Nat. Hazards Earth Syst. Sci. Discuss., 3, 5547–5597, 2015
www.nat-hazards-earth-syst-sci-discuss.net/3/5547/2015/
doi:10.5194/nhessd-3-5547-2015

Natural Hazards and Earth System Sciences Discussions
Open Access

Assessment of physical vulnerability of buildings and analysis of landslide risk at the municipal scale – application to the Loures municipality, Portugal

C. Guillard-Gonçalves, J. L. Zêzere, S. Pereira, and R. A. C. Garcia

CEG, Institute of Geography and Spatial Planning, Universidade de Lisboa, Lisbon, Portugal

Received: 5 August 2015 – Accepted: 19 August 2015 – Published: 10 September 2015

Correspondence to: C. Guillard-Gonçalves (clemence_guillard@hotmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

This study offers a semi-quantitative assessment of the physical vulnerability of buildings to landslides in the Loures municipality, as well as an analysis of the landslide risk computed as the product of the vulnerability by the economic value of the buildings and by the landslide hazard. The physical vulnerability assessment, which was based on a questionnaire sent to a pool of Portuguese and European researchers, and the assessment of the subjectivity of their answers are innovative contributions of this work. The generalization of the vulnerability to the smallest statistical subsection was validated by changing the map unit and applying the vulnerability to all the buildings of a test site (approximately 800 buildings), which were inventoried during fieldwork. The economic value of the buildings of the Loures municipality was calculated using an adaptation of the Portuguese Tax Services formula. The hazard was assessed by combining the susceptibility of the slopes, the spatio-temporal probability and the frequency-magnitude relationship of the landslide. Finally, the risk was mapped for different landslide magnitudes and different spatio-temporal probabilities. The highest landslide risk was found for the landslide with a depth of 3 m in the landslide body, and a height of 1m in the landslide foot.

1 Introduction

Landslides are natural phenomena that can cause expensive damage when occurring in constructed areas. The analysis of the landslide risk is useful to locate the zones where the risk is highest, but it is a complex and time-consuming task especially when the study is conducted at the regional scale. Indeed, during the last three decades the landslide risk has been considered as the product of the landslide hazard by the vulnerability and by the value of the elements at risk (Varnes and IAEG, 1984; Michael-Leiba et al., 1999; Cardinali et al., 2002; Remondo et al., 2005; Uzielli et al., 2008; van Westen et al., 2008; Zêzere et al., 2008; Garcia, 2012). Thus landslide risk analysis

NHESSD
3, 5547–5597, 2015

requires a study of the landslide hazard, which means the assessment of the geographical location of the slope susceptibility, of the magnitude and recurrence time of landslides and of the vulnerability of the elements at risk and of their value (Varnes and IAEG, 1984; Guzzetti et al., 1999; Cardinali et al., 2002). Whereas the landslide susceptibility and the landslide hazard itself have been extensively studied, whether with heuristic, statistic-probabilistic or deterministic methods, less work has been done, for various reasons, on the spatial assessment of landslide vulnerability and on the assessment of the value of the elements at risk (e.g. Glade, 2003; Bell and Glade, 2004; Alexander, 2005, Papathoma-Köhle et al., 2012; Silva and Pereira, 2014). Firstly, there are different types of landslides, which pose different threats to the various elements at risk; for example, a fast rock fall can be fatal for a passer-by while posing a small threat to the road, whereas a slow slide could be devastating for a road and harmless to a passer-by (Cardinali et al., 2002). In addition, the landslide volume can vary from few cubic decimetres to several cubic kilometres (Schuster and Highland, 2001) and its velocity from some millimetres per year to several metres per second (Cruden and Varnes, 1996). Secondly, the landslide predisposing factors can be very different according to the landslide type (e.g. Zêzere, 2002) as can be the landslide triggering factors (e.g. Weng et al., 2011). Lastly, the position of the element at risk (e.g. a building) on the course of the landslide is also a source of uncertainty, because the effects would not be the same if it is located on the crown of the landslide or on its run out zone (van Westen et al., 2005).

Moreover, a study conducted at the regional level typically implies the existence of a large number of elements at risk with little information available about them, which may lead researchers to reduce their study area. For example, Papathoma-Köhle et al. (2007) only assessed the vulnerability of buildings that were within the “medium” and “high” susceptibility zones of their study area in the Swabian Alb instead of mapping the vulnerability of the entire study area, mainly because the data were scarce (Papathoma-Köhle et al., 2007). Data limitation explains why the landslide risk has rarely been analysed in its whole at the regional scale.

NHESSD
3, 5547–5597, 2015

Vulnerability is thus difficult to assess and the vulnerability models that have been proposed have a non-negligible uncertainty. Indeed, in addition to the lack of research and the insufficiency of data, the subjectivity is another factor that increases the uncertainty of the vulnerability assessment (Jaiswal et al., 2010). In many vulnerability models, the lack of data has been compensated by the incorporation of expert opinion, which results in high subjectivity models.

The vulnerability is defined as "the degree of loss to a given element or set of elements exposed to the occurrence of a landslide of a given magnitude/intensity. It is expressed on a scale of 0 (no loss) to 1 (total loss)" (e.g. Safeland, 2011). In this study, we focused on the physical vulnerability of buildings, which is a function of the intensity or magnitude of the hazard and of the degree of physical protection provided by the natural and built environment, or the resistance levels of the exposed elements (Safeland, 2012).

Previous studies have attempted to assess the landslide vulnerability and to analyse the landslide risk. Some of them are qualitative, e.g. Santos (2003) or Macquarie et al. (2004), who assessed the landslide vulnerability focusing on human lives, and buildings and human lives, respectively. Other studies are semi-quantitative, e.g. Silva and Pereira (2014) who assessed the vulnerability of buildings to shallow slides considering the building resistance, defined by the construction technique and materials, the floor and roof structure, the number of floors and the conservation status. Godfrey et al. (2015) assessed the physical vulnerability of buildings to hydro-meteorological hazards on the basis of two vulnerability models, one based on vulnerability curves and the other on indicators of vulnerability, to calculate a generic function that they transferred to their study area, in Romania. Some few vulnerability studies are quantitative in nature. For example, Du et al. (2013) proposed a quantitative vulnerability assessment model that relates the landslide intensity (defined by the velocity and the depth of the landslide and the local deformations of the structure and the ground) and the physical vulnerability of the elements at risk (defined by the structure type, the maintenance state, the ratio of service years to design service life and the difference between the direction of landslide movement and the principal longitudinal direction of the structure).

Furthermore, some researchers only focus on the vulnerability, while others combine the physical vulnerability assessment of buildings with its economic value, thus assessing the potential losses, as Silva and Pereira (2014) did for a municipality located in the north of Portugal. Other researchers combine the potential losses with the hazard, hence obtaining a risk analysis. Zêzere et al. (2007, 2008) analysed landslide risk in Portugal through the evaluation of direct and indirect costs resulting from a motorway disruption caused by a translational or rotational slide (Zêzere et al., 2007), and the reconstruction costs of buildings and roads affected by landslides (Zêzere et al., 2008).

Papathoma-Köhle et al. (2011) summarized the state of the art of the physical vulnerability assessment for alpine hazards, comprising slides, avalanches, debris flows, rock falls and floods. These authors concluded that the vulnerability assessments made by different researchers are very diverse and a common vulnerability assessment method that satisfies all researchers is impossible; they further pointed out that a multidimensional approach is necessary in order to address all dimensions of the vulnerability (physical, economic, social) (Papathoma-Köhle et al., 2011). The assessment of all the dimensions of the vulnerability by scientists from various disciplines would be interesting since the different dimensions have an effect on each other (ibid.). The main drawback of this approach at the regional scale is that a study of only one dimension is complex and time-consuming, therefore the assessment of all the dimensions of the vulnerability would increase the time of study as well as the uncertainty of the results.

The main purpose of this study is to develop and apply a method for building vulnerability assessment that can be applied at a municipal or regional scale and which enables a landslide risk analysis. Given the difficulty in validating the model of vulnerability because of the too few records on buildings damage caused by landslides, we attempted to limit the subjectivity of the vulnerability assessment by submitting a questionnaire to a pool of experts. The uncertainty resulting from this questionnaire

NHESSD
3, 5547–5597, 2015

is assessed by the standard deviations of the vulnerabilities obtained. Then, the economic value of the buildings is assessed. Moreover, the susceptibility of the slopes is modelled for deep-seated and shallow slides and the hazard is assessed, considering the probability of occurrence of the slides in each susceptibility class and the frequency of the slides according to their magnitude. This method is applied to a Portuguese municipality of the Greater Lisbon area and the landslide risk for the buildings of this municipality is mapped.

2 Study area

For various reasons we chose to analyse the risk of slides triggered by rainfall in the Loures municipality, which is close to Lisbon. First, this municipality is prone to different natural hazards in particular to landslides. Most of the landslides in the Loures municipality are rotational or translational and are triggered by rainfall (Zêzere et al., 2004, 2008). These landslides often affect buildings and roads with significant direct and indirect consequences. Out of the 686 landslides (Fig. 1) inventoried by Guillard and Zezere (2012), 462 occurred within 50 m from buildings and roads. Second, Loures is adjacent to the city of Lisbon (Fig. 1) hence a large number of inhabitants, buildings and infrastructures are exposed to landslide hazard; indeed, about 205 000 persons currently live in the Loures municipality (density around 1220 inhabitants per km^2), which is 6 % higher than in 2001 according to the National Institute of Statistics (INE). The 32 495 buildings of the Loures municipality represent a total built up area of 9.25 km^2 and the number of buildings, most of which were erected without taking into account the possibility of future landslide occurrence, increase every year. Indeed, according to the results obtained in the framework of the new Master Plan for the Lisbon Metropolitan Area, the construction on potentially unstable slopes within the Loures municipality increased by 64 % between 1995 and 2007.

Third, a study on the susceptibility of slopes to landslides was previously conducted in this municipality (Guillard and Zezere, 2012). Therefore, we intend to complete the

NHESSD
3, 5547–5597, 2015

risk analysis for buildings in this study area, in order to offer a complete risk analysis to the stakeholders of the Loures municipality.

Finally, a social vulnerability assessment was conducted for the Greater Lisbon area (Guillard-Gonçalves et al., 2015), which opens up an avenue for a future study that combines these two dimensions of the vulnerability.

Additional information about the study area can be found in Guillard and Zezere (2012).

3 Data and methods

3.1 Physical vulnerability of the buildings

According to Cruden and Varnes's (1996) classification, most of the landslides in the study area were slow, very slow or extremely slow; therefore inhabitants' lives are unlikely to be endangered. However, buildings, roads, and infrastructures may suffer damage, thus generating relevant costs both direct and indirect. That is why the vulnerability assessment is focused on the study of buildings, for which some data is available. Nevertheless, only direct costs will be considered in the current study, due to scarcity of data.

3.1.1 Definition of a vulnerability matrix for buildings based on a questionnaire

In order to predict damage caused by landslides it is important to know the properties of the buildings foundations (Douglas, 2007). As the data related to the foundation properties of each building are not available for a large study area, such as a region or a municipality, mainly because of the huge number of elements at risk, other elements of buildings like age, structure type and number of floors are used as proxies (ibid.).

In contrast to social vulnerability, which is a measure of the sensitivity of a population to hazards and its ability to respond to and to recover from the hazards impacts (Cutter and Finch, 2008), physical vulnerability is related to a specific scenario (Uzielli et

NHESSD
3, 5547–5597, 2015

al., 2008; Papathoma-Köhle et al., 2011). That is why we focused on rotational slides for which we considered nine different scenarios: five scenarios in which the building location is on the body of the slide assuming different depths of the slip surface (1, 3, 5, 10 and 20 m); and four scenarios in which the building location is on the foot of the slide assuming different heights of affected material (0.5, 1, 3 and 5 m) (Fig. 2). The slip surface depth and the height of the affected material within the various scenarios are in accordance with the typical landslide parameters observed in the study area (Zêzere, 2002; Zêzere et al., 2008).

Physical vulnerability assessment is often based on historical records (Dai et al., 2002) and on expert judgments (Sterlacchini et al., 2007) and is largely subjective (Léone et al., 1996; Uzielli et al., 2008; Silva and Pereira, 2014). To reduce this subjectivity, we decided to ask the opinion of a pool of experts. A questionnaire was formulated and sent to more than 300 international experts on landslides and other natural risks.

The experts were asked to fill in the questionnaire in which they divided, into five categories, the potential damage on four structural types of buildings (Table 1) caused by landslides of different magnitudes (Table 2); the magnitudes of the landslides were associated with the depth of the slip surface and with the height of the affected material. The experts provided 36 answers, corresponding to each situation.

Fifty-two experts completed the questionnaire and we used their answers to obtain an average value of physical vulnerability for each type of building, for location within the landslide body and landslide foot, and for each landslide magnitude. We were also able to assess the uncertainty of the obtained results by calculating and mapping the standard deviation of the answers.

3.1.2 Assessment of the physical vulnerability of the buildings using statistical mapping units

The Loures municipality services provided us with a geodatabase with a variety of different elements at risk, which we used for all the buildings that still exist and excluded the buildings that appeared as ruins on the most recent high-resolution images of the

Loures municipality provided by the World Imagery File ESRI (2014). However, the only data provided and used by this geodatabase is the geographical location of the buildings. In order to obtain more information about the buildings, like their structure, age, or functionality, we had to use data from the census of the INE. We chose, as mapping unit, the smallest statistical unit, which is the "Geographic Basis for Information Reference" subsection (BGRI). The BGRI is the geographic reference basis used for the 2011 census operations, which divides each basic administrative unit – which is the "civil parish" into sections and subsections. The BGRI-subsections are territorial units, whether built-up or not, which represent a block in urban areas, a locality or part of a locality in rural areas, or residual areas which may or may not have dwellings (INE, 2011). Their boundaries were defined by the INE, and the statistical information was also collected by the INE. The 3061 BGRI-subsections of the Loures municipality used for the 2011 census are the ones we used for this study.

We classified the buildings of the study area into four structural types corresponding to the data which is available for the whole area at the BGRI-subsection scale, considering their structural elements and construction materials (Table 1). It should be noted that although the information provided at the BGRI-subsection scale included the number of structural types of buildings, no information was provided as to the type of construction of each individual building.

Therefore, the number of buildings pertaining to each structural building type class (from SBT1 to SBT4, see Table 1) is known for each BGRI, although the association of this information with the building polygons cannot be made directly. As the physical vulnerability of buildings was established for each structural building type, the vulnerability of the buildings was assessed for each BGRI-subsection by making a weighting average, which takes into account the number of buildings of each structural building type within the BGRI. Then, the mean vulnerability was assigned to all the buildings of the BGRI-subsection. This limitation of the study in which the value of vulnerability is the same for all the buildings of a BGRI comes from limited data. However, the average

NHESSD
3, 5547–5597, 2015

number of buildings per BGRI in the Loures municipality is 11, and most of the BGRI have a large number of buildings belonging to the same structural building type.

This means that the generalized vulnerability, which is attributed to the buildings of a BGRI is not so far from what it would be for a vulnerability assessment made building by building in most cases.

The standard deviations of the answers given by the experts were calculated for each scenario and for each structural type of building. They represent the uncertainty of the vulnerability values coming from the questionnaires and they were shown on the vulnerability maps.

3.1.3 Assessment of the physical vulnerability of the buildings in a test site based on a buildings inventory made during fieldwork

The above-mentioned method has the advantage to be time-saving, in contrast to a study that considers each building of the study area, as Silva and Pereira (2014) did for the Santa Marta de Penaguião municipality. In order to assess the accuracy of this method, we selected a test site inside the Loures municipality to develop fieldwork; the relevant building characteristics to assess physical vulnerability were inventoried for each individual building. The choice of the test site was made considering several criteria, the first one being that this test site is very prone to landslides. The fact that the area had several structural types of buildings and several types of urbanization (concentrated in the north and southwest, and scattered in the centre) was also a selection criterion. The test site is the northern part of the Bucelas civil parish and it has an area of 6.71 km^2 and 782 buildings (Fig. 3). The comparison of the results from this study, for which the building is the mapping unit, with the first study approach made with the BGRI mapping unit would help us to assess the cost/benefice ratio of the two methods.

3.2 Economic value of the buildings

The economic value (EV) of the buildings has been calculated using the same equation as Silva and Pereira (2014) (Eq. 1):

$$EV = ACC \times TA \times FC \times LC \times AC \quad (1)$$

where EV is the Economic Value, ACC is the Average Cost of Construction, TA is the Total Area, FC is the Functionality Coefficient, LC is the Location Coefficient, and AC is the Age Coefficient. The ACC is established by the Portuguese Government (Decree Number 1456/2009) and expresses the costs associated with the construction of the building. It was fixed at EUR 603/m^2 for the year 2011. As ACC is expressed per square metre, it had to be multiplied by the TA, which was calculated by multiplying the buildings area, provided by the Loures municipality geodatabase, by the average number of storeys in each BGRI-subsection. The FC is related to the function of the buildings (habitation, store or storages are the main functions of the Loures municipality buildings), also provided by the BGRI-subsection data and the coefficients were defined by the Portuguese Tax Services (Dec.-Law Number 287/2003 of 12 November) ranging from 0.35 (storage buildings) to 1.2 (buildings that have a commercial use). The AC values are also classified by Portuguese Tax Services (Law Number 64-A/2008 of 31 December) ranging from 1 (building less than 2 years old) to 0.40 (buildings older than 60 years). The information about number of buildings per function or construction data was obtained from BGRI data. The weighted average values were calculated for each BGRI for both coefficients and assigned to the buildings. LC is determined by the Portuguese Tax Services according to property market and accessibility (Law Number 64-B/2011 of 30 December). At the national level, the LC values range from 0.4 to 3.5; in the Loures municipality, the LC values vary between 0.85 for the more rural areas and 2.25 for the zones of the Moscavide and Sacavém civil parishes (Fig. 3), which are located near Lisbon and have a better accessibility and proximity to social facilities and public transports.

NHESSD
3, 5547–5597, 2015

We calculated the Economic Value per pixel (EVpix) from the EV values obtained for each building. Indeed, as the landslide hazard was calculated at a pixel-base, we needed to obtain an economic value per pixel to calculate the risk. The EVpix value was obtained by dividing the EV value by the area of the building and multiplying it by 25, which is the pixel area in square metres.

3.3 Frequency-Magnitude of the landslides, susceptibility and hazard

3.3.1 Frequency-Magnitude relationship

In order to complete the assessment of the landslide hazard and risk, we needed to establish a relationship between the magnitude of the landslides and their frequency. Ideally a landslide hazard model should incorporate not only the spatio-temporal probability of occurrence of the landslides, but also the landslide magnitude (Guzzetti et al., 1999; Cardinali et al., 2002). A landslide with a depth of 20 m can cause severe damage, but its frequency in the study area is much lower than a 1 m deep landslide. Which magnitude of landslide would present the highest risk for the Loures municipality?

Assuming that future landslides would have similar characteristics to the past ones, we considered the 686 landslides inventoried inside the Loures municipality. A curve representing the probability of occurrence of a landslide versus its area was computed in the same way as Malamud et al. (2004) and Guillard and Zezere (2012) for the deep-seated and shallow landslides of the Loures municipality. In this study, the landslides were considered all together in order to know the probability associated to each scenario.

Then, in order to read the probability of occurrence of each scenario on the curve, we had to link the depth of the slide slip surface to the slide area and to link the height of accumulated material to the slide area. The relationship between the depth and the area of landslide used in this study is the statistically-based one established by Garcia (2012), because the landslides of the Loures municipality are similar to the ones in Garcia's study area, which is located about 20 km north of Loures. As there is no established relationship between the accumulated material height and the slide area, or between the accumulated material height and the depth of the slide, we considered that the height-to-depth ratio is 0.5. This is an assumed relationship with significant uncertainty that can be an important source of bias, but which is based on some landslides studied in the field whose depth is known.

3.3.2 Annual and multiannual spatio-temporal probabilities

The temporal probability has to be associated to the spatial probability in order to determine the spatio-temporal probability, which is part of the landslide hazard. First of all, the spatial probability of a shallow and of a deep landslide occurrence was assessed constructing two susceptibility maps. The susceptibility was mapped using a bi-variate statistical method called Information Value Method (Yin and Yan, 1988). The first model represents the susceptibility of the slopes to shallow landslide occurrence, published in a previous study (Guillard and Zezere, 2012). The total area of the shallow landslides is 319 975 m^2. The second model represents the susceptibility of the slopes to deep-seated landslide occurrence, and was built and validated by the union of the 292 deep-seated rotational slides and the 61 deep-seated translational slides inventoried in the Loures municipality (Guillard and Zezere, 2012). The total area of the deep-seated slides is 1 343 525 m^2. These two models provided two landslide susceptibility maps in a raster format with a pixel size of 5 × 5 m. Each map was classified as one of four susceptibility classes. Additional details on the landslide susceptibility assessment in the study area can be found in Guillard and Zezere (2012).

The spatio-temporal values for shallow and deep-seated landslides were then calculated for each susceptibility class by dividing the product of the total affected area and the predictive capacity by the area of the class (Zêzere et al., 2004). As the inventoried landslides occurred from 1967 to 2004, we managed to calculate the hazard values for the next 38 years, and to deduce the 1 year, 10 years, 25 years and 50 years probability values.

NHESSD
3, 5547–5597, 2015

3.4 Landslide risk

The buildings shape files were converted into raster files in which the pixel size is 5 × 5 m. Then, the risk value was computed according to the Eq. (2):

$$R_{ij} = H_i \times P_j \times \mathrm{PV}_j \times \mathrm{EVpix} \quad (2)$$

where R is the Risk, H is the spatio-temporal probability, P is the magnitude probability, PV is the physical vulnerability, and EVpix is the economic value per pixel. The index i takes the values of 1 year, 10 years, 25 years and 50 years; the index j takes the values of 1, 3, 5, 10, and 20 m for the slip surface depths, and 0.5, 1, 3, and 5 m for the accumulated material heights.

The multiplication of the last two terms (the physical vulnerability and the economic value) represents the potential damage for the buildings.

First, the annual spatio-temporal probability was considered (i.e. index $i = 1$ year) to calculate the landslide risk values for a year with different probabilities of occurrence according to the different landslide magnitude values. Box plots were computed to compare the effect of the landslide magnitude on the landslide risk.

Then, the probability of occurrence was fixed (index $j = 1$ m deep) and the risk was calculated for different spatio-temporal probabilities.

4 Results and discussions

4.1 Physical vulnerability of the buildings

4.1.1 Vulnerability matrix for buildings based on a questionnaire

Out of the 52 questionnaires completed by the experts, 30 came from Portuguese experts, 23 of whom are doing research in the Lisbon area, one is doing research in Brazil (and studied in the Lisbon region for some months) and the others are doing research

NHESSD
3, 5547–5597, 2015

in other European countries. Most of the experts merely completed the questionnaire, but some of them expressed doubts that arose while filling in the questionnaire or made some comments. Whenever necessary, emails were exchanged before the experts completed the questionnaire. Most of the experts who had doubts expressed that it was difficult to assess the potential damage caused by a landslide to a building based only on the depth of the landslide slip surface or the height of accumulated material. Additionally, the structure of the building and its position on landslide body or foot was one of the majors concerns. However, it was not useful to give them more detailed information about the building position or about the characteristics of the landslides (e.g. the velocity of the landslide, the type of affected material, the height of the scarp) as they requested, because such information was not available for the complete landslide inventory and the aim of this study is to assess the vulnerability of the buildings of a whole municipality in a systematic fashion. One adopted solution was to consider the worst case scenario for the potential damage assessment, i.e. the height of the scarp is slightly smaller than the depth of the slip surface, the building is partly within the body and partly outside (on the scarp), the foot is perpendicular to length of the building, and the building is well within the foot, not simply touched by it. This model is quite conservative in that in more favourable situations damage would logically be lower. But as part of the experts expressed the potential damage as maximum, and the other as medium, the average values provide a not too conservative model, but neither too low in terms of expected potential damage, and this is what the authors were seeking.

All the answers were kept so as not to bias the results. As the damage level is a proxy for the physical vulnerability, the damage values provided in the answers to the questionnaires, comprised between 1 and 5, were converted into vulnerability values, comprised between 0 and 1 (see Table 2). The vulnerability averages are presented in Tables 3 and 4, along with the standard deviation for each scenario, which was calculated in order to evaluate the uncertainty of the answers through the differences between the experts' answers. The vulnerability averages were used to calculate the vulnerability of each BGRI-subsection. These averages range from 0.25 (for a type

NHESSD
3, 5547–5597, 2015

4 building on a 0.5 m high landslide foot) and 0.94 (for a type 1 building on a 5 m high landslide foot). As expected, the vulnerability of the buildings increases with the landslide magnitude, and is lowest for buildings of type 4 and type 3. The standard deviation ranges from 0.12 (for type 1 and type 2 buildings located on a 5 m high landslide foot) to 0.24 (for a type 1 building located on a 1 m deep landslide body). The standard deviation tends to be higher for lower magnitude landslides, for which the potential damage is more difficult to assess than for the higher magnitude landslides, which are considered as highly destructive by the large majority of experts within the pool.

4.1.2 Physical vulnerability of the buildings of the Loures municipality based on statistical mapping units

In each BGRI-subsection the average vulnerability was calculated taking in account the number of buildings of each structural building type. Then, the average vulnerability was attributed to each building included into the BGRI-subsection in order to obtain more explicit maps (Figs. 4 and 5). The standard deviation of the BGRI-subsection vulnerability was also represented in shades of blue in Figs. 4 and 5.

As expected, the vulnerability depends on the type of structure of the buildings, and increases with the landslide magnitude. However, when the magnitude is maximum - which is for a 20 m deep landslide, all the buildings have maximum vulnerability (PV $\geq$ 0.81), independently of their structural type (Fig. 4e). This means that the structure type may play a role when the landslide magnitude is low, but all the buildings have the same vulnerability when the landslide magnitude reaches a certain level of damage power. In relation to the standard deviation, some of the BGRI-subsections in Figs. 4a, b, 5a and b present a high value (up to 0.21). Therefore, the uncertainty about the expected damage on buildings among the experts is highest for damage generated by low magnitude landslides (e.g. 1 m deep landslide and 1 m high accumulated slide material) on buildings of structural types 1, 2 and 3. The maps shown in Figs. 4 and 5 enable to identify the location of the buildings and their vulnerabilities according to different magnitude landslides, but also highlight the uncertainty associated to the attributed vulnerabilities. For example, Fig. 5b, which shows the potential damage caused by a 1 m high accumulated slide material, shows that vulnerability ranges between 0.41 and 0.6 in the BGRI-subsections where there is a large proportion of type 3 buildings, but these subsections also present high standard deviation values, thus indicating a high uncertainty on vulnerability. On the other hand the BGRI-subsections which have a large proportion of type 4 buildings in Fig. 5b, have lower vulnerabilities (between 0.2 and 0.4), and the robustness of these results is proved by the low standard deviation values which illustrate a more consistent opinion among the experts.

4.1.3 Physical vulnerability of the buildings in a test site based on a buildings inventory made by fieldwork and comparison with vulnerability based on statistical mapping units

The vulnerability of the test site buildings inventoried during fieldwork (Fig. 3) is presented in Figs. 6 and 7 for locations in the landslide body and the landslide foot, respectively. As each building has its own vulnerability, the results are more accurate than when an average value is calculated for all the buildings of the BGRI-subsection. However, the comparison of building vulnerability expressed in Figs. 6 and 7 with the corresponding area at the BGRI-subsection level shows that global results are similar. In order to have a more accurate comparison, the box plots of the vulnerability values obtained by both methods for the test site are shown in Fig. 8. Indeed, Fig. 8 enables the comparison of vulnerability values of the test site buildings inventoried by fieldwork (in grey) with the vulnerability values of the buildings of the BGRI-subsections (in black). In each case, the range of the vulnerability values obtained by fieldwork is wider than the one obtained by the BGRI-subsections calculations. This can be explained by the fact that the data obtained by fieldwork is much more detailed because the buildings were considered one by one; therefore the results are less generalized. Moreover, for each scenario, the median of the fieldwork data is the same as the one calculated from BGRI-subsections data, which validates the accuracy of the vulnerability values ob-

NHESSD
3, 5547–5597, 2015
Physical vulnerability of buildings
C. Guillard-Gonçalves et al.

tained by calculations in the BGRI-subsections. The vulnerability assessment method based on BGRI-subsection mapping unit is much less time-consuming than the field-work method and has the advantage of being reproducible. As the obtained results are satisfactory we recommend the application of the first method at the municipal level.

4.2 Economic value of the buildings

The economic value of the buildings was calculated according to the Eq. (1). We found that 3417 buildings have an economic value above EUR 100 000 per pixel (which corresponds to EUR 4000/m^2), that is 3 % of the buildings of the whole municipality. Most of them are located in the southern half of the Loures municipality (near Lisbon), which is more urbanized than its northern half and presents the highest concentration in the civil parishes of Portela, Moscavide and Sacavém (Figs. 3 and 9). The civil parishes of Santo António dos Cavaleiros, Loures, Santa Iria de Azóia, São João da Talha and Bobadela also have a certain amount of buildings with a high economic value. Most of them are recent residential and industrial buildings located near social facilities.

4.3 Frequency-Magnitude of the landslides, susceptibility and hazard

4.3.1 Frequency-Magnitude relationship

The probability of occurrence of the different landslide magnitudes was assessed using the curve shown in Fig. 10. The landslide area was used as a proxy for both the depth of landslide slip surface and the height of affected material in the landslide foot; the results are summarized in Tables 5 and 6. The corresponding slide areas range from 706 to 14 127 m^2. The landslides that have a maximum probability of occurrence are the 1 m deep landslides and the ones with an accumulated material height of 0.5 m, which have a probability of 0.57. The landslides that have a lower probability of occurrence are the 20 m deep landslides, with a probability of 0.02. In general terms, the probability value

NHESSD
3, 5547–5597, 2015

of the landslides decreases when their magnitude increases, which is consistent with the results previously obtained by Guillard and Zezere (2012) for this study area.

4.3.2 Annual and multiannual spatio-temporal probabilities

The deep-seated and shallow landslides susceptibility models were validated based on the random partition of the landslide inventories in two groups: modelling group and validation group. The modelling group was used to weight the classes of each landslide predisposing factor and to build the landslide susceptibility models, whereas the validation group was crossed with the susceptibility results for its independent validation. The prediction-rate curves show the robustness of the models (Fig. 11): the Area Under Curve (AUC) value is about 0.872 for both models, which proves the robustness of the models.

The landslide susceptibility maps are shown in Fig. 12, with the landslides used for computing and for validating the models. The separation of the classes was done using the fraction of correctly classified landslide area (Fig. 11, and "predictive capacity" in Tables 7 and 8). Therefore, 50 % of the future landslides should occur in the "Very high" susceptibility class, which represent only 7 and 6 % of the total area, for the deep-seated and shallow landslides, respectively. Moreover, 25 % of the future landslides should occur in the "High" susceptibility class, which represent only 10 and 12 % of the total area, for the deep-seated and shallow landslides, respectively.

Tables 7 and 8 show the probabilities of a pixel within a susceptibility class to be affected by a deep-seated (Table 7) or shallow (Table 8) slide, for different time periods (1 year, 10 years, 25 years and 50 years). Their values were calculated from the total area to be affected by landslides in the future, the area of the class and the class predictive capacity, as explained in Sect. 3.3.2. They can be calculated for any time period from the "1 year probabilities", but we chose to select 10, 25 and 50 years, which are significant time periods considering that stakeholders of municipal planning have to make choices that will have repercussions for decades. Indeed, even if a pixel within the "High" susceptibility class has only a probability of 0.000170 (that is 1 chance in

1832) to be affected by a deep-seated slide during the next year, it has a probability of 0.027305 (that is 1 chance in 37) to be affected by a deep-seated slide during the next 50 years (Table 7). Moreover, each pixel within the "Very high" susceptibility class has a probability of 0.075416 (that is 1 chance in 13) to be affected by a deep-seated slide during the next 50 years. That is why the "High" and "Very high" susceptibility classes, which have the highest probability of occurrence values during the next years (Tables 7 and 8), are the ones that those involved in civil protection and municipal planning need to focus on.

A limitation of these probabilities comes from the fact that their values are based on the landslide areas, without taking into account the characteristics of the rainfall which triggered the landslides (amount and duration); this data is not available for the whole landslide inventory.

4.4 Landslide risk

Figures 13 and 14 illustrate the risk for buildings according to the building vulnerability and value and the spatio-temporal landslide probability and the landslide magnitude. The buildings have been transformed into raster in order to multiply the potential loss associated to the buildings by the hazard values. The value of risk is the value per pixel and each pixel has an area of 25 m^2. Figures 13 and 14 show that the risk values are closely related to the landslide susceptibility values. As the buildings have similar economic values, the ones that have been constructed in "High" or "Very high" susceptibility zones have a high risk in comparison to the ones constructed in the "Low" or "Very low" susceptibility zones.

The box plots of the risk values were plotted for each scenario in order to compare them (Fig. 15). Outliers have been considered, but their values are too high to be shown on this figure (the maximum value is EUR 23 per pixel, for a 3 m deep slide). Figure 15 shows that the maximum values of risk correspond to 3 m deep landslides, for which 691 pixels buildings (that is 0.2 % of the buildings of the Loures municipality) have a risk above EUR 5 per pixel. Indeed, these landslides are the ones which combine a relatively high probability of occurrence in the Loures municipality (0.34, cf. Table 5) with a substantial damage potential (the median vulnerability value associated to them is 0.61, cf. Fig. 8). The landslides which are more frequent have a lower magnitude and are therefore less destructive whereas the ones which have a higher magnitude have a very low frequency; for example, the annual probability of a landslide having a depth of 20 m or more in the Loures municipality is 0.02 (cf. Fig. 10 and Table 5). Therefore, despite the high median vulnerability associated to these landslides (0.89, cf. Fig. 8) the risk values associated to them are quite low (the median value is 0.01, cf. Fig. 15).

The risk was then calculated considering different time periods. Figure 16 shows the risk to 10 m deep landslides in a part of the Loures municipality, for 1 year, 10 years, 25 years and 50 years. In this zone where the zoom was carried out, the annual risk is between EUR 1 and 5 per pixel in the "Very high" susceptibility zones, and below EUR 1 per pixel in the rest of the zoomed area. However, the risk increases when we consider longer periods of time: for instance, for a 50 year period, risk values are above EUR 20 per pixel for "High" and "Very high" susceptibility zones and between EUR 5 and 20 per pixel for "Low" susceptibility zones. This means that solutions have to be found, chiefly in the "High" and "Very high" susceptibility zones, because even if the risk is quite low for the next few years, its probability increases when longer periods of time are considered, independently of other aggravating factors like climate change.

5 Conclusions

An assessment of buildings vulnerability to landslides, based on an inquiry of a pool of experts, was developed and applied to Loures – a municipality of the Greater Lisbon area. The vulnerability of all the buildings of the Loures municipality was assessed at the BGRI-subsection scale. The accuracy of the vulnerability of the buildings was assessed by comparing the vulnerability of the buildings of a test site, in the municipality of Loures, with the vulnerability attributed to all the inventoried buildings of this test site. The risk was then analysed by multiplying the potential damage, (which is the product of the vulnerability by the economic value of the buildings) by the landslide hazard; the latter is in turn the product of the spatio-temporal probability by the magnitude probability of landslides in the Loures municipality. The obtained vulnerabilities vary from 0.2 to 1 as a function of the structural building types and increase with the landslide magnitude, being maximal for a 20 m deep landslide.

The analysis of the landslide risk for the buildings of the Loures municipality enables the municipality planners, the civil protection department and the insurance companies to focus on the buildings for which the landslide risk is higher.

The main advantages of the vulnerability assessment developed in this study are: firstly its applicability to the buildings of the whole Loures municipality despite its huge number (more than 30 000) and the few data available for these buildings; secondly the assessment of the uncertainty of results by calculating the standard deviations of the attributed vulnerabilities and thirdly, the vulnerability assessment method developed in this study was applied to the Loures municipality but it can be reproduced in another municipality or a region in reasonable time.

However, the risk analysis presented here has some limitations and drawbacks involving both the hazard assessment and the potential damage assessment. In relation to the hazard assessment, the spatio-temporal probabilities were overestimated in that they were calculated for the landslide areas as a whole, whereas the risk was calculated for a building belonging to a landslide body on the one hand and to a landslide foot on the other hand. In addition, the spatio-temporal probabilities were calculated on the basis of the total areas of the inventoried landslides, considering that the 686 landslides of the Loures municipality were the only ones that occurred from 1967 (first landslides inventoried and dated) until 2004 (date of the orthophoto maps used to complete the inventory); in reality, it is obvious that the real total area is larger because we could not have inventoried all the landslides that occurred in the Loures municipality during this period. An annual inventory of the whole municipality and extensive fieldwork from 1967 to 2004 could be the solution to have a complete inventory. From this point of view, the hazard was underestimated.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

NHESSD

3, 5547–5597, 2015

Physical vulnerability of buildings

C. Guillard-Gonçalves et al.

In relation to the potential damage assessment, the costs were underestimated. Indeed, the value of the contents inside the buildings was not considered as they were not known. Moreover, indirect costs linked to the function of the building are difficult to quantify and were not considered in this study, although they play an important role in a risk analysis. Some examples of these indirect costs would be the costs linked to the temporary or definitive resettling of families whose house had been destroyed by a landslide, as well as the eventual additional costs of transportation if their resettled home is farther from their work place etc. Another example of indirect costs is the capital lost by the cessation of activity in case of an industry or an office destroyed or damaged by the landslide. Last but not least, it would be even worse if the destroyed building was a strategic building such as a hospital or a school; the vital and sensitive role of these kinds of buildings was not considered in this study, which is another limitation.

Finally, the risk has been calculated on the base of scenarios which have already occurred; however, if the landslide preparatory and triggering conditions change (e.g. due to climate change or direct human interference on slopes), the number of landslides and their magnitude would increase, as would the associated damage, and that would have to be considered.

Acknowledgements. Clémence Guillard-Gonçalves and Susana Pereira were supported by the Portuguese Foundation for Science and Technology (FCT) through grants SFRH/BD/64973/2009 and SFRH/BPD/69002/2010, respectively.

References

AGS (Australian Geomechanics Society Sub-Committee on Landslide Risk Management): Landslide risk management concepts and guidelines, Aust. Geomech. J., 35, 49–92, 2000.

Alexander, D.: Landslide damage to buildings, Environ. Geol. Water Sci., 8, 147–151, doi:10.1007/BF02509902, 1986.

Alexander, D.: Vulnerability to landslides, in: Landslide Hazard and Risk, edited by: Glade, T., Anderson, M., and Crozier, M. J., John Wiley & Sons, Ltd. Chichester, UK, 175–198, 2005.

Bell, R. and Glade, T.: Quantitative risk analysis for landslides – Examples from Bíldudalur, NW-Iceland, Nat. Hazards Earth Syst. Sci., 4, 117–131, doi:10.5194/nhess-4-117-2004, 2004.

Cardinali, M., Reichenbach, P., Guzzetti, F., Ardizzone, F., Antonini, G., Galli, M., Cacciano, M., Castellani, M., and Salvati, P.: A geomorphological approach to the estimation of landslide hazards and risks in Umbria, Central Italy, Nat. Hazards Earth Syst. Sci., 2, 57–72, doi:10.5194/nhess-2-57-2002, 2002.

Cruden, D. and Varnes, D.: Landslides types and processes, Turner AK, Schuster RL, Washington, DC, 36–75, 1996.

Cutter, S. L. and Finch, C.: Temporal and spatial changes in social vulnerability to natural hazards, P. Natl. Acad. Sci. USA, 105, 2301–2306, doi:10.1073/pnas.0710375105, 2008.

Dai, F. C., Lee, C. F., and Ngai, Y. Y.: Landslide risk assessment and management?: an overview, Eng. Geol., 64, 65–87, 2002.

Douglas, J.: Physical vulnerability modelling in natural hazard risk assessment, Nat. Hazards Earth Syst. Sci., 7, 283–288, doi:10.5194/nhess-7-283-2007, 2007.

Du, J., Yin, K., Nadim, F., and Lacasse, S.: Quantitative vulnerability estimation for individual landslides, in 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013, Paris, 2181–2184, 2013.

Garcia, R. A. C.: Metodologias de avaliação de perigosidade e risco associado a movimentos de vertente. Aplicação na bacia da ribeira de Alenquer, Ph.D. thesis, Institute of Geography and Spatial Planning (IGOT), Universidade de Lisboa, Lisbon, Portugal, 469 pp., 2012.

Glade, T.: Vulnerability Assessment in Landslide Risk Analysis, Die Erde, 134, 123–146, 2003.

Godfrey, A., Ciurean, R. L., Van Westen, C. J., Kingma, N. C., and Glade, T.: Assessing vulnerability of buildings to hydro-meteorological hazards using an expert based approach – An application in Nehoiu Valley, Romania, Int. J. Disaster Risk Reduct., 13, 229–241, doi:10.1016/j.ijdrr.2015.06.001, 2015.

Guillard, C. and Zezere, J.: Landslide susceptibility assessment and validation in the framework of municipal planning in Portugal: the case of Loures Municipality, Environ. Manage., 50, 721–735, doi:10.1007/s00267-012-9921-7, 2012.

Guillard-Gonçalves, C., Cutter, S. L., Emrich, C. T., and Zêzere, J. L.: Application of Social Vulnerability Index (SoVI) and delineation of natural risk zones in Greater Lisbon, Portugal, J. Risk Res., 18, 651–674, doi:10.1080/13669877.2014.910689, 2015.

Guzzetti, F., Carrara, A., Cardinali, M., and Reichenbach, P.: Landslide hazard evaluation?: a review of current techniques and their application in a multi-scale study, Central Italy, Geomorphology, 31, 181–216, 1999.

Jaiswal, P., Westen, C. J. van, and Jetten, V.: Quantitative assessment of direct and indirect landslide risk along transportation lines in southern India, Nat. Hazards Earth Syst. Sci., 10, 1253–1267, doi:10.5194/nhess-10-1253-2010, 2010.

Highland, L. M. and Bobrowsky, P.: The Landslide Handbook – A Guide to Understanding Landslides, Reston, Virginia, 2008.

INE (Instituto Nacional de Estatística): Portuguese population grids for the years 2001, 2006 and 2011, available at: http://www.efgs.info/data/portugal/Metodology_Portuguese_GridData2001_2006_2011.docx/view (last access: 13 July 2015), 2011.

Léone, F., Aste, J. P., and Leroi, E.: Vulnerability assessment of elements exposed to mass-movement: working toward a better risk perception, in: Landslides, edited by: Senneset, K., Balkema, Rotterdam, 263–270, 1996.

Macquarie, O., Thiery, Y., Malet, J. P., Weber, C., Puissant, A., and Wania, A.: Current practices and assessment tools of landslide vulnerability in mountainous basins-identification of exposed elements with a semi-automatic procedure, in: Landslides: evaluation and stabilization, edited by: Lacerda, W. A., Ehrlich, M., Fontoura, S. A. B., and Sayao, A. S. F., Taylor and Francis Group, London, 171–176, 2004.

Malamud, B. D., Turcotte, D. L., Guzzetti, F., and Reichenbach, P.: Landslide inventories and their statistical properties, Earth Surf. Process. Landf., 29, 687–711, doi:10.1002/esp.1064, 2004.

Michael-Leiba, M., Baynes, F., and Scott, G.: Quantitative landslides of Cairns. Australian Geological Survey Organisation, Department of Industry, Science & Resources, AGSO Records 1999/36, 40, 1999.

Papathoma-Köhle, M., Neuhäuser, B., Ratzinger, K., Wenzel, H., and Dominey-Howes, D.: Elements at risk as a framework for assessing the vulnerability of communities to landslides, Nat. Hazards Earth Syst. Sci., 7, 765–779, doi:10.5194/nhess-7-765-2007, 2007.

Papathoma-Köhle, M., Kappes, M., Keiler, M., and Glade, T.: Physical vulnerability assessment for alpine hazards: state of the art and future needs, Nat. Hazards, 58, 645–680, doi:10.1007/s11069-010-9632-4, 2011.

NHESSD
3, 5547–5597, 2015

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Papathoma-Köhle, M., Totschnig, R., Keiler, M., and Glade, T.: A new vulnerability function for debris flow – The importance of physical vulnerability assessment in Alpine areas, 12th Congress Interpraevent, Grenoble, France., 2012.

Remondo, J., Bonachea, J., and Cendrero, A.: A statistical approach to landslide risk modelling at basin scale: from landslide susceptibility to quantitative risk assessment, Landslides, 2, 321–328, doi:10.1007/s10346-005-0016-x, 2005.

Safeland deliverable 2.4: Guidelines for landslide susceptibility, hazard and risk assessment and zoning, available at: ftp://ftp.itc.nl/pub/westen/Safeland/LecturenotesLandslidehazardandRiskSafelandD2-4_final.pdf (last access: 13 July 2015), 2011.

SafeLand deliverable 2.6: Methodology for evaluation of the socio-economic impact of landslides (socio-economic vulnerability), 2012.

Santos, J. G.: Landslide susceptibility and risk maps of Regua (Douro basin, NE Portugal), in: Proceeding of the IAG and IGU-C12 Regional Conference “Geomorphic hazards; towards the prevention of disasters”, Mexico City, Mexico, 2003.

Schuster, R. L. and Highland, L. M.: U.S. Geological Survey Open-File Report 01-0276., available at: http://pubs.usgs.gov/of/2001/ofr-01-0276/ (last access: 13 July 2015), 2001.

Silva, M. and Pereira, S.: Assessment of physical vulnerability and potential losses of buildings due to shallow slides, Nat. Hazards, 72, 1029–1050, doi:10.1007/s11069-014-1052-4, 2014.

Sterlacchini, S., Frigerio, S., Giacomelli, P., and Brambilla, M.: Landslide risk analysis: a multi-disciplinary methodological approach, Nat. Hazards Earth Syst. Sci., 7, 657–675, doi:10.5194/nhess-7-657-2007, 2007.

Tinti, S., Tonini, R., Bressan, L., Armigliato, A., Gardi, A., Guillande, R., Valencia, N., and Scheer, S.: Handbook of Tsunami Hazard and Damage Scenarios, JRC Scientific and Technical Reports, 41 pp., doi:10.2788/21259, 2011.

Uzielli, M., Nadim, F., Lacasse, S., and Kaynia, A. M.: A conceptual framework for quantitative estimation of physical vulnerability to landslides, Eng. Geol., 102, 251–256, doi:10.1016/j.enggeo.2008.03.011, 2008.

van Westen, C. J., Asch, T. W. J., and Soeters, R.: Landslide hazard and risk zonation—why is it still so difficult?, Bull. Eng. Geol. Environ., 65, 167–184, doi:10.1007/s10064-005-0023-0, 2005.

van Westen, C. J., Castellanos, E., and Kuriakose, S. L.: Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview, Eng. Geol., 102, 112–131, doi:10.1016/j.enggeo.2008.03.010, 2008.

Varnes, D. and the International Association of Engineering Geology Commission on Landslides and Other Mass Movements: Landslide hazard zonation: a review of principles and practice, UNESCO Pre., Paris, 1984.

Weng, M. C., Wu, M. H., Ning, S. K., and Jou, Y. W.: Evaluating triggering and causative factors of landslides in Lawnon River Basin, Taiwan, Eng. Geol., 123, 72–82, doi:10.1016/j.enggeo.2011.07.001, 2011.

Yin, K. and Yan, T.: Statistical prediction models for slope instability of metamorphosed rocks, Proceedings of 5th ISL, edited by: Bonnard, C., 1269–1272, Rotterdam, 1988.

Zêzere, J. L.: Landslide susceptibility assessment considering landslide typology. A case study in the area north of Lisbon (Portugal), Nat. Hazards Earth Syst. Sci., 2, 73–82, doi:10.5194/nhess-2-73-2002, 2002.

Zêzere, J. L., Reis, E., Garcia, R., Oliveira, S., Rodrigues, M. L., Vieira, G., and Ferreira, A. B.: Integration of spatial and temporal data for the definition of different landslide hazard scenarios in the area north of Lisbon (Portugal), Nat. Hazards Earth Syst. Sci., 4, 133–146, doi:10.5194/nhess-4-133-2004, 2004.

Zêzere, J. L., Oliveira, S., Garcia, R., and Reis, E.: Landslide risk analysis in the area North of Lisbon (Portugal): evaluation of direct and indirect costs resulting from a motorway disruption by slope movements, Landslides, 4, 123–136, doi:10.1007/s10346-006-0070-z, 2007.

Zêzere, J. L., Garcia, R., Oliveira, S., and Reis, E.: Probabilistic landslide risk analysis considering direct costs in the area north of Lisbon (Portugal), Geomorphology, 94, 467–495, 2008.

Table 1. Structural building types in the Loures municipality (National Institute of Statistics, Census 2011).

Structural building type	Structural elements and construction material	Number of buildings
SBT1	Wood or metal (light structures)	221
SBT2	Adobe, rummed earth or loose stone walls	577
SBT3	Brick or stone masonry walls	9947
SBT4	Masonry walls confined with reinforced concrete	21 750

NHESSD
3, 5547–5597, 2015

Table 2. Damage level on buildings.

Damage class		Physical Vulnerability	Damage level on buildings (based on Alexander, 1986; AGS, 2000; Tinti et al., 2011; Garcia, 2012)
1	Negligible damage	0.2	No significant damage – slight accumulation of material originating aesthetic damages (dirt, chipping paint, etc.)
2	Slight damage	0.4	No structural damage – minor repairable damage: chipping of plaster, slight cracks, damage to doors and windows
3	Significant damage	0.6	No structural damage – major damage requiring complex repair: displacement or partial collapse of walls or panels without compromising structural integrity, highly developed cracks. Evacuation required.
4	Severe damage	0.8	Structural damage that can affect the stability of the building: out-of-plane failure or collapse of masonry, partial collapse of floors, severe cracking or collapse of sections of structure due to settlement. Immediate evacuation; demolition of the element may be required.
5	Very severe damage	1	Heavy damage seriously compromising the structural integrity: partial or total collapse of the building. Imperative and immediate evacuation and complete demolition.

NHESSD
3, 5547–5597, 2015
Physical vulnerability of buildings
C. Guillard-Gonçalves et al.

Table 3. Average vulnerability and standard deviation for each structural building type located on landslide body (cf. Table 1 for building type).

	Landslide body: depth of the slip surface (in m)									
	1 m		3 m		5 m		10 m		20 m	
	Avg. Vuln.	SD	Avg. Vuln.	SD	Avg. Vuln.	SD	Avg. Vuln.	SD	Avg. Vuln.	SD
SBT1	0.60	0.24	0.73	0.21	0.84	0.18	0.90	0.19	0.90	0.20
SBT2	0.57	0.23	0.72	0.20	0.85	0.17	0.92	0.14	0.91	0.17
SBT3	0.46	0.22	0.60	0.22	0.76	0.18	0.88	0.18	0.91	0.18
SBT4	0.35	0.20	0.48	0.18	0.66	0.19	0.80	0.18	0.86	0.19

NHESSD
3, 5547–5597, 2015

Table 4. Average vulnerability and standard deviation for each structural building type located on landslide foot (cf. Table 1 for building type).

	Landslide foot: height of accumulated material (m)							
	0.5 m		1 m		3 m		5 m	
	Avg. Vuln.	SD	Avg. Vuln.	SD	Avg. Vuln.	SD	Avg. Vuln.	SD
SBT1	0.45	0.22	0.61	0.20	0.85	0.17	0.94	0.12
SBT2	0.38	0.23	0.53	0.21	0.78	0.18	0.93	0.12
SBT3	0.30	0.18	0.40	0.22	0.66	0.17	0.83	0.17
SBT4	0.25	0.16	0.31	0.19	0.54	0.19	0.72	0.20

NHESSD
3, 5547–5597, 2015

NHESSD
3, 5547–5597, 2015

Table 5. Probability of occurrence of slides according to their slip surface depth in the Loures municipality.

Slip surface depth (m)	Slide area (m^2)	Probability
1	706	0.57
3	2119	0.34
5	3532	0.19
10	7064	0.07
20	14 127	0.02

Table 6. Probability of occurrence of slides according to the height of their accumulated material in the Loures municipality.

Accumulated material height (m)	Corresponding slip surface depth (m)	Slide area (m^2)	Probability
0.5	1	706	0.57
1	2	1413	0.48
3	6	4238	0.16
5	10	7064	0.07

Table 7. Probability of occurrence of deep-seated landslides in 1 year, 10, 25 and 50 years in the Loures municipality.

Susceptibility class	Area (no. of pixels)	Predictive capacity	1 year probability	10 years probability	25 years probability	50 years probability
Very high	468 814	0.5	0.001508	0.015083	0.037708	0.075416
High	647 436	0.25	0.000546	0.005461	0.013652	0.027305
Low	1 246 342	0.15	0.000170	0.001702	0.004255	0.008510
Very low	4 362 465	0.1	0.000032	0.000324	0.000810	0.001621

NHESSD
3, 5547–5597, 2015

NHESSD
3, 5547–5597, 2015

Table 8. Probability of occurrence of superficial landslides in 1 year, 10, 25 and 50 years in the Loures municipality.

Susceptibility class	Area (no. of pixels)	Predictive capacity	1 year probability	10 years probability	25 years probability	50 years probability
Very high	400 890	0.5	0.000420	0.004201	0.010502	0.021004
High	810 140	0.25	0.000104	0.001039	0.002598	0.005197
Low	1 176 564	0.15	0.000043	0.000429	0.001074	0.002147
Very low	4 337 463	0.1	0.000008	0.000078	0.000194	0.000388

NHESSD
3, 5547–5597, 2015

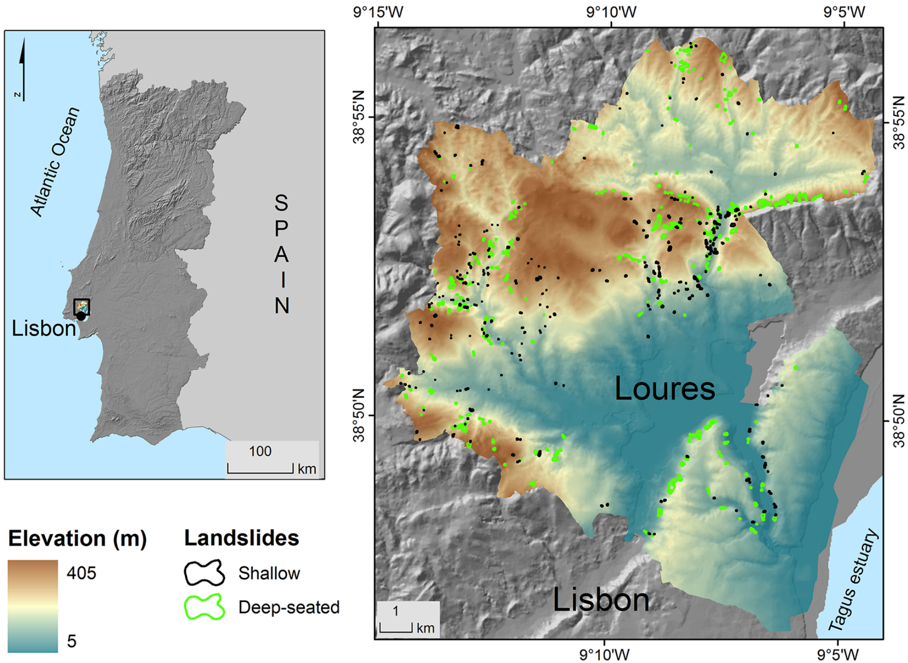

Figure 1. Loures municipality location, elevation and location of the 686 inventoried landslides.

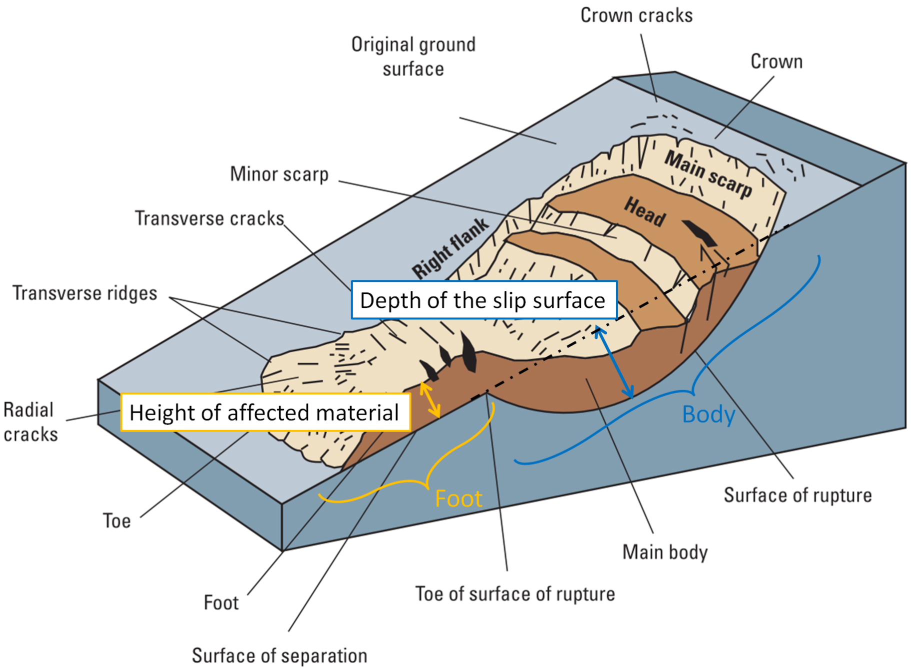

Figure 2. Rotational slide body and foot (adapted from Highland and Bobrowsky, 2008).

NHESSD
3, 5547–5597, 2015

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂◂ ▸▸
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

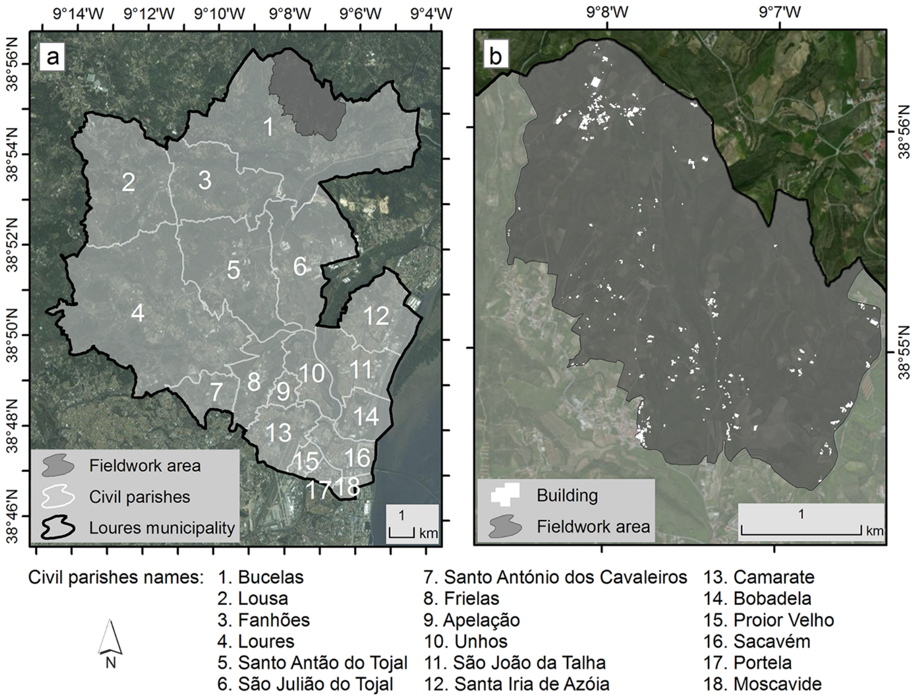

Figure 3. (a) Civil parishes of the Loures municipality and location of the fieldwork area; **(b)** buildings of the fieldwork area.

NHESSD
3, 5547–5597, 2015

Physical vulnerability of buildings

C. Guillard-Gonçalves et al.

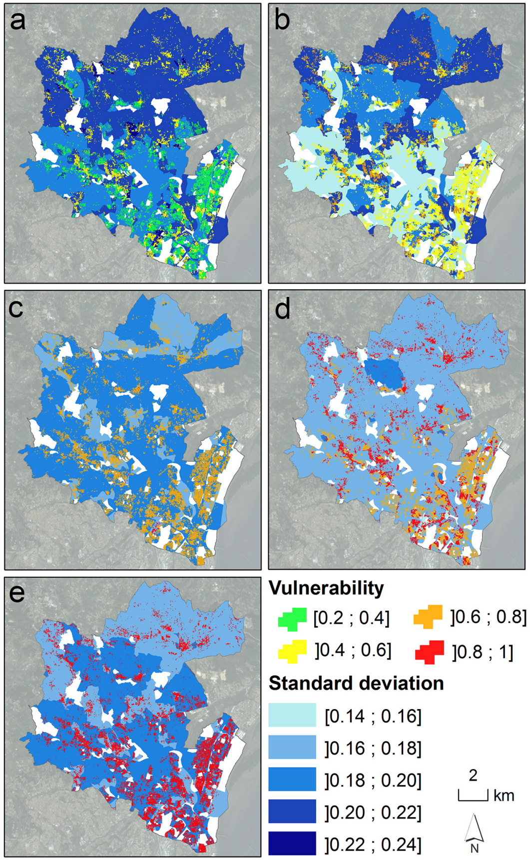

Figure 4. Average building vulnerability and standard deviation per BGRI-subsection for buildings located on landslide body, for slip surface depths of: **(a)** 1 m; **(b)** 3 m; **(c)** 5 m; **(d)** 10 m; and **(e)** 20 m. White polygons are BGRI-subsections without buildings.

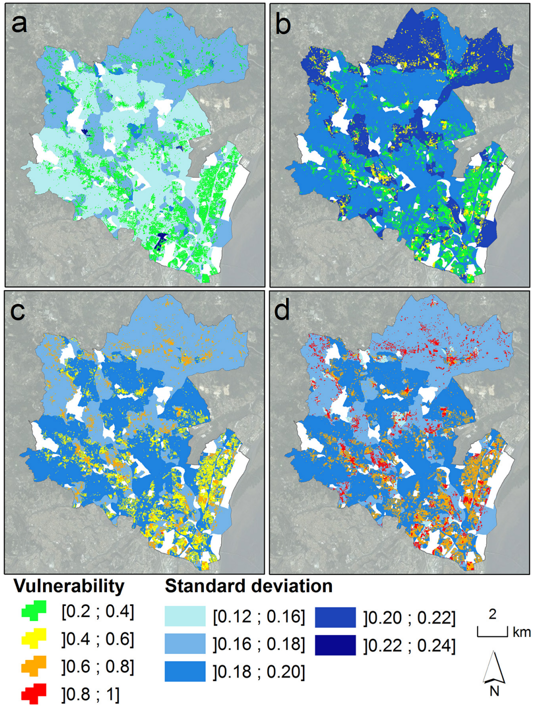

Figure 5. Average building vulnerability and standard deviation per BGRI-subsection, for buildings located on landslide foot having an affected material height of: **(a)** 0.5 m; **(b)** 1 m; **(c)** 3 m; and **(d)** 5 m. White polygons are BGRI-subsections without buildings.

NHESSD
3, 5547–5597, 2015

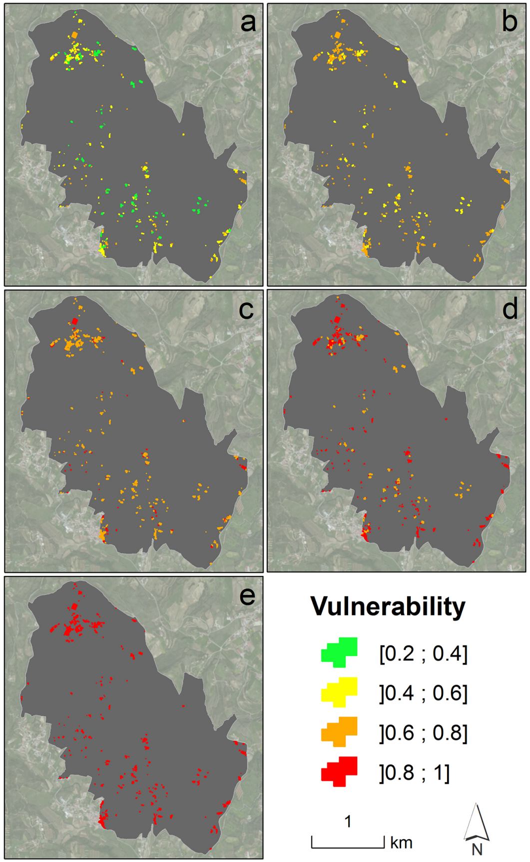

Figure 6. Vulnerability of buildings inventoried in the fieldwork area, being on landslide body having a slip surface depth of: **(a)** 1 m; **(b)** 3 m; **(c)** 5 m; **(d)** 10 m; and **(e)** 20 m.

NHESSD
3, 5547–5597, 2015

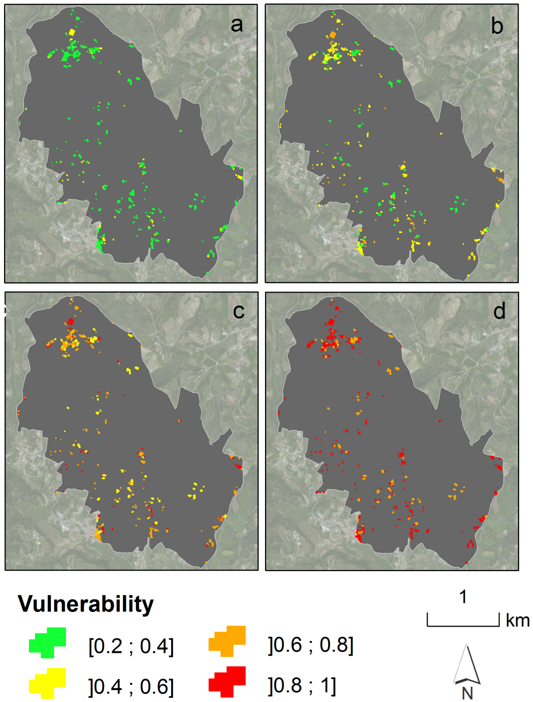

Figure 7. Vulnerability of buildings inventoried in the fieldwork area, being on landslide foot having an affected material height of: **(a)** 0.5 m; **(b)** 1 m; **(c)** 3 m; **(d)** 5 m.

NHESSD
3, 5547–5597, 2015

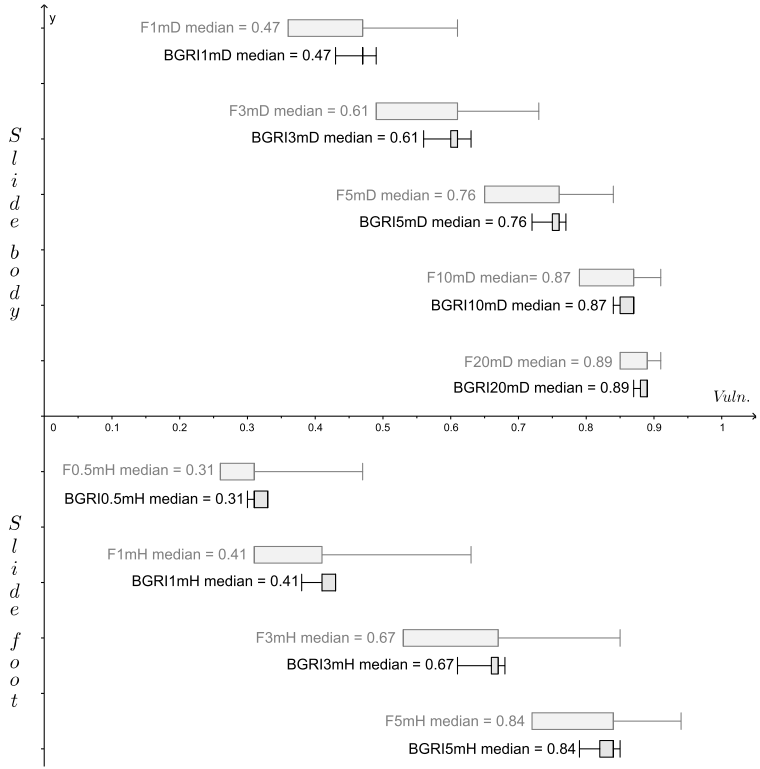

Figure 8. Box plots of the vulnerability of the test site buildings for each scenario: on the positive *y* axis are the boxes and the medians of scenarios of building on a slide body, for a slip surface depth of 1, 3, 5, 10, and 20 m; on the negative *y* axis are the boxes and the medians of scenarios of building on a slide foot, for an accumulated material height of 0.5, 1, 3, and 5 m. The vulnerability values for the buildings inventoried by fieldwork are in grey and the vulnerability values for the buildings of the BGRI-subsections are in black.

NHESSD
3, 5547–5597, 2015

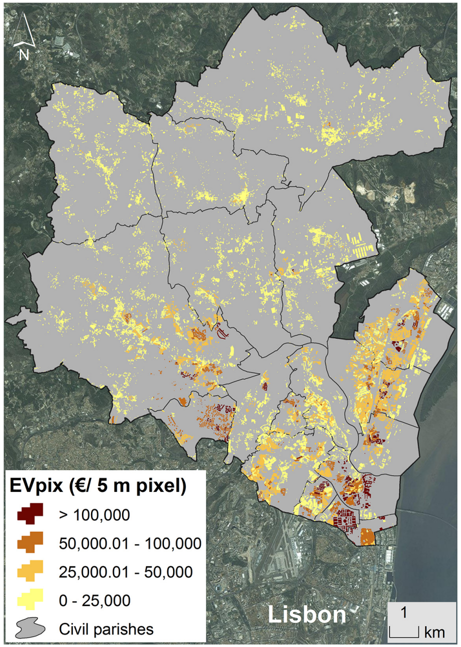

Figure 9. Economic value of buildings per 5 m pixel in the Loures municipality.

NHESSD
3, 5547–5597, 2015

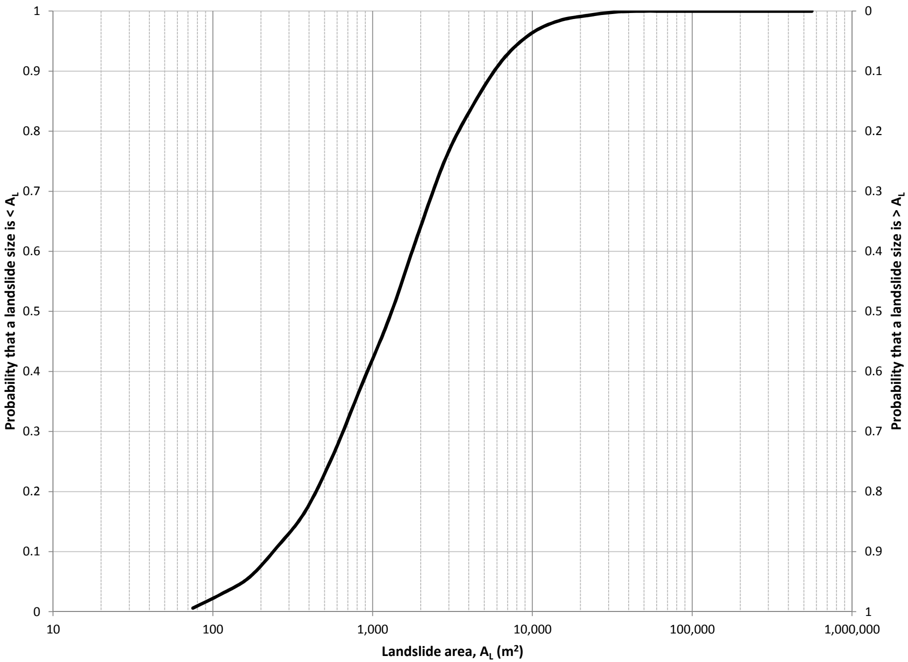

Figure 10. Probability of landslide area in the Loures municipality.

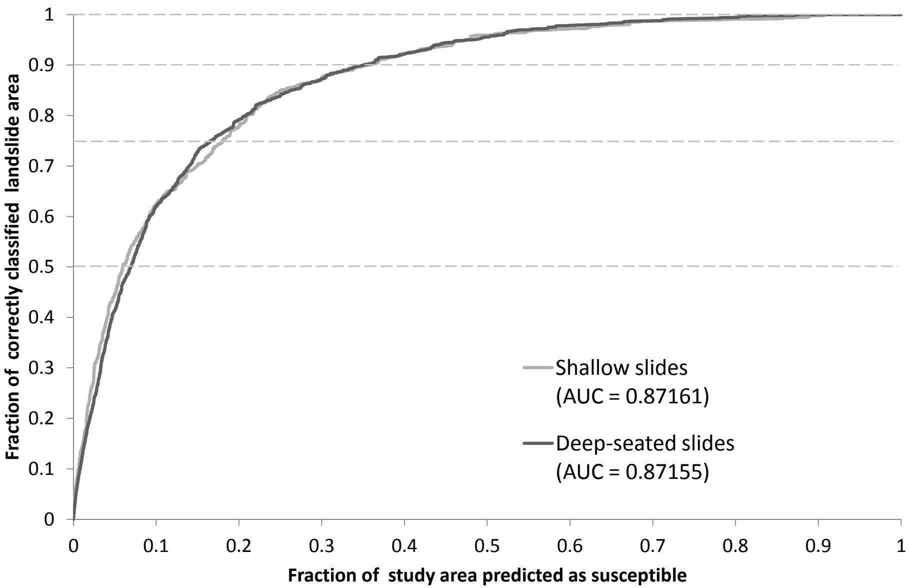

Figure 11. Prediction-rate curves and area under the curve (AUC) of landslide susceptibility models in the Loures municipality.

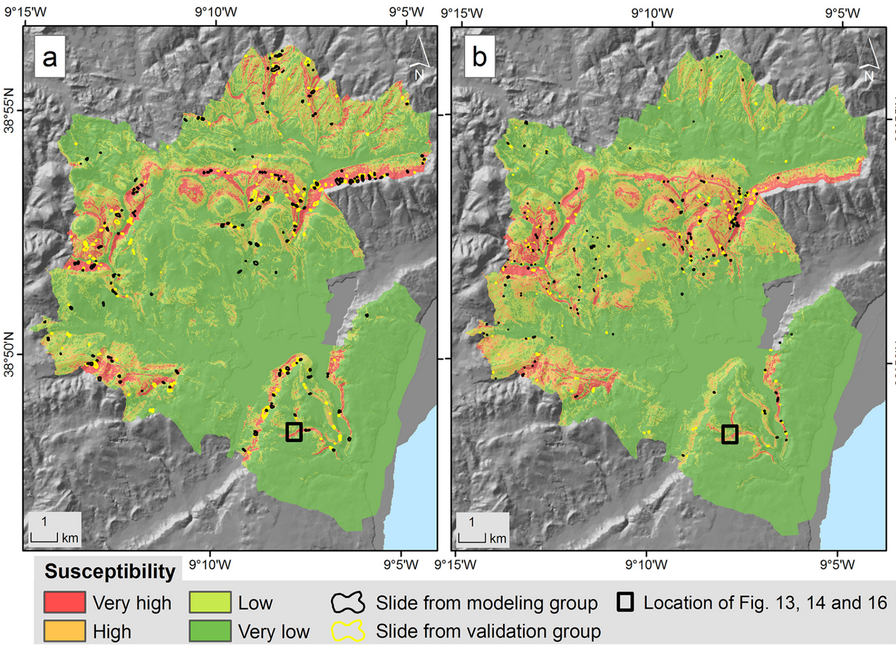

Figure 12. Landslide susceptibility maps in the Loures municipality for: **(a)** deep-seated slides, **(b)** shallow slides.

NHESSD
3, 5547–5597, 2015

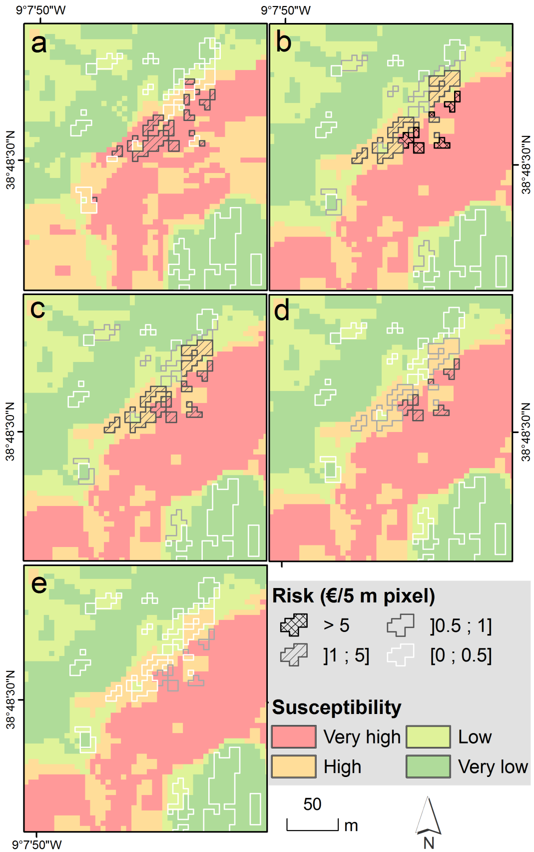

Figure 13. Detail of risk for buildings of the Loures municipality located on a landslide body, for: **(a)** 1 m; **(b)** 3 m; **(c)** 5 m; **(d)** 10 m; and **(e)** 20 m slip surface depths. For location, see Fig. 11.

NHESSD
3, 5547–5597, 2015

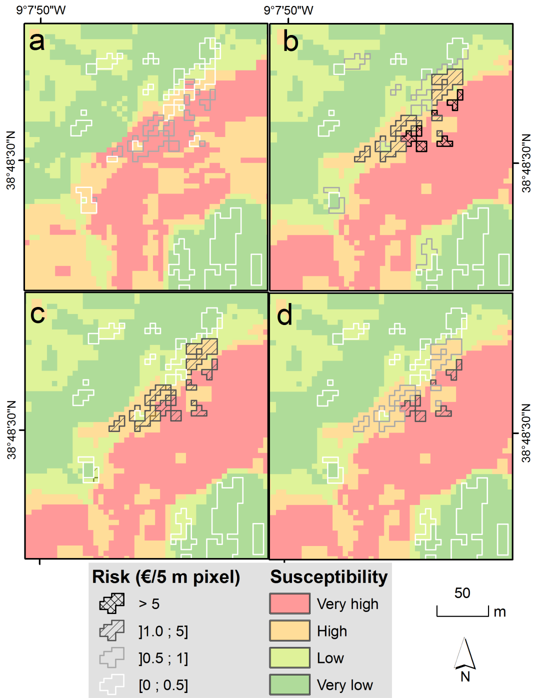

Figure 14. Detail of risk for buildings of the Loures municipality located on a landslide foot, for: **(a)** 0.5 m; **(b)** 1 m; **(c)** 3 m; **(d)** 5 m of affected material height. For location, see Fig. 11.

NHESSD
3, 5547–5597, 2015

NHESSD
3, 5547–5597, 2015

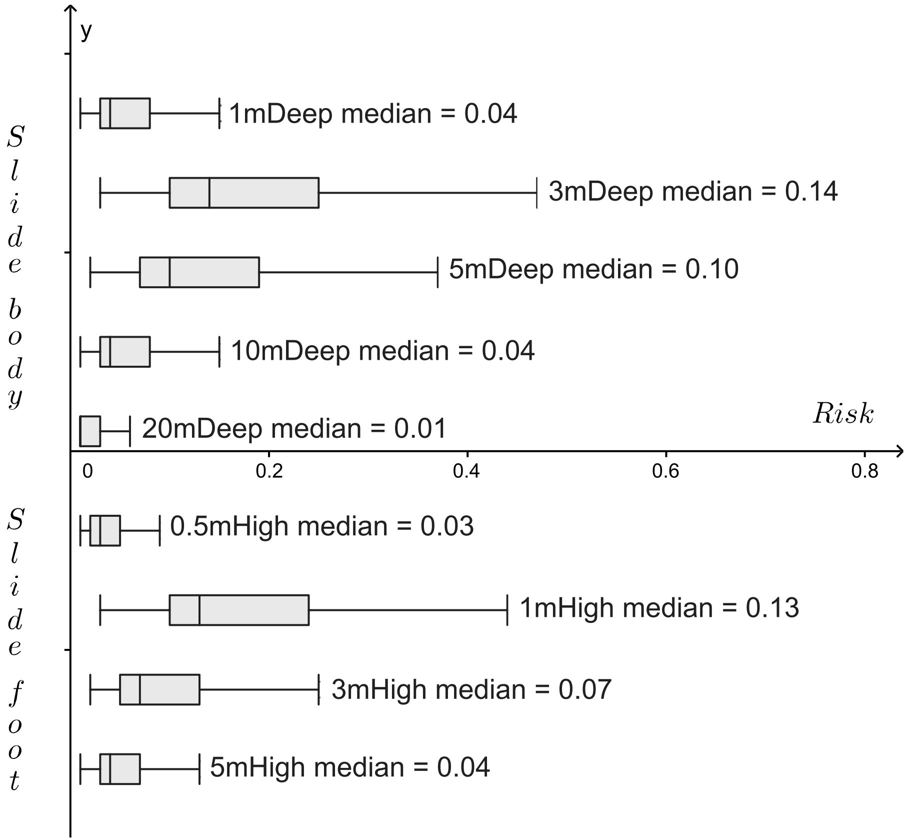

Figure 15. Box plots of the risk for the buildings per 5 m pixel, for each scenario: on the positive *y* axis are the boxes and the medians of scenarios of building on a slide body, for a slip surface depth of 1, 3, 5, 10, and 20 m; on the negative y-axis are the boxes and the medians of scenarios of building on a slide foot, for an accumulated material height of 0.5, 1, 3, and 5 m. Outliers are not shown.

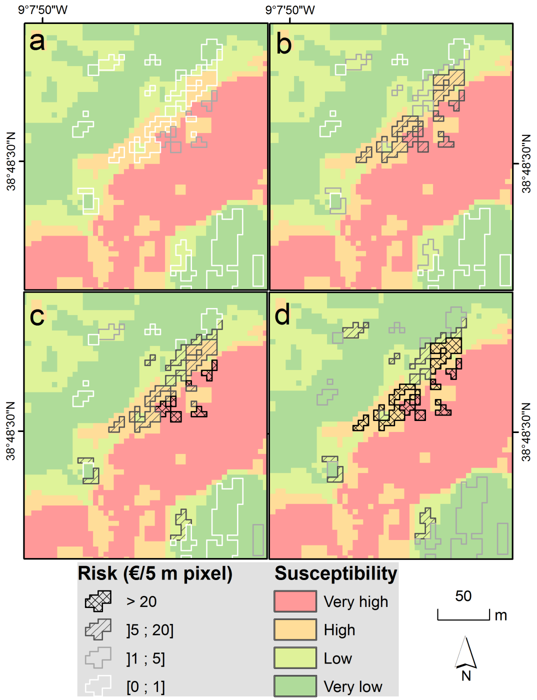

Figure 16. Detail of risk for buildings of the Loures municipality located on a landslide body with slip surface of 1 m depth, for a hazard of **(a)** 1 year, **(b)** 10 years, **(c)** 25 years, **(d)** 50 years. For location, see Fig. 11.