Soils and Rocks
An International Journal of Geotechnical and Geoenvironmental Engineering
www.soilsandrocks.com
ISSN 1980-9743
ISSN-e 2675-5475

Analysis of field monitoring of precipitation and pore pressure over seven years at Morro do Boi of Serra do Mar/Brazil

Giancarlo Domingues[1#], Vítor Pereira Faro[1], Elisangela Aparecida Mazzutti[1]

Article

Keywords
Field monitoring
Pore water pressure
Stability of slopes
Geotechnical analysis

Abstract

The stability of slopes or the occurrence of mass movements is directly related to the incidence of rainfall. In this work a qualitative analysis of the historical series was made for the period between May 2012 and February 2019, where the development of pore pressures was evaluated, analyzing the behaviors of the instruments, correlating their readings with precipitation and with variations in the water table. Pore pressure was measured using vibrating wire piezometers, and precipitation data was collected using pluviometers with tipper buckets, whose readings were obtained by a datalogger model ML1-FL. From the data collected, it was possible to estimate the duration of a rainfall event for the soil, as that time interval between the occurrence of rain and the dissipation of excess pore pressure. These intervals are between 3 and 26 days in duration. The main results were: the period between the end of June and August is the driest and the highest precipitation occurs from December to early June; Precipitation of up to 100 mm of daily accumulation is well distributed throughout the year and occurs in all seasons. The pore pressure values developed were low, with a maximum of 9.3 kPa for the deepest piezometer on elevation 92.40 m. There is a delay between the occurrence of precipitation and the recording of the peak pore pressure. The in-depth knowledge of variations in precipitation and pore pressure can support the development of more robust geotechnical engineering projects. This preventive approach, based on concrete data and correlations, offers a more reliable strategy for mitigating the risks associated with landslides, directly contributing to the safety and continuous operation of the BR-101/SC highway.

1. Introduction

Serra do Mar Mountain Range is one of the most prominent orographic features of the south and southeast coast of the country. It measures 1500 km in length and is the site of the highest number of landslides in Brazil (Listo et al. 2021). In the period between 1991 and 2012, there were several mass movements along the BR-101 highway, in Serra do Mar. One of these movements was the landslide at km 140+700 m, in Morro do Boi, which interrupted the traffic, causing damage to society (Pretto, 2014a). This occurrence motivated the implementation of a containment system and an instrumentation plan in 2012 that served as the basis for the research project to which this work is linked.

This slope has already been the subject of some research. Sestrem et al. (2015) analyzed changes in groundwater levels and their relationship with rainfall in sixteen months of monitoring, Lazarim (2012) conducted a geotechnical characterization of the colluvial layer, González et al. (2017) evaluated the first 10 months of results and gave statistical treatment, Pretto (2014a) obtained permeability parameters and water retention curves in the soil and Joly (2018) evaluated the depth of the wetting front.

Santos (2014) reports 94 occurrences of landslides in 2008 and 31 in 2011 along the BR-101. Only in the area that is the object of this study, 14 occurrences of landslides were recorded between January 2015 and December 2018 related to rainfall events (Salah et al., 2019).

Therefore, the contribution and objective of this article was the general evaluation of the behavior of Morro do Boi in relation to precipitation and the development of pore pressures. Data from 7 years of monitoring were analyzed, estimating the duration of a pluviometric event for the soil, and establishing correlations between precipitation and pore pressure variations, in order to better understand the mechanisms that promote slope instability and provide more technical information to engineers working on site trying to avoid catastrophes.

2. Materials and methods

The Serra do Mar region in Brazil experiences a high frequency of landslides. This study investigates the impact

#Corresponding author. E-mail address: enggian@yahoo.com.br
[1]Universidade Federal do Paraná, Departamento de Engenharia Civil, Curitiba, PR, Brasil.
Submitted on December 9, 2023; Final Acceptance on August 8, 2024; Discussion open until February 28, 2025.
https://doi.org/10.28927/SR.2024.011823

of rainfall on pore pressure development, analyzing data collected from May 2012 to February 2019, using Excel software. Although the analysis of time series is defined as a technique for observing trends, seasonality, and predicting values of historical series, in this work a qualitative analysis of trends and seasonality was performed with no aim of predicting future values.

Pore pressure was measured using vibrating wire piezometers (Geokon sensor model 4500S), and precipitation data was collected using pluviometers with tipper buckets was model TB4/0.2 from Hydrological Services, whose readings are obtained by a datalogger model ML1-FL. Detailed calibration and data collection procedures are described. Readings from both types of instruments were collected automatically.

The vibrating wire 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, one uphill of the stabilized area (cluster 1 with elevation 102.5 m), which includes piezometers 04, 05, and 06, and the other inside it (cluster 2 with elevation 92.40 m), which includes piezometers 01, 02 and 03. This use enabled a comparative analysis between both places (Sestrem et al., 2015). It is also noteworthy that piezometers have an accuracy of 0.35 kPa (Sestrem, 2012).

A pluviometer of the tipping bucket type was set up on cluster 2 to monitor rainfall, capable of recording events for every 0.25 mm of precipitation. The recorded data was stored in a data logger with a maximum reading capacity of 700 mm/h, and it also had the capability to record the date and time of each event (Hydrological Services, 2014a, b).

The monitoring of all sensors commenced in May 2012 through an automated data logger (Geokon, 2014), with initially configured time intervals of 8 hours. However, between 11/08/2012 and 12/12/2012, data collection was hindered due to technical issues.

2.1 Description of the place

The study site was a slope on the banks of the BR-101 on the south lane at km 140+700 m, with latitude of -27.0494 and longitude of -48.6122, having already been the subject of detailed descriptions by several authors (Sestrem et al., 2015; González, 2013; Pretto et al., 2014b), being a natural slope, belonging to the Serra do Mar, in the State of Santa Catarina/Brazil.

The Morro do Boi area features two main types of rock: the intrusive Nova Trento granites and Morro do Boi migmatites. These lithologies are lightly fractured and maintain relatively high strength when not exposed to significant climatic variations. The region is influenced by NE-SW and NW-SE shear surfaces and sub-horizontal fractures that segment the rock mass into blocks, significantly weakening the mechanical stability of the slope. Additionally, the presence of colluvial/talus soils creates a highly heterogeneous structure with a high degree of weathering and very low cohesion (Fiori, 2011). A detail is presented in Figure 1.

Additional characterization and laboratory tests on shear strength were conducted by Lazarim (2012). The findings revealed an average grain density of 2.66 g/cm^3, with an average liquid limit of 32% and an average plastic limit of 27%, indicating materials with low plasticity and compressibility. The particle size distribution demonstrated that the soils were predominantly sandy (60.4%), with 27.0% silt, 8.3% gravel, and only 4.3% clay. Direct shear tests on four different block samples yielded effective friction angles ranging from 28° to 39° and cohesion intercepts between

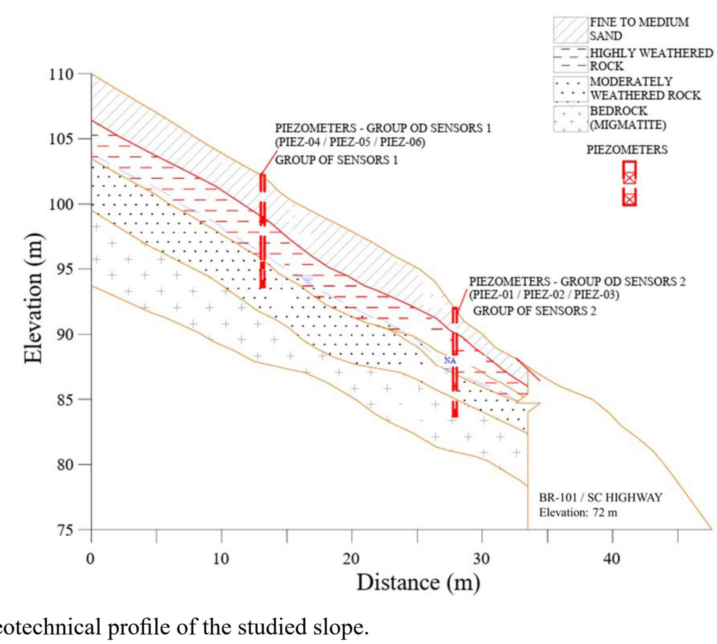

Figure 1. Geological and geotechnical profile of the studied slope.

1 and 17 kPa. The samples were collected at depths ranging from 0.25 to 1.27 m, with water content between 3% and 10% and saturation levels between 2% and 8%.

2.2 Precipitation

In the precipitation analysis, a characterization of the rains was made according to their daily accumulation, and statistical treatment was given for a better understanding of the rains in the analyzed period. The lack of data was observed, and a linear correlation was made with three nearby stations to evaluate the possibility of filling them.

A correlation was made between the data from Morro do Boi and from each of the stations for the period with equivalent dates through simple linear regression. The station was chosen according to the existence of the data and the correlation obtained with the data from Morro do Boi. Preferably, data from station C-2927 - Laranjeiras was used, and in the absence of records at this station, C-2385 - Tijucas was used, and in the absence of data from this station, C-2033 - Rio Canoas with the respective linear correlations 0.83, 0.68 and 0.65.

The data were completed preferring the station with the best linear correlation. Analysis of monthly averages was carried out to identify the seasonality of rainfall and analysis of their distribution by daily accumulated, in addition to the distribution according to the CIRAM classification (2016 apud González et al., 2017).

2.3 Pore pressure

Pore pressure readings were taken using piezometers. As with precipitation data, there was no data in certain periods for positive pore pressure as well. Where there was no data from all instruments, these data were ignored, and when there was only one instrument, data was filled in through simple linear regression with data from the instrument with the highest linear correlation.

2.3.1 Analysis of the relationship between water level variation (WL) and pore pressure readings

For comparison between piezometer readings and manual WL readings, both were transformed into total potential values. To obtain measured potential values, or measured elevation (ME), in piezometers, add the instrument elevation value (IE) to the ratio between the measured pore pressure value (PP) and the unit weight of water (γ_w). The instrument elevation (IE) is the subtraction of the piezometer depth (PD) from the elevation of the terrain where the instrument is positioned (TE). Urciuoli et al. (2016) use a similar approach but adopt measured depth rather than total potential. Table 1 shows the elevation values of the instruments and water level reading wells and Figure 2 shows a scheme of the adopted methodology.

2.3.2 Linear correlation between pore pressure readings and precipitation records

A linear correlation analysis was performed between the values of precipitation and pore pressure, where daily accumulated values of 1, 2, 3, 5, 7, 10, 15, 21, 30, and 45 days and delays in readings of 2, 3, 4, 5 and 7 days. The data were organized in such a way that accumulated precipitation could be obtained in the periods analyzed and delays in the readings could be imposed as suggested by Buzzi (2007).

Table 1. Elevation of instruments.

	PZE-01	PZE-02	PZE-03	MP-04	PZE-04	PZE-05	PZE-06
PD (m)	8.65	6.40	3.90	-	8.60	7.20	3.70
TE (m)	92.40	92.40	92.40	92.40	102.50	102.50	102.50
IE (m)	83.75	86.00	88.50	-	92.90	94.30	97.80

PD: piezometer depth; TE: elevation of the terrain; IE: instrument elevation.

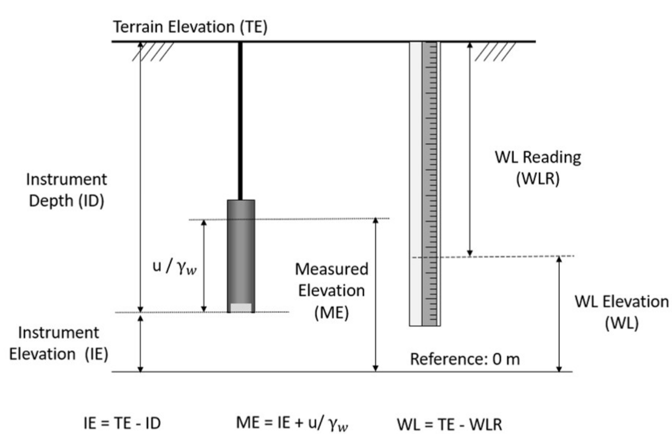

Figure 2. Scheme for transforming WL and pore pressure readings into elevation values in meters or total potentials.

2.3.3 Qualitative analysis of pore pressure increases

Time intervals were analyzed where the dates of the highest daily precipitation records and the date of the highest pore pressure records were chosen. These dates were called "events". The analysis interval was defined as the one where it is possible to observe a significant variation in pore pressure values, starting from zero or a minimum value to a peak and returning to the initial value, which would represent the duration of a pluviometric event. Table 2 presents the chosen events. Event 3 represents the date with the highest pore pressure record and the others represent events with daily rainfall above 100 mm. Events 7 and 8 were divided into 7 and 7A and 8 and 8A due to the low variation in the reading of some instruments in the main event.

The time to reach peak PP in the interval was obtained by comparing the date of the event with the date of the highest pore pressure (PP) record. The increase in pore pressure generated after the event was obtained by comparing the PP reading on the day before the event with the peak reading of the interval.

To estimate the time needed to dissipate the increase in pore pressure, the best reduction trend was analyzed after reaching the PP peak in the period. For this purpose, the first trend after the peak was chosen, and this same trend was extended until its projection reached the PP level of the day before the event. This criterion was adopted, as there is a clear change in the tendency and speed of dissipation, which was possibly caused by later rains. Therefore, in order to disregard the possible effect of these later rains, the second dissipation trend was disregarded. The crossing between dissipation trends and the PP level on the previous day can occur between two dates. Therefore, it was adopted as a criterion, to choose the closest date, and in doubt, the smallest date.

3. Analysis and results

3.1 Precipitation

Figure 3 presents precipitation data summarized in monthly terms. Despite the variation over the years, it is

Table 2. Range of events chosen for qualitative analysis.

Event	Date of the event	Precipitation in the Day (mm)	Analyzed ranges	
			Start	End
1	04/03/2013	155.20	03/23/2013	05/09/2013
2	01/11/2014	121.40	12/27/2013	02/16/2014
3	11/04/2015	96.00	08/29/2015	12/06/2015
4	03/25/2016	238.60	03/20/2016	05/02/2016
5	04/13/2016	189.20	03/20/2016	05/02/2016
6	10/25/2016	123.00	10/20/2016	11/13/2016
7	05/31/2017	119.80	05/18/2017	07/02/2017
7A	06/05/2017	67.40	05/18/2017	07/02/2017
8	01/10/2018	106.20	01/04/2018	02/12/2018
8A	01/15/2018	18.20	01/04/2018	02/12/2018

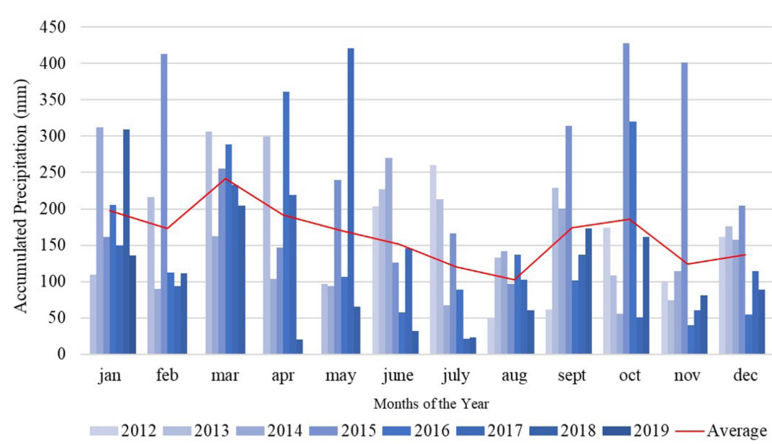

Figure 3. Monthly rains.

possible to observe that the rainiest periods are from January to April and between September and October. The rainiest season is summer (end of December to end of March) and the least rainy is winter (end of June to end of September), but with small differences in relation to the other seasons, making the region with frequent rain all year round.

It was found that the highest number of rainfall occurrences was recorded in the summer (end of December to end of March), and the highest daily accumulated records occurred in the spring (end of September to end of December). It is noteworthy that the analysis without filled data showed rainfall distribution in 27% spring, 30% summer, 23% fall, and 20% winter. Also, the accumulated in mm/day was 47% of 0 mm, 17% between 0 and 1 mm, 21% between 1 and 10 mm, 9% between 10 and 25 mm, 4% between 25 and 50 mm, 2% of 50 and 100 mm, 0% above 200 mm. It is observed that about 84% of the rainfall events had daily accumulations of less than 10 mm.

The analysis with the filled-in data showed rainfall distribution in 25% spring, 28% summer, 25% fall, and 22% winter. Also, the accumulated in mm/day was 43% of 0 mm, 17% between 0 and 1 mm, 25% between 1 and 10 mm, 9% between 10 and 25 mm, 4% between 25 and 50 mm, 2% of 50 and 100 mm, 0% above 200 mm. With the data filled in, a reduction of 4 percentage points is observed in the proportion of days without rain. This happens because there is a linear coefficient in the regression equation and, therefore, even on days without rain in the correlated stations, the regression will indicate a value greater than zero to fill in the data. But, in general, no significant change in the distribution of rainfall is observed with filling in the missing data. Following the CIRAM classification (2016 apud González et al., 2017), the analyzed period can be divided as shown in Table 3.

3.2 Positive pore pressure

Evaluating the pore pressure values measured through the 6 piezometers, it is observed that the magnitude of the readings is small, with maximum values that do not reach 10 kPa and averages close to zero. This observation is consistent with the draining capacity of the geotechnical profile, whether due to the type of soil and its permeability or the presence of fractures in the layers of rock alteration, as observed in Domingues (2020). Table 4 presents the maximum, minimum, mean, and standard deviation values for the values measured in the 6 piezometers.

Figures 4 and 5 show the frequency diagrams for pore pressure and daily precipitation values, with the piezometers grouped by instrumentation cluster. Salah et al. (2019) identify the dates of occurrences of landslides in the Morro do Boi area between January 2015 and December 2018. These dates are identified on the charts. But, despite the low magnitude recorded, the development of positive pore pressures is observed in all instruments, except for piezometer 2 (PZE-02). The averages of all instruments are close to 0 kPa, except the PZE-02 which is close to -5 kPa.

It is observed that the frequency diagram for the PZE-02, although it has variations consistent with the precipitation and with the other instruments, is at a differentiated pore pressure level, presenting an average of values around -5 kPa. A possible justification would be the possibility of this instrument not being influenced by the elevation of the water level (WL) or the wetting front.

3.2.1 Variation of pore pressure with water level

Figures 6 and 7 show the frequency diagrams of pore pressure values and WL measurements in terms of total potential for clusters 2 and 1, respectively. It is noteworthy that, for Figure 7, the WL of inclinometer 2 from Domingues (2020) was used for the analysis.

On cluster 2, the total potential change according to the WL readings was 5.11 m while the potential change for the piezometers was 1.35 m, 0.35 m, and 0.78 m for the PZE-01, PZE-02, and PZE-03 respectively. It is observed that

Table 3. Classification according to CIRAM (2016 apud González et al., 2017).

Classification	Precipitation Range (mm/day)	Events (days)	Events (%)
Dry Day (DD)	P < 0.2	1055	42.40
Drizzle (D)	0.20 < P < 0.60	284	11.41
Light Rain (LR)	0.60 < P < 3.20	476	19.13
Moderate Rain (MR)	3.20 < P < 13.0	367	14.75
Heavy Rain (HR)	13.0 < P < 45.6	249	10.01
Violent Rain (VR)	P > 45.6	57	2.29

Table 4. Maximum, minimum, average and standard deviation values of positive pore pressure.

u (kPa)	PZE-01 (8.65 m)	PZE-02 (6.40 m)	PZE-03 (3.90 m)	PZE-04 (8.60 m)	PZE-05 (7.20 m)	PZE-06 (3.70 m)
Max	9.30	-2.31	4.64	6.56	3.40	2.30
Min	-3.91	-5.75	-3.05	-4.07	-3.40	-2.27
Average	0.01	-5.07	-0.83	-0.69	-0.92	-0.61
SD	2.21	0.66	0.87	2.12	0.76	0.59

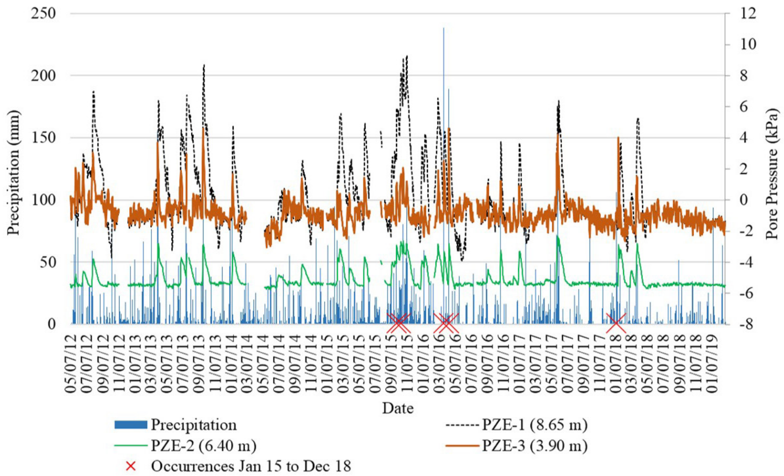

Figure 4. Piezometer frequency diagram for cluster 2.

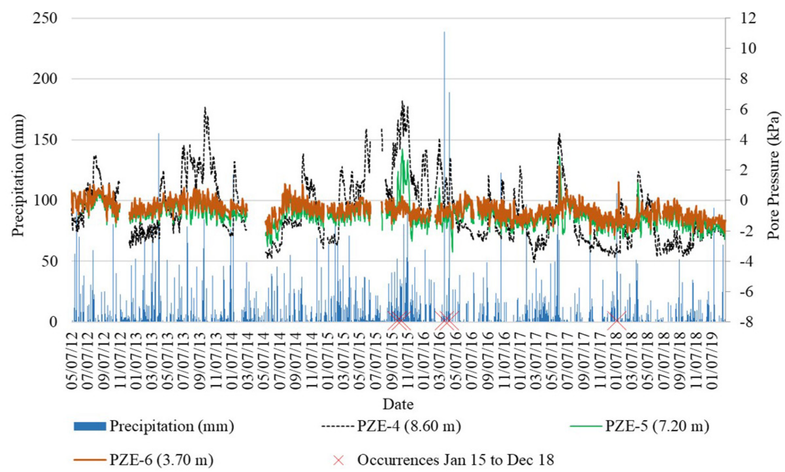

Figure 5. Piezometer frequency diagram for cluster 1.

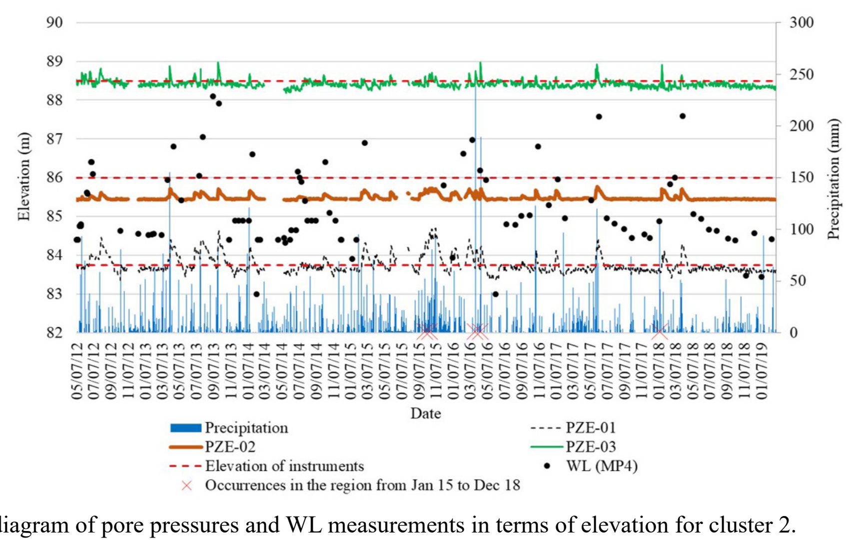

Figure 6. Frequency diagram of pore pressures and WL measurements in terms of elevation for cluster 2.

the WL was above the PZE-01 quota practically the entire period. In relation to the PZE-02, the WL alternates higher quota records than this Instrument with periods with lower quotas. For the PZE-03, WL depth measurements indicate that it was always below the instrument's height.

Based on these observations, it is possible to argue that the PZE-02 may have an error in its readings or that it is positioned on a lens made of less permeable material to the point of imposing this condition of differentiated pore pressure in relation to the other instruments. It can also be seen that this instrument is installed at the interface between a layer of weathered rock and a thin layer of 1.1 m of silty sand with mica and gravel, according to Domingues (2020). It is also observed that there is a relationship between rainfall and variations in the readings in the piezometers and the water level. The potential values of the WL readings and the PZE-01 and PZE-02 piezometers showed good linear correlation (0.72 and 0.70), while the correlation between WL and PZE-03 was lower (0.36).

In cluster 1, whose frequency diagram is shown in Figure 7, there is a smaller variation in the measured potential values in the PZE-05 and PZE-06 instruments. The potential variation measured in the WL readings was 3.7 m while for the piezometer readings, it was 1.08 m, 0.69 m, and 0.47 m for PZE-04, PZE-05, and PZE-06, respectively. The WL records were almost the entire period below the instrument installation quota, except on 3 dates where they exceeded these quotas, indicating that on cluster 1, even the deepest instrument is rarely submerged.

The linear correlation coefficients between the measured potential values in the PZE-04, PZE-05, and PZE-06 piezometers and the WL values were, respectively, 0.65, 0.40, and 0.30. A lower correlation can be seen in relation to cluster 2 and the PZE-04 has a better correlation with WL than the PZE-05 and PZE-06 piezometers.

3.2.2 Correlation of pore pressure values with precipitation

The linear correlation values obtained were relatively low, ranging from 0.10 to 0.61. Table 5 presents the best values obtained from linear correlation combining daily accumulated variations and delays in readings.

For the piezometers on cluster 1 (PZE-04 to PZE-06), the correlation values were higher for 45 days. For the cluster 2 piezometers, the best correlations were for daily accruals

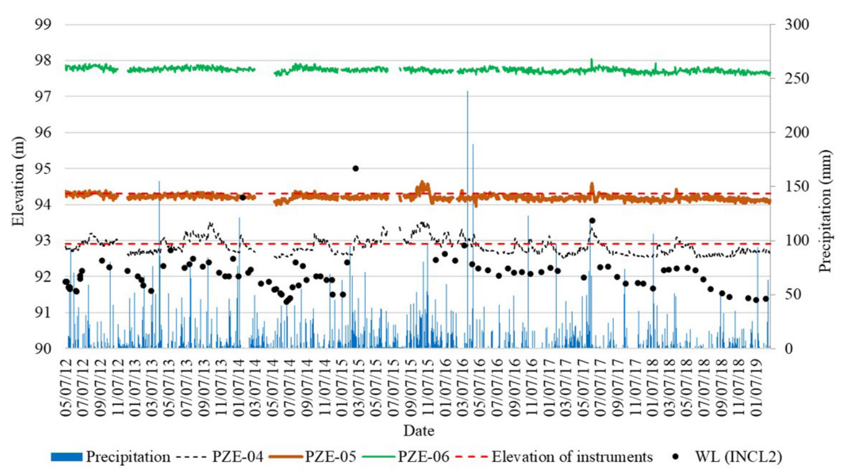

Figure 7. Frequency diagram of pore pressures and WL measurements in terms of elevation for cluster 1.

Table 5. Better correlations obtained between piezometer readings and precipitation.

Instruments		Late			Without delay		Better Correlation with delay
PZE	Depth	Delay (days)	Accumulated (days)	r	Accumulated (days)	r	
1	8.65 m	1	30	0.55	30	0.55	0.64%
2	6.40 m	1	21	0.61	21	0.60	1.61%
3	3.90 m	1	7	0.39	7	0.38	4.46%
4	8.60 m	2	45	0.47	45	0.46	2.34%
5	7.20 m	1	45	0.23	45	0.22	2.09%
6	3.70 m	7	45	0.13	45	0.10	31.23%

Values other than 0 with significance level, alpha = 0.05; r: linear correlation.

of 30, 21, and 7 days for instruments PZE-01, PZE-02, and PZE-03 respectively. By imposing delays on the readings, small improvements were obtained in the values of the linear correlation coefficient. From the point of view of statistical analysis, these values are low and from the point of view of the phenomenon involved, many days of daily accumulation or delay do not seem to make much sense because, depending on the rainfall regime in the region, long periods later or earlier are affected by other events. Therefore, it is assumed that there is a low correlation between the values of the piezometer readings and the precipitation records.

This absence of a good correlation is expected since not all precipitation infiltrates. A part of the rain is intercepted by the vegetation, other drains superficially, another evaporates through the plants (evapotranspiration), and other infiltrates (Urciuoli et al., 2016).

Another factor is that the relationship between infiltration and rainfall is not linear, since it depends on the soil moisture condition prior to the rain, the intensity and duration of rainfall, and the slope (Tsaparas et al., 2003; Rahardjo et al., 2005; Cuomo & Della Sala, 2013). Rahardjo et al. (2004) report a relationship between infiltration and precipitation of 40% to 74%, Rahardjo et al. (2005) found infiltration rates ranging from 40% to 100% of precipitation and Li et al. (2005) suggest a relationship of 59% to 75%, however, this proportion is variable and maybe 100% for small accruals and at the beginning of an event until the runoff starts and the ratio begins to fall. In addition, in sandy soils, the moisture absorption capacity is high when the soil is dry (Ridley et al. 2003), but its permeability in this condition is very low, in the levels of fine soil (Urciuoli et al., 2016). However, it is possible to analyze and identify the relationship between precipitation and the development of pore pressures qualitatively.

3.2.3 Qualitative analysis of the development of pore pressures

Table 6 presents the chosen events, which are the dates with rainfall records greater than 100 mm and the dates with the highest pore pressure record in the series. In addition to the precipitation values for each event (daily record), the highest pore pressure values measured after the event (pore pressure peak) are presented.

It should be noted that some observations on analyses carried out and the results obtained are presented below. Figure 8 represents event 1 on 04/03/2013 for instrumentation cluster 2. In this event, the rain on 04/03/2013 with a daily accumulation of 155.2 mm is followed by rain on the following day with a daily accumulation of 85.80 mm. It is actually the same rain event, as the hourly records indicate that the rain started on 04/03/2013 between 1:01 pm and 2:00 pm and ended on 04/04/2013 between 5:01 am and 6:00 am.

Figure 9 shows event 1 for instrumentation cluster 1, where in addition to the pore pressure magnitudes being smaller than that recorded on cluster 2, the PZE-05 and PZE-06 instruments were practically not influenced by these rains and recorded increases in pore pressure of 0.10 kPa and 0.12 kPa, respectively, values lower than the precision of the instrument. Therefore, for this event, analysis was performed only for PZE-04.

In event 3, on 11/04/2015, with a daily accumulation of 96 mm, there was the highest pore pressure record, which was 9.30 kPa in the PZE-01. Figure 10 shows the frequency diagram for cluster 2. The sequence of increments in the pore pressure values generated by smaller rainfall prior to the event is observed but with short intervals between one and the other. The dates where there are records of landslides in the region from January 2015 to December 2018 are marked, according to Salah et al. (2019).

The days in which landslides were recorded in the region, in this interval, do not coincide with days of greater precipitation or greater pore pressure. The frequency diagram for the same period relative to event 3 for cluster 1 is shown in Figure 11. For the PZE-04 piezometer, the development of pore pressures is similar to that recorded in the PZE-01 on cluster 2, but with a peak of lower pore pressure. It is observed that the PZE-05 is less influenced by the rains of

Table 6. Events chosen for qualitative analysis.

Event	Date	Rain (mm)	Highest pore pressure value of the range (kPa)					
			PZE-01	PZE-02	PZE-03	PZE-04	PZE-05	PZE-06
1	04/03/2013	155.20	6.40	-2.80	3.71	1.05	-0.43	-0.17
2	01/11/2014	121.40	4.81	-3.36	1.70	2.56	-0.55	-0.09
3	11/04/2015	96.00	9.30	-2.79	1.21	6.16	2.66	-0.22
4	03/25/2016	238.60	4.41	-3.31	2.51	1.52	-0.71	-0.45
5	04/13/2016	189.20	4.66	-2.81	4.64	2.81	-0.34	-0.15
6	10/25/2016	123.00	3.75	-3.21	1.24	1.37	-0.28	0.06
7	05/31/2017	119.80	6.03	-2.31	4.22	4.13	0.48	-0.25
7A	06/05/2017	67.40	6.37	-2.49	2.18	4.48	2.90	2.30
8	01/10/2018	106.20	-0.78	-5.33	-0.51	-2.88	-0.88	-0.59
8A	01/15/2018	18.20	2.59	-2.86	4.01	-3.29	-1.24	1.23

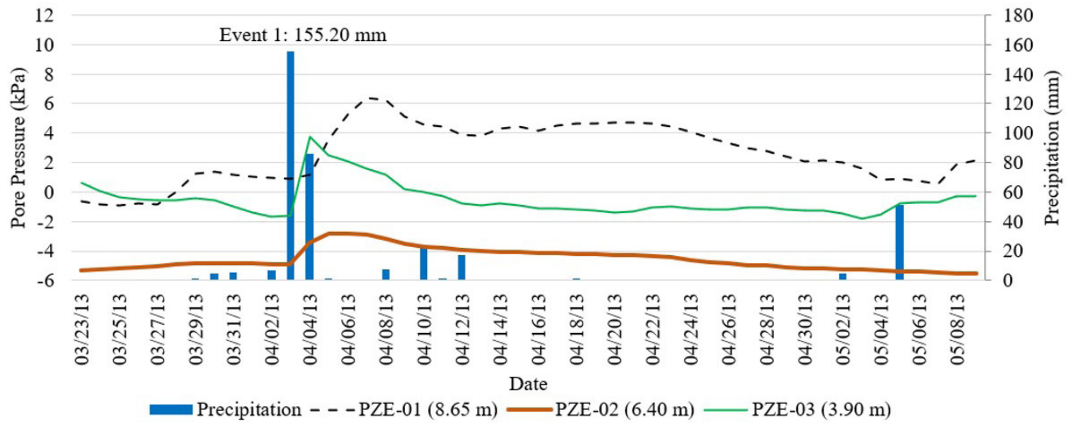

Figure 8. Frequency diagram of pore pressures and precipitation in event 1 on cluster 2 - period from 03/23/2013 to 05/28/2013.

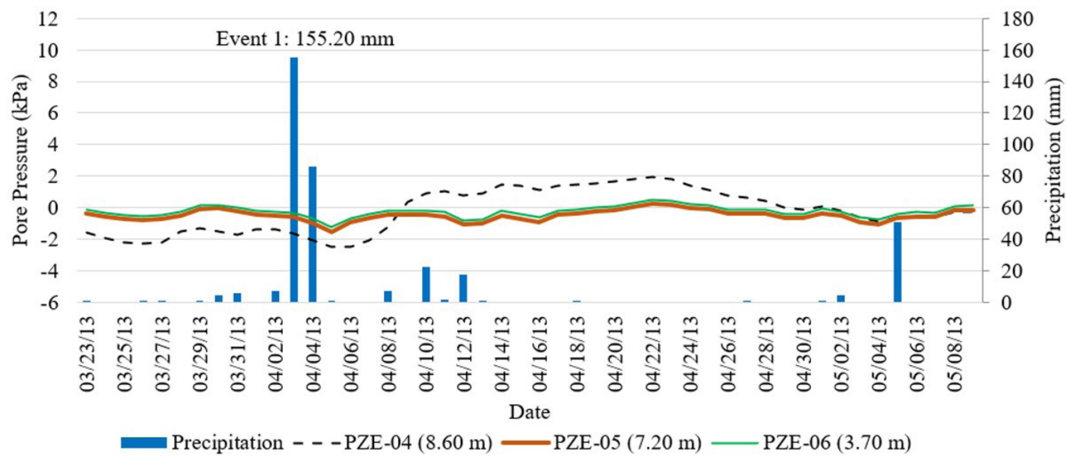

Figure 9. Frequency diagram of pore pressures and precipitation in event 1 on cluster 1 - period from 03/23/2013 to 05/09/2013.

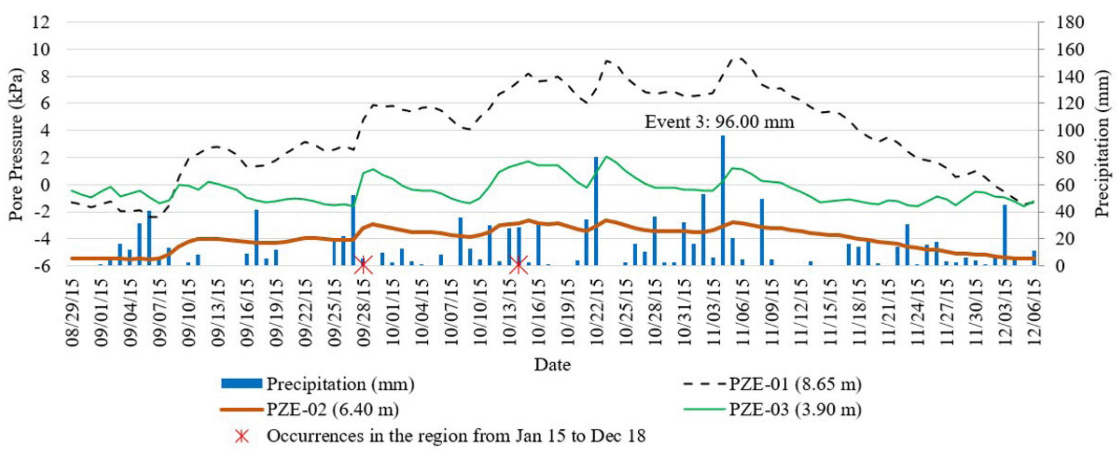

Figure 10. Event 3 frequency diagram on cluster 2.

that period and that the PZE-06 is practically not influenced by these rains. The pore pressure peak of the analyzed period occurred on 08/29/2015, before event 3, on 11/04/2015.

Event 4 on 03/25/2016 and event 5 on 04/13/2016 for cluster 2 are shown in Figure 12. As in the events presented above, there are pore pressure peaks clearly related to the

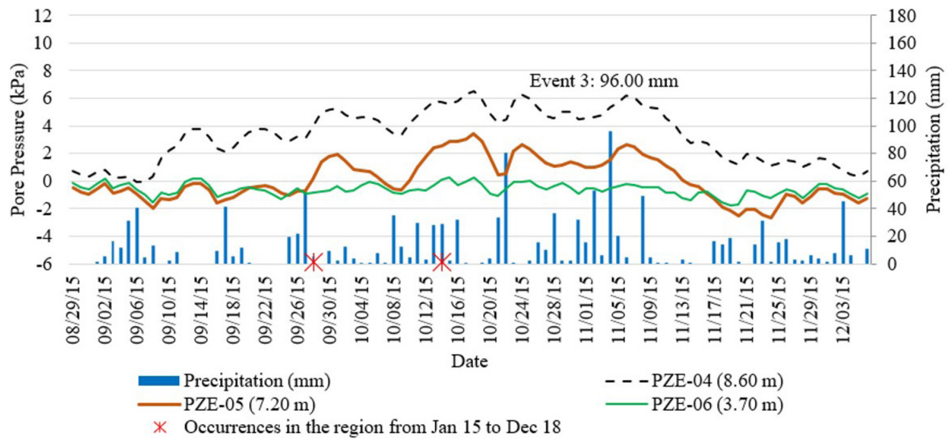

Figure 11. Event 3 frequency diagram on cluster 1.

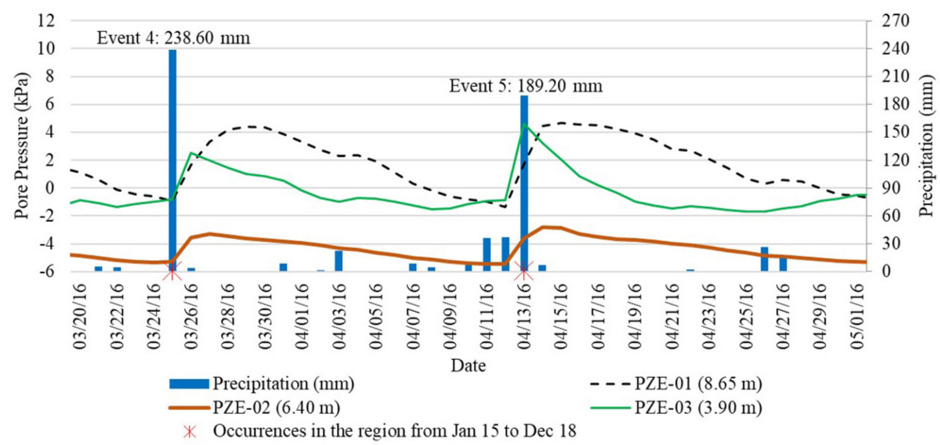

Figure 12. Cluster 2 frequency diagram for events 4 and 5.

events, and trends of fall after the events. On these two dates, there were also records of landslides in the region and they do not coincide with the dates of the pore pressure peaks.

Figure 13 presents the frequency diagram for the period comprising events 4 and 5, referring to the piezometers on cluster 1. It is observed that the magnitudes of the increases and pore pressure peaks are relatively small, even for the two largest records of accumulated daily rainfall throughout the analyzed period.

The pore pressure additions of the PZE-05 and PZE-06 piezometers were 0.29 kPa and 0.26 kPa, which are lower than the precision of the instrument, therefore, they were disregarded for this analysis.

Ferreira et al. (2018) analyzed the rainfall preceding events 4 and 5 and identified that the difference in instrument response between events can be explained by the difference in accumulated rainfall in the previous days. While in event 4 the accumulated for the previous 7 days was 40 mm for event 5 it was 100 mm.

Events 7 and 8 were divided into 7 and 7A and 8 and 8A due to the little influence of events 7 and 8 on the instruments. In event 7 for cluster 2, there was an influence on the instruments, but the later event called event 7A, despite having less precipitation, raised the pore pressure value in PZE-01 beyond the peak generated by event 7. Figure 14 shows the frequency diagram for these events.

For instruments on cluster 1, event 7 generated a pore pressure increase of 1.62 kPa and 1.25 kPa and peaks of 4.12 kPa and 0.48 kPa for PZE-04 and PZE-05, respectively. The increase in pore pressure of the PZE-06 was lower than the accuracy of the instrument and therefore was disregarded. Figure 15 presents the frequency diagram for these cluster 1 readings.

Figure 16 shows events 8 and 8A for cluster 2. Event 8 on 01/10/2018, with 106.20 mm of precipitation, generated pore pressure increases of 0.07 kPa, 0.01 kPa, and 0.37 kPa in the PZE-01, PZE-02, and PZE-03, which are smaller values or very close to the accuracy of the instruments.

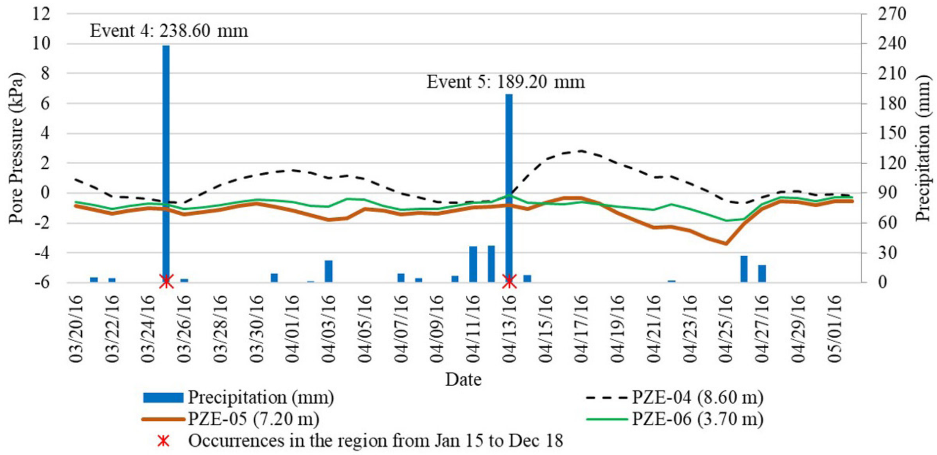

Figure 13. Frequency diagram of piezometers on cluster 1 in events 4 and 5.

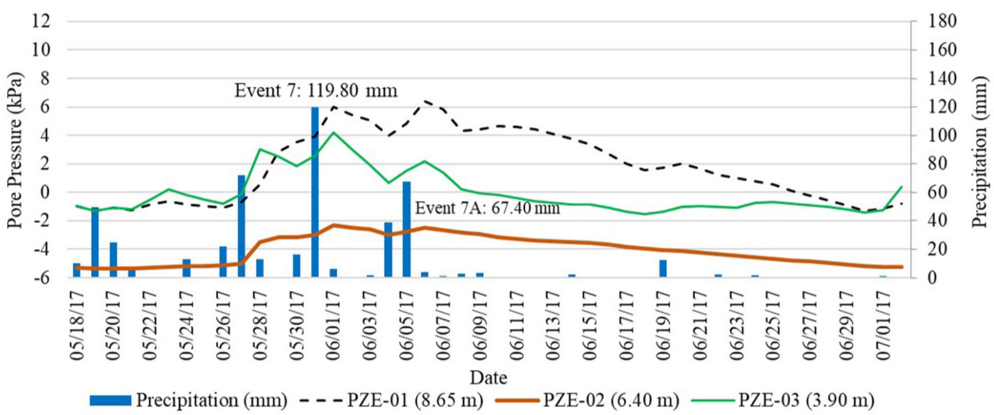

Figure 14. Frequency diagram for events 7 and 7A on cluster 2.

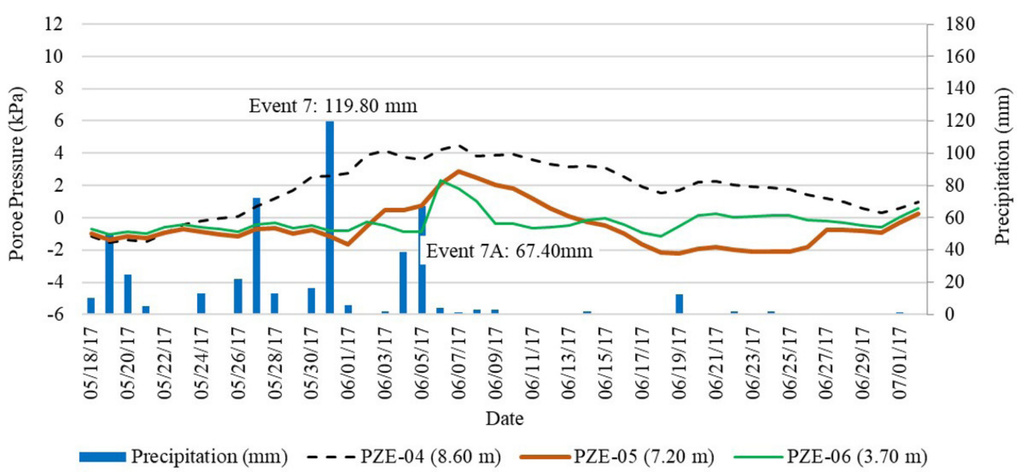

Figure 15. Frequency diagram for events 7 and 7A on cluster 1.

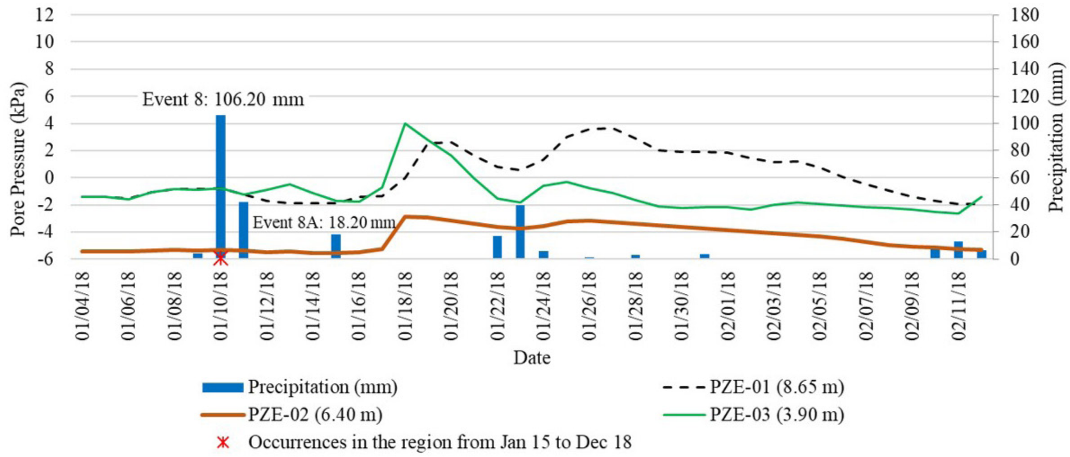

Figure 16. Frequency diagram for events 8 e 8A on Cluster 2.

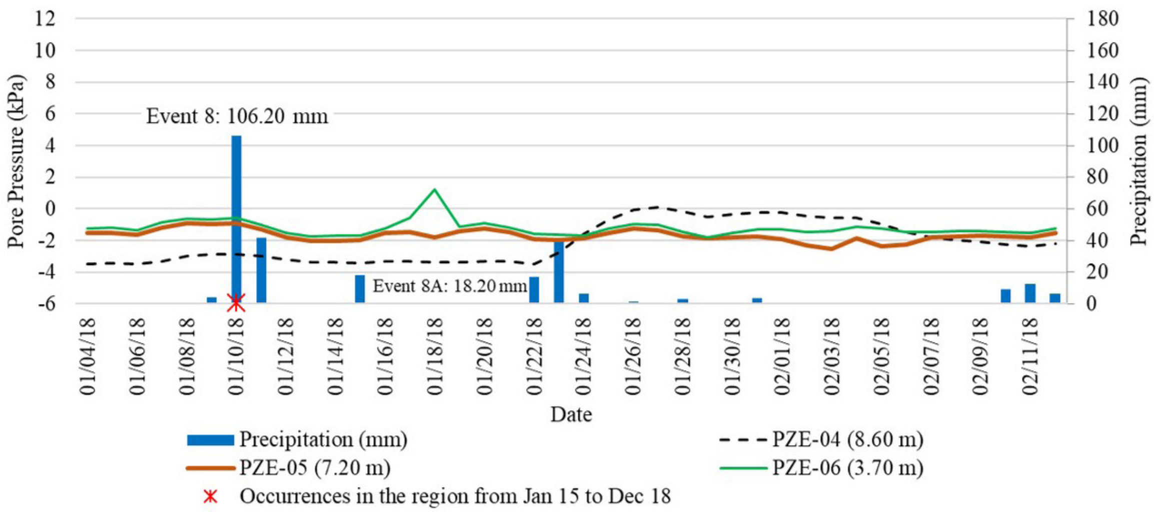

Figure 17. Frequency diagram for events 8 e 8A on Cluster 1.

Therefore, although landslides were recorded in the region on that day, this analysis considers that there were no effects on the piezometers due to this event.

Figure 17 presents events 8 and 8A for cluster 1. As in cluster 2, event 8 did not influence the pore pressure records in the piezometers and in event 8A, only PZE-05 and PZE6 suffered pore pressure and small magnitude increases.

Analyzing events 7, 7A, 8, and 8A, significant differences are identified. On 01/10/2018 (event 8) there was an accumulation of 106.20 mm with rainfall records in 22 hours and with an average intensity of 4.83 mm/h, while on 01/15/18 (event 8A) there was an accumulation of 18.20 mm in two hours, with an average intensity of 9.10 mm. On the other hand, event 7A, with rainfall intensity similar to that of event 8, generated increases in pore pressure. In addition to the daily cumulative being different, the highest hourly cumulative is also different. In event 8A, the highest hourly accumulation is 14.2 mm, while in event 8 it is 52.6 mm, which could indicate that the distribution of rainfall throughout the day would influence the impact of the increase in pore pressure. However, in event 5 on 04/13/2016, the highest hourly accumulation was 51.0 mm and this was one of the events with the highest increase in pore pressure.

In Domingues (2020) the measures of pore pressure increase, the time to reach the pore pressure peak after the event, and the estimated time for dissipation of the pore pressure increase are presented. Where there was a large dispersion of data and an absence of clear trends since heavy rainfall does not necessarily generate the greatest increases in pore pressure, nor is it possible to establish a clear relationship with the intensity or duration of rain. Frequency diagrams

Table 7. Summary of times to peak and dissipation of pore pressure.

Instrument	Time to reach peak pore pressure (days)		Time to dissipate increased pore pressure (days)	
	Smaller	Bigger	Smaller	Bigger
PZE-01 (8.65 m)	1	5	2	14
PZE-02 (6.40 m)	1	3	3	23
PZE-03 (3.90 m)	1	3	1	10
PZE-04 (8.60 m)	2	8	1	16
PZE-05 (7.20 m)	1	4	1	5
PZE-06 (3.70 m)	0	4	1	5

and pore pressure dissipation graphs for all events are fully presented in the same work. Table 7 presents a summary of observations of the delay to reach peak pore pressures and time to dissipate excess pore pressure.

4. Conclusion

The instrumentation used for this study provided important information regarding precipitation and pore pressure variations over nearly seven years on a slope in a tropical area of the Southern part of the Serra do Mar in Brazil. The following conclusions can be drawn from the present research:

The pluviometric regime recorded by the pluviograph of Morro do Boi is widely distributed throughout the year, making it impossible to clearly define dry and wet periods, which according to Monteiro (2001) is a characteristic of the rainfall regime of Santa Catarina. Despite this, it was possible to identify the period between June and August as the driest and that the highest rainfall occurs in summer and fall.

Precipitation of up to 100 mm of daily accumulation is well distributed throughout the year and occurs in all seasons. Approximately 73% of the daily records are classified as, from dry day to light rain, and only 27% as, from moderate to heavy rain, according to the CIRAM classification (2016 apud Kormann et al., 2016).

Finally, the pore pressure values developed were low, with a maximum of 9.3 kPa for the deepest piezometer on Cluster 2. Furthermore, it was not possible to establish a direct correlation with precipitation, which was expected, since it is only a portion of rain that infiltrates. This proportion depends on the intensity and duration of the rain, the condition of soil moisture before the rain, slope, and vegetation cover.

The results obtained in this study on precipitation and pore pressure in Morro do Boi have direct implications for the maintenance of road infrastructure and the safety of the people who use it. Understanding how climatic phenomena influence the geotechnical properties of the soil, especially precipitation, will allow identifying potential zones of instability with greater precision. This will enable the implementation of more effective preventive measures. Identifying the areas most prone to pore pressure variations could lead to the installation of real-time monitoring systems, such as additional sensors and piezometers at critical locations. In addition, the development of drainage and vegetation control strategies could be optimized to reduce water infiltration and minimize the impact of seasonal precipitation variations. Such preventive measures, based on concrete data and identified correlations, would offer a more effective approach to mitigating risks associated with landslides.

However, the study has some limitations, such as the lack of a direct correlation between precipitation and pore pressure, which can be attributed to factors such as rainfall intensity and soil condition. Future research should focus on expanding the data collection to include these additional variables and explore different types of weather events and their interactions with soil properties.

In addition, the results of this study provide a solid foundation for developing more advanced predictive models on the relationship between precipitation and pore pressure. Future studies could use this information as a starting point for creating statistical and machine learning models that integrate additional variables such as rainfall intensity and duration, pre-rain soil moisture, slope, and vegetation cover. Advanced statistical techniques such as time series analysis and multiple regression models, along with machine learning algorithms such as neural networks and decision trees, could be applied to identify more subtle patterns and more accurately predict pore pressure variations based on weather conditions. Integrating these methods can further refine the analysis, revealing complex relationships and improving the ability to predict instability events.

Finally, in-depth knowledge of variations in precipitation and pore pressure can support the development of more robust geotechnical engineering projects. This preventive approach, based on concrete data and correlations offers a reliable strategy for mitigating the risks associated with landslides, directly contributing to the safety and continuous operation of the BR-101/SC highway.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Giancarlo Domingues: conceptualization, methodology, project administration, data curation, formal analysis, investigation, visualization, writing - original draft. Vítor Pereira Faro: data curation, resources, methodology, supervision, validation, writing - original draft. Elisangela Aparecida Mazzutti: methodology, visualization, supervision, validation, writing - reviewing and editing.

Data availability

Data generated and analyzed in the course of the current study are available in the UFPR Digital Collection: https://hdl.handle.net/1884/76056.

List of symbols and abbreviations

CIRAM Information Center for Environmental Resources and Hydrometeorology of Santa Catarina

D	Drizzle
DD	Dry day
HR	Heavy rain
ID	Instrument depth
IE	Instrument elevation
LR	Light rain
ME	Measured elevation
MP	Mixed Probe
MR	Moderate rain
P	Precipitation
PD	Piezometer depth
PP	Pore pressure
PZE	Piezometer
R	Linear correlation
TE	Terrain elevation
VR	Violent Rain
WL	Water level
WLR	Water level reading
γ_w	Unit weight of water

References

Buzzi, M. (2007). *Avaliação das correlações de séries temporais de leituras de instrumentos de monitoração geotécnico-estrutural e variáveis ambientais em barragens: estudo de caso de Itaipu* [Master's dissertation]. Federal University of Parana (in Portuguese).

Cuomo, S., & Della Sala, M. (2013). Rainfall-induced infiltration, runoff and failure in steep unsaturated shallow soil deposits. *Engineering Geology*, 162, 118-127. http://doi.org/10.1016/j.enggeo.2013.05.010.

Domingues, G. (2020). *Análise qualitativa dos dados de monitoramento de um talude rodoviário na serra do mar catarinense* [Master's dissertation]. Federal University of Parana (in Portuguese).

Ferreira, K.S.D.M., Silva, M.A., Acevedo, A.M.G., Faro, V.P., Sestrem, L.P., & Kormann, A.C.M. (2018). Anlysis of a stabilized slope during a critical pluviometric events through field geotechnical instrumentation data. In *Proceedings of the International Symposium on Field Measurements in Geomechanics*. Rio de Janeiro, Brazil.

Fiori, A.P. (2011). *II Internal Research Report. Resources for Technological Development. Project 03*. (in Portuguese.

Geokon. (2014). *Instruction manual model 8021 (Micro 1000) Multi-Channel Datalogger*. Geokon.

González, A.A.M., Passini, L.B., & Kormann, A.C.M. (2017). Rainfall effects on pore pressure changes in a coastal slope of the Serra do Mar in Santa Catarina. *Soils And Rocks*, 40(3), 263-278. http://doi.org/10.28927/SR.403263.

González, A.M.A. (2013). *Estudo de séries de leituras obtidas através do monitoramento da instrumentação geotécnica implantada em uma encosta litorânea* [Master's dissertation]. Federal University of Parana.

Hydrological Services. (2014a). *Instruction manual TB4 Tipping Bucket RainGauge model TB4*. Hydrological Services.

Hydrological Services. (2014b). *Instruction manual Minilog Digital Data Logger model ML1-FL*. Hydrological Services.

Kormann, A.C.M., Sestrem, L.P., Lazarim, T.P., Passini, L.D.B., & Asakawa, S.S. (2016). Integração de modelos geológico-geotécnicos e dados de instrumentação: um caso desafiador de reforço de maciço na Serra do Mar Brasileira. *Geotecnia*, 1(138), 61-84. http://doi.org/10.24849/j.geot.2016.138.04.

Joly, N.H. (2018). *Análise do efeito das chuvas no desenvolvimento das Poro pressões: estudo de caso para um talude contido na Serra do mar* [Master's dissertation]. Federal University of Parana (in Portuguese).

Lazarim, T.P. (2012). *Caracterização e retroanálises da ruptura de um talude rodoviário - BR-101, Santa Catarina* (Completion of course work). Federal University of Parana (in Portuguese).

Li, A.G., Tham, L.G., Lee, C.F., & Law, K.T. (2005). Field-monitored variations of soil moisture and matric suction in a saprolite slope. *Canadian Geotechnical Journal*, 42(1), 13-26. http://doi.org/10.1139/t04-069.

Listo, F.D.L.R., Gomes, M.C.V., & Ferreira, F.S. (2021). Evaluation of shallow landslide susceptibility and Factor of Safety variation using the TRIGRS model, Serra do Mar Mountain Range, Brazil. *Journal of South American Earth Sciences*, 107, 103011. http://doi.org/10.1016/j.jsames.2020.103011.

Monteiro, M.A. (2001). Caracterização climática do estado de Santa Catarina: uma abordagem dos principais sistemas atmosféricos que atuam durante o ano. *Geosul*, 16(31), 69-78.

Pretto, J.H.F. (2014a). *Análise de tensão x deformação de uma encosta natural: um estudo de caso: Morro do Boi - Balneário Camburiú/SC* [Master's dissertation]. Federal University of Parana (in Portuguese).

Pretto, J.H.F., Sestrem, L.P., Kormann, A.C.M., & Campos, A.L. (2014b). Mapeamento geotécnico de uma encosta litorânea em Santa Catarina a partir de ensaios geofísicos eletrorresistivos. In *Anais do XVII Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica – Cobramseg*. Goiânia, Brazil.

Rahardjo, H., Lee, T.T., Leong, E.C., & Rezaur, R.B. (2004). A flume for assessing flux boundary characteristics in rainfall-induced slope failure studies. *Geotechnical Testing Journal*, 27(2), 145-153. http://doi.org/10.1520/GTJ11503.

Rahardjo, H., Lee, T.T., Leong, E.C., & Rezaur, R.B. (2005). Response of a residual soil slope to rainfall. *Canadian Geotechnical Journal*, 42(2), 340-351. http://doi.org/10.1139/t04-101.

Ridley, A.M., Brady, K.C., & Vaughan, P.R. (2003). *Field measurement of pore water pressures*. Transport Research Laboratory.

Salah, I.C., Oenning, L.M., Neves, M.B., Acevedo, A.M.G., Sestrem, L.P., Kormann, A.C.M., & Faro, V.P. (2019). Classificação da Precipitação Diária numa Região Litorânea de Santa Catarina e Relação com Ocorrências de Deslizamentos. In *Anais do Simpósio de Práticas da Engenharia Geotécnica da Região Sul – GEOSUL*. Joinville, Brazil.

Santos, D.R. (2014). *Casos de instabilidade de taludes ao longo das rodovias BR376/PR e BR-101/SC - Eventos de 2008 e 2011* [Master's dissertation]. Aeronautical Technological Institute (in Portuguese).

Sestrem, L.P. (2012). *Concepção e implantação de um plano de instrumentação para avaliação das condicionantes geotécnicas de uma encosta litorânea* [Master's dissertation]. Federal University of Parana (in Portuguese).

Sestrem, L.P., Kormann, A.C.M., Pretto, J.H.F., & Marinho, F.A.M. (2015). Precipitation influence on the distribution of pore pressure and suction on a coastal hillside. *Soils and Rocks*, 38(1), 81-92. http://doi.org/10.28927/SR.381081.

Tsaparas, I., Rahardjo, H., Toll, D.G., & Leong, E. (2003). Infiltration characteristics of two instrumented residual soil slopes. *Canadian Geotechnical Journal*, 40(5), 10121032. http://doi.org/10.1139/t03-049.

Urciuoli, G., Pirone, M., Comegna, L., & Picarelli, L. (2016). Long-term investigations on the pore pressure regime in saturated and unsaturated sloping soils. *Engineering Geology*, 212, 98-119. http://doi.org/10.1016/j.enggeo.2016.07.018.