

Influence of parameters on the development of landslides in the Estrada de Ferro

Vitória-Minas slopes

Influência dos parâmetros no desenvolvimento de deslizamentos em encostas da Estrada de Ferro

Vitória-Minas

Influencia de los parámetros en el desarrollo de deslizamientos en las laderas de Estrada de Ferro

Vitória-Minas

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Abstract

Landslides have been the object of extensive studies in the world, not only for their importance as active agents of modifications of relief forms, but also because can damages and losses to people and exposed structures, affecting various kinds of enterprises. This study had as objective the determination of influencing parameters on the development of landslides in the slopes aside of Estrada de Ferro Vitória-Minas (EFVM). EFVM is located in the southeastern region in Brazil and is an important railroad for the transportation of iron ore to the steel mills and for exportation, as well as for passenger transportation. The database used herein was collected from field work in EFVM, together with image processing and data in laboratory tests. The parameters selected to be evaluated were Atterberg limits, cohesion, friction angle, permeability and classification of soil in the slopes. Estimates were done on the volumes and areas of landslides that have already occurred in the slopes. Among the studied parameters, the results obtained for the Atteberg limits and soil cohesion were the most relevantly correlated with the field results, which is in accordance with other studies from literature. It is concluded that Atterberg limits are directly related to soil ruptures, and soil cohesion contributes to soil stabilization in slopes.

Keywords: Slopes landslides; Landslides influencing parameters; Estrada de Ferro Vitória-Minas; Multivariate statistics; Principal component analysis.

Resumo

Deslizamentos têm sido objeto de grandes estudos no mundo, não apenas por sua importância como agentes modificadores do relevo, mas também por causarem danos e prejuízos a pessoas e estruturas expostas, afetando vários tipos de empreendimentos. O objetivo deste estudo foi a determinação de parâmetros influenciadores no desenvolvimento de deslizamentos nas encostas da Estrada de Ferro Vitória-Minas (EFVM). A EFVM está localizada na região sudeste do Brasil, é uma ferrovia importante para o transporte de minério de ferro para as siderúrgicas e para exportação, bem como para o transporte de passageiros. O banco de dados aqui utilizado foi coletado a partir de trabalhos de campo na EFVM, juntamente com o processamento de imagens e dados de testes laboratoriais. Os parâmetros selecionados para serem avaliados foram limites de Atterberg, coesão, ângulo de atrito, permeabilidade e classificação do solo nas encostas. Foram feitas estimativas dos volumes e áreas de deslizamentos de terra que já ocorreram nas encostas. Dentre os parâmetros estudados, os resultados obtidos para os limites de Atteberg e a coesão do solo foram os mais correlacionados com os resultados de campo, o que está de acordo com outros estudos da literatura. Conclui-se que os limites de Atterberg estão diretamente relacionados às rupturas do solo, e a coesão do solo contribui para a estabilização do solo nas encostas.

Palavras-chave: Deslizamentos de encostas; Parâmetros influenciadores de deslizamentos; Estrada de Ferro Vitória-Minas; Estatística multivariada; Análise de componente principal.

Resumen

Los deslizamientos han sido objeto de amplios estudios en el mundo, no sólo por su importancia como agentes activos de modificación de las formas de relieve, sino también porque pueden causar daños y pérdidas a las personas y estructuras expuestas, afectando a diversos tipos de empresas. Este estudio tuvo como objetivo la determinación de los parámetros que influyen en el desarrollo de deslizamientos en las laderas laterales de la Estrada de Ferro Vitória-Minas (EFVM). La EFVM está situada en la región sureste de Brasil y es una importante vía férrea para el transporte de mineral de hierro a las acerías y para la exportación, así como para el transporte de pasajeros. La base de datos utilizada en este trabajo se recogió a partir del trabajo de campo en la EFVM, junto con el procesamiento de imágenes y los datos en las pruebas de laboratorio. Los parámetros seleccionados para ser evaluados fueron los límites de Atterberg, la cohesión, el ángulo de fricción, la permeabilidad y la clasificación del suelo en los taludes. Se realizaron estimaciones de los volúmenes y áreas de los deslizamientos ya ocurridos en los taludes. Entre los parámetros estudiados, los resultados obtenidos para los límites de Atteberg y la cohesión del suelo fueron los más correlacionados con los resultados de campo, lo que concuerda con otros estudios de la literatura. Se concluye que los límites de Atterberg están directamente relacionados con las rupturas del suelo, y la cohesión del suelo contribuye a la estabilización del suelo en los taludes.

Palabras clave: Deslizamientos de laderas; Parámetros de influencia de los deslizamientos; Estrada de Ferro Vitória-Minas; Estadística multivariante; Análisis de componentes principales.

1. Introduction

Natural disasters associated with mass movements on slopes occur in a wide range of frequencies in various parts of the world. In linear infrastructures such as railways, for example, studies about landslide characteristics assume particularly relevance due to the essential nature of the project, which consists of a long trajectory crossing different regional landscapes with its distinct geological, geotechnical, topographies, and vegetation characteristics. In this context, several works were developed (Junior & Cabral, 2019; Pedrosa *et al.*, 2020; Santos *et al.*, 2020; Silva & Santos, 2020) in order to assist in decision making regarding the management and prioritization of works, not only in the railway network, but also in highways, housing complexes and in mining areas.

Landslides have been the object of extensive studies in the world, not only for their importance as active agents of modifications of relief forms, but also because of implications and for importance from the economic point of view (Guidicini & Nieble, 1984). This phenomenon can cause damages and losses to people and exposed structures, affecting various kinds of enterprises. There are different scopes for the previous studies related to slope landslides, with different objectives, for example, relationship propositions either to predict landslide volumes on slopes (Silva *et al.*, 2018; Guzzetti *et al.*, 2009; Guo *et al.*, 2014; Lee & Chi, 2011; Silva *et al.*, 2021); classifications of landslide types (Varnes, 1978; IAEG, 1990), or identification of the events that trigger landslide development (Terzaghi, 1950).

This research was developed taking as a reference the railway called Estrada de Ferro Vitória-Minas of the company Vale S.A., which is located in the southeast region of Brazil, between Minas Gerais and Espírito Santo states (Figure 1). In 2014, the railroad handled about 100 million tons of ore, besides others cargo such as agricultural products and coal (Vale, 2018). As far as passenger transport is concerned, the railway carried almost 1 million people over the same period.

Figure 1: Railroad location, in the Minas Gerais and Espírito Santo states.



Source: Silva *et al.* (2020).

This study aimed to determine the influence of parameters on the development of landslides in Estrada de Ferro Vitória-Minas slopes (EFVM). The database used herein was collected from field work in EFVM, with image processing with Google Earth Pro, together with database and laboratory tests from work of Gomes (2014). The parameters selected to be evaluated were Atterberg limits, cohesion, friction angle, permeability and soil classification of slopes. To determine the occurrence of landslides in EFVM, data on the volumes and areas of landslides that occurred in the slopes were collected and estimated.

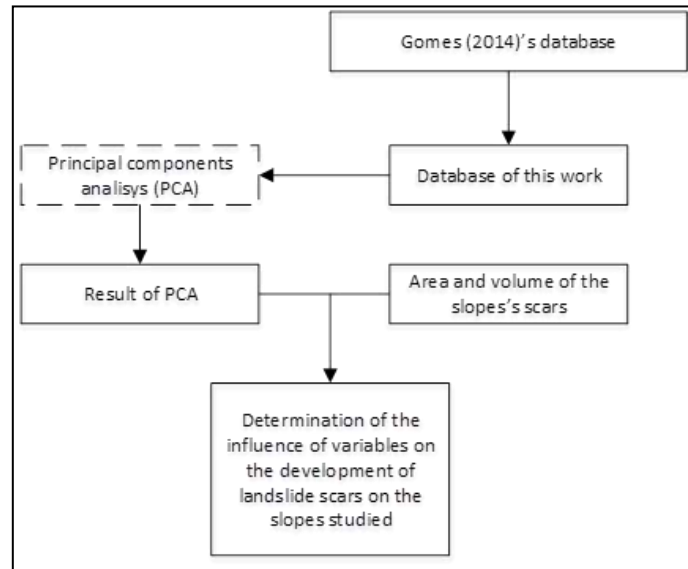
Multivariate statistical techniques have been used in the literature for different purposes. Investigation of damage from seismic events (Massumi & Gholami, 2016), landslide susceptibility mapping (Ahmed & Dewan, 2017) problem solving in mining (Kulatilake *et al.*, 2012) and prevision of the stability condition of slopes (Santos *et al.*, 2018; and Santos & Silva, 2021) are some examples of research carried out with these techniques. Thus this work, the methodology to determine the influence of previously mentioned parameters for the development of landslides was based on techniques of multivariate statistics, such as principal component analysis. The determination of the influence of these parameters may help decision making related to measures of containment, mapping and investigation of landslides in the stretches of the road.

2. Methodology

The first part of the research was the use of the principal component analysis technique to the Gomes (2014) database. The variables assessed by the Gomes (2014) database are: liquidity limit, plastic limit, total cohesion, friction angle, effective cohesion, friction angle drained and permeability.

The values of area and volume of the landslide scars on the slopes studied were compared to the results of the principal component analysis, allowing the determination of the influence of these variables on the development of landslide scars on the slopes studied. Figure 2 shows the applied methodology.

Figure 2: Flowchart of data processing procedure.



Source: Authors.

The values of area and volume of the landslide scars were estimated by imaging in Google Earth Pro together with field work on the slopes chosen for study.

The principal component analysis technique allowed the determination of the influence of the variables in the phenomena that were registered within the database by means of the element score graph together with the analysis of the eigenvectors of the original variables in each principal component generated. In addition, the technique allowed the reduction of variables by the methods of Catell (1966) and Kaiser (1958).

3. Results and Discussion

The database used in the present study is a result of the Gomes (2014) study, together with the addition of two other variables related to the area and respective volume of landslide scars in the slopes studied. The variables used in the database proposed by Gomes (2014) were: liquidity limits, plastic limit, cohesion, friction angle and permeability. Table 1 presents the variables used in the application of the principal component analysis.

Table 1: Variables used in the principal component analysis, all of them are classified as quantitative parameters.

Parameter	Definition	Type
LL	Liquidity limit	Quantitative
PL	Plastic limit	Quantitative
c	Coehsion	Quantitative
ϕ	Friction angle	Quantitative
c'	Effective coehsion	Quantitative
ϕ'	Friction angle drained	Quantitative
e	Permeability	Quantitative
A	Scar's area	Quantitative
V	Scar's volume	Quantitative

Source: Authors.

In the application of the principal component analysis, the following variables were used: liquidity limit, plastic limit, cohesion, friction angle, effective cohesion, friction angle drained and permeability. The variable's area and volume of the scars were used as the results of the principal component analysis technique, aiming to investigate an influence of the other variables on development of landslides in the studied slopes. In this case, the development of landslide scars is represented by the area and volume of landslide scars.

Table 2 presents the values of the liquidity limit and plastic limit in relation to each slope studied. It is possible to observe the liquidity limit values range from 33.6 to 60.1 in the seven analyzed slopes. And the highest plastic limit values were found on the 4 and 6 slopes.

Table 2: Liquidity limit and plastic limit at each relevant slope for occurrence of landslides.

Slope	LL	PL
1	43.80	15.20
2	40.80	17.60
3	33.60	9.40
4	43.30	24.40
5	44.30	17.70
6	60.10	30.20
7	50.60	23.40

Source: Authors.

The values of cohesion, friction angle and permeability for each slope studied are presented in Table 3. The highest values of cohesion are present on 1, 3 and 5 slopes. While the highest values of friction angle are present on 2, 1 and 5 slopes.

Table 3: Cohesion, friction angle and permeability at each relevant slope for occurrence of landslides.

Slope	c	ϕ	c'	ϕ'	e
1	25.90	14.00	29.30	19.70	0.0001
2	7.20	20.60	4.77	33.60	0.0004
3	17.90	11.00	10.30	29.30	0.0001
4	5.57	10.60	4.19	26.10	0.0000
5	8.06	13.00	4.77	28.00	0.0001
6	15.70	12.90	7.73	32.20	0.0000
7	2.00	12.40	1.00	28.70	0.0000

Source: Authors.

Table 4 presents the values of the area and volume variables of the scars on the slopes studied. It is possible to observe that the slopes with the largest landslide areas are 7 and 6. Consequently, these slopes also have the largest displaced volumes. This may be related to the fact that these slopes have the lowest values of cohesion and friction angle.

Table 4: Area and volume of the scars at each relevant slope for occurrence of landslides.

Slope	A (m ²)	V (m ³)
1	1624.9362	340.3258
2	4302.6842	901.1521
3	5451.3766	12559.0701
4	8083.9680	8465.5115
5	8174.2787	51360.5079
6	16522.7300	76131.2745
7	100336.2560	63043.1290

Source: Authors.

The principal component analysis technique was applied in the Gomes database (2014). Thus the first results related to the application of the principal component analysis in the database are presented in Table 5, which shows the explained variance of the database for each principal component, both in individual proportion and as accumulated.

Table 5: Eigenvalue of parameters correlation matrix with the obtained proportions of occurrences explained both in individual proportion and as accumulated proportion.

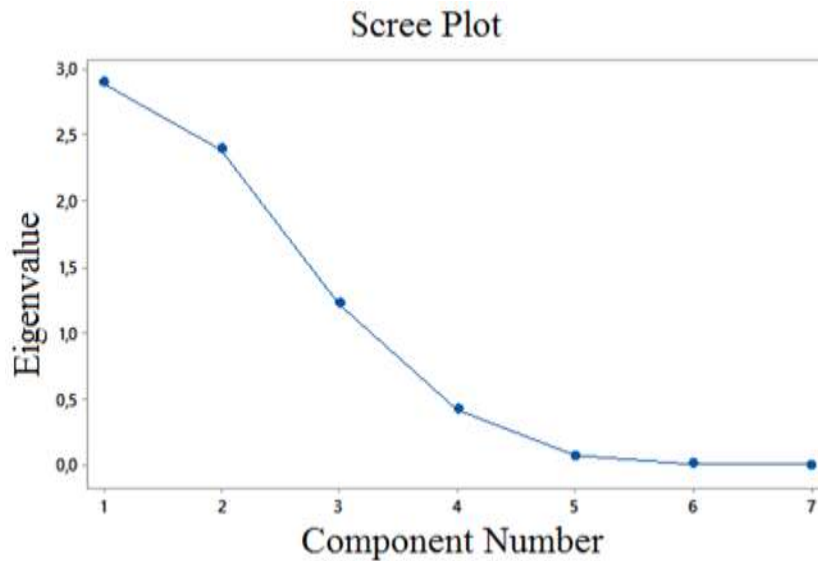
	CP1	CP2	CP3	CP4	CP5	CP6	CP7
Eigenvalue	2.896	2.388	1.221	0.422	0.067	0.006	0.000
Proportion explained	0.414	0.341	0.174	0.060	0.010	0.001	0.000
Proportion explained (Accumulated)	0.414	0.755	0.929	0.990	0.999	1.000	1.000

Source: Authors.

Based on the results presented in Table 5, it is noticed that with the first three principal components, it is possible to explain 92.9% of the total variability of the database. Thus the technique of the main components allows a reduction of variables of the order of 3/7, considered that seven original variables were used to apply the multivariate technique.

Figure 3 shows the Screen Plot for the values of the eigenvectors for each generated component. By the Screen Plot graphic, it would be possible to apply the Criterion of Catell (1966), which guides the selection of the components by stabilizing the values of the eigenvectors.

Figure 3: Screen plot for the seven parameters influencing the occurrence of landslides.



Source: Authors.

According to Kaiser's criterion (1958), the principal components are identified as those with eigenvalues greater than 1, in order to maintain the components that explain the variability of at least one original variable. By the criterion of Kaiser (1958), the first three main components are identified that explain 92.9% of the total variability present in the database. The Table 6 shows the eigenvectors of original variables in relationship to each component generated.

Table 6: Eigenvectors of variables.

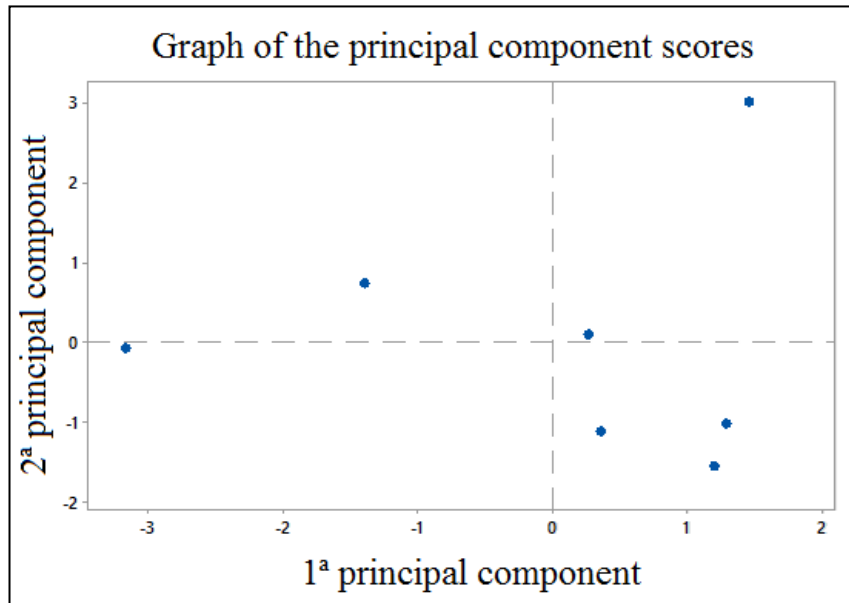
Variables	CP1	CP2	CP3	CP4	CP5	CP6	CP7
II	0.265	-0.408	0.553	0.048	-0.589	-0.287	0.157
lp	0.371	-0.401	0.374	-0.178	0.720	0.091	-0.062
C	-0.488	0.002	0.373	0.572	0.199	-0.278	-0.423
Ø	0.153	0.515	0.462	-0.282	-0.192	0.379	-0.487
c'	-0.528	0.014	0.393	-0.066	0.053	0.455	0.593
ø'	0.481	0.204	0.004	0.738	0.019	0.365	0.220
E	0.146	0.604	0.215	-0.095	0.234	-0.590	0.394

Source: Authors.

From the values presented in Table 6, it is possible to verify the structure of the first two components, specifically CP1 and CP2. In the first component CP1, we have significant values, indirectly proportional to CP1, for the total and effective, being -0.528 and -0.488, respectively. Still in CP1 there are directly proportional values, significant for the limits of liquidity and plasticity, being 0.265 and 0.371, respectively.

In relation to CP2, liquidity and plastic limits presented significant values, indirectly proportional to CP2, being -0.408 and -0.401. For CP2, the permeability value was significant, and directly proportional to CP2, being 0.604. Figure 4 shows the graph of the slopes studied for the first two components.

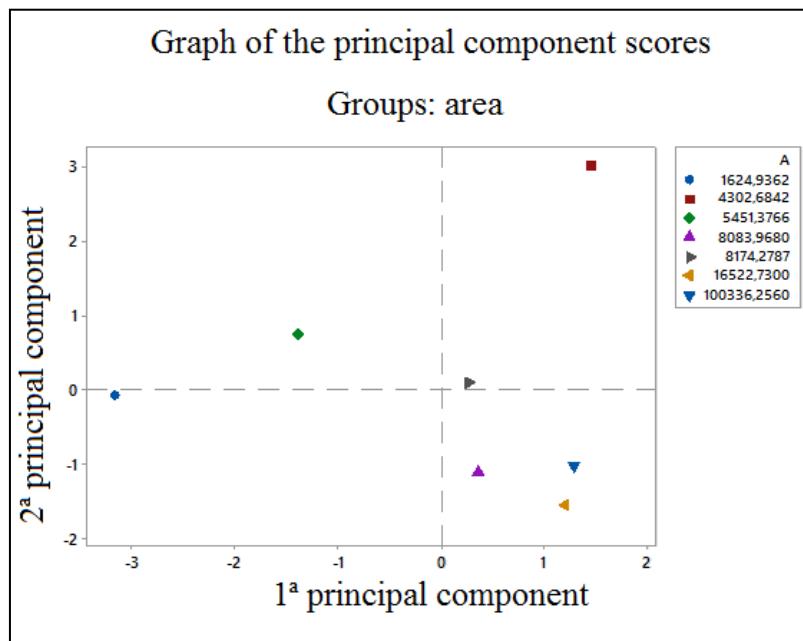
Figure 4: Plot of the principal component scores.



Source: Authors.

In order to allow a better visualization and interpretation of the influence of the variables on the development of scars, the scores of the principal components related to the slide scar area and the volume of the landslide scars are presented in Figures 5 and 6, respectively.

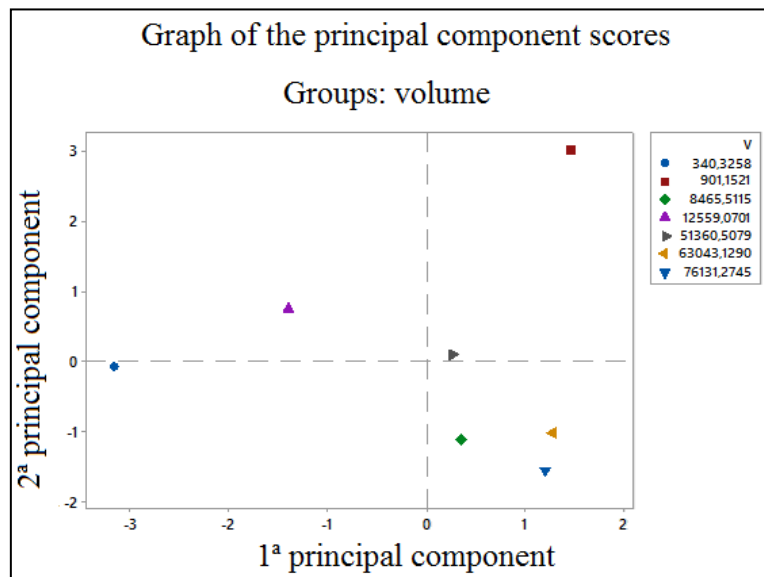
Figure 5: Plot of the principal component scores related with groups area.



Source: Authors.

Figure 5 shows the phenomenon of development of the scar areas, by the filter of the area variable. Figure 6 shows the phenomenon of development of landslide scar volumes.

Figure 6: Plot of the principal component scores related with groups volume.



Source: Authors.

Through Figures 5 and 6, it is possible to observe the agreement of the scale of values, both for area and for volume, in groupings by the first and second principal component. The largest values for volume and area are grouped, as the smallest values are also grouped. Thus, this result allows validating the adjusted components.

4. Conclusion

The present research allowed the investigation of the influencing variables on the development of landslide scars in the Estrada de Ferro Vitória-Minas in Brazil, through the application of multivariate statistical principal component analysis.

Among the variables studied, the behavior of the liquidity limit and plastic limit variables were positively correlated with the development of the landslide scars. In the same structure, it was possible to observe that the total cohesion values contribute negatively to the development of the scars.

The results obtained are in accordance with the results seen in literature and in the field, where the Atterberg limits are directly related to soil ruptures. The same is true for the total cohesion that contributes to soil stabilization on slopes. For future work, it is suggested that laboratory tests be carried out on other slopes of the railway and other parameters estimated to expand the database. In addition, other techniques of multivariate statistics can be used in the expanded database.

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