Residual Soil and Rock Slides in Santos (Brazil)

Glissements de Pentes en Sols Détritiques Recouvrant le Roche à Santos, Brésil

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Summary

Back in 1928 a spectacular landslide occurred on the hills of the city of Santos, causing great damage and taking a heavy toll of life. Twenty-eight years later, in the same month of March, a great number of similar slides came down the hills nearly simultaneously, repeating the catastrophe of 1928. Most of the slides took place along the residual soil mantle that partially covers the underlying crystalline formation, but some rock slides also occurred. An analysis of the causes, prolonged heavy rain being the main one, is made. The local geological conditions as well as those concerned with the soil properties are studied and an attempt is made to compare the shear characteristics of the residual soil *in situ* with that obtained in the laboratory.

Sommaire

Pendant l'année 1928 un glissement spectaculaire à eu lieu dans les collines de Santos, Brésil, y causant de grands dommages et beaucoup de morts. Vingt-huit ans aprés au même mois de mars, de nombreux glissements semblables, survenus presque simultanément, ont répété la catastrophe de 1928.

La plupart des glissements ont eu lieu dans le sol detritique qui recouvre partiellement des roches cristallines sous-jacentes dans les talus des collines entourant la ville de Santos. On présente ici une analyse des causes, la pluie forte et prolongée qui a tombé sur la ville, la nuit précédant les évènements pouvant être considérée la principale. On étudie les conditions géologiques de la région aussi bien que les propriétés caractéristiques du sol, et en particulier on compare sa résistance au cisaillement en place avec celle obtenue au laboratoire.

Introduction

On 10 March 1928 a great slide occurred at the northern side of a hill that surrounds the city of Santos. A mass of several thousand cubic metres of residual soil moved down the hill and destroyed a number of houses and part of a hospital. Fig. 1 shows a view of the slide.

Also during the rainy season of 1947 a mass of about one million cubic metres of detritus from old slides which was at rest just behind a big electric power-house at the foot of the coastal range, locally called Serra do Cubatão, some 10 km west of Santos, started to move. Well-designed drainage works prevented the movement. About one year later another similar movement, also at an old slide area about a kilometre from the first one, took place as the result of an excavation for a cut in the construction of a new express-way road linking Santos with São Paulo. Fig. 2 shows an aerial view of the slide area. Here again drainage works successfully stopped the movement.

Fig. 1 Old slide at Monte Serrate (1928)
Ancient glissement au Monte Serrate (1928)

On 1 March, after a heavy rainstorm, some slides occurred at the slopes of a hill called Morro Sta. Terezinha, at the Marapé quarter of the city of Santos. The most important one was a rock slide in the vicinity of an operating quarry. Twenty-one people were killed, 42 hurt and more than 50 houses were destroyed. Fig. 3 presents a picture of the site before the slide and Fig. 4 after the occurrence.

Fig. 2 Slide at the foot of Serra do Cubatão (1948)
Glissement au pied de la Serra do Cubatão (1948)

From the 2nd to the 18th of March rains were light and no slides occurred. During the following period from the 18th to the 25th of the same month a number of successive rainstorms occurred and a series of small slides followed. Then there was an exceptionally heavy rainstorm in the night of the 24th. As a consequence, about 60 slides occurred almost simultaneously on the hills of Santos and neighbouring counties, where identical geological and soil conditions prevail.

Studying the slides observed at the slopes of the coastal mountain range in southern Brazil it is possible to classify them into the following three main classes:

(1) Creep of the superficial residual soil layer which covers the great majority of the slopes. These are very slow movements which can frequently be observed over vast areas, but which have not till now caused any major disaster.

Fig. 3 Marapé scarp before slide
La pente du Marapé avant le glissement

(2) Movements of detritus accumulated at the lower places by older slides. Many of these so-called 'old slide areas' are enormous and so unstable that a simple excavation through them is sufficient to start a movement. The above-mentioned slides at the foot of the Serra do Cubatão were of this type.

(3) Slides caused by sudden rupture of the residual soil mantle, decomposed rock on boulders, that covers the rocky nucleus of the hills or mountains. All the slides which occurred in Santos belong to this class.

Fig. 4 Marapé slide (1 March 1956)
Le glissement du Marapé (1er mars 1956)

Particular Aspects of the Santos Slides

The hills of Santos occupy an area of about 72,000 hectares and attain an average elevation of 150 m. The slopes are rather steep; up to 45 degrees they are covered with residual soil and up to 60 degrees they exhibit bare rock. At the top of the hills the residual soil mantle has a thickness of about 20 m, this thickness being reduced at the slopes to a few m, if the bare rock is not directly exposed as in some places. At several places the mantle consists entirely of residual clay down to the surface of the sound rock. At other places there is a transition from residual soil to the rock through a zone of partially decomposed rock. The rocky nucleus of the hills is of crystalline formation, including granites, gneisses and schists. There is a tendency to exfoliation resulting in the domed structure of the hills. This kind of structure may be considered a peculiar morphologic aspect of the mountains in the coastal southern Brazil.

Fig. 5 shows a general and schematic outlay of the prevailing geological conditions in the Santos slides, all belonging to the above-mentioned class (3). According to their situations they can be divided into three major types:

Type A. Slides of the thick residual soil mantle at the top of the hills. At the left side of Fig. 5, sound rock is shown covered by a strata of residual soil of some thickness. Slides occurring at places like this are very dangerous because they involve great volumes of earth. A typical example of this kind of slide was the 1928 slide at Monte Serrate (Fig. 1).

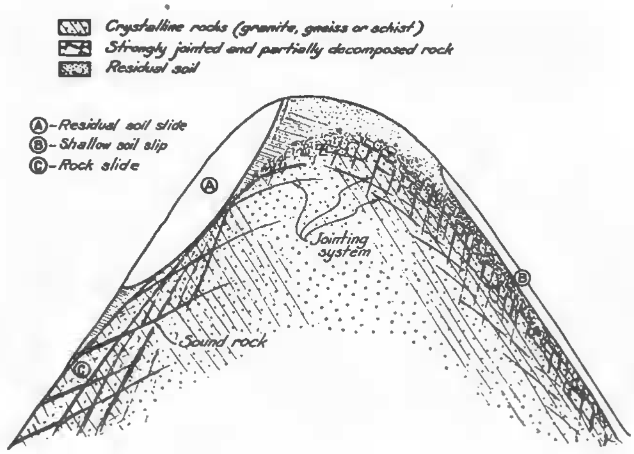

Fig. 5 Diagram of geological slide conditions in Santos
Schéma des conditions géologiques des glissements à Santos

Type B. Shallow residual soil slides. At the right side of Fig. 5 rock is shown covered by a shallow mantle of residual soil. Below the mantle the rock is broken along its natural jointing system producing a layer of blocks of various dimensions reaching depths of tens of metres. Slides in cases like this are mainly slips of the residual mantle along the fissured blocks, producing long shallow strips on the slopes. Fig. 6 shows a view of the Caneleira scarp, which is of the above-mentioned formation, before the slide. Fig. 7 is a photograph taken of the same site after the landslide occurred.

Type C. Rock slides. Where the rock surface is laid bare, as in the lower left-hand side of Fig. 5, a jointing system is observed, which tends to separate large blocks of rock from the main body. After heavy rainstorms these blocks may slip along the sound rock surface as occurred at the Marapé slide (Figs. 2 and 3).

Besides these simple conditions, some of the slides were very complicated, involving a combination of the above basic circumstances.

The effective cause of all these slides was undoubtedly the exceptionally heavy and prolonged rainfall. The saturation of the soil mantle and the reduction of its shearing resistance, due to the pore pressures produced by the percolation of the water through the soil, started almost simultaneous slides wherever that resistance was overcome.

There has been, in Santos, during the last 21 years an average precipitation of 2160 mm with a maximum of 315 mm in February and a minimum of 82 mm in July. During the period from 1935 to 1955 only five precipitations of more than 500 mm per month were registered. The maximum of 721 mm was in February 1938. During the months of January and February 1928, previous to the big slide of the Monte Serrate, the monthly precipitations were respectively 649 and 564 mm, very high when compared with the precipitations of 178 and 312 mm that were registered during the same months in 1956. However, during March 1956 the registered rainfall attained 954 mm, about four times the monthly average. The day before the Marapé rock-slide, 2 March, a rainfall of 129 mm was registered. During 19 and 20 March precipitation attained 268 mm and in the night 24–25, 264 mm of rainfall were registered. During that night 70 per cent of all the slides took place.

Fig. 6 Caneleira scarp before slide
La pente de la Caneleira avant le glissement

Fig. 7 Caneleira slide (24 March 1956)
Le glissement de la Caneleira (24ème mars 1956)

Analysis of Three Typical Slides

As typical examples of slides of the residual mantle, the three cases already mentioned are analysed, comparing what occurred in the field with results of laboratory test results.

The first one is the old Monte Serrate slide, which occurred in 1928. It was a typical slide of the above-mentioned class 3, type A. Slides of this type are residual soil slips and can be analysed by the classical methods for analysis of slopes using slip circles.

The residual soil which covers the rock at that site is a sandy-clay with a very small clay content ($< 0{\cdot}002$ mm), about 5 per cent; an average liquid limit of about 40 and a plastic index averaging 12. So the activity (as defined by Skempton) would be high: about 2·5. The average dry density of this soil is about 1·35 g/cm^3 and the natural water content about

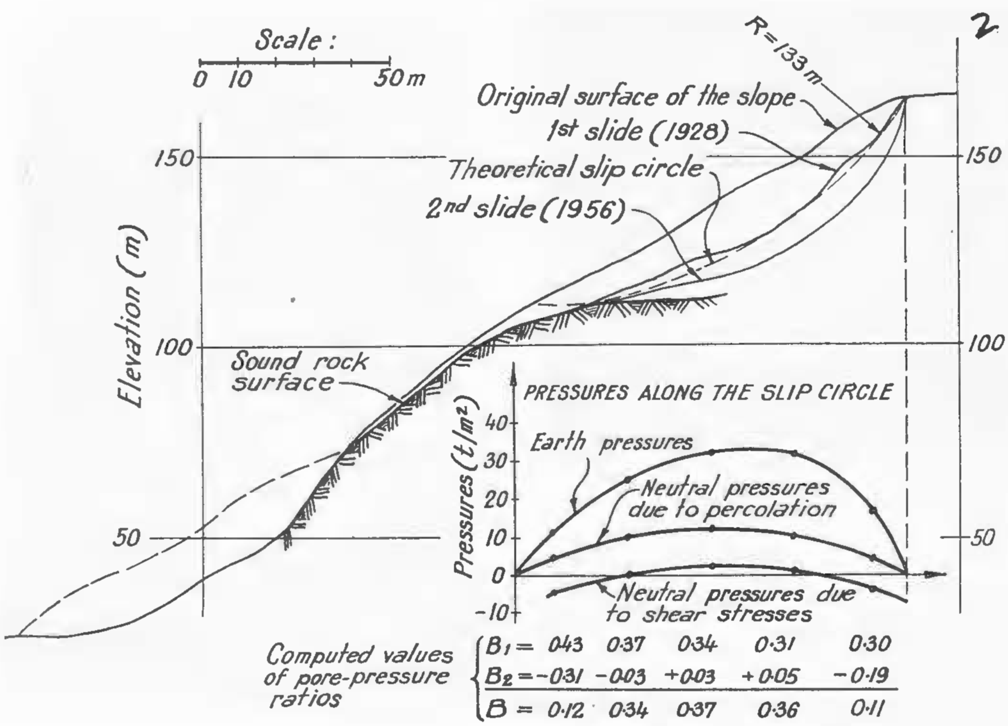

Fig. 8 Monte Serrate slides—cross-sections
Glissement du Monte Serrate—sections transversales

22 per cent. Thus the clay is not saturated and its degree of saturation averages 63 per cent.

Laboratory tests have shown, for the shear resistance, the following average values:

(1) Direct shear test (slow):

cohesion: 4 t/m^2

ϕ: 42 degrees

(2) Undrained triaxial compression:

(a) undisturbed samples, natural water content:

cohesion: 6 t/m^2

ϕ: 23 degrees

(b) remoulded samples, natural water content:

cohesion: 5 t/m^2

ϕ: 21 degrees

One can observe from these results that the clay is not very much affected by disturbance of its structure. An attempt was made to saturate triaxial compression test specimens, but the result was negative. They could not be saturated by ordinary methods; after many trials it was only possible to reach 95 per cent average degree of saturation. Undrained triaxial compression tests on these almost saturated samples showed a cohesion of 8 t/m^2 and an angle of shear resistance of 18 degrees.

Fig. 8 shows a cross-section of the slide area. One can observe that the 1928 slide slipped along a circular surface with a radius of 133 m. The stability analysis of the slope was made according to the classical slices method, in which the static equilibrium of the mass of soil is considered satisfied, at the moment of rupture, by the following equation:

$$\Sigma W \sin \alpha = \Sigma\{cl + (W \cos \alpha - ul) \tan \phi\} \quad \ldots (1)$$

where:

W is the total weight of the slices of soil,
α is the angle between the radius of the slip circle, passing through the centre of the element of the sliding surface and the vertical at that point,
l is the length of the sliding surface,
c, ϕ are the cohesion and the angle of shearing resistance of the soil, in terms of effective stresses,
u is the pore pressure in the sliding surface.

Pore pressures at points on the sliding circle are often expressed as a proportion of the total soil pressure at the point:

$$u = B\frac{W}{b}$$

where $b = l \cos \alpha$ is the breadth of each slice. Substituting, equation 1 becomes:

$$\Sigma W \sin \alpha = \Sigma cl + \tan \phi \Sigma W(\cos \alpha - B \sec \alpha) \quad \ldots (2)$$

The result of such an analysis is shown on a graph in Fig. 9 where the required values of cohesion and angle of shearing resistance are expressed in curves for three values of B. As the available shear characteristics of the soil correspond to point A in the graph, one can conclude that, at the moment of rupture, a pore pressure had developed at the sliding surface. As can be observed on the graph, the corresponding value of B is 0·35.

Now, the pore pressure u can be considered as the sum of two components: $u_1 = B_1(W/b)$, due to the percolation of water through the soil mass, and $u_2 = B_2\,(W/b)$, due to the deformation of the soil pores during rupture. The first one can be easily computed by a flow-net analysis. Fig. 8 shows the results of such an analysis on a graph which indicates percolation pore pressures along the slip circle. The second component can be obtained from the results of slow shear tests in comparison with those of triaxial undrained tests on the same material. The same graph, in Fig. 8, shows neutral pressures due to shear stresses, along the sliding circle, obtained in this way. From the values of u_2 thus obtained, the values of B_2, in Fig. 8, were computed, which added to B_1 gave the theoretically computed values of B at five points along the slip circle. These values are shown in the lower part of Fig. 8. It can be seen that these values are in close accord with the average B value obtained by the slice method computation.

The second typical example is given by the Caneleira slide shown in Figs. 6 and 7. It was produced by the slip of a shallow residual soil mantle along fissured blocks of partially decomposed rock. Fig. 10 shows a cross-section of the slide area.

This slide can be easily analysed if it is assimilated to a slip of a layer of constant thickness, h, along a rigid surface, as indicated in the right corner of Fig. 10.

At any point N of the said surface the pressure due to the weight of the soil will be:

$$p = \gamma h \cos \alpha \quad \ldots (3)$$

and its normal and tangential components:

$$\sigma = \gamma h \cos^2 \alpha \quad \ldots (4)$$

$$\tau = \gamma h \cos \alpha \sin \alpha \quad \ldots (5)$$

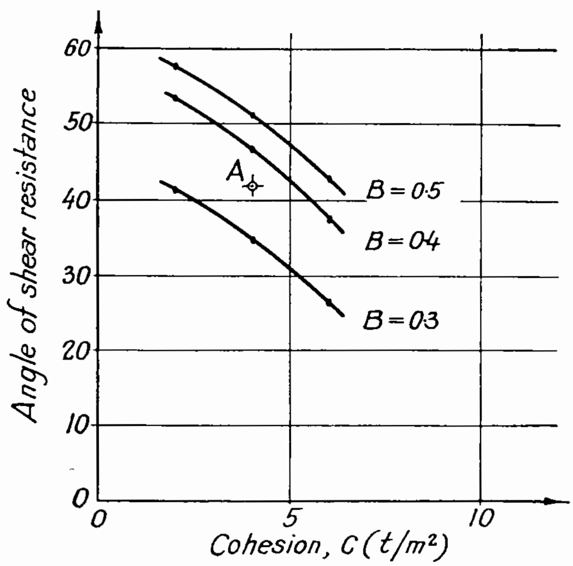

Fig. 9 Required values of c and ϕ for stability at verge of rupture in the Monte Serrate slope

Valeurs de c et ϕ pour la stabilité au moment de la rupture du talus du Monte Serrate

Considering that the slip surface is very near to the rock surface but still inside the soil, that is, the soil mantle will slip exhibiting a dirty rock surface, then the shearing resistance at point N will be that of the soil:

$$\tau = c + (\gamma h \cos^2 \alpha - u) \tan \phi \quad \ldots (6)$$

Combining 5 and 6 the equilibrium equation at the verge of rupture of the slipping layer is:

$$\cos \alpha \sin \alpha = \frac{c}{\gamma h} + (\cos^2 \alpha - B) \tan \phi \quad \ldots (7)$$

where $B = u/\gamma h$ is the previously defined ratio of the pore pressure to the earth pressure at point N.

The average results of classification tests on the clay of this site are as follows: clay content (< 0·002 mm): 7 per cent; liquid limit: 18; dry density: 1·5 t/m^3; natural moisture

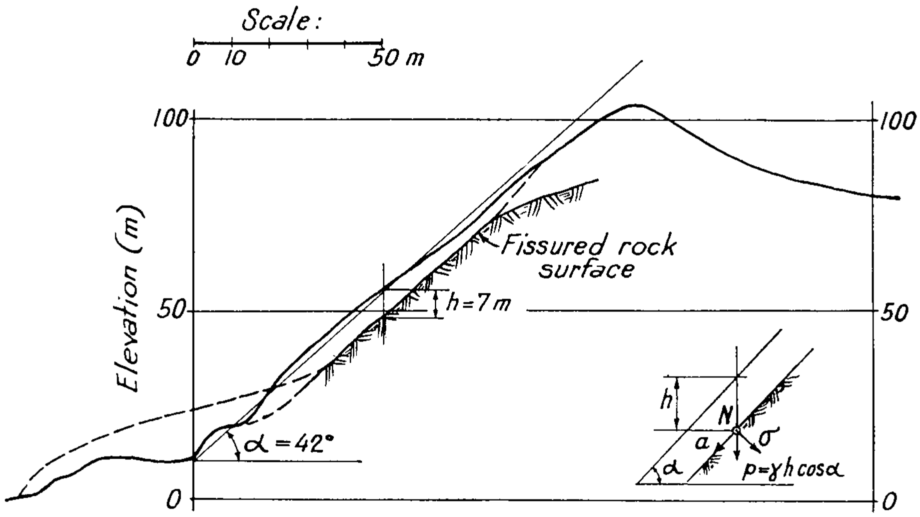

Fig. 10 Caneleira slide—cross-section
Le glissement de la Caneleira—section transversale

content: 19 per cent; degree of saturation: 70 per cent. Direct shear slow test on undisturbed samples gave $c = 4$ t/m^2 and $\phi = 40$ degrees. Undrained compression tests show:

$c = 7$ t/m^2 and $\phi = 20$ degrees at the natural non-saturated condition (70 per cent saturation).

$c = 7$ t/m^2 and $\phi = 18$ degrees, at 85 per cent saturation.

$c = 5$ t/m^2 and $\phi = 20$ degrees, remoulded at natural water content.

Substituting the numerical values in equation 7 the value of B will be found to be 0·3, which is just what should be expected, assuming that the flow-net equipotentials are straight lines normal to the rock surface.

The last example to be analysed is the Marapé rock-slide already shown in Figs. 3 and 4. In the first photograph a system of jointing can be easily observed at the place where the slide occurred. This system consists mainly of exfoliation joints which tend to separate large slabs of rock from the main body. Also dislocation joints are shown throughout the fall area having the same direction and dip. These latter joints had broken the rock slabs into large blocks which hung on the slope. Circulation of rain water through the fissures had accelerated the decomposition of the less resistant minerals, so that after a certain time conditions had become more and more favourable to sliding. Also vibration from blasting at a nearby quarry had contributed to a certain extent in aggravating these conditions so that at the time of the slide the heavy rainstorm could disrupt the already weakened material.

The mechanics of a slide such as the last described is similar to that of the previously described type, if it is analysed in terms of friction resistance and adhesion between the rock blocks instead of the shear resistances of the other cases, and hydrostatic pressures in the fissures instead of pore pressures. It seems clear that water from the 1st of March rainstorm percolated through the fissures between the rock blocks, creating water pressures which produced the slip by reducing friction between the blocks.