Various Approaches to Infinite Slope Stability in the Prediction of Shallow Rain-induced Landslides

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Shallow, rain-induced landslides are often described with an infinite slope model, which considers the stresses acting on a slope's slice to calculate the factor of safety. In this paper, a literature review is conducted to assess different approaches to this physically based method, considering the success of various assumptions about traditional slope stability. These may be used to mitigate the disaster caused by mass movements in the case study, the Northern shore of the state of São Paulo, in Brazil, which suffers a lot from shallow landslides. While most studies in the area have focused on the empirical prediction of landslides, mechanistic analysis backed by proper approximations could be of great benefit to the region.The use of critical values of pore-water pressure and sliding plane depth is recommended, along with study-specific measurement of constant cohesion and angle of internal friction. Computational methods of water infiltration, such as TRIGRS, have been proved to be accurate but are not recommended for wide-range use in the case study area.

Introduction

Landslides are one of the world's most catastrophic natural disasters, causing the loss of thousands of lives each year[1]. Defined as "the movement of a mass of rock, debris, or earth down a slope"[2], they are a common feature of various geographic settings. Hence, it is important to evaluate different methods for the prediction of mass wasting movements.

There are various types of landslides. Shallow, rapid landslides are more prevalent than deeper ones, so they deserve special attention from predictive strategies. These phenomena typically occur in soils with low cohesion reaching depths up to two meters, and are primarily triggered by individual rainstorms, although they may be intensified by preceding moist conditions[3].

There are several types of models used in the prediction of landslides, most of which are empirical, statistical or process-based[4]. In the context of predicting shallow rain-induced landslides, the latter is especially prominent in literature. The physically based approach offers several advantages, such as spatial and temporal specificity and adaptability to different local conditions. In this context, traditional slope stability analysis establishes a quantitative measure of the possibility of a mass movement happening. The factor of safety, the ratio between a landslide's resisting and driving force, may consider a slice of land unaffected by horizontal forces within a slope. This approach, which applies Coulomb's equation to an infinite slope, is idealized. However, it is particularly useful for examining shallow landslides, since it assumes that the extent of the sliding surface is significantly larger than the depth of the soil mass.

Although theoretical analysis has been used to predict landslides[5–7], its application to real-life mass wasting phenomena encounters several impediments, mainly due to the variability and difficulty of measuring the relevant physical parameters involved. Therefore, different assumptions must be made regarding the assessment of these variables, both in terms of how their behavior in nature is interpreted and in how they are mathematically treated within the mechanistic model.

Several different approaches have been taken to infinite slope stability. However, they have not been comprehensively judged, particularly in contexts of little information about soil characteristics. Therefore, this review critically examines different presumptions inherent in traditional slope stability concepts and their overall success in the prediction of shallow rain-induced landslides. The evaluation of which of them has the most potential for accurate predictions will be used to suggest improvements in landslide management strategies.

To underscore practical implications, these considerations are applied to the historical context of mass wasting disasters in the Northern coast of the state of São Paulo, Brazil. There, low cohesion soils and heavy rainfall during summer prompt the occurrence of many shallow landslides, which, due to the social vulnerability of several communities in the area, cause significant losses. Historical landslide management strategies and studies are evaluated in this paper, with insights on how the mentioned slope stability concepts may be of help to avoid future disasters.

Traditional Slope Stability

The main factors that drive a mass of earth down a slope are gravitational forces and, in the case of rain-induced slides, transversal water seepage[8]. Both of these forces increase the shear stress acting on the soil, which will cause failure unless the resisting stress is intense enough. This is the base for the analysis of limit equilibrium in a slope.

Coulomb's Equation

The stresses acting on a slope obey Coulomb's empirical equation:

$$s = c + \sigma \tan\phi \tag{1}$$

where s is the resisting stress or shearing resistance, and σ is the total normal stress. Cohesion (c) represents the bond between the soil particles and is equivalent to the amount of shearing resistance when no normal stress is applied. The angle of internal friction (ϕ) determines the relationship between σ and s[9]. Both c and ϕ are properties of the soil material and can be measured through direct shear tests.

Total normal stress is composed of neutral stress and effective stress. Neutral stress is called pore-water pressure (u_w) and is caused by the water column on the slope. Thus, the effective stress (σ') is calculated as $\sigma' = \sigma - u_w$. As opposed to u_w, σ' produces measurable effects such as compaction or an increase in shearing resistance[9]. Hence, the resisting stress acting on a slope is determined by the equation:

$$s = c + \sigma' \tan\phi \Rightarrow s = c + (\sigma - u_w)\tan\phi \tag{2}$$

Infinite Slope Analysis

An infinite slope (i.e., one of unlimited extent) is assumed to simplify the computation of stresses acting on a real one. Obviously, no such structures exist in nature. However, this approximation can be used to represent most slopes subject to shallow landslides, since a fundamental assumption of the model is that the length of the sliding surface is much larger than the depth of the soil above it. According to Griffiths, a real slope's length/depth ratio has to be greater than 16 for the model to be suitable[10], which is true for a lot of settings where shallow mass movements happen.

Another assumption inherent to the infinite slope model is that soil properties are constant throughout all dimensions. Natural slopes are composed of non-homogeneous and non-isotropic soils[10]. Nevertheless, the model may be applied to locations where soil properties remain relatively close to an average.

This leads to the following representation of a slice AB of the slope, which represents typical characteristics of the entire soil mass. In Fig. 1, β is the inclination of the slope, z is the depth of the slip surface and l is the transversal area of the soil column. Since the slope is considered infinite, slice AB is symmetrical relative to the entire cliff. Thus, the horizontal forces acting on either side of it are opposite and equal, so they cancel each other. Additionally, if γ_t is the total unit weight of the soil, then the weight W acting on this slice is represented by $\gamma_t l z \cos\beta$. The total normal stress is the normal component of the weight divided by the area l on which it acts:

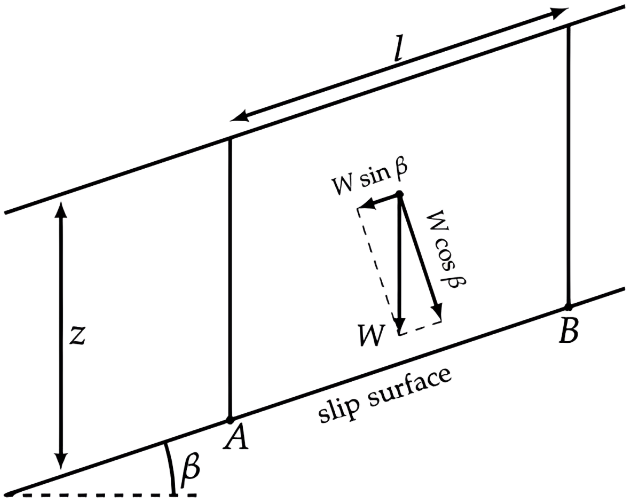

Fig. 1 Representation of an infinite slope. Adapted from Taylor, 1948[8]

$$\sigma = \frac{W\cos\beta}{l} = \gamma_t z \cos^2\beta \tag{3}$$

And the shear stress, or driving force of a possible landslide, is given by the transversal component of the weight divided by the area l on which it acts:

$$\tau = \frac{W\sin\beta}{l} = \gamma_t z \cos\beta \sin\beta \tag{4}$$

The shearing resistance can be found with Coulomb's equation:

$$s = c + \sigma\tan\phi \Rightarrow s = c + \gamma_t z \cos^2\beta \tan\phi \tag{5}$$

The overall stability of a slope can be examined with the factor of safety (F_s), which is defined as "the ratio of shear strength of the soil (s) to the shear stress (τ) required for equilibrium"[11]:

$$F_s = \frac{s}{\tau} \Rightarrow F_s = \frac{c + \gamma_t z \cos^2\beta \tan\phi}{\gamma_t z \cos\beta \sin\beta} \tag{6}$$

When the resisting force (i.e. the shearing resistance) is smaller than the driving force (i.e. the shear stress), slope failure occurs. Hence, instability ensues when $F_s < 1$.

Heretofore, all equations have contemplated a dry slope. However, a better analysis takes into consideration the effect of water between the soil particles, since that is the main cause of landslides analyzed in this paper. This scenario can be represented as an infinite slope similar to Figure 1, but with a layer of saturated soil of height h above the sliding plane:

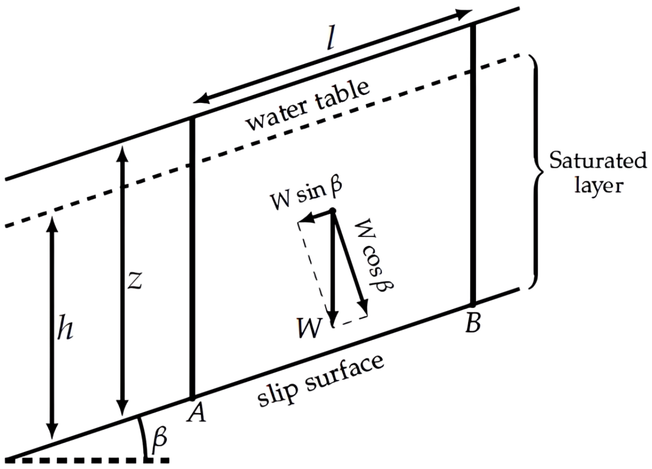

Fig. 2 Infinite slope with layer of water-saturated soil. Adapted from Sidle and Ochiai, 2006[3]

The layer above the water table consists of moist, but not saturated soil[3]. Here, the unit weight of this material is symbolized by γ_t. Furthermore, pore-water pressure may be calculated in terms of the unit weight of water (γ_w):

$$u_w = \gamma_w h \cos^2 \beta \tag{7}$$

Coulomb's equation is used again to equate for the shearing stress:

$$\begin{aligned} s &= c + (\sigma - u_w) \tan \phi \\ &= c + (\gamma_t z - \gamma_w h) \cos^2 \beta \tan \phi \end{aligned} \tag{8}$$

Finally, the factor of safety is calculated for this scenario[11]:

$$F_s = \frac{c + (\gamma_t z - \gamma_w h) \cos^2 \beta \tan \phi}{\gamma_t z \cos \beta \sin \beta} \tag{9}$$

Equation 9 lets us appreciate the effect of rainfall on the initiation of shallow landslides. The introduction of water into the soil causes the rise of its groundwater level, making h bigger and decreasing the factor of safety. As h increases, pore-water pressure becomes larger and the effective normal stress decreases, making the shear strength of the slope smaller.

Alternatively, groundwater height can be represented as a fraction m of the soil depth[12]. In this case, $h = mz$, so the factor of safety is:

$$F_s = \frac{c + (\gamma_t - \gamma_w m) z \cos^2 \beta \tan \phi}{\gamma_t z \cos \beta \sin \beta} \tag{10}$$

A case in which $m = 0$ represents completely unsaturated soil, that is, when the water level coincides with the slip surface ($h = 0$). Conversely, when $m = 1$, the water level coincides with the ground surface ($h = z$). According to Sidle and Ochiai, slope failure happens in a state between these two; as water penetrates the soil and h goes from 0 to z, pore-water pressure increases and the effective normal stress decreases, thus prompting instability[3], as shown in Fig 3.

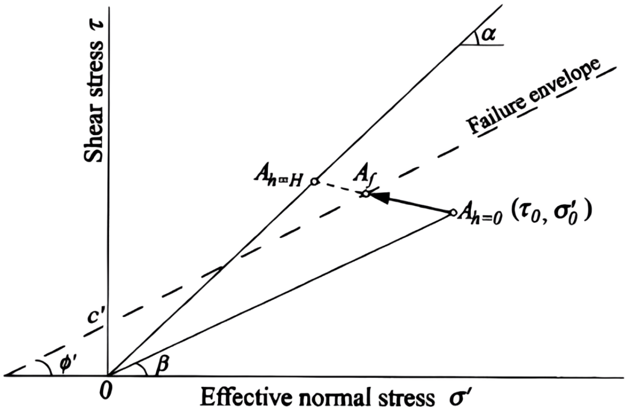

Fig. 3 Stress changes and resultant slope failure for conditions of a rising groundwater table"[3]. Instability happens at some point between $m = 0$ and $m = 1$.

Instead of calculating F_s based on the unit weights of soil and water, it is also possible to use the unit weights of saturated (γ_{sat}) and unsaturated (γ_t) soil. In this case, the factor of safety is[3]:

$$F_s = \frac{c}{W \sin \beta} + \frac{\tan \phi}{\tan \beta} - \frac{u \tan \phi}{W \sin \beta} \tag{11}$$

Where $W = [\gamma_t (z - h) + \gamma_{\text{sat}} h] \cos \beta$.

Assumptions and Approximations

Soil wetness

Keefer assumes that "for any given slope, there exists a critical level of the pore-water pressure, u_{wc}, acting on a critical area on the developing slip surface, at which the slope becomes unstable"[5]. This assumption is based on the fact that effective normal stress is calculated as $\sigma' - u_w$ (see Equation 2); thus, as pore-water pressure increased, σ' would decrease. The critical value of neutral stress is equated as

$$u_{wc} = z \gamma_t \left(1 - \frac{\tan \beta}{\tan \phi}\right) \tag{12}$$

Additionally, u_{wc} is considered to be caused by a critical volume of water retained in the saturated zone (Q_c), which is calculated as

$$Q_c = \frac{u_{wc}}{\gamma_w} nef \tag{13}$$

where n_{ef} is the effective soil porosity.

Assuming that pore-water pressure has a critical value at the moment of a landslide's initiation is advantageous because it provides a way to compute rainfall into soil stability equations. Indeed, the water column above the sliding plane becomes higher due to rainfall and, consequently, pore-water pressure increases. Hence, there may be a moment when this causes slope instability, which is represented by a factor of safety of less than one.

Nevertheless, the latter equations do not fully represent the influence of water on the initiation of shallow landslides. Soil wetness varies not only due to the amount of rainfall; the rates of infiltration and subsurface water transport also have a great impact on slope stability and are to be discussed next.

Water infiltration and drainage

Darcy's law governs water flow through porous media:

$$v = K\left(\frac{\partial H}{\partial l}\right) \tag{14}$$

where v is water flow velocity, K is the hydraulic conductivity, H is the hydraulic head and l is the total traveled distance; thus, $\frac{\partial H}{\partial l}$ is the hydraulic gradient. Richards used concepts of hydrodynamics to expand Darcian flow to different slope conditions, applying it to both saturated and unsaturated soil[13]. Since then, "Richards' equation" has been used by many authors in the context of slope stability to assess the subsurface movement of water and its relation to landslides. This way, a better notion is available of a mass movement's timing. This equation, in its reduced form, may be represented as

$$\frac{\partial}{\partial z}\left[K_z(\psi)\frac{\partial(\psi - z)}{\psi z}\right] = \frac{\partial \theta}{\partial t} \tag{15}$$

where "z is the slope-normal coordinate, t is the time, K_z is the vertical hydraulic conductivity that depends on the pressure head ψ, and θ is the volumetric water content"[4].

Richards' equation can be related to the traditional factor of safety based on infinite slope analysis[4,14,15]

$$F_s = \frac{\tan\phi}{\tan\beta} + \frac{c - \psi\gamma_w \tan\phi}{\gamma_t z \sin\beta\cos\beta} \tag{16}$$

The calculation of time-variant pressure head ψ may yield different values of F_s. Thus, throughout different moments of a rainfall event, the risk of a shallow landslide can be calculated with more certainty. However, the partial differential equation 16 cannot be solved in a closed form. While it may not be solved analytically, numerical approximations can be used to calculate solutions. In the context of landslide prediction, various studies have attempted to solve Richards' equation based on different assumptions about its variables.

The US Geological Survey (USGS) adopts the "Transient Rainfall Induced and Grid-Based Regional Slope-Stability Model", or TRIGRS, to numerically examine the effect of rainwater infiltration based on Richards' equation[16]. TRIGRS is "a Fortran program designed for modeling the timing and distribution of shallow, rainfall-induced landslides"[15]. The program calculates pore-water pressure and, consequently, the factor of safety (see equation 16) based on the variation of elapsed time (t), yielding a numerical indicator of mass movement risk. This method was successfully tested to predict real landslides in the United States.

TRIGRS is based on Iverson's proposed solution for Richards' equation. His study assumed that slope failure is associated with rainfall "over a typically shorter timescale H^2/D_0, where H is the soil depth and D_0 is the "maximum hydraulic diffusivity of the soil"[14]. Additionally, the traditional factor of safety was split into different terms, separating it into a "steady, background factor of safety $FS0$", which does not change over a short timescale, and FS, which accounts for the effects of transient rainfall. Iverson's factor of safety does not assume steady seepage parallel to the surface, as infinite slope equations usually do[10].

Slip surface

The infinite slope model assumes that a landslide's sliding plane is straight and parallel to the cliff's surface. That assumption is distant from most scenarios where mass movements occur right above a bedding plane, since it is seldom close to being completely straight. However, it seems to be reasonable not to consider the effects of bedding conditions when it comes to shallow landslides[17]. That makes intuitive sense considering that mass movements have several potential failure planes, which may not coincide with the bottom of the soil layer[10]. Since shallow landslides occur closer to the surface, it is more likely that their slip surface is above the bedding.

Therefore, the value of z in infinite slope equations may be chosen as whichever one that results in a lower F_s, that is, the one that implies the largest likelihood of a landslide happening. Iverson adopts this strategy in his study of landslides caused by rain infiltration: several depths z are assumed and the one that "first yields $F_s = 1$ determines the depth of landsliding"[14]. This strategy proved to be successful, since data from different mass movements corroborated predictions made in the paper.

Griffiths et al. assumed a critical slip surface depth z_{crit}, which is the one that yields the lowest F_s. Based on the assumption of a varying cohesion throughout a slope's weathering profile, it was asserted that "the critical failure plane for constant ϕ develops where c/z reaches a minimum". From the factor of safety, the value of z_{crit} was deduced to be $\sqrt{\frac{p}{q}}$, where p is the cohesion at ground surface level and q is a constant[10].

The heterogeneity of soil properties challenges the assumption of homogeneous soil, which is inherent to the infinite slope model. The analysis of non-homogeneous soil profiles can be done through "finite element" methods, as was done by Griffiths et al. This method aims at "predicting failure in long slope profiles where the critical mechanism is not necessarily at the base of the soil layer"[10]. Variations of soil properties used in this analysis are described in the next section.

Soil properties

According to Terzaghi, soil cohesion and angle of internal friction vary depending on test conditions. These properties are influenced by the rate of stress application and water content, for example[9]. Hence, theoretical slope stability does not truly represent soil properties at every moment, since conditions in nature cannot always remain the same as those used in tests. However, most studies consider both c and ϕ constant, which seems to be a reasonable approximation about their nature in a real slope.

Lu and Godt analyzed the variation of the angle of internal friction throughout a slope's weathering profile[6]. Unlike traditional slope stability, the study found that ϕ is "inversely linearly proportional to [the soil's] porosity". Since porosity was found to be higher closer to ground surface level, the angle of internal friction is higher in deeper layers.

Griffiths et al. assumed that cohesion increases parabolically with depth according to the relation

$$c = p + qz^2 \tag{17}$$

where p is the cohesion at ground surface and q is a constant[10]. This supposition might not be very realistic, but it recognizes the variation of cohesion throughout a slope's weathering profile, which better represents reality than considering it constant. Using equation 17, the factor of safety was calculated as

$$F_s = \frac{p + qz^2}{\gamma_t z \sin\beta \cos\beta} + \frac{\tan\phi}{\tan\beta} \tag{18}$$

In some cases, cohesion, instead of assuming a constant value, is disregarded altogether. Skempton and DeLory used stability equations to calculate critical slope inclination angles in London[12]. The study made two simplifying assumptions: that soils were cohesionless and that groundwater height coincided with the ground surface. Thus, it is concluded through the factor of safety equation that

$$\tan\beta_c = \frac{\gamma_t - \gamma_w}{\gamma_t} \tan\phi \tag{19}$$

where β_c is the critical slope inclination. Assuming that $m = 1$ at the moment of failure is not a perfect representation of reality (see Figure 3). Moreover, considering $c = 0$ is a significantly idealized view of soil properties. However, the study successfully found that theoretical critical slopes matched real settings[12]; therefore, it seems the assumptions made in this case were reasonable for the analyzed area.

Keefer also assumed a null cohesion in his calculation of a critical pore-water pressure value (see equation 15). Although idealized, this approach was also successful. The study was able to predict and generate warnings for several landslides in the San Francisco Bay region[5].

In some cases, it seems acceptable to disconsider cohesion in slope stability equations. Usually, soil less than 2 m deep has low cohesion[6]. Therefore, field evidence can suggest that calculations with $c = 0$ are a reasonable representation of reality, at least in the case of shallow landslides.

Case Study: Northern Coast of the State of São Paulo, Brazil

Mass movements are the natural disasters that cause most fatalities in Brazil. From 1988 to 2022, more than four thousand deaths have been registered because of landslides in the country[18]. The Northern coast of the state of São Paulo, in the southeast of Brazil, has been suffering with the intensification of extreme climate phenomena, leading to a greater vulnerability of most people in the region. Disordered urban growth in this zone has worsened the situation, leading to the occupation of risky places[19]. Moreover, shallow mass movements and debris flows are expected to become more frequent in this area due to climate change[20].

In the northeast of São Paulo, the Serra do Mar, a coastal mountainous region, is significantly close to the shore itself, as shown in figure 4. Thus, the narrow coastal plain is interrupted by steep and tall slopes reaching higher than 800m of altitude[22]. According to Köppen's classification, the climate is Cfa, with humid summers and cold to mild winters[23]. Therefore, aside from topographic conditions, humid winds from the sea prompt the occurrence of heavy rainfall particularly during the summer; therefore, annual rainfall values often reach 2000 mm[24,25]. In February 2023, the region was subject to 683 mm of rainfall in 24 hours, the most intense rainfall ever recorded in the country. Additionally, 65 people died in the municipalities of São Sebastião and Ubatuba due to mass movements[26].

The understanding of landslide processes in the region also relates to its soil characteristics. Coelho et al., for example, analyzed the weathering profile of slopes in the municipality of Itaóca, in the Serra do Mar. They identified the existence of three distinct layers of soil, each one with different morphological features: "mature residual (well-developed), young residual soil

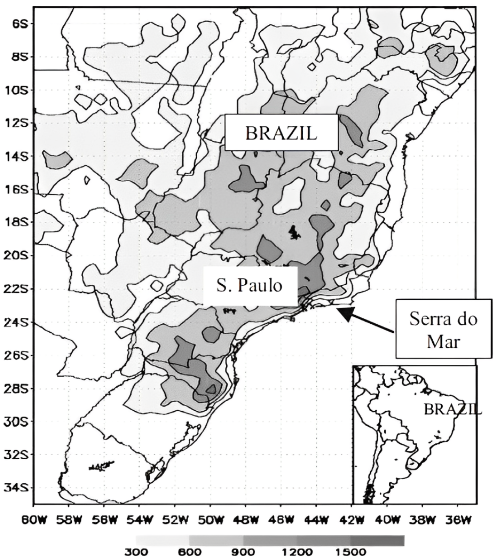

Fig. 4 "Topography (meters) and location of the Serra do Mar and São Paulo state in Brazil"[21]

(saprolitic soil), and saprolite"[27], as shown in figure 5. The study performed in situ hydraulic conductivity tests, and found that the most superficial layer, mature residual soil, with depth of up to one meter, had greater permeability than the deeper ones, attributing this to the higher porosity measured in this material[27]. Hence, although the bedrock is about 6m deep, a potential slip surface occurs between the first and second layers, inducing shallow landslides. Additionally, superficial soil in the Serra do Mar is colluvial[28] and consequently has low cohesion, which is characteristic of shallow mass movements[3]. For this reason, shallow landslides are the most common in the region[29].

Shallower soil layers in São Paulo usually have a considerable concentration of plant roots[27], which can reduce the risk of mass movements[3]. However, the native vegetation of the region, the Atlantic Forest, has been severely devastated mainly due to urban growth and farming[31], so nowadays many landslide-prone areas are not covered by plants. The devastation of local forest may lead to an increase in soil moisture and a reduction in soil strength[32]; as a consequence, landslides in general might become more frequent. Although most studies seem to agree that vegetation correlates positively with shear strength, Ploey and Cruz analyzed slopes in Caraguatatuba (see Figure 6) and suggested that landslides happened in forested areas too. According to the study, rootlet matrices in the region's shallow soils provoke a higher water infiltration rate[24]. A more recent study in Ubatuba supports an opposite observation, though; Mendes and Filho suggested that "higher levels of human intervention on natural slopes", such as urban growth, "reduce the amount of accumulated precipitation required for a landslide outbreak"[25].

Several studies have been conducted to better understand, predict or mitigate the effects of landslides in the region. The Preventive Civil Defense Plan (PPDC), for example, has used rain limits in the state of São Paulo to prevent deaths in mass movement scenarios. The program works through the precautionary evacuation of people in degrees of risk "R3 (high)" or "R4 (very high)"[29], which represent high chances of mass movements. However, this method is not specific enough. The said rain limits were measured only in the city of Cubatão, and later expanded for the whole state[29], so that there is significant uncertainty in the prediction of landslides in specific areas. The National Center for Natural Disaster Monitoring and Alerts (Cemadem) also uses rainfall data, collected from a net of rain gauges, to provide landslide alerts in the national scale[33]. Mendes et al. highlight the need for more specific predictive measures, claiming that "the critical rain limits used in certain areas may not represent critical rainfall situations"[29], referring to the PPDC. Additionally, the study emphasizes the need for other environmental factors, such as soil wetness, in landslide prediction: the use of humidity sensors, according to the authors, led to a more accurate risk evaluation. Therefore, a thorough analysis of physical parameters, which is provided by mechanistic analysis, offers a better predictive power than only rain limits.

Vieira et al. used physically based models to understand the spatial distribution of landslides in the Serra do Mar. The authors used values of cohesion, angle of internal friction and unit weight from another study[34], and measured hydraulic conductivity in the city of Cubatão, an area prone to landslides in São Paulo. Additionally, detailed topographic information was measured through a digital elevation model (DEM), and rainfall data was extracted from the Information System for Water Resources Management of São Paulo State database. This detailed description allowed the use of the TRIGRS program, which related mechanical soil characteristics to the density of landslide scars in the area. The study aimed to relate TRIGRS' prediction to the occurrence of mass movements in the 1985 disaster in the region, whose scars were mapped through aerial photographs. The Scar Concentration index, "the ratio between the number of cells with scars, in each class of F_s, and the total number of cells with scars in the catchment"[7], exceeded 50% in all scenarios, showing a high correlation between simulated predictions and real events. Therefore, the use of computational methods and the infinite slope model accomplished a high degree of specificity in the prediction of landslides in the region, proving to be a valuable tool for future studies.

Ploey and Cruz analyzed the conditions that led to the 1967 landslide catastrophe in Caraguatatuba, one of the largest cities in the Northern coast of São Paulo. The study found that rainwater infiltration led to a decrease of the angle and internal friction and cohesion, reducing slopes' shearing resistance. Additionally, higher soil plasticity index (I_p) and the fraction sci (percentage

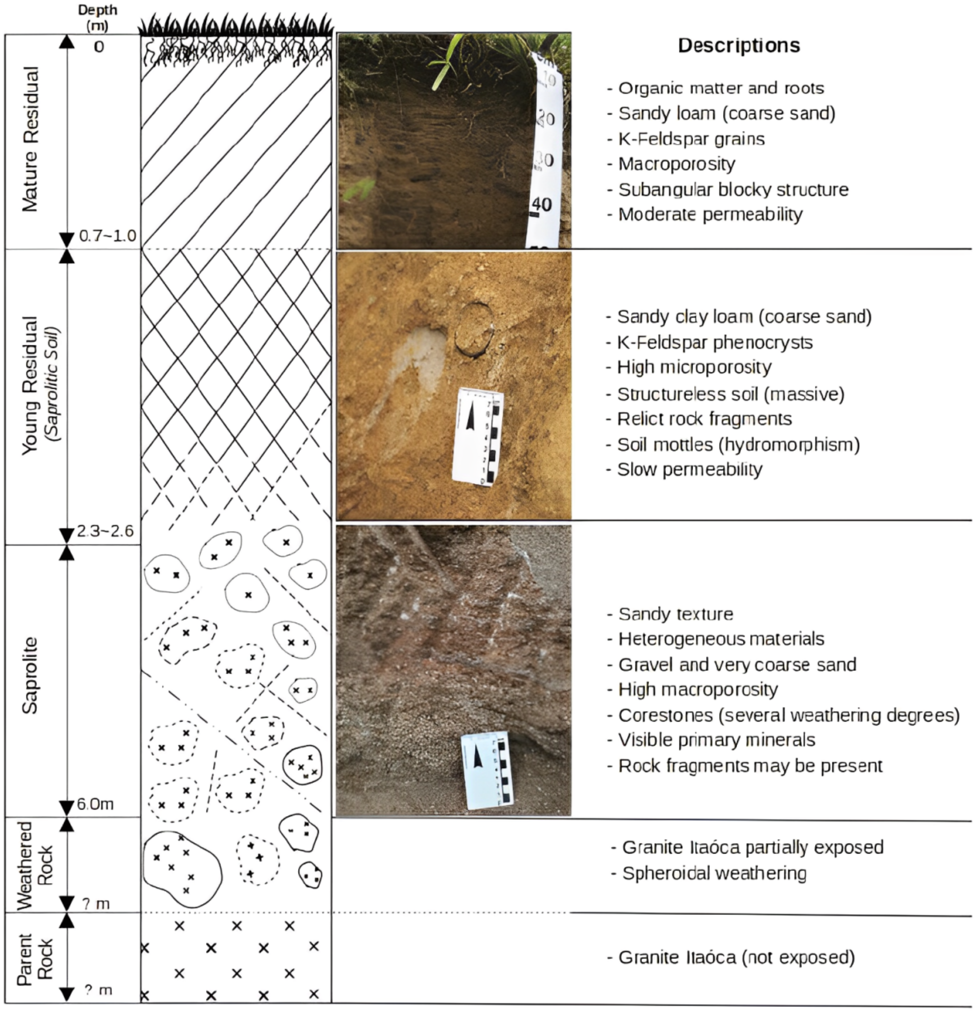

Fig. 5 "Typical weathering profile of Itaóca granite, Brazil"[27]

of silt, clay and iron) were related to a reduced shear strength[24]. Shear tests were conducted in landslide deposits, which were found to have a low cohesion value of 175 to $420 g/cm^2$ (see figure 7), pointing to the use of low values of c in slope stability analyses in the region.

Overall, literature about the Northern coast of the state of São Paulo has gathered substantial information about the conditions that prompt shallow landslides in the region. However, government strategies still rely on empirical rainfall observations, not taking advantage of physical prediction models. Most studies that conducted mass movement predictions successfully did so isolatedly, focusing on assessing the feasibility of predictive models, not on their long-term application.

Discussion

The infinite slope method has shown to be of great success in shallow landslide prediction. In spite of its idealized nature, the measurement and mathematical interpretation of soil and slope characteristics in the mechanistic method have enabled several precise forecasts of mass movements. However, the success of such predictions is conditioned to a reasonable representation of real settings, which is not always possible given the uncertainty about the spatial distribution of certain places' characteristics.

The collection of relevant data in the area presented in the case study is scarce and its spatial distribution is too scattered[29], so there are significant uncertainties in the prediction of shallow landslides. For this reason, most studies and governmental strategies, such as the PPDC, have turned to empirical methods, relating rainfall data to the susceptibility of mass movements

Fig. 6 Northern shore of the state of São Paulo. Its main cities (Ubatuba, araguatatuba and São Sebastião) are shown. Retrieved from Google Maps[30]

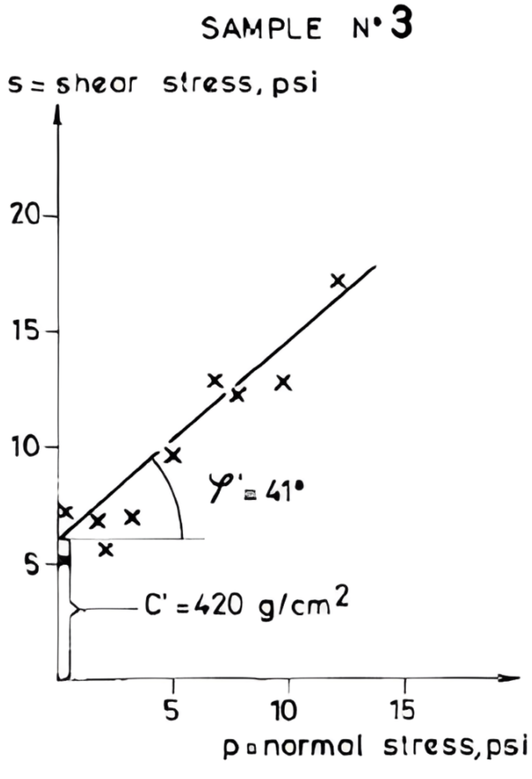

Fig. 7 Result of a landslide deposit's shear test in Caraguatatuba[24]

known from historical events. Therefore, the Northern coast of the state of São Paulo could greatly benefit from the use of physical landslide prediction methods. That way, it may be possible to achieve a greater degree of specificity of warnings, possibly mitigating the devastation caused by mass movement disasters. Given that most landslides are shallow[24], it is reasonable to follow the infinite slope model, which provides more specific predictions than empirical methods. However, since the specificity of available measures is low, the assumptions that are made about soil characteristics must be carefully chosen based on previous observations.

Altogether, one of the most accurate prediction methods tested in the area is TRIGRS. Conducted by Vieira et al., it was successful in relating past mass movement scar maps to mechanical analyses[7]. However, the use of this program requires very specific values of slope, hydraulic conductivity, initial infiltration rate, and other relevant measures. According to the creators of the model, "in the absence of accurate initial conditions, use of TRIGRS is limited to modeling hypothetical scenarios"[15]. Therefore, this might not be the most convenient strategy for avoiding disasters in the Serra do Mar, considering the lack of precise measurements.

It seems reasonable to assume a critical depth of slip surfaces, since this approach has been tested successfully to predict shallow landslides[10,14]. In the case study area, due to soil characteristics, a potential sliding surface is formed between the shallowest soil layer, which is more permeable, and the subsequent layer[27]. Therefore, there is a characteristic slip surface depth that can be found by calculating for the lowest F_s. By doing so, a critical depth z_{crit} which represents real landslides may be found.

Additionally, although soils in the Northern coast São Paulo have been shown to have low cohesion, the assumption of cohesionless soils in the area has not been empirically supported by any study. Therefore, though studies elsewhere have succeeded with calculating the factor of safety from $c = 0$[5,12] this approximation still must be tested in mass movement predictions in the case study region. Successful predictive attempts, like that by Vieira et al., have used values of cohesion provided by older studies in São Paulo; nevertheless, it is recommended to conduct study-specific shear tests to avoid miscalculations.

Finally, it is suggested to adopt a critical value of pore-water pressure. It has been shown that there exists an amount of neutral pressure u_{wc} that causes a landslide through the reduction of shearing resistance[5]. Hence, it may be strategic to adopt critical values of rainfall based on u_{wc}; since these values have been assessed empirically in São Paulo, they should be more accurate following a theoretical base.

Conclusion

Simplifying assumptions in the use of physically based shallow landslide prediction models can be very convenient for mass movement management strategies, particularly in scenarios of few measurement resources or uncertainty about soil and slope characteristics, such as the Northern coast of São Paulo. Depending on the characteristics of study sites, it may be reasonable to adopt critical values of u_w, mainly because this allows the establishment of theoretically proved limit values of rainfall. Additionally, it has been shown that the computation of different values of z is advisable, since it can indicate a depth z_{crit} that yields a lower factor of safety and is consequently related to a higher risk of landslides; otherwise, values of sliding surface depth can be chosen empirically, since shallow landslides are usually related to soil weathering profiles and thus happen at characteristic depths in each region. Newer studies have had success by calculating specific values of soil properties and considering them constant; therefore, it is recommended to conduct shear tests to find c and ϕ. Finally, if there is enough site-specific information, computational methods like TRIGRS have been shown to be the most accurate in the prediction of mass movements; however, that is not the case of the Northern coast of São Paulo, since there is insufficient knowledge about the physical properties of this region. Future studies should test these findings in the prediction of shallow rain-induced landslides, particularly in the area discussed in the case study.

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