Post-wildfire slope stability effects and mitigation: a case study from hilly terrains with unmanaged forest

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Abstract

The combined effects of wildfires and storms strongly induce slopes stability phenomena, thus requiring mitigation measures to manage long-lasting wildfire-induced risks. In Portugal, thousands of increasingly destructive wildfires occur during the hottest months. In the last two decades, almost 3,000,000 ha of forest, bush and agricultural land burned in Portugal, 20% of which caused by massive wildfires that occurred in 2017. Portuguese central mountain range was one of the most affected areas, namely the study area of Serra do Açor and Serra da Estrela, where extreme rainfall events in 2018 and 2019 caused extensive slope instability phenomena that created a unique opportunity for assessing long-term field performance of treated and untreated burnt areas. The registered phenomena as well as the treatment solutions applied to mitigate instability effects on slopes were studied in two sites. Over 3 years, several field research trips were carried out to scientifically assess the situation over time. By comparing areas with distinct response to the extreme rainfall events and based on the data collected, namely prior to 2017, it was been possible to link the registered instability events and the October 2017 wildfires and qualitatively evaluate the effectiveness of the adopted mitigation solutions. This study not only confirms that the study area is prone to slope instability wildfire-related phenomena, with a 13-year return period between similar events in the study area, but also validates the use of protective barriers as a mitigation measure, contrary to previous studies carried out in other countries.

Keywords Wildfire-related slope instability phenomena · Landslides · Erosion · Slope stabilization · Extreme weather conditions

Mathematics Subject Classification 74L10 (Soil and Rock Mechanics)

1 Introduction

Each year, Portuguese rural territory is plagued by thousands of wildfires during the hottest months, namely during the so-called Charlie phase, which usually elapses between the first of July and the thirtieth of September [1], 100,000 ha of forests being consumed each year on average [2]. In Portugal, as well in the rest of southern Europe, wildfires are becoming more frequent, not only because

of direct ignition [3], but also because of demographic changes and the increase in flammable biomass [4]. Due to inadequate road network, lack of industry and other socio-economics reasons [5], the population of Portuguese mountain areas has decreased since the second half of the 20th century [4]. In addition to the consequent farmland abandonment, which has favoured horizontal and vertical fuel continuity, the introduction of commercial plantations of fire-prone species, namely maritime pine (*Pinus pinaster*)

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and eucalypt (*Eucalyptus globulus*), also increases the frequency and extent of wildfires [6]. The Centre-North of the country gathers all the previous characteristics, thus being particularly affected by the fire season, namely the region where the Portuguese central mountain range stands out. This mountain range includes the Serra do Açor and the Serra da Estrela, where the two main areas of study in this article are located.

Since 1975, thousands of hectares of forest have been burnt in Serra do Açor e Serra da Estrela, namely during fire seasons of 1987, 1991, 2005 and, more recently, 2017. In the rainiest periods after these fires, several flood events were registered in 1988 and 2006 [7] or debris flows and other slopes instabilities such as the ones that occurred in 1993 [8] and 2005 [9–11]. This relationship between forest fire and slope instability phenomena is well documented. According to Esteves et al. [12], not only wildfires are responsible for the destruction of vegetation, but also they alter the hydrological response of soil. The removal of protective vegetation and litter cover reduces rainfall interception, enhancing runoff and erosion rates [13, 14]. These authors also refer that changes in soil characteristics induced by heat also have an important contribution in instabilities phenomena. Despite all the negative effects resulting from fires on the vegetation and mineral cover of slopes, these, alone, are seldom sufficient to cause instabilities. Indeed, in Portugal, rainfall events are the most import triggering factors of landslides and other related phenomena [15], and it is known that post-fire intense rainfall events increase soil erosion and other instability phenomena when compared with similar unburned sites or pre-burn conditions [12].

The 2017 fire season was followed by extreme climatic conditions that caused slope instability phenomena scattered around several locations around the Portuguese central mountain range. Although other locations with instability examples are reported, the present study focuses essentially on two study areas in the municipalities of Oliveira do Hospital and Guarda. Contrary to what is common practice in Portugal, where despite the surface burnt, post-fire soil erosion mitigation treatments are rarely applied [6], these two municipalities carried out extensive containment works, applying several solutions described in the literature. The range and severity of wildfires that broke out in October 2017 and the different mitigation measures used to stabilise unprotected slopes and embankments from the effects of typical winter hazards offer a great opportunity to assess the effectiveness of the mitigation solutions applied. The fact that severe rainy and stormy seasons occurred in 2018 and 2019 in the regions previously affected by the wildfires enhances the value of the observations of the performance of the different mitigation measures.

Considering that the overall impact of natural disasters is expected to grow significantly as a result of climate changes and the economic importance of the country's forestry activities using flammable species [16], building resilience and planning disaster mitigation requires a proper understanding of the wildfire hazard. The extremely severe wildfires in California in 2018 [17] and Australia, Brazil, Indonesia and Russia in 2019 [18] show that this natural hazard is still on the rise, the environmental effects being particularly highlighted during the events observed in 2019 [18]. Therefore, detailed analysis of case studies focussing on the secondary effects of these natural hazards and the effectiveness of different mitigation measures is critical for the progress in this field.

This paper discusses the main geological and geotechnical hazards on slopes resulting from 2017 wildfires, which are described and exemplified with situations observed along Serra do Açor and Serra da Estrela. Also, based on the stabilization works carried out in the above referred municipalities, the various solutions available to mitigate the effects of fires on soil and slopes are presented and assessed. The systematization of both instability phenomena and stabilization techniques allows the broad discussion on the combined effects of wildfires and storms on the stability of real slopes and on the field performance of applied mitigation measures implemented after an unusually challenging sequence of extreme weather events.

2 Relevant factors affecting wildfire-related geotechnical risks

The immediate or direct threats of a forest fire are the loss of human lives, partial or total destruction of private property, damage to infrastructures and loss of natural resources. However, after a forest fire, changes in vegetation, surface coverage conditions and/or hydrological processes can increase the probability and consequences of slope instability phenomena which can affect the areas in front or above the slopes long after forest fire extinction. In general, the first 4–6 months after the fire is the period of greatest vulnerability because of the likelihood of intense rainfall associated with winter–autumn period and because vegetation has not yet regrown [4]. However, the window of disturbance is estimated to last between 3 to 10 years, depending on several factors [5, 19–21]. Since the greatest effects of fire on hydrology and slopes instabilities occur shortly after fire and rates of erosion declines with time [22], data analysis and discussion tend to be limited to more or less 1 year after the fire event [4]. As stated by Esteves et al. [12] and Zêzere et al. [15], slope instability phenomena are usually triggered by rainfall

events, highlighting the importance of the saturation degree of soils and water table conditions. Also, it is commonly accepted that vegetation and the characteristics of the soil, which may be considerably affected by the occurrence of wildfires, plays an important role in the mitigation of the risks of slope's failure and surface erosion.

2.1 Identification of natural disasters risks

The probability of occurrence of natural disasters or hazards, which can be defined as processes or situations that have the potential to destroy or cause damage, can be expressed in both quantitative and qualitative terms [23]. This probability is vital to assess the risk associated with a particular event, because the risk is the combination, defined as a product, of the probability of a disaster occurring and the consequences if it occurs. The consequences should ideally include all the possible aspects of the effects of the hazard occurrence, including short-term and long-term financial, economic, social, environmental consequences, amongst other. To improve the coherence of the analysis, the consequences are often defined as a product of the total value at risk, termed exposure and the vulnerability, a measure of the potential loss with respect to the total, varying between 0 and 1. According to Hope et al. [23], in British Columbia, Canada, wildfires of concern and therefore requiring post-event risk assessment are those where: (1) burnt area is greater than 50 ha; (2) fire broke out with moderate or high intensity; (3) fire broke out above or near populated areas or near communication routes; or (4) are within community watersheds.

In forest fires, the endangered elements are located downstream or below the places where the fires broke out. In such situations, one may identify residences areas, main communication routes, places of storage or collection of water, recreation areas and agricultural or industrial area [23]. In fires at the urban forest interface, most of the elements at risk are identified during the firefighting operation and the risk mitigation measures are often initiated at that time. In these situations, once the forest fire has been extinguished, it is commonly verified which of the identified elements are in danger after the fire.

There are several procedures for assessing the risk of natural hazards after forest fires. The identification of the element(s) at risk and the assessment of the situation are key phases in the analysis. General data on the area, maps of vegetation and the severity of the soil burnt should be collected, as well as the identification of possible hazards. Herein, the effects of wildfires on slope instability phenomena and the use of different

techniques currently used in practice to mitigate related hazards are addressed.

2.2 Factors that affect the occurrence of slope instability phenomena

For a better understanding of the various types of slope instabilities following forest fires, it is important to introduce some factors that influence the response of burnt areas over time. It should be noted that, in the present study, slope instability phenomena include all the events, from surface erosion to deep landslides. Although the inclusion of erosion in mass movements concept is not usual, from a geotechnical point of view, it can be seen as the beginning of more serious processes. The various factors can be grouped in two sets: (1) the factors that are not related with the forest fire and (2) the fire-dependent factors [24]. According to these authors, the first set includes factors such as orography, anthropogenic activities and precipitation characteristics, namely its intensity. The second set of factors consists of the severity of the forest fire and the burnt area, the amount of soil without vegetation cover, soil's water repellency, soil's erodibility and the elapsed time after the fire. Despite the importance of the previous factors, and due to their influence on the mechanical behaviour of soils, three aspects should always be considered in any study: the hydrological response of the hydrographic basins, the alteration of soil characteristics and the natural reinforcement of soils provided by vegetation roots. These aspects are briefly described, highlighting how these can be influenced by the occurrence of wildfires.

2.2.1 Hydrological response of watersheds

The occurrence of instability phenomena cannot be dissociated from hydrological conditions, since they are responsible for most of slope instability phenomena, being particular important in landslides triggering [15]. The influence of water in soil behaviour is well known, and it is supported by the principle of effective stress proposed by Terzaghi [25] and expressed by Eq. (1):

$$\sigma' = \sigma - u \quad (1)$$

in which σ , σ' and u represent, respectively, the total stress, the effective stress and the pore pressure. During rainfall events, and independently of the initial saturation degree of soil, the pore pressure increases and the effective stress decreases. Thus, according to Mohr–Coulomb failure criterion, expressed by Eq. (2), the shear resistance of soil (τ) decreases, and instability events are more likely to occur.

$$\tau = c' + \sigma' \cdot \tan(\phi') \quad (2)$$

This constitutive law is governed by the cohesion (c'), the angle of shear resistance (ϕ') and the effective normal stress (σ').

Wildfires deflagration affects the response of watersheds by changing their infiltration characteristics and erodibility of soils [26]. According to these authors, two processes may be the source of instability: (1) surface run-offs that are responsible for erosion, culminating in debris flows and (2) water infiltration into the soil that triggers processes of soil mass rupture. As summarized by Zêzere et al. [15], the instability type depends on the rainfall duration and soil conditions. It should be noted that hydrological response of watersheds depends on the removal of surface vegetal layer, which change the surface roughness and, consequently, the rate of flow. It may also cause depressions that store water and give rise to new infiltration routes [27].

2.2.2 Modification of soil characteristics

The combustion of organic matter in the more superficial layer of soil can result in loss or degradation of mechanical behaviour. Wildfires tend to generate more friable and consequently more erodible soils. This is due to the disappearance of roots and the destruction of microbial activity, which improve soil mechanical characteristics [26]. It should also be noted that some physical properties of the soils, such as grain size distribution or plasticity, particularly when due to the presence of organic matter, may change during wildfires. Several studies point to the reduction of clay and silt fractions in soils, giving rise to coarser and less cohesive soils that are more vulnerable to erosion [26].

In the presence of water, the existence of ashes can also affect slope stability due to the generation of solutions with high pH that facilitate the dispersion of particles [26]. Another factor to consider is the appearance or strengthening of soil repellency to water, a process that has been found in places burned by high intensity forest fires. This phenomena has also been identified under some types of dead blanket, such as foliage produced by eucalyptus woods [28].

2.2.3 Influence of roots

The reinforcement provided by roots in soils is well known, influencing the spatial variation of soil resistance and being an important factor in the stability of steep slopes [29]. The increase in resistance provided by the roots can be included in the Mohr–Coulomb failure criterion as an additional cohesion, as defined in Eq. (3), where c_r represents the contribution of roots to soil cohesion [30].

$$\tau = c_r + c' + \sigma' \cdot \tan(\phi') \quad (3)$$

The contribution of roots to soil resistance depends on the plant species and the geometry of the roots themselves. However, previous studies point to values for root contribution ranging from 1.5 kPa in deforested areas to 94.3 kPa in natural forests [31]. Wildfires can damage crowns, trunks and roots of trees and shrubs, leading to the death of this vegetation and, consequently, to the loss of resistance provided by roots in the short to medium term [32] or to the decrease of soil layer thickness [33]. Root depletion can occur in two ways: by direct contact with flames, exposing them to extreme temperatures, especially in the first 5–10 cm of soil, or due to tree or shrub death caused by injuries during or after wildfires (diseases or pests) [32]. In the first case, roots die shortly after the fire, while in the second case, death can occur long after the forest fire. The process of reduction of root resistance reaches its minimum value 8–12 years after the tree death, which can favour instability phenomena [31, 32].

2.3 Climate changes' effects on post-wildfires slope stability

According to the most recent predictions [34, 35], climate changes in Mediterranean regions such as the Iberian Peninsula are expected to result in longer and more extreme periods of unusually dry weather causing serious droughts in large areas, as well as shorter but more intense storm-like periods of rain. Predictions and recent experience suggest that, while dry periods may result in uncontrollable wildfires during summer, extremely wet periods may follow in the subsequent winter seasons. Considering the relevant factors governing the problem of slope stability, namely the hydro-geological conditions and the characteristics of the natural vegetation, and how these can be affected by wildfires and by subsequent stormy periods, few doubts exist that climate changes certainly increases the risk of slope failure-related hazards [36]. Case studies like the ones shown in this paper can provide important evidence for future risk management in this field [37]. This is particularly clear in the research herein presented due to the unique sequence of meteorological events that occurred in Portugal after 2017 wildfires.

3 Materials and methods

3.1 Study area

The study area includes six municipalities located in the Portuguese central mountain range, known as Mon-tejunta-Estrela system, which includes the mountains

(*serras*) of Aire e Candeeiros, Sicó, Açor and Estrela. Arganil and Oliveira do Hospital are part of Serra do Açor, while Seia and Guarda are part of Serra da Estrela. Although, geographically, the municipalities of Penacova and Belmonte are not considered as part of this mountainous system, as they are borderline municipalities that were also harassed by the fire and climatic events, they are also included in the study area. All the municipalities are illustrated in Fig. 1, which also highlights the two main study sites of the present work. These study sites were chosen due to the amount of slope instability phenomena recorded and/or to the extension of the stabilization works carried out. The climate of Serra do Açor and Serra da Estrela are classified as a Mediterranean climate Csb type according to the Köppen-Geiger classification [38]. According to these authors, in general, these regions are characterized by dry and hot summers. The more frequent wind directions, namely in Serra da Estrela, are west and north-west [39].

3.1.1 Case study 1—Penalva de Alva

The first study site, hereinafter referred to as Case Study 1 (or CS1), is located in the municipality of Oliveira do Hospital, east-southeast of the city of Oliveira do Hospital, near the settlement of Penalva de Alva. Taking, as reference, the road intersection illustrated in Fig. 1, located 285 m above sea level at $40^{\circ} 20' 14.27''$ N and $7^{\circ} 49' 30.44''$ W Greenwich, the analysed slopes develop to the North, along the municipal road M506 towards the city of Oliveira do Hospital, to the West, along the municipal road M514 towards the settlement of Penalva de Alva, and to the West, along the Municipal Road M514 towards the settlement of São Gião. The inclination of the slopes varies between 17° and 45° , presenting an average inclination of around 30° . All slopes are oriented to the south and, according to ICN [40], there is a geological transition from the main formations of coarse-grained porphyritic two-mica granite (Seia granite) to schists formations with rare intercalations of greywacke stone (formation of the Rosmaninhal), with contact metamorphism. Near the study area, soils have been classified as predominantly shallow and stony soils (Umbric leptosol)

Fig. 1 Location of the study area and the two study sites, with indication of orientation and slope inclination, identifying the area burnt in 2017. Adapted from Viegas [43]

[4, 5]. This study site is characterized by an average annual rainfall ranging between 900 mm (Penalva de Alva) and 1200 mm (São João) over 110–120 days a year [41, 42]. Rain fall is more common from October to May, while July and August are dry months [39].

3.1.2 Case study 2—Santa Cruz

The second study site, hereinafter referred to as Case Study 2 (or CS2), is located in the municipality of Guarda, south of the city of Guarda. The slopes are located along the national road EN18 that connects Guarda and Belmonte, and although mitigation works were carried out over several kilometres, the analysed slopes are located at 2.5 km from Santa Cruz village, 755 m above sea level at 40° 28' 16.02" N and 7° 16' 36.48" W Greenwich. As Fig. 1 illustrates, the inclination of slopes varies between 22° and 45°, presenting an average inclination around 30°. The slopes are oriented to west-northwest, and they lie on granitic formations of medium- to coarse-grained porphyritic two-mica granite (Covilhã granite) [40, 44]. The cover soil in this region is classified as a Cambisol [43]. The average annual rainfall ranges between 1000 and 1200 mm over 90–110 days a year [41, 42]. The rainfall is also concentrated between October to May, being July and August the dry months [39].

3.2 Methodology

This study involved, firstly, collecting the most relevant information concerning the October 2017 wildfires using the database and the annual reports of the Portuguese Institute for the Conservation of Nature and Forest and the report commissioned by the Portuguese government to the University of Coimbra concerning the October wildfires (Reference?). Also, the most relevant meteorological data for understanding the pre- and post-fire situation were retrieved from the Portuguese Institute for Sea and Atmosphere reports concerning the relevant period of time (2017–2019).

The post-wildfire analysis of the instability phenomena that occurred in the study area, as well as the stabilization works carried out, is based on fieldwork to collect evidences of the various phenomena that occurred. The data presented results from the information collected in three local inspections. The first occurred in spring 2018, during the month of May, the month following the extreme rainfall events recorded. The second local inspection took place throughout summer 2019, and the last field visit was carried out in winter 2020, more precisely in January, after the occurrence of various storms by the end of 2019. The collected information is then cross-checked with the data

prior to 2017 provided by public institution and news from some of the most read local newspapers.

These three periods of inspection allowed not only to collect information about the slope instability phenomena but also to qualitatively assess the effectiveness of the stabilization techniques implemented in Case Studies 1 and 2.

4 Data collection

4.1 October 2017 wildfires

Since the beginning of the twenty-first century, almost 3000,000 ha of forest, bush and agricultural land burned, 20% of which as a result of the wildfires that occurred in 2017 [45, 46], namely due to two significant outbreaks in June and in October that caused a combined death toll of 111 and more than 300 injured and burned an area corresponding to 6.1% of the Portuguese national territory [47]. According to 2017 AON annual report, economic losses in Portugal due to wildfires totalled almost USD 1.2 billion, being declared by the local insurance sector as the costliest natural disaster in the country's history [47]. However, this problem affects all the globe, as the economic losses arising from natural disasters in 2017 were, according to AON, among the highest ever recorded on a comparable basis, the wildfire hazard having its costliest year on record for the insurance industry and causing overall economic losses in excess of USD 21 billion [17]. This was mostly due to major outbreaks in California and in Southern Europe, which suffered the largest extent of land burned since the earliest records dating back from 1980, in excess of one million ha.

In October 2017, 2945 wildfires events were registered in Portugal, having consumed 223,901 ha, 144,527 ha of forest and 79,374 ha of bushes. Among these, 38 wildfires with a burnt area over 100 ha started between the 14th and the 16th of October, consuming a total of 207,948 ha. In other words, 47% of the burnt area in Portugal in 2017 originated from fires that broke out in this time interval. In the study area, 80,610 ha of forest and bushes burnt, of which 23,641.5 ha were classified as national forest or were part of the protected area of the Serra do Açor or the National Park of Serra da Estrela [48]. It should be noted that, while the burnt area and the following consequences in Case Study 1 resulted from the October fires, the fire at the origin of Case Study 2 occurred on the 27th of August and a total of 303 ha of forest and bushes burnt [48]. The burnt area in 2017 is illustrated in Fig. 1. Taking into account the last major wildfires that ravaged Serra do Açor and Serra da Estrela (1987, 1991, 2005 and 2017), the return period of such events in the study area is about 13 years, which

agrees well with the information for other Mediterranean mountain regions [5].

After the 2017 wildfires, namely the ones occurred in October, the Portuguese Institute for the Conservation of Nature and Forest (ICNF) carried out an assessment of the needs for intervention in the affected areas, in order to mitigate the direct and indirect consequences of the fires. The total intervention costs in the area under consideration amounted to more than EUR24.3 million, of which EUR 9.3 million were intended solely to the recovery and stabilization of slopes [49–52].

4.2 Climatic events after October 2017 wildfires

As previously mentioned, slopes instability events are usually triggered by rainfall events [12, 15]. However, meteorological drought conditions also create favourable conditions for instabilities to occur. Not only drought can weaken roots strength over time, but also reduce the capacity of a slope to store sediment by reducing the protective soil cover [53]. This author also mentions that drought and fire have broadly similar effects. Additionally, the drought effects on rainfall-related slope instability events should not be overlooked [54], namely when extreme rainfall occurs [55]. As stated by Lee et al. [54], slaking-induced instabilities, i.e. repeated wetting and drying cycles affect slope failure mechanisms. 2017, 2018 and later, at the end of 2019 were characterized by the occurrence of extreme climatic conditions and events. The next sections briefly describe these conditions, given special emphasis to the study area.

4.2.1 2017 meteorological drought

According to the Portuguese Institute for Sea and Atmosphere (IPMA), the year of 2017 was the second warmest and the third driest, in Portugal, since the installation of the observation network in 1931 [56]. Indeed, the average air temperature was 1.07 °C higher than the 1971–2000 reference period, namely during the month of October, which was the hottest of the last 87 years, anomalies of 4 °C or higher being registered. Additionally, the lack of precipitation led to a situation of meteorological drought in 99% of the territory.

Two heat waves occurred in October: the first from the 1st to the 16th and the second between the 23rd and the 30th. These heat waves covered the entire territory, with greater incidence in the interior of Portugal Mainland. The first heat wave is considered one of the longest heat waves for October [56]. On the 15th of October, the day when most of the wildfires started, namely in the study area [48], Hurricane Ophélie passed close to the Iberian Peninsula, bringing strong and warm winds, worsening the

already unfavourable weather conditions. These events created the ideal conditions for the occurrence of massive wildfires.

The situation of meteorological drought continued until the end of the year. By the end of 2017, even with the passage of storm Ana through Portugal Mainland, 6% of the territory was in extreme drought, 58% in severe drought and 29% in moderate drought. The meteorological drought of 2017 was different from the six previous historical drought situations because it started later, by the end of June, and worsened in the autumn, with 97% of the country in severe or extreme drought in November [56]. The drought continued for the first two months of 2018. By the end of February 2018, 83% of the Portugal Mainland was in severe drought and 1% in extreme drought [57].

4.2.2 2018 extreme rainfall events

2018 spring has been classified as cold and extremely rainy [57]. Between March and May, the average precipitation was 429 mm, which corresponds to 200% of the regular average, being the third rainiest spring since 1931. During the month of March, two tornados were registered, and the heavy rainy period made this month the second rainiest since 1931. It should be noted that the highest amount of precipitation in twenty-four hours occurred in Covilhã. Although this municipality is not part of study area, it integrates, together with the municipalities of Seia and Guarda considered in the present study, the Natural Park of Serra da Estrela (UNESCO Geopark Estrela) as well as Serra do Açor. On the 9th of March, a total of 92 mm of rain was measured in Covilhã.

In the meteorological station of Penhas Douradas, located in the municipality of Manteigas, a small municipality between Seia and Guarda (Fig. 1), which is also part of the Natural Park of Serra da Estrela, a total precipitation of 585 mm was recorded, being the highest values since the beginning of data collection at this station [57]. In fact, the highest values for the total precipitation and the daily maximum precipitation was registered in the district of Guarda, in which a vast area of the Natural Park of Serra da Estrela is located [58]. The spatial distribution of the total precipitation in March reveals that, at Case Study 1, 400–500 mm of precipitation was recorded and, at Case Study 2, 300–400 mm of precipitation was recorded. These values represent 400% more precipitation than March average. According to IPMA, these precipitation events put an end to the severe drought condition in Portugal.

April was considered the fourth rainiest month in Portugal since the beginning of the 3rd millennium [57]. In the area of Case Study 2, the monthly total precipitation was lower than in March, the values measured (50–100 mm) being in line with the average values for April. In the area

of Case Study 1, a total precipitation of 150–200 mm was recorded, which represents 125% of April's average [59]. Also, before the end of the year, Hurricane Leslie caused widespread damage in Portugal due to extreme winds and rain, especially in the centre of Portugal. The district of Coimbra, which includes the municipality of Oliveira do Hospital is part, was one of the most affected areas. In the study areas, wind velocities between 90 km/h and 110 km/h were recorded [57].

4.2.3 2019 drought and storms

2019 was considered the second hottest year since 1850 [60], being the hottest year in Europe. In Portugal, 2019 has been classified as hot and dry, but it stands only as the 26th hottest year since 1931 [61]. A meteorological drought was registered throughout Portugal Mainland from January to October. The study area registered the largest thermal anomaly in the territory, rising to 1.5 °C above the normal value considered for the period of time 1971–2000. The total precipitation in Portugal reached only 86% of the normal value for the aforementioned period of time. However, its spatial distribution reveals that the Natural Park of Serra da Estrela was the Portuguese region with higher values of precipitation, having been registered value 150–200% above the normal value [61].

Between the 15th and the 22st of December 2019, Portugal was ravage by three consecutive storms, named Daniel (15th–17th), Elsa (18th–20th) and Fabien (21st–22nd) [61]. The weather station located in Guarda registered a precipitation three times higher than the average value for December and 1.5 times higher than the average for winter (December, January and February). In several location in the centre and the north of Portugal, namely at the greatest altitudes, precipitation values accumulated in 24 h over 100 mm were recorded, reaching, on the 16th of December, an absolute maximum of 141.9 mm in Guarda weather station. During the aforementioned 7 days, a total precipitation higher than 200 mm and 300 mm were recorded in Serra do Açor (Case Study 1) and in Serra da Estrela (Case Study 2), respectively. For the same period, the weather stations of Guarda, Covilhã and Penhas Douradas, located in Serra da Estrela and Serra do Açor, registered 440.1 mm, 399.6 mm and 374 mm of accumulated precipitation, respectively. By the end of December, the study area had a Palmer Drought Severity Index of extremely wet [62].

5 Instability phenomena and protection measures adopted

The post-wildfire instability phenomena are complex and depend, as mentioned in previous sections, on several interrelated factors. Therefore, it is not obviously difficult to identify which phenomenon is the most dominant for each specific case. Some authors suggest that although all erosion and sediment transport processes are possible, a few will dominate at a particular time in response to the characteristics of the wildfire, precipitation and hydro-geomorphic regimes [27].

After October 2017 wildfires, the great majority of typical instability phenomena could be observed in the study area, namely in Case Study 1. It should be noted that, to mitigate and prevent such effects, the Portuguese Institute for the Conservation of Nature and Forest [63] and local city councils [64] carried out stabilization works along the slopes in both study sites during the month of December 2017.

5.1 Registered and observed instability phenomena

To better understand the number of occurrences as well as the magnitude of some of them, a brief historical context of the case studies is necessary. In Oliveira do Hospital, only two references to slope instabilities occurring before 2017 were found. Both events occurred in March–April 2013 [65, 66], but only one of them took place near Penalva de Alva, where Case Study 1 is located. It should be noted, however, that during 2012, this municipality was also ravaged by wildfires and several reforestation actions were taken from May 2013 onwards [67, 68]. After the October 2017 wildfires, the number of instabilities registered increased significantly. By the end of 2017, with the passage of storm Ana, and according to the local chief of civil protection [69], dozens of instability phenomena were registered, namely through Alva Valley. It should be noted that these events took place less than three weeks after the first stage of implementation of mitigation measures along the Alva Valley slopes. Later, by the end of 2019, after the passage of storm Elsa, the emergency plan was activated in Oliveira do Hospital due to the several events that occurred [70]. More than 42 slope instabilities requiring geotechnical works were recorded in Oliveira do Hospital, 19 of which in the surroundings of Case Study 1. Seven of these events occurred along the municipal road M514, which cross this first study site. The damages to municipal infrastructures in Oliveira do Hospital amounted to EUR 3 million, EUR 450,000 of which being spent on the recovery

of the slopes along the M514 road and this municipal road itself.

The data available concerning Case Study 2 is more limited. Prior to 2017, no instability phenomenon was reported by the local media. Only in 2018, more precisely, in March, a landslide was recorded along the national road EN 18 [71]. This event took place 3 months after the stabilization works, which cost EUR 120,000 [72]. Later, in December 2019, other instabilities occurred, which were registered during the third technical visit to this second study site.

5.1.1 May 2018 local inspection

During and/or after March and April 2018 rainfall events, slope instability event took place all over the study area. The effects of such events could be seen at various locations of the Portuguese central mountain range, such as sheet erosion (Fig. 2a) and landslides (Fig. 2b) phenomena along Serra do Açor. Sheet erosion is one of the most common effect of rainfall events. After forest fires, soil surface is exposed to the physical action of climatic condition, namely rain, due to the disappearance of the vegetation cover that protected the soil. The impact of raindrops on soil is one of the most obvious processes of soil disaggregation, which, combined with runoff along the slope, leads to sediments transportation and/or surface landslides [27]. The occurrence of these phenomena depends, essentially, on the slope inclination as well as on the duration and intensity of the rainfall event recorded at a certain time. It should be noted that the soil disaggregation processes depend largely on the void ratio of soils [27], being more pronounced in loose soils.

The influence of the protection provided by the vegetation cover is very clear. In Fig. 2a, on the left side of

the slope, vegetation has grown up and no sheet erosion occurred. The absence of vegetation cover on the right side allowed the occurrence of surface erosion due to water runoff along the hill. It should also be noted that the outer and inner limits of this instability phenomena are also influenced by small vegetation islands along the slope. Although more examples of slope instabilities were observed and registered along Serra do Açor and Serra da Estrela, considering the large number of occurrences, the simple access to the affected area and the significant stabilization work carried out, the next examples focus only on Case Study 1.

Along municipal roads M506 and M514, several instability phenomena were registered, whose impacts range from negligible to severe. The less severe occurrences were dry ravel examples, such as the one illustrated in Fig. 3. Along the slopes in Case study 1, several examples of dry ravel could be seen. Non-singed particles over the burnt area confirm the sediment movements along the slope

Fig. 3 Unburnt particles (pebbles) along the municipal road M514 slope towards Penalva de Alva (Case Study 1)

Fig. 2 Intense rainfall consequences along the study area: **a** sheet erosion at Ribeira de Gualdim (Arganil); **b** landslide at Oliveira do Mondego (Penacova)

from higher positions. Evidences of these kind of instability were usually found on the bottom of slopes, in the ditches of roads.

Dry ravel is a generic term that describes the downward movement of individual particles rolling, sliding or jumping along slopes. This process, which is typical of arid and semi-arid areas, where vegetation coverage is scarce, can also be originated during or immediately after a fire [73]. In fact, burnt vegetation exposes areas of accumulated sediments under the vegetation cover, which tend to move along the slope. In this process, the fragmentation and transport of sediment depends more on gravity, wind and animal activity than on water, under normal raining conditions [73]. Large amounts of sediment can be mobilized and, being a phenomenon independent of precipitation, its study is important for understanding the response to erosion after forest fires, especially when temperature increases or when periods of drought or future wildfires events are expected [27].

Another phenomenon registered along the slopes of Case Study 1 is the evidences of rill erosion occurrence as well as gully erosion. Rill erosion is defined as an erosive process by which the flow accumulates in narrow channels recurrently and, in short periods, removes the soil from this narrow area to considerable depths [74]. It is estimated that this type of erosion in burnt areas of high severity reaches scales three orders of magnitude higher than those occurring in non-burnt areas [27]. According to the same authors, the magnitude tends to decrease with time due to changes in the availability of sediments to be transported. The intense rainfall events of March and April 2018 aggravated some of these channels, having evolved to gully erosion, as illustrated in Fig. 4a. This picture was taken on the side of municipal road M514, towards São Gião. The disappearance of the vegetal layer led to the accumulation of the water runoff on a single channel that is progressively directed towards the interior of the soil

mass. It should be noted that, gully erosion phenomena in this region are not new. The destruction of vegetation caused by the October wildfires made it possible to identify more examples of gully erosion occurrence, such as the one illustrated in Fig. 4b. As illustrated, most of the extension of the gully remains burnt despite the rainfall events.

The previous examples of slope instability phenomena are only a small example of the events registered in the Alva Valley slopes. Indeed, the great majority of the recorded events were landslides. Landslide stability depends on the shear resistance of soil, which, by applying Mohr–Coulomb failure criterion, is a function of the angle of shear resistance and the cohesion of the soil mass. This criterion may be extended in order to contemplate the surplus of shear strength provided by roots, as expressed in Eq. (3). In a first phase, wildfires destroy trees and shrubs, leaving the soil uncovered, which facilitates water infiltration. The increase in soil water content, besides increasing the slope weight itself, reduces the effective stress in the soil and its shear resistance. Later, the deterioration and death of roots lead to an increase in the probability of deep landslides [27]. According to these authors, it is estimated that the surplus resistance provided by roots reaches its minimum value eight to twelve years after the death of the tree or shrubs. Along the municipal road M514 towards São Gião (Case Study 1), wildfire effects on tree roots and on the stability of slopes following the October 2017 forest fires could easily be seen (Fig. 5). The figure shows how the death of the most superficial roots lead to shallow landslides, which uncover deeper and thicker roots of larger vegetation. This phenomenon is also aggravated by the increased erosion along the slope surface, namely during periods of heavy rain.

Several examples of landslides were observed along the slopes in Case Study 1. Along the M514 road, the vast majority of landslides were shallow landslides. However,

Fig. 4 Gully erosion in Case Study 1: **a** new phenomenon as consequence of October 2017 wildfire and subsequent extreme rainfall events; **b** older phenomenon, accentuated by the events of 2017 and 2018

Fig. 5 Example of reduction of soil shear resistance due to the death of roots after October 2017 wildfire (Case Study 1)

as they took place next to this infrastructure, the consequences were more serious, culminating with restriction in traffic to allow cleaning works. Figure 6 illustrates some of these instability events, the original slopes being very steep with inclination higher than 35° , which, according to Ancey [75], are prone to surface erosion and the occurrence of landslides. Figure 7 shows more shallow landslides registered along municipal road M514. In fact, for over more than 1 km, the embankments on the roadside showed clear signs of surface erosion and/or recent landslides. In addition to these superficial landslides, it was possible to identify at least one deep landslide, which took place near the top of the hill. Luckily, it occurred in an area far from any infrastructure or structures.

All the instability events illustrated in Figs. 3, 4, 5, 6 and 7 to took place in slopes orientated south or south-east. This information differs from what some authors state that slopes facing north and north-west are more prone

Fig. 7 Shallow landslide along municipal road M514 towards São Gião and deep landslide that occurred close to the top of the hill (Case Study 1)

to geomorphological instabilities [10], but supports the opinions of the authors who argue that the relationship is weak or meaningless [76].

5.1.2 January 2020 local inspection

This technical visit to the two study sites took place some days after the storms Daniel, Elsa and Fabien ravaged Portugal Mainland, namely the centre of Portugal, as described in Sect. 4.2.3. The consequences of these storms were more severe in Case Study 1. Along the municipal road M514, towards São Gião, the several instability phenomena led to the closure of the road for several weeks, while the emergency repairs were not concluded. From the roads M506 and M514 intersection, dozens of

Fig. 6 Shallow landslides registered in Case Study 1 along: **a** municipal road M506 towards Oliveira do Hospital; **b** municipal road M514 towards São Gião

events could be observed. Although most of the events were superficial, such as those illustrated in Fig. 8, others required more precautions, since the integrity of the municipal road M514 was at stake. As shown in Fig. 9, the severity of the situation required the design of geotechnical solution in order to assure the stability of the slope and the road itself. Along municipal road M506, towards Oliveira do Hospital, no instability phenomenon was recorded and along municipal road M514, towards, Penalva de Alva, a couple of phenomena occurred. However, all the events were superficial erosion phenomena with no serious consequences.

In Case Study 2, along the national road EN 18, two major instability phenomena were registered, which led to the closure of the road for a couple of day for cleaning operations. The first event, illustrated in Fig. 10a, was a

shallow landslide in a rocky slope, being an example of an infinite slope. This occurrence may be related to the loss of soil reinforcement provided by the roots between the wildfires 2017 and the December 2019 storms. The second occurrence, which was the most significant, was the failure of a 6 m height gravity wall made of stone (Fig. 10b). Although this failure is not a slope instability-related phenomenon, the causes of this event cannot be dissociated from the consequences of the 2017 wildfires and the stabilization solutions adopted. Although the adopted barrier ensured the maintenance of soil behind it, in front of it, due to the absence of vegetation protection layer, longitudinal fissures developed, which allowed water to infiltrate behind the wall. The increase in hydrostatic lateral pressure and lateral earth pressure

Fig. 8 Instability phenomena registered after December 2019 storms in Case Study 1: **a** surface erosion; **b** shallow landslides

Fig. 9 Deep landslide occurred on municipal road M514 (adapted from Irmãos Lopes & Cardoso Lda [77]): **a** situation after December 2019 storms; **b** adopted solution to stabilize the road and slope

Fig. 10 Instability phenomena recorded along national road EN18: **a** infinite slope landslide; **b** gravity wall failure

due to the increase of soil weight led to the failure of the wall.

5.2 Mitigation techniques applied to protect slopes

Various stabilization solutions were employed to promote slope stability. A summary of the techniques adopted in Case Study 1 and 2 after 2017 wildfires is presented in this section. It should be noted that, despite the high surface burnt each year in Portugal, post-fire soil stability treatments have been rarely applied [6], granting even more interest to the two study sites.

5.2.1 Temporary barriers for erosion control

Erosion control barriers, made from natural or man-made materials, have been used for decades to mitigate the effects of erosion and surface landslides [24].

These structures are designed to: (1) promote infiltration (thus reducing water flow along the surface); (2) storing sediments; and (3) reducing sediment movements on burned slopes [78]. When the burned areas are very wide and trunks of trees are hopelessly burned, these trunks can be used as barriers, as observed in Case Study 1 (Fig. 11a). In the absence of large trunks, identical eco-friendly solutions can be developed using smaller trunks and burned branches, as also observed in the same location (Fig. 11b). It should be noted that the stabilization work illustrated in Fig. 11 did not occur along all the municipal roads. In fact, the municipal road M514 towards São Gião, i.e. from the reference road intersection to north-east, none of the slopes were submitted to any stabilization work. These interventions only took place along the municipal roads M506 and along M514, towards Penalva de Alva (from the referents road intersection to south-west). Also, the stabilization techniques were only applied to the northern slopes of the aforementioned roads. On the downstream slopes of both

Fig. 11 Temporary barriers for erosion control in Case Study 1: **a** treatment of wide extension; **b** local treatment along the excavation slopes of the municipal road M506

municipal roads M506 and M514, despite the serious problems described, no stabilization works were carried out.

When small amounts of sediment are to be retained or in areas with low availability of natural material, the previous barriers can be replaced with nylon barriers with straw. These structures are permeable, retaining surface landslides and reducing flow velocity. Like the barriers made of trunks or burned branches, nylon barriers are placed along the contour lines and are kept in place thanks to small piles [78]. This solution was adopted to mitigate erosion effects and surface landslide along the national road EN18 in Case Study 2 (Fig. 12).

Fig. 12 Temporary fibre rolls installed along national road EN18, in Case Study 2

5.2.2 Mulches

Mulches, which are frequently used for agricultural purposes, usually consist of organic material spread on the surface to be protected. Its application as a post-wildfire emergency treatment has been increasing because its stabilizing effects are immediate [24]. This technique is often used in conjunction with seeding, enhancing soil infiltration capacity, soil moisture content and the soil ability to retain larger soil particles. There are two main types of cover: dry mulch and hydromulch [24]. Although there are references of application of the second technique in some regions of the centre of Portugal [79], after the forest fires of October 2017, only the application of dry mulch is known in the Natural Park of Serra da Estrela.

In Mata do Desterro, in the municipality of Seia, both stabilization with temporary barriers and mulch were carried out. As can be seen in Fig. 13a, the use of dry straw creates a vegetation cover layer and it was also used in erosion control barriers together with existing burned vegetal residues. In Case Study 2, slopes of the roads embankments built to allow the installation of the temporary nylon barriers along the national road EN18 were protected by nonwoven geotextile and straw (dry mulch) (Fig. 13b).

5.2.3 Channels treatment

Barriers in channels are structures made up of stones and sticks, among other materials, which are installed to reduce water flow velocity and to retain sediments, especially during the first rainy season following wildfires. These barriers, which are usually built during slopes stabilization works, should be small in size in order to reduce the risk of failure and possible downstream damaging consequences.

Fig. 13 Slopes protection examples: **a** temporary barriers and dry mulch in Mata do Desterro in Seia; **b** use on nonwoven geotextile and dry mulch along the national road EN18, in Case Study 2

Fig. 14 Channel barrier installed in Case Study 2

During the stabilization of slopes along the national road EN18, in Case Study 2, several channel barriers were built both in natural water channel and in firebreaks opened to place others slope protection measures. An example of such channels barriers is illustrated in Fig. 14.

6 Effectiveness of the implemented stability measures

A qualitative evaluation of the performance of the different mitigation techniques implemented in order to avoid instability phenomena in natural and man-made slopes, after extreme wildfires, in the areas of Case Studies 1 and 2, enabled assessing their effectiveness under field conditions. Other stability measures can also be used in similar circumstances, such as creation of infiltration opportunities [78] or chemical treatment of soil [24]. However, such solutions were not employed in the study area. When choosing and sizing the adopted solution, several aspects must be taken into account, among which the costs, the human and material resources needed and the simplicity of application. However, considering that the decision is taken in a context of emergency and provided that basic financial and environmental conditions are met, the most important feature to consider is the time that each measure requires to be effective. In fact, some solutions are not effective in the first year, only reaching their objectives 2 years after their implementation [80]. Therefore, this study was carried out for a long period after the implementation of the measures, namely after extreme weather events that were particularly challenging with respect to slope instability phenomena.

From a general perspective, cover treatments, namely the straw used in Natural Park of Serra da Estrela (Case

Study 2 and Seia), tend to present a better performance because they have a broader field of application. According to Napper [80], this solution fully meets the surface protection of slopes by reducing erosion processes, increasing vegetation cover, improving moisture retention and increasing infiltration of water. It also provides surface roughness, which reduces water runoff velocity. None of the other most usual treatments (hydromulch, slash spreading or seeding) achieve better results than straw mulch. Concerning barrier treatments, the solutions applied in Serra da Estrela region usually present identical performances that are often below expectations. In fact, both log erosion barrier and fibre rolls tend to achieve only part of the desired results [80]. When compared to straw mulch treatment, barrier treatments are considered to have a worse performance in reducing erosion and increasing infiltration. However, the latter allows trapping sediments and they reduce the length of the slope from the perspective of instability phenomena. Regarding the channel protection measures, independently of the technique selected, the accumulation of sediments and the reduction of both flow velocity and sediment delivery are usually achieved. Although log check dams as the ones built along the national road EN18, in Case Study 2, are not the most suitable solutions, these simple, cost-effective and environmental friendly measures tend to attenuate peak flows [80].

The qualitative evaluation of the effectiveness of the stability solutions implemented in the study area is mostly based on the visual inspection and the photograph report carried out during the second and the third technical visit to the study area. These two visits allowed not only to assess the effectiveness of the applied techniques from the point of view of the environmental visual impact, namely during the visit carried out during summer 2019, but also from a stability point of view, thanks to the distinct geotechnical response of identical protected and unprotected slopes observed in Case Study 1 in winter 2020.

6.1 Environmental integration of the adopted solutions

By the end of summer 2019, along the municipal roads M506 and M5014 (Case Study 1), the adopted solutions to treat both wide and localized areas fulfilled the objective they were designed for and were barely visible. As it can be seen in Fig. 15, slopes were already covered with vegetation and small bushes. Even the steepest slopes did not show any signs of instability phenomena. No significant amount of debris could be found along the side road ditches, which proves that the temporary barriers retained sediments during the rainiest periods of 2018/2019 winter and spring.

Fig. 15 Temporary barriers installed in Case Study 1: **a** dead trees barriers; **b** small branches and bushes barriers

Fig. 16 Environmental integration of the mitigation measures adopted in Case Study 2: **a** fibre rolls integrated in the landscape; **b** fibre rolls location and damages after cleaning works; **c** channel barriers integrated in the landscape; **d** channel barriers after cleaning works

Identical situation was found in Case Study 2, the majority of the temporary nylon barriers installed along the national road EN18 slopes being imperceptible from the road (Fig. 16a). In fact, vegetation reclaimed all the available land and the slopes surfaces were again covered by bushes and grass. The firebreaks that were opened as part of a land management strategy and that allowed the installation of the temporary barriers hampered climbing to higher grounds to check the integrity of the barriers. This situation clearly evidences the effectiveness of the adopted solution to protect slopes from soil erosion and other shallow instabilities. Even if this solution is not primarily intended to enhance land cover, 2 years after the October 2017 wildfires, local flora grew up and fully covered the slope, suggesting that the loss of organic cover was minimized. Also, the channel barriers were swallowed up by the vegetation (Fig. 16c). As far as it was possible to verify, none of the barrier failed during the 2018/2019 winter and spring. In a UNESCO geopark area as Serra da Estrela, this landscape integration of mitigation measures is primordial.

6.2 Qualitative assessment of the effectiveness of the adopted solutions

The assessment is based on the field observations during the third and last technical visit to the two study areas. In Case Study 1, as previously presented in Sect. 5.1.2, after December 2019 storms, several instability phenomena were recorded. These instabilities, some of which are illustrated in Figs. 8 and 9, occurred along the municipal road M514 towards São Gião. As previously stated, apart from minor rain-flow and dry ravel occurrences no significant instabilities were recorded along the municipal roads M506 and M514 towards Penalva de Alva. Taken into account that the study area is less than 2 km long and the geological conditions, the slopes inclinations and environmental conditions are identical; the distinct response of the slopes along Case Study 1 to the extreme rainfall event of December 2019 can only be explained by the effectiveness of the mitigation measures under the particular field conditions at the site. This observation is reinforced by the fact that there is no previous history of slope instability phenomena in the study side. According to the collected data, prior to October 2017, only one reference to an instability phenomenon was found in Case Study 1, which unsurprisingly also occurred sometime after wildfires affected the area.

A second interesting observation should be pointed out from the third technical visit carried out. As Fig. 9 illustrates, the most severe slopes instability recorded in the study site located in Oliveira do Hospital (CS1), occurred on the downstream slope of municipal road M514 towards

São Gião. Surprisingly, no technical intervention was planned for the downstream slopes after the October 2017 wildfires. This may be justified by the common belief that infrastructures below burnt areas are more prone to wild-fire risks [23]. However, attending the severity of the fire as well as the instability phenomena identified downstream of the road, such as gully erosion illustrated in Fig. 4b, more attention should have been given to this side of the road to avoid the landslide that nearly destroy municipal road M514.

In Case Study 2, between the second and the third visit, cleaning works of slopes along the national road EN18 were carried out. With these maintenance works, all the stabilization measures implemented became visible again (Fig. 16b). As it is indicated in this figure, the only noticeable damages on the temporary barriers were inflicted by the cutting machinery used to clean the vegetation. Some of the meshes of the fibre rolls were cut but no significant straw was lost. Concerning the channel barriers, none of the inspected barriers presented damages and all of them had sediments trapped behind them, as illustrated in Fig. 16d.

Figure 10 shows two major landslides that occurred in this study area, which caused safety problems and limitations to traffic along national road EN18. Since no instability phenomena were reported before the wildfires of 2017, these events cannot be dissociated from the fire effects in the natural slopes. Since both the affected slopes had been stabilized with fibre roll barriers (Fig. 10b), the effectiveness of this mitigation measures is limited for the conditions found in situ. However, in both cases, it is possible to see that the instability took place downstream the fibre roll, which partially reduced the consequences of the instability. The crest of the landslide is located after the temporary barrier, which was not damaged. The roots of the vegetable layer, even if made up of herbaceous vegetation, prevent the opening of cracks, which will lead to greater infiltration of water. In more impervious soils, such as clayey or organic soils, these cracks not only allow water to accumulate, giving rise to hydrostatic lateral pressure at the top of slope, but they also establish the beginning of potential slip surfaces with no mobilized shear strength. In geotechnical engineering, whatever the approach (effective or total stresses) or the applied method to the slope stability problem, these two factors always lead to a decrease of the safety factor of the slope in stability analysis. Thus, even if the vegetable layer does not provide any significant reinforcement, it protects the surface from soil erosion and avoids cracks and the aforementioned problems.

The response of the barrier protection observed in both case studies contradicts what is generally established for this technique. According to several authors, log barriers

tend to be ineffective unless rain events are few and small [6]. The main factors pointed out for this malfunction are the lack of contact between the erosion barriers and the ground surface and their displacement along the slope due to downward movements [81]. In Case Study 1, no damage or displacement could be seen in the shrubs and branches barriers and, in Case Study 2, the only visible damage was due to the cleaning operation of the slopes. At this second study site, the fibre roll barrier still properly installed and anchored to the piles driven into the ground to support them (Fig. 16b). Giving the extreme rainfall events that took place in March 2018 and December 2019, it is possible to conclude that the adopted solution to stabilize the slopes in the study area was well designed and effective.

7 Conclusions

Wildfires are becoming more frequent and intense in many regions around the globe due to climate, demographic and land-use changes. In addition to the more immediate and visible human and economic losses and environmental and social consequences, amongst others, caused by devastating wildfires, other long-term effects may increase the risk related to this natural hazard. Wildfire-induced slope instabilities, for example, may amplify the consequences and the duration of the social, economic and environmental distress caused by the original event.

Portuguese central mountain range, known as Montejunto-Estrela system, is a fire-prone area where major wildfires have a return period of about 13 years, which agrees well with the data from similar Mediterranean regions and enhances the importance of suitably managing wildfire-related slope instability phenomena. The last significant event occurred in 2017, when more than 80,000 ha of forest and bushes of Serra do Açor and Serra da Estrela were devastated by uncontrolled wildfires. The extreme rainfall events that occurred in the following years, namely in March 2018 and December 2019, increased the effects of the 2017 wildfires with respect to slope instability phenomena. This sequence of extreme natural events created the unique conditions for studying the effects of wildfire-induced slope instability phenomena and the effectiveness of relevant mitigation measures under realistic local field conditions. This paper presents and discusses the data observed during a period of over 2 years in two study areas, located in the municipalities of Oliveira do Hospital (Case Study 1) and Guarda (Case Study 2). Even if the research is mostly based on qualitative evaluation obtained through three field trips covering relevant periods, the fact that the

observations include different instability phenomena and mitigation measures and were carried out during a long and particularly challenging period of extreme weather events offers a unique opportunity for enhancing our current understanding on these problems in the field.

The study identified various types of slope instabilities, ranging from dry ravel, sheet and gully erosion to shallow and deep landslides, which caused significant environmental impacts and seriously affected the use of local roads for significant periods of time, with obvious economic and social implications. In addition, the observations at the two sites prove that:

- Many of the observed instabilities occurred with the first extreme rainy event, which supports the current belief that mitigation measures should be applied as soon as possible after the wildfires occur because the vulnerability of the slopes is maximum when vegetal cover has not yet recovered;
- Untreated sites that remained stable during the first extreme climate events underwent some slope instability phenomena some years after the wildfire, namely as a result of storm Elsa, which suggests that the negative effects of wildfires decrease slowly with time;
- Although deep landslides occurred, shallow landslides, that occurred in great numbers, caused larger and long-lasting disruption of local roads operation;
- Unlike observed by other authors in other locations, there is no evidence that the slope direction has an effect on the extent of slope instability phenomena observed in the studied areas, which suggests that other local conditions play a more important role than the slope direction;

The study also assessed the performance of several mitigation measures applied to stabilize the slopes affected by the wildfires, particularly channel protection and protection barriers. The observations demonstrate that:

- Treated slopes performed generally better than untreated slopes, irrespective of the mitigation measure selected;
- The effectiveness of the mitigation measures applied is unaffected by time, even if extreme climate events occurred during the period under consideration and some man-made damage was caused;
- From the environmental point of view, all the mitigation measures applied showed great visual integration with the local landscape, being virtually imperceptible soon after installation;
- Protection barriers, whether made of fibres or wood, showed the best overall performance with respected

to slope stability, contrary to the conclusions presented in other study sites in other countries, which suggests that the effectiveness of this mitigation measure depends on the local geological, topographic and climate conditions.

The results suggest that simple, economic and environmentally-friendly mitigation measures can strongly reduce the number and/or the consequences of instability phenomena induced by wildfires, even if several extreme winter events occur after the implementation of the solutions. As a result, the current practice in wildfires-prone countries like Portugal of not applying mitigation measures should be radically changed.

Finally, it should be noted that despite of the fact that most of the stabilization works observed were funded by public investment, several stabilizations works were also carried out on private land. This proves that civil society is alert to the problems associated with slope stability after wildfires and also that it empirically recognizes the benefits of applying mitigation measures in situ. However, the lack of scientific information is still notorious, which limits the ability to make the most suitable decisions after such severe events. A practical implication of this study is that, unlike the current practice of cutting all burned wood in order to reduce some of the immediate losses, owners should be advised to use part of it to construct mitigation measures, ensuring soil protection and allowing a faster plant generation, particularly in soils susceptible to erosion.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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