



## Preliminary analysis of the mechanisms, characteristics, and causes of a recent catastrophic structurally controlled rock planar slide in Esposende (northern Portugal)

**Abstract** A catastrophic rock planar slide occurred in the parish of Palmeira de Faro, Esposende (N Portugal), on November 23, 2022, in the middle of the night, killing two people while they were asleep in the first floor of a building close to the affected cut slope. The collapsed slope presented a maximum height of about 23 m, and was excavated in a granitic rock mass strongly weathered, in some areas by mechanical means and, locally, with the support of blasting. The displaced material, with an estimated volume of 2000 m<sup>3</sup>, described an oblique trajectory with respect to the dip direction of the slope with a maximum length of about 44.6 m. The direction of the trajectory could be explained by the strong structural control of the instability through three discontinuity sets which delimit the slid rock mass causing multiple damage on the above-mentioned building. Although further detailed studies are necessary to elucidate the causes of the landslide, the unfavorable geological conditions, the anomalous accumulated rainfall during the previous two months (more than double than in the historic records), and some excavations apparently performed on the cut slope could be related to this instability. Therefore, this recent landslide highlights the important influence of the rock mass structure on the development of rock planar slides.

**Keywords** Mechanism · Characterization · Rockslide · Rock planar slide · Structural control · Esposende · Portugal

### Introduction

Portugal presents a variety of natural hazards, as earthquakes, tsunamis, tornadoes, wildfires, landslides, and floods, which could affect different regions of the country. Among these hazards, landslides were responsible of 238 deaths between 1865 and 2015 in Portugal (Pereira et al. 2017). More specifically, landslides caused 136 deaths, 173 injured, and left 460 people homeless between 1900 and 2010 in the North of Portugal (Pereira et al. 2014). In fact, most of landslide's fatalities occurred northwards of the Tagus River due to the unfavorable existing geological and geomorphological conditions of this area, which make it more prone to landslides (Pereira et al. 2017). Furthermore, previous studies have reported that landslides are more frequent in rainy years, and mainly develop on rainy seasons (i.e., December, January, and February) (Pereira et al. 2014).

In November 23, 2022, close to 3:55 am (local time), a catastrophic landslide, which caused two deaths and large economic losses, occurred in the parish of Palmeira de Faro, Esposende, North of Portugal (Fig. 1). The instability is located in 41°32'41.1"N and

8°44'11.8"W and developed on a granitic cut slope. The failed cut slope originally presented an approximate E-W orientation with a near vertical dip, and a maximum height of 23.0 m, which decreases towards the W up to a minimum of 5.4 m. According to the aerial images available in Google Earth, the excavation of the slope had been started in August 2003. However, it can be recognized as completed in October 2006. The semi-detached building affected by the landslide and the cut slope appear as built for the first time in the images of October 2009.

The displaced rocky material of the landslide slid on a planar rupture surface and described a clear oblique trajectory with respect to the original existing cut slope with an approximate direction of N208°E. The length of center line was 51.4 m while the total length was 55.7 m. The width of the surface of rupture and the displaced mass were 26.6 and 36.8 m, respectively, and the depth of the rupture surface and the displaced mass were 14.3 and 7.7 m, respectively. The dimensions of the landslide, as per the standardized criteria established by the UNESCO Working Party on World Landslide Inventory (1993), are summarized in Table 1.

According to Cruden and Varnes (1996), the landslide is classified as a rockslide, while Hungr et al. (2014) classify it as a rock planar slide. Additionally, the event can be classified as “extremely rapid” according to the classification of Cruden and Varnes (1996), since it developed very quickly, without any apparent previous sign of instability according to the witnesses.

In this work, a preliminary description of the main characteristics and the potential mechanisms of this catastrophic rock planar slide are analyzed.

### Description of the study area

The study area is placed in the Portuguese parish of Palmeira de Faro, Esposende, in the North of Portugal (Fig. 2a). This area is placed in the subregion of Cávado according to the geological map of Portugal (scale 1:50,000) (Fig. 2b). The failed slope is made of a coarse and coarse-medium-grained monzonitic granite with an important content of biotite that presents a porphyritic texture (Teixeira and de Medeiros, 1969). This granite is in contact with a non-porphyritic granite of coarse-medium grain size. The host rocks of the above-described granites are metamorphic rocks from the Siluric, classified as hornfels and bright schists with garnets from Andalusian (Teixeira and de Medeiros, 1969). Plio-Pleistocene fluvial and beach deposits are locally placed over the granite units (Teixeira and de Medeiros, 1969).



Fig. 1 (a) Aerial and (b) ground general views of the rock planar slide that occurred in Esposende on November 23, 2022

Table 1 Dimensions of the studied rock planar slide based on the criteria outlined by the UNESCO Working Party on World Landslide Inventory (1993)

Parameter	Dimension (m)	Parameter	Dimension (m)
Width of displaced mass, $W_d$	36.8	Depth of displaced mass, $D_d$	7.7
Width of surface of rupture, $W_r$	28.6	Depth of surface of rupture, $D_r$	14.3
Length of displaced mass, $L_d$	44.6	Total length, $L$	55.7
Length of surface of rupture, $L_r$	28.3	Length of center line, $L_{cl}$	51.4

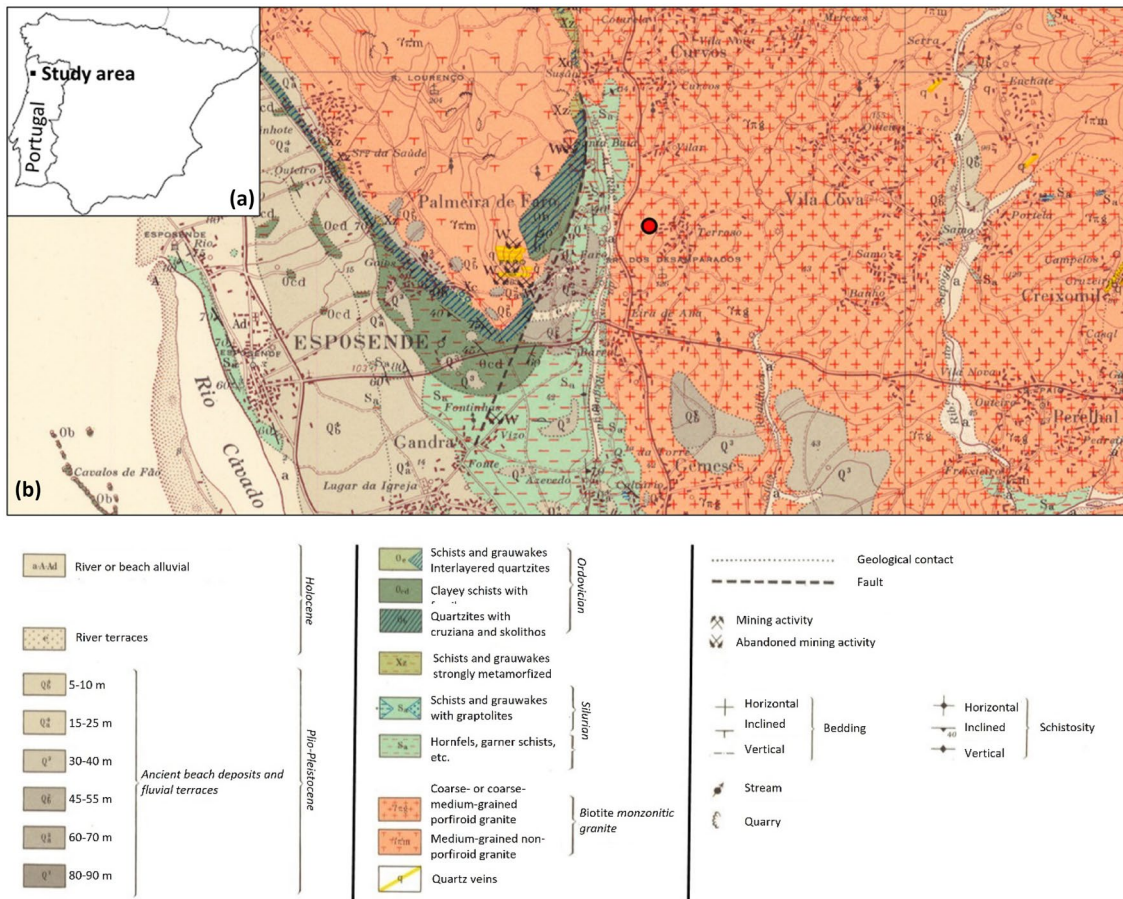


Fig. 2 (a) Location of the study area. (b) Geological map (Folha 5-C, Barcelos, obtained from Geoportal (<https://geoportal.ineg.pt/>) at scale 1:50,000). The position of the rock planar slide is indicated by a red point



**Fig. 3** (a) Geology of the slope. (b), (c) Detail of the different defined lithological units. The weathering degree is expressed in Roman numerals into brackets. Notice tooth marks from the bucket of a mechanical excavator in the slope on (b) evidencing the high weathering of the granite in some parts of the slope

In detail, the failed granitic slope presents weathering degrees varying between II (slightly weathered) and IV–V (highly or completely weathered) following the ISRM's (1981) suggested methods. The top of the slope also presents a thin topsoil layer, being partially covered by shrubs and grass, as well as some pine and eucalyptus groves (Fig. 3).

Tectonically, this region presents important NNE–SSW and ENE–WSW, with some additional faults with a NW–SE orientation (Dias da Silva et al. 2008).

According to the Köppen climate classification, this area presents a warm-summer Mediterranean climate (Csb), with an average temperature of 14.2 °C and an annual accumulated rainfall of 1155 mm. The wet season extends from October to January, being November the rainiest month with an average value of 184.9 mm.

### Methodology

Some of the authors visited the rock planar slide just after the occurrence of the event to collaborate in the rescue operation, to perform a preliminary assessment of the existing risk, and to ensure safety of the rescue services and the neighboring houses.

During the subsequent days, new field visits were performed by the authors, and new details about the landslide, the slope, and other relevant information were noted down from interviews with local people and eyewitnesses.

Moreover, an inspection of the area was performed by means of a four-axis unmanned aerial vehicle (UAV) with a 20 MPix optical camera and 15-mm F1.7 prime lens. Additionally, a FARO Focus3D X 130 laser scanner was used to scan some sectors of the failed slope. A high-resolution topographic map of the slope was then elaborated using the UAV images (1.25 cm/pix).

A historic study of the aerial images of the area from 2002 to 2021 was also conducted using the historical imagery feature of Google Earth Pro, despite the aerial images provided insufficient resolution, given the magnitude of the rock planar slide.

A geomechanical survey was performed near the site of the rock-slide to assess the basic Rock Mass Rating (RMR, Bieniawski 1989) of the granitic rock mass. Subsequently, the original (Romana 1985) and continuous (Tomás et al. 2007) slope mass rating (SMR) were calculated based on the geometry of the failure plane identified using UAV



**Fig. 4** Picture of the damage caused by the rock planar slide on the building placed on the foot of the slope. **(a)** Plan view showing the different elements affected. **(b)** Oblique image of the affected building and the room in which the two deceased people were sleeping. **(c)** Car garage buried by the landslide. **(d)** Front image of the rock planar slide and the room impacted by the landslide. **(e)** Rear façade of the building in which the three bedrooms were placed. **(f)** View of the part of the building struck by the landslide in which the removed pillar and enclosure of the affected bedroom can be observed

imagery and the RMR values obtained from the geomechanical survey conducted in the nearby area. This approach provided a thorough evaluation of the slope stability, taking into account both the geological characteristics of the rock mass and the geometry of the failure plane.

#### Socio-economic impacts

The rock planar slide struck the rear façade of a semi-detached house built with a reinforced concrete structure, although only the NW corner of this building, in which three bedrooms were placed

on the first floor, was severely affected (Fig. 4). Since the event occurred near 3:55 a.m., the house was occupied by 5 members of a family. The two occupants of the westernmost room died while they were sleeping. Although the detached rocks and soil mass and the sucked trees also affected the adjacent rooms, there were no more injuries. The N and W enclosures of the house and the NW corner pillar were torn down by the slid soils and rock mass, although the general structure of the building did not collapse. Some adjacent constructions, as the car garage of the house, were partially buried

by the landslide. As a result of the rock planar slide, the households of the semi-detached adjacent house and the four additional houses placed under the slope were preventively evacuated.

Additionally, other psychological impacts of this event have been reported. First, the landslide has generated a feeling of insecurity on the dwellers of the near houses. Furthermore, at least two members of the national security forces who participated in the rescue activities have experimented some post-traumatic stress.

### Interpretation of the instability: mechanisms, characteristics, and possible causes

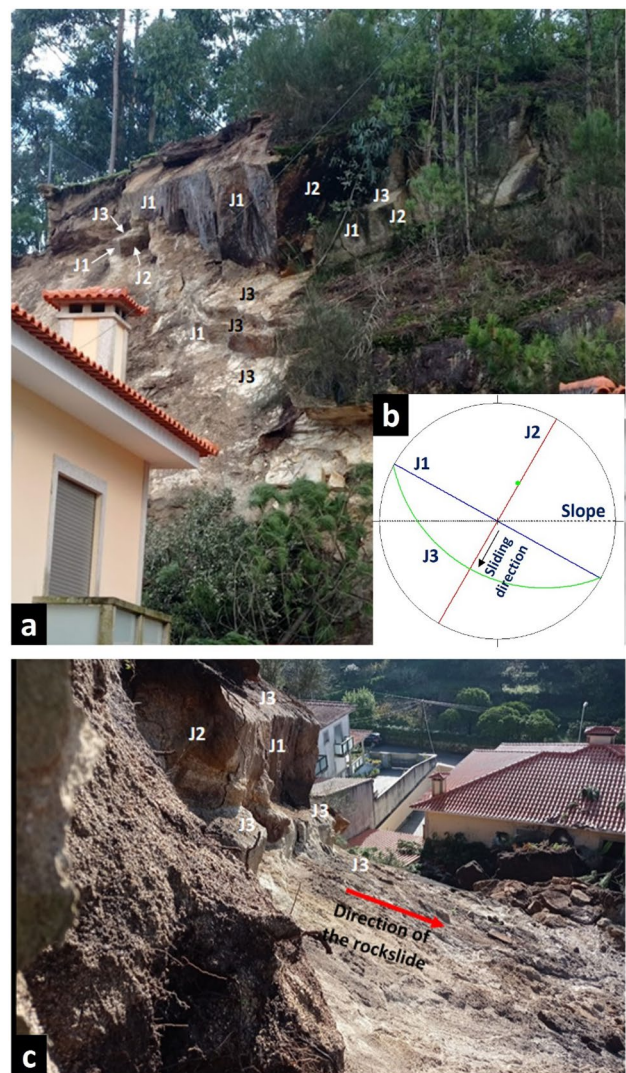
The studied rock planar slide developed on a steep cut slope excavated by mechanical means. However, some drill hole traces could be identified in the face of the stable slopes, indicating that blasting was used for the excavation of some parts of the slope. It should be highlighted that the use of poor blasting can induce dynamic stresses mainly due to the detonation and the expanding gases generated by the explosion, considerably decreasing the stability of the rock slopes (Hoek 2007). Nevertheless, it is difficult to assess the extent of rock mass disturbance resulting from blast damage due to the influence of multiple factors, as noted by Zheng et al. (2018). Hoek (2007) and Hoek and Brown (2019) suggested that controlled small-scale blasting in civil engineering slopes can result in minimal damage to the rock mass. Consequently, although detailed information about the excavation method is not yet available, in this case study, the excavation method is expected to have a limited impact on the stability of the slope.

The high degree of weathering of the rock mass (i.e., between II and V) also reduced the shear strength of the rock and the discontinuities, strongly conditioning the stability of the slope (Barton and Choubey 1977).

Other factors as the possible vibrations developed during the construction of the building placed on the crown of the slope, even if its foundation was excavated by mechanical means and is located more than 20 m far, could have impacted on the fracturing of the slope (Hoek 2007). In fact, some neighbors living in the buildings at the toe of the slope confirmed the occurrence of some small size rockfalls (i.e., smaller than 1 m<sup>3</sup>) during the construction of the detached building located on the crown of the cut slope.

However, the main conditioning factor of the instability seems to be the existing rock mass structure. Three sets of discontinuities are clearly recognized in the source area of the landslide. Two of them are subvertical sets of discontinuities (J1 and J2) and exhibit approximate orientations N119°E and N210°E (Fig. 5), respectively. These discontinuity sets were also measured in the natural outcrop existing on a granitic rock mass placed on the other side of the road. Figure 6c shows a perfect match of the strike of J1 and J2 with the strike of the failure plane in the main scarp, and the direction of sliding derived from the topographic map obtained from the UAV imagery. Additionally, a discontinuity set J3 defines the surface of failure, which presents a similar strike to J1 and a dip value between 35 and 40° dipping towards the SW (Figs. 5, 6, and 7). The combination of the three discontinuity sets (Fig. 5b) explains the shape and the oblique direction of displacement of the rock planar slide observed in Figs. 6b, c, and 7.

The original and continuous slope mass rating (SMR) of the slope are reported to be 51–63 (classes II–III) and 49–59 (class III), respectively. According to the original SMR evaluation, the slope

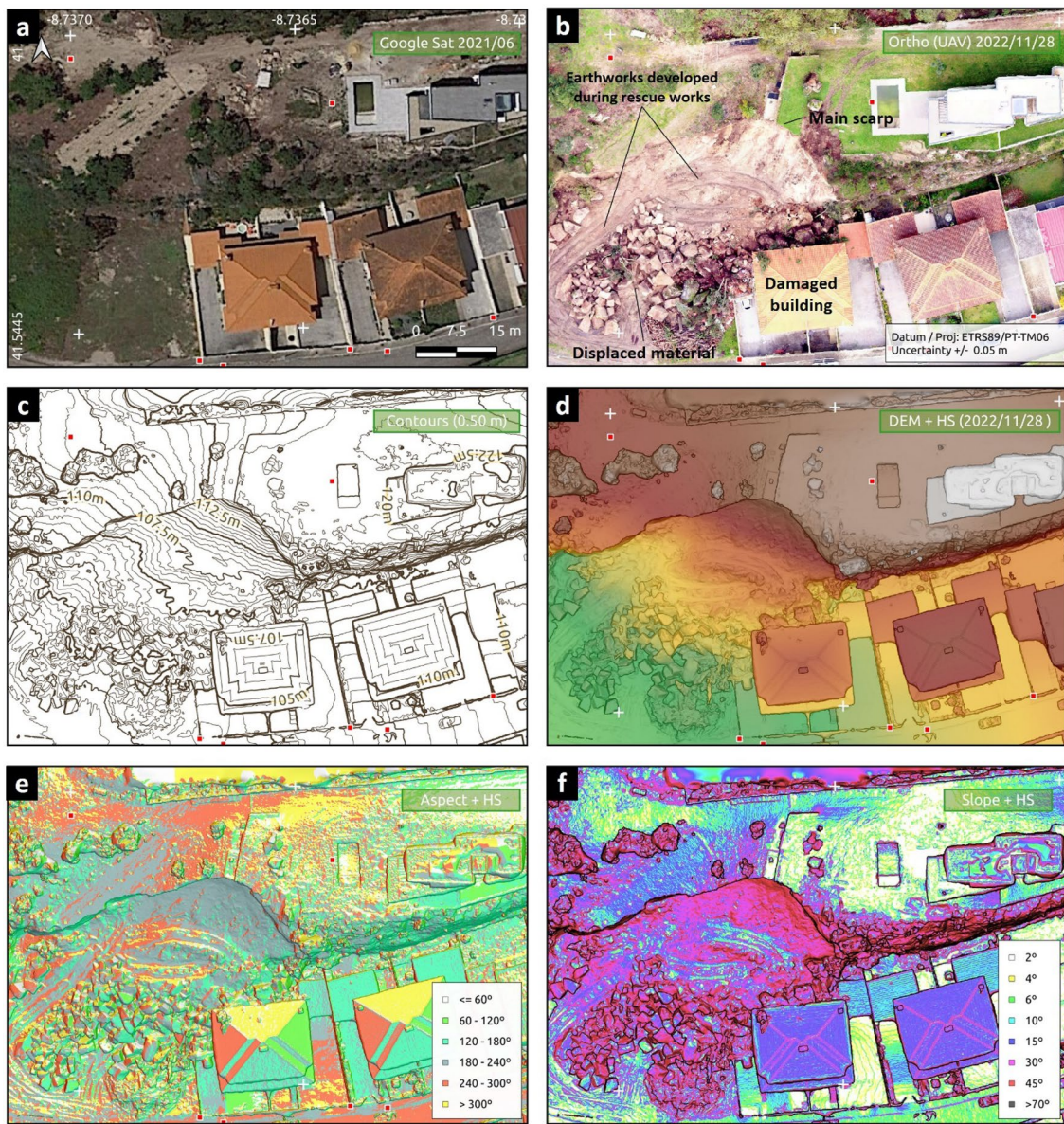


**Fig. 5** (a), (c) Detail of the discontinuity sets observed in the area of the main scarp from two different points of view. (b) Stereoplot of the discontinuities

can be classified as “Stable” or “Partially stable.” The continuous SMR also classifies the slope as “Partially stable.”

Regarding the possible triggering factors, accumulated rainfall during the month of November was exceptionally high (Figs. 8 and 9). Up to the date of the event, the monthly rainfall time series recorded in Braga 30 km away from the study area, the November accumulated rainfall was 352.2 mm, i.e., +176.8 mm more than the average for the whole month of November (Fig. 8). This value represents an increment of +100.8% with respect to the average value of the historical data between 1971 and 2000, set in 175.4 mm. September and October saw an unusually high amount of rainfall, with precipitation levels exceeding historical records by +66.3% and +134.2%, respectively. During September and October, there was an unprecedented amount of rainfall, exceeding historical records by +66.3% and +134.2%, respectively.

Out of the 42 years from 1980, only 15 months (December 1981, November 1984, October 1987, January 1996, November



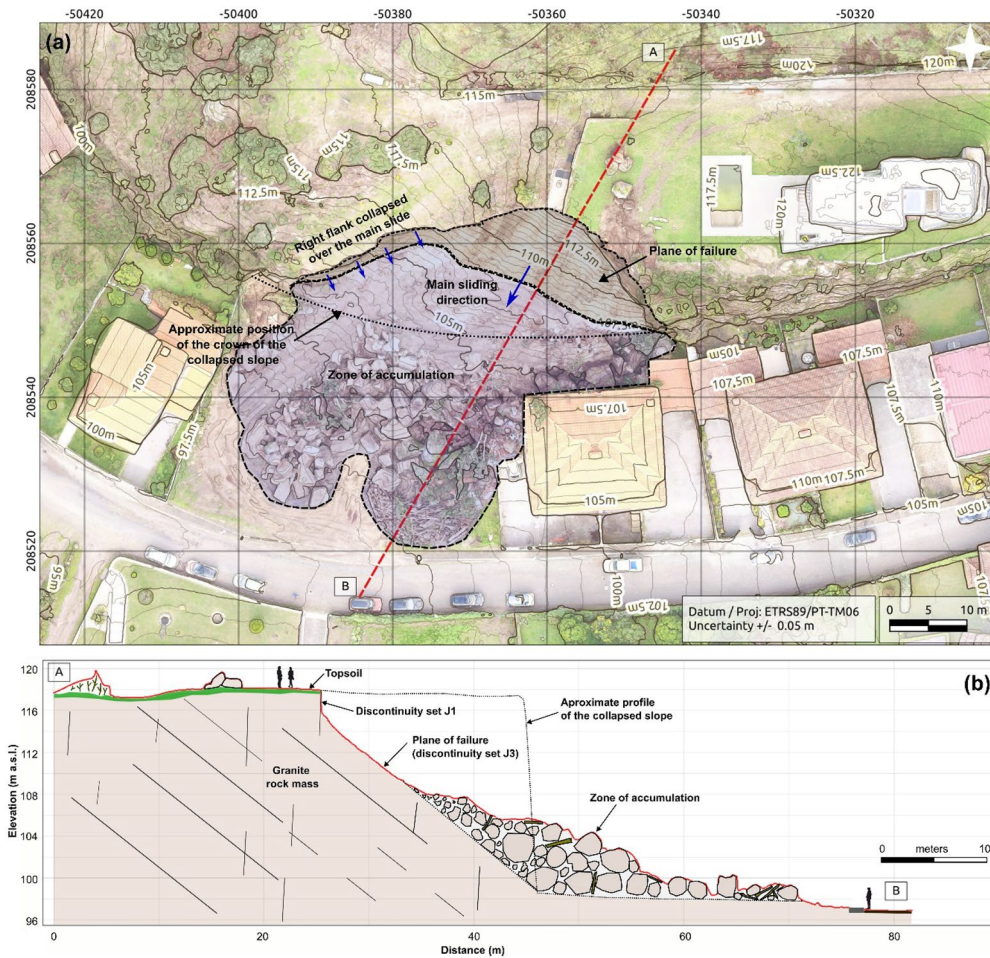
**Fig. 6** Orthophotos of the studied area acquired in (a) June 2021 and (b) November 2022. (c) Topographic map and (d) DEM produced using photogrammetric method from the UAV imagery. (e) Aspect and (f) slope derived from the DEM shown in (d)

1997, November 2000, December 2000, January 2001, March 2001, October 2006, November 2006, January 2014, February 2014, November 2014, and January 2016) exceeded the recorded monthly rainfall of October 2022, while only 11 months (December 1981, November 1984, October 1987, January 1996, November 1997, December 2000, January 2001, March 2001, October 2006, February 2014, and January 2016) exceeded the recorded monthly rainfall of November 2022 (Fig. 9B). Finally, although the exact date of the slope excavation is unknown, from the beginning of excavation in August 2000 until the present day, the precipitation levels recorded in November 2022 have exceeded a maximum of three times (October 2006, February 2014, and January 2016). This data emphasizes just how extraordinary the rainfall levels were during those months.

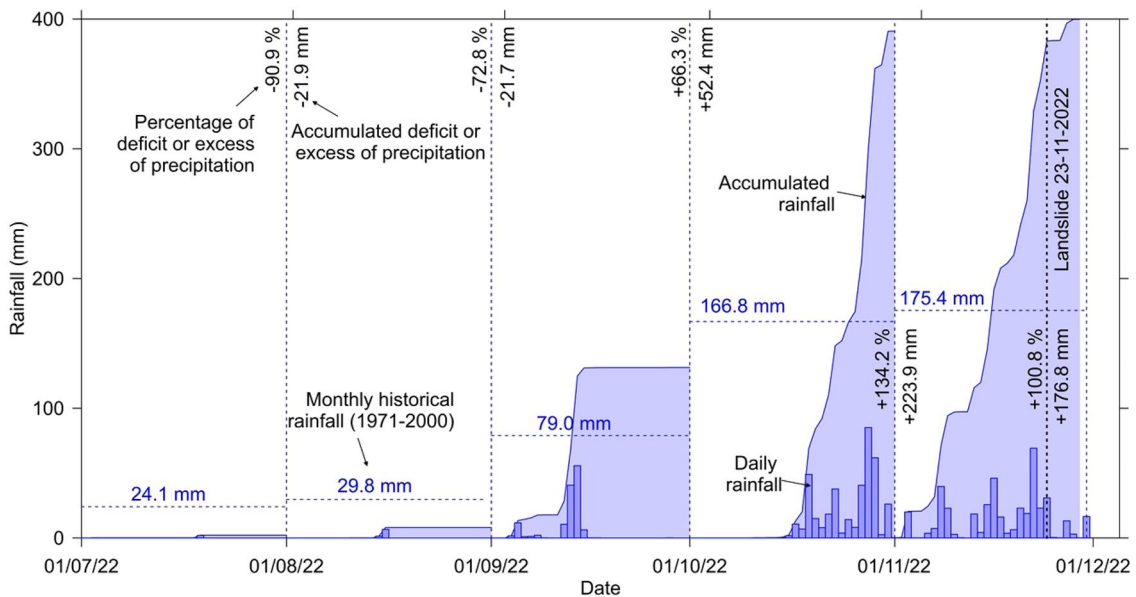
It should be also pointed out that these anomalous records of rainfall were preceded by an important drought period, with significant deficits of precipitations for a long time.

Finally, it should be mentioned that apparently some excavations were performed on the slope in the months leading up to the failure, what might have reduced the resisting forces of the sliding unstable rock block.

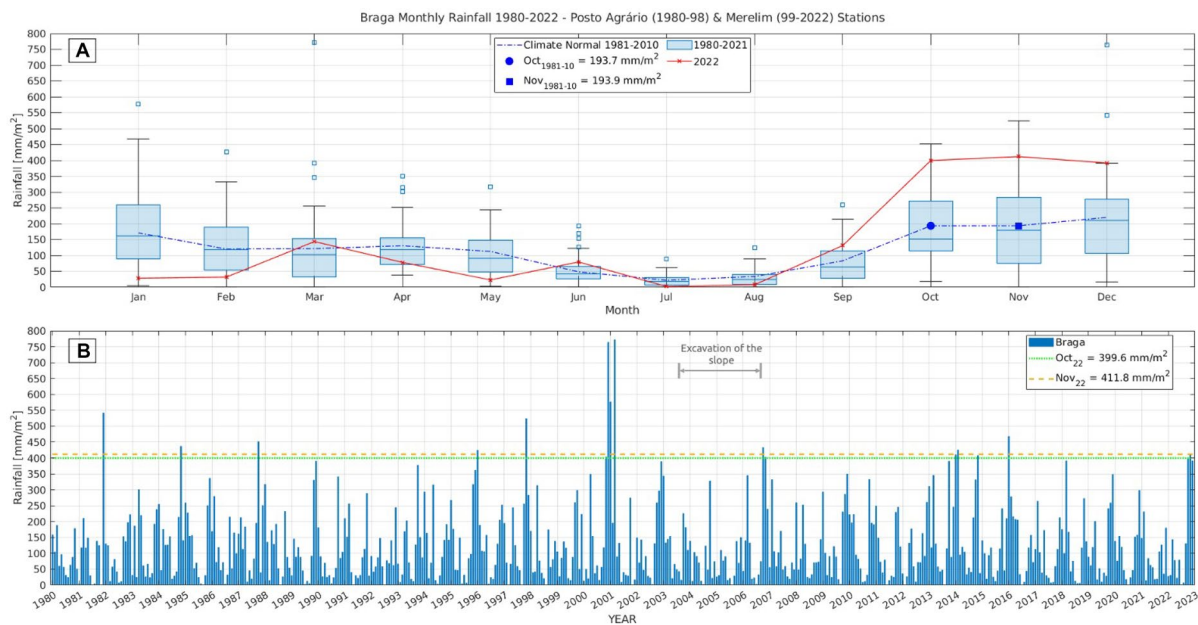
Consequently, it may be concluded that discontinuity sets J<sub>1</sub> and J<sub>2</sub> separated the sliding mass, which slid over the surface of rupture defined by the discontinuity set J<sub>3</sub>. Additionally, the cut slope placed on the right flank of the rock planar slide, which presented a high degree of weathering (Fig. 3), partially collapsed over the slid mass (Fig. 7a). Likewise, the combination of different conditioning factors, jointly with the triggering effect of rainfall and, perhaps, the excavation performed on the toe of the slope, could have caused this



**Fig. 7** (a) Topographic map of the rock planar slide obtained from photogrammetry using UAV imagery. (b) Cross-section of the rockslide



**Fig. 8** Daily rainfall and accumulated monthly rainfall from July 2022 to December 2022 in a meteorological station placed in Braga. Note that the mean monthly historical values of precipitation, and the percentages and accumulated deficits or excesses of precipitation are also shown in the plot



**Fig. 9** (A) Box-and-whisker plot of monthly historical rainfall recorded in Braga. The actual monthly rainfall recorded in 2022 has been overlaid. (B) Monthly rainfall time series recorded in Braga between 1980 and 2022. Note that the monthly rainfall accumulated in October and November 2022 has been plotted as horizontal dashed lines

catastrophic rock planar slide. However, further detailed research will be necessary to better understand the precursors of this event, as well as the susceptibility of the slope to new instabilities.

### Conclusions

This preliminary study provides observations into the 2022 Esposende's rockslide event, its mechanisms for movement, and possible triggering and conditioning factors. This catastrophic rock planar slide occurred at 3:55 a.m. in the parish of Palmeira de Faro, Esposende (N Portugal), on November 23, 2022. Two people were killed by the landslide while they were asleep in the first floor of a building close to the collapsed cut slope. The slope was excavated in a granite rock mass strongly weathered in some areas (up to degree V) by means of mechanical means and locally with the support of blasting. The displaced material described a clear oblique trajectory with respect to the dip direction of the slope. This can be explained by the strong structural control of the instability, which is conditioned by three discontinuity sets. In addition to the casualties, the rock planar slide caused multiple damage on the above-mentioned building and impacted psychologically the people who collaborated on the rescue tasks and the adjacent neighbors. The unfavorable geological conditions of the rock mass, some earthworks apparently performed on the cut slope, and mainly the anomalous accumulated rainfall during the previous two months (more than twice as high as the historically recorded averages) may have originated this instability. However, further research will be necessary to better understand the conditioning factors and the precursors of this event, as well as to evaluate the susceptibility of the slope to new instabilities.

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### Data availability

The data that support the findings of this study are available on request from the corresponding author.

### Declarations

**Competing interests** The authors declare no competing interests.

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## References

- Barton N, Choubey V (1977) The shear strength of rock joints in theory and practice. *Rock Mech* 10:1–54. <https://doi.org/10.1007/bf01261801>
- Bieniawski ZT (1989) Engineering rock mass classification. Wiley, Chichester
- Cruden DM, Varnes DJ (1996) Landslide types and processes. In: Turner, A.K. & Schuster, R.L. (eds.) *Landslides: investigation and mitigation (Special Report)*. National Research Council, Transportation and Research Board Special Report, Washington, DC, USA, 36–75
- Dias da Silva I, Cruz I, Araujo Gomes J, Costa A, Almeida P, Cabral J, Taborda R, Caranova R, Laiginhas C, Angelucci D, Carrilho F, Luis M (2008) GIS Seismotectonic database for mainland Portugal. ESIG'08, Actas do X Encontro de Utilizadores de Informação Geográfica, Oeiras, Guimarães, Universidade do Minho
- Hoek E (2007) Practical rock engineering, Vancouver, Canada. Available at: <https://www.rocksience.com/assets/resources/learning/hoek/Practical-Rock-Engineering-Full-Text.pdf>. Accessed May 2023
- Hoek E, Brown ET (2019) The Hoek–Brown failure criterion and GSI – 2018 edition. *Journal of Rock Mechanics and Geotechnical Engineering*, 11, 445–463. <https://doi.org/10.1016/j.jrmge.2018.08.001>
- Hungr O, Leroueil S, Picarelli L (2014) The Varnes classification of landslide types, an update. *Landslides* 11:167–194. <https://doi.org/10.1007/s10346-013-0436-y>
- ISRM (1981) Rock characterization, testing & monitoring: ISRM suggested methods. International Society for Rock Mechanics, Commission on Testing Methods
- Pereira S, Zêzere JL, Quaresma I (2017) Landslide societal risk in Portugal in the period 1865–2015. In: Sassa K, Mikoš M, Yin Y (eds) *Advancing culture of living with landslides*. Springer International Publishing, Cham, pp 491–499
- Pereira S, Zêzere JL, Quaresma ID, Bateira C (2014) Landslide incidence in the North of Portugal: analysis of a historical landslide database based on press releases and technical reports. *Geomorphology* 214:514–525. <https://doi.org/10.1016/j.geomorph.2014.02.032>
- Romana M (1985) New adjustment ratings for application of Bieniawski classification to slopes. *International Symposium on the Role of Rock Mechanics in Excavations for Mining and Civil Works*. International Society of Rock Mechanics, Zacatecas, Mexico, 49–53
- Teixeira C, de Medeiros C (1969) Carta geológica de Portugal na escala 1/50 000 notícia explicativa da folha 5-C Barcelos. Serviços Geológicos de Portugal, Lisboa, 49
- Tomás R, Delgado J, Serón JB (2007) Modification of slope mass rating (SMR) by continuous functions. *Int J Rock Mech Min Sci* 44:1062–1069
- UNESCO Working Party on World Landslide Inventory (1993) *Multilingual Landslide Glossary*. BiTech Publishers British Columbia, Canada, Richmond, Canada, p 32
- Zheng H, Li T, Shen J, Xu C, Sun H, Lü Q (2018) The effects of blast damage zone thickness on rock slope stability. *Eng Geol* 246:19–27. <https://doi.org/10.1016/j.enggeo.2018.09.021>

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