UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

Colegio de Ciencias e Ingenierías

Stability Modelling of Clay and Silt Slopes to Evaluate the Feasibility of Rheometer Test Results

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Ingeniería Civil

Trabajo de fin de carrera presentado como requisito
para la obtención del título de
Ingeniero Civil

Quito, 09 de diciembre del 2021

UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

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DISCLAIMER

The following document consists of a short academic paper written by undergraduate student Gabriel Nicolás Urquía Maya. Its content includes material's description, methodology and procedure, results and conclusions of a computational model of silt and clay slopes, conducted throughout during the 9th semester of the Civil Engineering career. It was intended to be sent to the 7th International Conference on Geotechnical Research and Engineering (ICGRE'22) later in December, waiting for an acceptance of submission to be published.

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RESUMEN

Para realizar análisis de estabilidad en taludes, se requiere de mediciones previas de las propiedades índice y propiedades mecánicas del suelo del cual está conformado. Se han desarrollado varios procedimientos de laboratorio para la obtención de parámetros de resistencia: ensayos triaxiales no drenados, pruebas de corte directo y ensayos en odómetros para mencionar unos pocos. Este trabajo evalúa la factibilidad de resultados obtenidos en ensayos con reómetros para desarrollar un modelo de estabilidad para un talud de arcilla y para uno de limo. Se realizaron análisis SEEP/W y SLOPE/W en la versión estudiantil de GeoStudio, modelando periodos de sequía y de lluvia para evaluar los efectos de la succión dentro del talud en su resistencia al corte. Los resultados se compararon con publicaciones pasadas que desarrollaron ensayos tradicionales de laboratorio para encontrar las propiedades descritas anteriormente. El factor de seguridad en el tiempo se comportó de manera consistente a la información existente, la presión de poro siguió una evolución similar a la de modelos previos. Asimismo, se incluye información de la masa de suelo movilizada sobre el plano de falla crítico. Se concluye que las pruebas en reómetros son factibles para entender la evolución de la estabilidad de taludes, dado que los resultados reportados en este trabajo fueron consistentes con los obtenidos previamente por otros autores que recurrieron a otros ensayos de laboratorio.

Palabras clave: Estabilidad, Infiltración, Factor de Seguridad, Modelo Computacional, Reómetro, Succión.

ABSTRACT

Stability analyses in slopes requires the measurement of index and mechanical properties of soil samples. Many laboratory procedures had been developed to obtain strength parameters: triaxial undrained tests, direct shear tests and oedometer tests to mention a few. This paper evaluates the feasibility of rheometer tests results to develop a stability model of clay and silt slopes. SEEP/W and SLOPE/W analyses were developed in GeoStudio Student Edition, modelling drought and rain periods to evaluate the effect of matric suction in shear strength. Results are compared to previously done work, where traditional tests were developed to obtain the necessary parameters to characterize the slope's soil. The safety factor vs time curve behaved consistently to recorded data, the pore water pressure followed a similar evolution as that from previous models. Information regarding the mobilized soil mass is also included. It is concluded that rheometer tests are feasible to understand the evolution of slopes' stability as the results reported in this paper were consistent with previously obtained ones, relying on different laboratory tests.

Key words: stability modelling, seepage modelling, factor of safety, rheometer test results

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Proceedings of the 7th World Congress on Civil, Structural, and Environmental Engineering (CSEE'22)
Lisbon, Portugal– April 10 – 12, 2022
Paper No. ICGRE XXX (The number assigned by the OpenConf System)
DOI: TBA

STABILITY MODELLING OF CLAY AND SILT SLOPES TO EVALUATE THE FEASIBILITY OF RHEOMETER TEST RESULTS

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***Abstract* –** Stability analyses in slopes requires the measurement of index and mechanical properties of soil samples. Many laboratory procedures had been developed to obtain strength parameters: triaxial undrained tests, direct shear tests and oedometer tests to mention a few. This paper evaluates the feasibility of rheometer tests results to develop a stability model of clay and silt slopes. SEEP/W and SLOPE/W analyses were developed in GeoStudio Student Edition, modelling drought and rain periods to evaluate the effect of matric suction in shear strength. Results are compared to previously done work, where traditional tests were developed to obtain the necessary parameters to characterize the slope's soil. The safety factor vs time curve behaved consistently to recorded data, the pore water pressure followed a similar evolution as that from previous models. Information regarding the mobilized soil mass is also included. It is concluded that rheometer tests are feasible to understand the evolution of slopes' stability as the results reported in this paper were consistent with previously obtained ones, relying on different laboratory tests.

***Keywords*:** stability modelling, seepage modelling, factor of safety, rheometer test results

Introduction

It is commonly known that landslides linked to climatic fluctuation are associated to slopes conformed by permeable materials -granular soils- that let humidity in. Subsequently, the pore water pressure (PWP) rises withing the particles, lowering the loading-capacity ratio represented by the Safety Factor (Ng & Shi, 1998; Rahardjo, Leong, Deutscher, Gasmo, & Tang, 2000). Nonetheless, rain-induced stability failure is also present in clay and silt slopes with lower conductivity, by rising the specific weight of soil and losing tensile stresses due to a decrement in matric suction between particles (Pedone, Ruggieri, & Trizzino, 2018). In tropical countries such as Ecuador, several reports had been made regarding clayey and silty slope failures after raining periods that exceeded the design intensity, leaving behind high-cost damages and even human casualties (Montalvo, Sánchez, López, & Estévez, 2017; Rosales, 2021; Wilcke, y otros, 2003). For that reason, researchers had focused towards understanding the behavior of less permeable slopes under unsaturated conditions and how their strength is compromised by water infiltration after rainy seasons (Pedone, Ruggieri, & Trizzino, 2018; Montalvo, Sánchez, López, & Estévez, 2017).

Pedone et al (Pedone, Ruggieri, & Trizzino, 2018) modelled a uniform clay slope representative of the Southern Apennines, with its mechanical and index properties taken from undrained triaxial tests (Cotecchia, Vitone, Santaloia, Pedone, & Bottiglieri, 2015). Their stability results were determined only by the slope's variation in its specific weight as the one that drove the behavior of the safety factor throughout time. For rain periods, the deviator moments increased as the weight of slides in the FE analysis rose. For negative infiltration periods, slices lost weight, increasing the safety factor. In the other hand, Ng and Shi (Ng & Shi, 1998) modelled a clayey sand slope under drought and rain periods, with their index and mechanical properties taken from triaxial tests results (effective cohesion, effective angle of friction and ϕ_b). Results showed that the safety factor varies rapidly during drought periods compared to infiltration periods, concluding that short drought periods compensated the loss of resistance during wet season in the modelled slope. Finally, Alonso et al (Alonso, Gens, & Delahaye, 2003) modelled a clay slope with its parameters taken from triaxial laboratory tests, including an infiltration greater than the carrying capacity of the slope to achieving higher differences in the SF compared to Ng and Shi, and Pedone et al.

This paper evaluates the feasibility of the obtainment of the parameter ϕ_b and the effective cohesion via rheometer tests, applied in computer generated models of clay and silt slopes to understand the behavior of the safety factor under variable climatic conditions. The change in the rigidity moduli results in a variable shear strength dependent of matric suction, where the mentioned parameters can be obtained. The process distinguishes three main stages: identifying the resultant parameters of rheometer tests, input them in SEEP/W and SLOPE/W analyses, to finally compare the results to those given by other authors that evaluated the evolution of the SF over time after drought and rain periods.

Materials

Rheometer tests results (Villacreses, Granados, Caicedo, Torres, & Yépez, 2021) were used to plot Stress-Strain data by applying different suction loads to a high plasticity clay sample with a plasticity index of 50, P200 (mass of particles smaller than 75 μm) of 100%, specific weight γ of 13.142 $kN.m^{-3}$ and a saturated water content w_s of 0.4835 $m^3.m^{-3}$. Tests results are plotted in *Figure 1a*. A climatic chamber was used as well to evaluate the maximum negative unit flux in the clay sample, which resulted in 3E-07 $m.s^{-1}$. The value for the internal friction angle of high plasticity clay soils is proposed as 20° (Das, 2001) being it the lesser of the given interval by Das from 20° to 30°. Ning Lu (Lu & Likos, 2004) proposes a range of saturated conductivity for clay and silt, so it is taken as 1E-08 for the former and 1E-07 for the latter.

Silty-sand specimens were tested to obtain their resistance parameters, by subjecting them to direct shear tests (García-Navarro, Camacho, Morales, & Alonso, 2011). Values for the friction angle and cohesion were obtained, being 32.19° and 32.1 kPa respectively. Granulometry tests were also made to find that 64% of the specimens were finer than 75 μm. The data is summarized as following: plastic index of 10, *P200* of 64%, γ of 15.50 $kN.m^{-3}$ and w_{sat} of 0.3969 $m^3.m^{-3}$. Dhanauri's soil ϕ_b (16.2°) was taken because of its similarities in cohesion and internal friction with the tested silty sand (Lu & Likos, 2004; García-Navarro, Camacho, Morales, & Alonso, 2011).

Fredlund and Xing (Fredlund & Xing, 1994) stated that the relationship between the saturation degree of soil and its mechanical properties at an unsaturated state are related through its characteristic curve. Working under Fredlund and Xing model requires that the model does not experience a matric suction over 1 million kPa, whereas it is sand, silt or clay. Caicedo (Caicedo, 2019) adjusted a new equation that had the Plastic Index PI and the percentage in mass of the 75 μm sieve passing material P_{200} -via granulometric tests- as input variables, easing the plotting of the characteristic curve by relying on cheaper and practical procedures.

Caicedo's equations (Caicedo, 2019) were used to approximate the soils' characteristic curve and obtain the parameters *a*, *m* and *n*, to later evaluate them in GeoStudio (GEO-SLOPE International, Ltd., 2012), which works under the Fredlund and Xing model (Fredlund & Xing, 1994). The soil conductivity k behavior under unsaturated conditions is calculated following *equation 1* (Caicedo, 2019), which is appliable to Fredlund and Xing's model. Results are shown in *figures 1a* and *1b.*

$$k = \frac{\int_{\ln(\psi)}^{b} \frac{\theta_{e^y} - \theta_{\psi}}{e^y} \theta'_{e^y} \, dy}{\int_{\ln(\psi_{aev})}^{b} \frac{\theta_{e^y} - \theta_{sat}}{e^y} \theta'_{e^y} \, dy} \tag{1}$$

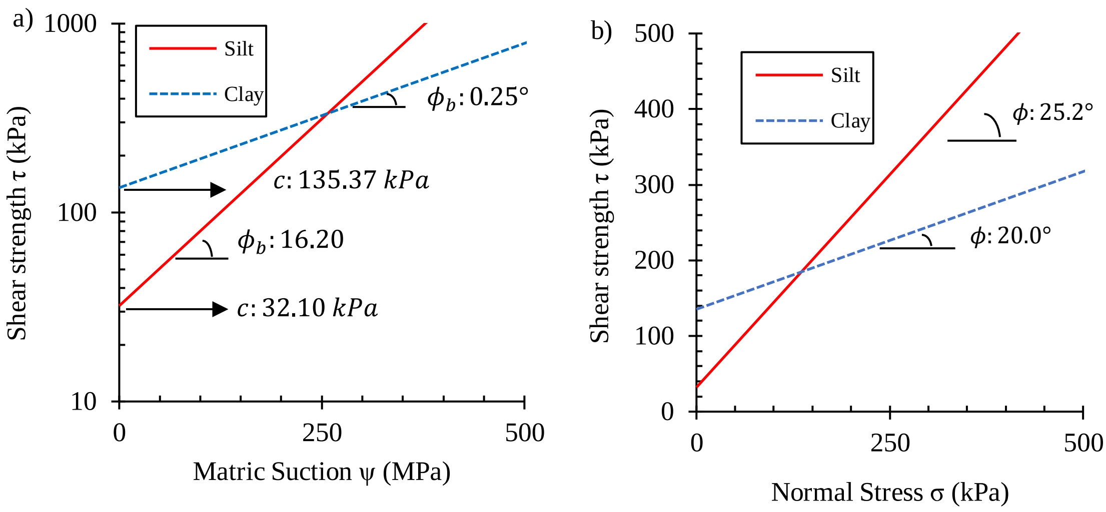


Fig.1: Strength parameters for the soil used in the stability model: a) Strength parameters of clay and silt, describing shear strength as a function of matric suction. b) Strength parameters of clay and silt, describing shear strength as a function of normal stress.

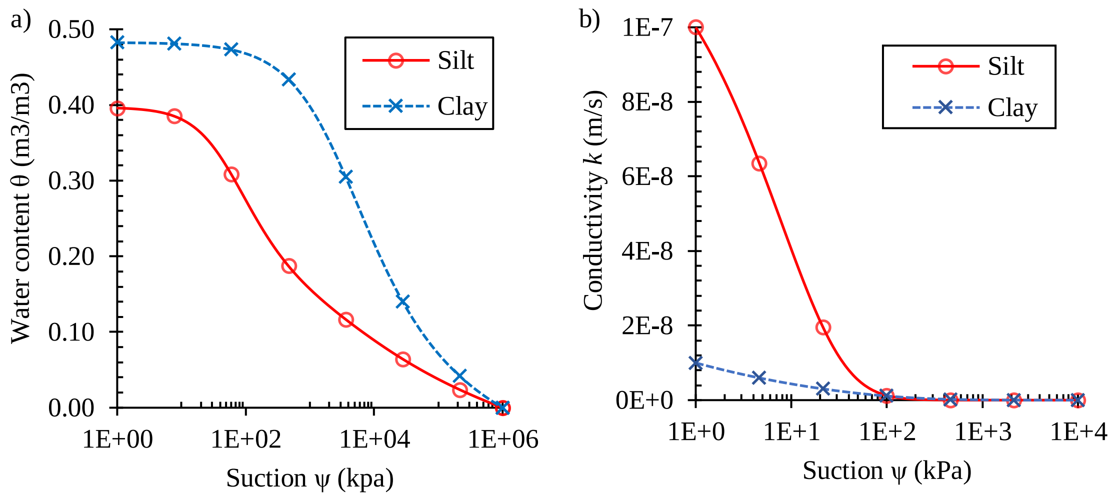


Fig.2: Soil behavior under unsaturated conditions: a) Soil-water characteristic curve built with Caicedo's parameters, that relates the water content in clay and silt with the experimented water suction. b) Conductivity in the model's clay and silt soil as a function of matric suction, representing *equation 1*.

Methods

Geometry of Model.

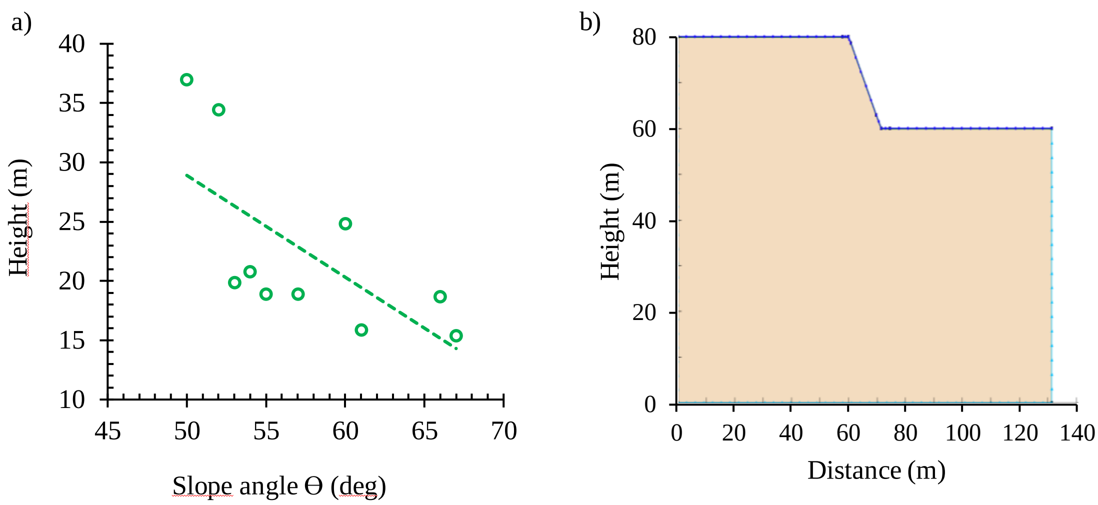


Fig.3: a) Scattered plot and best fit lineal function for the characterized slopes (Montatixe & Chango, 2018). b) Geometry of the model develop din GeoStudio, obeying the correlation in *equation 2*.

The proposed slope's geometry obeys a correlation obtained from a scattered plot of heights and angles of several silt slopes in the Avenue Simón Bolívar in Quito, Ecuador (Montatixe & Chango, 2018), adjusting a linear function to describe the height *h* of the slope as a function of its angle with respect to the horizontal Θ.

$$h = 71.826 - 0.8585\Theta \quad (2)$$

The corresponding height for a 60° angle is 20.316 m. Hence, the height is approximated to 20 m. To avoid any effects of the boundary conditions on the seepage and stability results of the model, the toe and crown extend 3 times the height of the slope, as well as the depth under the toe, meaning 60 m.

Seep and Slope Modeling

For the Seepage Analysis the following boundary conditions were stablished: Zero Flux for the limits of the model and specific points or lines that compromise the performance of the model by adding extra pressure heads to infiltrate water, Evaporation Unit Flux (m/s) of -3E-07 (Villacreses, Granados, Caicedo, Torres, & Yépez, 2021) and Infiltration Unit Flux modeling rain infiltration (m/s) stablished as 1×10^{-9} for both soil materials as after various runs and corrections, it was seen that an infiltration rate below the saturation conductivity extends the valid period of analysis, in which there aren't present any extra heads of water due to the waterbed emerging to the surface.

The Bishop Stability Analysis was used (GEO-SLOPE International, Ltd., 2012), stablishing and Entry and Exit range of slip surfaces that starts and ends from a distance equal to h from the crown and from the toe respectively, separating the entry from the exit range at the middle of the slope. This method of analysis takes into account the effects of PWP as shown in the term $(1 - r_u)$ of *equation 3*, where *SF* is the safety factor, c and ϕ strength parameters of cohesion and friction angle of the material, b_i is the width and m_i an angle-dependent geometrical parameter, both resulting from the discretization of the taken slip surface in various slices, and r_u being the ratio of the PWP and the weight W_i of the slide.

$$SF = \frac{\Sigma[(c' b_i + W_i(1 - r_u) tan\phi') \times \mathrm{m_i^{-1}}]}{\Sigma \mathrm{W_i} sen\alpha_i} \tag{3}$$

Specifications for Transient Analysis

The model starts completely saturated, with the waterbed level aligned with the surface of the slope. Then the analysis is set to give results for a period of 50 days of drought, but as mentioned before, the last valid value will be considered when the maximum matric suction reaches 1 million kPa. The raining period analysis was set to start at the time when the maximum suction was reached, this only being possible after one run of the model. For the clay slope, the maximum suction was reached after 41 days of drought, while for the silt slope were 33 days.

If the model presents at some time a head of water that should not be there due to the rise of the waterbed in the finite elements analysis, the last valid value is taken as the end of the raining period. There weren't any extra water heads after a year of infiltration in the clay slope, while for the silt slope, they started to appear after 158 days.

Results

The presented results were be compared to the results that were mentioned in the introduction of this paper. *Figures 4a* to *4d* present the contour lines of PWP. A cross is marked 2.5 meters under the surface of each slope. There, the PWP increases for the clay slope in approximately 50 kPa after 1 year, and for the silt slope approximately 35 kPa after 120 days. After 60 days in Alonso's model (Alonso, Gens, & Delahaye, 2003), the PWP increases in approximately 75 kPa. This happens due to the infiltration ratio being higher than the one applied in the clay and silt model reported in this paper.

It is also observed that a crust-like area is formed at the end of the drought period, implying that water will infiltrate significantly slower than how it would if the soil was saturated and hence, counting with a higher conductivity. As expected, the waterbed level stays unaltered at the toe, and even lowers near the crown. This happens because as the top of the slope saturates the conductivity rises as well, absorbing water under the phreatic level at a higher rate than it is infiltrated. Conductivity in the slope is higher near the waterbed level than at the top where the soil is nearly dry.

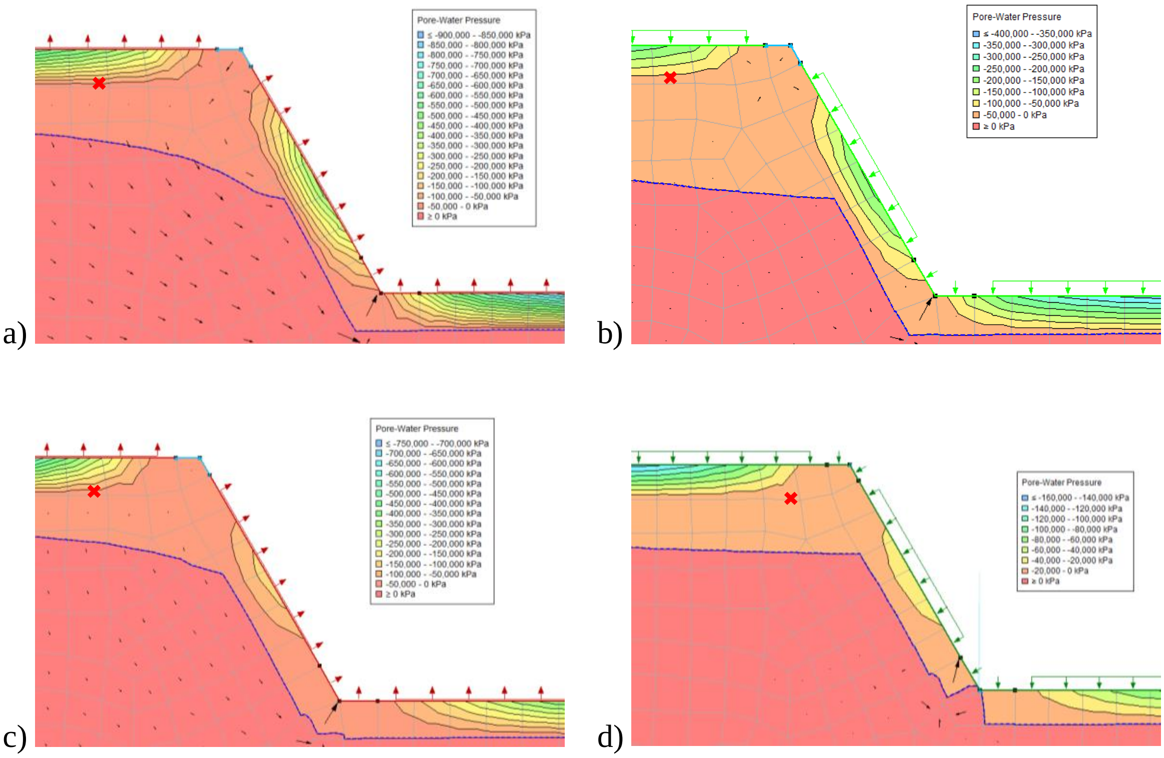


Fig 4: Contour lines of PWP in a) the clay slope at the end of the drought period, b) the clay slope at the end of the rain period, c) the silt slope at the end of the drought period, d) the silt slope at the end of the rain period.

As expected, the SF increases during drought faster than it decreases with rain, as seen for both scenarios in *figures 5a* and *5b*. During drought, SF takes 41 days to increase in 0.94 and a year to decrease 0.38. For the silt slope, the values change to 0.99 and 0.59 respectively. The behavior of the SF is similar to that presented by Ng and Shi (Ng & Shi, 1998), where drought periods compensated almost completely the decrements during extended periods of rain. Also, with the results in *Figures 5a* and *5b*, different stages of the transient analysis can be compared. SF for the silt slope at a completely saturated state (initial state) has a value below 1.0, presenting instability until a week of drought has taken place. The clay slope has enough cohesion to count with an initial value of 1.67 at complete saturation.

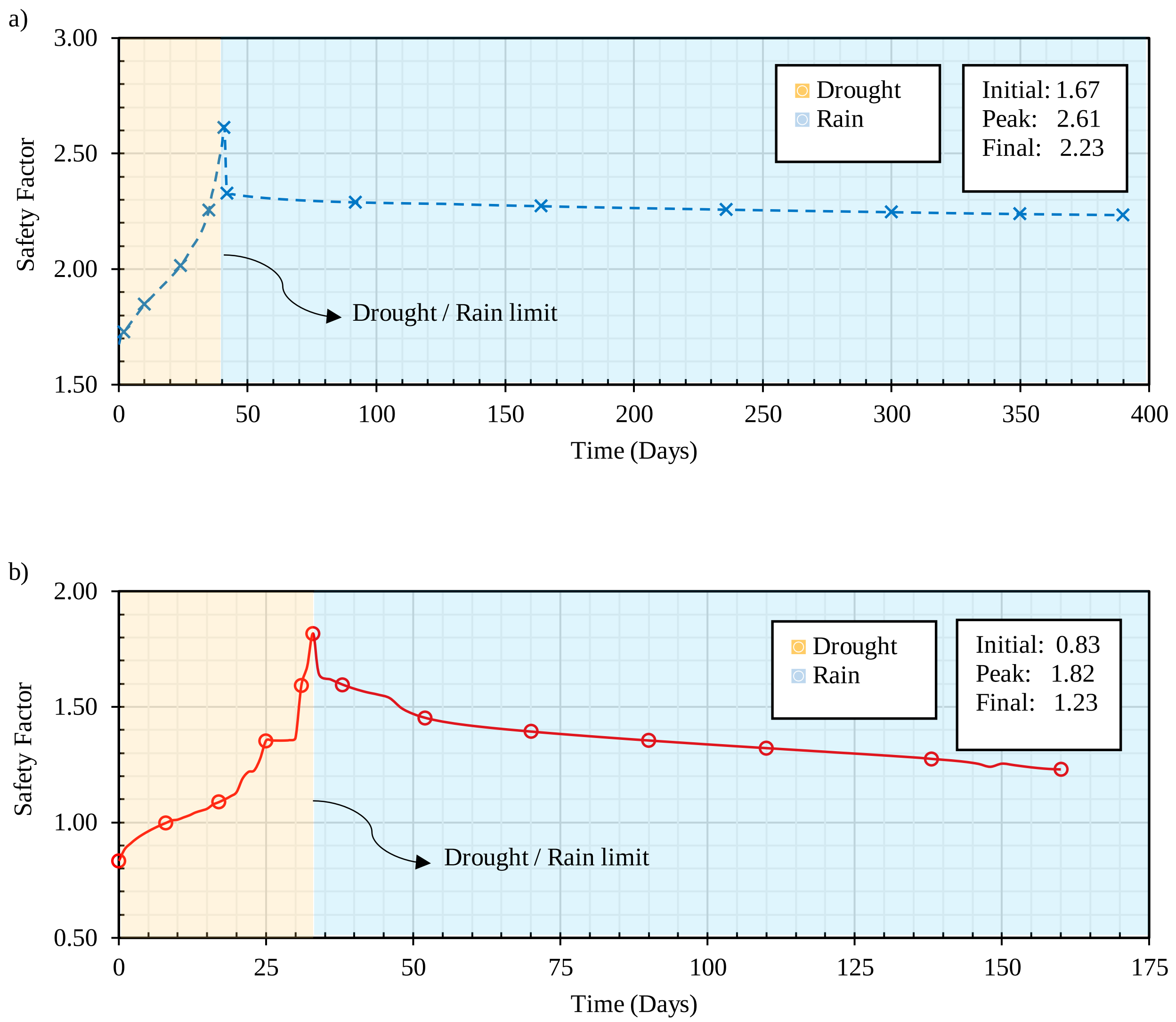


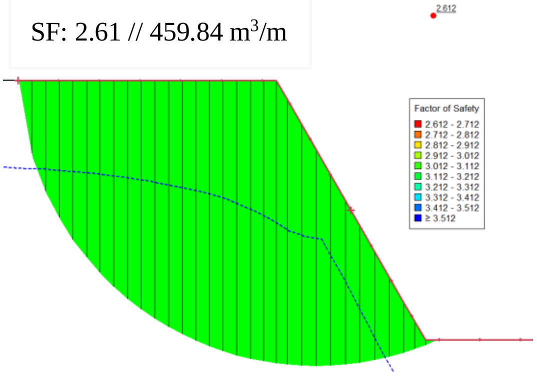
Fig 5: a) Evolution of the Safety Factor during drought and infiltration periods in the clay slope model. b) Evolution of the Safety Factor during drought and infiltration periods in the silt slope model.

Ecuadorian normative (Secretaría de Gestión de Riesgos, Ministerio de Desarrollo Urbano y Vivienda, Programa de las Naciones Unidas para el Desarrollo, Oficina de Ayuda Humanitaria y Protección Civil de la Comisión Europea, 2016) states that slopes must have a SF over 1.05 to meet seismic design requirements. The clay slope meets these requirements throughout the entireness of the analysis, while the silt one did not until day 8 of drought, implying that a slope with characteristics of saturation and geometry similar to those under day

8 of the model, will have an increased risk of failure. A significant variation in the first days of rain is seen in both models, suggesting that after extended periods of drought, one rain event loaded enough to surpass the carrying capacity of the soil, will lower SF nearly to its 70%.

Clay - Peak

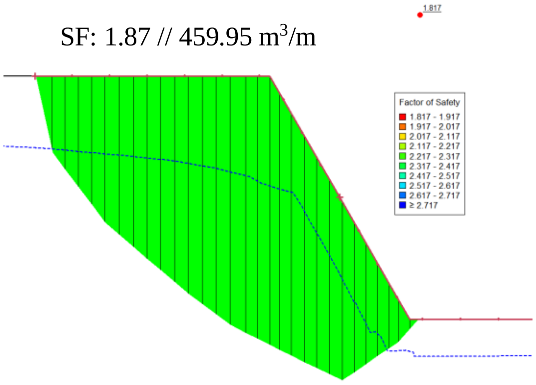
SF: 2.61 // 459.84 m^3/m



a)

Silt - Peak

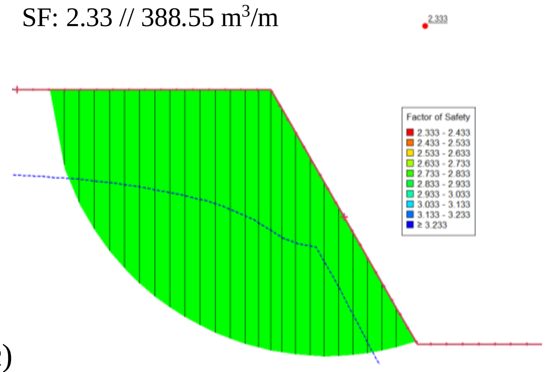
SF: 1.87 // 459.95 m^3/m



b)

Clay Rain

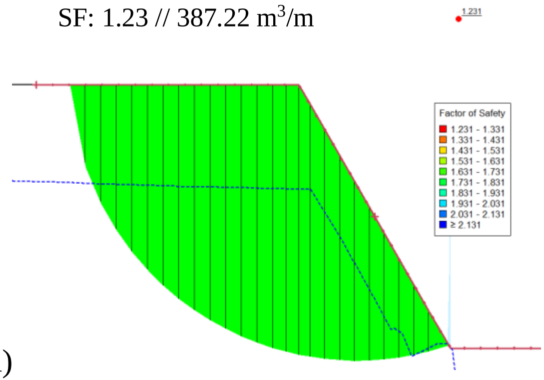
SF: 2.33 // 388.55 m^3/m



c)

Silt Rain

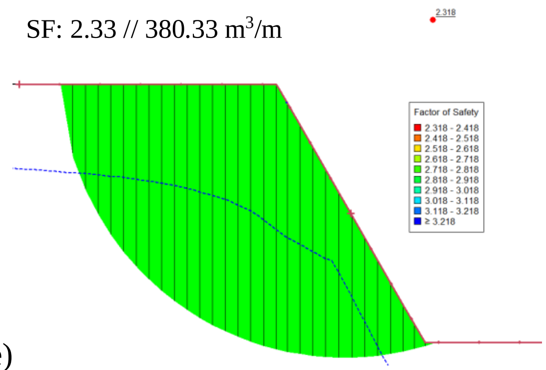
SF: 1.23 // 387.22 m^3/m



d)

Clay Drought

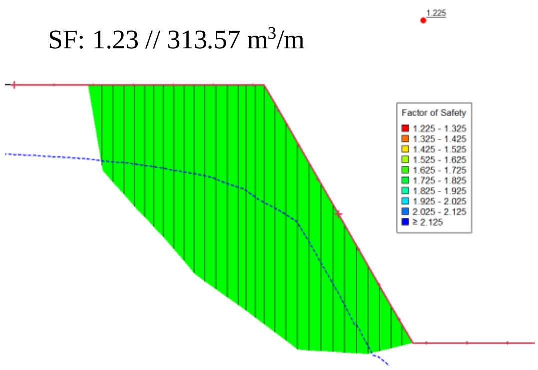
SF: 2.33 // 380.33 m^3/m



e)

Silt Drought

SF: 1.23 // 313.57 m^3/m



f)

Fig 6: Critical slip surface at a) peak SF for the clay slope, b) peak SF for the silt slope. Critical slip surface at c) last valid SF for the clay slope, d) last valid SF for the silt slope. Drought-associated critical slip surface for e) the clay slope, with SF equal to *Figure 5c*, f) the silt slope, with SF equal to *Figure 5d.*

Later, the critical slip surface associated to the peak SF was compared for both models, as well as the last valid critical slip surface during rain, and their corresponding slip surfaces during drought (counting with the same SF). The mobilized mass of soil was measured with the free software ImageJ and reported in *figures 6a* to *6d.* It is seen that at complete saturation, the carried mass is at its biggest value, decreasing at its 84.49% and 84.19% as it reaches the peak value for SF for the clay and silt slopes respectively. This implies that stability safety of the slopes is not only attached to the shear stress increment due to matric suction, but to the reduction of the carried mass over the slip surface. However, the carried mass associated to drought with the same SF is lower than its equivalent for rain, being 17.29% and 31.83% lower than the peak for the clay and silt slope respectively. This implies that even if both scenarios count with the same SF, it takes more soil mass to drive failure in a slope during rain periods. An explanation might be attached to the distribution of matric suction stresses, being more isolated in the dry crust of the drought stages, and better distributed in the infiltration periods, as well as having the waterbed at a lower level.

Conclusions

To summarize, the main objective was to evaluate the feasibility of rheometer tests results to describe the evolution of the SF throughout drought and rainy seasons. Strength parameters were taken from rheometer tests for the clay slope model, while external data was taken for the silt slope model. SEEP/W and SLOPE/W analyses were performed to evaluate the variation in PWP due to negative and positive infiltration, representing drought and rain periods respectively. The model was only valid under values of matric suction under 1 million kPa, drawn limit by Fredlund and Xing's model. Hence, applying a negative infiltration of 3E-07 m/s to both models, the clay slope reached the maximum matric suction after 41 days of drought, while the silt slope took 34 days to do so. Then, positive infiltration was applied, it being lower than the saturated conductivity of the soil to avoid the appearance of extra heads of water in the model and the rise of the waterbed over the slope's surface. Finally, SF vs time plots were obtained, as well as contour curves for the PWP and critical slip surfaces at stablished stages of the transient analysis.

SF for both models behaved as that from the referenced publications, increasing rapidly during drought periods and a decreasing gently during rain periods that do not exceed the carrying capacity of the soil. The model also matched sudden decrements of the SF in rain events after extended periods of drought. Compared to results that input a rain infiltration higher than the carrying capacity, the results of this model were lower, implying that at rainfalls with flooding capacity, the pore water pressure will increase significantly and faster, while lowering at that same rate the SF. It described peaks for both slopes after the maximum matric suction was achieved. Ecuadorian normative was evaluated and this model's results met the basic and seismic requirements for slope design. The mass driven by the critical slip surfaces is also compared, having less mobilized mass under a same SF during drought periods than during rain periods. This said, it is concluded that slope stability models that work with strength parameters taken from rheometer tests are appliable, and that easier methods to calculate the characteristic curve of materials are also appliable, giving consistent results comparing to previously done research.

It is recommended to work with layered models that count with different kinds of soil throughout their depth. Also, it is recommended to calculate as many parameters as possible for a same sample, to give away more accurate results instead of associating different results from different researchers. Laboratory tests such as triaxial stress, shear and rheometer tests are necessary to obtain strength parameters (ϕ', c', ϕ_b). Permeability tests are also necessary to measure de peak negative infiltration capacity and saturated conductivity. Most importantly, plastic index and granulometry tests are also necessary for this model, as it works under Caicedo's model for the characteristic curve.

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