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Stability analysis of a slope and runout analysis movement of the mobilized-mass volume

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Case Study

Keywords
Landslides
Serra do Mar
Deterministic
Probabilistic
Material point method

Abstract

This research aims to present a deterministic and probabilistic analysis of the stability in 2D/3D of a road slope, located in the state of São Paulo, Brazil, in the Serra Pelada region, incorporating scenarios with and without surface suction and water level, and predict the movement of the mobilized-mass volume. The results of the stability analysis showed the variability of the safety factor, the probability of failure, and the mobilized-mass volume, in the twenty-six simulated scenarios. The results of the runout analysis of the mobilized-mass volume indicated that any possible landslide would interdict, at least, two of the three lanes of traffic, equivalent to 59.7% of the lanes. Therefore, it can be concluded that a 2D and 3D stability analysis combined with the material point method to predict the post-failure soil displacement provides a better understanding of all processes involved in a landslide, which helps to establish more adequate and effective mitigation and remedial measures for each situation. Finally, in conclusion, the studied slope, with a maximum failure probability of 1.24%, is safe in terms of its overall stability for all twenty-six simulated scenarios.

1. Introduction

Landslides are mass movements that occur in Brazil and elsewhere, and can cause damage, affecting the population and region and generating economic losses. Often these landslides are caused when mobilized stresses exceed the soil or rock strength, either by changing slope geometric factors or by triggering factors such as climatic factors, overloads, slope mass removal, and reduction of soil strength parameters.

According to Fernandes et al. (2001), the slopes's morphological parameters stand out among the landslide factors because they control the balance of forces on the slope and the hydrological dynamics of the soils. As well as the loss of suction, which is also a possible cause of instability, since there is an increase in moisture in the material due to the progress of the infiltration front in the ground (Fredlund, 1987).

The slope stability analysis is of great importance since it guarantees more physical safety of the slope itself and of the elements that might be impacted by a possible landslide. Moreover, predicting the movement of the mobilized-mass volume, after the failure, is very useful to evaluate the risk of catastrophes or to establish mitigation measures more adequate for that slope (Troncone et al., 2019).

According to Wang et al. (2018), the behavior of a landslide can be divided into two stages: failure and post-failure. The failure stage is characterized by presenting a continuous shear surface, generating little movement of soil mass. The post-failure stage is represented by its rapid formation of plastic deformations and the kinematics of the unstable soil mass until its break.

As a way of studying the two failure stages, foremost one must understand the models involved in each of the stages. A mathematical model, such as the limit equilibrium method (LEM), is the most known method of simulating the first failure stage, which focuses on the calculation of the safety factor employing material-strength theories. As to model the landslide post-failure with good precision, it is necessary a numerical model capable of simulating large deformations and distortions, such as the material point method (MPM), which uses constitutive models based on the continuum mechanics (Toro-Rojas et al., 2021).

The limit equilibrium method (LEM) is used in the stability analysis of slopes and has the objective of evaluating the possibility of the occurrence of a landslide (Gerscovich, 2016). The LEM includes the method of slices that divides the soil above the potential-failure surface in a series of slices to calculate each one's equilibrium. Among the methodologies that employ the method of slices, there are examples such

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as Janbu, Spencer, Simplified Bishop, and Morgenstern-Price, which are widely used to calculate the safety factor (Liu et al., 2019). Also, this method is well-known for being a statically undetermined problem and is solved by considering the distribution of the internal forces (Liu et al., 2015). Furthermore, in the limit equilibrium method, various potential-failure surfaces are generated, by optimization or trial-and-error techniques, so then one may find the critical failure surface that corresponds to the minimal safety factor (Reale et al., 2015).

The stability analysis can be done following two approaches: deterministic and probabilistic. The deterministic stability analysis considers only the average value of the soil strength parameters and calculates only one safety factor (SF) for the problem (Tonus, 2009). This SF, in a given failure surface, is determined by the ratio of the shear strength over the mobilized shear stress, considering the equilibrium of the forces and/or moments acting on the failure surface (Liu et al., 2019). Research points out that the stability of a slope cannot be completely evaluated only by the deterministic safety factor since some slopes with high SF still fail (Chen et al., 2020).

The probabilistic stability analysis stems from the variation of the geotechnical parameters of the soil (average and standard deviation), quantitatively considering the various origins of uncertainties and determining the probability of failure and the reliability rate of the results (Wang et al., 2020). In such analysis, one must select an appropriate probabilistic method, such as the first order reliability method (FORM), the second order reliability method (SORM), the point estimative method (PEMs), or the Monte-Carlo simulation (MCS) (Ahmadabadi & Poisel, 2015). MCS is an easy implementation tool that determines the probability of failure with a desired precision, even though it is time-consuming due to the high computational effort (Fang et al., 2020).

The material point method (MPM) has been used to model various types of geotechnical problems, such as mass movements. Toro-Rojas et al. (2021) studied the effect of a landslide in the failure and post-failure stages by the analysis of the strength parameters and deformation of a slope. Conte et al. (2019) and Conte et al. (2020) demonstrated the MPM's capacity to evaluate landslides and their behavior post-failure. Bhandari et al. (2016) utilized the MPM to simulate a progressive failure of a slope caused by an earthquake, and Li et al. (2016) simulated and analyzed the post-failure process of the landslide in Wangjiayan, China.

The numerical methods are divided into two main categories: Lagrangian and Eulerian methods. The MPM combines the performance of the two methodologies, in which one continuum is discretized by a set of subdomains with information (velocity, acceleration, density, displacement, external loads, material parameters, etc.), which are concentrated on a Lagrangian point, called a material point. A computational mesh (Eulerian mesh) overlays the continuum and covers all the issue's domain, while being usually maintained fixed with time and not bound to material information. In the nodes of this mesh, equilibrium equations are resolved, and in the material points, constitutive equations and mass conservation equations are established (Conte et al., 2020).

At the beginning of each time step, the data is transferred from the material points to the mesh nodes, so then the nodal accelerations are obtained, and the acceleration, velocity, and dislocation points are determined in the stipulated time. Lastly, the position of the material points is updated on the Eulerian mesh for the later time step (Conte et al., 2020).

In light of all this context, this article seeks to analyze the stability in 2D and 3D of a road embankment, located in the state of São Paulo, Brazil, in the Serra Pelada region, via deterministic and probabilistic approaches, embodying scenarios with and without superficial suction and variation of the water levels, and predicting, in case of failure, the movement of the mobilized-mass volume.

2. Case study: data and information from the location and methodology adopted

This section of the article presents the materials and methods employed, divided into a description of the field of study, input parameters, stability analysis, and runout analysis of the movement of the mobilized-mass volume. Figure 1 represents the flowchart of the activities conducted in order to develop the analysis of stability and prediction of mass movement of the slope under study.

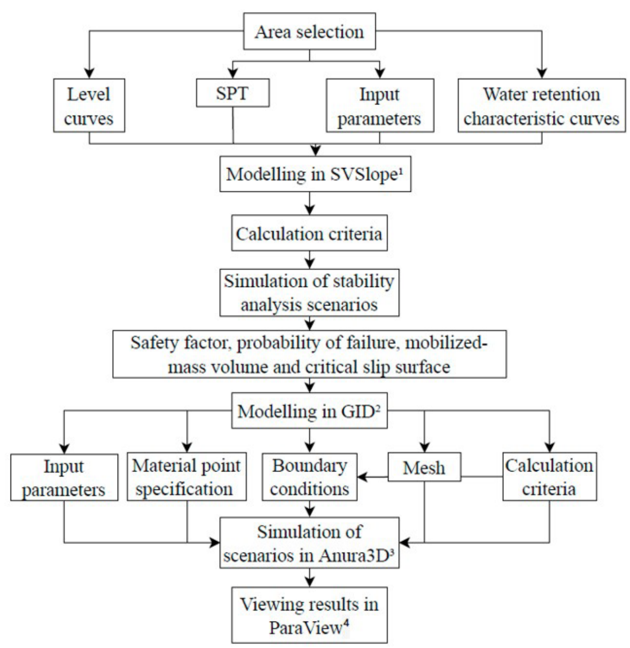

Figure 1. Flowchart of the applied method. [1]Slope stability analysis software. [2]Universal numerical simulation processor. [3]Software for numerical modeling of large strains using the material point method (MPM). [4]Open-source multiple-platform application for interactive, scientific visualization.

Beginning with the selection of the field of study, it was then determined the basic data to perform the stability analysis, such as level curves, Standard Penetration Test (SPT) results, soil parameters (cohesive intercept and friction angle, natural unit weight, Poisson's ratio, modulus of elasticity, suction) and soil-water characteristic curves.

Thereafter, the slope was modeled on the software SVSlope, the calculation criteria were indicated in it, and the stipulated scenarios of stability analysis were simulated, resulting in the safety factors, probability of failure, mobilized-mass volume, and critical slip surface.

With the results of the stability analysis, the slope was modeled in another software, GID, followed by the insertion of the slope's materials, calculation criteria, and modeling data such as the specification of the material point, boundary conditions of the model, and mesh. Finally, the scenarios of mass movement prediction were simulated on Anura3D, and the results were visualized on ParaView.

2.1 Description of the study area

The slope serving as the case study is located in the Régis Bittencourt highway, stretch of Serra do Mar, at Serra Pelada, in the state of São Paulo, Brazil, at km 551 + 600 (South Lane) (Figure 2).

In Figure 2d it is possible to notice that the slope is near the road's traffic, which contains three lanes and drainage ditches at their ends. The traffic lanes are 3.6 m wide, and the drainage ditches up until the beginning of the traffic lanes are 0.8 m wide.

The Régis Bittencourt highway poses economic importance in the Brazilian highway network since it is part of the Mercosul route and is also the main road corridor that connects important economic poles from the country's Southeast (São Paulo) and South (Paraná) (Batista, 2019). Thus, the evaluation of possible instabilities on slopes along the highway is of great relevance.

According to APRB (2019), the region of Serra Pelada, specifically the Régis Bittencourt road, presents a history of instability, with records from 2010 to 2019, amounting to 93 registered occurrences of landslides, the last nine taking place at Serra Pelada. Besides that, Batista (2019) appointed, in his study, the region in question as the most critical in his analysis of economic risks performed all around Serra Pelada.

The geological formation at Serra Pelada, according to CPRM (2013), is characterized by Amphibolitic Gneiss. The geological-geotechnical profile of the slope was defined, based on geotechnical investigations of the Standard Penetration Test (SPT) executed near the slope, as being three layers of soil: 1.5 m of superficial colluvium layer, 4.5 m of residual soil formed by sand silt, and the remaining is composed by a weathered rock (saprolite). The water level was considered in a few simulated scenarios, that being at two different depths, 6.5 m and 7.5 m below the surface. The 7.5 m depth was defined based on the data of the geotechnical investigation of the SPT that indicated a water level with a depth of less than 7.0 m, and the depth of 6.5 m was selected to comprehend the influence of the variation in the position of the water level in the results.

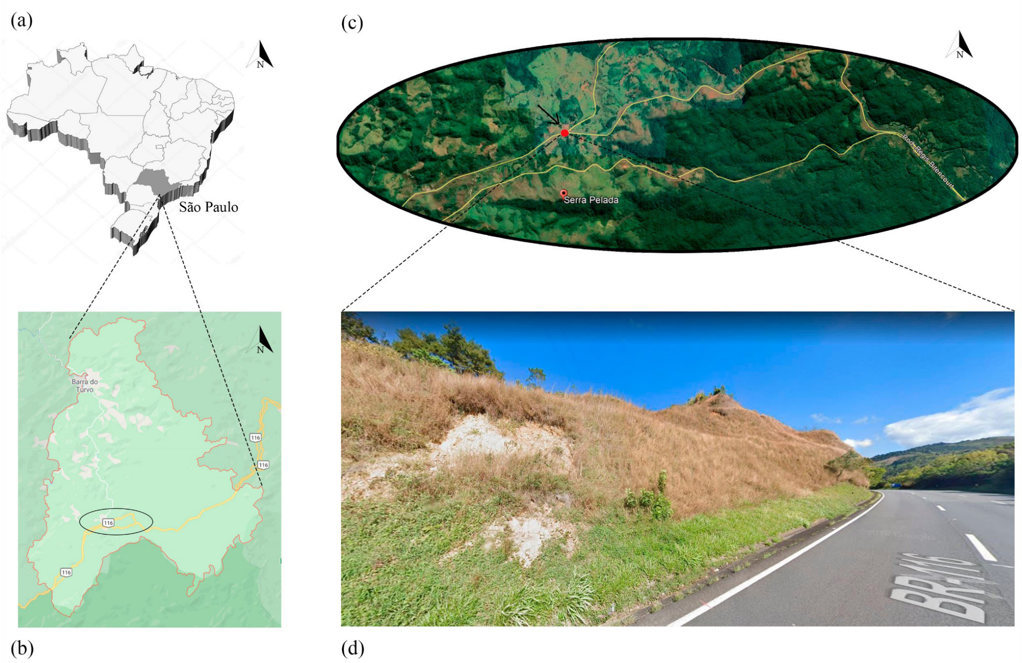

Figure 2. Study area location: (a) Brazil-São Paulo, (b) city of Barra do Turvo-SP, (c) Serra Pelada – highway BR-116 – slope point, and (d) front view of the slope in study.

2.2 Input parameters

The input parameters used in the simulations of stability and mass movement prediction were the strength parameters of soil, such as cohesive intercept (*c'*) and friction angle (ϕ›), natural unit weight of the soil (γ_{nat}), Poisson's ratio, modulus of elasticity, suction, and the characteristic curves of water retention. Table 1 shows, for the colluvial, residual soils, and saprolite, the value intervals of the cohesive intercept and friction angle, and the average value of these parameters, besides the natural unit weight of the soil, Poisson ratio, and modulus of elasticity. The minimum value of the parameters is the value of the residual strength parameters, and the maximum value is the value of the peak strength parameters.

The shear strength parameters of the soil were determined based on the data by Trevizolli (2018). The author obtained these results by saturated direct shear tests implemented in three intact samples, in three levels of normal stress (50, 100, and 200 kPa), performed on a near slope, at km 552 + 000 (North Lane).

In the deterministic stability analyses, the average values of the geotechnical parameters, natural unit weight of the soil, internal friction angle, and cohesive intercept were considered. And in the probability analyses, in addition to the average values of the geotechnical parameters, the minimum, and maximum values were considered (Table 1), for the colluvial and residual soils. For each variable of the probabilistic data, the statistical normal distribution was considered, and truncation was not adopted, that is, the extreme values of the data intervals were determined in the direct shear test.

The suction was incorporated, in some of the stability analysis scenarios, in the first 3 m deep, 1.5 m in colluvial soil and 1.5 m in residual soil. According to Trevizolli (2018), it was adopted the interval of 20 to 120 kPa for the total suction on the surface of the soil, varying in each simulation at intervals of 20 kPa by 20 kPa. This parameter was incorporated in the surface soil decreasing with depth, that is, with maximum value at the top and null at the end of the first 3 m deep.

Finally, the characteristic curves of water retention were grounded on the compilation of experimental points of Trevizolli (2018), obtained by the filter paper method, presenting a curve in a bi-modal format for the colluvial soil and a curve in a tri-modal format for the residual soil. The residual water content levels indicated by the curves were 20% for the residual soil and 30% for the colluvial soil. The porosity, which corresponds to the volume of voids that can be filled by water when the soil is saturated, was 44% for residual soil and 52% for colluvial soil.

2.3 Stability analysis of a road slope

The slope was modeled in 2D and 3D (Figure 3), and stability analyses (deterministic and probabilistic) were performed in the two dimensions in the software SVSlope by SoilVision. The determination of the safety factor was calculated based on Morgenstern-Price's limit equilibrium method, and the probabilistic method used was Monte Carlo's with 5000 iterations.

In the slope modeling on the software, it was used the Mohr-Coulomb criteria for the strength parameters of the three

Table 1. Input parameters of colluvial soil, residual soil, and saprolite (Riselo, 2021).

Material	Colluvial soil				
Parameter	γ_{nat} (kN /m^3)	Poisson's ratio	Modulus of elasticity (kPa)	ϕ' (º)	*c'* (kPa)
Average value	16	0.4	3000	23.5	11.4
Minimum value	-	-	-	17.8	4.7
Maximum value	-	-	-	30	16.8
Standard deviation	-	-	-	6.5	6.7
Coefficient of variation	-	-	-	27.5	58.7
Material	Residual soil				
Parameter	γ_{nat} (kN/m^3)	Poisson's ratio	Modulus of elasticity (kPa)	ϕ› (º)	*c'* (kPa)
Average value	18	0.3	10000	26	7.8
Minimum value	-	-	-	21.8	5.1
Maximum value	-	-	-	30.2	10.4
Standard deviation	-	-	-	4.2	2.7
Coefficient of variation	-	-	-	16.2	34.2
Material	Saprolite				
Parameter	γ_{nat} (kN/m^3)	Poisson's ratio	Modulus of elasticity (kPa)	ϕ› (º)	*c'* (kPa)
Average value	17	0.3	15000	39	10.4
Minimum value	-	-	-	-	-
Maximum value	-	-	-	-	-

Note: kN: KiloNewton; kPa: KiloPascal.

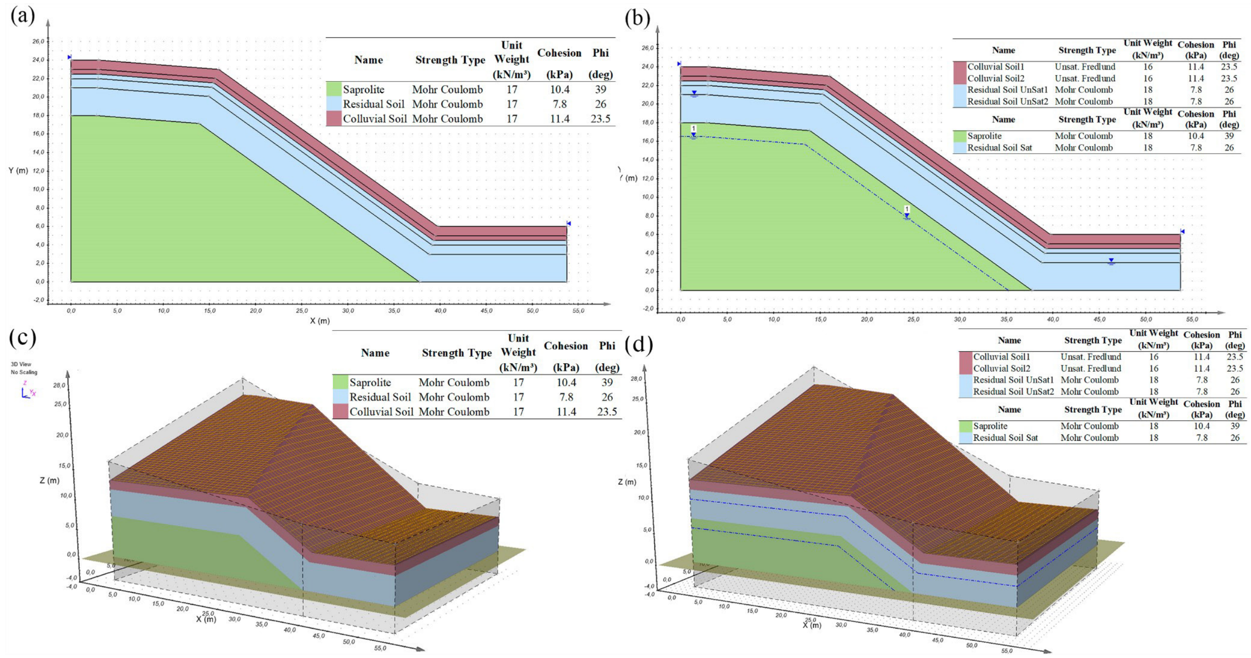

Figure 3. Slope modeling: (a) 2D without water level, (b) 2D with the water level, (c) 3D without water level, and (d) 3D with the water level.

soils. However, in the simulations that were modeled with the incorporation of the water level and superficial suction, the first 3 m of depth was considered non-saturated, thus, for these soils was adopted the respective water retention curves.

The failure surface was defined as non-circular for all simulations and the research method of this surface was the Cuckoo Search, since it was one of the only available methods for the 2D analysis as well as the 3D analysis. This way 50 nests, 350 iterations, and 500 number of vertices were considered in the method.

In the analysis, it was determined the critical failure surface, that is, the software determined the position of the failure surface that presented the lowest safety factor for the determined situation (Bentley, 2019). In total, 52 scenarios were simulated, half 2D and half 3D. From the 26 scenarios from both 2D and 3D models, only in two of them the superficial suction and water level were not considered. In the remaining scenarios, twelve simulations were performed with the water level depth at 6.5 m deep and twelve simulations were performed with the water level depth at 7.5 m deep. The deterministic analysis counts as one simulation and the probabilistic analysis counts as another simulation, even though in some cases they both obtained the same result.

The results obtained with this method were safety factor, probability of failure, and quantification of movement of the mobilized-mass volume. In addition to these numerical data, it was also possible to obtain the critical failure surface of each simulation, a necessary piece of information to perform the runout analysis of the mobilized-mass volume.

2.4 Runout analysis of the mobilized-mass volume in the hypothetical rupture

The runout analysis of the mobilized-mass volume indicates the reach, in meters, of this volume after a possible landslide on the slope, based on the material point method (MPM). In this method, a continuum is discretized by a set of subdomains that concentrate its mass, whose value is fixed to guarantee mass conservation, at a material point (Lagrangian point), which also contains information on soil properties. The movement of these material points defines the deformation state of the considered continuum (Conte et al., 2020).

The interaction between the particles is performed at the nodes of a stationary background computational mesh (Eulerian mesh), which remains constant during the calculation, eliminating the distortion problem. Also, this mesh is superimposed on the continuum and covers the entire domain, remaining fixed over time and not linked to material information (Toro-Rojas et al., 2021).

In MPM, the relationship between material points and mesh nodes is done by linear interpolation shape functions. The nodal accelerations at a given time are unknown to the problem and are calculated by solving the governing equations (equilibrium, constitutive, and mass conservation equations) in the computational mesh. After determining the nodal accelerations, an explicit scheme is used to evaluate the displacement and velocity of the material points in the analyzed time, which are updated in the Eulerian grid for the next time step (Conte et al., 2019). Due to the method using constitutive models of continuum mechanics, the elastoplastic model with the Mohr-Coulomb failure criterion was used on the slope.

The choice to use the MPM was due to the numerical method being able to simulate large distortions and deformations, indicated to follow the movement of a simulated body, such as the slope failure, and post-failure stage. In addition, the software that runs the MPM is freely available for research and studies, further favouring the choice of method.

The runout analysis was performed on the software GID with the Anura3D's plugin, being that the first software performs the pre-processing and the generation of the mesh, and the plugin generates the input files for the software Anura3D. With the position of the critical failure surface of each simulation and its respective mobilized-mass volume, the slope in the study was modeled on GID in 2D, with the three layers of soil. On Anura3D's plugin, the materials were incorporated into the model, according to Table 1, considering the soil shear strength parameters (natural unit weight, friction angle, and cohesive intercept) and the deformability parameters (Poisson ratio and modulus of elasticity). Also, it was established the boundary conditions on the model in directions "x" and "y", the number of material points of each cell, and the calculation criteria, such as the number of steps of calculation and time stage of the calculation. After incorporating and defining the data, the two input files for the software Anura3D, GOM and CPS files, were generated in text format.

With the files generated, the analyses were calculated on the software Anura3D by Windows' Command Prompt. On average, the time of analysis was 5 h and 30 min, using a notebook with an Intel i5 9300H processor, 16GB of RAM, and a 4GB NVIDIA GTX 1650 video card (Mobile). The analyses were performed in three scenarios derived from the 2D stability analyses.

Anura3D is a software used for modeling and numeric simulation of soil-water-structure interaction and great deformations, that utilizes the material point method (MPM). This software is being developed by Anura3D MPM Research Community (Anura3D, 2021).

The software allows the choice of different constitutive models for the material model solid, such as rigid body, linear elasticity, Mohr-Coulomb, and external material model. The external model option makes it possible to load other constitutive models implemented in the FORTRAN language, but the simulation must be performed only if the subroutines are compiled and referenced in DLL (Dynamic Link Library) format (Anura3D, 2021). The Mohr-Coulomb constitutive model was chosen because in the stability analysis, performed in another software (SVSlope), this model was used, keeping the same line of reasoning as it is the same slope. Other papers on the same topic that used Anura3D, employed and indicated the use of the Mohr-Coulomb model, obtaining good results. Also, as MPM uses constitutive models based on continuum mechanics and due to the complexity and little knowledge of FORTRAN language, among the available codes of models compatible with the software, the Mohr-Coulomb model was the one that best applied to the slope context.

The Mohr-Coulomb equation results in a linear shear strength envelope, which is the result of a set composed of at least 3 tests under different normal stresses to the failure plane (Trevizolli, 2018). The real envelope of shear resistance is not linear, so the Mohr-Coulomb equation is valid only for the tested stress range. Thus, the stress level of the test must be compatible with the stress level that the slope will receive throughout its useful life for the equation to be valid. Therefore, in runout analysis of soil slopes, the use of the Mohr-Coulomb constitutive model might be limited.

Based on the studies by Toro-Rojas et al. (2021) and the time of analysis, the number of elements on the mesh was defined as 46213 (0.2 m × 0.2 m), and the number of material points in each cell was defined as 6. Among these two parameters, the number of elements on the mesh is the one that has the most influence on the results of the runout analysis of the movement of the mobilized-mass volume, being more important than the number of material points.

In the first load stage, only gravity was applied to initiate the stresses. Then, in the second stage some, boundary conditions were removed, and the fragility of the failure surface was indicated. Lastly, in the third stage, the boundary conditions were returned to evaluate the mass movement on the slope over time. In total, 50 calculation steps were defined, one in the first load stage, one in the second load stage, and 48 in the third load stage.

The visualization of the results from Anura3D was done on the software ParaView, following the recommendation of the manual (Anura3D, 2021), which enabled the visualization of the displacement of the soil in the slope in 2D, during the 50 calculation stages.

3. Results and discussions

This section contemplates the results obtained with the application of the methodology, presenting the results of the stability analysis and the runout analysis of the movement of the mobilized-mass volume.

3.1 Stability analysis of a road slope

The results of the stability analyses are presented in Table 2 and Table 3. Table 2 shows the results of the simulations without considering surface suction nor water level, and Table 3 presents the results of the simulations that considered the surface suction and the two positions of the water level, at 6.5 m and 7.5 m deep. The volume result (m^3/m) is considered in the cross-section for 1 m of slope extension, and the volume result (m^3) is the total for the 37 m extension of the slope.

Table 2. SVSlope results with no surface suction and no water level (Riselo, 2021).

Analyse	Probability of Failure (%)	Safety Factor (SF)		Volume (m^3/m)		Volume (m^3)	
		Det.	Prob.	Det.	Prob.	Det.	Prob.
2D	1.24	1.21	1.19	111.70	86.59	4132.9	3203.83
3D	0.64	1.27	1.23	26.45	38.97	978.6	1442

Table 3. SVSlope results with surface suction and water level (Riselo, 2021).

WATER LEVEL AT 6.5 METERS								
Analyse	Suction (kPa)	Probability of Failure (%)	Safety Factor (SF)		Volume (m^3/m)		Volume (m^3)	
			Det.	Prob.	Det.	Prob.	Det.	Prob.
2D	20	0.28	1.25		159.9		5916.3	
	40	0.04	1.29					
	60	0.02	1.33					
	80	< 0.0002	1.36					
	100	< 0.0002	1.38					
	120	< 0.0002	1.39					
3D	20	< 0.0002	1.44		40.89		1513	
	40		1.46		35.3		1306	
	60		1.52		31.81		1177	
	80		1.68		49.59		1835	
	100		1.77		41.78		1546	
	120		1.85		58.05		2148	
WATER LEVEL AT 7.5 METERS								
Analyse	Suction (kPa)	Probability of Failure (%)	Safety Factor (SF)		Volume (m^3/m)		Volume (m^3)	
			Det.	Prob.	Det.	Prob.	Det.	Prob.
2D	20	0.28	1.25		159.9		5916.3	
	40	0.04	1.29					
	60	0.02	1.33					
	80	< 0.0002	1.36					
	100	< 0.0002	1.38					
	120	< 0.0002	1.39					
3D	20	< 0.0002	1.36		36.57		1353	
	40		1.53		47.05		1741	
	60		1.54		42.3		1565	
	80		1.61		23.43		867	
	100		1.65		48.05		1778	
	120		1.71		51.38		1901	

Among the 26 simulated scenarios, the one that presented the higher probability of failure was the first one, a 2D analysis with no surface suction nor water level, obtaining a value of 1.24%. The minimum safety factor required for a landslide of the slope is 1.3, according to the Brazilian standard ABNT NBR 11682 (ABNT, 2009), which depends on the consequences of failure, considering the level of security against material and environmental damages as low and the level of security against damages to human lives as medium. It is worth mentioning that this highway might face high consequences in case of failure. It is noticeable that the increase in surface suction in the analyzed slope provided an increase in the safety factor, guaranteeing greater safety to the slope.

It is important to assess both results, SF and probability of failure, since a low safety factor does not always indicate a failure in the slope, such as this slope, which in all simulated scenarios was considered stable. Assis (2020) points out that it is preferable to have an approximated probabilistic result than a precise deterministic result that is certainly wrong, which corroborates the importance of the probability of failure to analyze the problem.

The results of the deterministic analysis were different from the results of the probabilistic analysis only for the scenarios with no suction nor water level. Besides that, the deterministic analysis presented a more optimistic scenario due to the safety factor being higher.

The mobilized-mass volumes, for the scenarios without suction and water level, presented on Table 2, do not possess a behavior pattern. This difference in values is due to the critical surface failure considered for each analysis being different, mainly in the 3D geometry of the failure zone.

Also, due to the slope geometry, the intermediate stress (σ_2) acting on the 3D slope, which was disregarded in the 2D analysis, contributes to this difference in volumes.

The mobilized-mass volumes in the scenarios with surface suction and water level, presented in Table 3, were the same in the 2D, for both water levels, and different in the 3D. In 2D the critical surface failure was the same for all the simulations, while in 3D, for each scenario, it was found a different surface. Troncone et al. (2014), in their study, indicate that the analysis in 2D does not take into account the entire failure process, differently from the 3D analysis, which is able to evaluate all of the extension of the failure, becoming a more realistic simulation.

The difference in values of 2D and 3D is evident in the results in Table 3. The distinction in values is due to the possibility of considering all the possible landslides in the three dimensions, and also the consideration of the intermediate stress (σ_2) acting on the 3D slope, contributing to greater safety in the context

Firincioglu & Ercanoglu (2021) reported in their study that the tridimensional analyses of limit equilibrium provide a more realistic approach to the stability problems of slopes, corroborating the result found in this analysis.

Lastly, the proximity of the results with the two water level positions was observed, being the same in the 2D. In the 3D the value difference was small, having most safety factors a little higher at 6.5 m deep and volumes mobilized without behavior pattern.

Figure 4 exemplifies the deterministic analyses made in the software SVSlope and the results obtained in 2D and 3D.

3.2 Runout analysis of the mobilized-mass volume in the hypothetical rupture

The results of the runout analysis of mass movement are presented in Table 4. In this table the three simulated scenarios are listed, initially identifying the input parameters, such as mobilized-mass volume, and the results the total distance and percentage of traffic lanes intercepted.

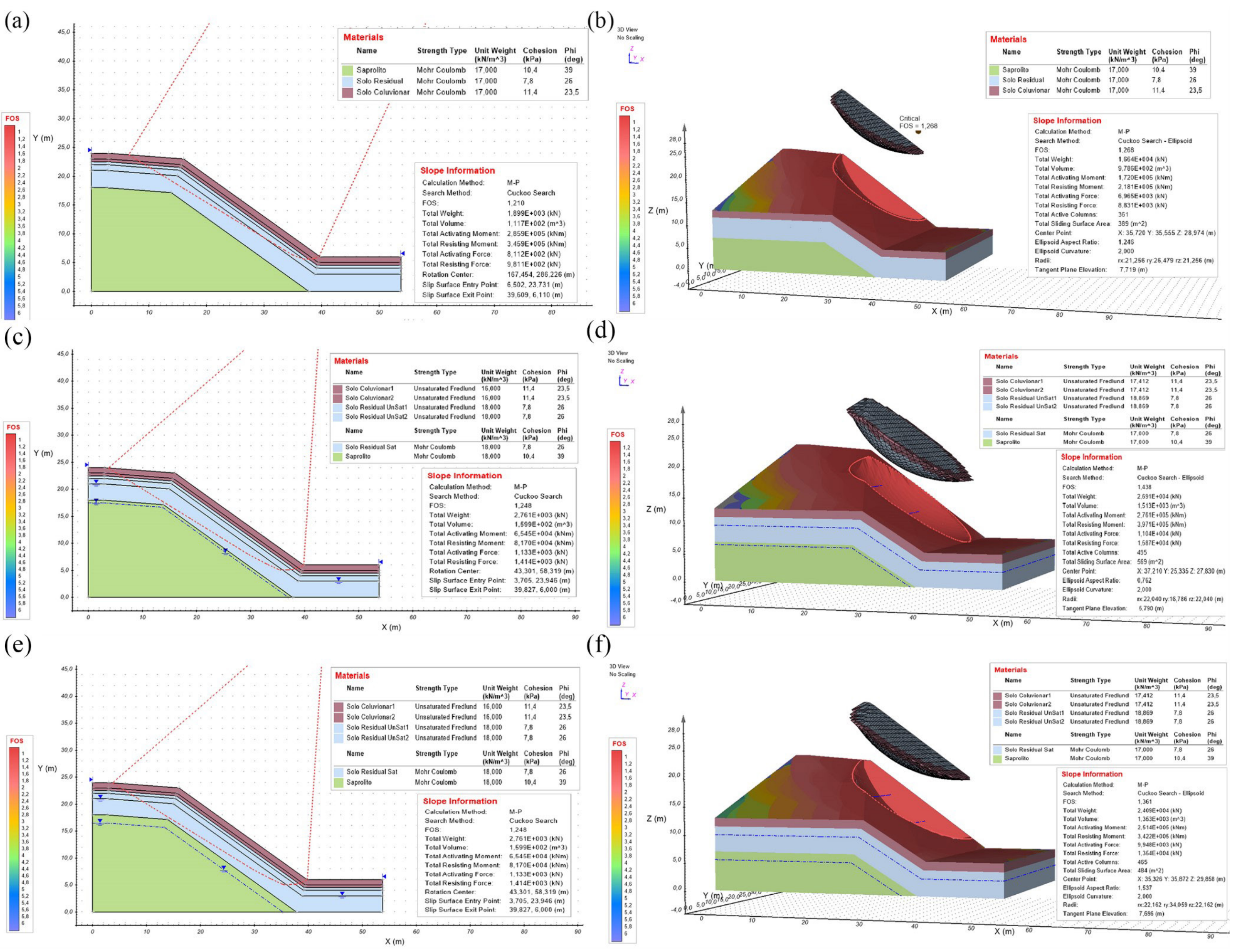

Figure 4. Deterministic analysis in SVSlope: (a) with no surface suction and no water level 2D, (b) 3D, (c) with 20 kPa surface suction and water level at 6.5 m depth 2D, (d) 3D, (e) with 20 kPa surface suction and water level at 7.5 m depth 2D and (f) 3D.

Table 4. Anura3D results of mass movement prediction.

Inputs				Outputs	
Simulation	Surface suction and water level	Stability analysis type	Mobilized-mass volume (m^3/m)	Distance covered (m)	Percentage of traffic lanes intercepted (%)
1	Not	Deterministic	111.70	8.62	72.4
2	Not	Probabilistic	86.59	7.25	59.7
3	Yes	Deterministic/ Probabilistic	159.9	10.41	89

Simulation 1 refers to the 2D deterministic analysis without surface suction and water level (line 1 – Table 2). Simulation 2 regards the 2D probabilistic analysis without surface suction and water level (line 1 – Table 2). Lastly, simulation 3 reflects all of the deterministic and probabilistic analyses with surface suction and water level (lines 1 to 6 and lines 13 to 18 – Table 3). The choice of these simulations is due to the fact that they are scenarios that presented different volumes. The selection of only the 2D analyses was due to the modeling of the software GID permitting the manual definition of the failure surface.

It is noticeable that the higher the mobilized-mass volume, more lanes are affected, as in simulation 3, which reached 89% of the traffic lanes, that is, practically all three lanes (Table 4).

Analyzing the three simulations, simulation 1 (2D deterministic analysis – with no surface suction and water level – Table 2) presented a total displacement of 8.62 m, affecting 3 traffic lanes, with an interception of up to 0.62 m of the third lane, leaving practically only the last lane free for traffic passage. Simulation 2 (2D probabilistic analysis – with no surface suction and no water level – Table 2) had 7.25 m of distance covered, affecting two traffic lanes, with a displacement of up to 2.85 m on to the second lane, also leaving only the last lane of traffic free. Simulation 3 (2D deterministic/probabilistic analysis – with surface suction and water level – Table 3) presented a displacement of 10.41 m, affecting the three traffic lanes, intercepting up to 2.41 m of the third lane, obstructing practically the whole traffic lanes.

The development of the failure surface indicates the beginning of the movement of the unstable soil mass of the slope, which moves towards the foot of the slope and later towards the traffic lanes. The displacement of the material point is what defines the kinematics of the landslide. Thus, over time, this displacement increases until the moment when the material points are in equilibrium, defining the final post-failure profile of the landslide and the total displacement distance. This distance is determined between the endpoint of the failure surface on the slope before the landslide and the endpoint of the material displaced after failure.

The displacement obtained with the analysis is typical of a post-failure rotational landslide, with distance values that increase until the slips become stable. Therefore, the mobilized soil mass accelerates until it reaches a maximum speed and then decelerates until it stops.

The methodology used was able, based on the material point method (MPM), to predict the displacement of the mobilized-mass volume. Furthermore, the MPM was able to simulate the landslide process, from the beginning of the failure to its progression in time, being able to solve failure simulations on slopes with different geometries of the failure surface. Thus, this methodology is applicable to assessing risks of traffic interruptions, based on the analysis of landslides in practical cases of slopes located close to highways. However, the choice of the constitutive model of the materials significantly influences the results of failure ranges, therefore, it is recommended the judicious choice of the model within the software. Also, the computational effort of the simulations is very high, so it is worth a previous analysis of the mesh size and the number of material points of each cell to be used in the MPM, so that the time and data processing are adequate for the desired accuracy.

Finally, a focus on the utilization of the software Anura3D to predict the movement of the mobilized-mass volume of a landslide, since it presented satisfactory results. Conte et al. (2019) and Conte et al. (2020) also used this software to assess the post-failure stage of two distinct landslides in south Italy, obtaining results consistent with those in the field. Both authors used the Mohr-Coulomb constitutive equation, obtaining a total displacement of 28 m in the sand and clayey silt, in the first paper, and a total displacement of 350 m in silty sand and clayey silt, in the second paper. That being, the utilization of the material point method (MPM), by the software Anura3D, provides reliable and applicable results to landslide problems on slopes.

Toro-Rojas et al. (2021) reported in their study that the utilization of the MPM to analyze a process of post-failure of a landslide on a slope is efficient, corroborating the result achieved in this analysis. Also, Troncone et al. (2019), concluded that the use of the MPM to simulate a landslide in all its stages and determine the distance of displacement of the slope's material is effective. Both authors used the Mohr-Coulomb constitutive equation, obtaining a runout distance of 2.5 m, in the first paper, and a runout distance of 1.7 m in a purely frictional soil, in the second paper.

Figure 5 exemplifies the 2D results visualized on ParaView, after the 50 steps of the calculation, for simulations 1 (a),

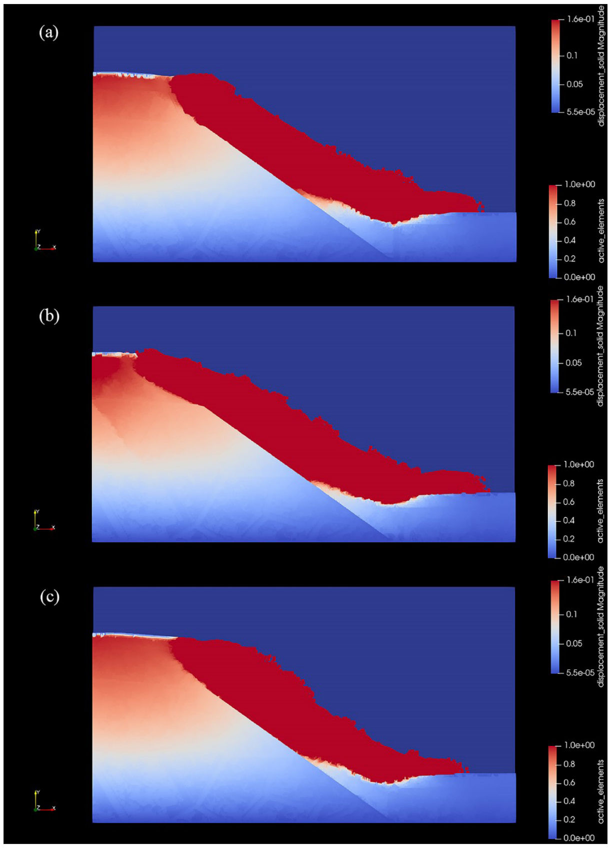

Figure 5. Mass movement prediction results in ParaView from simulations: (a) 1, (b) 2, and (c) 3.

2 (b), and 3 (c). The part in red refers to the mobile area of the slope, that is, the area above the critical failure surface.

4. Conclusions

According to the results of this study, it finds that the probabilistic analysis (applying Monte Carlo) provides a result that is more complete, since it produces, aside from the safety factor, the probability of failure of the slope. Then, even though in some scenarios the calculated safety factor, in a deterministic approach (applying Morgenstern-Price), was lower than the minimal safety factor, the probability of failure indicated a maximum value of 1,24%. According to the USACE classification (USACE, 1999), this probability value indicates a level of expected performance below average.

The incorporation of the surface suction on the unsaturated soils, by the characteristic curves of water retention, interfered in the results of safety factor (deterministic) and probability of failure. Regarding the mobilized-mass volume, no relation could be established, since it did not present a behavior pattern. It was obtained the highest quantity of volume, 159.90 m^3/m, in the 2D deterministic and probabilistic analyses with surface suction.

The results of the numeric simulation also showed that the 3D analysis presented more optimistic results when compared to the 2D analysis. The tridimensional analysis on small slopes is affected by the effect of the intermediate stress, so the results in 3D, when compared to the two-dimensional analysis, are more reliable and accurate to reality.

Regarding the shifting in the position of the consideration of water level in the slope, it was obtained a proximity to the results. The small difference in values is due to the water level being positioned in a fracturing material (saprolite), which obstructs the water flow to the shallower grounds. It is also due to the critical failure surface not reaching both water levels in the analyses, creating similar results.

The material point method (MPM), considering the Mohr-Coulomb constitutive model, utilized in this study was efficient to analyze the proposed simulations regarding the distance covered by the mobilized-mass volume, especially when compared with results obtained in other papers that used the same method. With the MPM it is possible to predict the displacement of this volume and assess the risks of traffic interruptions in practical cases of slopes close to highways.

For this study, any landslide that may come to occur, coming from this slope, will intercept at least two traffic lanes, which equals 59.7% of the existing lanes, damaging the vehicle flow and putting the safety of the highway and users at risk.

Therefore, in front of the whole study, it is concluded that the analyzed slope is safe regarding its global stability for failure. For application in other places, the best constitutive equation must be analyzed and, preferably, the parameters required by the equation must be validated by retro-analysis of known similar failures, tests, and/or bibliographic references. Furthermore, the results obtained in this article may be used as input data for future studies, such as the evaluation of the economic risk of a possible landslide and others points of this road.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Bianca Riselo: conceptualization, data curation, methodology, software, formal analysis, writing – original draft preparation. Larissa Passini: supervision, validation, writing – reviewing, and editing. Alessander Kormann: supervision.

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