Road Network Exposure to Deep-Seated and Shallow Slides at the Basin-Scale (Grande da Pipa River Basin, Portugal)

Igor Branco, Sérgio C. Oliveira, and Raquel Melo

Abstract

Landslides are well-known for their destructive capacity; however, risk only exists if an interaction with people, activities, structures and infrastructures occurs. When landslides affect roads and potential human losses, both road damage and road disruption can cause significant economic losses. Therefore, in the framework of spatial planning, civil protection, emergency and risk management and the evaluation of road network landslide exposure is necessary. The primary goal of this work is to assess the present road network exposure to deep-seated and shallow slides at the Grande da Pipa River basin (North of Lisbon region, Portugal), an area naturally prone to geomorphological hazards. Our approach to assessing road network exposure is sustained by two different dataset inputs: (i) three landslide susceptibility maps and (ii) one road network map. The susceptibility to landslides, computed with the Information Value method and validated with success and prediction rate curves, as well as with the estimation of the area under the curves, was individually assessed for deep-seated rotational, shallow rotational and shallow translational slides. The road network exposure to each landslide type resulted from the intersection between the two top landslide susceptibility classes and the classified road network according to its rank, allowing the critical road sections to be identified. The road network is mainly exposed to deep-seated rotational slides. However, the other landslide types can also disrupt the road functionality and affect residents and economic activities.

Keywords

Deep-seated and shallow slides • Road network • Susceptibility • Exposure • Basin-scale

1 Introduction

Risk, as considered by the conceptual model of risk, equals the crossing of a hazard with the value of the elements at risk through their vulnerability (Zêzere et al., 2008). Identifying each of these components is very important to the risk analysis. However, identifying elements at risk is possibly the most crucial step in risk assessment (Zêzere et al., 2008). The area north of Lisbon is one of Portugal's most critical landslide-prone areas, and landslides have been responsible for road damage in the last decades (Zêzere et al., 2007). When landslides affect roads and potential human losses, both road damage and road disruption can cause significant economic losses. The primary objective of this research is to evaluate the present road network exposure to landslides (REL) and to identify critical road sections (CRS) at the Grande da Pipa River (GPR) basin (North of Lisbon, Portugal), an area naturally prone to geomorphological hazards (Oliveira et al., 2015), represented in Fig. 1.

2 Materials and Methods

Our approach to assessing REL is sustained by two different dataset inputs: (i) three landslide susceptibility maps and (ii) one road network map. Three slide inventories and seven predisposing factors were applied to assess the susceptibility to landslides.

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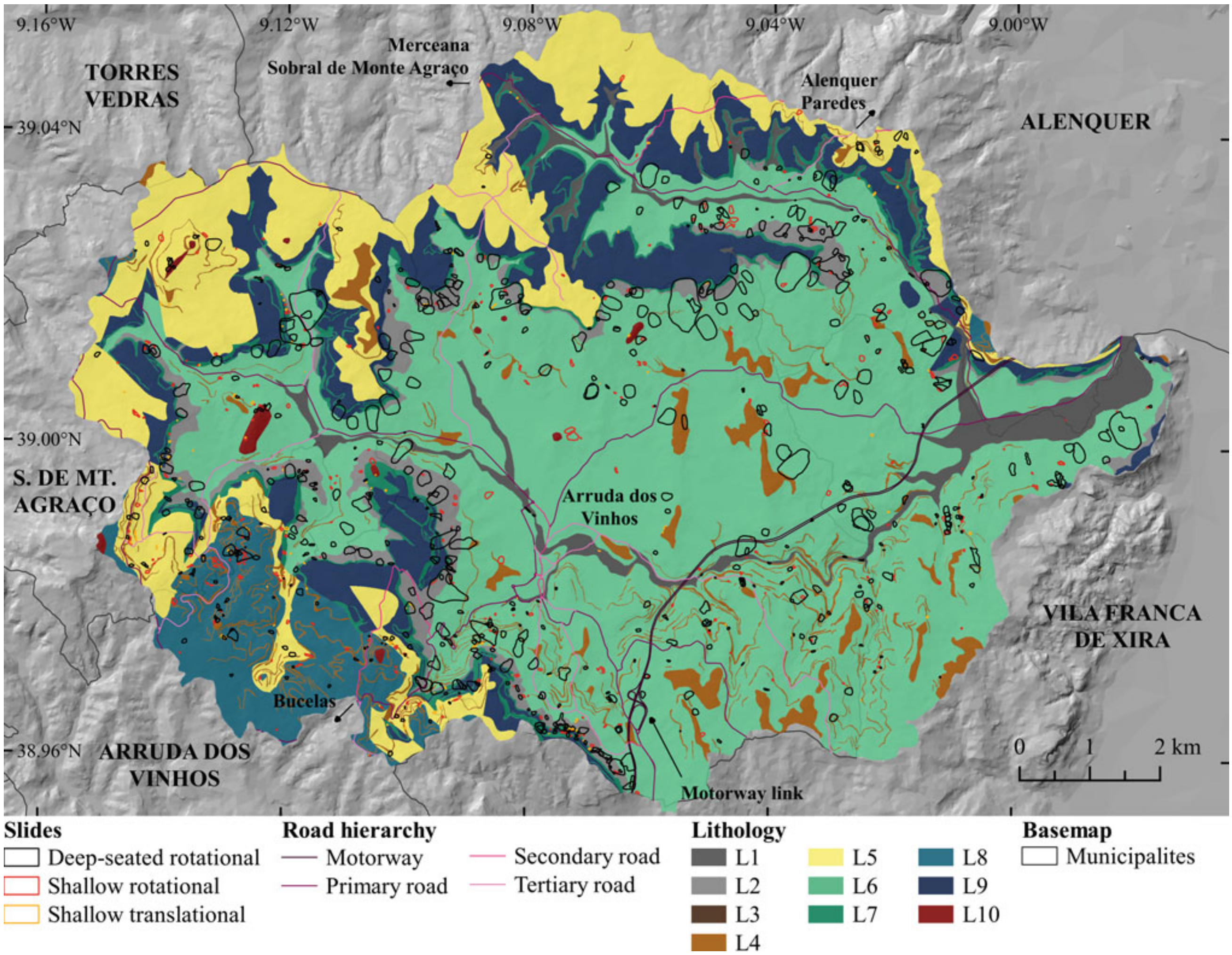

Fig. 1 Grande da Pipa River basin. Slides' distribution can be seen, as well as the road network hierarchy and lithology, organized by lithological type. L1—Alluvium, L2—Slope deposits, L3—Conglomerates, sandstones, and mudstones, L4—Sandstones, L5—Mudstones, sandstones, marls, and limestones, L6—Marls and mudstones, L7—Marls, L8—Limestones and marls, L9—Limestones, and L10—Igneous intrusive rocks

2.1 Susceptibility Assessment

The landslide susceptibility was individually assessed for each one of the three landslide types that most frequently occur in Portugal's most important landslide-prone areas: deep-seated rotational (DR), shallow rotational (SR), and shallow translational (ST) slides. The data required for this step included three landslide inventories (Oliveira et al., 2015), one for each landslide type (DR, SR and ST), and seven independent predisposing factors (slope, aspect, plan curvature, Topographic Position Index, Slope Over Area Ratio, soil thickness, lithology), selected due to their acknowledged importance for the constrain of landslide activity in GPR basin (Oliveira et al., 2015). Concerning the landslide susceptibility processing, the inventories for each type of landslide were randomly partitioned into a 70–30% ratio, where 70% of the landslides were used for training and 30% to validate the modelling results. For the statistical relationship assessment between each type of landslide and the dataset of predisposing factors, we used the Information Value (IV) method, a bivariate statistical and Bayesian approach that quantifies, in scores, the landslide susceptibility for every single class of any given predisposing factor (Yin & Yan, 1988). The scores can be estimated by the following formula (Yin & Yan, 1988):

$$li = \ln\frac{SI/NI}{S/N} \tag{1}$$

in which li is the IV of the Xi factor, SI is the amount of unstable map area units (cells with a resolution of 5 m) with episodes of slope failure and the occurrence of the Xi factor, NI is the amount of map area units with the Xi factor, S is the amount of unstable map area units with episodes of slope failure, and N is the amount of map area units. Due to the logarithmic normalization, the IV cannot be assessed when $SI = 0$; in these cases, we assume the IV as the decimal below the lowest IV value. Positive values demonstrate that there is an association between the class of the predisposing factor and the occurrence of landslides. The higher the value, the stronger the relationship. Negative values indicate that the class of the predisposing factor has less influence on the phenomenon's occurrence (Piedade et al., 2011). The susceptibility value for each map area unit corresponds to the total IV, determined by the expression hereinbelow (Yin & Yan, 1988):

$$lj = \sum_{i=1}^{n} Xjili \qquad (2)$$

where lj is the final IV for each map area unit, n is the amount of conditioning factors, and Xji is equal to 1 or 0, depending on the factor's existence or absence in the j map area unit, respectively.

Both landslide susceptibility training performance and independent prediction capacity were computed with success and prediction rate curves, respectively, and with the estimation of the area under the curves (AUC). Regarding the classification for each landslide susceptibility map, it was defined that each class must cumulatively validate, respectively, 50% (very high), 70% (high), 85% (moderate), 95% (low) and 100% (very low) of the landslide area from the validation group (e.g. 70% of the landslides from the validation group are included in the very high and high susceptibility classes).

2.2 Road Network Exposure

The road network was extracted from OpenStreetMap, downloaded at the Geofabrik server (https://download.geofabrik.de/europe/portugal.html), and ranked in four main categories: motorways (21.5 km), primary/national roads (51.4 km), secondary/municipal roads (8.6 km) and tertiary/rural roads (36 km). The motorway's viaduct sections were not considered for road network exposure to shallow rotational and translational slides, as we do not expect shallow slides to damage the pillars that support those motorway's viaduct sections.

The road network exposure to landslides (REL) relative to each landslide type (REL-DR, REL-SR and REL-ST) results from the intersection between the two top landslide susceptibility classes (high and very high) and the different road categories. Therefore, every road section has a susceptibility value attached. Road sections that intersect with high and very high susceptibility areas are classified as exposed (value 1) and the remaining road sections as not exposed (value 0). Furthermore, we summed the three binary REL maps and classified the roads assigned with value 3 (indicating exposure to all slide types simultaneously) as critical road sections (CRS). This set of methods allowed us to identify the roadways which we consider a priority from an emergency and risk management perspective.

3 Results and Discussion

3.1 Susceptibility Assessment

The IV scores show that the areas with the ideal conditions for the occurrence of DR, SR, and ST slides at the GPR basin are generally located on moderate (>10° in the case of DR) to steep (>25°) concave slopes, covered by poorly developed soils (0.5 to 1.5 m thick), and characterized by medium to high Slope Over Area Ratio indexes, which indicates the potential to accumulate water. Nevertheless, DR slides tend to occur on L2 and L6 units, while SR and ST slide occurs on L5, L6 and L8 layers (Fig. 1). The success and prediction AUC's resulted in the following values: 0.80 (DR), 0.76 (SR) and 0.88 (ST) by the former and 0.76 (DR), 0.73 (SR) and 0.84 (ST) by the latter. After the classification, it was ascertained that the high and very high susceptible classes cover 30% (DR), 34% (SR) and 23% (ST) of the GPR basin and are mainly located at the L6 complex, on slopes distinguished by a moderate slope angle (DR), and at the hilly southwestern side of the basin (SR and ST), as shown in Fig. 2.

3.2 Road Network Exposure

Considering the total length of the road network, 29%, 27% and 25% are exposed to DR, SR, and ST slides, respectively. These sections are mainly located (i) on the south side of the basin, from Arruda dos Vinhos village to Vila Franca de Xira municipality; (ii) on the southwestern side of Arruda dos Vinhos municipality; (iii) at the northeast side of the basin, where the road network heads straight to the north and to Alenquer municipality; (iv) and at the west side of the basin, from central Arruda dos Vinhos municipality to Sobral de Monte Agraço municipality (Fig. 2).

About the road network exposure to deep-seated rotational slides (REL-DR), these sections are mostly located along primary roads (16.4 km; 48%), tertiary roads (8.1 km;

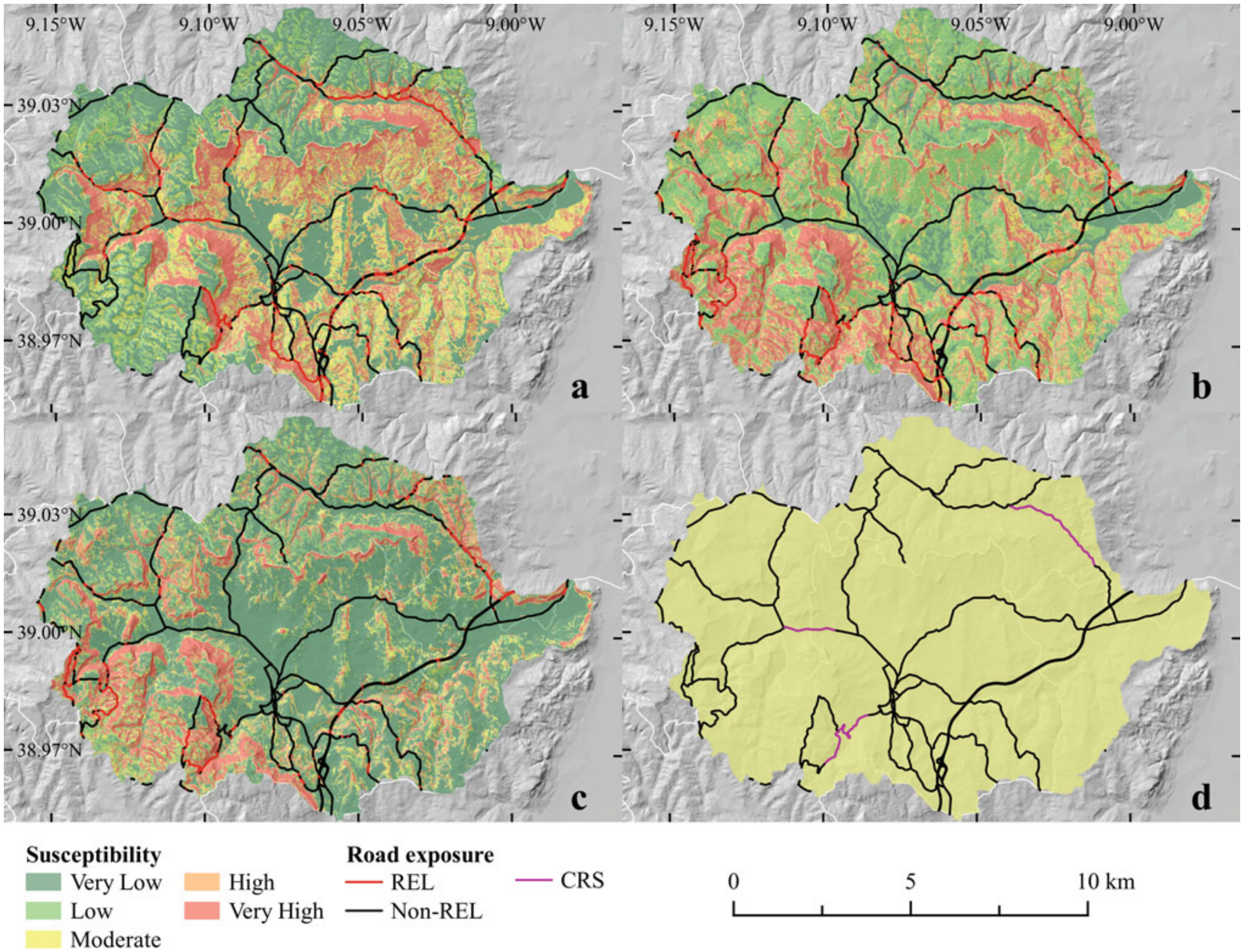

Fig. 2 Grande da Pipa River basin landslide susceptibility (green-yellow–red palette) and road network exposure (red lines) to DR slides (**a**), SR slides (**b**), and ST slides (**c**). Critical road sections (CRS) are highlighted in purple at **d**

24%) and the motorway (8.2 km; 24%), and include the unique section that links all the road network in the basin to the motorway (Figs. 1 and 2).

The road network is also highly exposed to SR slides. These sections are found along primary roads (13.6 km; 45%) and tertiary roads (10.8 km; 36%). Regarding the ST slides, the road network is less exposed than REL-DR or REL-SR, but some sections also should receive attention, mainly along primary roads (8.5 km; 48%) and tertiary roads (5.6 km; 32%). The critical road sections (CRS) are located at the (i) northeast side of the basin, (ii) south side of the basin and (iii) between the west side and the centre side of the basin. These CRS are important means of communication, not only because they establish the connection between the north and south sides of the basin to its centre, as well as to its most crucial settlement (Arruda dos Vinhos), but also by providing connection to other municipalities' settlements (Alenquer, Sobral de Monte Agraço, Bucelas).

4 Concluding Remarks

The primary goal of this research was to assess the road network exposure to landslides at the basin-scale. First, the landslide susceptibility was assessed for three different slide typologies: deep-seated rotational, shallow rotational and shallow translational slides. The most susceptible areas are mainly found at the L2 and L6 units, on slopes distinguished by a moderate slope angle. Then, the road network exposure to landslides (REL) was assessed by intersecting each model's two highest landslide susceptibility classes with the road network. The road network is highly affected by all landslide types, mainly by deep-seated rotational slides. These sections are located at the basin's south, northeast, and west sides, linking the basin's centre and the Arruda dos Vinhos village with the neighbouring municipalities. Finally, the critical road sections (CRS) were also assessed considering the sum of the three REL maps. The selected three CRS represent the sections that should receive more attention from an emergence and risk management perspective.

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