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STUDY OF SEEPAGE AND STABILITY OF RURAL DAMS COMPACTED IN THREE DIFFERENT MOISTURE CONTENTS

ESTUDO DA PERCOLAÇÃO E ESTABILIDADE DE TALUDES DE PEQUENAS BARRAGENS RURAIS COMPACTADAS EM TRÊS DIFERENTES UMIDADES

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ABSTRACT

This paper presents the study of stability and percolation of two dams sections with 5 m high, one composed by horizontal sand filter, and the other by a rockfill drain localized at the toe of the downstream slope. The stability analyzes were performed using Slope / W software, using the Simplified Bishop Method (1955), while the percolation analyses were performed by Seep / W software based on the theory of finite elements. In order to obtain the necessary parameters were conducted laboratory tests using disturbed and undisturbed soil samples collected at the Faculty of Agricultural Engineering at Unicamp. The samples used for shear strength determination and permeability tests were compacted at optimum moisture content and in 4% moisture deviation from this value in order to verify the influence of compaction moisture content on variation of slopes safety factors. The performed stability analyses demonstrated the variation of the safety factors depending of compaction moisture content, geometrical characteristics and type of drainage element. It was also observed that the flow in the analyzed sections occurs predominantly in foundation.

KEYWORDS: Earthfill dams, compaction moisture content, slope stability, seepage.

RESUMO

Este trabalho apresenta o estudo da estabilidade e percolação de duas seções de barragens com 5 m de altura, uma composta por filtro horizontal, e outra por dreno de enrocamento no pé do talude de jusante. As análises de estabilidade foram realizadas com uso do programa computacional Slope/W empregando-se o Método de Bishop Simplificado (1955), enquanto que as análises de percolação foram efetuadas pelo programa computacional Seep/W, baseado na teoria dos elementos finitos. Para a obtenção dos parâmetros foram conduzidos ensaios laboratoriais em amostras deformadas e indeformadas coletadas na Faculdade de Engenharia Agrícola da Unicamp. Os corpos de prova utilizados nos ensaios de resistência e permeabilidade foram compactados na umidade ótima e com desvios de umidade de 4% em relação a este valor no intuito de se verificar a influência da umidade de compactação na variação dos coeficientes de segurança de taludes. De acordo com as análises de estabilidade efetuadas pôde–se verificar que as seções estudadas apresentaram variação nos fatores de segurança em função do teor de umidade, de aspectos geométricos e tipo de elemento de drenagem. Também se concluiu que o fluxo nas seções analisadas ocorrerá predominantemente na fundação.

PALAVRAS-CHAVE: barragens de terra, compactação, estabilidade de taludes, percolação.

1 – INTRODUCTION

The moisture content at which soil is compacted significantly influence shear and compressive strengths, deformability and permeability parameters of soil. This way, in earthworks such as dams and landfills, the importance of performing an effective control of compaction moisture during construction is very important to guarantee performance of the earthwork.

Compaction reduces void soil by application of dynamic energy. This operation has great advantages in dealing with earthworks. By performing field compaction with appropriate equipments, the soil used to build an embankment has its strength increased and both its permeability and deformability reduced.

The stability of a slope earthfill dam can be defined by safety factors (SF), which can be specified as the ratio between strength (s) soil shear and the acting shear stresses (τ), i.e.: $Fs = s/\tau$. Generally, these slopes, in a limit equilibrium situation tend to present a displacement oriented by slip surface, which may be circular, linear or translational according to the local geological conditions.

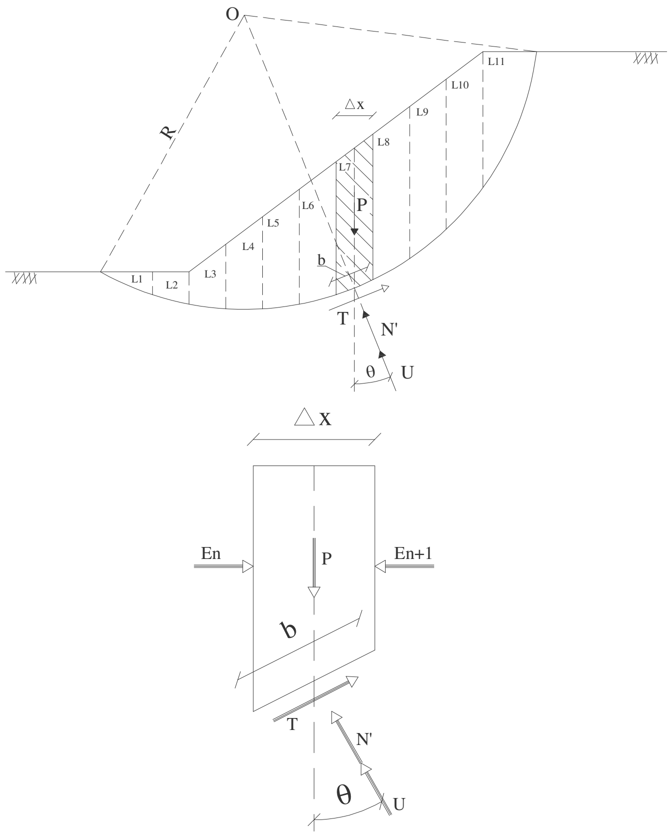
Among methodologies most commonly used for stability evaluation of earthfill dams, can be highlighted the Bishop's simplified method (1955), presented in Massad (2003). According to Massad (2003), this methodology assumes the occurrence of a circular slip surface in a limit equilibrium condition (SF = 1,0). The portion of soil situated above this slip surface may be divided in many soil slices. This method satisfies vertical force equilibrium for each slice and overall moment equilibrium about the center of circular trial surface. Since horizontal forces are not considered at each slice, the Bishop's simplified method also assumes no one interslice shear forces. The safety factor can be calculated by Equation (1):

$$FS=\frac{\sum\left[c'l+\dfrac{P-u.\Delta x-(c'\Delta x.\tan\theta/FS)}{\cos\theta+\tan\varphi'.sen\theta/FS}.\tan\varphi'\right]}{\sum(P.sen\theta)} \tag{1}$$

Where:
c´ and φ'= cohesion and angle of friction to the base center of soil slice;
l = length of the lamella base;
P = slice weight;
u = pore pressure in the slice center;
Δx = thickness of the slice;
θ = inclination of the slice base.

The following figure shows the stress distribution considered by the Bishop's simplified method (1955), as shown in Massad (2003).

Figure 1 – Stress distribution in the Bishop's simplified method (1955)



Source: Massad, 2003

Thus, the analysis of slope stability in a dam should be based on safety factors peculiar to the following efforts to which a dam is subject to: a) end of construction, b) full reservoir ($NA_{maximum}$), c) quick reservoir lowering ($NA_{maximum}$ to $NA_{minimum}$). In Table 1 is listed the minimum safety factors for each stability condition according to Cruz (1996).

Table 1 – Minimum safety factors (SF) recommended by Cruz (1996)

Stability condition	Slope	Minimum SF
End of construction	Upstream	1.3
	Downstream	1.3
Quick reservoir lowering	Upstream	1.1
Full reservoir	Upstream	1.5
	Downstream	1.5

The stability conditions presented in Table 1 are described by Bordeaux (1980) and can be considered as: a) End of construction – During the compaction of an earthfill dam's embankment, most of solicitant efforts are in function of compacted soil weight and pore pressures dissipation. In addition, these efforts are dependent of type and moisture content of the soil used and the velocity of the compaction works. b) Full reservoir – After the complete reservoir filling, a seepage flow through embankment can be observed, raising a seepage pattern. Considering that water flows from upstream to downstream, the seepage pressures are favorable to stability of the upstream slope and unfavorable to stability of downstream slope. c) Quick lowering reservoir - in this situation, the water Table of the reservoir is lowered from maximum to minimum level with velocity superior than pore pressures dissipation. Thus, the saturated portion inside the embankment remains until a determined period of time that will depend of permeability conditions of the compacted soil. In this situation, the critical slope in terms of stability is the upstream slope.

An earthfill dam construction should follow design specifications, developed for the local soil geotechnical properties, obtained through laboratory and field testing. However, sometimes the dam execution is performed based solely on the empirical experience of its executioners, adopting, for example: inadequate slopes of embankments, in addition to insufficient internal and external drainage systems. (PASCHOALIN FILHO, 2002).

2 – METHODOLOGY

To obtain the necessary parameters for this research, laboratory tests were carried out according their technical standards. The used procedures are described in the following sections.

2.1 – Experimental site soil characterization

The soil samples were collected from the Experimental Field for Soil Mechanics Studies located in the Faculty of Agricultural Engineering of State University of Campinas (UNICAMP), in the east-central region of São Paulo State, on the Atlantic Plateau. Its geographic position is determined by the coordinates 22°53'22" for south latitude and 47°04'39" for longitude.

Concerning geologic conditions, there can be found in the studied area basic intrusive rocks from Serra Geral formation. The lithology is predominantly diabase, mineralogical composed of labradorite, augite clinopyroxene or pigeonite (or both), and accessories of titanite, magnetite and apatite. Basic magmas also often occur in the northern region of Campinas, totalising 98 km^2 with 14% from the total area of Campinas. The subsoil of the experimental field consists of a thick layer of unsaturated soil, in which the groundwater level is found at the depth of 18 m. The bedrock is not verified to a depth of 40 m.

To conduct laboratory tests, undisturbed samples were collected by extracting 0.3 x 0.3 x 0.3 m monolithic soil blocks according to ABNT (Associação Brasileira de Normas Técnicas) NBR: 9604:1986 recommendations. Disturbed soil samples were also obtained, which were immediately packed in plastic bags after collection, aiming to keep their natural moisture content. After collection, the samples were prepared as suggested by ABNT: NBR 6457: 1986 recommendations.

2.2 – Laboratory tests carried out

The following geotechnical parameters were obtained for the undisturbed samples: natural specific weight (ρnat); natural moisture content (w = water mass/dry mass); dry density (ρd = dry mass/total volume); void ratio (e); porosity (n); degree of saturation (Sr). The following tests were performed using deformed samples, by procedures recommended by specific technical standards: Grain Size Distribution (ABNT NBR 7181:1984); Liquid Limit (ABNT NBR 6459:1984); Plasticity Limit (NBR 7180/1988); Specific Gravity of Solids (ASTM D 854-00); and Compaction Test (ABNT NBR 7182:1986).

The compaction tests were performed with the lowest energy compaction provided by the ABNT NBR 7182:1986: Metal cylinder with mass of 2,500 g, drop height of 305 mm, compacting the soil in three layers within a 1,000 cm^3 cylinder by applying 26 blows on each layer. This test is technically known as Proctor Compaction Test.

To obtain the shear strength parameters of soil in its natural and compacted conditions necessary for the slope stability analysis, quick undrained triaxial shear tests were conducted, with pore pressure measurement in saturated and unsaturated specimens (CU and CU$_{sat}$). The tests were carried out based on the recommendations obtained in Head (1992).

To determine the saturation zone located within each studied dam cross section, (this information is necessary for calculating the stability of the upstream and downstream slopes), laboratory tests were carried out aiming to obtain permeability coefficients. Thus, there were preformed permeability tests using vertical and horizontal flow directions according to the recommendations of ABNT NBR 14545:2000. This procedure was used to verify the variation of this parameter with the flow direction, which occurs within earth dams as a function of the lamination formed by overlapping layers of compacted soil. After obtaining the permeability coefficients in the horizontal and vertical flow directions, it was calculated an equivalent permeability coefficient by means of the following equation presented by Cruz (1996). After, there was obtained the water Table inside the each studied section. This water Table consists in a boundary line between the saturated and unsaturated areas inside the earthfill dams.

$$k' = \sqrt{kh * kv} \quad \text{(cm/s)} \tag{2}$$

Where:
k' = equivalent permeability coefficient;
kh = permeability coefficient in the horizontal flow direction (T=20 ºC);
kv = permeability coefficient in the vertical flow direction (T=20 ºC).

2.3 – Specimens

To characterize the soil foundation of the studied dam´s cross sections, specimens carved from blocks of undisturbed soil samples were used. There were also compacted specimens in their optimum moisture and in a range of more 4 % and less 4 % from such value. This procedure was adopted aiming to obtain the geotechnical soil parameters variation according its compaction moisture content, and how this it may influence the studied dam´s stability. For shear strength tests were molded 10 cm high by 5 cm in diameter specimens, respecting the height/diameter relation equal to 2. For permeability tests were molded specimens 10 cm high and 10 cm in diameter. In Table 2 is showed the amounts of specimens for each laboratory test performed.

Table 2 – Number of specimens carved for each laboratory test carried out

Test	+4 % W$_{optimum}$	W$_{optimum}$	–4 % W$_{optimum}$	Undisturbed samples	Total
Triaxial shear tests	6	6	6	6	24
Permeability tests	3	3	3	3	12

W$_{optimum}$= Optimum moisture content; Total of carved specimens: 36. Source: the authors

2.4 – Cross sections determination

Aiming to study the safety factors variations of dam´s slopes according to their geometry and geotechnical characteristics, two hypothetical cross sections were modeled with 5 m height. One cross section was provided with horizontal sand filter, and the other cross section was provided with a rockfill drain at the toe. The subsoil of the studied experimental site was considered as foundation for the studied hypothetical dam sections by the carried out analyses. The foundation was considered as a homogeneous residual soil layer of 6 m thickness.

The preliminary analysis was performed using upstream and downstream slopes of 3 horizontal: 1

vertical and 2.5 horizontal: 1 vertical, respectively. These slopes were chosen because they are commonly used in small rural earthfill dam designs in the region of Campinas, SP according to Paschoalin Filho (2002). After that, different slopes were also analyzed in order to obtain the variation of the safety factors according to slope rates. In Table 3 are presented the geometric characteristics adopted for each hypothetical cross section. The geotechnical parameters for sand and rockfill drains were adopted considering materials already known in the region and used in other dam designs and are shown in Table 4. In Figures 2 and 3 are presented the analyzed cross sections.

Table 3 – Dam geometric parameters

H (m)	NA$_{max}$ (m)	Crest width (m)	Freeboard (m)	Cut off depth (m)	LFH (m)	EFH (m)	Cut off slope (H):(V)	Rockfill drain slope (H):(V)
5	4.5	3	0.5	1.0	---	---	1:1	1.5:1.0
5	4.5	3	0.5	1.0	12.5	0.7	1:1	---

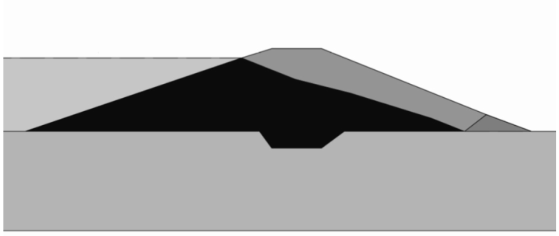
LFH = length of horizontal sand filter; EFH = thickness of the horizontal sand filter. Source: the authors

Table 4 – Geotechnical parameters adopted for sand

Material	ρnat (kN/m3)	c (kPa)	φ (o)	k20 (cm/s)
Sand	26.7	0	30	$1\cdot10^{-2}$
Rockfill	30.0	0	35	1.0

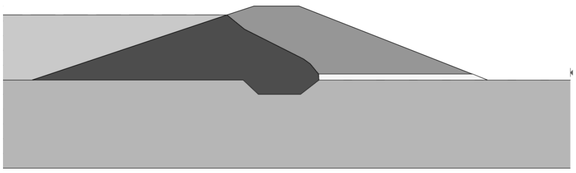
ρnat = specific natural weight; c = cohesion intercept; φ=effective friction angle; k$_{20}$=coefficient of permeability. Source: the authors

Figure 2 – Analyzed hypothetical cross section provided with rockfill drain



Source: the authors

Figure 3 – Analyzed hypothetical cross section provided with horizontal sand filter



Source: the authors

2.5 – Slope stability analysis

For the slope stability analyses the Bishop's simplified method (1955) was carried out considering circular slip surfaces corresponding to the following stability conditions: a) end of construction, b) full reservoir c) quick reservoir lowering. The safety factors used were in accordance with those presented by Cruz (1996) (as presented in Table 1). For demands relating to the full reservoir and the quick reservoir lowering, the water Table line was initially determined for each studied cross section. For the stability condition relative to full reservoir in the saturated portion of the simulated embankments, were used strength parameters obtained by saturated triaxial shear tests, while in dry portion (above the water Table) were used strength parameters obtained by unsaturated triaxial shear tests. In order to simulate the stability condition relative to quick reservoir lowering, the saturated portion was maintained, however, with water Table quota reduced to zero (NA$_{minimum}$). For the stability condition relative to end of construction, the analyses carried out considered unsaturated shear strength parameters and the reservoir completely empty.

Cross section's foundations were considered saturated in analyses carried out for the stability conditions relative to full reservoir and quick lowering. For the stability condition relative at the end of construction, cross section´s foundations were considered unsaturated. With the progression of analyses, the stability of upstream and downstream slopes of simulated embankments was determined. If embankments presented safety factors above the minimum presented in Table 1, their slopes would have been increased and new stability analyses would have been performed.

For the stability condition relating to full reservoir, analyses were processed for upstream and downstream slopes. When considering the stability conditions relating to quick lowering of reservoir, the analyses were carried out only for upstream slope, since according with Cruz (1996), this slope trends to prove more critical in terms of stability for this condition. Based on the stability analyses conducted to each studied condition for moisture content, were obtained slopes that led to safety factors closer to those recommended by Cruz (1996), in order to optimize each section as possible. After obtaining these optimized slopes, stability analyses considering the stability condition relative to end of construction were carried out. It was thus possible to obtain the slopes with satisfactory safety factors in all simulated requests and for moisture contents considered.

The stability analyses were performed using the software Slope/W developed by the Geo-slope Company. This program uses the limit equilibrium theory to calculate safety factors for slopes of compacted embankments, natural, and rocky among others. This is also used for determining the stability of solids with several layers of different materials and complex stratigraphy.

2.6 – Seepage analysis

After determination of initial hypothetical cross sections to be analyzed, studies of seepage flow within each section were carried out using software Seep/W. This software was developed by Geo-Slope Company and calculates seepage flow through embankments using the theory of finite elements. The computer analyses were processed considering the application of Darcy's theory for laminar flows. Phreatic lines were determined for the analyzed cross sections, considering each moisture content compaction studied. The seepage analyses were carried out only for sections with upstream and downstream slopes of 3 horizontal: 1 vertical and 2.5 horizontal: 1 vertical, respectively. Aiming to simulate the seepage flow under cross sections the experimental area subsoil was considered as foundation. The seepage flow analyses were carried out using parameters of equivalent permeability coefficients (as presented in Equation 1) obtained by permeability laboratory tests using specimens compacted in studied moisture contents.

3 – ACHIEVEMENTS AND DISCUSSIONS

The following section presents the obtained parameters by the tests carried out.

3.1 – Physical characteristics of experimental area

The obtained geotechnical parameters for each meter depth soil in its natural state are presented in Tables 5 and 6. The natural soil moisture content (water mass/dry mass) was obtained monthly by a period of one year and indicated values ranging from 22 % to 28 %. Determination of these parameters was very important to slope stability analyses conduction, because they were used to simulate the soil foundation of the studied dams sections.

Table 5 – Geotechnical parameters obtained for the studied experimental area in different depths.

Depth (m)	ρnat (kN/m^3)	ρs (kN/m^3)	w (%)	e	n (%)	Sr (%)
1	13.4	29.7	24.3	1.7	64.0	40.8
2	13.0	29.1	23.4	1.7	64.0	38.7
3	13.0	29.5	22.8	1.8	64.0	37.6
4	13.0	30.1	23.7	1.8	65.0	38.4
5	13.3	30.0	24.2	1.7	63.0	45.0
6	15.4	30.1	24.6	1.4	59.0	51.4
Av.value	13.5	29.7	23.8	1.7	60.0	41.9
SD	0.9	0.4	0.6	0.1	0.02	5.3
CV(%)	6.9	1.3	2.7	8.4	3.3	12.6

ρnat = natural specific weight; ρ s = specific grain weight; w = natural moisture content; e = void ratio; n = porosity; Sr = degree of saturation; SD = Standard Deviation; CV = Coefficient of Variation. Source: the authors

Table 6 – Grain Size Distribution and Atterberg's Limits

Depth (m)	Grain Size Distribution			Atterberg's limits		
	Clay (%)	Sand (%)	Silt (%)	Liquid limit (%)	Plastic limit (%)	Plasticity Index (%)
1	63	27	10	52	35	17
2	65	25	10	52	38	14
3	67	26	07	51	36	15
4	61	26	13	52	37	15
5	60	26	14	49	37	12
6	44	34	22	58	41	17
Average value	60.0	27.3	12.7	52.3	37.3	6.0
SD	8.2	3.3	5.2	3.0	2.1	8.2
CV (%)	13.7	12.2	41.1	5.8	5.5	13.7

Where: SD = Standard Deviation; CV = Coefficient of Variation. Source: the authors

3.2 – Compaction tests

Average values for optimum moisture content (w_{opt}) and maximum dry density (ρd_{max}), determined by compaction tests were 28 % and 15.3 kN/m^3, respectively. In Table 7 are presented the physical parameters obtained for specimens compacted at 24 % (–4 % w_{opt}), 28 % (w_{opt}), and 32 % (+4 % w_{opt}) in moisture content.

Table 7 – Physical indices obtained for compacted soil

Specimen	ρnat (kN/m^3)	ρdmax (kN/m^3)	ρsat (kN/m^3)	e	n (%)	Sr (%)
24 % (–4 % w_{opt})	17.6	14.2	19.5	1.1	52	65
28 % (w_{opt})	19.6	15.3	20.2	0.9	47	87
32 % (+4 % w_{opt})	18.9	14.3	19.6	1.1	52	88

Where: ρnat = natural specific weight; ρdmax = maximum dry density; ρsat = saturated specific weight; e = void ratio; Sr = degree of saturation. Source: the authors

Analyzing the values presented in Table 7, compacted soil is noted at optimum moisture content, presenting highest values of natural specific weight (ρnat), maximum dry density (ρdmax), and saturated specific weight (ρsat) among all studied compaction moisture contents. The specimens compacted at optimum moisture content also presented lower value of void ratio (e) and lower porosity (n). In an earth dam's situation, the compaction of embankment at optimum moisture content promotes the void ratio reduction increasing its impermeability, offering greater resistance to water flow thought the embankment. The compaction at optimum moisture content also increases soil shear strength parameters, causing embankment deformability reduction due the closer approximation between soil grains promoted by compaction. Thus, the expected benefits by compaction are obtained in their best values, when the soil is in its optimum moisture content.

3.3 – Permeability parameters

The effect of compacted soil structure is clearly demonstrated by coefficient of permeability obtained and presented in Table 8. The specimens compacted at optimum moisture content were those with the lowest average value of permeability coefficient among the tested samples; indicating that embankment compacted at this moisture level will present greater obstacle to the water percolation.

Table 8 – Parameters obtained in the permeability test.

Specimen	k_{20} vertical (cm/s) *	k_{20} horizontal (cm/s) *	K' equivalent(cm/s)**	$k_{20}h/k_{20}v$
24 % (–4 % $w_{optimum}$)	$5.60 \cdot 10^{-6}$	$5.0 \cdot 10^{-5}$	$1.67 \cdot 10^{-5}$	8.9
28 % ($w_{optimum}$)	$5.15 \cdot 10^{-7}$	$4.6 \cdot 10^{-6}$	$1.54 \cdot 10^{-6}$	8.9
32 % (+4 % $w_{optimum}$)	$6.41 \cdot 10^{-7}$	$5.5 \cdot 10^{-6}$	$1.84 \cdot 10^{-6}$	8.6
Undisturbed samples (w = 27.4 %)	$2.27 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	$3.40 \cdot 10^{-4}$	2.2

* For standard water temperature of 20 ºC, ** obtained from Equation (1). Source: The Authors

3.4 – Shear strength parameters

According to results presented in Tables 9 and 10, it is possible to verify that the specimens compacted at optimum moisture content were those with the highest values of shear strength. Therefore, the influence of moisture on the compaction shear strength of soils was check out. The shear strength of compacted specimens also varied according to degree of saturation. Saturated specimens had lower strength parameters in relation to unsaturated ones.

Table 9 – Shear strength parameters obtained by unsaturated consolidated undrained triaxial shear tests with pore pressure measurement ($\overline{CU}$).

Specimen	Test	c (kPa)	φ (º)	c´ (kPa)	φ´ (º)
24 % (–4 % $w_{optimum}$)	$\overline{CU}$	57	33	16	31.4
28 % ($w_{optimum}$)	$\overline{CU}$	92	20.5	35	24.1
32 % (+4 % $w_{optimum}$)	$\overline{CU}$	46	14.7	0	41.1
Und. samples (w = 27.4 %)	$\overline{CU}$	20	26.1	0	23.9

c'= effective cohesion intercept; φ' = effective friction angle; c= total cohesion intercept; φ= total friction angle. Source: the authors

Table 10 – Shear strength parameters obtained by unsaturated consolidated undrained triaxial shear tests with pore pressure measurement ($\overline{CU}_{sat}$).

Specimen	Test	c (kPa)	φ (º)	c' (kPa)	φ' (º)
24 % (–4 % $w_{optimum}$)	$\overline{CU}_{sat}$	40	12.5	30	18.2
28% ($w_{optimum}$)	$\overline{CU}_{sat}$	51	13.5	33	26.7
32% (+ 4 % $w_{optimum}$)	$\overline{CU}_{sat}$	19	9.4	18	20.9
Und. samples (w = 27.4 %)	$\overline{CU}_{sat}$	3	11.8	0	25.9

c' = effective cohesion intercept; φ' = effective friction angle; c = total cohesion intercept; φ = total friction angle. Source: the authors

3.5 – Slope stability analyses

Stability analyses were performed using the Bishop's simplified method (1955) as presented by Massad (2003), aiming to obtain the safety factors for each studied cross section in different stability conditions. The safety factors (SF) obtained was compared to the minimum safety factors for each stability condition related by Cruz (1996) as presented in Table 1. In Table 11 are presented safety factors obtained for cross sections with downstream and upstream slopes equal to 2.5(H): 1.0(V) and 3.0(H): 1.0(V) respectively. This procedure aimed to determinate the safety factors for slopes commonly used in small earthfill dams designs in the region of Campinas, SP, according to Paschoalin Filho (2002). In Tables 11 and 12 are presented the maximum upstream and downstream slopes that conducted to satisfactory safety factors.

Table 11 – Safety factors for cross sections with downstream and upstream slopes equals to 2.5(H):1.0(V) and 3.0(H):1.0(V), respectively

Cross Section	Compaction moisture content	Downstream slope	SF downstream slope	Upstream slope	SF upstream slope
5 m high section provided with horizontal sand filter	24 % (−4 % $w_{optimum}$)	2.5(H):1.0(V)	$2.0^{(1)}$, $1.8^{(2)}$, $1.6^{(3)}$	3.0(H):1.0(V)	$3.6^{(1)}$, $2.5^{(2)}$, $1.8^{(3)}$
	28 % ($w_{optimum}$)		$3.0^{(1)}$, 2.8 $^{(2)}$, $2.0^{(3)}$		$3.9^{(1)}$, $2.7^{(2)}$, $2.8^{(3)}$
	32 % (+4 % $w_{optimum}$)		1.8 $^{(1)}$,1.7 $^{(2)}$, $1.4^{(3)}$		$2.7^{(1)}$, $1.8^{(2)}$ $1.5^{(3)}$
5 m high section provided with rockfill drain	24 % (−4 % $w_{optimum}$)		$1.8^{(1)}$, 1.6 $^{(2)}$, $1.8^{(3)}$		$3.9^{(1)}$, $2.1^{(2)}$, $2.5^{(3)}$
	28 % ($w_{optimum}$)		2.0 $^{(1)}$, 1.8 $^{(2)}$, $1.8^{(3)}$		$4.0^{(1)}$, $2.5^{(2)}$, $3.0^{(3)}$
	32 % (+4 % $w_{optimum}$)		$1.7^{(1)}$, 1.5 $^{(2)}$, $1.7^{(3)}$		$2.9^{(1)}$, $1.6^{(2)}$, $2.0^{(3)}$

$^{(1)}$ stability condition of full reservoir; $^{(2)}$ stability condition of quick reservoir lowering; $^{(3)}$ stability condition of end of construction.

According to Table 11 the safety factor obtained for upstream and downstream slopes were conservative when compared to safety factor recommended by Cruz (1996) and presented in Table 1. The safety factors varied according to stability condition (full reservoir, quick reservoir lowering and end of construction) and with geotechnical parameters obtained for each studied moisture content. It also can be highlighted that the stability condition of full reservoir presented the higher values of safety factors comparing to other stability conditions, independent of slopes and studied moisture contents.

The upstream slope presented significant reduction in safety factors when compared to stability conditions of full reservoir with quick reservoir lowering, whereas downstream slope does not presented significant variation considering these both stability conditions. This fact can be explained considering the imposed solicitations to the dam´s embankment and both stability conditions. After the reservoir reaches it maximum water level, a phreatic line is established inside the embankment, dividing it in a saturated and in an unsaturated portion. The water reservoir weight, in this situation, increases the slope stability, providing the addition in stabilizer vertical efforts. When the stability condition of quick reservoir lowering occurs, the velocity of water reservoir lowering is higher than the velocity of pore pressure dissipations inside the embankment. Due to this situation the upstream slope loses the vertical stabilizing effort promoted by reservoir weight, keeping the saturation portion inside the embankment. This situation can explain the reduction of safety factors when compared these stability conditions. However the safety factor obtained for downstream slope does not presented significant variation due quick reservoir lowering, demonstrating that the stabilizing efforts caused by water reservoir weight have low influence for this slope stability.

After safety factors determinations for initial slopes, new stability analyses were conducted aiming to obtain upstream and downstream slopes in order to obtain nearest safety factors of those presented in Table 1. Safety factors obtained by these analyses are presented in Table 12. It is important to highlight that low safety factor variation was found for downstream slope for stability condition referring to quick reservoir lowering stability condition. The stability analyses were conducted to downstream slopes only for stability conditions of full reservoir and end of construction.

Table 12 – Maximum slopes obtained for each studied stability condition and compacted moisture content

Cross Section	Compaction moisture content	Maximum downstream slope	SF downstream slope	Maximum upstream slope	SF upstream slope
5m high section provided with horizontal sand filter	24% (-4% $w_{optimum}$)	1.0(H):1.0(V)	$1.7^{(1)}$, $1.4^{(3)}$	1.5(H):1.0(V)	$2.7^{(1)}$, $1.3^{(2)}$, $1.5^{(3)}$
	28% ($w_{optimum}$)	1.0(H):1.0(V)	2.1 $^{(1)}$, $2.9^{(3)}$	1.5(H):1.0(V)	$3.7^{(1)}$, $1.5^{(2)}$, $1.9^{(3)}$
	32% (+4% $w_{optimum}$)	2.0(H):1.0(V)	$1.5^{(1)}$, $1.4^{(3)}$	2.5(H):1.0(V)	$2.6^{(1)}$, $1.1^{(2)}$, $1.6^{(3)}$
5 m high section provided with rockfill drain	24% (-4% $w_{optimum}$)	2.0(H):1.0(V)	$1.5^{(1)}$, $1.8^{(3)}$	1.5(H):1.0(V)	$2.7^{(1)}$, $1.1^{(2)}$, $1.4^{(3)}$
	28% ($w_{optimum}$)	2.0(H):1.0(V)	$1.5^{(1)}$, $1.8^{(3)}$	1.5(H):1.0(V)	$3.5^{(1)}$, $1.4^{(2)}$, $1.7^{(3)}$
	32% (+4% $w_{optimum}$)	2.0(H):1.0(V)	$1.5^{(1)}$, $1.7^{(3)}$	2.5(H):1.0(V)	$2.0^{(1)}$, $1.1^{(2)}$, $1.3^{(3)}$

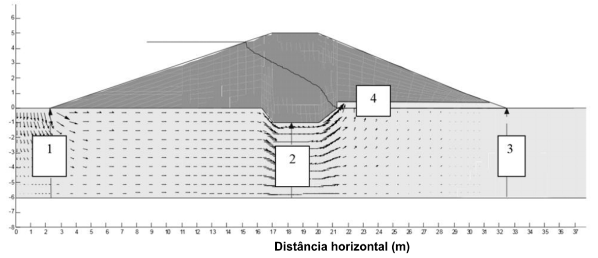
$^{(1)}$ stability condition of full reservoir, $^{(2)}$ stability condition of quick reservoir lowering, $^{(3)}$ stability condition of end of construction.
Source: the authors

In Table 12 are presented all simulated sections with satisfactory safety factors comparing to suggestions made by Cruz (1996) presented in Table 1. The obtained safety factors indicate that the initial slope of 2.5(H):1.0(V) and 3.0(H):1.0(V) for downstream and upstream slopes, commonly used for small earthfill dams, according to Paschoalin Filho (2002), are conservative.

3.6 – Seepage analyses

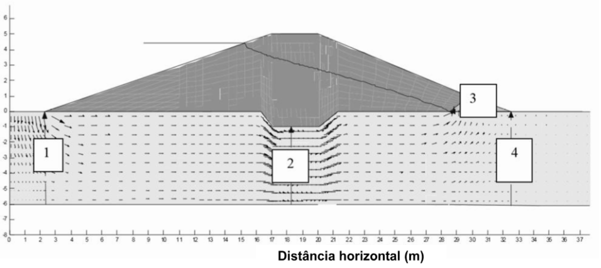
In Figures 4 and 5 were presented the determined areas where discharge values were studied in each section. The arrows showed in both figures indicate the direction and the concentration of seepage. In Table 13 are presented the obtained discharge values in each studied region of studied cross section.

Figure 4 – Cross section provided with horizontal sand filter and areas where discharge values were obtained



Source: the authors

Figure 5 – Cross section provided with rockfill drain and areas where discharge values were obtained.



Source: the authors

Table 13 – Discharge values obtained for each studied cross section simulating different compaction moisture contents.

Compaction moisture content	Region analysed	Cross section provided with sand filter	Cross section provided with rockfill drain
		Discharge (liters/day/m)	Discharge (liters/day/m)
24 % (−4 % $w_{optimum}$)	1	300	290
	2	390	370
	3	16	10
	4	14	80
28 % ($w_{optimum}$)	1	300	280
	2	390	370
	3	16	11
	4	15	75
32 % (+4 % $w_{optimum}$)	1	311	290
	2	390	380
	3	16	12
	4	15	80

Source: the authors

According to Figures 4 and 5, and Table 13 the seepage concentration occurred preferentially through foundation. This fact can be explained comparing different permeability coefficients obtained for analyzed embankments (at any compaction moisture content) and the obtained values for foundation layer. The permeability coefficients for compacted soil obtained by the laboratory tests carried out are smaller than the values obtained for foundation, determined by conducted field tests. Thus the studied embankments can be considered impermeable when compared with foundation layer. It also can be verified in both cross sections that the biggest values of discharge were found in area localized between the cut off and the impermeable layer at 6 m depth. In Table 13 is presented that compaction moisture contents of the simulated embankments do not influenced the obtained discharge values. The highlighted areas provided with drainage elements (regions 4 and 3, respectively) presented low discharge values, indicating low water amounts collected by the considered drainage elements.

CONCLUSIONS

1 – Safety factors for downstream and upstream slopes were influenced by the compaction moisture contents. The embankments compacted in optimum moisture content presented better safety factors. In the other hand, the embankments compacted above optimum moisture content showed lower safety factors. Thus, this variation of safety factor appoints the importance of an effective control of compaction of the embankment during its construction.
2 – The upstream slopes of $1_{Vertical}:3_{Horizontal}$ and downstream slopes of $1_{Vertical}:2.5_{Horizontal}$, commonly used in small dams design were conservative.
3 – Comparing safety factors obtained from the sections provided with horizontal filter with the one provided only with rockfill drain (both with 5 m high), downstream slopes varied with the kind draining element type. The conclusion is that the horizontal filter is not only an element of protection against internal erosion in the embankment, but also an element which could lead to more economical slopes.
4 – Lower safety coefficients for the upstream slopes were obtained for the condition of the fast lowering reservoir. It is important to perform slope stability analysis for each project taking under consideration on safety factors following demands to which a dam is subject: a) end of construction, b) full reservoir ($NA_{maximum}$), c) quick reservoir lowering ($NA_{maximum}$ to $NA_{minimum}$).
5 – The geotechnical properties of compacted soil in studied moisture contents, as compared with the soil in its natural moisture content, indicate that the compaction process produces a significant reduction in the porosity, permeability, and a significant increase in shear strength. It is concluded that the soil used in this study for construction of dams' embankments is viable.
6 – A dam project that is based on numerical analyses, geotechnical parameters obtained in the laboratory and performed with due field control will allow the

construction of less conservative structures, reflecting in a reduction of deployment costs, execution time and the need of fill material.

7 – Based on the seepage analyzes performed, it brings to a conclusion that the studied sections not tend to have flow problems through the landfill, because it may be regarded as impermeable with respect to the foundation. Thus the flow is preferably through the soil foundation, and so even in small volumes. The sections analyzed did not tend to have problems related to the rise of water in downstream areas of dams, since the presence of filters and drainage elements are included in project for the dam.

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