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Toward the next generation of research on earthquake-induced landslides: Current issues and future challenges

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ABSTRACT

Although, thanks to the new developments in investigation techniques, modeling, and data analyses, much progress has been made in our understanding of collateral seismic hazards, important new lessons are still being learned from historic and recent earthquakes. By referring to the accompanying papers included in this Special Issue and other recent literature, we present an overview of current issues and future challenges of research on earthquake, triggered landsliding. We also offer some recommendations for future research priorities, as a proposed starting point for the next generation of research on earthquake-induced slope failures. These include i) the compilation of many more complete seismic landslide inventories with adequate contextual information, as well as of retrospective inventories; ii) the improvement of regional-scale assessments of seismic landslide susceptibility and hazard; iii) the development of new methods for regional scale analysis of hazards from large catastrophic landslides; and iv) the long-term monitoring of representative test slopes instrumented with an array of accelerometer stations.

Contents

1. Introduction

This work briefly reviews current issues and future challenges of research on earthquake-induced landslides. It is intended to accompany the present Special Issue of Engineering Geology, which is based on the outcomes of an international conference “The Next Generation of Research on Earthquake-Induced Landslides” held in September 2009 at National Central University, Taiwan, in commemoration of the 10th anniversary of the 1999 Chi-Chi, Taiwan earthquake. This earthquake ($M_w = 7.6$) resulted in over 2400 deaths and triggered about 26,000 landslides (Wang et al., 2002). Landslide-related effects from the earthquake persisted long after the event itself, with greatly enhanced levels of landslide occurrence and fluvial transport of sediments continuing for years afterward in the affected area (Dadson et al., 2003, 2004, 2005; Lin et al., 2006, 2008; Hovius et al., 2011) Significantly, the 1999 Chi-Chi event resulted in the world's most extensively studied dataset on seismically triggered landslides, thus greatly advancing our understanding in this area.

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Thanks to a unique, multidisciplinary gathering of international experts (engineering geologists, geomorphologists, geotechnical engineers, seismologists) from Asia, Europe, North America, and Oceania, with over 20 invited key-note lectures, the 10th anniversary conference, which included ample time for discussions, represented a milestone for inspiring the development of new ideas and new collaborative research on scientifically and socio-economically important questions concerning landslides caused by earthquakes. We trust this Special Issue will convey the progress that has been made internationally in this field to the wider scientific research community as well as to geo-hazard mitigation and disaster management authorities.

The problem of seismic landslide hazards has received considerable attention in recent years (e.g. Special Issues of Engineering Geology (2000, vol. 58, nos. 3–4, and 2006, vol. 86 nos. 2–3), and Surveys in Geophysics (2002, vol. 23, no. 6)). However, important new lessons are still being learned from the 1999 Chi-Chi event and other recent earthquakes. In addition the death toll and destruction from seismically-induced landslides in the May 12, 2008 Wenchuan, China earthquake, in which landslides are estimated to have killed more than 20,000 people (see Tang et al., 2011–this issue) remind us that much further work is needed to reduce losses from collateral seismic hazards such as landslides.

In addition to articles related to the Chi-Chi earthquake, this Special Issue, includes works discussing, i) seismic landslide inventories with examples of earthquake-induced landsliding during the 2008 Wenchuan (China) and the 2004 Niigatan Chuetsu and 2008 Iwate-Miyagi Inland (Japan) events; ii) regional scale analysis iii) methods of evaluating seismic stability of slopes and analyzing permanent slope deformations; iv) variability and uncertainty in input data used in modeling and in slope deformation estimates; v) amplification and directivity phenomena in the dynamic response of slopes to seismic shaking; and vi) laboratory tests and modeling of seismically induced landslides.

The study of earthquake triggering of landslides is an important component in hazard reduction in seismically active areas, and the reduction of casualties and economic losses from earthquakes is what ultimately motivates our efforts. Indeed, earthquake losses due to landslides and related ground failures can be very high (e.g. Keefer, 1984; Bird and Bommer, 2004). By referring to the papers in this Special Issue and other recent literature, we offer here first a brief overview of current issues and future challenges of research on earthquake-triggered landsliding. This overview is followed by recommendations for future research priorities, as a proposed starting point for the next generation of research on earthquake-induced landslides.

2. Current issues and future challenges

The articles in this Special Issue and a review of recent literature on seismically induced landsliding indicate that current issues in this field:

- Generation of comprehensive post-earthquake inventories of landslides and related ground failures, with ever increasing applications of new, higher resolution space-borne remotely sensed imagery.
- Regional-scale analysis of earthquake-induced landslide distributions and seismic landslide hazard assessments, with applications of physically-based models, statistical analyses and GIS techniques.
- Analysis of mechanisms of seismically induced landslides and related ground failures causing permanent deformations in slopes, with applications of physical, numerical, and shaking table modeling.
- Measurement and analysis of seismic site response, including topographic and litho-stratigraphic (soil) factors affecting ground motion amplification; ground motion directivity, and slope dynamic response.
- Uncertainty in ground motion inputs and in outputs from seismic slope stability analysis.
- Impact of earthquakes on mountain slope evolution and sediment yields, including enhanced landslide generation by precipitation events following earthquakes.

All these topics are covered by the papers included in this Special Issue, as well as in the proceedings from the 10th anniversary of the 1999 Chi-Chi earthquake conference, which contains numerous expanded abstracts (Lee, 2009).

2.1. Seismic landslide inventories

Although landslide inventories represent the basic ground truth for collateral seismic hazard assessments (e.g. Keefer, 1984; Rodríguez et al., 1999; Hancox et al., 2002), the number of complete or nearly complete inventories is relatively small (see Keefer, 2002 for a comprehensive review). For a comprehensive discussion of problems related to the preparation of landslide inventories (and inventory maps), their limitations and completeness, as well as their quality assessment the interested readers are referred to the work of Malamud et al. (2004). Their work also presents a statistical approach, based on landslide frequency-size distributions from complete inventories, which can be used to obtain useful information from incomplete landslide-event inventories and infer landslide-event magnitude or severity.

Harp et al. (2011–this issue) offer an overview of the issues related to the preparation of detailed and accurate seismic landslide inventories. Some of these are summarized below.

Preparation of a comprehensive inventory requires the availability of suitable remotely sensed imagery. As pointed out by Harp et al. (2011–this issue), ideally such imagery should meet the following requirements:

- It must be continuous and cover the entire area affected by landslides
- It must have a resolution adequate for the recognition and mapping of even very small landslides (few meters across)
- It has to be stereoscopic or, alternatively, monoscopic but suitable to provide good quality 3D perspective views after being draped over a digital elevation model (DEM); this also implies that good quality DEMs are available
- It must be acquired as soon as possible following the earthquake (to distinguish between co-seismic and post-seismic failures) and possibly during cloud-free conditions.

Timely acquisition of remotely sensed imagery can be critical for i) the distinction between co-seismic slope failures and the so-called delayed failures with the initiation or re-activation of landslide movements hours or days after the earthquake (e.g. Keefer, 2002) and ii) the assessment of enhanced landslide activity that can be triggered by post-earthquake rain storms.

Although in recent years there has been a gradual increase in studies that exploit very high resolution satellite imagery (e.g. IKONOS, QuickBird, WorldView-1) for landslide mapping (cf. van Westen et al., 2008), significant challenges persists regarding their practical use for producing comprehensive landslide inventories of seismic events. These include:

- high cost of imagery,
- incomplete coverage,
- orthorectification problems leading to errors in geo-positioning,
- time consuming manual image interpretation versus much quicker but more error prone semi-automatic mapping based on image classification, change detection or object-oriented methods.

The above problems can be exacerbated in cases involving high-magnitude seismic events that affect very large regions of steep terrain (e.g. the 2008 Wenchuan earthquake, China).

The new semi-automatic landslide detection methods, which make use of high resolution multispectral satellite imagery, have good potential to assist in rapid landslide risk assessment during the early post-seismic phase (e.g. Martha et al., 2010; Harp et al., 2011–this issue). However, unlike all-weather, day-night operating satellite radar sensors, optical satellites necessitate solar illumination and relatively cloud-free conditions to acquire useful imagery. Thus, for example, considerable delays in optical image acquisition can be expected during wet seasons in tropical and sub-tropical regions.

It is envisaged that thanks to the improving resolution and shorter re-visit times of radar satellite sensor, the detection and monitoring of post-seismic landslide displacements should become more feasible through the applications of the Synthetic Aperture Radar (SAR) interferometry techniques (cf. Colesanti and Wasowski, 2006). Furthermore, recent works (e.g. McKean and Roering, 2004; Schulz, 2007; Bull et al., 2010) indicate that high-resolution DEM and images from airborne laser radar, also called Light Detection and Ranging (LiDAR), will represent another type of remotely sensed data that can be expect to be increasingly used for landslide inventory mapping. In this case, however, relatively high costs currently are a significant limitation.

Additional information, including mapping criteria that have to be met to obtain detailed and reliable seismic landslide inventories, can be found in the paper by Harp et al. (2011–this issue), who also provide some examples of such inventories. Clearly, the availability of good quality information on pre-earthquake landslide distributions is also important for the proper evaluation of co-seismic slope failure hazards (e.g. Wasowski et al., 2002).

Tang et al. (2011–this issue) use both pre- and post-seismic event landslide inventories to gain better understanding of the impact of the 2008 Mw 7.9 Wenchuan earthquake (Sichuan Province, China) on slope stability. The 2008 Wenchuan event was one of the most devastating earthquakes documented in China and represents an important opportunity for studying the impact of seismic shaking on landslide occurrence (e.g. Huang and Li, 2009). So far extensive mapping has shown that the earthquake caused more than 56,000 shallow, disrupted landslides, rock falls, deep-seated landslides, and rock avalanches (e.g. Dai et al., 2010; Qi et al., 2010).

The work of Tang et al. (2011–this issue) provides an account of the occurrence of disastrous co-seismic landslides as well as many debris flows triggered by heavy rainfall a few months after the 2008 Wenchuan earthquake. The authors focus their attention on the Beichuan area, sadly known for very high human losses due to co-seismic landslides. The study area (414 km^2) was located close to the co-seismic surface rupture and suffered very high intensity of seismic shaking. It included nearly 4% of the total number of landslides triggered the Wenchuan earthquake and about 1% of the overall area affected by slope failures (41,750 km^2) reported by Dai et al. (2010).

Furthermore, the comparative analysis of the impact of the earthquake and the subsequent, heavy rainfall event on landslide evolution by Tang et al. (2011–this issue) revealed that the rainstorm has increased the total landslide area by 30%. The landslide potential was inferred to have been increased by weakening of the slope materials due to the earthquake. Keeping in mind the prolonged impact of large earthquakes on the mountainous environments (e.g. the case of the 1999 Chi-Chi event, Hovius et al., 2011, and references therein), it is to be expected that the destabilized slopes will continue to bring damage and casualties in the years to come.

2.2. Regional scale analysis and seismic landslide hazard evaluation

In recent years the development of new regional-scale analyses of evaluating seismic landslide hazard benefited from the development of Geographic Information Systems (GIS) tools, which incorporate digital terrain data (and landslide inventories). These analyses are based on the integration of seismic shaking parameters, ground geotechnical and geomorphic data including landslide inventories (e.g. Mankelow and Murphy, 1998; Miles and Ho, 1999; Jibson et al., 1998, 2000; Miles and Keefer, 2000; Del Gaudio et al., 2003; Saygili and Rathje, 2009). Newmark displacement (Newmark, 1965) is commonly taken as a measure of permanent displacement caused by seismic shaking along a slide surface.

In essence, Newmark-based seismic landslide hazard or, strictly speaking, spatial variation in slope failure probability or susceptibility, is expressed through regional distribution of Newmark displacements (D_n) that are predicted via empirical relations calibrated using actual seismic landslide records (e.g. Jibson et al., 2000). Subsequent work by Jibson (2007), based on a larger data set of strong motion records (2270 strong-motion records from 30 worldwide earthquakes), provided a series of new/updated regression equations to estimate D_n as a function of i) critical acceleration ratio, ii) critical acceleration ratio and magnitude, iii) Arias intensity and critical acceleration, and iv) Arias intensity and critical acceleration ratio. Although all of the regressions have standard deviations of roughly ± 0.5 log units, which correspond to an order of magnitude variation in estimated Newmark displacements, this does not compromise their principal intended use as an indicator of relative hazard that can be quickly obtained for preliminary regional scale assessments (Jibson, 2007).

Most recently, Hsieh and Lee (2011–this issue) used strong-motion data from the 1999 Chi-Chi earthquake, the 1999 Kocaeli earthquake, the 1999 Duzce earthquake, the 1995 Kobe earthquake, the 1994 Northridge earthquake and the 1989 Loma Prieta earthquake to further refine the relationship among critical acceleration (A_c), Arias Intensity (I_a), and Newmark displacement (D_n). After testing different forms of the regression equations it is shown that an addition of $A_c \log I_a$ term to the Jibson's (1993) empirical formula produces the best results in terms of higher goodness of fit ($R^2 = 0.89$) and lower range of displacements (standard deviation $D_n = 0.295$). Hsieh and Lee (2011–this issue) also indicated that it is useful to separate the Taiwanese dataset from the other data and thus develop Taiwan-specific regressions. Similarly, it was shown that the development of separate empirical equations for rock and soil sites leads to statistically better estimates of D_n.

However, in many areas of the world accelerometer records and geotechnical information will not be available. In this context it is of interest to recall the work of Meunier et al. (2007), who investigated patterns of well documented events of widespread seismic landsliding in relation to the strong motion data. They proposed an expression for the spatial variation of landslide density comparable to regional seismic attenuation laws, and suggested that it can be exploited to provide insight to shaking intensities in the regions where strong motion recordings are not available.

Furthermore, two different approaches have recently been proposed for modeling seismic landslide susceptibility without requiring specific geotechnical data input. Lee et al. (2008) presented a new method for predicting earthquake-induced landslide susceptibility based on multivariate statistics with discriminant analysis. It was shown that for a given scenario (1999 Chi-Chi earthquake) their model was capable of successfully predicting shallow landslide distributions without the information on material strength, groundwater and failure depth. Another approach is that of Miles and Keefer (2000, 2007, 2009a,b), who proposed a new Comprehensive Areal Model of Earthquake-induced Landslides (CAMEL). This knowledge-based model uses fuzzy logic systems and allows regional scale analysis of the differing types and degrees of hazards due to different types of landslides.

Comprehensive hazard assessment requires that the time frame of the landslide occurrence be taken explicitly into account. Del Gaudio et al. (2003) were the first to present a fully time-probabilistic approach to regional-scale evaluation of earthquake-induced landslide hazard. They used standard methods of seismic hazard assessment to obtain the occurrence probabilities for different levels of seismic shaking in time horizons of interest. Then, empirical relations, based on the Newmark model, were employed to evaluate the slope critical (or yield) acceleration (A_c) for which a prefixed probability existed that seismic shaking would lead to landslide triggering. The output map with distribution of the calculated A_c values can be compared with the actual in situ A_c values of specific slopes to estimate whether these slopes have a significant probability of failing under seismic action in the future.

The method proposed by Del Gaudio et al. (2003) does not include information on the actual slope susceptibility to failure. From a practical point of view, the inclusion of this information will be more important on a local scale where the possibility of obtaining actual site-specific data should lead to the achievement of reliable hazard assessment. Thus, following the regional scale identification of slopes having a significant probability of failing under seismic action, relevant factors conditioning slope stability (i.e., geotechnical, morphological, hydrogeological) can be represented through suitable parameters, possibly expressed in probabilistic terms to take into account both the uncertainty of their values and seasonal variability, when appropriate. Finally, we recall that, per definition (e.g. Fell et al., 2008), a comprehensive assessment of (seismic) landslide hazard would necessitate not only the prediction of the location and the temporal probability of a slope failure, but also additional quantitative assessment of landslides in terms of their "intensity", i.e. volume, (or area), type and velocity of movement, run-out length. This is still very difficult to achieve, considering the complexity and variety of landslide types.

2.3. Methods of evaluating seismic stability of slopes and analysis of slope permanent deformations

Jibson (2011–this issue) provides an excellent, retrospective overview of methods for assessing the stability of slopes during earthquakes. These methods are conveniently grouped into i) pseudostatic analysis, ii) stress-deformation analysis, and iii) permanent displacement analysis, and their advantages and limitations are discussed. Subsequently, useful guidelines for the proper selection of these methods and recommendations regarding their applicability to different cases of slope stability investigations are offered.

In particular, it is recommended that pseudostatic analysis, which provides only a very rough approximation of slope behavior during earthquake shaking, be used only for preliminary assessments and screening procedures, which then should be followed by more sophisticated analysis (cf. Stewart et al., 2003). Stress deformation analyses are recommended for site-specific investigations where high density and high quality soil property data can be obtained and where the presence of critical infrastructure (e.g. dams, embankments) and lifelines can justify their application in terms of costs-benefits (Jibson, 2011–this issue).The permanent displacement analysis, which is based on Newmark's (1965) original method for estimating the displacement of slopes under seismic shaking, have a wide range of applications. However, it is useful to recall one important limiting assumption of Newmark's method, i.e. that the effects of dynamic pore pressure are ignored. Where the development of dynamic pore pressures is unlikely, the rigid-block analysis, which represents the basic type of the permanent displacement analysis, is well suited to investigations of thinner landslides in relatively stiff (and dry) surficial material, i.e. shallow slides and falls in rock and in soil (Jibson, 2011–this issue). For deeper and larger failures in softer materials more sophisticated types of the permanent displacement analysis i.e. decoupled and coupled are recommended, the latter being in general more appropriate (Jibson, 2011–this issue).

Considering the wide spectrum of slope-failure types and the variety of the materials involved, the selection of the most appropriate analysis for co-seismic displacement estimation may not be simple. According to Jibson (2011–this issue), at present the best guidance for selection could be provided by the period ratio, T_s/T_m, i.e. the ratio of the fundamental site period (T_s) to the mean period of the earthquake motion (T_m).

The above problem is further addressed by Rathje and Antonakos (2011), who present a unified simplified model for predicting earthquake-induced sliding displacements of rigid and flexible landslide masses. Within their new empirical framework, the seismic loading for the sliding mass is first predicted in terms of the maximum seismic coefficient (k_{max}), defined as the maximum value of the k-time history (rather than an acceleration time history), and the maximum velocity of the seismic coefficient-time history ($k\text{-vel}_{max}$), defined as the maximum velocity of the k-time history. The predictive models are a function of PGA, PGV, the natural period of the sliding mass (T_s), and the mean period of the earthquake motion (T_m). Then, to obtain landslide mass displacement, a predictive model for k_{max} is constructed as a function of PGA and T_s/T_m, and a predictive model for $k\text{-vel}_{max}$ is developed as a function of PGV, PGA, and T_s/T_m. The unified framework of Rathje and Antonakos (2011) thus provides a coherent approach for predicting the sliding displacement of slopes characterized by rigid and flexible behaviors under seismic loading.

2.4. Variability in input data and uncertainty in earthquake induced deformation estimates

Evaluations of seismic stability of slopes relying on D_n estimates require the integration of different types of input data (topographic, geotechnical, hydrogeological, seismological), which are characterized by a certain degree of natural dispersion (e.g. seasonal temporal variability), as well as variable resolution, quality, and reliability (cf. Murphy et al., 2002). Uncertainties in data input can be exacerbated especially on a regional scale and thus lead to unreliable hazard assessments.

The issue of uncertainties in the seismic ground motion input used for predictions of D_n has recently been addressed by Rathje and Saygili (2008). A review of their probabilistic methodology, as well as its application extension to regional seismic landslide hazard mapping can also be found in Saygili and Rathje (2009). Saygili and Rathje's (2009) example of application (Southern California) also illustrates that even where a considerable amount of the geotechnical laboratory test data are available, the selection of representative shear-strength parameters on a regional scale is not simple and requires a careful judgment (cf. Jibson et al., 2000; Keefer, 2000).

Strenk and Wartman (2011–this issue) tackle the problem of how variability in both the seismic ground-motion input and in slope material properties (including groundwater level fluctuations) influences uncertainty in seismic slope deformation predictions. By applying a series of probabilistic Monte Carlo simulations to two established slope deformation models, the Newmark (1965) rigid-block displacement model and the Makdisi and Seed (1978) decoupled model, it is demonstrated that, under certain conditions, a high degree of displacement prediction uncertainty can result from commonly observed natural variability in input parameters. In particular, the extent to which the parametric variability propagates through the analysis and generates uncertainty is related to the highly non-linear relationship between acceleration ratio and displacement. In other words, the model non-linearity has a direct influence on the precision of the displacement predictions.

With reference to the displacement–acceleration ratio relationship, Strenk and Wartman (2011–this issue) identify three regimes or slope conditions (low, moderate, and high uncertainty), differentiated on the basis of their relative degree of non-linearity and influence on the displacement predictions. For slopes under low uncertainty conditions displacement predictions can be relatively precise. For slopes under highly uncertain and to some extent those under moderately uncertain conditions, Strenk and Wartman (2011–this issue) recommend robust probabilistic analyses (e.g. Monte Carlo simulations) to aid the interpretation of poorly constrained displacement predictions. An accurate site-specific assessment of variability in input parameters (material properties and ground motion) is a necessary pre-requisite in this case. Thus a general recommendation for seismic slope deformation analysis is to include a preliminary assessment on the sensitivity of the displacement predictions to input parameter variability.

It is of interest to recall that the extent to which the parametric variability influences displacement predictive uncertainty depends on a slope's relative stability (Strenk and Wartman, 2011–this issue). Indeed, low acceleration ratios, which indicate marginally stable slopes, have greater displacement uncertainty than high acceleration ratios (slopes with high ratios are commonly highly stable under static conditions).

Although epistemic uncertainty is not considered by Strenk and Wartman (2011–this issue), the lack of site-specific data also contributes to the overall predictive uncertainty in seismic slope displacements. This seems especially significant in the case of deep slope failures, whose analysis can be additionally complicated by generally limited knowledge of factors such as groundwater conditions or site effects. The issue of slope seismic response is discussed further below.

2.5. Seismic site response

The influence of site amplifications on landslide triggering during earthquakes has been inferred in several studies on the basis of relations between landslide distribution and topographic relief characteristics (e.g. Harp and Jibson, 2002; Sepúlveda et al., 2005a,b) or through numerical modeling that pointed out impedance contrasts between surface materials and underlying substrata as possible causes of site amplifications favoring landsliding (e.g. Bourdeau and Havenith, 2008; Bozzano et al., 2008).

Some workers (e.g. Lee et al., 2008), have attempted to incorporate site effects in regional seismic landslide hazard assessments, but such efforts can suffer from considerable uncertainties linked to the complexity of the phenomena, especially where both soil and topographic amplification factors co-exists (e.g. Del Gaudio and Wasowski, 2007). Nevertheless, recent findings of Meunier et al. (2008), who investigated the impact of topographic site effects on seismic landslide distributions in the context of seismic wave field modeling, indicate that the role of topographic site effects can be predominant on a regional scale. They also showed that the understanding of topographic site effects and the propagation of seismic waves through mountainous morphology can be used in regional level predictions of spatial distribution patterns of earthquake-triggered landslides.

However, because of the scarcity of accelerometer recordings on slopes, our knowledge of the actual ground motions experienced by slopes having different combinations of geomorphic and lithostratigraphic characteristics is still rather limited. This has obvious influence on the accuracy of the seismic landslide hazard assessments, especially at local scale, which require appropriate quantification of earthquake loading. Of particular interest are those slope conditions that can result in considerable amplifications of shaking. In this context, it is apparent that historical information on landslides triggered at anomalously large distances from an earthquake epicenter (or fault rupture) can indicate hillslopes potentially influenced by site effects (Wasowski and Del Gaudio, 2000).

Del Gaudio and Wasowski (2011–this issue) draw attention to the issue of seismic site response of potentially unstable slopes. Their work builds up on the ongoing long-term (since 2002) accelerometric monitoring of a landslide prone-area (few square km) in the Apennine mountains of central Italy, which provided evidence of amplifications with systematic directional differences in seismic energy by a factor of 2–3 or larger (Del Gaudio and Wasowski, 2007). The characterization of these directional amplification phenomena, initially depended on recordings of relatively low-energy seismic events, has been now updated by expanding the analysis to include the data registered during a seismic sequence that hit the area of L'Aquila, central Italy, whose mainshock (M_w 6.3) occurred on 6 April, 2009 (Del Gaudio and Wasowski, 2011–this issue). The comparative analysis of these new data with those of previously recorded events having different distances and azimuths helped to further clarify conditions determining amplifications of seismic ground motion on slopes.

In particular, Del Gaudio and Wasowski (2011–this issue) reported evidence that seismic ground motion on slopes covered by thick colluvia or by deep-seated landslides can be considerably amplified and that in some cases this amplification can have a pronounced directional character with maxima oriented along potential sliding directions. The causes of the directivity are still poorly understood. It is possible that a combination of topographic, lithologic and structural factors acts to re-distribute shaking energy, focusing it in site-specific directions.

Amplifications associated with thick colluvia most probably result from a high impedance contrast with substrata. In the case of deep landslides, in addition to high impedance contrast with the substratum, the 3D geometry of a landslide body can also have some role in causing seismic wave trapping and prolonged shaking. These effects can increase susceptibility of slopes to seismically induced failures and facilitate landslide reactivations, especially when shaking energy is concentrated along potential sliding directions.

Although there seems to be an increasing awareness of the role played by site effects (e.g. soil and topographic amplification) in favoring seismic triggering of landslides, the complexity of factors controlling such phenomena makes it difficult to assess slope conditions that determine potential seismic landslide hazard. Considering also that a wide area long-term accelerometer monitoring of slopes is not feasible, it is desirable to develop low-cost reconnaissance methods for characterizing relevant properties of slope dynamic response to seismic shaking.

Some promising results from reconnaissance-type field investigations have already been obtained in Italy. For example, Del Gaudio et al. (2008) were able to derive information on the occurrence of directional resonance by recording ambient noise with portable seismic sensors and by analyzing the azimuthal variations of the spectral ratios between horizontal and vertical component of noise recordings (HVNR). Most recently some tests were performed by using broad-band sensors in an attempt to extend the frequency band of observations towards lower frequencies that could be important when investigating the mobilization of large landslides. It is apparent that additional field measurements of ambient noise at varying environmental conditions should help to evaluate the reliability of the results in determining relevant properties of landslide-prone slope response to seismic shaking.

2.6. Catastrophic landslides, laboratory tests and modeling of seismic failure mechanisms

In addition to the uncertainties concerning seismic shaking input, the low level of detail and of accuracy in geotechnical characterization of slope material properties are also important factors that can severely limit the reliability of seismic landslide modeling efforts. More advanced numerical modeling methods typically necessitate better resolution and better quality input data in order to guarantee realistic outputs (e.g. Jibson, 2011–this issue; Strenk and Wartman, 2011–this issue).

The above mentioned problem seems particularly relevant when analyzing large catastrophic slope failures that may require the application of sophisticated modeling approaches to account for the variation in subsurface material properties and groundwater conditions, as well as for the complexity of the failure and mass-movement mechanisms. Large seismic slope failures deserve special attention because they commonly result in loss of many lives. This was the case in two historic events recently re-examined by Evans et al. (2009a,b). The first event regards the 1949 Khait earthquake (M 7.4) in Tajikistan, which triggered a major disastrous, high velocity flow in loess killing more than 6000 people (Evans et al., 2009b). The other event, which resulted in a similar loss of life, was the Nevado Huascaran rock avalanche triggered by a M 7.9 earthquake in the Peruvian Andes in 1970 (Evans et al., 2009a).

Also the 1999 Chi-Chi earthquake ($M_w = 7.6$) induced a number of catastrophic landslides, and this prompted several studies focused on numerical modeling. For example, much insight on the kinematic behavior of the catastrophic Tsaoling landslide triggered by the 1999 Chi-Chi earthquake has recently been gained by Kuo et al. (2009) and Tang et al. (2009) who used, respectively, the continuum model of hydraulic flow and discrete element method (DEM). In both cases, modeling indicated that low friction angle is needed to account for the observed landslide features.

One major difficulty afflicting these modeling efforts is a realistic representation of the material strengths and pore pressure conditions that need to be based on high quality data. However, obtaining appropriate strength properties that are representative of dynamic loading conditions in the field is not a simple task for many natural materials.

Two contributions to this Special Issue address the issue of proper geotechnical characterization of the strengths of slope materials that undergo seismic shaking. Hsieh et al. (2011–this issue) demonstrate that dynamic tests such as shaking table tests used in their study are necessary to obtain reliable data on sliding thresholds. In particular, it is demonstrated that the sliding thresholds measured via a tilt test in static conditions are much higher than the sliding thresholds obtained from shaking table tests (i.e. under dynamic conditions).

Liao et al. (2011–this issue) present a new ring-shear device developed for testing rocks under high normal stress and dynamic conditions. This new apparatus should help to overcome the limitations of applicability of the existing ring shear devices that were designed for conducting cyclic loading tests on soil (e.g. Sassa et al., 2005). The work of Liao et al. (2011–this issue) describes a series of tests with the new apparatus to investigate the sliding mechanism of the Tsaoling landslide, a large rock avalanche triggered by the Chi-Chi earthquake. This new testing procedure as well as the Tsaoling landslide case is of much interest.

Furthermore, it is recognized that much improvement in our understanding of the dynamic slope behavior can also come from laboratory modeling (e.g. Wartman et al., 2005; Lin and Wang, 2006; Wang and Sassa, 2009). Wang and Lin (2011–this issue) present results from large scale laboratory tests with a shaking table, which are used to analyze slope behavior under seismic loading. The integrated analyses of limit equilibrium, particle image velocimetry and acceleration time history registered in the model slope provide useful information on landslide initiation (characterized by surface and local slope movements) followed by slope failure (marked by massive displacements).

Finally, the paper by Kokusho et al. (2011–this issue) reviews a theoretical framework of the energy balance in a slope subject to an earthquake; the review is supported by earlier experimental laboratory tests using a model shake table compared with rigid block modeling, of the energy balance in a slope subject to an earthquake. Then Kokusho et al. (2011–this issue) present applications of an innovative, simplified method for the assessment of seismically-induced landslides and their runout distance in terms of the energy released by the earthquake and transmitted to the soil mass. Field observational data on slope failures during recent earthquakes in Japan (the 2004 Niigatan Chuetsu and 2008 Iwate-Miyagi Inland events) are used and interpreted within the energy-based framework, and back-calculated mobilized friction coefficients are discussed.

3. Recommendations and research priorities

Many of the recommendations presented here incorporate the ideas and suggestions that surfaced during the plenary discussions at the conference "Next Generation of Research on Earthquake-Induced Landslides" held in 2009 in Taiwan. One of the top research priorities identified is the necessity of compiling many more complete seismic landslide inventories, with adequate contextual information. This reflects the pressing need for more and better quality basic data to conduct more reliable seismic landslide hazard analysis, especially where landslide distributions can be related to spatially dense strong motion records. It is also recognized that a complete coverage (via remotely sensed data) of the entire area affected by an earthquake is most important, and that inventories involving large areas can be accomplished through a joint effort of several international research and geological survey organizations. Timely acquisition and availability of adequate imagery are essential for both post-earthquake early response teams, as well as for subsequent geomorphological, geological and engineering investigations.

It is also recommended that seismic landslide inventories be prepared on a regular basis to assure continuity of observational information. Building up time series of such inventories is important for, among others, those investigating the impact of earthquake-induced landsliding on long-term slope erosion, sediment delivery, and landscape evolution. Regions characterized by high rates of tectonic activity and high susceptibility to landsliding (e.g. Japan, Taiwan) represent the most suitable test areas on which the international scientific community could focus. Japan and Taiwan benefit also from regular satellite and aerial coverage, and this implies that adequate imagery and complete mapping can be achieved there. In this context, an establishment of an open international repository of remotely sensed imagery (with metadata specifications) acquired following major earthquakes would be highly desirable.

As for the past events, it is recognized that retrospective inventories (e.g. from historical imagery) can be very useful and should be compiled at least for the epicentral areas, whenever aerial photos are available. However, caution should be exercised while interpreting inventories that cover only part of the area affected by an earthquake.

Improvement of regional-scale assessments of seismic landslide susceptibility and hazard represents another top research priority, given their potential in guiding land use planning and development of major infrastructure and lifelines. Clearly, the importance of regional studies is dictated by the large extent of the areas affected by seismically triggered landslides during large earthquakes. Regional analyses benefit from applications of physically-based models, statistical analysis, and GIS techniques, but more well-documented case (event) studies relying on good strong-motion data from dense seismic networks are needed. Focused efforts are required to assure realistic characterization of slope groundwater conditions and material properties and hence the selection of appropriate input data into regional-scale modeling. This will help to reduce some uncertainties in seismic slope deformation predictions.

Another research priority area involves large catastrophic landslides, because these can kill great numbers of people during an earthquake and have long-term socio-economic impact. Identification of slopes susceptible to seismically induced catastrophic failures is very difficult, and the development of new methods for regional-scale analysis of hazards from large landslides is recommended. There are indications from recent studies and field measurements conducted in Italy and Taiwan that seismic triggering of some large, deep landslides can be facilitated by seismic site effects (local amplification and directivity phenomena). In this context, the potential of spectral analysis of ambient noise recordings acquired using portable seismographs to provide a quick and low-cost reconnaissance method should be further explored. This approach can be applied in wide-area investigations of slopes suspected of being affected by directional amplifications. Indeed, while it is generally recognized that site effects can have major influence on the distribution of earthquake damage to engineering structures, in comparison the role of site amplifications on the spatial pattern of seismic slope failures has received more attention only in recent years. Additional research on the influence of sites effects on seismic landslide triggering is desirable.

A further research priority linked to the issue of catastrophic failures regards accelerometeric monitoring of slopes that have been and may still be subject to re-activations of large landslides by earthquakes. It is recommended that a representative test slope be selected and instrumented with an array of seismic stations. The record of large catastrophic landslides triggered by the 1999 Chi-Chi earthquake and high seismic activity of the affected area suggests that a suitable slope can be identified in Taiwan.

The focus on accelerometer monitoring reflects also a general need to acquire data from stations sited on hillslopes (including potentially unstable slopes). Indeed, the available recordings of actual strong motions affecting slopes are very few and generally limited to the aftershock phases. More such data is needed to provide constraints on slope dynamic behavior modeling. Furthermore, accurate assessments of other relevant input parameters (e.g. material properties, slope and slip surface geometries, groundwater conditions and their variability) are also necessary to secure more reliable outputs from modeling. Although long-term monitoring of different input variables is costly and often impractical, a comprehensive analysis of both causative factors (in terms of temporal variation of slope's susceptibility to failure) and triggering factors (seismic shaking) is needed to advance substantially our understanding of seismic slope failure mechanisms.

Finally, it is apparent that balanced and integrated approaches between the scientific communities focused on local scale and regional scale investigations ought to be further encouraged. This should help to foster the practical applicability of the research on seismic landslide hazards.

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