International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:13, No:6, 2019

Effect of Moisture Content Compaction in the Geometry Definition of Earth Dams

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***Abstract*—**This paper presents numerical flow and slope stability simulations in three typical sections of earth dams built in tropical regions, two homogeneous with different slope inclinations, and the other one heterogeneous with impermeable core. The geotechnical material parameters used in this work were obtained from a lab testing of physical characterization, compaction, consolidation, variable load permeability and saturated triaxial type CD for compacted soil samples with standard proctor energy at optimum moisture content (23%), optimum moisture content + 2% and optimum moisture content +5%. The objective is to analyze the general behavior of earth dams built in rainy regions where optimum moisture is exceeded. The factor of safety is satisfactory for the three sections compacted in all moisture content during the stages of operation and end of construction. On The other hand, the rapid drawdown condition is the critical phase for homogeneus dams configuration, the factor of safety obtained were unsatisfactory. In general, the heterogeneous dam behavior is more efficient due to the fact that the slopes are made up of gravel, which favors the dissipation of pore pressures during the rapid drawdown. For the critical phase, the slopes should have lower inclinations of the upstream and downstream slopes to guarantee stability, although it increases the costs.

***Keywords*—**Earth dams, flow, moisture content, slope stability.

I. INTRODUCTION

BRAZIL is a country with approximately 8.516.000 km^2 of territorial extension, and due to this fact it is possible to observe different topographies and climates according to a specific region. Moreover, it is a tropical country, thus the Brazilian soil presents different behavior and properties in comparison with temperate soils. For this reason it is necessary to study the mechanical and hydraulic behavior of tropical soils in order to use it in constructions, as foundation materials or building materials.

The present article discusses the behavior of a typical lateritic soil from Distrito Federal, Brazil, to be used in earth dams constructions in regions of high rainfall. In these regions, the construction of earth dams becomes difficult and inefficient then it is usual to make soil treatments in the soil to reduce moisture before compaction. However, this practice can cause major delays and increase costs of work.

The compaction of the core and shell materials is extremely necessary once the geotechnical properties depend directly on the degree of compaction achieved.

The unsaturated soils formed by the compaction process are highly heterogeneous, with groups of particles forming aggregates. The voids within the aggregates are usually filled with water in such a way that each individual aggregate consists of a saturated soil. The inter-aggregate voids are filled with air or with a mixture of air and water in such a way that the soil is unsaturated at a macro-scale level [1].

In general, the compaction process improves the mechanical behavior of soils. However, it also changes the soil structure and modifies the anisotropy of its mechanical properties [2].

Compacted soils in the dry side of the compaction curve have higher peak shear strength when compared to the wet side. In addition, the failure is considered fragile for the soils compacted in the dry condition and plastic for the wet condition. The reason for this behavior consists in the difference between the soil structures after compaction and consequently, in the pore pressures that develop during the triaxial tests, which are higher in the wet side. Certain compacted soils may have a collapsible structure, and when saturated they result in an abrupt deformation and cracking [3].

Soils that are compacted above to the optimum moisture content area of the compaction curve have lower modulus of elasticity, creating low resistance and high pore pressure during the construction process.

This context led to performing an investigation to evaluate the influence of the moisture compaction in the flow and slope stability of three typical earth dam sections widely used in Brazil and other tropical countries. The safety factors were obtained for upstream and downstream slopes during the stages: end of construction, operation and rapid drawdown condition.

II. MATERIALS AND METHODOLOGY

Numerical simulations of flow and slope stability for three typical hypothetical sections were developed. The first one, heterogeneous with clay core and gravel shells and another two homogeneous sections with different slope inclinations.

A. Geotechnical Parameters of the Soil

The geotechnical soil parameters used were presented by [4]. This soil was collected at the University of Brasilia - Brazil, at a depth of about 1,5 m. It represents the soils from Distrito Federal that, according to [5] are covered by a layer of soil originated from chemical weathering processes associated with leaching and lateralization of Tertiary and Quaternary periods.

The soil was classified as sandy lateritic clay according to the MCT methodology, and as silt of low plasticity according to the

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USCS methodology. MCT methodology is more coherent with tactile and visual evaluation of the soil under study.

The results of characterization tests from the collected soil are presented in Table I.

TABLE I
SOIL PROPERTIES

Soil properties		
With deflocculant	Gravel (%)	0
	Sand (%)	58,9
	Silt (%)	24,4
	Clay (%)	16,7
Without deflcocculant	Gravel (%)	0
	Sand (%)	74,8
	Silt (%)	24
	Clay (%)	1,2
	Unit weight - ϒ (kN/m³)	17,55
	Specific gravity of the soil - G	2,74
	Moisture content - Wnat (%)	27
	Liquid limit - Wl (%)	35,74
	Plastic limit - Wp (%)	23,2
	Plasticity index - IP (%)	12,54
	SUCS Classification	ML
	MCT Classification	LA'-LG'

Table II shows the geotechnical parameters obtained from lab testing of compaction, permeability, consolidation and triaxial for all different materials of the dam. The parameters of foundation, shells and filter materials were found in the literature for similar works.

B. Numerical Simulations in GeoStudio Software

Numerical simulations of flow and slope stability were performed in Seep / W and Slope / W software, respectively. The software belongs to GeoStudio package, created by Slope International Ltda.

C. Modeled Sections

Three hypothetical sections, common in tropical countries with high rainfall regimes, were analyzed. The first section being a homogeneous earth dam with slope inclinations of 1: 3 for the upstream slope and 1: 2.5 for the downstream slope. The second one also constituted a homogeneous earth dam, however with inclinations of 1: 4 in both the upstream and downstream slopes. Finally, the last section consisted of a zoned earth dam with impermeable central core and slopes made of gravel with inclination of 1: 2, this material allows a greater inclination of the slope. Fig. 1 shows the typical sections modeled.

TABLE II
GEOTECHNICAL PARAMETERS USED FOR THE NUMERICAL SIMULATIONS

Material		γ(kN/m³)	Φ(°)	c (kPa)	k (m/s)	Ko	Ru
Foundation soil		18	28	30	1.00E-11	0.5	0.2
Gravel Shells		20	38	10	1.00E-04	0.5	0
Transition material		20	32	0	1.00E-03	0.5	0.05
Filters		20	30	0	1.00E-03	0.5	0.05
Clay core	w optimum moisture	19.1	27	48	1.00E-09	0.55	0.25
Embankment soil (homogeneous)		19.1	27	48	1.00E-09	0.55	0.25
Clay core	w optimum moisture +2%	18.9	26	30	5.00E-09	0.56	0.3
Embankment soil (homogeneous)		18.9	26	30	5.00E-09	0.56	0.3
Clay core	w optimum moisture +5%	18.5	14	50	1.00E-08	0.7	0.5
Embankment soil (homogeneous)		18.5	14	50	1.00E-08	0.7	0.5

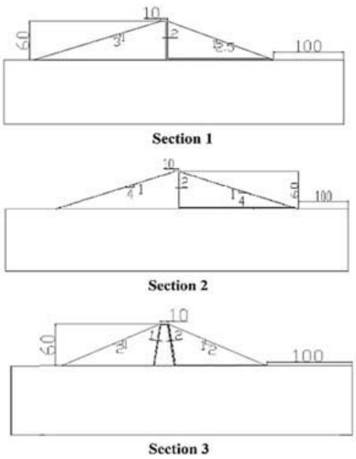

Fig. 1 Typical sections used for the analysis

III. RESULTS AND ANALYSIS

A. Percolation Analysis

Water flow analysis was performed through the three studied sections according to the following steps:

1) Operation, where the flownet was established considering the water load on the upstream slope.
2) Rapid drawdown condition, considering a drawdown period of 15 days (1.296.000 seconds).

Fig. 2 shows the water flow rate values in $m^3/s/m$ for the three sections analyzed in the three moistures compaction of study.

It is possible to observe that the water flow rate values are low because the material used is silty clay with low permeability. The homogeneous sections have lower water flow rates because they are homogeneous masses, while the shells of the heterogeneous dam were built with gravel, which increases the permeability value of the dam. Hydraulic gradients were below 3 for all cases.

By analyzing the rapid drawdown condition, it is evident that this process affects more the compacted soil at optimum moisture content, which has a greater value of impermeability, what causes a slower dissipation of pore pressures in comparison with the other optimum moisture content conditions that have been studied.

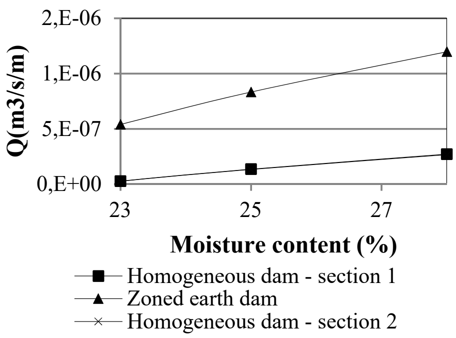

Fig. 2 Water flow values for the studied sections at different moistures compaction

B. Slope Stability Analysis

The minimum safety factors (FSmin) were verified by the software Slope / W and using the rigorous method of [6]. This method considers the equilibrium of vertical and horizontal forces and moments. This analysis was performed through three situations: end of construction, operational stage and rapid drawdown condition.

1) End of Construction

The evaluation of the safety factor in the final stage of construction is performed for both upstream and downstream slopes as shown in Table III.

TABLE III
SAFETY FACTORS FOR END OF CONSTRUCTION CONDITION

Moisture content	Section	FS upstream slope	FS downstream slope
Optimum moisture content	Homogeneous section 1	2,24	2,21
	Homogeneous section 2	2,70	2,69
	Zoned earth dam section 3	2,01	1,89
Optimum moisture content + 2%	Homogeneous section 1	2,18	1,90
	Homogeneous section 2	2,50	2,45
	Zoned earth dam section 3	1,97	1,99
Optimum moisture content + 5%	Homogeneous section 1	1,61	1,61
	Homogeneous section 2	1,70	1,76
	Zoned earth dam section 3	1,94	1,97

It can be seen that the safety factors of the homogeneous sections drastically decrease with an increasing of the moisture compaction, while in heterogeneous dam the safety factor remains almost constant. This can be explained because the shells are made up of gravels and the geomechanical characteristics of this material ensure stability. The thin core material is confined and does not have much influence on the stability during the end of construction.

2) Operational Stage

At this stage the netflow and pore pressure values were imported from percolation analysis made in the Seep/W software. The upstream slope presents the most critical condition, since the water reservoir downstream generates stability whenever it maintains a constant level of operation.

Table IV shows the safety factors for the three sections of study.

TABLE IV
SAFETY FACTORS FOR THE OPERATIONAL CONDITION

Moisture content	Section	FS downstream slope
Optimum moisture content	Homogeneous section 1	1,85
	Homogeneous section 2	2,31
	Zoned earth dam section 3	1,68
Optimum moisture content + 2%	Homogeneous section 1	1,83
	Homogeneous section 2	2,24
	Zoned earth dam section 3	1,66
Optimum moisture content + 5%	Homogeneous section 1	1,36
	Homogeneous section 2	1,73
	Zoned earth dam section 3	1,64

Analyzing Table IV is possible to observe that in all situations the safety factor value decreases in comparison with the final stage of construction, due to the establishment of a netflow. Furthermore, the soil compacted with optimum moisture content +5% had the lowest safety factors. The 1,36 value obtained for section 1 represents an unsafe condition, thus is necessary to reduce the slope inclination as in the case of section 2. The other safety factor values are above 1,5 representing a favorable condition for this stage.

3) Rapid Drawdown Condition

The data was imported similarly as to the operation stage from Seep/W. The critical situation of this analysis occurs when the dams are built with thin materials compacted with low permeability coefficient. The excess of pore pressure can lead to dam failure if it is not properly drained.

A drawdown period of 15 days was adopted through a linear function and the water level has gone from 57 m to 0 m at the dam foundation. In this situation the analysis was performed only on the upstream slope which presented excess of pore pressure.

Fig. 3 shows how the safety factor varies with time for section 1. The graph represents the behavior of the homogeneous dam until the day 266, due to the slow dissipation of pore pressures.

Fig. 4 shows the results for section 2. It may be seen that the safety factor values are slightly larger in comparison with Section I, because of the smaller slope inclination.

Fig. 5 considers the third situation which represents a heterogeneous dam built with gravel material for the shells and a siltly clay material for the core.

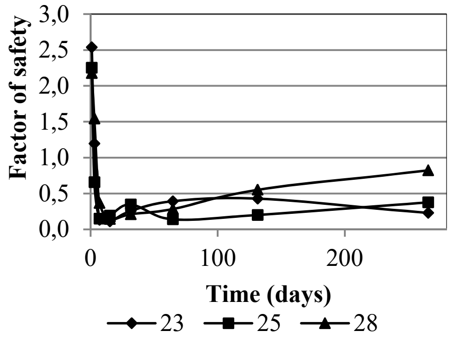

Fig. 3 Safety factor vs Time (homogeneous dam - section 1).

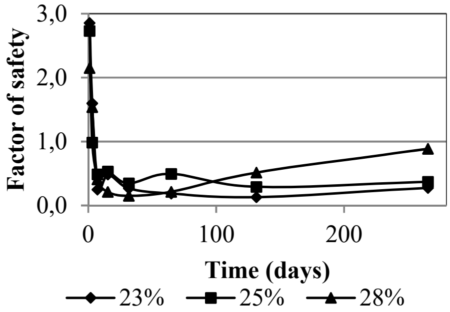

Fig. 4 Safety factor vs Time (homogeneous dam - section 2)

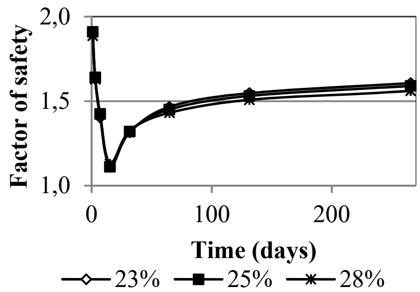

Fig. 5 Safety factor vs Time (heterogeneous dam - section 3)

It can be observed that, due to the high gravel permeability coefficient, the heterogeneous dam rapidly dissipates excess pore pressure. This dam is considered safe because the safety factor never reaches values below 1.1, the FSmín value recommended in the technical literature for this type of analysis.

It is important to note that in the three graphs, the compacted soils with standard proctor energy at optimum moisture + 5% (28%) underperformed, considering a short term. However, observing the dissipation of pore pressures over time, it is possible to see that this material has a greater performance and quickly recovers the stability because with such compaction moisture the permeability coefficients are larger.

IV. Conclusion

According to the percolation analysis, it can be concluded that the three studied sections tend to have no flow issues due to the low permeability coefficient of the compacted material in the three optimum moisture content energies analyzed. The material gradient values are lower than 3 and it cans also be concluded that there is no risk of piping.

The slope stability is satisfactory during the operation and end of construction stages.

The rapid drawdown stage is the critical phase for compacted materials with low permeability. Granular soils favors the dissipation of pore pressures in heterogeneous dam.

Sections I and II have similar behavior for the rapid drawdown condition. Once the section 2 has a slightest slope inclination, its safety factor is higher at the beginning of this phase. However, from the third day of drawdown, this dam presents safety factor values lower than 1.0 which indicates that none of the sections would be stable in this situation.

The heterogeneous dam has greater overall performance in all stages and safety factors are quite similar in the three moistures core compaction, which means that the core material does not have much influence on the results of the slope stability analysis. Stability is governed by the properties of the granular material of the shells.

Acknowledgment

The support of the Foundation for Research Support of the Federal District (FAP – DF) is acknowledged and appreciated.

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