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REDACTt

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The REDACt project Educational Hub

Earthquake induced Geotechnical failures

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1. Background of the document

1.1 Scope and Objectives

Whenever a strong earthquake occurs, part of damages is related to ground failures. There is a significant variety of ground failures triggered by an earthquake. Even though the number of earthquake-induced ground failures is rather extensive (rotational and translational landslides, rock slides, rock falls, toppling, lateral spread, debris flows, lahars, debris avalanches, earthflows, slow earthflows or creep, liquefaction, etc), herein we focus on landslide and liquefaction hazard assessment at a regional scale.

Citizens living next to areas prone to slide or liquefy, should know to what extent they might be exposed to such a hazard in order to act accordingly. Moreover, Civil Protection authorities would like to have an estimation of the geospatial distribution of possible damage and losses especially in urban or non-urban environment to appropriately respond towards mitigation of seismic risk within the first hours after the earthquake. Scope of the deliverable is to provide information to the public about two basic geotechnical hazards, such as landslides and liquefaction, and also to the Civil Protection stakeholders in order to focus on areas where people and infrastructure might be seriously affected.

The document is a part of the REDACt Educational Hub (Edu-Hub). It capitalizes on respective material published by competent Authorities at National and Regional Levels and is based on research carried out during the project and on internationally recognized and widely acceptable principles. Democritus University of Thrace has led this effort and partners contributed with data, information and translations.

1.2 Related Documents

1.2.1 Input

Table 1. List of former deliverables acting as inputs to this document

Document ID	Descriptor
D.T.3.5.1	The REDACt project Educational Hub

1.2.2 Output

Table 2. List of other deliverables for which this document is an input.

Document ID	Descriptor
D.T3.2.1	Earthquake triggered geotechnical hazard assessment (pilot study)

2. Seismic motion and ground failures

Engineers, geologists and other professionals often rely on slightly differing definitions of landslides. This diversity is due to the complexity of the phenomenon. Nevertheless, in this deliverable, landslide is treated as a generic term we use in order to describe the downslope movement of soil or rock under the effect of gravity which is triggered by seismic forces induced during a strong seismic event. The target, is to prepare landslide hazard assessment maps at a regional scale, based on various seismic scenarios. These maps do not intend to substitute site specific projects, being absolutely necessary for design purposes, but they are meant to help civil protection for prevention purposes and preparedness stage and also in strategic planning (actions before an event). They can also be used as a response tool during and just after a seismic event, in order to focus on the areas that landslides are likelihood to occur and the exposure of an object is at risk.

3. Landslide hazard maps

Landslide hazard maps show the areal extent of threatening processes, where landslide processes have occurred in the past (if inventory maps exist for the examined area), recent occurrences, and most important the likelihood in various areas that a landslide might occur in the future. A complete landslide hazard map for a given area, should contain detailed information on the types of landslides, extent of slope subject to failure and the probable maximum extent of ground movement.

The landslide hazard maps can be produced with different approaches according to the scale used (national, regional, local, site-specific) as we move from small to large scales. Since we are interested for hazard maps at a regional scale, we adopted two different approaches, as follows:

- statistically based methods, and
- physically based methods

The "*statistical methods*" provide hazard maps in terms of probability of landslide occurrence and frequency of landslide occurrence. In order to assess a quantitative landslide hazard map at a regional scale, it is necessary to know the spatial probability (P_S), the probability of landslide size (P_M) and the temporal probability for different time periods (P_T).

The "*physically based methods*", on the other hand, are based on slope stability models. Most of them are applied on local scale and the infinite slope model (IFS) is widely used. The IFS model is a simple model quite successful for description of shallow landslide processes. The resulting maps depict the safety factor per each pixel for a given scenario. Physically-based models are applicable to areas with incomplete, or even inexistant landslide inventory. The results of such models are more concrete and more consistent than the heuristic and statistical methods. However, whenever used at regional scales or large areas, they suffer from the main drawback which is either the high degree of oversimplification, or the need for large amounts of reliable input data. Physically-based methods can be successfully used when the geological and the geomorphological conditions of the examined area are fairly homogeneous and the types of landslides relatively simple. In conclusion, not all methods are equally applicable at each scale of analysis. This is why the parallel use of two different methods, statistical and physically-based, guaranties a more complete and less subjective assessment of landslide hazard.

In order to provide an idea of the landslide hazard maps (earthquake-induced) that are produced and used, we present an example from the causative seismic fault of Lefkada earthquake (Mw6.4, 17-11-2015). The landslide hazard maps produced due to the triggering effect of the Lefkada causative seismic fault are treated by both, a statistical method (Nowicki et al., 2014; Jessee et al., 2018), and a physically-based method based on the Infinite Slope Model (ISM). In Figure 1 we present the necessary data of the causative seismic fault of the Lefkada earthquake (Mw6.4, 17-11-2015) as input data. The statistical approach provides maps with the probability of landslide occurrence and the frequency of landslide occurrence (Figure 2), whilst the infinite slope model, physics based, provides values of factor of safety (Figure 3). Regional landslide hazard maps produced by the two different approaches are validated by surveyed co-seismic landslides (Papathanassiou et al., 2017; 2021)

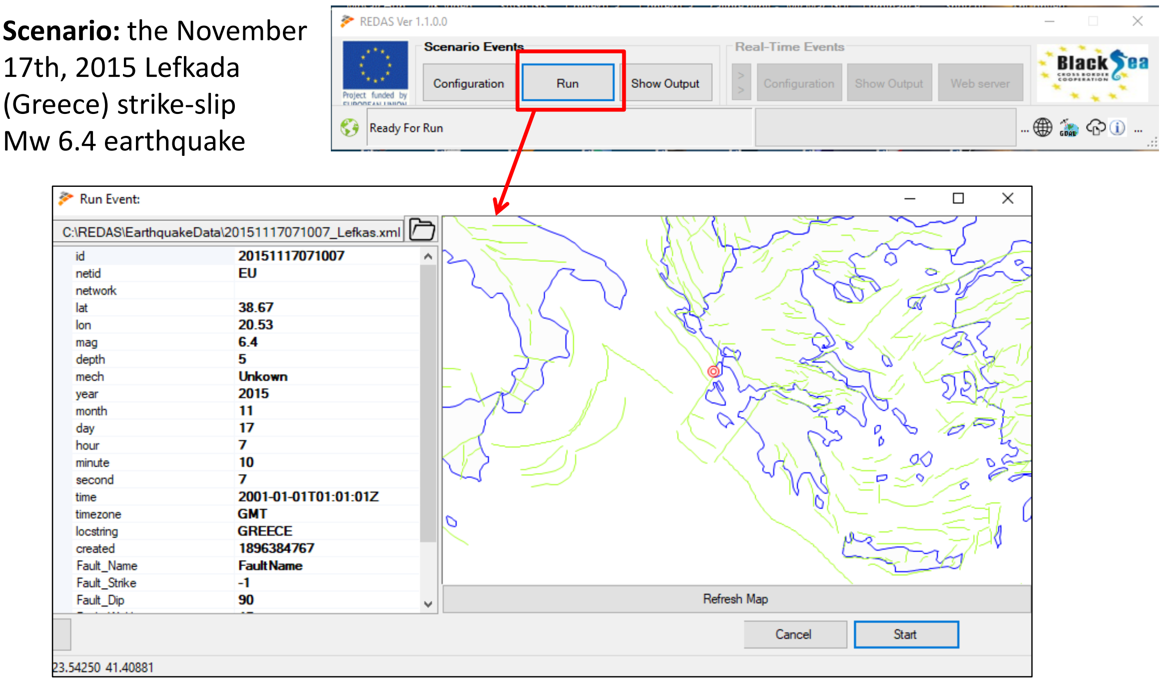


Figure 2: The Lefkada earthquake (Mw6.4, 17-11-2015) used as the triggering effect for validation of the statistical model landslide hazard assessment (Jessee et al., 2018) incorporated into REDAS (Rapid Earthquake Damage Assessment System)

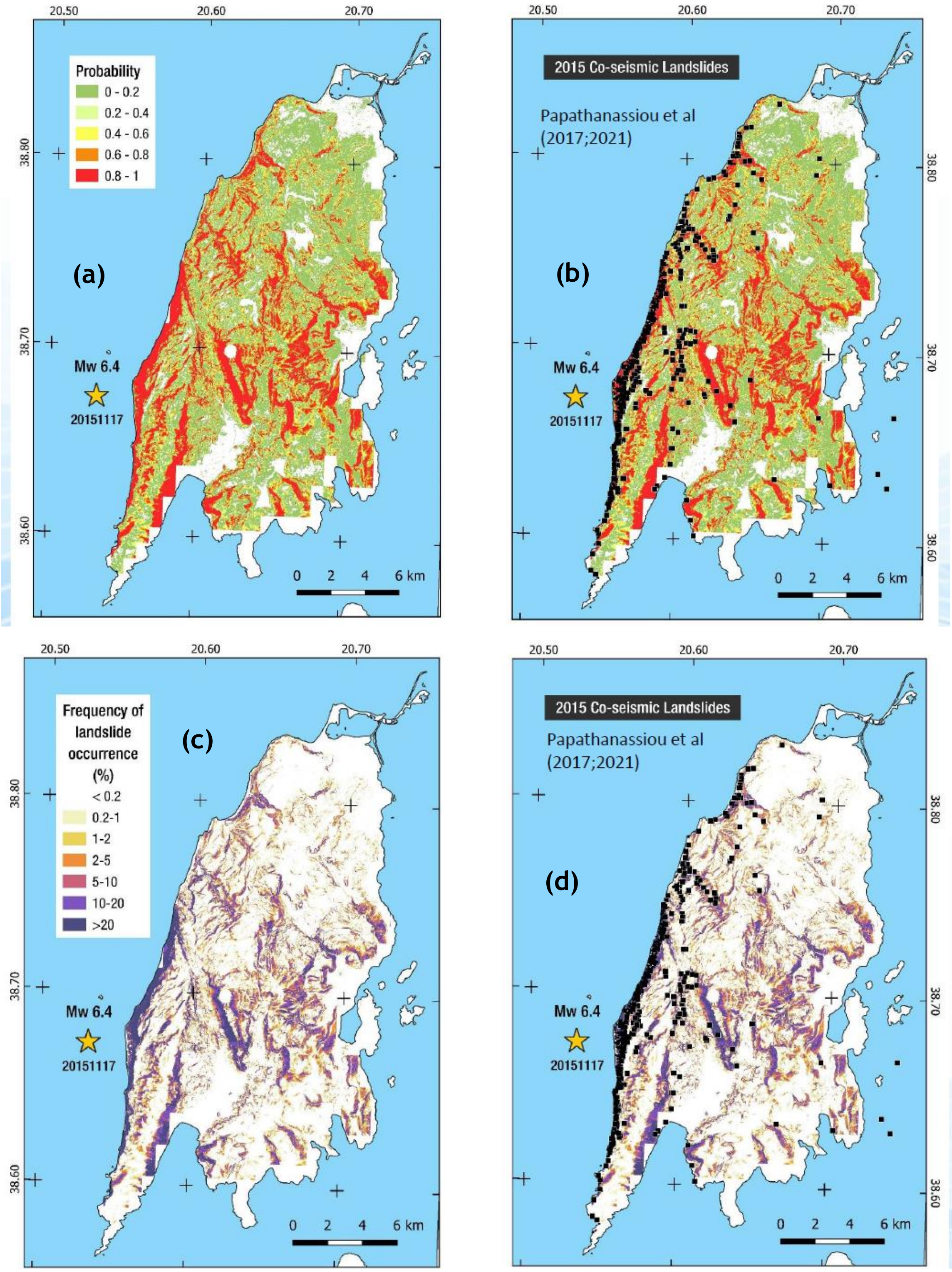


Figure 2: Landslide statistical model output (Jessee et al., 2018) and validation with surveyed co-seismic landslides as black dots (Papathanassiou et al. 2017;2021); (a) vs (b): probability landslide occurrence vs surveyed co-seismic landslides, and (c) vs (d): frequency landslide occurrence vs mapped co-seismic landslides.

In Figure 2 we note the correlation of high landslide probabilities and also of the frequency of landslide occurrence with mapped landslides indicating good model performance.

The same conclusions are also driven by implementation and validation of the infinite slope model predictions in terms of factor of safety, as depicted in Figure 3.

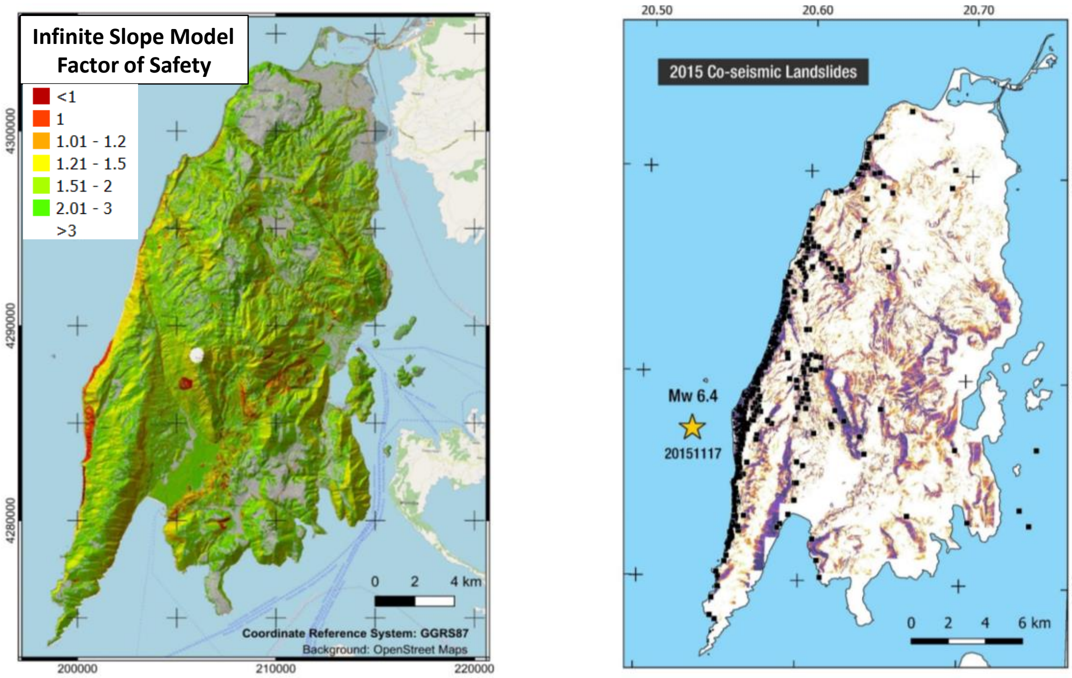


Figure 3: Infinite slope model output for wet conditions and thickness of sliding mass of 1m (left part) validated with statistical model's output and mapped landslides (right part).

In Figure 3 it also appears that both statistical and physical-based models provide essentially converging results, both of them well correlated to mapped earthquake-induced landslides.

4. Understanding, evaluating and communicating landslide hazard

Information about landslides varies in its quantity and complexity ranging from detailed inventories of past landslides and resultant susceptibility and hazard maps to no information at all. There are areas where people have experienced historically landslides in earthquake prone zones and gained empirical knowledge where they should avoid building and living. However, many areas are not readily obvious as to potential landslide hazard, and ground failure does not occur on any kind of regular basis.

Features that might indicate landslide movement, are presented hereafter, as stated in Highland and Bobrowsky (2008):

• Springs and wet or saturated ground in previously dry areas on, or below, slopes.

• Ground cracks—cracks in snow, ice, soil, or rock on, or at, the head of slopes.

• Sidewalks or slabs pulling away from structures if near a slope; soil pulling away from foundations.

• Offset fence lines, which were once straight or configured differently.

• Unusual bulges or elevation changes in the ground, pavements, paths, or sidewalks.

• Tilting telephone poles, trees, retaining walls, fences.

• Excessive tilting or cracking of concrete floors and foundations.

• Broken water lines and other underground utilities.

• Rapid increase or decrease in stream-water levels.

• Sticking doors and windows and visible open spaces, indicating walls and frames are shifting and deforming.

• Creaking, snapping, or popping noises from a house, building, or grove of trees.

• Sunken or down-dropped roads or paths.

The above features could be used as indices for an area prone to slide once one of the triggering effects, appears.

According to Highland and Bobrowsky (2008) the successful translation of landslide hazard information into a practical and useful information for the non-specialized public, conveys the following elements:

- Likelihood of the occurrence of an event that would cause casualties, damage, or disruption to an existing standard of safety.
- Expected location and extent of the effects of the event on the ground, structures or socioeconomic activity.
- Estimated severity of the effects on the ground, structures, or socioeconomic activity.

The above are necessary because engineers, planners, and decision makers usually will ignore a potential hazard if its likelihood is rare, its location is unknown, or its severity is slight. For a product to qualify as useful hazard information, the nontechnical user must be able to perceive likelihood, location, and severity of the hazard, so that they become aware of the danger, be able to communicate the potential risk to others, and can use the translated information directly to reduce a threat.

Evaluation of landslide hazard can be assessed in different ways; it is always advisable to consult with an expert, even though not always possible. However, two types of landslide hazard evaluation are discussed: direct observation and use of technological tools, such as: map analysis, aerial reconnaissance, field reconnaissance, drilling, instrumentation, geophysical measurements, acoustic imagery, etc.

Local authorities can outreach landslide hazard and prevent public, in different ways, such as the following proposed by Highland and Bobrowsky (2008) in the framework of USGS:

- Newspaper bulletins/advertisements.
- Public-service brochures distributed door-to-door or displayed in public places.
- Community meeting discussions.
- Posters in public buildings and (or) marketplaces with as much visual information as possible.
- Media announcements through radio, television, internet, or other means.
- Public lectures by experts or other officials.
- Signs posted in areas of hazards, informing people of the kind of hazard and warning them to be cautious.
- A local Internet Web site is a useful source of safety information and contact phone numbers and emails for emergency personnel.
- Conduct public education and information programs through community meetings, city council, or other councils.
- Adopt and enforce appropriate land-use policies, such as: discuss with landowners, developers, buyers, and sellers.
- Monitor changes in unstable slopes and undertake appropriate actions.
- Construct street and drainage projects that meet local safety needs.
- Be informed about insurance programs available and liability issues.
- Have an emergency response plan for the community.

5. Liquefaction hazard maps

Liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking. Liquefaction and related phenomena have been responsible for severe amounts of damage in historical earthquakes around the world.

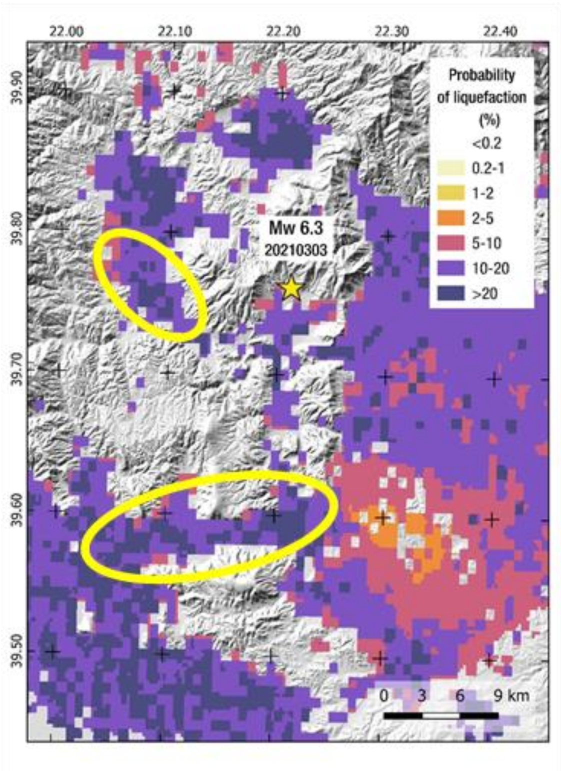
Liquefaction occurs in saturated, loose, non-cohesive, non-plastic or of low plasticity soils (sands, silty sands, silts, clayey silts), that is, soils in which the space between individual particles is completely filled with water. This water exerts a pressure on the soil particles that influences how tightly the particles themselves are pressed together. Prior to an earthquake, the water pressure (pore pressure) is relatively low. However, earthquake shaking can cause increase of the water pressure to the point where the soil particles can readily move with respect to each other, zeroing the friction between grains and cancelling thus the shear strength of these soils (Figure 4). Liquefaction can cause severe damage, or even complete destruction of buildings and infrastructure (Figure 5).

Figure 4: "Waves" of liquefied soil (left) and area severely liquefied (right). Photos from New Zealand Christchurch earthquake (M6.3, 21-2-2011) source: http://www.nzherald.co.nz.

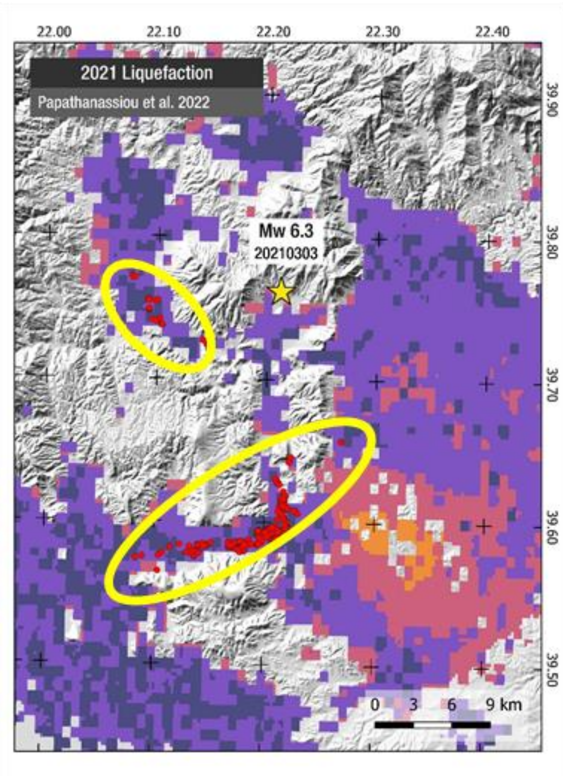
Often, damage to buildings from earthquakes are due to ground failures or the foundation of the building (*Figure* 5). Cases of differential settlement of the foundation can lead to significant damage to the superstructure, while more extensive phenomena, such as soil liquefaction, might result in the global failure of the construction.

Figure 5: (left) Collapse of buildings due to soil liquefaction during the 1964 Niigata, Japan earthquake (photo: Joseph Penzien), (right) Vertical displacement with significant tilt of the building in Adapazari Türkiye, 17-8-1999.

Liquefaction hazard maps show the likelihood of liquefaction and are designed to provide to civil protection, general public, land-use planners, utilities and lifeline owners, as well as, emergency response officials, new and better tools to assess their risk from earthquake damage. Earthquake induced soil liquefaction is an important secondary hazard during earthquakes and can lead to significant damage to infrastructure. Mapping liquefaction hazard is important in both planning for earthquake events and guiding relief efforts by positioning resources once the events have occurred. There exist two aspects of liquefaction hazard mapping at a regional scale: 1) predictive liquefaction hazard mapping and 2) post-liquefaction cataloging. First, current predictive hazard liquefaction mapping relies on detailed geologic maps and geotechnical data, which are not always available in at-risk regions. The predictive liquefaction hazard mapping is based on geospatial liquefaction models that predict liquefaction extent and are appropriate for global application. The geospatial liquefaction models are developed using logistic regression from a liquefaction database consisting of the data from 27 earthquake events from six countries. The model that performs best over the entire dataset (Zhu et al., 2017) includes peak ground velocity (PGV), V_{S30}, distance to the nearest river (d_r), distance to the nearest coast (d_c) and precipitation (mean annual). The model that performs best over the noncoastal dataset includes PGV, V_{S30}, water table depth (w_{td}), distance to water body (d_w), and precipitation (mean annual). The liquefaction hazard maps depict the probability of liquefaction and spatial extent of liquefaction.



(a)



(b)

Figure 6: (a) predictive liquefaction hazard map for Pineios river area depicting the probability of liquefaction based on Zhu et al. (2017) regression model, (b) validation of predictive liquefaction hazard (Zhu et al., 2017) vs surveyed liquefaction locations delimited by yellow color elliptic curves (Papathanassiou et al., 2022). The validation was based on Thessalia's earthquake (Mw6.3, 3-3-2021).

6. References

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