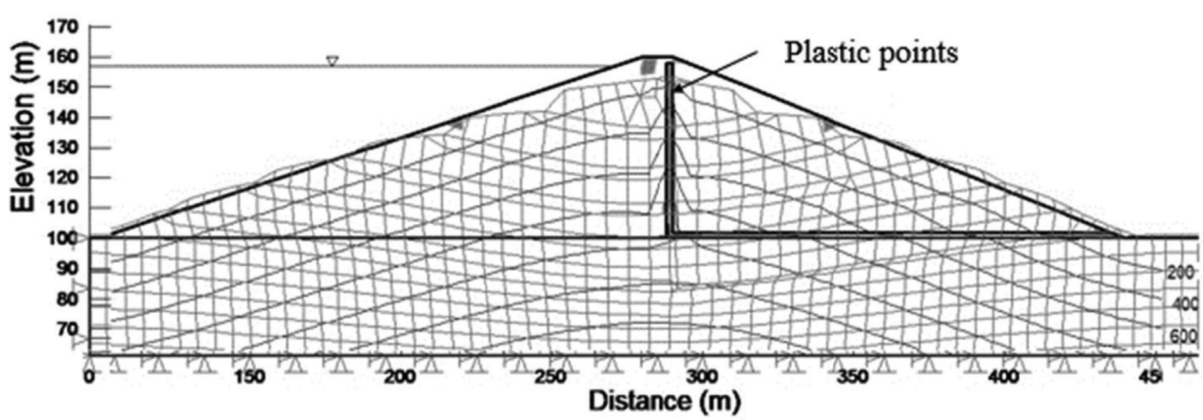

Figure 23. Plastic points for the homogeneous dam.

3. Conclusions

This research analyses the influence of water content in compacted soil for dam construction. The study begins with the characterization of the construction materials. Then a numerical model uses these results to model two geometries of dams. The research found that earthen dams could be constructed using soil above the optimum water content under strict conditions of this research. These results could be an aid in the construction of dams in tropical regions. The conclusion was divided into material characterization and numerical model results. The conclusions are summarised as follows:

3.1 Experimental campaign

The macro and micro-structures of the samples constructed with different water contents presented a diverse configuration. Soils compacted above the optimum present a random particle orientation, where the aggregation is more notorious in samples with height water content.

The variable head permeability tests show that the soil samples compacted at optimum moisture content presented the lowest hydraulic conductivity value. Additionally, an increment of hydraulic conductivity was observed

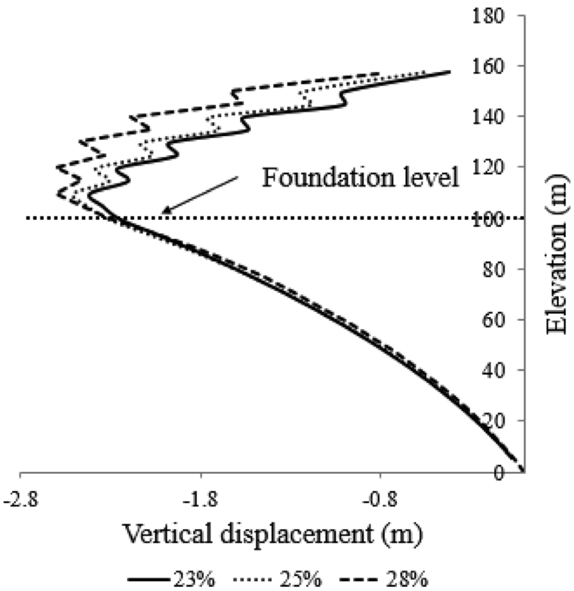

Figure 26. Maximum vertical settlement in the central axis (elevation) for the homogeneous dam.

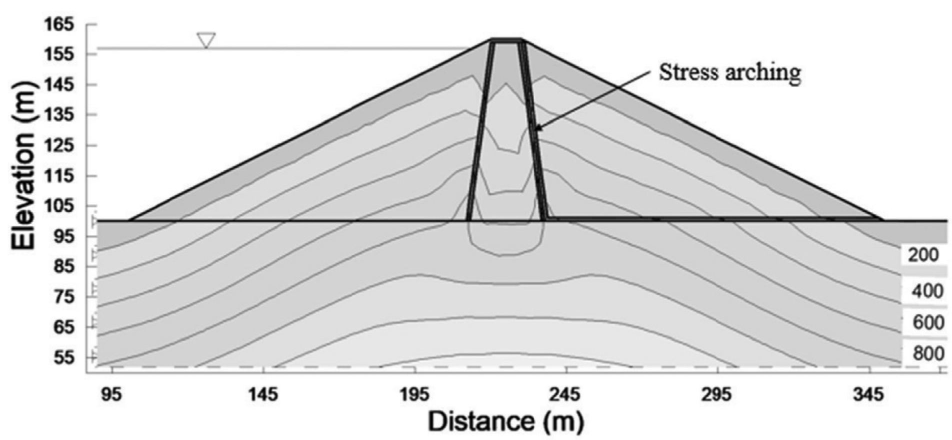

Figure 24. Total stress for the heterogeneous dam.

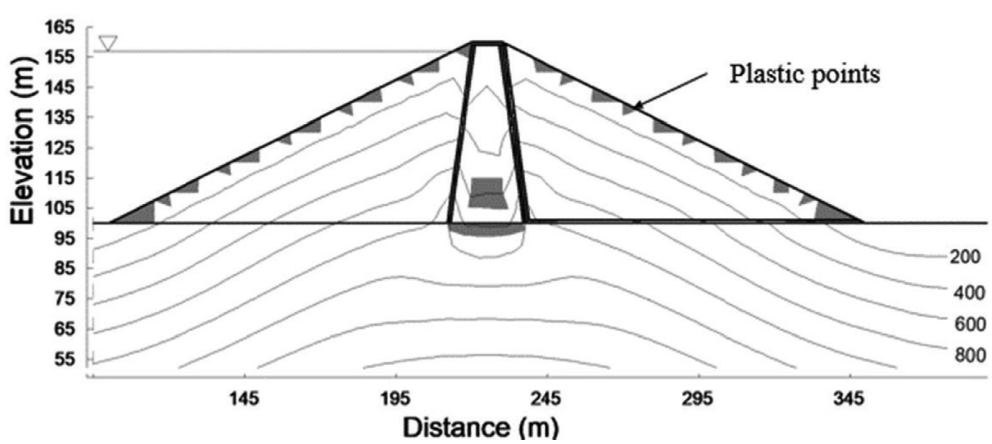

Figure 25. Plastic points for the heterogeneous dam.

for samples constructed with 2 % to 5 % water content above the optimum.

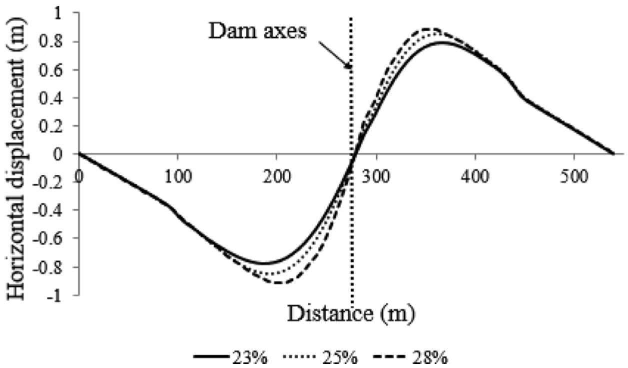

Figure 27. Maximum horizontal displacement along the homogeneous dam base.

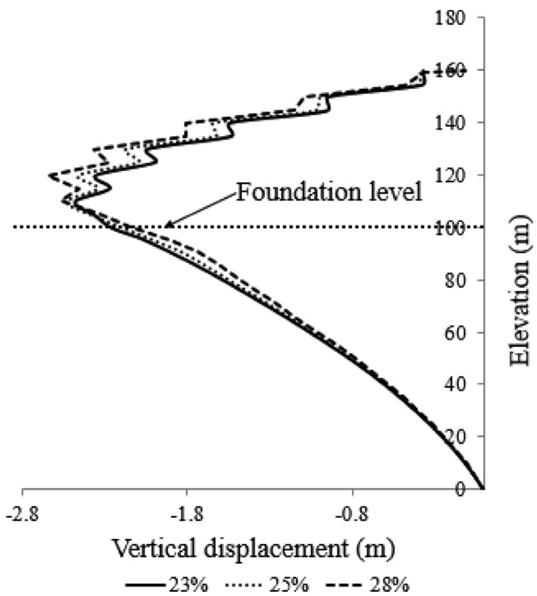

Figure 28. Maximum vertical settling in the central axis for the heterogeneous dam.

From the consolidation, it is possible to conclude that the samples compacted at optimum moisture content present the minimum compressibility, and they have similar behavior to the soil compacted 2 % above optimum. On the other hand, the soil compacted +5 % above the optimum moisture content have the maximum compressibility.

The soil compacted at optimum moisture content exhibited the best strength parameters from the consolidated drained triaxial tests. The soil compacted 2 % above optimum moisture content showed a decrease in the cohesion and friction angle, while the soil compacted at optimum moisture +5 % content showed a significant reduction in the friction angle but an increase of cohesion.

3.2 Numerical simulations

The two studied cross-sections will not tend to have problems related to flow across the dam, due to the material low permeability coefficients. Also, observing the gradients, it is possible to conclude that both cross-sections will not tend to suffer from *piping*.

According to the stability analysis for the homogeneous dam during the end of construction and operation phases, it can be observed that the safety factor decreases as the compaction moisture content increases, for the end of construction stage, the safety factors were always higher than the recommended minimum values. Additionally, it is possible to observe that the safety factors during the operation phase are inferior to those obtained at the end of construction. This fact can be attributed to seepage developed in the operational phase.

In the case of the homogeneous dam, the lowest safety factor corresponds to the soil compacted at optimum moisture +5 % content. The minimum factor of safety was 1.4 for the upstream slope, very close to the recommended minimum value. Thus soils with water content above the optimum could be used with small changes in geometry or

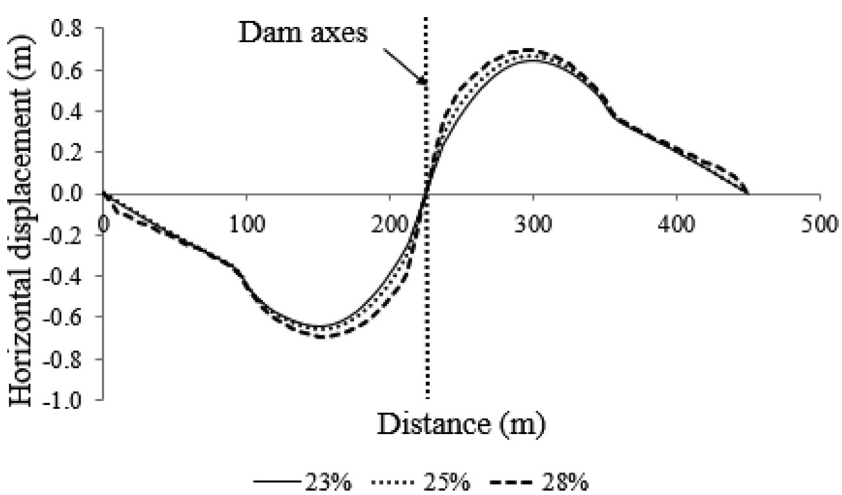

Figure 29. Maximum horizontal deformations along the heterogeneous dam.

compaction energy when considering the steady-state operation regime.

For the rapid drawdown analysis, the homogeneous dam showed lower safety factors than heterogenous dams. In the case of homogeneous dams, water pore pressures were relived in a longer period which leads to an inferior factor of safety.

On the other hand, the heterogeneous dam shows satisfactory safety factors. Also, it is possible to observe that for both analyzed cross-sections, the material compacted with higher moisture content has a superior long-term stability behavior than the other materials. This can be attributed to the rapid dissipation of pore water pressure. During the construction stage, the maximum vertical displacement is located between the base and the first 30 m of the dam height.

In general, it is possible to conclude that the behavior of the compacted fine material above the optimum moisture content for the heterogeneous dam presents an acceptable mechanical performance during the seepage, slope stability, and stress-strain analyses. The simulations exhibited favorable safety factors. The deformations were below the permitted limits, showing the acceptable mechanical performance of the tested soils. Therefore, using soil above the optimum water content is technically acceptable and can represent significant savings for projects built in tropical regions with high rainfall, difficult access, and difficulty accessing certain materials.

Using compacted local fine soils with water content above the optimum may be the only and the best option from the economic point of view in these high precipitation regions. The technical requirements necessary to guarantee the stability and functionality could be achived using this soil.

It is important to take into account that the moisture content control during the compaction process must be rigorous so that it does not exceed the upper limit and the best characteristics of the materials are achieved. Additional studies must be carried out for different types of materials. The permeability, deformability, and strength depend on factors such as mineralogy, particle shape, and structure of the material.

This research shows the importance of the topic, and leave guidelines to professional practitioners about the considerations taken when non-standard materials are used.

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