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A PROPOSAL FOR PROBABILISTIC ANALYSIS OF STABILITY OF EARTH DAMS BASED ON FIRST ORDER RELIABILITY METHOD

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ABSTRACT

A new probabilistic method for stability analysis of earthfill dams is presented in this paper. The method is based on First Order Reliability Method and, differently the traditional ones, considers some variables as random. Some important results pointed are: the probability of rupture and the reliability index for a structure. Real data from a cross section from Left Bank Earth Dam of Itaipu Hydroelectric Power Plant, located in Foz do Iguaçu, Paraná, Brazil, are used to illustrate the method. A back analysis of permeability coefficients are made before performing the stability analysis. Thereby, the actual flow conditions are considered, which allows obtain results consistent with reality. The numerical results show that Left Bank Earth Dam has currently good structural conditions, confirming that the safety procedures adopted in Itaipu Dam may be considered as appropriate. The application results show the satisfactory performance of the proposed method, which enables to complement the previously existing knowledge about the structural conditions, improving the process of risk management.

Keywords: ***Earth Dam, Probabilistic Stability Analysis, Probability of Rupture, Reliability Index.***

1. INTRODUCTION

In Brazil, Law number 12,334 from 2010 establishes that national dams must be evaluated regarding their risk according to a methodology that, besides considering technical and conservation techniques, also considers economic, social, environmental and personal impacts. According to the mentioned law, the employer, who is the responsible by the dam, must provide the necessary resources to ensure the structural safety [1]. The current society is increasingly aware about the inherent risks involving the safety analysis of Civil Engineering structures [2].

The deterministic stability analysis is based on the calculation of the traditional factor of safety (FS). However, geotechnical variables involved in calculating FS are subject to variability due to several reasons: simulating the field conditions of the geotechnical tests, different interpretations during the performance of tests, human failures during tests, spatial variability inherent to the soil properties in distinct places, among others [3]. Once FS value is determined, without considering the randomness of its variables, its value leaves questions when indicating the safety level of the structure. Therefore, the absolute structural safety cannot be guaranteed with the traditional rules for security only.

In face of this, this paper proposes a new probabilistic methodology for analyzing the stability of earth dams, based on the technique of the First Order Reliability Method for Structural Reliability. Differently from other methods present in literature, the proposed method interprets the

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involved variables as random ones. Thus, three results are provided: the structural reliability index, the probability of rupture and the most probable values of the random variables for the occurrence of a break in the dam. The structural failure to be analyzed is the simulated rupture of the downstream slope. In order for the flow conditions in the compacted earthfill and in the foundation to be considered, before the stability analysis an update of the permeability coefficients is performed based on data from the installed instrumentation. This process is known as back analysis of permeability coefficients. In order to illustrate the method, data from the cross section of Station 122+00 from the Left Bank Earthfill Dam (LBED) of Itaipu Hydroelectric Power Plant are used.

1.1. Cross Section of Station 122+00

Itaipu Dam is classified, according to Law no. 12,334, as a undertaking of low risk and high potential damage. For structures with this classification, are recommended: regular yearly inspections, special inspections when necessary and periodical revision of safety in an interval of 12 years [1]. In Itaipu, currently, routine daily, weekly, biweekly, monthly, and tri-monthly inspections are performed in 2,400 instruments installed in the structure. Real time monitoring readings of 270 instruments are automatically executed every 30 minutes. All measurements obtained are stored in database and, with the help of some computer programs, information is organized for the management of risks such as: fault trees, control charts and statistical analyses [4].

The Left Bank Earthfill Dam has an extension of 2,294 meters of length. The cross section of Station 122+00 is shown in Figure 1. The whole structure exhibited in Figure 1 is over dense basalt. The dense basalt, after suffering processes of disintegration and decomposition (weathering), gave rise to the yellow layer, known as weathered basalt. Above of weathered basalt, is the saprolite layer, of orange color. The purple layer is the plastic clay of the foundation. The dam body, represented in brown, is composed by clay from the lending area. There is a sand filter, in the body structure, of gray color. Green parts are the berms, composed by materials from excavations performed for building other parts of the dam. In pink, upstream, represents a layer of riprap, rocks with several sizes, gradually organized [5].

Figure 1: Cross Section of Station 122+00.

This paper is divided into five sections. In Section 2 a literature review of theory involved in the method is presented. Section 3, of materials and methods, presents the data of cross section of Station 122+00. The numerical results from the method application to section of Station 122+00 are exhibited and commented, in the Section 4. Conclusions about the proposed methodology, its results as well as about its use to complement the risk management of dams, among which LBED stands out, are discussed in Section 5.

2. LITERATURE REVIEW

2.1. Back Analysis of Permeability Coefficients

In order to contextualize the subject, permeability coefficient (k) is defined, described by Darcy's law, as the soil property that allows the flow of liquids through it and, therefore, it is measured in speed unities. During the building time of a dam are estimated, from tests simulating the field conditions, the future values of permeability coefficients for when the dam is in operation. With a back analysis of those coefficients, it is possible to obtain k values more near the current ones based on information obtained from instruments installed in the structure. For this purpose, the instrument to be considered is the piezometer.

The piezometer is an instrument that measures water pressure from the layer of soil where it is installed. Piezometers installed in the cross section of LBED, for which the method proposed in the paper was applied to, are from standpipe type. Figure 2 illustrates it [6]. The instrument consists in a tube with grooves in the lower part which is fixed washed sand. An impermeable seal is placed on the permeable material for insulating surrounding pressures. The remaining of the hole, where the tubes are, is filled with cement grout. The reached quota by the water column in the tube, known as piezometric head (H), is measured with a device called electrical dipmeter. In Itaipu, quota H is measured in meters above sea level (masl).

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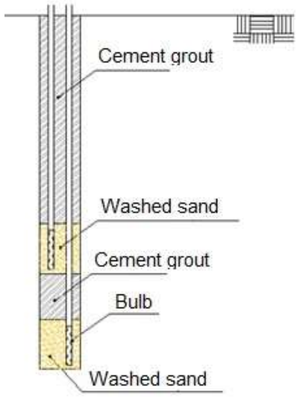

Figure 2: Installation Scheme of Standpipe Piezometers in Itaipu.

It is possible to obtain the value of the piezometric head H in any point of the earthfill dam and its foundation as well, by solving the Laplace's two-dimensional flow equation (Equation 1). Notice that the permeability coefficients, k_x and k_y, regarding the directions x and y, respectively, are known.

$$k_x \cdot \frac{\partial^2 H}{\partial x^2} + k_y \cdot \frac{\partial^2 H}{\partial y^2} = 0 \qquad (1)$$

Since it is needed solving Equation 1 by Finite Element Method, it follow that the method proposed here has been implemented in the software SEEP/W® (http://www.geo-slope.com/support/geostudio2007/). By means of a sequence of manual adjustments of the permeability coefficients (k) and of comparisons between the head piezometric H in Equation 1 and the quota from the instrument readings, the back analysis for the permeability coefficients of dam materials has been performed.

2.2. First Order Reliability Method

Among the structural reliability objectives is the estimated calculation of the probability of occurrence of fail in the engineering structures, in any stage of their life [7]. In order to apply the methods of structural reliability, first, it is necessary to define the structural failure to be analyzed. This failure is mathematically represented by a function G, which, regarding structural reliability is called limit state function. The violation of the limit state occurs when $G(\underline{X}) < 0$.

The First Order Reliability Method (FORM) algorithm is carried out in the space on which the random variables have standard normal distribution (i.e., normal probability distribution function, whose average equals zero and standard deviation equals one) and are also stochastically independent. This space is usually referred to as a "reduced space". The limit state function – that is written as a function of variables from the "reduced space" – provides the rise to the failure surface. This surface describes both regions: safety and failure. During the development of FORM algorithm, firstly the reliability index is obtained – that consists of the smaller distance from the origin of the reduced space to the failure surface. Then the probability of failure is determined. The nearer geometric point on the failure surface of the origin indicates the most probable values that random variables must assume so that violation of the limit state happens. This point is called project point.

The iterative actions of FORM for the case when variables are normal and correlated are described next [8,9]:

Step 1: Transform the random variables into standardized normal and independent ones.

The random vector $\underline{X}$ is written as a function of vector $\underline{z}$ of variables belonging to a "reduced space", with helps of the diagonal matrix of standard deviations estimated for $\underline{X}$ (denoted by $[\sigma_{\underline{X}}]$). The vector of the estimated averages of the random vector $\underline{X}$ is represented by $\underline{\mu}_{\underline{X}}$, and T denotes the matrix composed by the normalized eigenvectors of the estimated correlation matrix R. Accordingly, $\underline{X}$ can be decomposed as the in Equation 2:

$$\underline{X} = [\sigma_{\underline{X}}] \cdot T \cdot \underline{z} + \underline{\mu}_{\underline{X}} \qquad (2)$$

Step 2: Obtain the limit state equation or, equivalently, the failure surface.

The limit state function $G(\underline{X})$ is written as a function of variables from the reduced space ($\underline{z}$) and equated to zero (Equation 3).

$$g(\underline{z}) = 0 \qquad (3)$$

Step 3: Write a new project point.

The new project point $\underline{z}^*$ (Equation 4) consists of a function of the reliability index (β), which must be determined in **Step 4**.

$$\underline{z}^* = -[\sigma_{\underline{z}}] \cdot \underline{\alpha} \cdot \beta \qquad (4)$$

The director cosines vector $\underline{\alpha}$ (Equation 5), is given by function of the vector of partial derivatives of g in relation to variables of $\underline{z}$ and of the diagonal matrix of standard deviations estimated of variables from the reduced space $[\sigma_{\underline{z}}]$ (defined by the root of eigenvalues of matrix *R*).

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$$\underline{\alpha} = \frac{[\sigma_{\underline{z}}]\cdot\dfrac{\partial g}{\partial \underline{z}}}{\left\|[\sigma_{\underline{z}}]\cdot\dfrac{\partial g}{\partial \underline{z}}\right\|} \qquad (5)$$

Step 4: Calculate a new reliability index.

The new reliability index is obtained from the roots of the limit state equation (Equation 3), when it is written as a function of the new project point $\underline{z}$*, as in Equation 6:

$$g(\underline{z}^*) = g(-[\sigma_{\underline{z}}]\cdot\underline{\alpha}\cdot\beta) = 0 \qquad (6)$$

Step 5: Verify the stopping criterion of the algorithm.

If the difference between reliability indexes from the last two successive iterations is an acceptable value, then the execution of the algorithm is stopped and the flow goes to **Step 6**. Unlike, a new project point is calculated by using Equation 4 and the procedure restarts from **Step 3**.

Step 6: Check the final results of the algorithm execution.

By means of the reliability index (β) from the last iteration, the project point of the "reduced space" is achieved by employing Equation 4. Then, the project point is written in the original space with Equation 2. In turn, through the standard normal cumulative distribution function (Φ), the probability of failure (Equation 7) is estimated.

$$p_f = 1 - \Phi(\beta) \qquad (7)$$

To application of the proposed method in this paper, based on FORM, the structural failure to be analyzed is the simulated rupture of the downstream slope. Two functions of limit state are considered, the factors of safety simplified of Janbu and of Bishop, presented in Section 2.3.

2.3. Function of Limit State

Values that factor of safety (FS) assumes are interpreted as performance indicators of a structure being analyzed. The good performance of the structure happens when FS > 1; if FS = 1, then the structure is under imminence of rupture; and, finally, if FS < 1, it means that the structure breaks [10, 11]. For calculating the factor of safety, a cross section of the dam is considered. The analysis is performed two-dimensionally and the soil over the rupture surface divided into slices. In Figure 3, for example, is observed the cross section of Station 122+00, with circular rupture surface and over this surface, the soil slices, in green.

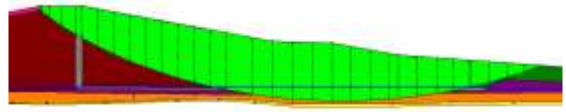

Figure 3: Rupture Surface Associated with Calculation Methods of Factors of Safety.

Considering: the soil breaks abruptly, FS is the same along of entire rupture surface and equations of static equilibrium are satisfied until the imminence of rupture. Suppose that the rupture surface is divided into m slices. The factor of safety is called simplified when only the equilibrium of forces or moments is considered [12].

The factor of safety simplified of Janbu (Equation 8), considers the forces equilibrium [10].

$$FS_{k+1} = \frac{1}{\sum_{i=1}^{m} P_i tg\alpha_i}\cdot \sum_{i=1}^{m}\left[[c'_i b_i + (P_i - u_i b_i) tg\phi'_i] \frac{\sec^2\alpha_i}{1+\dfrac{tg\alpha_i tg\phi'_i}{FS_k}} \right] \qquad (8)$$

The factor of safety simplified of Bishop (Equation 9) considers the moments equilibrium [11].

$$FS_{k+1} = \frac{1}{\sum_{i=1}^{m} P_i sen\alpha_i}\cdot \sum_{i=1}^{m}\left[[c'_i b_i + tg\phi'_i P_i (1 - \frac{u_i}{\gamma_i})] \cdot \frac{\sec\alpha_i}{1+\dfrac{tg\alpha_i tg\phi'_i}{FS_k}} \right] \qquad (9)$$

The variables, of the Equation 8 and of the Equation 9, are:

P_i : total weight of slice i;
α_i : inclination angle of the slice base;
c'_i : effective cohesion of the slice i;
b_i : breadth of the slice i;
φ'_i : effective friction angle of the slice i;
u_i : neutral pressure (water pressure in the pores) in the slice i;
γ_i : specific weight of material of the base of slice i.

Nowadays there exists some software capable to calculate the factor of safety. Here the software SLOPE/W® (http://www.geo-slope.com/support/geostudio2007/examples.aspx) has been adopted to do so.

The use of recursive functions such as the FS (Equation 8 and Equation 9) as a function of the limit state mays difficult the execution of FORM

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algorithm in steps in which the calculation of partial derivatives and of the roots of the limit state equation is required. In effect, an alternative procedure proposed in this paper is detailed next.

2.4. Alternative Procedure

The partial derivatives described in **Step 3** must be determined by numerical approximation (Equation 10), where h is a value to be incremented.

$$\frac{\partial g}{\partial z_i} = \frac{g(z_1 + ... + z_i + h, ..., z_n) - g(z_1 + ... + z_i, ..., z_n)}{h} \quad (10)$$

In order to obtain the roots of the limit state function described in **Step 4**, [13] suggests the approximation of the equation by a second order Taylor Series (Equation 11) centered in a supposed initial Reliability Index β_0.

$$g(\beta) \approx \frac{1}{2}\left(\frac{\partial^2 g}{\partial \beta^2}\right)\Bigg|_{\beta=\beta_0} (\beta - \beta_0)^2 + \left(\frac{\partial g}{\partial \beta}\right)\Bigg|_{\beta=\beta_0} (\beta - \beta_0) + g(\beta_0) = \quad (11)$$

Such as $g(\beta_0)$ corresponds to the value of g in the last $\underline{z}$* (Equation 4) with $\beta = \beta_0$.

The partial derivative of g with respect to β, with $\beta = \beta_0$ is given by Equation 12.

$$\left(\frac{\partial g}{\partial \beta}\right)\Bigg|_{\beta=\beta_0} = \sum_{i=1}^{n} \left(\frac{\partial g}{\partial z_i}\right)\left(\frac{\partial z_i}{\partial \beta}\right)\Bigg|_{\beta=\beta_0} \quad (12)$$

Where $\left(\frac{\partial g}{\partial z_i}\right)$ is obtained from Equation 10 and $\left(\frac{\partial z_i}{\partial \beta}\right)\Big|_{\beta=\beta_0}$ from Equation 4, making $\beta = \beta_0$.

The second partial derivative of g in relation to β with $\beta = \beta_0$ is given by Equation 13.

$$\left(\frac{\partial^2 g}{\partial \beta^2}\right)\Bigg|_{\beta=\beta_0} = \sum_{i=1}^{n} \left(\frac{\partial^2 g}{\partial z_i^2}\right)\left(\left(\frac{\partial z_i}{\partial \beta}\right)\Bigg|_{\beta=\beta_0}\right) \quad (13)$$

Where $\left(\frac{\partial z_i}{\partial \beta}\right)\Big|_{\beta=\beta_0}$ is obtained from Equation 4, making $\beta = \beta_0$ and $\left(\frac{\partial^2 g}{\partial z_i^2}\right)$ is given as Equation 14.

$$\frac{\partial^2 g}{\partial z_i^2} = \frac{g(z_1, ..., z_i + 2h, ..., z_n) - 2g(z_1, ..., z_i + h, ..., z_n) + g(z_1, ..., z_i, ..., z_n)}{h^2} \quad (14)$$

The calculation of the reliability index (β) implicates in calculating the roots of Equation 11 approximated. Once a reliability index is obtained from those roots, the procedure of executing FORM algorithm continues from **Step 5**.

3. MATERIAL AND METHODS

3.1 Data for back analysis of permeability coefficients

The permeability coefficients (k), calculated at the period of the project for long-term conditions, aiming to preview the current coefficients are given in Table 1 [14].

Table 1: Permeability Coefficients at the Period of Project.

Material	k (m/s)
Dam body's clay	3.4×10^{-9}
Berms	8.0×10^{-8}
Sand of filters	3.0×10^{-3}
Foundation's clay	4.4×10^{-7}
Saprolite	2.5×10^{-5}
Weathered basalt	1.1×10^{-3}
Basalt	1.0×10^{-12}
Rip rap	1.0×10^{-1}

The piezometric heads (H), used in back analysis, consist of the average quotas for the period from January 2008 to December 2013 (see Table 2).

Table 2: Average Piezometric Heads of Piezometers Installed in the Section of Station 122+00.

Instrument	Average piezometric head (masl)
PS-K-02	188.875
PS-K-05	187.429
PS-K-06	186.523

3.2. Data for Probabilistic Stability Analysis of the Section of Station 122+00

The variables interpreted as random ones with their averages and standard deviations for clay of dam body are shown in Table 3. Notice that the normal distribution is supposed here to them.

Table 3: Random Variables.

	Clay of dam body	
Random variables	c' (KPa)	φ' (degrees)
Average	55.5181	27.275
Standard deviation	13.4967	1.3892

The estimated correlation matrix (R) - Pearson's correlation [15] - between the variables of $\underline{X}$ is given by:

$$R = \begin{bmatrix} 1 & -0.5401 \\ -0.5401 & 1 \end{bmatrix}$$

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On the other hand, the deterministic considered variables, used for performing the stability analysis, are exhibited in Table 4.

Table 4: Deterministic Variables.

Material	γ (KN/m^3)	c' (KPa)	φ' (degrees)
Dam body's clay	19.025	-----	----
Foundation's clay	17.8482	18.2649	25
Saprolite	18.0443	0	25
Weathered basalt	19.1427	19.123	28
Sand of filters	22.065	0	40
Berms	19.025	58.2517	24
Rip rap	21.5747	0	40

3.3. Proposed Methodology

The procedure of back analysis, of permeability coefficients, consists of using as initial values data from Table 1 for solving Equation 1 by means of the SEEP/W® program. The piezometrics heads (H), presented in the solution of the model (Equation 1), are compared with average piezometric heads from instrument readings, given in Table 2. Then coefficient values (k) are manually adjusted in order to obtain the smaller squared difference between modeled H and measured H. At the end of this sequence of adjusts of k values and comparisons, the permeability coefficients that better fit with the current conditions are achieved, according the measurements of instrumentation.

The permeability coefficients to be changed in back analysis are the ones of the materials: clay from the dam body, berms, clay from foundation, saprolite and weathered basalt. The horizontal coefficient permeability of dam body's clay is considered equals four times the vertical coefficient, due to the compaction of this material in layers.

The violation of the limit state occurs when FS ($\underline{X}$) < 1, therefore, the considered limit state function was G($\underline{X}$) = FS($\underline{X}$) – 1. This allows to state that the limit state violation occurs when G($\underline{X}$) < 0, according with FORM explanation in Section 2.2.

During the development of the FORM algorithm for calculating the partial derivatives (**Step 3**) by numerical approximation as described Equation 10, accesses are made to SLOPE/W® in the same file containing actualized information from the flow.

The value h = 0.001 is incremented in the variable of "reduced space" ($\underline{z}$), and the values of variables in the original space ($\underline{X}$) are obtained from Equation 4. Thus, accesses are made to SLOPE/W® in order to determinate the values of the factor of safety, with the variables in the original space and not in the reduced one. Due to this alternative procedure, it is not necessary to write the equation of limit state as a function of variables of the "reduced space" ($\underline{z}$), according to Equation 3 of **Step 2**. For obtaining a new reliability index (**Step 4**), the proposed method suggests the approximation of the limit state equation (Equation 6) by a second-order Taylor Series (Equation 11) as a function of the reliability index (β). Then, **Step 4** is performed without the need of writing Equation 3 (limit state equation) as a function of the new project point, according to Equation 6. In this proposed methodology, the limit state equation (Equation 3) of **Step 2** is treated indirectly, according to approximations given by Equation 10 and Equation 11 indicated in the alternative procedure.

The rupture surface was fixed, passing through the saprolite layer.

The method presented in this Section allows performing the stability analysis of earthfill dams account for the randomness of some variables, differently the traditional methods. Importantly, even if a dam is considered to be safe according to traditional stability analysis, there exists residual risk that should be taken into account. Hence the proposed method aims to contribute to the risk management and to give more support to the final decision of the responsible technical sector.

4. NUMERICAL RESULTS

4.1. Results of Back Analysis of the Permeability Coefficients

At the end of the back analysis, the permeability coefficients displayed in Table 5 were obtained. It is possible to observe the precision of data previously selected by [14]. Only the alteration of the dam body's clay permeability coefficient produced a satisfactory back analysis.

Table 5: Permeability Coefficients at the End of Back Analysis.

Material	k (m/s)
Dam body's clay	$3{,}4 \times 10^{-10}$
Berms	$8{,}0 \times 10^{-8}$
Sand of filters	$3{,}0 \times 10^{-3}$
Foundation's clay	$4{,}4 \times 10^{-7}$
Saprolite	$2{,}5 \times 10^{-5}$
Weathered basalt	$1{,}1 \times 10^{-3}$
Basalt	$1{,}0 \times 10^{-12}$
Rip rap	$1{,}0 \times 10^{-1}$

The permeability coefficients of Table 5 were the ones that describing the smaller sum of the squares of differences between the piezometric heads of the

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model (Equation 1) and the measurements from the instruments: 0.07975 (see Table 6).

Table 6: Squared Differences Between Average Piezometric Head and H Modeled.

Instrument	H medium (masl)	H modeled (masl)	Squared differences
PS-K-02	188.875	188.714	0.0259
PS-K-05	187.429	187.652	0.0497
PS-K-06	186.523	186.587	0.0041

Figure 4 presents the piezometric line (in blue) at the end of the back analysis. The portion at the left of the earthfill is upstream. The piezometric line indicates the reached quota by water due to its pressure. The flow follows in the direction of this line, from upstream to downstream.

Figure 4: Piezometric Line Through the Dam Body and Foundation at the End of the Back Analysis.

4.2. Results of Probabilistic Stability Analysis Through the Section of Station 122+00

Results from the analysis of probabilistic stability of the LBED through the section of Station 122+00, using the proposed methodology, with the Janbu Simplified FS and Bishop Simplified FS as a function of the limit state, are in Table 7. The reliability indexes had close values in both analyses, as well as the respective rupture probabilities. Those values, once determined, are not unique, but they depend on the limit state function chosen. It is important to observe that the dam is in good safety conditions, because the values of the reliability index and consequently of probability of rupture, are inside the interval considered as safe for earth dams [16].

Table 7: Reliability Index and Probability of Rupture.

Function of limit state	Reliability index	Probability of rupture
Janbu Simplified FS	4.949	0.0000373%
Bishop Simplified FS	4.741	0.000106%

The values of effective cohesion and of effective friction angle (project point), to dam body's clay, resulting from both analyses are presented in Table 8.

Table 8: Project Point Resulting from Both Analyses

Function of limit state	Effective cohecion (KPa)	Effective friction angle (degrees)
Janbu Simplified FS	5.572	26.209
Bishop Simplified FS	7.276	26.316

The variability of the effective cohesion is bigger than the variability of the effective friction angle, according Table 3. It's the probable cause of bigger difference between effective cohesion's values from resulting project point at both analyses.

The rupture surface with its slices at the end of both analyses is the same, because it was fixed and passing through the saprolite layer (Figure 5).

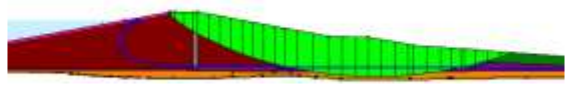

Figure 5: Rupture Surface Resulting from Both Analyses.

It was found that the convergence of the proposed method is associated with the selection of the initial reliability index and the increment value h. Thus, the beginning of the analysis was longer expended. For both analyses, the initial reliability index and the increment value of h chosen were the same: β_0 = 2.6 and h = 0.001.

5. CONCLUSION

A method for probabilistic analysis of stability of earthfill dams was proposed in this paper. The method, which is based on First Order Reliability Method technique from structural reliability, aims to obtain the reliability index for structure, the probability of rupture of the embankment and the more probable values that the random variables must assume for the rupture to happen. According to the function of limit state, chosen to describe the simulated rupture of the downstream slope, two analyses were realized – one with the simplified Janbu factor of safety, and other with the simplified Bishop factor of safety. The probabilistic methods of stability analysis differ from traditional deterministic methods for considering the randomness of the variables involved in the problem at hand. In the proposed methodology, the variables considered as random ones were the effective cohesion and the effective friction angle of dam body's clay.

Was used information from the cross section of Station 122+00 on the Left Bank of Earthfill Dam of Itaipu Hydroelectric Power Plant to the application the underlying method. The results obtained from the application show the excellent performance of the proposed method, as well as the good security conditions in which the dam is, according to comments about results in Section 4. This shows that the efforts taken by Itaipu, since its construction, for the risk management and the care

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with its structures, are preserving the safety and good working of LBED during its years of operation.

It was verified that both analyses have values close to the index of reliability and probability of rupture. Analysis performed by other methods of structural reliability was also indicated. The application of the Monte Carlo Simulation Method, with the same limit state functions considered in this paper, will probably point to values of index of reliability and probability of rupture close to the obtained ones. The greater the amount of information is, more precision there is to infer about structural security and for indicating procedures of risk management.

The method proposed in this paper, due to the fact of considering updated flow conditions, is very useful because it allows an evaluation about the safety state and performance of earthfill dams in their current conditions. The probabilistic view of the question, by considering the randomness of variables involved in the stability problem, favors the execution of analysis taking into account the risks, and that, by providing a vision closer to reality, may complement the previously existing knowledge about the structural conditions. The technical complexity, presented by the mathematical resources structuring the proposed methodology, is no bar for applying the method in earthfill dams, since they may be operated with relative simplicity, using the software used for the analysis and development of this paper.

REFRENCES

[1] Brasil, "Decreto-lei 12,334 de 20 de setembro de 2010", *Política Nacional de Segurança de Barragens*, Brasília, 2010.

[2] A.V. Melo and T.C. Fusaro, "Avaliação de Métodos de Análises de Riscos Aplicados à Barragens", *XXX Seminário Nacional de Grandes Barragens*, Foz do Iguaçu, 2015.

[3] Y.H. El-Ramly, N.R. Morgenstern and D.M. Cruden, "Probabilistic Slope Stability Analysis for Practice", *Canadian Geotechnical Journal*, Vol. 39, No. 3, 2002, pp. 665-683.

[4] C. Neumann Jr., C. Osako, J. Patias, C. Porchetto, "Reflexos da Lei de Segurança de Barragens na Itaipu Binacional", *XXVIII Seminário Nacional de Grandes Barragens*, Rio de Janeiro, 2011.

[5] Itaipu Binacional, "Usina Hidrelétrica de Itaipu: Aspectos de Engenharia", *Itaipu Binacional*, Foz do Iguaçu, 2009.

[6] J. Patias, "Zoneamento Geotécnico com Base em Krigagem Ordinária e Equações Multiquádricas: Barragem de Itaipu", *Tese de Doutorado do Programa de Pós-Graduação em Geotecnia da Universidade de São Paulo*, São Carlos, 2010.

[7] R.E. Melchers, "Structural Reliability: Analysis and Prediction", *John Wiley & Sons*, New York, 1987.

[8] A.H.S. Ang and W.H. Tang, "Probability Concepts in Engineering Planning and Design: Decision, Risk and Reliability", Vol. 2, *John Wiley & Sons*, 1984.

[9] G.B. Baecher and J.T. Christian, "Reliability and Statistics in Geotechnical Engineering", *John Wiley & Sons*, 2003.

[10] N. Janbu, "Stability Analysis of Slopes with Dimensionless Parameters", *PhD Thesis of Civil Engineering*, Faculty of Arts and Sciences on Harvard University, Cambridge, 1954.

[11] A. Bishop, "The Use of Slip Circle in the Stability Analysis of Slopes", Geotechnique, Vol. 5, No. 1, 1955, pp. 7-17.

[12] Y.M. Cheng and C.K. Lau, "Slope Stability Analysis and Stabilization, New Methods and Insights", *Routledge*, New York, 2008.

[13] Y. Su, X. Li and Z. Xie, "Probabilistic Evaluation for the Implicit Limit-State Function Stability of a highway tunnel in China", *Tunneling and Underground Space Technology*, Vol. 26, no. 12, December, 2010, pp. 422-434.

[14] P.C. Thá, "Estudos das Condições de Fluxo pela Barragem de Terra da Margem Esquerda de Itaipu", *Dissertação de Mestrado em Engenharia Civil, Pontifícia Universidade Católica*, Rio de Janeiro, 2007.

[15] R.A. Johnson and D.W. Wichern, "Applied Multivariate Statistical Analysis", *Pearson*, 2007.

[16] R.V. Whitman, "Evaluating Calculated Risk in Geotechnical Engineering", *Journal of Geotechnical Engineering Division*, Vol. 2, No. 110, 1984, pp. 145-188.