Geotechnical Characterization, Stability Analysis, and the Stabilization Process for a Landslide in a area of Barreiras Formation and Granite Residual Soils, Pernambuco

Caractérisation géotechnique, analyse de la stabilité et procédés de stabilisation pour un glissement de terrain dans des matériaux du type « Barreiras Formation » et sols de granite résiduel, Pernambuco

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ABSTRACT: A large number of Brazilians live in conditions that involve elevated risk for landslides. Both technical and social problems are involved. This study presents results of a research project involving technical support for the Municipal administration of the City of Camaragibe - PE. An important landslide occurred in an occupied area after a period of intense rainfall, causing considerable losses for the local population. Three years later, another period of intense rainfall exacerbated the problem, causing cracks to develop in the walls and foundations of many houses, and broadening the area initially affected. An important program involving investigation that included field and laboratory activities, instrumentation, and stability and flow analysis was carried out. The results produced were considered to be very satisfactory, and they were able to point out the main causal factors, along with the mechanisms involving the landslide, which could then be better understood, and thoroughly studied. Afterwards, a proposal for stabilization for the entire area was elaborated, aiming to significantly reduce the risk levels by means of superficial and sub-superficial drainage, geometric modifications, placement of structures for stabilization of the land, and other activities.

RÉSUMÉ : Un grand nombre de brésiliens vivent dans des zones à risque d'un point de vue des glissements de terrain. Cela engendre des problèmes aussi bien techniques que sociétaux. Les travaux présentés dans cet article découlent d'un projet de recherche financé par l'administration municipale de la ville de Camaragibe – PE. Suite à un épisode pluvieux très important, un glissement de terrain s'est produit et a causé des dégâts considérables pour la population locale. Trois années plus tard, un nouvel épisode pluvieux a aggravé la situation et de nombreux ouvrages furent endommagés (murs de soutènement, fondations de maisons, …). Un programme d'investigation important fût alors mis en place : instrumentation sur site, analyses de stabilité et d'écoulement. On présente dans cet article une synthèse des résultats obtenus ainsi que les mécanismes aux origines des instabilités. Pour finir, une solution de stabilisation du site est proposé, avec pour but de réduire significativement le niveau de risque (drainage, modification géométrique de la pente et mise en œuvre d'ouvrages de stabilisation).

KEYWORDS: geotechnical characterization, slope stability, stabilization process.

1 INTRODUCTION

This paper presents study results from a research project, including details involving technical support supplied to the Municipal administration of the City of Camaragibe – PE, Brazil. The area investigated is located in the Township of Camaragibe, belonging to the western portion of the Recife Metropolitan Region. The landslide that occurred was classified as a multiple rotational landslide, characterized by the appearance of various steps along its slope. Geological characteristics of the area studied define an unsaturated granite residual soil that is partially covered by the Barreiras Formation. The residual soil of granite is found throughout the entire city. In some places, the granite rock mass is exposed.

In the Recife Metropolitan Region, it is common to find crystalline based rocks (Granite-Gneissic complex) covered by granite residual soils that originate from a crystalline structure; and by sediments from the Barreiras Formation. The crystalline base is formed by ancient intrusive rocks (1.5 to 21 billion years) belonging to the Pernambuco – Alagoas Massif. It presents at least four phases of deformation, the latter of which, associated to the faults deformed, resulted in the formation of the "Pernambuco Lineamento".

The results presented here refer to a synthesis of the program of geotechnical characterization (field and laboratory testing, along with instrumentation), flow and stability analysis, and proposals for stabilization of the area in an attempt to significantly reduce the level of risk. This study aims to give continuity to a research project by the GEGEP – DEC / UFPE, with support from the CNPq/FACEPE, designed to comprehend and elaborate mechanisms involving instability of slopes, and providing manners in which stabilization can be achieved.

2 GEOTECHNICAL CHARACTERIZATION

In the studies, an extensive effort involving *in situ* and laboratory investigation was carried out. For basic geotechnical characterization, laboratory analysis consisted of physical, chemical, and mineralogical characterization tests, strength tests (including direct shear tests, and direct shear tests utilizing controlled suction), and oedometric tests.

The *in situ* investigation carried out in the area was performed by using topographic profiles of the region, cross sections, geological engineering mapping, subsurface exploration (soil / rock mass – SPT / RQD measurements), soil moisture content profiles, sampling of soils (Block and Denison), and field permeability tests (Guelf). Field instrumentation utilized piezometer, water table level, inclinometer, and rainfall measurement equipment. More information can be found in Silva (2007) and Silva *et al.* (2009).

2.1 Field Investigation Results

For the subsurface exploration, twelve boreholes were utilized in the area investigated. Ten were carried out in soil (SPT), and two more in soil and rocky mass (SPT / Core boring–RQD). All boreholes the SPT was measured for each 0.5 m, in general with a depth of 10 to 15 m, but some went down to 20 m (SM-01, SM-02 and SP-02). Geological characteristics were identified together with soil / material descriptions.

In general, for all borehole tests performed, the SPT values ranged from 2 to 17 down to a depth of 7 m from the level of the natural ground surface, within the limits of the two geological formations. From this point on, the SPT values increase markedly, up to an order of 30, until becoming impenetrable to the SPT borehole. In the vertical profile, soil types vary from clayey sand, to sandy clay, silty sand, and sandy silt, with the layers varying in thickness, and showing the presence of increased amounts of sandy materials. The greatest alterations in SPT values were found very close to the Barreiras Formation contact with the granite residual soil. An exception involved the SP-02 borehole, found to be basically granite residual soil (Figure 1). Due to high sand content, the Barreiras Formation in the area is identified as an alluvial plain facie. Based on technical interpretation, the failure surface was shown to be near to the geological formation contact point, later confirmed by instrumentation (inclinometer results).

The presence of granite residual soil from the ground level in the SP-02 region demonstrated a profound influence on the landslide process, as evidenced later on in the study.

Soil profile cross-sections were detailed from the subsurface exploration, along with results from geological engineering mapping. Typical soil profile information is shown in Figure 1.

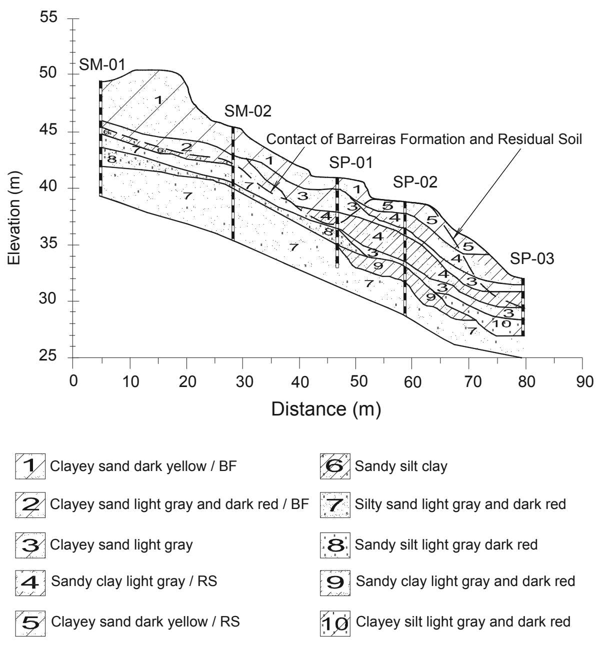


Figure 1. Typical Soil profile-cross section – post failure.

The climate in the area is classified by Koppen, as ´As´, described as humid tropical, with rainy periods during the autumn – winter seasons, and a dry period during the summer.

Rainfall precipitation in the Camaragibe township region was measured by instruments installed in two places, initially in a location within the city (during 2000 to 2004), and then later via instrumentation installed in the landslide area (2004 to 2006).

The rainy season is concentrated in the months from March to August, with the precipitation approximating average monthly maximum levels ranging from 150 mm to 600 mm. From January to March the average maximum monthly precipitation is around 150 mm, with April, May, July and August showing 250 mm. The month of June presented precipitation above 500 mm, being considered the critical period for landslides. During the period from September to December, precipitation levels were lower, averaging around 50 mm. The period from September to February normally presents less precipitation; however, in some years (examples being 2000, 2002, 2004 and 2010) significant rainfall occurs in the months of January and February. During 2000, the annual rainfall level was above the general average, with increased precipitation during most of the calendar months. This occurrence coincided with the first appearance of signals of a non-stabilization condition in the area. Landslides occurred in June of 2002, after a period of intense rainfall.

Hydraulic conductivity of the soils was determined through field testing using a Guelph permeameter, an in-hole constant head permeameter employing the Mariotte Principle. It delivers essentially a "point" measurement. The tests were made along of the slide, close for the SPT boreholes, and was performed for each 0.5 m to a depth of 2.5 m. In the Barreiras Formation soils, permeability results varied from 2 to 6 x 10-6 m/s, with higher values from the materials containing a higher percentage of sand. In the SP-02 region (Figure 1), granite residual soils are present in the surface levels, presenting permeability results in the order of 2 x 10-7 m/s, and demonstrating values 10 times lower than the corresponding Barreiras Formation. This difference influenced flow conditions in the slide area.

The field instrumentation program in the landslide area was based on 25 Casagrande type piezometers (with 18 Casagrande piezometers having the ability to register maximum levels during a rainy period), 6 water level instruments, 5 vertical inclinometers, and 1 rainfall registration instrument.

In general the period of highest elevation of the piezometric level coincides with the period of high rainfall, in the months from March to August (with water managing to emerge from the surface level of the ground near borehole SP-01). Starting during the month of September, piezometric levels show a reduction, tending to remain constant until March, coinciding with the dry season. Similar behavior can be observed regarding the water levels encountered. Even in periods of low rainfall intensity, piezometric levels are observed to be quite high, demonstrating hydraulic influence on slope stability.

Results obtained in the vertical inclinometer analysis relating to borehole SP-02 showed maximum horizontal displacement of 130 mm as a block mass. It should be noted that horizontal displacements measured refer to the stage of reactivation, featuring movements along the existing failure surface, given that instrumentation was implemented in November 2004, after the occurrence of the failure. The influence rainwater had in the acceleration of horizontal movements was clear in observations regarding the slope studied. It appears that during a period of reduced rainfall (November 2004 to March 2005) the displacements observed were virtually nil, without significance.

Results of the vertical readings from inclinometers confirmed the information obtained from the SPTs boreholes, showing that the failure surface seems to be very close to the contact between the Barreiras Formation, and the granite residual soils, measured to be located at a depth just over 7 m from the surface of the ground, the exception being the region around SP-02, where only residual soils are found.

2.2 Laboratory Investigation Results

The mature residual granite soil studied presents a fine texture, with a liquid limit of 54%, plasticity limit of 32% (PI=22%), grain size distribution of 39% clay, 26% silt, 23% fine sand, and 12% a mixture of medium and thick sand. The soil is classified as CL in the Unified Classification System.

Grain-size distribution test without the use of deflocculates was also performed. Grain size distribution was designated as

5% clay; 33% silt; 50% fine sand, and 12% medium and thick sand; showing a strong reduction in the portions of clay, and increases in the fine sand portions. Results indicate that the particles of clay in this soil are aggregated in their natural state.

The soil-water characteristic curve obtained through the paper filter method, Haines funnel and Richard´s chamber, is presented in Figure 2. The format of the curve displays a saddle aspect, allowing it to be divided into three distinct stretches. The curves indicate an initial air entry suction of 1 kPa, where de-saturation begins. After that, a region approximating horizontal is observed, where suction varies from 20 to 200 kPa. In the last stretch, a second air entry value is depicted, where the water content starts to diminish with the increase in suction due to the removal of water from the soil micro pores (see more information in Silva and Coutinho, 2009).

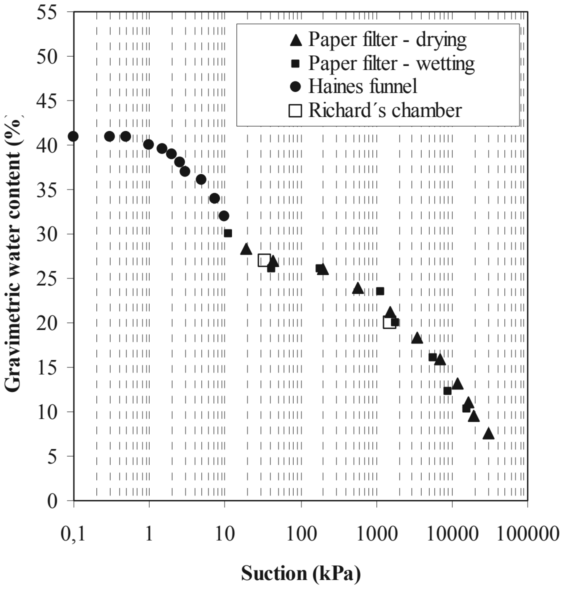
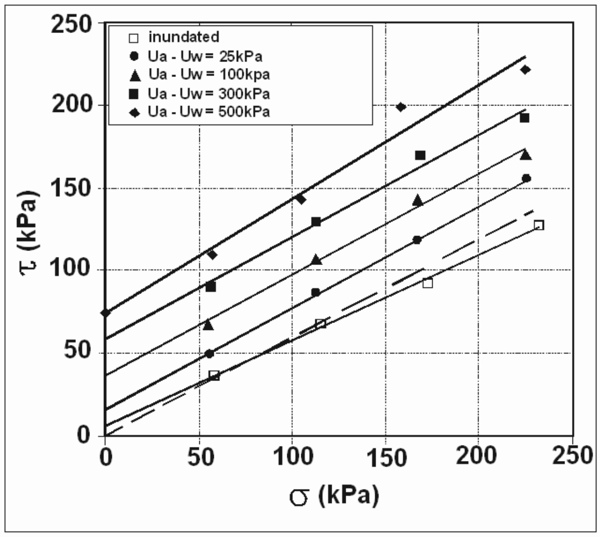


Figure 2. Soil-water characteristic curve from mature residual soil from Camaragibe-PE - Silva and Coutinho (2009)

The shear strength was determined using conventional and controlled suction direct shear tests. The equipment used consisted of a conventional press, adapted for use with a cell that allowed the imposition and control of suction through the principle of translation of axes.

The suction is imposed on the soil by the difference between air pressure supplied by hydrogen applied through an air valve, and the water column maintained in the reservoir fixed on top of the press. The tension is applied through a system of hanging weights, identical to the conventional direct shear tests. The air pressure was applied only under the weight of a charge transference plate, and it was maintained during 10 days. The horizontal force was determined through a load ring. The suctions employed were 25, 100, 300 and 500 kPa. After this period (of suction equilibrium), specific normal stress values were applied, accompanying the deformations up to stabilization. The normal stresses adopted were 50, 100, 150 and 200 kPa, and they were maintained for a minimum of 24 hours. Square samples were used that measured 50 mm or 100 mm the side, and 22 mm or 44 mm in height.

The shear strength envelopes in the plain (σ_v, τ) for the suction values of 25, 100, 300 and 500 kPa are represented in Figure 3. Envelopes considering suction of 0 kPa, obtained through conventional direct shear tests in the submerged condition, are also presented in this figure. It can be observed that the friction angle, in general, is close to 31°. The results indicate that the envelopes are near to linear in the stress range.



(Ua–Uw)= 0kPa	c = 9,7kpa	ϕ = 26,3°	R^2= 0,996
(Ua–Uw)= 0kPa	c = 0,0kpa	ϕ = 31,0°	estimated
(Ua–Uw)= 25kPa	c = 15,4kpa	ϕ = 31,6°	R^2= 0,999
(Ua–Uw)= 100kPa	c = 36,5kpa	ϕ = 31,3°	R^2= 0,991
(Ua–Uw)= 300kPa	c = 58,7kpa	ϕ = 31,5°	R^2= 0,987
(Ua–Uw)= 500kPa	c = 74,7kpa	ϕ = 34,4°	R^2= 0,956

Figure 3. Shear strength envelopes for different values of suction – mature residual soil from Camaragibe.

3 STABILITY ANALYSIS

Through the field investigation, together with flow and stability studies (failure and post failure conditions), a clear perception and understanding of the landslide mechanism was made possible. In this paper, only results corresponding to the failure state are presented. The slope stability evaluation was performed using Spencer method with consideration given to the original topography for the main cross section, as a two-dimensional saturated stability analysis, and considering the "actual" failure surface, along with the pore pressure distribution obtained from the flow analysis, and the geotechnical parameters obtained from laboratory testing (conventional direct shear tests in the submerged condition). Due to the intense rainfall during the failure period, the water level was considered at the surface position from the results produced through instrumentation and field observation, with the materials being in a saturated condition (Silva et al. 2009).

Flow analysis was performed for the failure condition, considering all the information from the studies, including the geotechnical profile, the geotechnical parameters of hydraulic conductivity for the materials composing the Barreiras Formation and residual soils, along with the rainfall and water level conditions. A summary of pore pressure distribution results is shown in Figure 4. Higher positive pore pressure values in the SP-01 and SP-02 regions were obtained showing ascends flow. These results are due to the variability of the soil profile and differences among the hydraulic conductivity values occurring for the materials. This condition is in conformity with water flow observed in this area during the period of intense rainfall.

With the flow analysis results that were provided, stability evaluation for global failure was initially performed (one-step failure) for the complete slope cross-section. The safety factor result was 1.278, showed not to be a condition for failure. Stability analysis was then performed considering the possibility of two-step failure, taking into account the concentrated high pore pressure values around the SP-01 region.

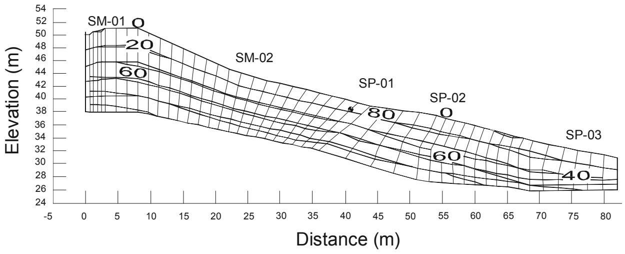


Figure 4. Flow Analysis – Pore Pressure Distribution.

The first landslide occurred between the positions SM 02 and SP-01. For this case, the safety factor value was 1.002, for practical purposes, considered to be a condition of failure, and initiating the landslide mechanism in the area (Figure 5).

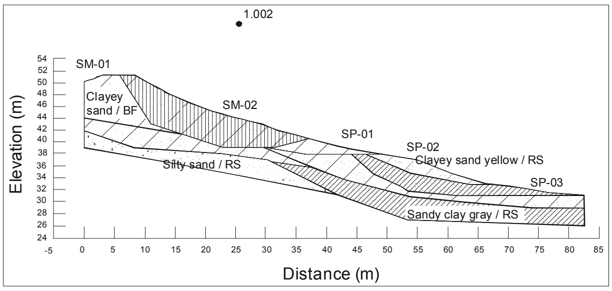


Figure 5. Back-analysis of the first slope failure – from SM-01 to SP01

The mass that moved in this area (from the first failure) caused a surcharge estimated at 30KN/m between positions SP-01 and SP-02, which associated with pore pressure conditions, provoked the second step of the landslide. With this understanding, stability analysis was performed (back-analysis) using geotechnical information from the field and laboratory investigations. Figure 6 presents the minimum safety factor value obtained (1.047), confirming the displacements, and the failure mechanism considered to be the cause of the landslide that occurred in the area.

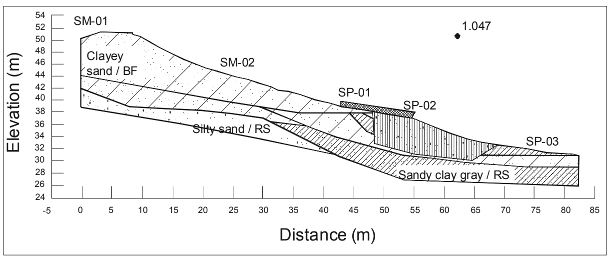


Figure 6. Back-analysis of the second slope failure – SP-01 to SP-03

After three years, another intense rainfall period amplified the problem, with cracks forming in many other houses, and extending the area initially showing damage. See the right side of the two upper-center squares of Figure 7.

4 MITIGATION AND REHABILITATION MEASURES

The mitigation and rehabilitation measures consisted of reducing damage and losses through control of the processes, and protection of the exposed elements in order to reduce their vulnerability. During the investigation and studies, it became possible to understand the processes involved, and to identify the causal factors and triggering mechanisms in the area. The general plan was to propose a risk management program that included both structural and non-structural mitigating actions, considering the social conditions of the area (Coutinho, 2011).

The stabilization measures proposed for all damaged areas (initial and extended areas) included: surface and subsurface drainage (sub-horizontal drains), surface protection, placement of access stairs with surface drainage, modification of slope shape, installation of retaining walls, definition of areas where occupation was to be prohibited, definition of houses to be relocated, dissemination of information to the public, and raising overall awareness of the conditions, along with community consciousness. Figure 7 shows some of the mitigation and control measures proposed.

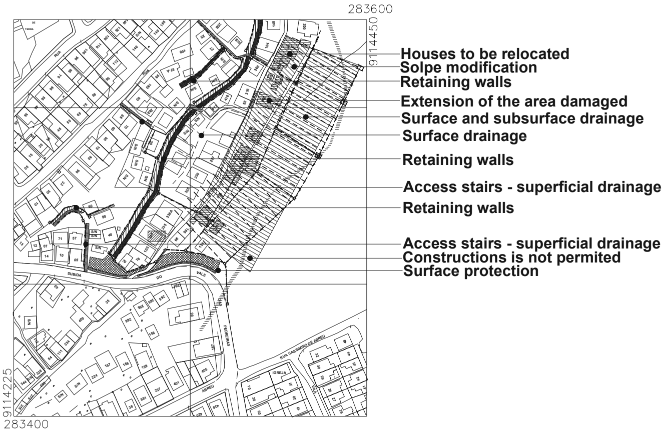


Figure 7. Measures Proposed for Mitigation and Control

5 CONCLUSION

The geotechnical characterization, along with flow and stability analyses / back-analysis results, were considered to be very satisfactory, and in accordance with the literature, permitting that the principal causal factors, and the mechanisms of the landslide could be comprehended and studied. It was understood that due to the heavy rainfall, the water level became elevated, saturating the soil, and producing a concentrated flow. The strength parameters used in the analysis were derived from direct shear laboratory tests in the corresponding condition. Considering all of the information available, mitigation and rehabilitation measures were then proposed, generating a risk management program that included structural and non-structural stabilization actions, considering the social conditions of the area.

6 ACKNOWLEDGEMENTS

The authors are grateful to the CNPq, FACEPE, and Camaragibe City Administration for research support, and all members of the GEGEP/UFPE who participated in the projects.

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