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Evaluation of the Mechanical Behavior of a Retaining Wall Structure on a Weathered Soil through Probabilistic Methods

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Abstract**—**Retaining slope structures are increasingly considered in geotechnical engineering projects due to extensive urban cities growth. These kinds of engineering constructions may present instabilities over the time and may require reinforcement or even rebuilding of the structure. In this context, statistical analysis is an important tool for decision making regarding retaining structures. This study approaches the failure probability of the construction of a retaining wall over the debris of an old and collapsed one. The new solution's extension length will be of approximately 350 m and will be located over the margins of the Lake Paranoá, Brasilia, in the capital of Brazil. The building process must also account for the utilization of the ruins as a caisson. A series of *in situ* and laboratory experiments defined local soil strength parameters. A Standard Penetration Test (SPT) defined the *in situ* soil stratigraphy. Also, the parameters obtained were verified using soil data from a collection of masters and doctoral works from the University of Brasília, which is similar to the local soil. Initial studies show that the concrete wall is the proper solution for this case, taking into account the technical, economic and deterministic analysis. On the other hand, in order to better analyze the statistical significance of the factor-of-safety factors obtained, a Monte Carlo analysis was performed for the concrete wall and two more initial solutions. A comparison between the statistical and risk results generated for the different solutions indicated that a Gabion solution would better fit the financial and technical feasibility of the project.

Keywords**—**Economical analysis, probability of failure, retaining walls, statistical analysis.

I. Introduction

GEOTECHNICAL engineers commonly consider earth stabilization projects. These earth movements occur naturally or may be induced by man, and they require the employment of different techniques and solution concepts. Such techniques contemplate retaining structures, superficial drainage and soil surface protection using natural and artificial materials. Economical and technical analysis will define which solution may solve the problems as well as the most adequate one considering the background situation involved.

A deterministic design, which uses the concept of safety factor is the most common approach employed by designers to determine the stability of retaining walls. The strength behavior of the retaining wall accurately takes into account the variability of the soil properties; this can lead to a great disagreement between real and expected performances.

Application of statistics and probability concepts quantify the uncertainty of the factor of safety more precisely. There are two main ways to interpret the failure probability [6]: statistical probability and decision making probability. The first one uses the concept of relative frequency through past engineering experiences, whilst the second shows the individual reliability degree.

This paper proposes a study about a retrofit project of a retaining wall in Brasília, Brazil. The Monte Carlo probabilistic method was chosen to develop a statistical-based project. This work follows the same line as the one from [4].

Most of the applications of statistical analyses in geotechnical engineering use the normal distribution, since this function is practically universal in science.

The authors [1], [2], [8] showed that the normal distribution can, indeed, lead to unsafe project solutions or even raise the costs unnecessarily. The symmetric property of the Gaussian distribution fails to grasp the correct distribution of values from the geotechnical parameters, as those are usually asymmetrically distributed.

The soil data were obtained by means of in situ tests. The data were validated from a collection of masters and doctoral works from the University of Brasília, whose soil characteristics are similar to the local ones.

For this paper, we previously studied three different gravity retaining walls: gabion, concrete and geotextile bags with soil cement. We drew a comparison between failure probability and final cost for a better decision procedure.

II. Theory

The Monte Carlo method was inspired by the mathematician Stanislaw Ulam, who used to attend the Monte Carlo Casino. Stanislaw Ulam and John Von Neumann formalized and published the method in 1949 in a paper entitled "The Monte Carlo Method".

The method consists on a mathematical system being described by functions of probability density (FPD). The method generates a defined number of values for the soil parameters from a probability distribution function. Then, Deterministic analyses generate the smallest factor of safety taking the soil parameters as inputs. The mean value and

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dispersion are calculated for the set of factors of safety, supposing they are a population from the same sampling space. The error of this kind of analysis decreases until it becomes minimal if the set size approaches infinite.

The Monte Carlo method, therefore, performs statistical analyses of the factors of safety on a sufficiently large sampling space. Therefore, this method requires computational efficiency, which is necessary to guarantee that the errors will reach reasonable values as well as that small computational time shall be consumed.

Addressing another subject, the risk relates directly to the geological failure potential of a slope or retaining structure. The definition of the risk is the product between the probability of occurrence of the event and the consequences of the failure [5].

The risk analysis is the process of risk estimation or a way of providing information to support decision making [9]. The risk management is the process of control or mitigation of the risk to reasonable and acceptable levels. Hence, the probability of success of a given structure in civil engineering must consider the probability of failure and the consequences of failure.

There is no universal procedure to evaluate the risks for every type of project. The choice depends on the most acceptable approach according to the data available, the dependence on subjectivity factors and the criteria that defines reasonable risks.

The probability of failure relates to the reliability. The reliability theory links the quality of safety to the procedure adopted. This quality is quantified through probabilistic analysis and professional experience based on previous engineering cases.

The quantified risk becomes a communication channel between client and engineer aiming to expresses the risk levels and to compare the relative risk between different solutions [11]. It is desirable to guarantee that the probability of failure that is under the engineers control is lesser than the probability of failure associated with uncontrolled factor (human failures, for example).

III. Soil and Structure Characteristics

The local where the retaining wall will be constructed is in Brasília, Brazil. It is located at the South Club Sector, stretch 2, allotment 69. This is the Associates' Aeronautics Club (CASSAB). The current structure stretches through 382.58 m and it is deteriorated through all its extension. This present state presents a risk to the users. Fig. 1 shows the location of the current structure as well as its status.

The water level of the lake varies 1.2 m over the year. The Paranoá dam serves to control the water level and to generate electricity.

Fig. 2 shows the topography of the lake shore near the location of the future retaining wall and its respective level curves. The figure also shows a cut view of the natural slope and it characteristics.

Fig. 1 Satellite image of the deteriorated structure and its location [3]

In order to determine the best solution for retaining structures, as can be seen in Fig. 3, the typical sections used in the analysis of this paper.

Finally, the SPT performed at the location shows that the soil is sandy clay with gravels and the water table is in the same level as the lake's surface. These results are in agreement with the MCT [7] tests performed with the soil. The clay from this region often exhibits the behavior of granular material when saturated, which is a typical behavior of the Brasília's soil.

IV. Data Analysis According to the Monte Carlo Method

A statistical analysis of each of the three retaining wall solutions was performed using the Monte Carlo method. The authors considered the factor of safety equals to zero in cases where the friction angle is smaller than the slope inclination and the cohesion is equal to zero, since it would lead to an unstable configuration or even the failure of the slope.

According to [2], Table I presents the statistical distributions that best fit the collected samples of cohesion, friction angle and specific weight from the Brasília's porous clay.

TABLE I
Distributions Parameters

Parameter	Number of Samples	Distributions	Distribution parameters
Friction angle	45	Inverse-Gamma	α = 59.63 β = 1731.99
Cohesion	45	Dagum	p = 1.44 × 10-6 a = 240,960 b = 29.0
Specific weight	93	Generalized Inverse-Gamma	α = 29.06 β = 49.25 γ = 2.97 μ = 1.26

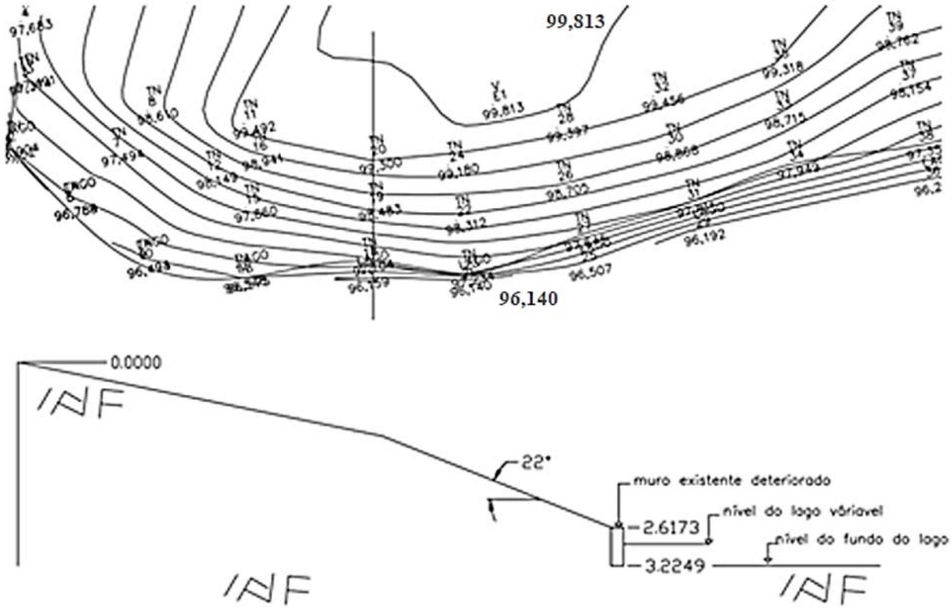

Fig. 2 Natural level curves and cut view of the region [3]

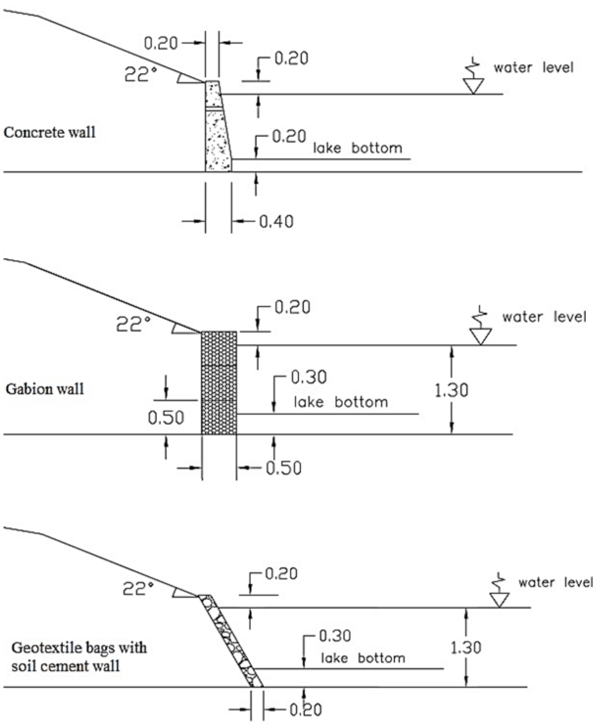

Fig. 3 Typical sections of retaining walls: gabion, concrete and geotextile bags with soil cement [3]

As it can be seen, Figs. 4-6 show the histograms containing the distribution of factor safety and probability of failure (FS<1) obtained from the analysis. Those analyses were performed with the same equations used by the authors in [3], considering sliding, overturning and bearing capacity as failure criteria. The histograms and all the analyses were made using the software Wolfram Mathematica 9 [12].

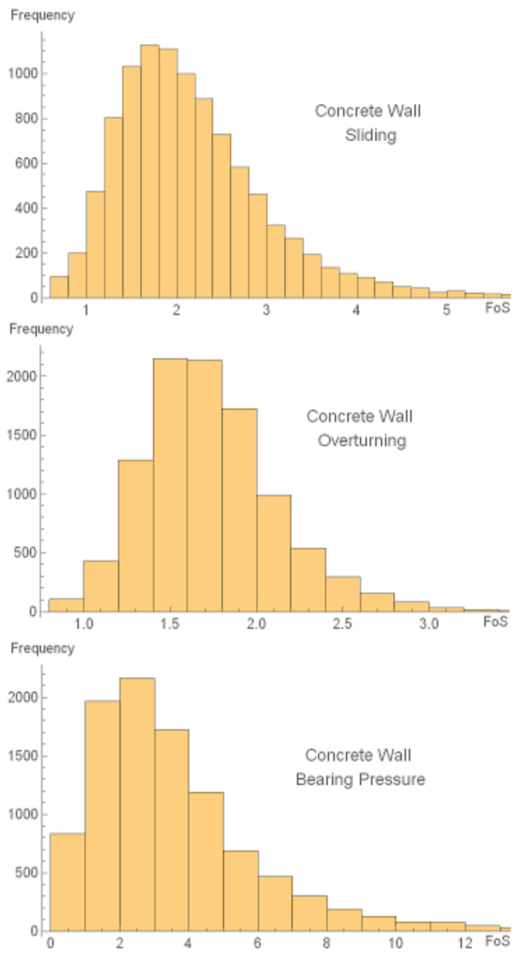

Fig. 4 Concrete wall FoS distribution: Sliding, overturning and bearing capacity

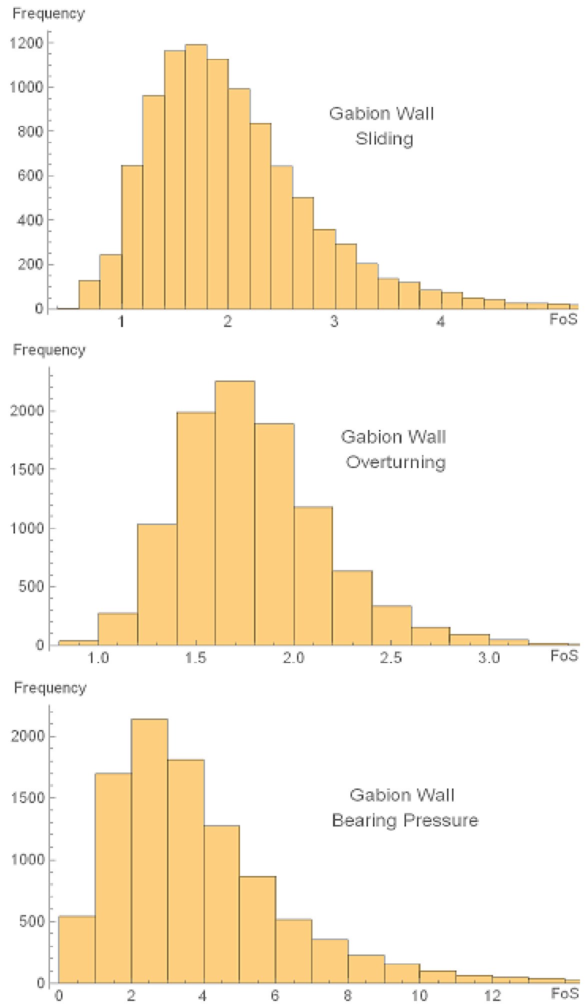

Fig. 5 Gabion wall FoS distribution: Sliding, overturning and bearing capacity

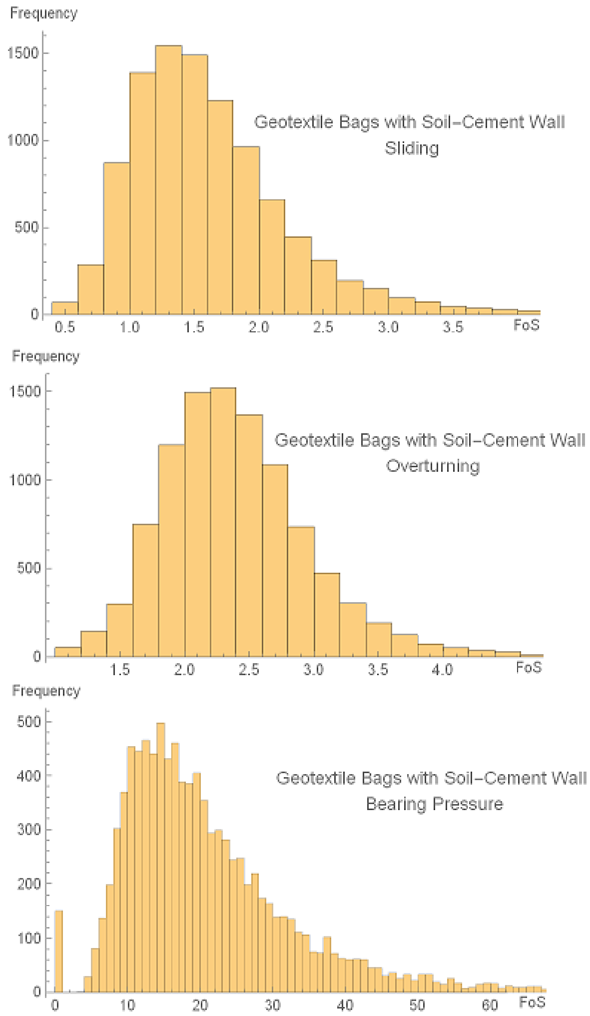

Fig. 6 Geotextile bags with soil cement wall FoS distribution: Sliding, overturning and bearing capacity

V. Risk and Economical Analysis

The cost analysis was based on a Brazilian costs and indexes table named SINAPI. A Brazilian national public bank is responsible for organizing this system and updating it monthly. Additionally, some costs were calculated based on the system maintained by the government of the Brazilian State Sergipe (ORSE). This system works in the same way as the SINAPE [10], but it is responsibility of Sergipe's Department of Habitation and Public Constructions. Costs were based on the April of 2017 version of both systems. Indirect expenses and provisory services were not considered for the cost computations.

Table II shows the probability of failure for each of the solutions proposed (individual and joint), comparing with the final cost of the construction, as seen by [3], and the risk analysis. It is important to note that the jointed probability of failure is determined by the chance of occurring any of the events, as represented by the region in blue in Fig. 7

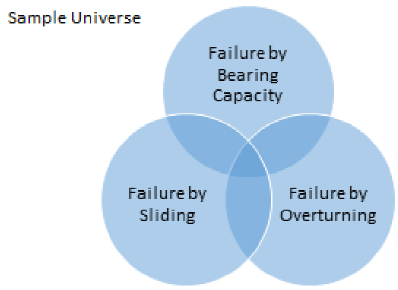

Fig. 7 Geotextile bags with soil cement wall FoS distribution: Sliding, overturning and bearing capacity

The probability of overturning has its higher value for the concrete wall and its lowest value for the geotextile solution. The geotextile showed the highest probability of failing by sliding, while the concrete presented the lowest. The probability of failure by bearing capacity was the highest for the concrete wall and lowest for the geotextile. Overall, the geotextile showed is the structure most prone to failure, while the gabion wall was the safest.

The probability of failure, as well as the cost, for each structure is close to each other. The fact that the overall probability of failure grows while the cost mitigates is a peculiar feature of the geotextile solution.

It is worth to mention that the probability was calculated with respect to the whole lifespan of the solutions, which explains the high values. It actually shows that the probability of failure is low.

It is noticeable that the geotextile bag solution has the greatest risk, although it has the lowest price. That is caused by its high probability of failure through sliding. Even the lowest price could not keep the risk at small values. That is an important difference between the probabilistic and the deterministic analysis.

TABLE II
DISTRIBUTIONS PARAMETERS

Retaining Wall	Probability of failure – Sliding (%)	Probability of failure - overturning (%)	Probability of failure – bearing capacity (%)	Probability of failure – joint (%)	Construction's cost	Risk analysis
Concrete	2,94	1,03	8,32	8,32	R$ 129.206,46	R$ 10.749,98
Gabion	3,75	0,40	5,41	5,41	R$ 137.091,68	R$ 7.416,66
Geotextile bags with soil cement	12,23	0,00	1,50	12,59	R$ 100.668,18	R$ 12.674,12

VI. CONCLUSION

The present paper brought an application of the statistical analysis to the retaining wall stability and its results contribute in practical engineering problems.

The probability and risk analysis play an important role in geotechnical engineering because the deterministic analysis may demand more tests and results to output better results, while a deterministic analysis would only determine if the solution is safe enough and subsequently choose the least expensive one, the probabilistic analysis takes into account how much safer a solution is compared to others. This tool, therefore, works as a guide for the engineer to make better decisions in practical aspects. Accordingly, the choice for the gabion wall as the containing structure is the best one from our perspective.

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