A METHODOLOGY FOR ASSESSING EARTHQUAKE-INDUCED LANDSLIDE RISK

Roberto W. Romeo[1], Randall W. Jibson[2] & Antonio Pugliese[3]

[1] *University of Urbino, ITALY (e-mail: rwromeo@uniurb.it)*
[2] *U.S. Geological Survey (e-mail: jibson@usgs.gov)*
[3] *Agency for the Environmental Protection, ITALY (e-mail: pugliese@apat.it)*

Abstract: Most moderate and large earthquakes trigger landslides, and these landslides commonly account for a significant portion of total earthquake damage and injuries. Thus, formulating scenarios where earthquake-induced landslides are likely to occur can help local authorities plan emergency response and mitigate landslide risk. We are developing a method to quantify the effects of landslides triggered by earthquakes using both deterministic and probabilistic seismic-hazard scenarios. Seismic shaking and the resulting slope performance are integrated in a capacity-demand analysis that estimates the probability that a specified threshold slope performance will be exceeded. Then, an expected damage distribution is estimated for a set of exposed elements, given the response to the landslide effects (i.e., fragility functions). Finally, the expected losses are estimated by relating the damage distribution to a real-estate inventory. This methodology is outlined in a prospectus for a research project funded by the Italian Ministry for the University and Research, in which we describe the logic and mathematics of the method, the GIS tools to be used, and some preliminary results obtained for a test area in Central Italy. We are currently developing a more rigorous probabilistic approach to compute losses and are applying it to test areas in southern California using data from the 1994 Northridge earthquake.

INTRODUCTION

Earthquake-triggered landslides cause extensive damage in many seismically active areas of the world. In light of significant landslide-related damages from historical earthquakes in Italy, the Italian Ministry of Universities and Research has funded us to conduct a research project on the role of seismic site effects on the triggering of landslides. Within this project, a sub-task has been established to develop methods to produce earthquake-induced-landslide risk scenarios. Figure 1 shows the project structure along with the list of the research units involved.

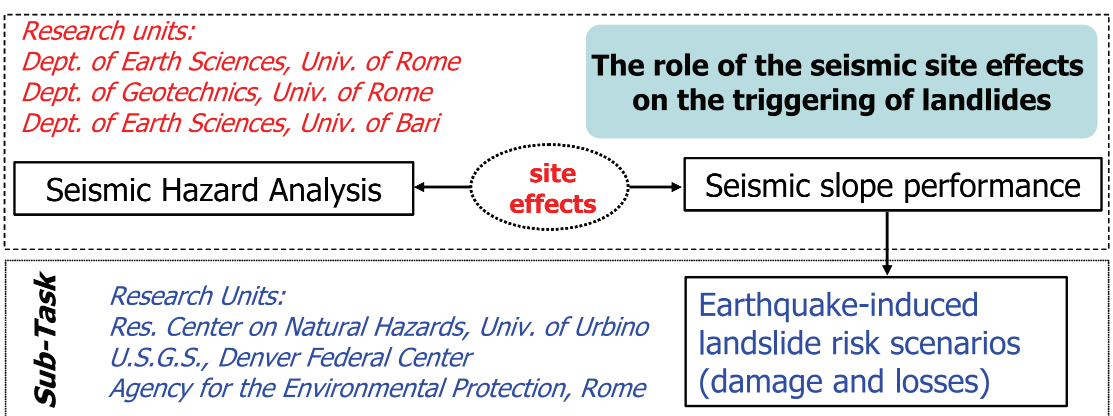


Figure 1. General framework of the project with the sub-task activity highlighted.

This paper describes the methodology we are developing and presents some preliminary results in two test areas: southern California and central Italy.

METHODOLOGY

Figure 2 outlines the methodology we developed, including the following steps:

- Static slope performance is evaluated using conventional limit-equilibrium slope-stability analysis, which expresses the slope stability in terms of a static factor of safety (F_S). Required inputs include a landslide inventory map, a geological field survey that facilitates assigning geotechnical properties to the existing landslides, a digital terrain model (DTM), and an estimate of ground-water levels.
- Seismic slope performance is assessed in terms of the coseismic displacement as computed using Newmark's (1965) sliding-block model (Figure 3). Newmark's method can be considered a capacity-demand model: the capacity is the seismic slope resistance, defined as the critical acceleration (a_c) needed to initiate basal sliding; the demand is the seismic shaking expressed in terms of Arias (1970) intensity values derived from formal seismic hazard analysis (Jibson 1993). A key component of the seismic hazard analysis is to evaluate the interaction between geological site conditions and dynamic amplifications. Methods to systematically quantify site amplification in landslide areas are still in development; for this preliminary study we use empirical correlations between site conditions and amplification effects to modify the Arias intensity values computed through both deterministic and probabilistic seismic hazard analyses (Romeo *et al.* 2000).
- Once the capacity-demand model has been defined, scenarios can be formulated in terms of slope performance. As shown in figure 4, slope performance is characterized both deterministically (coseismic displacement expected under the worst credible seismic shaking) and probabilistically (coseismic displacement expected in a given return period).

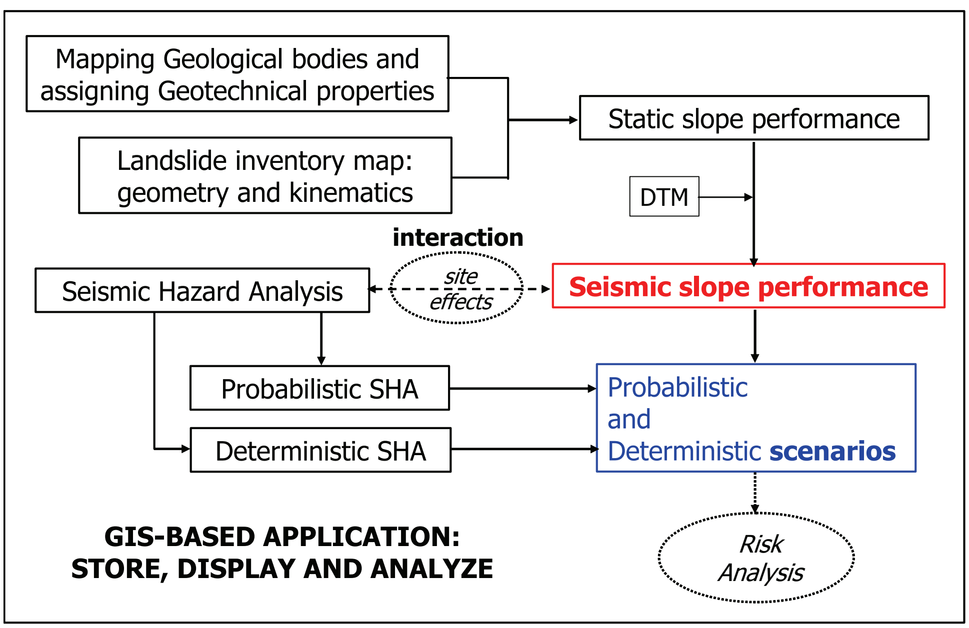


Figure 2. Flow-chart of the research studies carrying out for the development of the subtask involving earthquake-induced-landslide risk scenarios.

The capacity-demand model is governed by the following equation:

$$P(D > D_C|Y) = \int_0^{\infty} p_Y(y)\left[\int_0^{y} p_{D|Y}(d > D_C|Y)\,dD\right]dY\,,$$

where $P(.)$ is the mean annual rate of exceedance of a critical displacement D_C, given that an intensity measure Y (generally a ground-motion parameter such as Arias intensity) is exceeded.

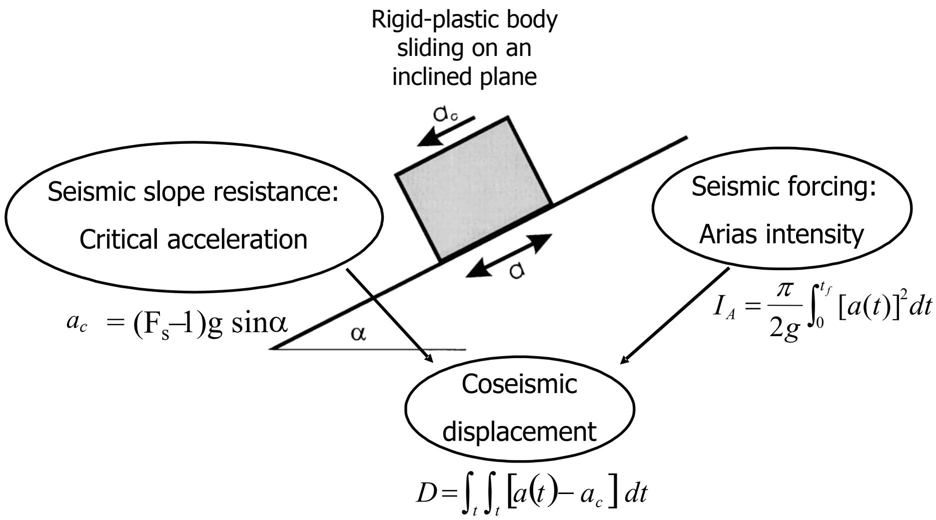


Figure 3. Diagram of Newmark's sliding-block model along with the mathematical functions employed in the capacity-demand model.

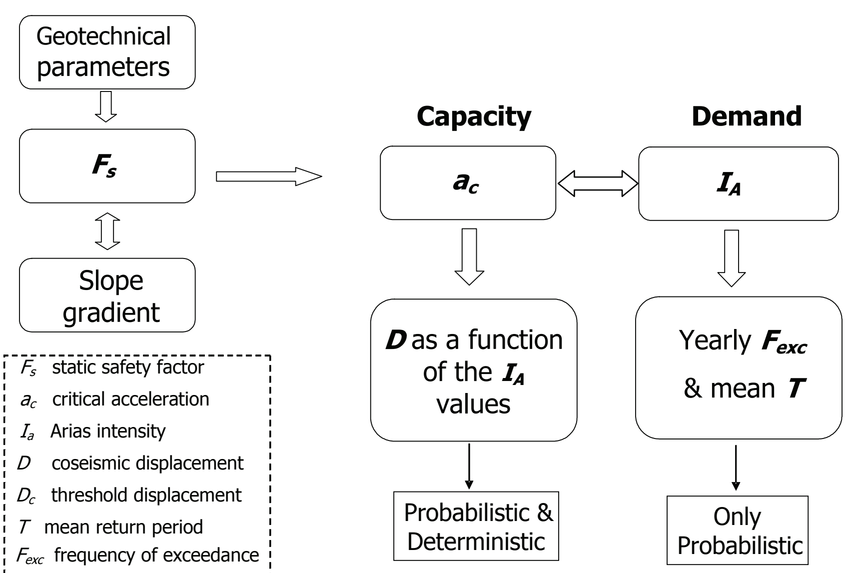


Figure 4. Scheme for the development of probabilistic and deterministic earthquake-induced landslide scenarios.

CASE STUDY IN SOUTHERN CALIFORNIA

The 1994 Northridge, California earthquake (**M** 6.7) was the first earthquake that produced all of the data sets needed to conduct a quantitative regional analysis of factors related to triggered landsliding (Jibson *et al.* 1998, 2000). These data sets included (1) a comprehensive inventory of triggered landslides (Harp and Jibson 1995, 1996), (2) about 200 strong-motion records of the main shock, (3) detailed geologic mapping of the region at 1:24,000 scale, (4) extensive data on the engineering properties (shear strength, unit weight) of geologic units, and (5) high-resolution digital elevation models (DEM) of the topography, from which slope maps are generated. Data layers consisted of 10-m raster grids of six 7.5′ quadrangles. These data sets were combined in a dynamic model based on Newmark's (1965) method to yield estimates of coseismic landslide displacement in each grid cell from the Northridge earthquake. The modeled displacements were then compared with the digital inventory of landslides triggered by the earthquake to construct a probability curve relating predicted displacement to probability of failure. Figure 5 is a flowchart showing the sequential steps involved in the hazard-mapping procedure (Jibson *et al.* 1998, 2000).

This analysis of landslides triggered by a well-recorded earthquake tested the hypothesis that Newmark's method could be used to predict areas that would likely experience slope failure in a specified ground-motion scenario. To test this hypothesis, the modeled Newmark displacements were quantitatively correlated with field performance by comparing the predicted Newmark displacements with the actual inventory of Northridge landslides. Newmark-displacement grid cells were grouped into bins, such that all cells having Newmark displacements between 0 and 1 cm were in the first bin; those having 1 to 2 cm of displacement were in the second bin, and so on. For Newmark displacements greater than about 10 cm, the number of cells in 1-cm bins became very small; therefore, broader ranges of displacement were grouped together. For each Newmark-displacement bin, the proportion of the grid cells in landslide source areas was calculated.

Figure 6 shows, for each displacement bin, the proportion of grid cells occupied by landslide source areas plotted as a function of modeled Newmark displacement. The data clearly demonstrate the utility of Newmark's method in predicting the spatial distribution of seismically

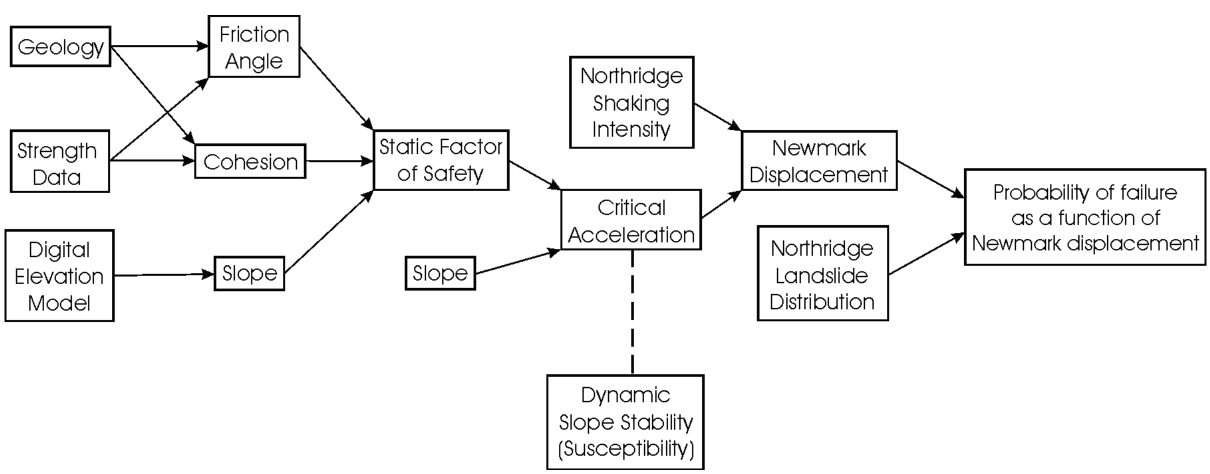


FIGURE 5. Flow chart showing method for producing seismic landslide probability maps for southern California (from Jibson *et al.* 2000).

triggered landslides: the proportion of landslide cells within each displacement bin increases almost monotonically with increasing Newmark displacement. This relation is critical in a predictive sense because the proportion of landslide cells in each displacement bin is a direct estimate of the probability that any cell in that displacement range will be occupied by a landslide source. The proportion of landslide cells increases steeply in the first few centimeters of Newmark displacement and then levels off abruptly in the 10- to 15-cm range at a failure proportion of about 34%. Jibson *et al.* (2000) noted that this maximum proportion of failed slopes is reasonable because, in documented worldwide earthquakes, failed slopes comprising more than 30-35% of the total slope area are rarely seen, even on the most susceptible slopes in epicentral areas.

Jibson *et al.* (2000) fit the data in Figure 6 using a Weibull (1939) curve, which was initially developed to model the failure of rock samples:

$$P(f) = 0.335[1 - \exp(-0.048\, D_n^{1.565})],$$

where $P(f)$ is the proportion of landslide cells, m is the maximum proportion of landslide cells indicated by the data, and D_n is the Newmark displacement in centimeters. The curve fits the data extremely well (R^2=97%), and prediction of the proportion of landslide cells, $P(f)$, can be used to directly estimate probability of slope failure as a function of Newmark displacement. Figure 7 shows an example of a seismic landslide probability map for part of southern California based on shaking from the Northridge earthquake (Jibson *et al.* 2000). This prototype probability map fit the Northridge landslide data very well. Now that a model has been calibrated using a very well-constrained data set, this equation can be used to model any ground-shaking conditions of interest to predict probability of slope failure as a function of Newmark displacement. Of course, this specific equation has only been calibrated to a single data set from southern California and so is valid only there. The principle issue, however, is that Newmark's method can be applied regionally to predict the locations of landslides likely to be triggered by future earthquakes. This forms the basis for the expanded work discussed in the following case study in Italy.

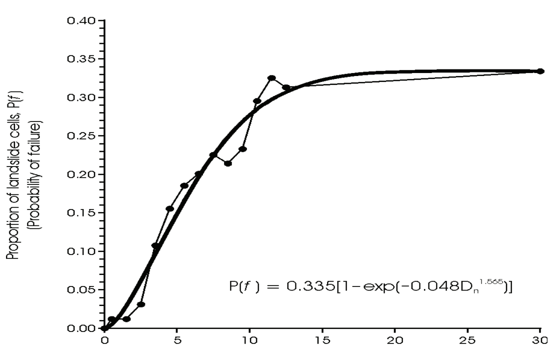


Figure 6. Proportion of landslide cells as a function of Newmark displacement (from Jibson *et al.* 2000).

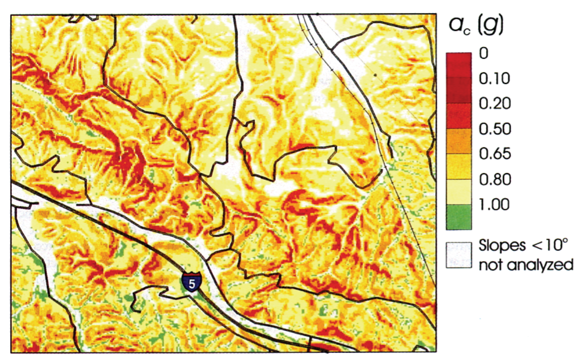


Figure 7. Map showing probability of slope failure in shaking conditions identical to those generated by the 1994 Northridge earthquake (from Jibson *et al.* 2000).

CASE STUDY IN CENTRAL ITALY

Analysis of a seismically active, hilly area in central Italy provides a useful case study (Figure 8). The area is located between two relevant seismic source areas: the nearest source is the Apennine chain, which can generate earthquakes having magnitudes as high as 6.5; the other source is the peri-Adriatic strip, where earthquakes having magnitudes up to 6.0 can occur. Clayey formations are exposed throughout the area.

The seismic hazard of the study area was assessed both deterministically and probabilistically. The deterministic analysis provided the worst-case scenario, regardless of the return period of the expected seismic shaking; the results were used to produce a preliminary assessment of expected damages for emergency planning. The probabilistic analysis provided an estimate of the seismic shaking expected with a 10% chance of being exceeded in 50 years, the commonly used return period for design purposes. The two approaches produced significantly different results because the deterministic approach considers only the single seismic source that most threatens the study area (Figure 9). In both cases the capacity of the system (i.e., the resistance of slopes to undergo failure under seismic conditions) was determined as the spatial distribution of the critical acceleration.

Figure 10 shows the seismic slope capacity (A, distribution of critical acceleration) and seismic slope performance (B, frequency of exceedance of a critical displacement).

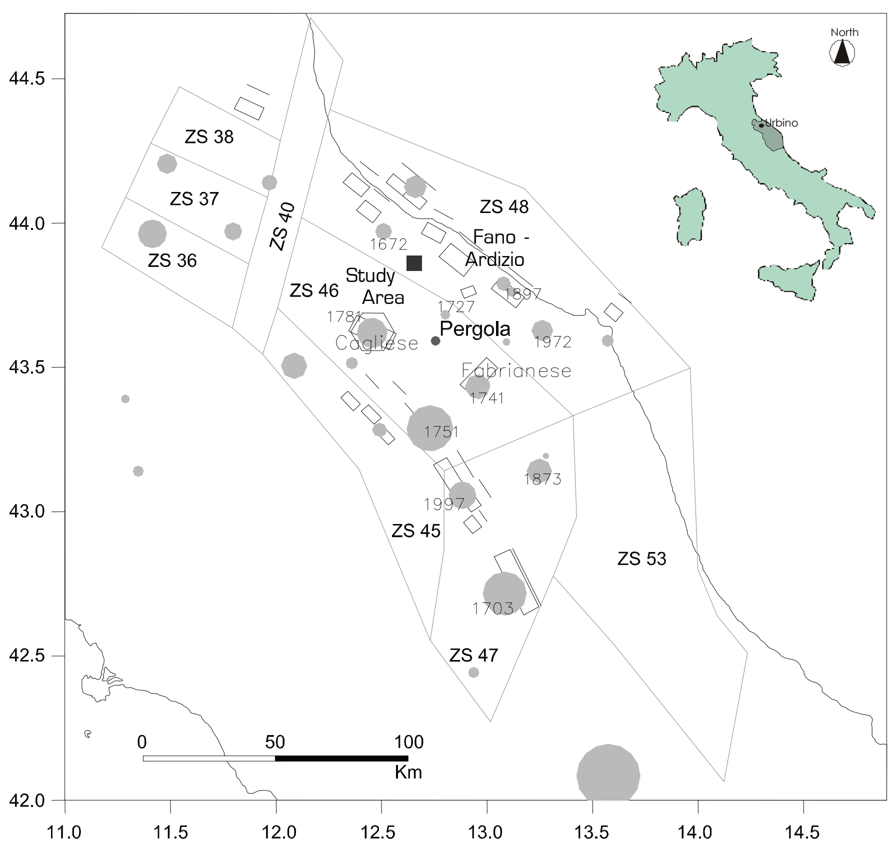
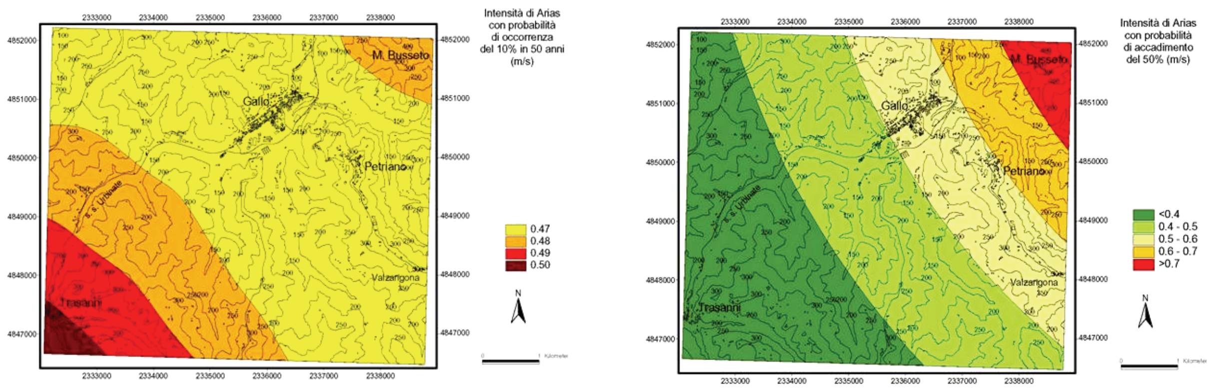


Figure 8. Seismic sources in the study area in central Italy.

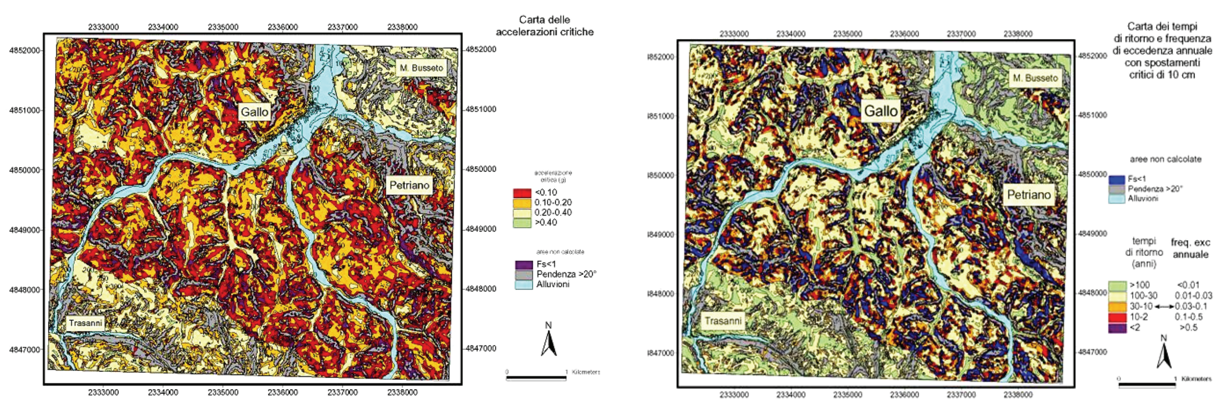


A B

Figure 9. Seismic demand: Arias Intensity values obtained through (A) probabilistic (10% chance of being exceeded in 50 years) and (B) deterministic (worst-case shaking) analyses.

The probabilistic analysis produces a distribution of annual rates of exceedance of a threshold value of coseismic displacement representing initiation of slope failure (10 cm in this example). Expected displacements at different return periods could also be computed using a probabilistic seismic hazard analysis.

Figure 11 shows a preliminary approach to a landslide seismic risk scenario. The results are based on the deterministic seismic hazard analysis and apply only to the behaviour of existing landslides; non-landslide areas were not included in this preliminary analysis. Red and orange areas show landslides whose risk can be defined as "sure" if exposed elements such as houses, structures, or infrastructure are located within the landslide body or within a 50-m-wide buffer zone. Green areas have been labelled "potentially at risk" only for those structures located within the landslide boundaries. For example, Figure 8B shows a landslide (red) whose buffer intersects a road that probably would be damaged during reactivation of the landslide during an earthquake. Alternatively, Figure 8C shows a small village that is affected by a landslide (green) whose seismic reactivation likely would affect only the structures inside the landslide body.



A B

Figure 10. A, distribution of critical accelerations (capacity) needed to bring the slopes to the critical limit state (F_S=1). B, distribution of the annual rate of exceedance of the critical displacement (10 cm) needed to bring slopes to an incipient failure state.

CONCLUSIONS

Preliminary results of our research project regarding the influence of seismic site effects on the triggering of landslides in central Italy and southern California are based on integrating the probabilistic functions of seismic forcing (ground motion) and slope resistance in a classical capacity-demand framework commonly used in the engineering design. The seismic slope performance, defined in terms of expected displacement, provided probabilistic and deterministic scenarios depending on what kind of seismic hazard analysis was performed. The probabilistic scenario gave the annual rate of exceedance of a critical threshold displacement above which the slopes could undergo failure; this type of analysis is particularly suitable for land-use development. The deterministic scenario gave the likelihood that exposed elements, such as houses, structures, and infrastructure, could suffer damages from seismically induced landslide reactivation; this type of analysis is useful for the emergency planning and warning systems.

The ultimate goals of the project, which is scheduled for completion at the beginning of 2008, include the following:

- Incorporating seismic site effects directly into the definition of the seismic slope performance;
- Extending the capacity-demand model to the exposed elements for a comprehensive damage and loss estimation analysis of the earthquake-induced landslide risk.

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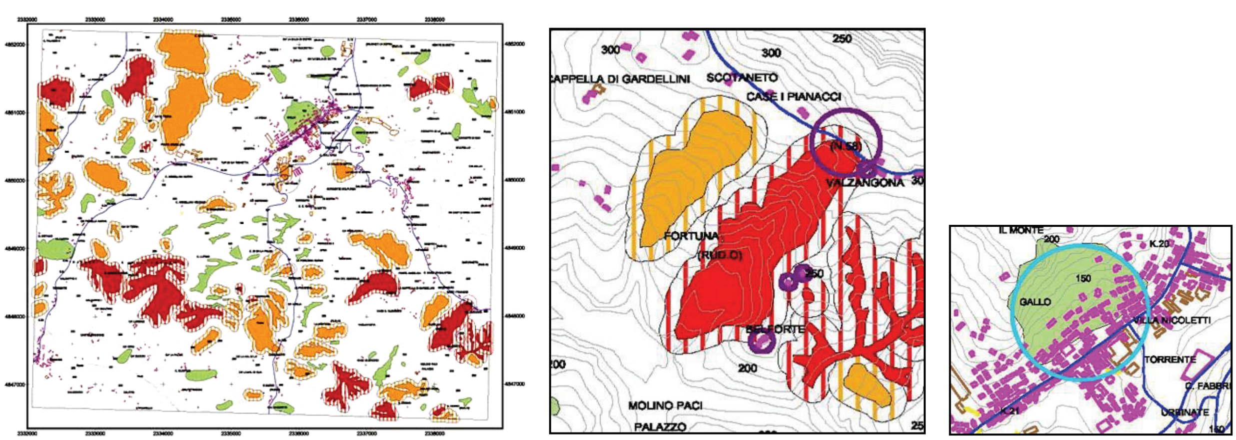

A B C

Figure 11. Preliminary results of the risk analysis of the potential to reactivate existing landslides during seismic shaking. A, study area; B, detail of area containing red and orange zones; C, detail of area containing green zone. Red and orange areas show where coseismic displacements are predicted to exceed 100 cm and 10 cm, respectively, and are defined to indicate "sure" likelihoods of causing structural damage. Green areas are predicted to have less than 10 cm of displacement and thus are defined to have only a potential risk of structural damage from landslides reactivated during earthquakes. Hachured areas are 50-m-wide buffer zones around red and orange areas. Purple polygons are existing structures; blue lines are roads.

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