Precipitation Influence on the Distribution of Pore Pressure and Suction on a Coastal Hillside

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Abstract. The frequent interruption of roads in some freeways in Brazil due to slope failure has caused economic losses and potential harm to users. The paper presents data from a monitoring system installed at Serra do Mar in Santa Catarina State, Brazil. The slope monitored is called Morro do Boi and is located on BR-101 south, near the municipality of Itapema. It was stabilised using anchor and flexible metal mesh. Hence, all the pore water pressure measured is due to environmental changes. After approximately sixteen months of readings, it was possible to observe that the suction variation in the unsaturated layers presents a time delay in relation to the rainfall observed in the area. The ground water table presented a variation of about 1.5 m. The analyses of the data allowed establishing a trigger accumulated rainfall that reduces the negative pore water pressure to values below 10 kPa. So far, no significant positive pore water pressure has been observed above the ground water table.

Keywords: coastal slopes, geotechnical instrumentation, mass movements.

1. Introduction

The implementation and operation of highways as well as the management of potential risks through their life cycle represent a major engineering challenge which involve multidisciplinary knowledge (geological, geotechnical and environmental). These operations become even more complex when structures are located along regions such as Serra do Mar (Tavares, 2010). Soil masses at this location, mainly composed of colluvial and residual soils, are characterized by a weathering profile as a result of physical, chemical and biological processes. Such formations are shaped by the strong influence of environment and geomorphology dynamic agents (climate, topography, rock matrix, etc.). The data obtained by an instrumentation system deployed in a stabilized slope are presented and discussed herein, aiming to correlate pore water pressure readings with rainfall events. The instrumentation system measured the pore pressure variations in order to better understand the mechanisms which promote slope instability.

2. Study Area Description

The instrumentation was installed at a slope located at km 140+70 m of freeway BR-101 south track between the cities of Balneário Camboriú and Itapema, in Santa Catarina. Figure 1 presents a satellite view of the area. The slope monitored is at an elevation of 160 m above sea level, with inclinations between 1.0V:1.5H and 1.0V:2.0H. Site history shows scars of instability created after a heavy rainfall (1005 mm accumulated that month) occurred in November 2008, which caused partial highway interruption. After these occurrences, the slope was stabilized with a passive anchors system combined to a specific metal mesh to retain the slipped masses in their remaining position (Kormann *et al.*, 2011).

The region of Morro do Boi is characterized by the occurrence of two types of rock: intrusive Nova Trento granites and Morro do Boi migmatites. Such lithologies are lightly fractured and have relatively high strength when they remain unexposed to considerable climate changes. Morro do Boi is affected by NE-SW and NW-SE shear surfaces, and by sub-horizontal fractures that divide the rock mass into blocks, considerably reducing the mechanical strength of the slope. It is worth noting that the presence of colluvial/talus soils results in a very heterogeneous structure with a high weathering degree and an extremely low cohesion (Fiori, 2011).

Another key aspect is the occurrence of localized underground water flow through the slope, resulting from connections between discontinuity families. Therefore, translational or wedge slides occur involving rock block movements along planar surfaces and rock block motions along two intersecting joint surfaces. The occurrence of shallow landslides in the soil-rock contacts or in adjacent planes of discontinuities is normally associated with cuts that result in soil layers with irregularly distributed thicknesses. Moreover, the phreatic level is not constant along the slope, being the rock permeability controlled by the fractures, particularly by the ones which experienced pressure relief, usually disposed in a parallel direction to the slope (Sestrem & Kormann, 2013).

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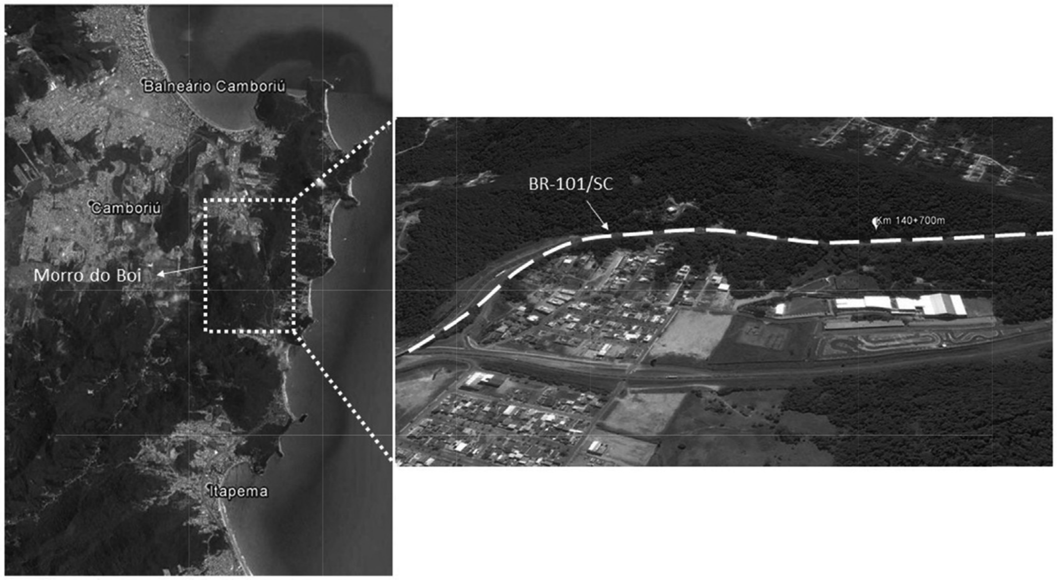

Figure 1 - Study area location.

In order to obtain more precise information about the local stratigraphy, prior to the instrument system installation, two boreholes were carried out at the site as can be observed in Fig. 2. The boreholes stopped at 3 m below the bedrock and its perforations were subsequently used for installing inclinometers. Figure 2 also indicates the three groups of instrumentation of the slope. The range of ground water table variation is indicated in Fig. 2. Based on the results, a layer of soil and weathered rock with total thickness varying between 8 and 10 m was identified. The following layers were observed: colluvial soil with thicknesses up to 3 m, highly weathered rock (residual soil) with thicknesses between 2 and 3 m and moderately weathered rock with thicknesses between 3 and 4 m. Underneath these layers, there is a bedrock of migmatite.

Further characterization and shear strength laboratory tests were performed by Lazarim (2012). Based on these tests, the results showed an average unit weight of 2.66 g/cm^3, average liquid limit of 32% and average plastic limit of 27%, representing materials of low plasticity and compressibility. Particle size distribution indicated predominantly sandy soils (60.4%) with 27.0% of silt,

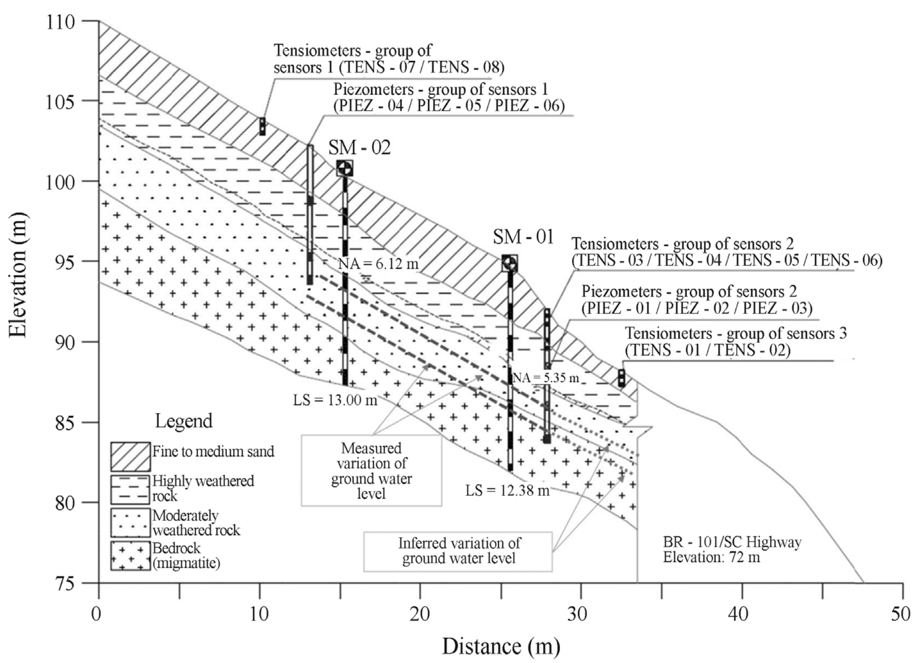

Figure 2 - Geological and geotechnical profile of the studied slope.

8.3% of gravel and only 4.3% of clay. Based on direct shear tests performed in four different block samples, effective friction angles between 28° and 39° and cohesion intercepts between 1 and 17 kPa were obtained. The collection depth ranged between 0.25 and 1.27 m, the water content between 3 and 10% and saturation degree ranged between 2 and 8%.

3. Instrumentation and Geotechinical Monitoring Plan

The monitoring system used was conceived aiming to increase the understanding of the water movement and pressure variation along the soil profile studied. For that purpose, an instrumentation plan with an automated data collection system was designed to evaluate the pore pressure variations due to rainfall. Figure 3 presents a topographic plan of the studied area indicating the groups of instrumentation.

The monitoring system began with the installation of 2 conventional inclinometers embedded 3 m in the bedrock (recovery above 95%). Based on the description of materials found in these borings (Fig. 2), it was possible to define the depth for the installation of the vibrating wire piezometers (Geokon, 2014b), with the initial objective of monitoring the ground water table. The piezometers were installed at the residual soil layer center, at the interface soil - weathered rock, and at the contact between the weathered rock and bedrock. This configuration was used in two sections of the slope, being one uphill of the stabilized area (group of sensors 1) and the other inside it (group of sensors 2), enabling a comparative analysis between both places.

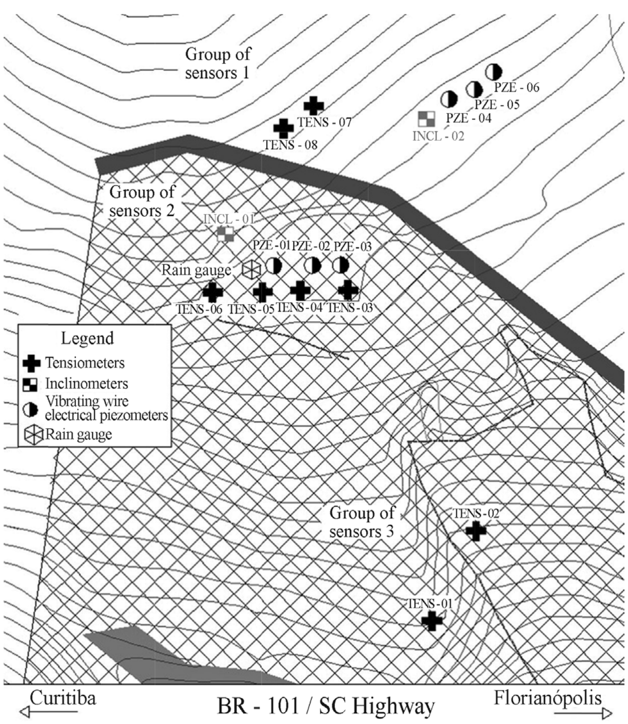

Figure 3 - Instruments location.

Regarding suction measurements, eight ordinary tensiometers using a pressure transducer with capability of reading between -100 to +75 kPa (Soilmoisture, 2014a; 2014b). The position of each sensor is shown in Table 1 and in Table 2.

For rainfall monitoring, a pluviometer of the tipping bucket type was installed, able to register events at each 0.25 mm of precipitation. Data were stored in a proper data logger with a maximum reading capacity of 700 mm/h and able to register date and time of each event (Hydrological Services, 2014a, 2014b).

The monitoring of all sensors began in May 2012 in an automated way through a data logger (Geokon, 2014a) with time intervals initially set to 8 h . During the period between 11/08/2012 and 12/12/2012, it was not possible to collect data due to technical problems.

4. Results and Discussions

In the following items, based on the monitoring system installed and on additional data related to the rainfall in the studied area, the results are presented and discussed. The main focus is to correlate the pore pressure readings with rainfall and with the geometric, geologic and geotechnical characteristics of the slope.

Table 1 - Installation depths of piezometers.

Group of sensors	Instrument	Installation elevation (m)	Depth (m)
1	PIEZ-01	92.4	8.65
	PIEZ-02	92.4	6.40
	PIEZ-03	92.4	3.90
2	PIEZ-04	101.5	8.60
	PIEZ-05	101.5	7.20
	PIEZ-06	101.5	3.70

Table 2 - Installation depths of tensiometers.

Group of sensors	Instrument	Installation elevation (m)	Depth (m)
1	TENS-01	86.0	1.00
	TENS-02	88.0	2.00
2	TENS-03	92.4	0.50
	TENS-04	92.4	3.00
	TENS-05	92.4	1.00
	TENS-06	92.4	2.00
3	TENS-07	103.7	1.00
	TENS-08	103.9	2.00

4.1. Rainfall

Figure 4 shows the total monthly precipitation during the monitoring period. It can be observed that the monthly precipitation presented an extremely variable pattern. Dividing the monitoring period in seasons, between the Summer and Autumn of 2015 the highest precipitation was observed. However, the Autumn of 2012 and the beginning of the Winter of 2012 presented a high level of precipitation as well. The extremely variable distribution of rain during the period of the study makes the use of monthly precipitation less useful from a geotechnical point of view.

To emphasize the great variability observed, Fig. 5 presents a comparison between the months of the different years monitored. The use of precipitation data for geotechnical purposes requires a detailed analysis.

A summary of some characteristics of rainfall events recorded by the rain gauge is shown in Fig. 6, listing the maximum daily volumes and respective occurrence schedules. The data for Nov/2012 and Jun/2013 include partial acquisition periods. From the results, March 2013 was verified to have the highest rainfall so far (382.50 mm) and the lowest ones occurred in June 2013 (55.75 mm), representing a variation of almost 700%. Regarding the distribution of these events, it is possible to observe periods whose cumulative monthly volumes are similar in spite of having very different average intensities, such as the months of February 2013 and July 2013. In the first one, rains were spread over 28 days (occurrence of daily events) and in the second one only over 16. Sestrem (2012) and Acevedo (2013) compared the precipitations measured by the rain gauge of Morro do Boi with the ones acquired in nearby cities (Navegantes and Itajaí), respectively. The authors report significant variations that show the importance of sensor installation in areas of specific interest.

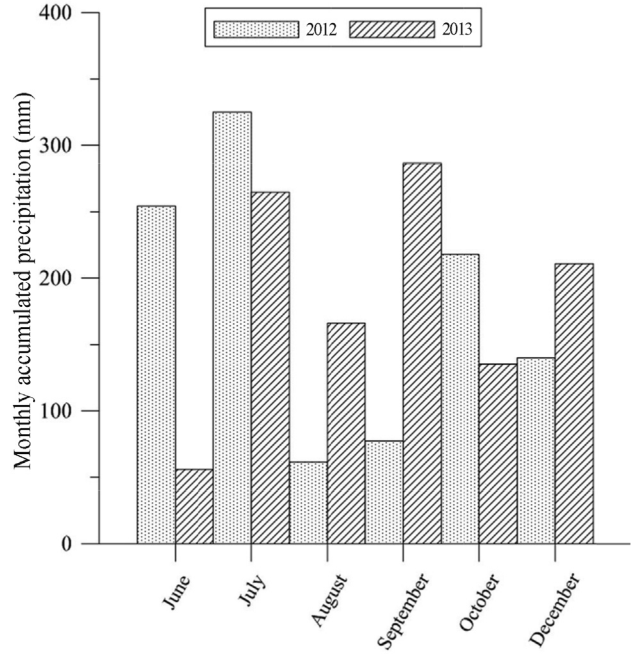

Figure 5 - Comparison between similar periods - monthly accumulated precipitation (mm).

Readings can also be assembled according to seasons, as displayed in Table 3. There are large differences between the values obtained in the same period for the first two years of monitoring, reinforcing the importance of precipitation

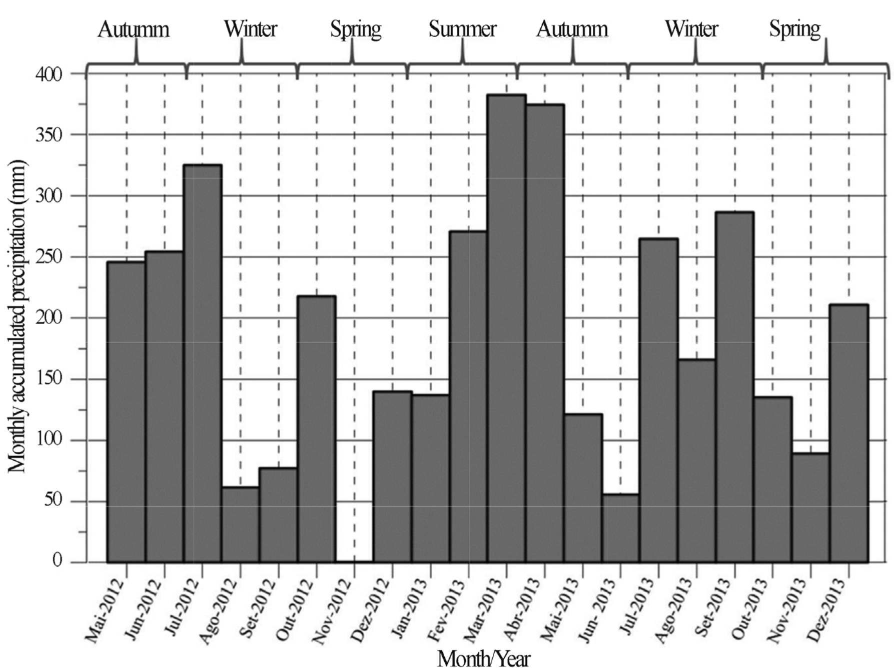

Figure 4 - Monthly accumulated rainfall (mm).

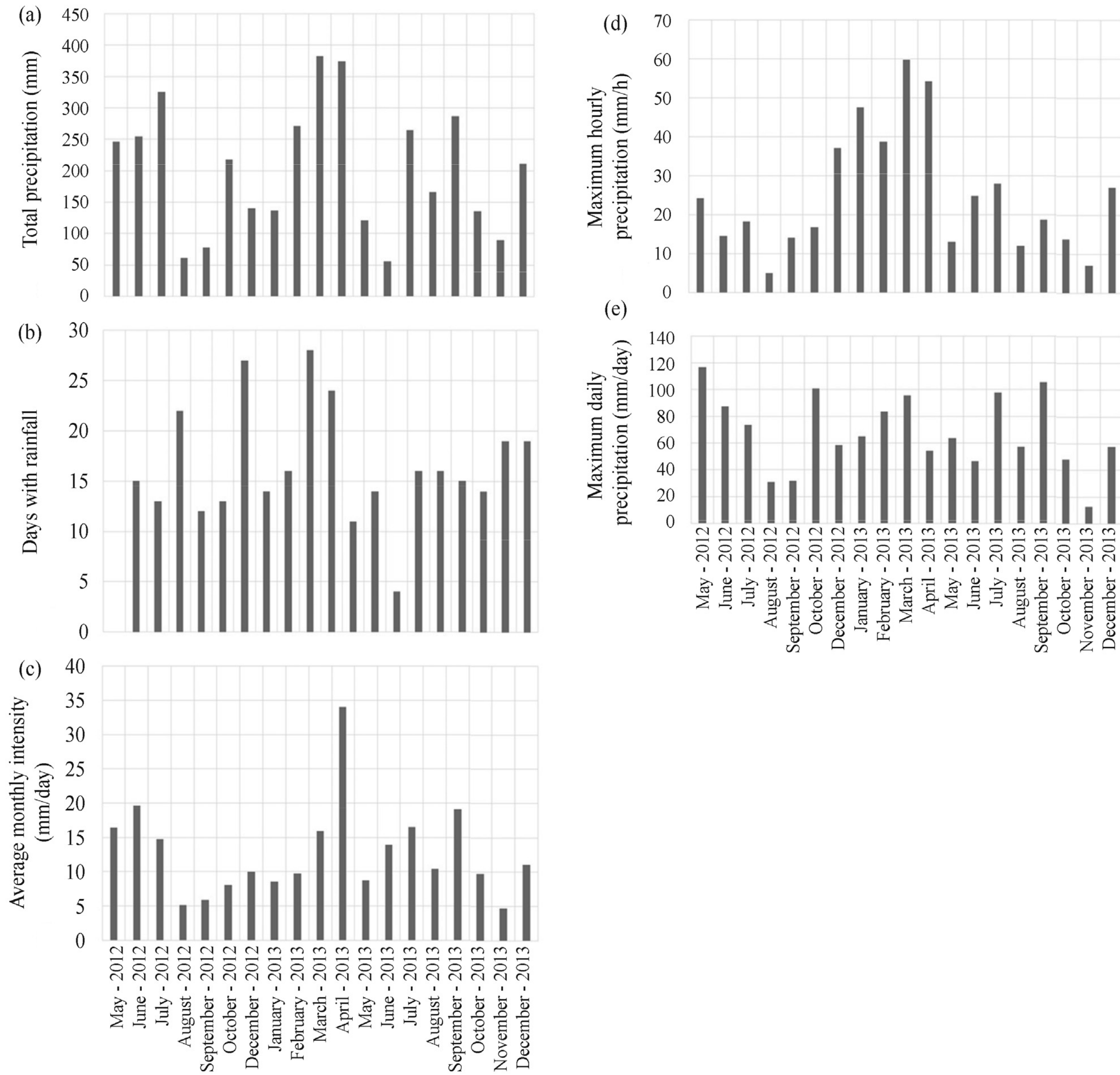

Figure 6 - Rainfall events during the monitoring period - (a) Total precipitation, (b) Days with rainfall, (c) Average monthly intensity (mm/day), (d) Maximum hourly precipitation (mm/h) and (e) Average monthly intensity (mm/day).

Table 3 - Precipitation according to seasons.

Number	Period	Precipitation (mm)		
		Daily maximum	Mean	Total
1	Autumn - 2012	116.75	8.69	451.75
2	Winter - 2012	73.75	5.35	502.50
3	Spring - 2012	100.75	3.56	317.00
4	Summer - 2012	95.75	9.14	822.75
5	Autumn - 2013	194.00	6.19	569.75
6	Winter - 2013	105.50	7.54	708.50
7	Spring - 2013	57.75	4.54	408.25

monitoring in areas of specific interest. However, the importance of continued monitoring is emphasized which is essential for a better interpretation as well as for developing reading forecasts and alert criteria.

4.2. Changes in pore pressure

The six vibrating wire piezometer installed aimed to monitor the water table, but they were also capable of measuring negative pore water pressure. According to Geokon (2014b, 2014c) those sensors can record pore water pressure between - 100 kPa and 350 kPa In Fig. 7a, the one-day accumulated rainfall with time is presented. Figure 7b presents the data from piezometers 04, 05 and 06 with time and Fig. 7c presents the results from piezometers 01, 02 and 03 with the daily accumulated precipitation. All of them are associated to the period of monitoring between May 2012 and December 2013. It seems that there is a correspondence between the piezometer readings and the rainfall, particularly for the piezometers with positive readings.

The most significant changes were observed at events with precipitations in excess of 20 mm. A clear correspondence is observed at the beginning of the Winter of 2012, beginning of Autumm of 2013 and the same occurred at the beginning of the Winter and Spring of 2013. The data from three-day accumulated rainfall shown in Fig. 6a show a clear trend.

Note that both absolute values and the maximum variations obtained so far (about 11 kPa) are consistent with the local stratigraphy, which is characterized by the occurrence of layers with irregular thicknesses of colluvial and

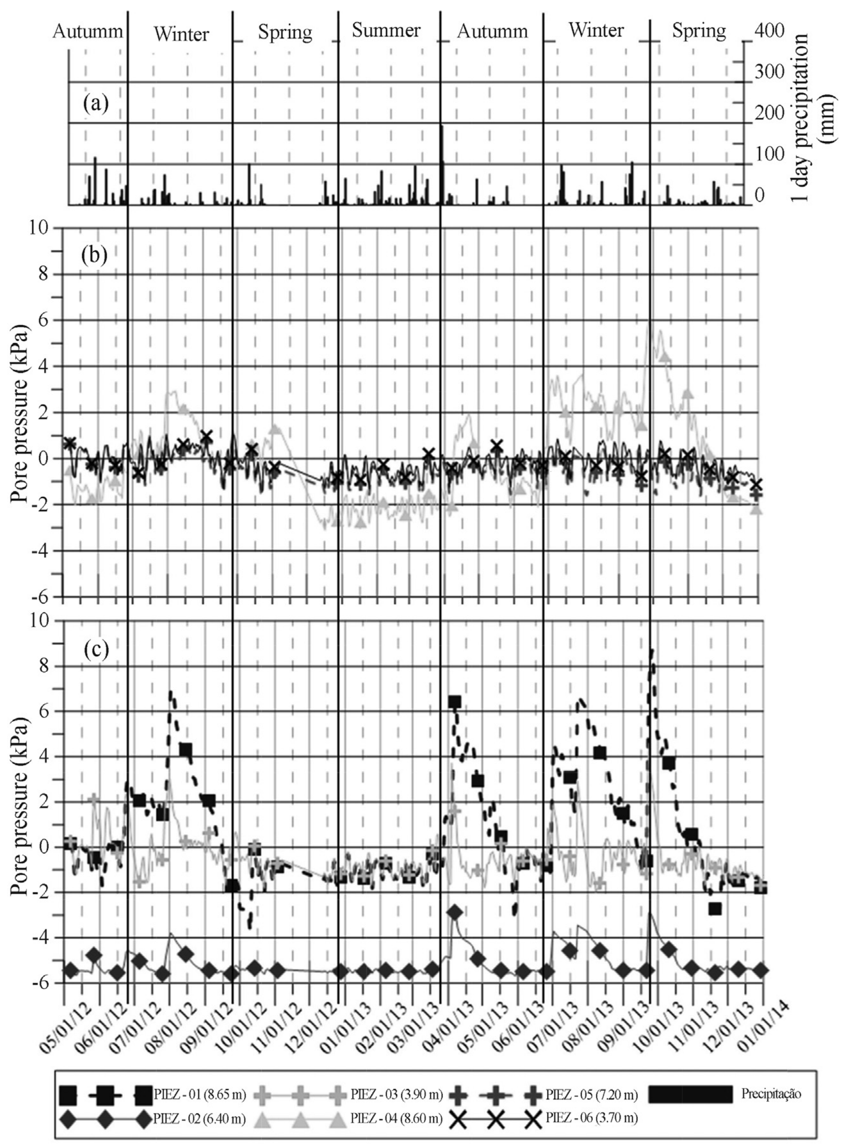

Figure 7 - Comparison between rainfall and pore pressure variation - PZE-01 to PZE-06.

residual soils. In addition, the occurrence of the families of fractures mentioned previously, responsible for the secondary order permeability of the slope, may act to control the ground water table. Figure 8 presents the maximum variations according to the depth of the piezometer and related to the season. Based on these analyses, it is possible to identify larger variations for deeper sensors (8.60 and 8.65 m), mainly during the Winters of 2012 and 2013. Some piezometers seem to be always above the ground water table.

The lack of coherence observed between rainfall events and pore pressure changes in the group of sensors 1 and 2 may be justified by the data presented in Fig. 9. The ground water level can be seen to be below the piezometers elevations for most of the time.

4.3. Suction variations

Readings obtained with the eight installed tensiometers are shown in Figs. 10 to 12, according to the instrumentation groups of sensors shown in Fig. 3. The results are shown with the daily precipitation data obtained from the rain gauge. The response of the tensiometers to the rainfall did not show the same behavior observed for the piezometers measuring the ground water table. This was clearly true for piezometers installed below the ground water table which showed an increase in level immediately after a daily rain fall higher than about 60 mm.

Although the response of the tensiometers was not directly related to the rainfall in the monitoring area, a systematic delay for the response can be observed both in terms of suction increases and reductions. One of the factors for the time delay for the response may be associated to the vegetation, as mentioned by Sestrem & Kormann (2013). Figure 13 presents two photos, one taken at the beginning of the monitoring (Fig. 13a) and the other four months later (Fig. 13a). It can be observed that the growth of vegetation in the area may contribute not only to the evaporation increase but also to a delay in the rainfall infiltration rate. Attention should be called to the difference in behavior observed for the tensiometers installed at group 3. The level of suction was most of the time below 10 kPa. It

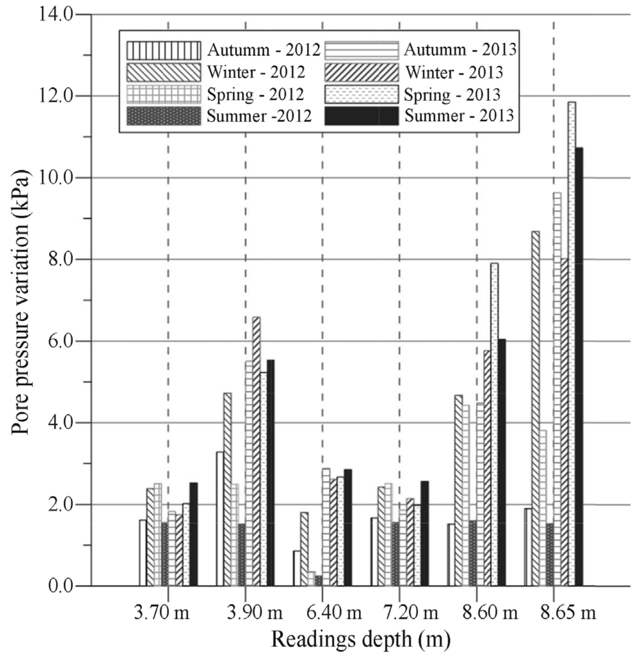

Figure 8 - Maximum pore pressure variations according seasons - data grouped by sensor.

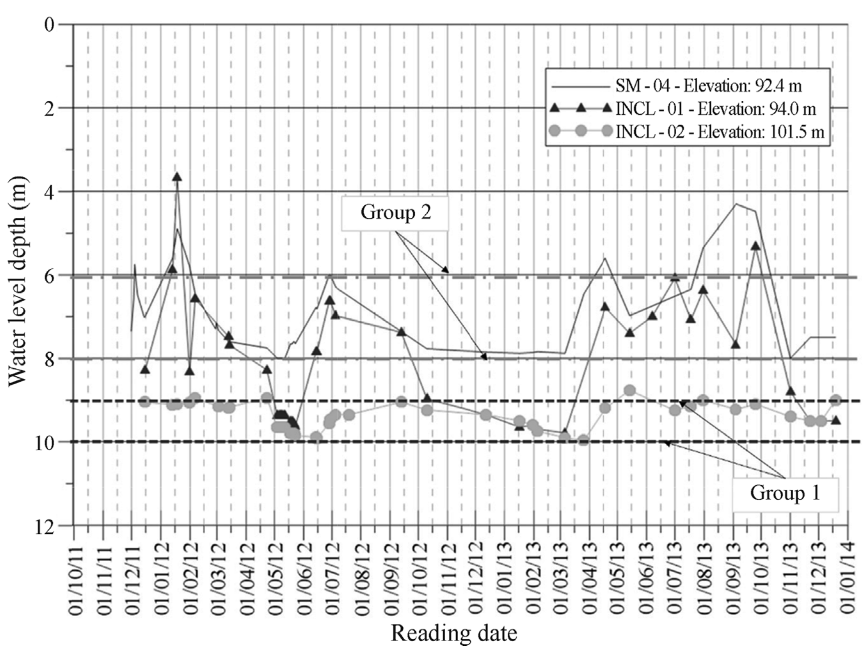

Figure 9 - Variation of water level.

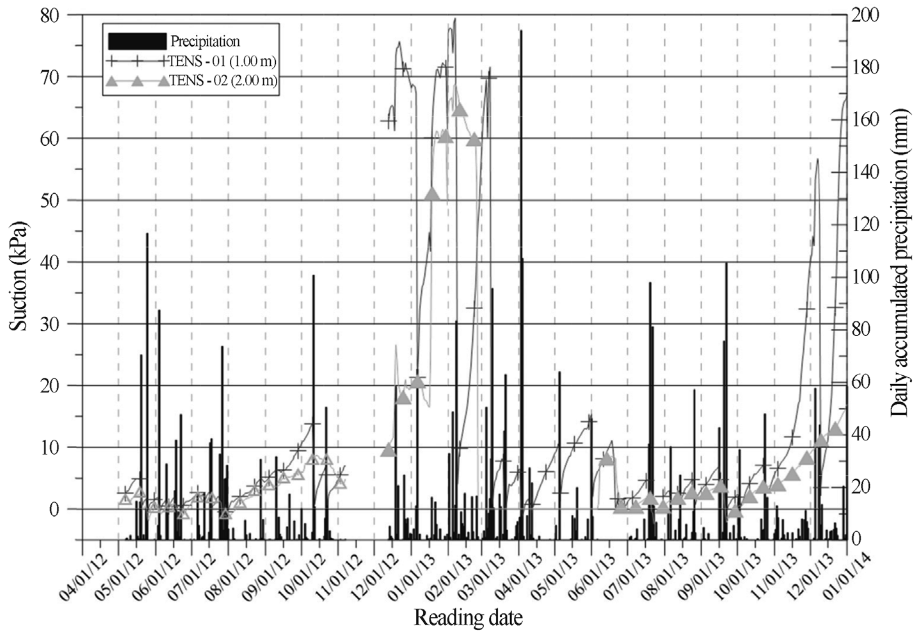

Figure 10 - Comparison between precipitation and suction variation - TENS-01 and TENS-02 (Group 1).

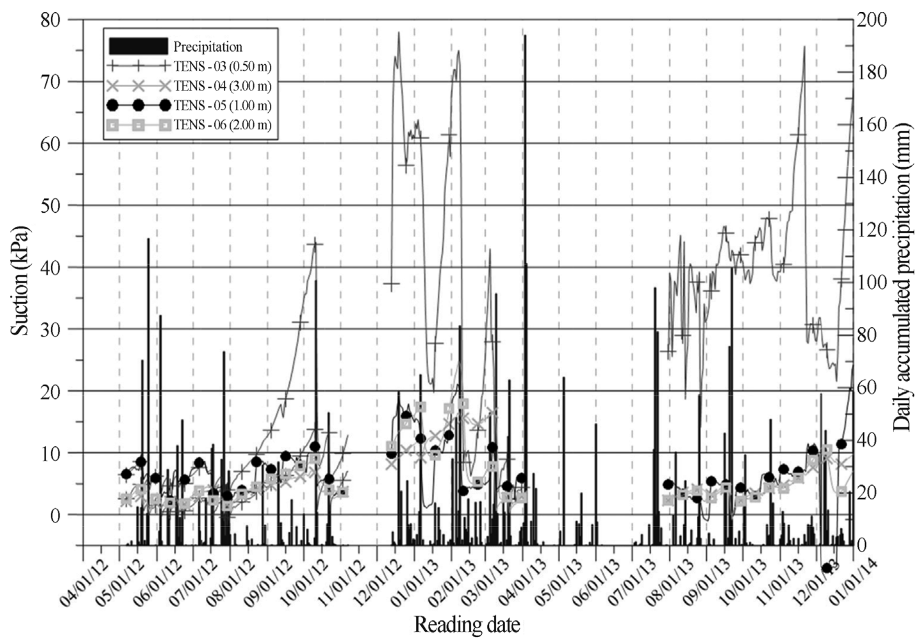

Figure 11 - Comparison between precipitation and suction variation - TENS-03 and TENS-06 (Group 2).

must be observed that the only difference between group 3 location and the others is the vegetation, which may affect superficial drainage.

In order to have a more comprehensive picture of the behavior of the suction with depth, the data were gathered by group and by months, giving the suction profile for each month. The results suggested a behavior that could be divided according to the season.

Figure 14 compares the seasonal variations of measured suction by group 2 in Spring and Winter in 2012. It should be noted the difference between these two periods. In Spring 2012, the magnitude of suction was higher, which could be associated with the low accumulated monthly precipitation in this period (317 mm). On the other hand, in Winter 2012, when the accumulated monthly precipitation was 502.5 mm (58% higher), the suction levels in the upper layers remained below 30 kPa. Based on the minimum and maximum groundwater level presented in Fig. 9, two additional lines were drawn in Fig. 14. It can be seen that the suction levels vary within the equilibrium range.

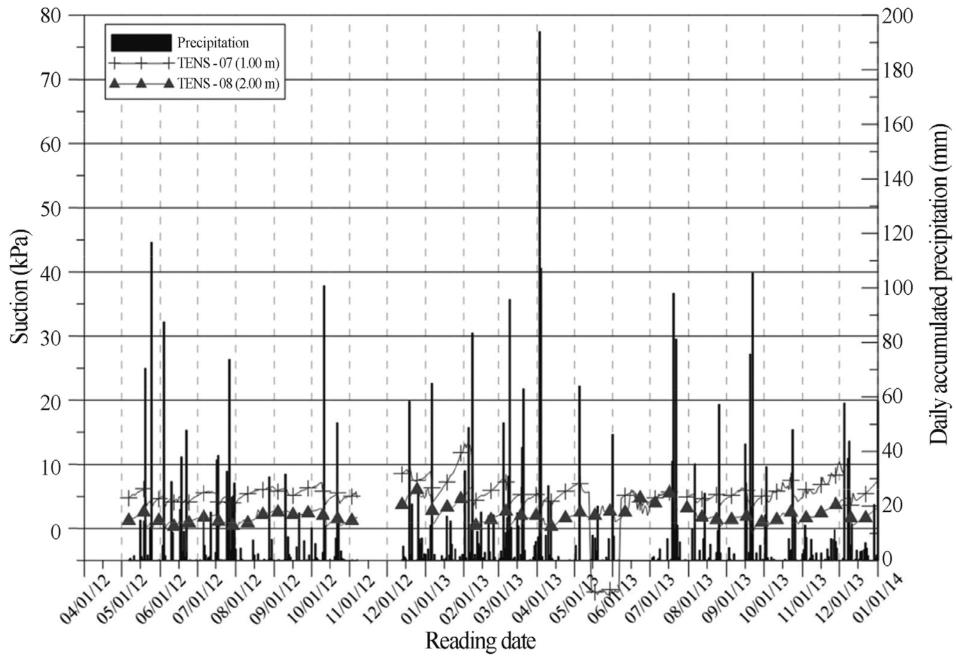

Figure 12 - Comparison between precipitation and suction variation - TENS-07 and TENS-08 (Group 3).

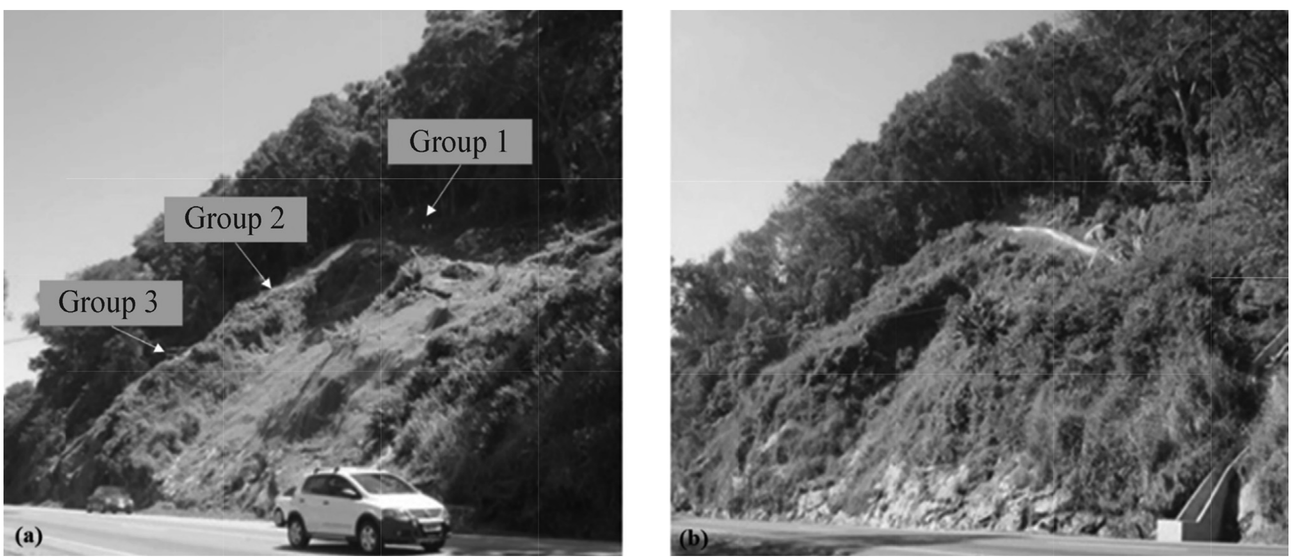

Figure 13 - Vegetation on the site the instruments were installed: (a) at the start of monitoring (b) after four-month monitoring.

Figure 15 shows the variation in the measured suction by sensors of group 2 throughout the study period. Based on these results, it appears that between 1 and 4 m suction level remains below 30 kPa. The most superficial sensor (TENS-03 at 0.5 m) reaches suction levels of about 80 kPa. These changes still seem to lie within the range of equilibrium.

Considering the lack of direct correlation between the rainfall and the suction change, it was investigated whether the accumulated rainfall for 3, 5 and 7 days could be used to justify the changes in suction. It was verified that the better correlation was associated to the three-day accumulated rainfall. The comparison between suction variation and the accumulated rainfall in three days are shown in Fig. 16 (a) and (b). Events above 150 mm of precipitation in 3 days are observed to keep the suction levels below 10 kPa. Furthermore, it is possible to conclude that the suction level is maintained above 20 kPa when 3-day accumulated precipitation is less than approximately 100 mm.

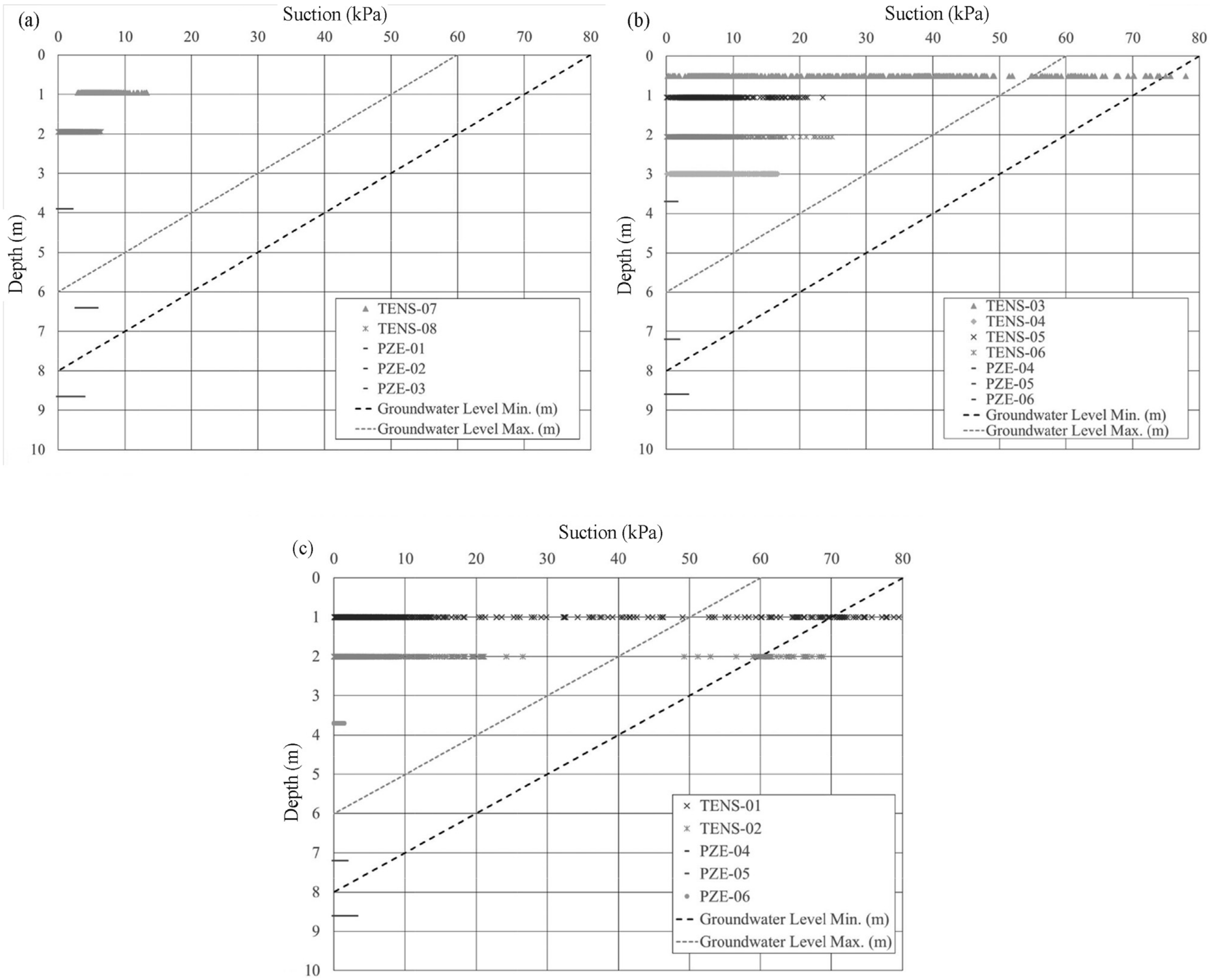

Figure 14 - Seasonal variations of measured suction by group - (a) Group 1, (b) Group 2 and (c) Group 3.

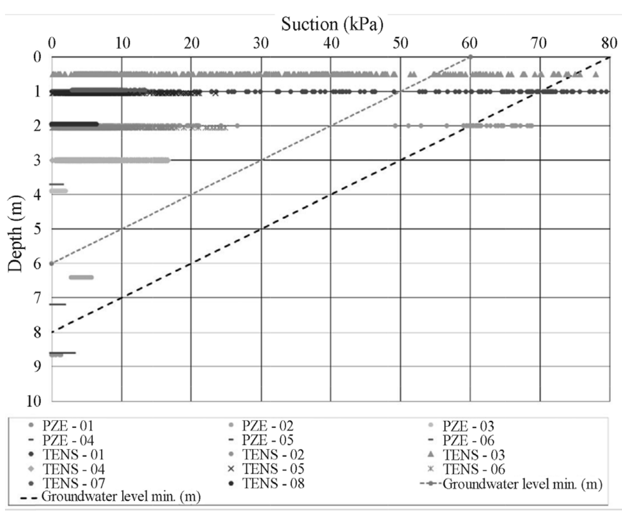

Figure 15 - Measured variations of suction by group 2 all over the monitored period.

Figure 17 presents the three-day accumulated rainfall according to time. Most 3-day rainfall events are lower than 100 mm which is important information regarding eventual reduction in the slope safety factor.

5. Conclusions

The instrumentation used for this study provided important information regarding the presence of water along nearly two years on a slope in a tropical area of the South part of the Serra do Mar in Brazil. The use of tensiometers and rain gauges associated with piezometers allowed better understanding the water movement along the soil profile during the study period. The following conclusions can be drawn from the present study:

The analyses of the rain distribution along the monitoring period could not be directly related to pore water pressure changes.

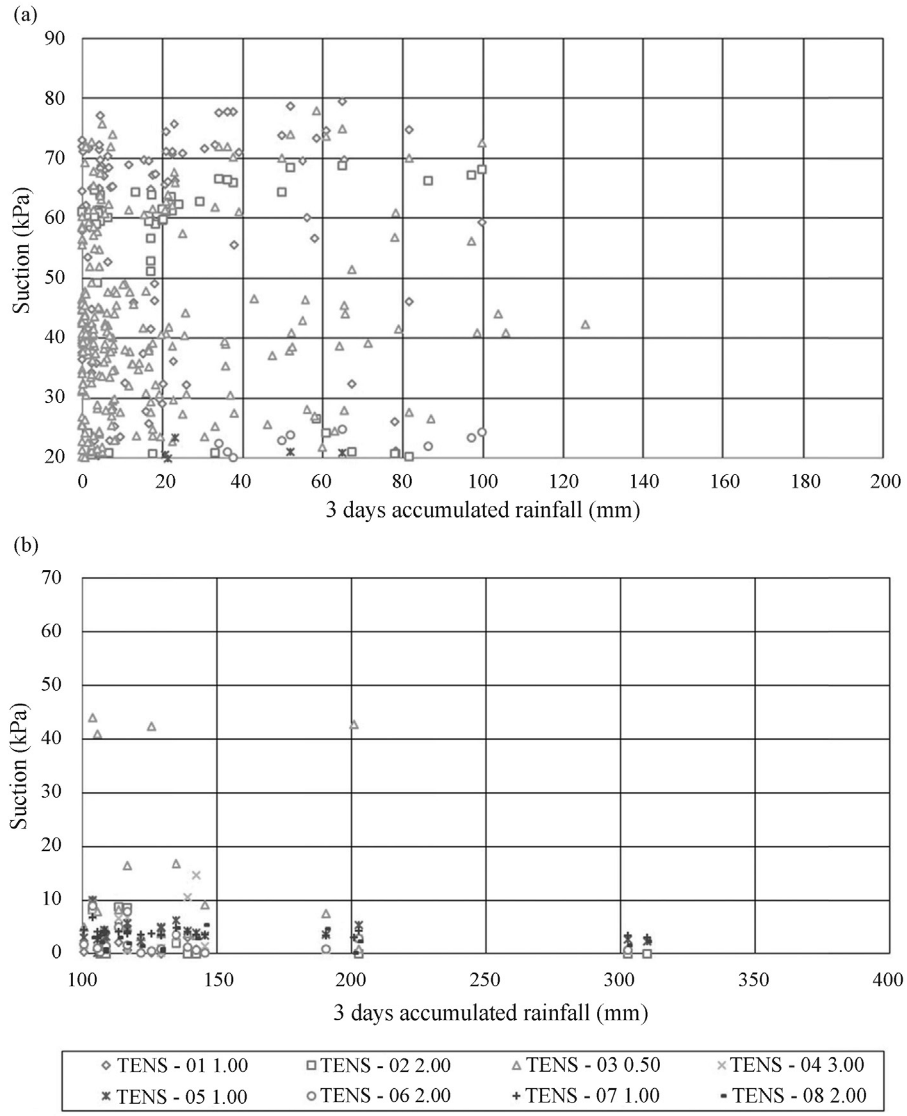

Figure 16 - Comparison between measured value of suction and 3-day accumulated precipitation.

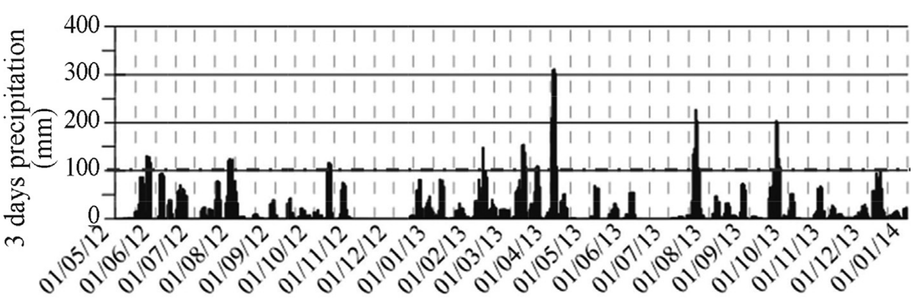

Figure 17 - Three days accumulated rainfall events.

A time delay was observed between the rainfall events. The three-day accumulated precipitation presented an interesting relation to pore water pressure variation.

When the three-day accumulated precipitation was higher than 100 mm, an important reduction in suction was observed along the soil profile.

In general, the suction level is maintained above 20 kPa when the three-day accumulated precipitation is less than approximately 100 mm.

The evaluation of the suction profile showed that only in very few occasions was the suction higher than the equilibrium value inferred from the ground water table level.

The suction profile during the monitoring period suggested that the region near the instrumentation group 1 presented the lower value of suction. The suction level was generally lower in the region where the vegetation is composed by grass. In areas with dense vegetation, higher suction levels were observed.

Continued monitoring and analysis is of utmost importance for deepening the understanding of the meteorological, geological and geotechnical factors which control the slope behavior.

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