Grant Agreement No.: 226479

SafeLand

Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies

7th Framework Programme
Cooperation Theme 6 Environment (including climate change)
Sub-Activity 6.1.3 Natural Hazards

Deliverable 1.8

Guidelines: recommended models of landslide triggering processes and run-out to be used in QRA

Work Package 1.6 – Identification of models best suited for QRA

Deliverable/Work Package Leader: AMRA Revision: 2 – Draft

April, 2011

Rev.	Deliverable Responsible	Controlled by	Date
2	AMRA		2011-04-04

CONTRIBUTORS

Lead partner responsible for the deliverable:

[AMRA]

Deliverable prepared by:

L. Picarelli

L.Olivares

Partner responsible for quality control:

[FUNAB]

Deliverable reviewed by:

Other contributors:

[AUTH]: K. Pitilakis, S. Fotopoulou, K. Senetakis, E. Riga

[FUNAB]: M. Pastor, S. Petrone, T. Blanc, V. Drempetic

[UPC]: J. Corominas, E. Alonso

CONTENTS

1. FOREWORD

Quantitative Risk Analysis (QRA) is the goal of all investigations and studies aimed at risk mitigation assessment and mitigation, whatever is the concerned event, natural or anthropogenic.

In the specific case of landslides, QRA should consider: i) the probability of landslide occurrence; ii) the run-out of the potential landslide body (that allows to identify the exposed goods located along its path); iii) their vulnerability and the damage caused by the interaction with the landslide body (which can be computed accounting for the energy possessed by the landslide body, often identified through its mass and acceleration); iv) the total potential loss (which includes the loss of lives and other consequences).

A complete QRA should then trust in computational tools capable to identify and quantify all the factors and conditions which can cause the triggering of a landslide and the volume, path and velocity of the landslide body at any point of its travel. As a matter of fact, the part I of this report presents a general overview of available models for landslide triggering and run-out analysis of landslide triggered by precipitations (rainfalls) providing short recommendations for their use in QRA. Some considerations will be reported about the limitations of such models. The report essentially summarises the work developed in Area 1, with particular reference to the WPs 1.2 and 1.4, which review models for analysis of landslide triggering, and the WP 1.6 and 1.7, which review analytical/empirical models for analysis of run-out of subaerial slides, submarine slides and snow avalanches, stressing their advantages and constraints.

The report includes also a relevant part concerning the analysis of earthquake-induced landslides and of their run-out, a special case which has not been considered in the other Work Packages of the Area 1 even though being of considerable interest for some important countries in Europe. These contents are the concern of the part II.

2. TRIGGERING OF RAINFALL-INDUCED LANDSLIDES

2.1 Foreword

This section is intended to focus on the main codes for analysis and prediction of rainfall-induced landslides examined in the deliverable D1.4, and to provide some suggestions for a quantitative prediction of landslide triggering. Their advantages and constraints are briefly discussed.
Weather-induced landslides are the result of adverse slope-atmosphere interaction. In general, the basic factors which affect the hydrological slope response are rainfall (or snow), temperature, humidity, soil radiation, wind. The effects of such factors may be emphasized or mitigated by factors related to the slope stratigraphy and structure, including any set of discontinuities, the hydraulic and mechanical properties of the single layers, the vegetation. Any modification of the factors depending on weather (typically, temperature and humidity, as well as intensity and duration of precipitations) govern the water content and the pore pressure regime n the subsoil thus the state of stress, and can give rise to changes in physical, hydraulic and mechanical properties of soil. Excessive changes in the state of stress and/or in soil properties can lead to slope failure.
The size and shape of the involved soil body and the same mechanisms of failure (for instance, progressive failure, liquefaction and so on) depend on the structure and nature of soil, on the initial state of stress and on its response to the induced strain field. The displacement and velocity of the landslide body, in turn, depend on slope morphology and length, stratigraphy, initial conditions, soil properties. In particular, soil brittleness, which affects the post-failure drop of strength thus the part of the potential energy which might be transformed into kinetic energy, play a prominent role (Leroueil et al., 1996). The soil response to any change in boundary conditions (e.g. drained/undrained) is also fundamental: for instance, loose saturated granular soils display a ductile behaviour under drained conditions and a brittle behaviour under undrained conditions. When the involved soil mass is large and its post-failure movement rapid, slope failure can lead to a catastrophic event.
Naturally, single factors play different roles. In fact, some of them could be neglected in the analysis without serious consequences on the quality of results; others play a prominent role. Expert investigators can recognize the fundamental ones, performing correct analyses. In any case, it is always suggested to carry out parametric studies to assess the role of each factor in the analysis. On the other side, the lesson coming from direct experience and study of the literature can greatly help: a good model must be able to reproduce the triggering of past landslides through the simulation of the effects of those phenomena that led to slope failure. If calibration reveals its reliability, the model may be used for prediction.
Any analysis presents some constraints. For instance, the reference scale (regional, basin or slope scale) plays a major role. A significant role is also played by the type of geomaterial involved in the failure and movement, sometimes requiring different approaches and input data.

2.2 Landslide triggering

2.2.1 *Foreword*

The deliverable D1.2 reviews case histories concerning well-instrumented natural and engineered slopes in different geo-environmental contexts whose documented behaviour provides important information about the role of rain water infiltration on the hydrological and mechanical slope response. The global knowledge provided by such case studies and by further data reported in the literature represents a significant starting point for any computational procedure having the goal to assess the conditions leading to landslide triggering and to predict the run-out of the mobilised landslide.
The main features of the available models used for slope analysis and identification of the failure conditions and of he soil volume involved are the concern of the deliverable D1.4. This describes the theoretical contents of the geotechnical models set up for the analysis and of the codes implemented to this aim, their potentialities and constraints and the conditions for a correct use of each of them; as a matter of fact, several numerical codes are available on the marked. However, further home-made codes have been produced by teams involved in researches on this issue; these are also considered and discussed in the deliverable D1.4.
Here only the reasons to select one code or the other one are briefly discussed, stressing advantages and constraints related to the specific problem in hand.

2.2.2 *Advantages and constraints of the available codes and recommendations for their best use*

Looking at the codes listed in D1.4, the following general remarks can be made:

- the reference scales considered in the analysis are very different, covering either the basin or even the regional scale (1/2000, 1/5000), i.e. study areas attaining a surface ranging between tens and hundreds km^2, or the slope scale (1/500, 1/1000), i.e. study areas of some hectares;
- the analysis consists of a deterministic approach which is sometimes implemented in a qualitative or semi-quantitative way (i.e. it is based on some assumptions regarding soil characterization and initial and boundary conditions, and consists of essentially parametric analyses), sometimes in a quantitative way (i.e. based on site and laboratory investigations): basically qualitative or semi-quantitative analyses are carried out when large scale problems are dealt with (basin or regional scale), while quantitative analyses concern a small scale (slope scale);
- probabilistic approaches are disregarded: this means that the hazard is not evaluated or is only indirectly determined; therefore, the analysis essentially provides a quantitative indication of the susceptibility of slopes to fail; and an assessment of the probability of failure can be only obtained through separate data and considerations.

About the last point, it is worth to mention that there are methods which can account, in some way, for all uncertainties of the analysis through the use of a probabilistic approach. These have not been considered in D1.4, but ca be easily found in the literature.
In the following, the codes examined in the deliverable D1-4 will be shortly discussed by dividing them as a function of the reference scale.

2.2.2.1 Regional and basin scale

Slope analysis at regional or basin scale requires a code based on a grid-based Geographic Information System (GIS), that enables to manipulate required data starting from a Digital Terrain Model (DTM). In general this provides all information regarding local slope geometry and structure (morphology, stratigraphy etc) and soil properties. GIS provides a friendly spatial representation of data and allows to manage them as well as the results of the analysis.
The main codes used for slope stability analysis, at a basin or regional scale, as a consequence of precipitations are: SHALSTAB (Montgomery and Dietrich, 1994), TRIGRS (Iverson, 2000; Baum et al., 2002; Savage et al., 2004), TRIGRS-unsaturated (Baum et al., 2008) and I-MOD 3D (Olivares, Tommasi, 2008). These codes couple a hydrological model, which can analyse the slope response to precipitations, and a geotechnical model which performs the stability analysis using the simplified scheme of infinite slope: the potential failure surface is located at the base of the deposit (SHALSTAB) or at different depths (TRIGRS, TRIGRS-unsaturated and I-MOD 3D). The shear strength of soil is expressed by the Mohr-Coulomb failure criterion for saturated soils (SHALSTAB and TRIGRS) or by an extension of this to unsaturated soils (TRIGRS-unsaturated and I-MOD 3D). All hydrological models, but I-MOD 3D, analyse 1D vertical infiltration; I-MOD 3D can investigate a pseudo-3D infiltration process (see D1.4). While SHALSTAB considers only steady-state conditions, the other codes can examine transient conditions, solving the Richards equations.
Every code presents some advantages and some constraints. A common constraint is the fact that the infinite slope is the only mechanism that can be investigated when dealing with stability analysis. This implies that every situation characterised by an irregular morphology or stratigraphy which is not consistent with such a simplified model, cannot be considered or must be simplified with obvious implications on the validity of the results. The same problem arises for those special situations that are characterised by a non uniform groundwater regime or by non uniform soil properties (quite usual situations for natural slopes), even within a realistic scheme (from the geometrical point of view) of infinite slope. On the other side, often irregularities in the slope profile or in the soil stratigraphy and/or properties are not put into evidence by investigations or can be disregarded when extensive areas are examined.
Further specific advantages or constraints of these codes are briefly discussed below.

SHALSTAB

SHALSTAB implements a simplified hydrologic model for 1D vertical steady-state infiltration. This is considered to be in equilibrium with a steady-state water flow parallel to the slope. The lowermost boundary of this is impervious and parallel to the ground surface. The soil is homogeneous and saturated. Rising of the groundwater surface, thus the safety factor, can be calculated based on rainfall duration and intensity.
The main advantages of SHALSTAB consist in the use of a low computer memory and in a low computational time. For such a reason, the analysis can cover very large sloping areas. On the other hand, as the area to analyse extends, the assumption of uniform rainfall, morphology, stratigraphy, soil properties and initial groundwater conditions become unlikely, vanishing such an advantage that becomes fictitious.
Looking at the limitations of the code, the assumption of steady-state is highly unrealistic being reliable only for continuous uniform rainfall (boundary conditions) and for very stiff saturated soils whose water content remains constant during precipitations (initial conditions and constitutive laws). This always imposes a model calibration and the adoption of

assumptions minimizing the errors associated with the limitations of the code. Therefore, SHALSTAB is of some utility in climatic areas characterised by continuous uniform precipitations and when the uppermost part of the slope located above the groundwater surface is stiff and fully saturated, a likely situation only for relatively fine-grained OC soils and for groundwater surface located at relatively shallow depth. Moreover, the double assumption of impervious base and vertical infiltration is a strong constraint for relatively long-lasting rainfalls. In fact, due to these assumptions the slope behaves as a reservoir that progressively fills up, eventually attaining a failure condition due to the progressive increase of the groundwater surface. Naturally, the initial conditions play a crucial role on the time of failure and/or the assessment of the “critical rainfall”. Since vertical infiltration occurs under steady-state conditions, the time at which the groundwater surface starts to rise does not depend on its initial depth: this is not realistic and shortens the duration of the critical rainfall, especially for deep bedrock. Another limitation of this code is in the fact that slopes consisting of cohesionless soil cannot be steeper than the friction angle. Therefore, the only way to analyse their response to precipitations is to assume a fictitious cohesion which affects the quality of the result.
In conclusion, there are several reasons that restrict the applicability of this code that is not recommended, mostly for non homogeneous unsaturated thick layers of cohesionless soil resting on pervious bedrock and for relatively long-lasting rainfalls. In other cases, it could be used for a preliminary assessment of the slope response to short precipitations over broad areas.

<u>TRIGRS</u>
This code performs one-dimensional analyses (one dimensional vertical flow, stability analysis of the infinite slope) based on a solution of the one-dimensional Richards’ equation for impervious basal boundary located at a finite depth. The soil is saturated and homogeneous. A simple procedure is adopted to assess the run-off whose amount is calculated as the volume of water that is not absorbed by the subsoil when the rainfall intensity is higher than the hydraulic conductivity of soil. Such a water volume is moved from the cell where it directly falls to the adjacent cells located downslope; there, it is added to the volume of falling water for evaluation of infiltration; therefore, groundwater rising in the soil columns bounded by the superficial grid can be different.
The slope stability conditions are assessed at any element of the grid independently from its size; this means that different safety factors might be calculated due to different local slope of the ground surface, to different local soil properties and to different local pore pressures. The output then consists of cells characterised by different safety factors; a question then arises about the meaning and interpretation of maps with small isolated red spots where the safety factor is equal to one.
As for SHALSTAB, the assumptions of 1D flow and impervious lowermost boundary don’t allow to perform reliable analyses for long-lasting rainfalls even though the transient nature of the vertical infiltration allows to account for the depth of the groundwater table on the hydraulic soil response (groundwater rising).
The stability of steep slopes consisting of cohesionless soils depends on the apparent cohesion which in turn has to be related to the initial suction which is then a fundamental mechanical parameter for analysis. Therefore, the initial conditions not only strongly affect the hydrological slope response, but also its mechanical response. Unfortunately, the initial

suction can be obtained only through monitoring. Often, a fictitious position of the groundwater table is established to obtain the established values of suction and cohesion, above it. Finally, the influence on water contents and suction changes due to the dry phases in between successive precipitations (evapotranspiration) cannot be accounted for. Even though this is a complex problem which cannot be certainly solved through these extremely simplified approaches, it cannot be disregarded at all since initial suction, hence cohesion, at the beginning of every precipitation is the fundamental factor which governs the stability of slopes.
In conclusion, the advantages and the constraints of this code are similar to those concerning SHALSTAB even though a more reliable approach is adopted in the analysis of the infiltration process. In particular, this code is non-recommended for non homogeneous unsaturated granular deposits and for long-lasting rainfalls.

The version of TRIGRS for unsaturated soil, which adopts a solution of the Richards equations and the Gardner expression for the water retention curve, solves the limitations of previous version, but requires the evaluation of complex and unusual soil tests for many laboratories, in order to obtain additional data for the analysis as the permeability function of soil and the relationship between apparent cohesion and suction. As usual for the most sophisticated codes, the selection of values of the required parameters is crucial and delicate since the global effect of small errors may be great, leading to wrong results.
This code allows to analyze the behaviour of shallow unsaturated slopes, bounded by an impervious bedrock, subjected to vertical infiltration. The possibility to consider the presence of unsaturated soils is a significant advantage, but the limitations due to the coupling of the assumptions regarding the permeability of the bedrock and the vertical direction of flow persist.
An important advantage compared to more advanced codes adopted at the slope scale is the low computer memory required for analysis and the low computation time that allow to investigate on the effects of precipitations over very large areas.

In conclusion, for several reasons these three commercial codes present severe limitations, but allow to quickly perform a simplified analysis of the effects of relatively short precipitations over large areas occupied by shallow deposits. In particular, TRIGRS-unsaturated provide rough information about the response of unsaturated deposits that cannot be correctly accounted for by the other codes. The best use of these is for a preliminary assessment of the slope stability conditions of wide areas subjected to short precipitations. In particular, reliable considerations can be made only after a careful calibration of the model, possibly based on parametric analyses and on a comparison with observed slope performance under similar precipitations.
A complete analysis of the performance of the three examined codes is reported in the deliverable D1.4 (Sorbino et al., 2010), where are discussed the results of analyses carried out in the Sarno area for the same precipitations which caused the catastrophic landslides of May, 1998, and using maps obtained prior to hose events. Those comparisons confirm previous considerations about the difficulty to implement SHALSTAB which requires the input of a uniform rainfall and the limitations of TRIGRS to assess the hydrological response of unsaturated soils.

I-MOD 3D

I-MOD 3D is a 3D Finite Volume home-made code developed as a GIS application at basin scale. It adopts an uncoupled formulation of the water flow for unsaturated porous medium under isothermal conditions neglecting the flux of the gas phase.

Well known expressions taken from the literature are adopted for both the water retention curve and the permeability function of unsaturated soils (see deliverable 1.2, section 4.1). Either water inflow either water outflow can be imposed a the ground surface as well as established values of suction. Similar conditions (a specified water flow or value of suction) can be imposed at the lowermost boundary. This allows to perform the analysis covering long time lengths featured by alternating phases of precipitation and evapotranspiration (water inflow and outflow from either the ground surface or the base), a potentiality which is not provided by the other codes.

The code has been developed to predict rainfall-induced landslides as a part of a "simulation chain" including a module capable to forecast precipitations during next 48 hours (see deliverable 4.1). Especially after a proper calibration phase based on data from monitoring, the code can be friendly used as a forecasting tool. The first component of the simulation chain is the COSMO LM model associated with a downscaling module which is used to establish the boundary conditions for the geotechnical module at the basin scale. The geotechnical module is I-MOD3D which has the goal to analyze 3D infiltration under simplified hypotheses and to assess the slope stability conditions under the assumption of homogeneous infinite slope. These two parts are integrated through an interface able to automatically define the soil domain to analyse starting from a Digital Terrain Model, and to capture the forecasted rain from the downscaling module.

I-MOD3D removes some uncertainties and simplified assumptions present in the other codes and adopts more realistic an useful boundary conditions but can be used only at a smaller scale (basin scale).

2.2.2.2 Slope scale

2.3 Landslide run-out

2.3.1 *Foreword*

In general, two classes of methods can be considered for run-out analysis:

- empirical methods for assessing travel distance of soil and rock slides which turn into debris flows or debris slides;
- dynamic and numerical methods for assessing travel distance of rockfalls (Bozzolo, Pamini, 1986; Pfeiffer, Bowen, 1989; Agliardi, Crosta, 2003), debris flows (Takahashi, 1991; Hungr, 1995; Laigle, Coussot, 1997; McDougall, Hungr, 2004), flowslides (Hutchinson, 1986) and rock avalanches (Soussa, Voight, 1991; Hungr, 1995; Eberhardt et al., 2004).

2.3.2 *Empirical methods*

Empirical methods for assessing travel distance of soil and rock slides which become debris flows and debris slides involve different approaches. They may be based on geometrical relations between the slope and the landslide deposits (Nicoletti, Sorriso Valvo, 1991; Hungr, Evans, 1998; Evans, Hungr, 1993; Corominas, 1996; Hunter, Fell, 2003; Hungr et al., 2005) or on volume change-methods (Cannon, 1993; Fannin, Wise, 2001). These methods are widely presented in section 2.1 of deliverable D1.9 where the references can be found.
Several empirical methods for assessing landslide travel distance and velocity for use in susceptibility mapping have been developed based on field observations and on the analysis of the relationship between parameters characterizing both the landslide (i.e. the volume of the landslide mass) and the path (i.e. local morphology, presence of obstructions), and the distance travelled by the landslide debris.

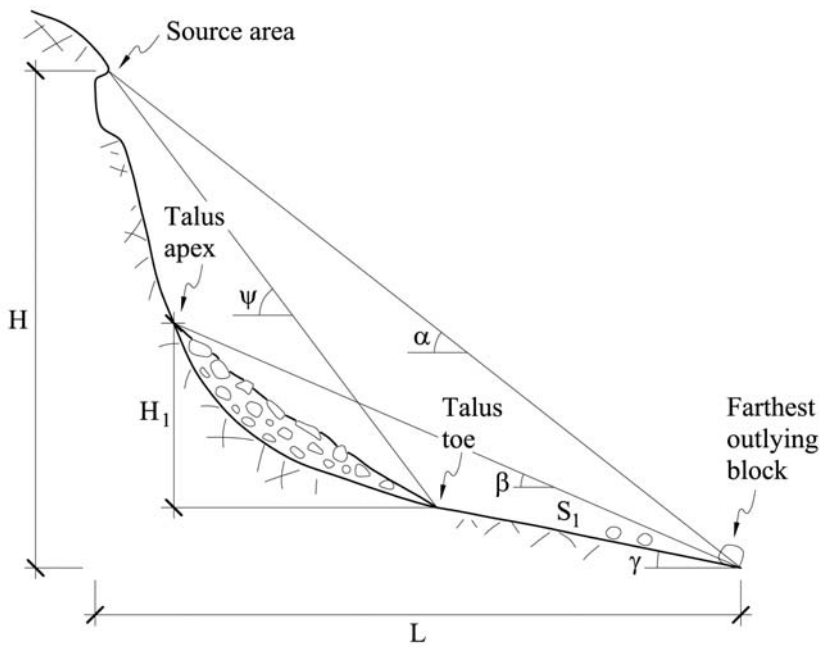

Figure 1. Geometrical variables: vertical drop (H), travel distance (L), reach angle (α), shadow angle (β), source-talus angle (ψ), substrate angle (γ), and shadow distance (S_1) (Hungr et al, 2005).

The geometrical variables used in empirical models are represented in Figure 1. These are:

- the travel distance (L) is defined as the horizontal projection of the line linking the upper part of the landslide source and the outermost edge of the landslide deposits;
- the angle of reach (α) is the angle of the line connecting the highest point of the landslide crown scarp to the distal margin of the displaced mass;
- the shadow angle (β) is the angle of the line linking the talus apex with the farthest block;
- the source-talus angle (ψ) is the angle of the line linking the rockfall source with the talus toe.

Empirical methods are very simple and travel distances can be obtained very easily. The main advantage is their simplicity and that they can be implemented in GIS to delineate the areal extent of potential slope failures for susceptibility and hazard mapping purposes (Ayala et al. 2003; Michael-Leiba et al. 2003L; Jabodeyoff et al. 2005; Copons , Vilaplana, 2008).
However, it should likewise be noted that assumptions implicit in these methods are not precise and their statistical scatter is very large. Also, they do not provide any kinematic parameters during the run-out process, which are needed for engineering design.

2.3.3 *Numerical methods*
Analytical methods model for moving landslides are based on continuum mechanics equations, i.e., balance of mass, linear momentum, and heat (if relevant to the case analyzed).

(i) 3D models based on mixture theory. The most complex model category involves all phases present in the flowing material, as solid particles, fluid and gas. Here relative movements can be large, and this group of models can be applied to the most general case. The model is based on the mixture theory. However, due to the great number of unknowns and equations, these models have not been used except when considering the mixture, which is correct for mudflows and rock avalanches. As the geometry is rather complex, no analytical solution exists and it is necessary to discretize the equations using a suitable numerical model, such as finite elements or SPH. As an example, we can mention the work of Quecedo et al. (2004) who analyzed the waves generated in reservoirs by landslides.

(ii) Velocity-pressure models (Biot-Zienkiewicz). In many occasions, the movement of pore fluids relative to the soil skeleton can be assumed to be small, and the model can be cast in terms of the velocity of the solid particles and the pore pressures of the interstitial fluids. This is the classical approach used in geotechnical engineering. Again, the resulting model is 3D, and the computational effort to solve is large. Material point models, SPH, and ALE methods, such as used by Crosta et al. (2009) can be used, but their field of application is restricted. One important point is that pore pressures can be fully described.
It is important to notice that these two groups of models present the most advanced features, being possible to predict run-out distances, depth of the deposits, and specially, forces over contention structures and buildings.

(iii) Taking into account the geometry of most of fast propagating landslides, it is possible to use a depth integration approximation. The equations reduce from 3D to 2D, as all variables depend on (x,y), the z information being lost in the integration procedure. This method has been classically used in hydraulics and coastal engineering to describe flow in channels, long waves, tides, etc. In the context of landslide analysis, they were introduced by Savage, Hutter (1991). Since then, they have been widely used by engineers and earth scientists (Laigle, Coussot 1997, Pastor et al., 2009). It is possible too to include information of the basal pore pressure, as done by Iverson et al. (2001) and by Pastor et al. (2009). It is important to notice that even if the results obtained by these models can be plotted in 3D, giving the sensation that is a full 3D simulation, the model is 2D.
One important conclusion about their use is that pressures and forces over structures are hydrostatic; therefore, if this information is needed, it is necessary to couple the 2D depth integrated models with the full 3D model in the proximity of the obstacle.

(iv) Depth integrated models can be still further simplified, as in the case of the so called infinite landslide approaches. Indeed, the block analysis performed in many cases does consist on a succession of infinite landslides evolving over a variable topography. Here, pore pressure dissipation can be included, as done by Hungr (1995).
Block models, due to their simplicity, are a reasonable bridge between empirical methods and analytical methods. They can be run in small computers, and the time of computation is very small. It is important to notice that some SPH codes can be used to this purpose, just by using a moving node without any interaction with other nodes

3. TRIGGERING OF EARTHQUAKE-INDUCED LANDSLIDES

3.1 Introduction

Seismically triggered landslides represent one of the most important collateral hazards associated with earthquakes. They commonly account for a significant proportion of total earthquake damage related to human losses and damage to the built environment. Some of the most pronounced seismically induced landslides in terms of direct and indirect losses are:

- Las Colinas landslide triggered by the 2001 El Salvador earthquake (Mw=7.7) involved a total volume 183,500 m^3 of stratified volcanic deposits (Crosta et al., 2004). Once mobilized, the landslide transformed into a flowslide and traveled an abnormally long distance of about 700 m, covering hundreds of residential houses and resulting in 500 casualties (Konagai et al, 2009).
- The Higashi-Takezawa landslide activated by the 2004 Niigata–Ken Chuetsu earthquake (Mw=6.8) in Japan involved a soil volume of about 1,200,000 m^3 (Kokusho, Ishizawa, 2005). The landslide mass filled a valley and stopped a river flow forming a large natural reservoir. The surprisingly large (100m) and rapid runoff of the soil mass motivated several researchers (Tsukamoto, Ishihara, 2005; Sassa et al., 2005; Kokusho, Ishizawa, 2009) to study the Higashi-Takezawa landslide, providing different interpretations of the sliding process.
- The Jiufengershan landslide was one of the major large and deep-seated landslides triggered by the 1999 Chi-Chi Taiwan earthquake (M_W=7.6). The slide affected weathered, jointed rock and soil materials, which slid along the bedding plane, generating a catastrophic rockslide-avalanche. The avalanche created a debris deposit with maximum thickness of 110 m, which dammed two small rivers and created three small lakes located upstream, resulting to 39 casualties (Chang et al, 2005).
- Among the landslides triggered by the 2008 Wenchuan earthquake (M_s=8.0) in Sichuan, China, the Chengxi landslide, which is located at the west side of the Beichuan County Town, is the most severe one; it caused 1,600 deaths and destroyed half of the old area of the Beichuan County Town (Yin et al, 2009).

Geographic Information Systems (GIS) and remote sensing have significantly improved the ability to map earthquake-induced landslides. Various earthquake triggered slides have been mapped and analyzed in California, Taiwan, Japan, Italy and elsewhere. With the aid of the GIS incorporating various models (geotechnical parameters, geology, hydrology, digital elevation model (DEM), land use, lithology, seismic parameters), analyses of the landslide susceptibility, hazard and risk in local, regional and national scales have been performed in a deterministic or probabilistic sense. The implementation of GIS tool in the landslide susceptibility, hazard and risk zoning at different scales is discussed among others by Wang et al. (2008), Van Westen et al. (2008), Hasegawa et al. (2009) and Miles et al. (2009).

Earthquake induced landslides are grouped into three main categories on the basis of type of material, type of landslide movement, degree of internal disruption of the landslide mass and geologic environment (Keefer, 1984; Keefer, 2002): (I) Disrupted Landslides, which occur fast and at high inclinations (>35°) in discontinuous rock masses or weakly cemented materials; (II) Coherent Landslides either in rock or soil with deep slip weakened surfaces or with a relatively broad distributed shear zone, reported for inclinations >15°; (III) lateral spreads and flows slides associated to liquefaction in granular materials; if residual strengths are lower than static shear stresses, flow slides can develop at very low inclinations. Considering the landslide type within a landslide hazard and risk analysis is crucial as different and complementary methods are usually required to model multiple landslide types.

3.2 Current practice to assess earthquake induced landslide triggering processes

According to APEGBC 2008 guidelines, there are various methods to assess earthquake induced landslide hazards. These include, but are not limited to, estimating:

- the likelihood or probability of occurrence of a landslide;
- the factor of safety of a slope;
- the slope displacement along a slip surface.

In order for the results of the above estimate to be incorporated in a QRA methodology, they must be combined with an estimate of landslide run-out distance (for residential development at the bottom of the slope), or an estimate of where the main scarp of the landslide will intersect the ground (for residential development on, or at the top of, the slope) (APEGBC, 2008).

3.2.1 *Likelihood or probability of occurrence of a landslide*

When assessing the probability of a particular slope experiencing landsliding within a reference period and within a given area, the recognition of the geotechnical, hydro-geological, topographic conditions that caused the slope to become unstable and the mechanisms that triggered the landslide movement is of primary importance. The triggering variables (e.g. the seismological characteristics) shift the slope from a marginally stable to an unstable state and thereby initiating failure in an area of given susceptibility (Dai et al., 2002). They are time-dependent factors that may change over a very short period of time. The historic frequency of landslides in an area can be determined to provide realistic estimates of landslide probability of occurrence throughout a region where landslides have caused a significant amount of damage. The trigger/landsliding and frequency-magnitude relations that help understanding landslide probabilities may be derived from landslide inventories. Considering that landslide inventories are usually incomplete or inaccurate, the use of aerial photographs and/or satellite images in conjunction with the landslide inventories may give further insight in the documentation of the landslide occurrence and the interpretation of the main landslide triggering processes.

The frequency of seismically induced landslides may be related to the peak ground acceleration at the site, the magnitude of the earthquake and the distance from the earthquake epicenter (Fell et al., 2008). Studies by Keefer (1984, 2002), Harp, Jibson (1995, 1996), Rodriguez et al. (1999), Jibson et al. (1998), Papadopoulos, Plessa (2000), have shown that there is a threshold magnitude, peak ground acceleration and distance from the earthquake epicenter above which landsliding will occur. This varies for different landslide types and sizes. However, smaller earthquake events can occasionally trigger landslides in correlation with non seismic causes. Hence, precedent intense precipitation may influence the response of slopes to earthquakes resulting to the initiation of the landslide mass in cases of even a weak earthquake (M<4) event. One problem with the characteristics of the expected ground shaking is that strong-motion stations are not usually widely distributed in areas where landslides are most likely to occur. Hence, the interpolation of the available data from the few stations available to grid points in mountainous areas is difficult and sometimes ineffective.

3.2.2 *Factor of safety of a slope*

For site-specific slopes, the probability of failure is usually considered as simply the probability that the factor of safety is less than unity. There are many different ways to compute the factor of safety of a slope including limit equilibrium and strength reduction method (SRM) methods. For simple homogenous soil slopes, it is found that the results from these methods are generally in good agreement. The strength reduction method, utilized in many finite element and finite difference codes, does not require any pre-definition of the sliding surface. Instead, the failure surface develops “naturally” based on the selected yield criterion (e.g. Mohr Coulomb, Hoek-Brown etc.). Nevertheless, the strength reduction method is incapable of determining other failure surfaces, which may be only slightly less critical than the SRM solution (Cheng et al., 2007). For this reason, a limit equilibrium analysis is generally preferable.

The factor of safety of a slope may be defined as the ratio of the shear resistance to the shear stress mobilized. In simple terms, a FS=1 is assumed when failure occurs and values successively greater than 1 suggest increasing stability and hence lower susceptibility to failure. When an earthquake occurs, the slope material is subjected to horizontal and vertical acceleration with reverse cycles. The inertial forces associated with these accelerations may momentarily reduce the factor of safety below 1.0 by increasing the shear stresses and possibly decreasing the shear resistance of the material, initiating down slope movement. If the accelerations are large enough or continue for a long period of time, they may lead to instability or extensive permanent deformations.

In a conventional limit equilibrium slope stability analysis, such as the ordinary method of slices, simplified Bishop’s method and simplified Janbu’s method, an additional horizontal static force is applied to simulate earthquake shaking (Fig. 2). Analyses that model the earthquake as an equivalent static force are commonly referred to as pseudo-static analyses. For pseudo-static analyses, the horizontal static force is calculated by multiplying the soil weight by a seismic coefficient, k, that represents the earthquake shaking. Seismic coefficients used in pseudo-static analyses are empirically derived to represent an equivalent seismic load. The selection of the proper value of the seismic coefficient is fundamental, as this value controls the inertial forces on the soil masses. According to Terzaghi (1950), who first introduced the pseudo-static (PS) approach, the values of the seismic coefficient should be k=0.1 for severe earthquakes, k=0.25 for violent-destructive earthquakes and k=0.5 for catastrophic earthquakes. In all cases the Author suggested that the design safety factor with respect to strength, Fs, may be close to 1.0. In contemporary seismic norms, e.g. Eurocode 8 (EC8 2004), the pseudostatic slope stability analysis is widely adopted for the design of natural and engineered slopes due to its simplicity. The selection of a seismic coefficient equal to a specific portion of the design peak ground acceleration at the site of interest is prescribed depending on the earthquake magnitude and peak ground acceleration values. However, a main limitation of the pseudostatic approach is that it provides only a single numerical threshold below which no displacement is predicted and above which total failure is predicted. Moreover, the fact that an equivalent static force models the earthquake does not permit the actual dynamic response of the structure to be taken into account, thus the real response and stability of the geo-structure cannot be accurately assessed during a moderate or severe seismic event. Therefore, in cases of loose, sensitive soils (sensitive clays, loose saturated silty sands) where the local site conditions play an important role, more sophisticated non-linear dynamic analysis procedures should be used (Lagaros et al., 2009).

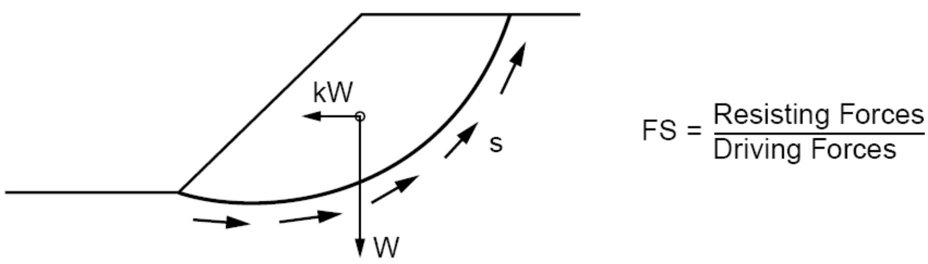

Figure 2. Pseudostatic slope stability analysis

3.2.3 *Slope displacement along a slip surface*

Typically, two different approaches of increased complexity are proposed to assess permanent ground displacements in case of seismically triggered slides:

- Newmark-type displacement methods;
- advanced dynamic methods.

The first class includes simplified or advanced displacement based approaches by means of the conventional Newmark rigid block model (Fig. 3), as well as through its improvements to account for the topographic amplification effects (Peng et al, 2009) and the soil deformability (Makdisi, Seed 1978; Rathje, Bray 1999; Ausilio et al., 2008, Bray, Travasarou, 2007, Rathje, Antonakos, 2010). Newmark-type methods are only applicable to soil slides. The dynamic site response and the sliding block displacements are computed separately in the 'decoupled' approach or simultaneously in the 'coupled' stick -slip analysis (Fig. 4). In general, coupled analysis yields reliable results for slopes of all dynamic stiffness and strength, but, of course, is the most complex to conduct. Rigid-block analysis is appropriate for analyzing thin, stiff landslides but yields quite unconservative results for deep, flexible slopes. The decoupled approach is generally considered to slightly overestimate displacements compared to the fully

nonlinear, coupled stick-slip analysis. However, it was found non-conservative primarily for projects undergoing intense, near-fault ground motions (Rathje, Bray 1999; 2000).
Advanced stress-deformation analyses based on continuum (finite element (FEM) or finite difference (FDM)) or discontinuum (e.g. distinct element method) formulations usually incorporating complicated constitutive models, are becoming more and more attractive, as they can provide approximate solutions to problems which otherwise cannot be solved by conventional methods e.g. the complex geometry including topographic and basin effects, material anisotropy and non-linear behavior, in situ stresses, pore water pressure built-up. Numerical methods have been applied to model the dynamic response of slopes using different constitutive models (e.g. Mohr Coulomb, strain softening, hysteretic model etc), boundary conditions and dynamic input motions (real or synthetic accelerograms, simplified wavelets). Recent work can be found in Zania et al. (2008), Bourdeau et al. (2008), Han et al. (2010), Latha at al. (2010), Taiebat et al. (2010). One basic limitation of the advanced numerical methods is that the parameters required for the definition of the models are not easily quantified in the laboratory or in situ. Moreover, they can be only used for specific case studies and not for a parametric analysis aiming to evaluate the landslide risk at local and regional scale. Finally, it should be emphasized that numerical modeling is a very powerful tool in the identification and comprehension of the coupled processes and complex mechanisms leading to instability of a given slope but it should be combined with engineering experience and critical thinking in order to yield reliable results.

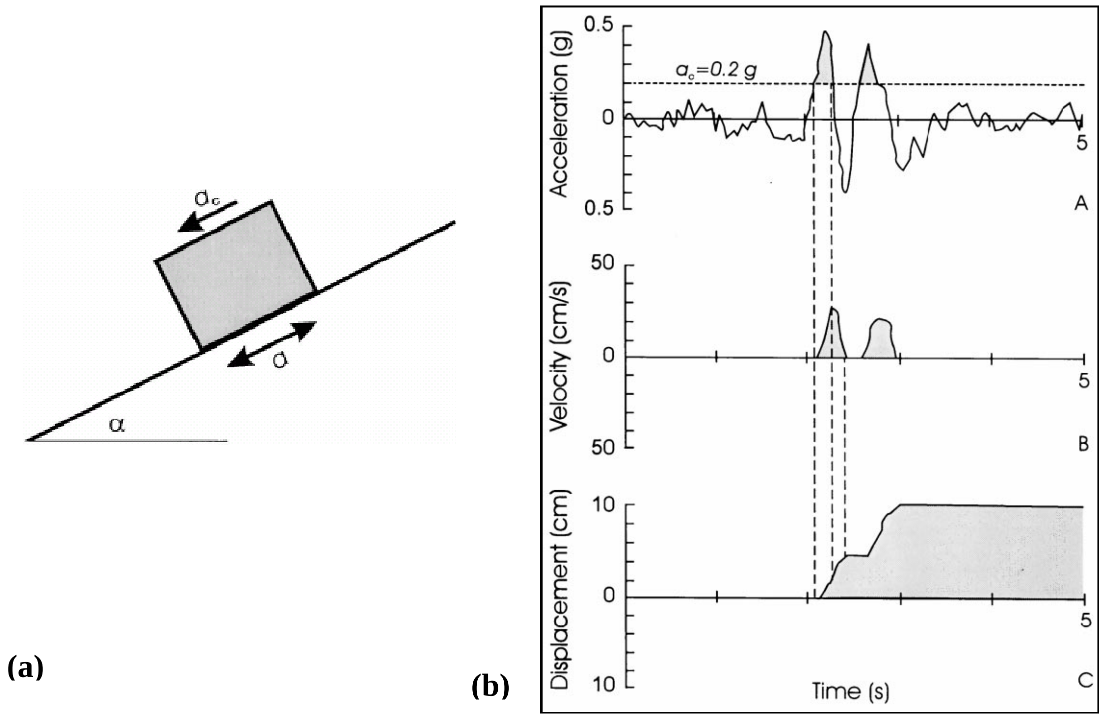

Figure 3. (a) Newmark Sliding-block model (b) Newmark algorithm (adapted from Wilson and Keefer, 1983) for seismically-induced permanent displacements.

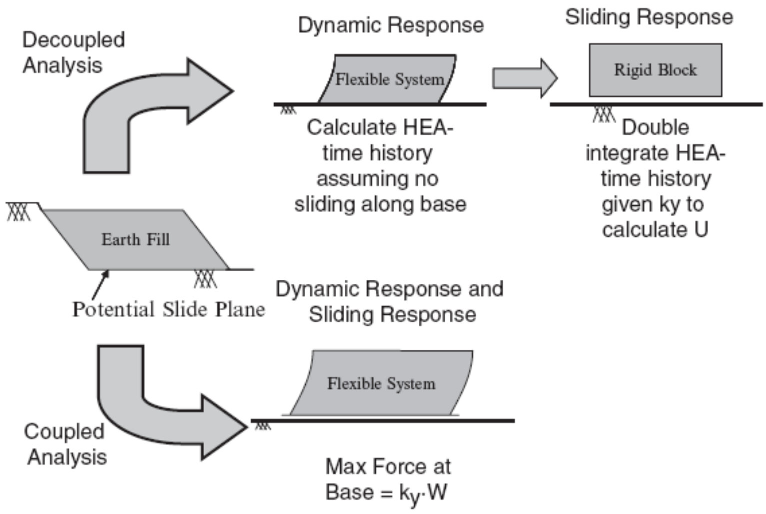

Figure 4. Decoupled dynamic response/rigid sliding block analysis and fully coupled analysis (Bray, 2007)

3.3 Recommended models of earthquake induced landslide triggering mechanisms

Similar to current practice, a screening analysis procedure is recommended for use in order to exclude slopes that are not expected to experience permanent deformations. When liquefaction or strain softening is not considered an issue, this can be done by estimating the factor of safety (or the critical acceleration) of the soil slope through a limit equilibrium or a simplified empirical method. Hence, if the resulting FS $\geq$ 1.0 (or ky$\geq$kmax), no further seismic slope analysis is required.

3.3.1 *Rigorous Newmark sliding block analysis*

A rigorous Newmark sliding block analysis (Newmark, 1965; Jibson et al., 2003) can be used to calculate permanent displacements of the slide mass for different seismic scenarios. The Newmark's method treats the potential landslide block as a rigid mass that slides in a perfectly plastic manner on an inclined plane (Fig. 3a). This assumption is reasonable for relatively thin landslides in stiff or brittle materials, but it introduces significant errors as landslides become thicker and material becomes softer. The mass experiences no permanent displacement until the base acceleration exceeds the critical (yield) acceleration of the block (α_c), that is the threshold base acceleration required to overcome the shear resistance of the slope and initiate failure; then, the block begins to move downslope. Displacements are estimated by double-integrating the parts of an acceleration-time history that lie above the critical acceleration. Figure 3b presents a schematic description of the rigorous Newmark Sliding Block procedure (adapted from Wilson and Keefer, 1983) for estimating permanent co-seismic landslide displacements. The critical (yield) acceleration may be determined through a pseudostatic analysis, by iteratively employing different horizontal earthquake accelerations in a static limit-equilibrium analysis until a factor of safety of 1.0 is achieved. Newmark (1965) showed that the critical acceleration of a potential landslide block is a simple function of the static factor of safety and the landslide geometry, expressed as:

$$a_c = (FS - 1)g \quad (1)$$

where a_c is the critical acceleration in terms of g; g the acceleration of Earth's gravity; FS is the static factor of safety; and a is the angle from the horizontal that the center of mass of the potential landslide block first moves, which can generally approximated as the slope angle. Similar empirical relationships for the estimation of critical acceleration have been introduced by other researchers (e.g. Graham, 1984; Jibson, 1993).
Recently developed methodologies (Peng et al., 2009) improve the rigorous Newmark approach by incorporating the effects of topographic amplification, that take place over a narrow zone near the crest of the slope, and the run-out behavior in the GIS earthquake induced landslide hazard assessment. The Authors calculated the theoretical topographic amplification factors based on the transfer function introducted by Paolucci (2002) and then estimated the corresponding amplified ground motion. By using this amplified motion a cumulative displacement map is generated through the rigorous Newmark displacement method. Once the calculated cumulative displacement is higher than a preset value of critical displacement (above this value a general failure is assumed to occur), the zone is regarded as a source area. The run-out simulation is performed on materials located on the predicted source areas. Finally, the complete set of landslide areas is constructed by recording the sliding routes and final deposition areas.

3.3.2 *Coupled stick-slip deformable sliding block model*

One of the most recent and reliable methods described by Bray, Travasarou (2007) is recommend for use in the estimation of co-seismic displacements of a slope. The Suthors proposed a simplified semi-analytical/empirical method to estimate PGD of soil slopes in case of earthquake loading. This semi-empirical predictive approach utilizes the nonlinear fully coupled stick-slip deformable sliding block model proposed by Rathje, Bray (2000) to capture the dynamic response of an earth-waste structure (Fig. 5). The model used is one dimensional to allow for the use of a large number ground motions with wide range of properties of the potential sliding mass.
The primary source of uncertainty in assessing the likely performance of an earth/waste system during an earthquake is the input ground motion. Hence, a comprehensive database (PEER strong ground motion database http://peer.berkeley.edu/smcat/index.html) containing 688 recorded ground motions from 14 earthquakes, has been used by B&T to compute co-seismic displacements (Travasarou, 2003).
The developed seismic displacement model captures the primary influence of the system's yield coefficient (ky), its initial fundamental period (Ts), and the ground motion's spectral acceleration at a degraded period equal to 1.5Ts. The slope's yield coefficient (ky) and initial fundamental period (Ts) were selected to represent the dynamic strength and stiffness, respectively, of the earth/waste slope in the seismic displacement model. The spectral acceleration at a degraded period equal to 1.5 times the initial fundamental period of the slope, i.e., *Sa* (1.5*Ts*), was found to represent the most efficient measure of the seismic intensity (Travasarou, Bray, 2003).The degraded fundamental period is considered to capture the overall average stiffness reduction for the earth/waste slopes.

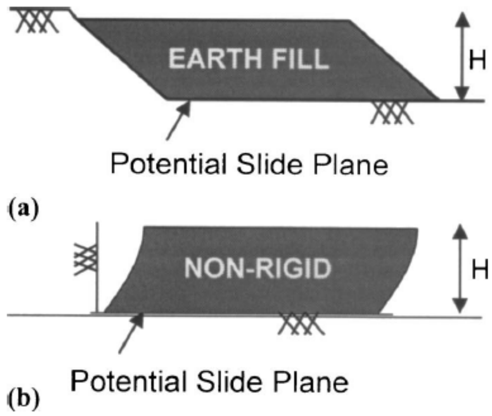

Figure 5. Generic seismic slope displacement problem of height H and initial stiffness Vs and (b) idealized nonlinear stick with one-way sliding used in Bray, Travasarou (2007).

The model separates the probability of "zero" displacement (i.e., 1 cm) occurring from the distribution of "non-zero" displacement, so that very low values of calculated displacement, with no engineering significance, do not bias the results.
The probability of negligible "zero" displacement is estimated as:

$$P(D = 0) = 1 - \Phi\,(- 1.76 - 3.22 \ln(k_y) - 0.484Ts \ln(k_y) + 3.52 \ln(S_a(1.5T_s))), \qquad (2)$$

where P(D=0): probability (as a decimal number) of occurrence of zero displacements; D- seismic displacement; Φ: standard normal cumulative distribution function; ky: yield coefficient; Ts: initial fundamental period of the sliding mass in seconds, and Sa(1.5Ts) : the spectral acceleration of the input ground motion at a period of 1.5Ts in tems of g.
The amount of nonzero seismic displacement (*D)* is given by the following equation:

$$\ln(D) = - 1.10 - 2.83 \ln(k_y) - 0.333 (\ln(k_y))^2 + 0.566 \ln(k_y) \ln(S_a(1.5T_s)) + 3.04 \ln(S_a(1.5T_s)) - 0.244(\ln(S_a(1.5T_s)))^2 + 1.50T_s + 0.278(M - 7) \pm \varepsilon \qquad (3)$$

where the *ky*, *Ts*, and $S_a(1.5Ts)$ are defined as previously for Eq. (3), and ε is a normally distributed random variable with zero mean and standard deviation σ=0.66.
For the Newmark rigid sliding block case (*Ts*=0), Eq. (3) is transformed as follows:

$$\ln(D) = - 0.22 - 2.83 \ln(k_y) - 0.333 (\ln(k_y))^2 + 0.566 \ln(k_y) \ln(PGA) + 3.04 \ln(PGA) - 0.244(\ln(PGA))^2 + 1.50T_s + 0.278(M - 7) \pm \varepsilon \qquad (4)$$

where PGA is the peak ground acceleration of the ground motion (i.e., $S_a(Ts=0)$).
The model can be implemented rigorously within a fully probabilistic framework for the estimation of the probability of exceedance of a selected threshold of displacement (d) for a specified earthquake scenario and slope properties.
The probability of the seismic displacement (*D)* exceeding a specified displacement threshold (*d)* is expressed as:

$$P(D > d) = [1 - P(D = 0)]\, P(D > d/ (D > 0)) \qquad (5)$$

The term $P(D=0)$ is computed using Eq. (2). The term $P(D>d/D>0)$ may be computed assuming that the estimated displacements are lognormally distributed as:

$$P(D > d/ (D > 0) = 1 - P(D \leq d/D > 0) = 1 - \Phi\left(\frac{\ln d - \ln \hat{d}}{\sigma}\right) \qquad (6)$$

where $\ln \hat{d}$ is computed using Eq. (3), σ is the standard deviation of the random error, which in this case is 0.66; and Φ is the standard normal cumulative distribution function.

The Bray and Travasarou (2007) seismic displacement model was shown to predict reliably the seismic performance observed at 16 earth dams and solid-waste landfills. Besides, the values of predicted displacements are not inconsistent with other simplified methods.

It is important to note the fact that the estimated range of seismic induced permanent displacement from semi-analytical and/or semi-empirical procedures both coupled and uncoupled, should be considered as an index of the expected seismic performance. Seismic displacement estimates will always be approximate in nature due to the complexities of the dynamic response of the soil materials involved and the variability of the earthquake ground motion. Moreover, it‘s worth noticing that the yield coefficient ky is assumed to be constant during seismic shaking. Thus, the methods described above should not be followed when significant strength loss is anticipated in the slope soil material. In the later, a more sophisticated numerical analysis capable to account for soil nonlinearity is recommended for use.

In any case, the choice of the most appropriate method primarily relies on the scale of the problem, data availability and quality concerning the geometrical, hydro-geological and the geotechnical characteristics of the site, the seismic motion parameters and soil dynamic properties (e.g. residual dynamic shear strength), the criticality of the structure and engineering judgment. A simplified empirical or semi-empirical method is generally preferable for the landslide hazard assessment in small scales (e.g. European scale, regional scale) while a more sophisticated method is usually adopted in large and detailed scales (e.g. for a certain case study).

3.4 Models of runout to be used in QRA

3.4.1 *Introduction*

As it has already been stated, the evaluation of the landslide triggering processes should be followed by a prediction of the expected run-out distance of the landslide mass (for residential development at the bottom of the slope), as it constitutes an integral part of a Quantitative Risk Assessment methodology. The landslide run-out distance needs to be estimated to calculate the annual probability of spatial impact P(S/H) (i.e. the probability of the landslide impacting a specific element at risk) given a specific landslide event, in the equation describing the risk in terms of the annual probability of loss of life or property (Morgan et al., 1992; Finlay et al, 1999). A run-out analysis is performed once the potential unstable slope exceeds a preset threshold displacement ($D_{Failure}$) above which a sharp acceleration of the slope movement, leading to a general failure of the slope, is expected to occur. The value of this critical displacement may vary for different landslide types and depends primarily on the

thickness of the basal shear zone. Hence, for thin shear zones (e.g. sandy soils) the pre-failure slope displacements may be limited to some centimeters. On the contrary, if a thick sliding surface is involved (e.g. homogenous clay material), the slope may experience significant deformation before failure can occur (Hungr et al, 2005).
The run-out or travel distance of the landslide deposit can be estimated either by using an analytical approach or statistical- empirical relationships and expert opinion (Finlay et al, 1999; Corominas 1996; Hunter, Fell, 2003; Rickenmann 2005; Hungr et al., 2005; Devoli et al., 2009; Copons et al., 2009). In case of earthquake triggered landslides the same methods are generally adopted for the estimation of the expected run-out path. Different landslide types (rockfalls, rock avalanches, debris flows, earthflows, and translational slides) usually require different methods to predict the travel distance.

3.4.2 *Empirical methods for estimating runout distance*

Several empirical methods have been developed for the prediction of the expected run-out distance. These are based on field observation and on the analysis of the relationships between parameters characterizing both the landslide (e.g. landslide volume) and the path (e.g. effect of obstacles and topographic constrains), and the distance traveled by the landslide debris (Corominas, 1996; Hungr et al., 2005). They can be classified as: geomorphological, geometrical and volume change methods. The main advantage of the empirical methods is their simplicity and that they can be quite easy implemented in a GIS-based hazard and risk assessment framework. However, empirical methods can only provide a preliminary estimate of the profile of the travel path.

3.4.2.1 Geomorphological assessment of the runout distance

In geomorphological methods the prediction of the travel distance is based on field work and photo interpretation assuming that future landslides will take place into the same environmental conditions having the same slope geometrical and geotechnical characteristics. However, this is not always the point, as the slope geometry and various environmental or anthropogenic conditions responsible for past landslides might have been changed. Furthermore, the identification of the landslide debris is not an easy task and it includes various uncertainties regarding the reconnaissance of the source area, the size and the mobility of the landslide mass. Hence, the applicability of geomorphological methods should be limited to the observed site without having the capability of transferring the results to other areas of interest (Hungr et al., 2005).

3.4.2.2 Geometrical assessment of the run-out distance

Another empirical approach is the geometrical method that is based on the angle of reach (α) concept, defined as the angle of the line connecting the highest point of the landslide crown scarp to the distal margin of the displaced mass (Fig. 1). The tangent of reach angle is expressed as the ratio of the vertical drop H to the horizontal projection of the distance L between the upper part of the landslide source and the lowest point of the sliding mass (Fig. 1). The angle of reach (α) is associated to the mobility index ((Nicoletti, Sorriso-Valvo, 1991, Corominas, 1996) and the friction coefficient (Shreve, 1968; Scheidegger, 1973) as follows: the higher the angle of reach (α), the higher the mobility of the mass (velocity) and the lower

the friction (φ) of the soil material. Domaas (1994) determined the reach angle from the angle (ψ) of the line linking the rockfall source with the talus toe (Fig. 1), for different intervals of height of vertical drop (H). Further, Evans, Hungr (1993) have used the concept of shadow angle (β) to determine the maximum travel distance of a fragmental rockfall defined as the angle of the line linking the talus apex with the farthest block (Fig. 1).
Several authors (Scheidegger, 1973; Li, 1983; Hutchinson 1988, Corominas 1996; Nicoletti, Sorriso-Valvo, 1991; Finlay et al., 1999; Rickenmann, 1999; Devoli et al., 2009; Copons et al., 2009) have proposed empirical relationships based on the inverse relationship between the tangent of the reach angle (H/L) and the landslide volume taking into account the different landslide types and sizes. Plots of the tangent of the reach angle (H/L) against the landslide volume show a reduction of H/L with volume increase and thus large landslides are characterized by a higher mobility compared to smaller ones (Scheidegger, 1973, Hsü, 1975). Such plots and the corresponding regression equations generally experience a large scattering (poor correlations) due to various reasons: different triggering mechanisms and material properties, presence of obstacles etc. Hence, the use of the regression equations for estimating the expected landslide travel distance needs to be applied with care because the mean values may give optimistic results. Many landslides will travel far beyond the calculated distance. It is recommended that the lower envelope that corresponds to the maximum landslide run-out be used (Hungr et al., 2005). Using envelopes derived through empirical methods are conservative but not unrealistic because they are based on observed cases.

3.4.2.3 Volume change assessment of the run-out distance
The volume change method (Cannon, Savage, 1988; Iverson et al., 1998; Fannin, Wise, 2001) estimates the potential travel distance of debris flows based on the initial volume of a debris flow and the rate at which material is entrained or deposited along its travel path. The path is subdivided into “reaches”, for which reach length, width and slope are measured. The model considers confined, transitional and unconfined reaches and imposes no deposition for flow in confined reaches and no entrainment for flow in transitional reaches (Fannin, Wise, 2001). Using the initial volume as input and the geometry of consecutive reaches, the model establishes an averaged volume-change formula by dividing the volume of mobilized material by the length of debris trails (Fannin, Wise, 2001; Hungr et al., 2005). As the landslide debris moves downslope, the initial volume/mass of the landslide is progressively reduced through loss or deposition of materials, and that the landslide debris halts when the volume of the actively moving debris becomes negligible. The results give a probability of travel distance exceedance that is compared with travel distances of two observed events (Fannin, Wise, 2001, Hungr et al., 2005). In addition to uncertainty in event volume, channel yield rate estimations (as well as the angle of reach methods) have the additional difficulty that an initiation point of the debris flow must be predicted. Not all debris flows initiate from a single failed landslide mass and thus the selection of a single point of initiation is sometimes impossible (Prochaska et al., 2008).

3.4.3 *Numerical methods for estimating run-out distance*
Numerical methods include different formulations based on the block (“lumped mass”) models, Continuum fluid mechanics and distinct element models. A comprehensive

description of the various methods can be found in Hungr et al. (2005). In the block ("lumped mass") method the moving landslide mass is represented by a dimensionless block that is a major simplification. The important effect of lateral and longitudinal spreading of the slide mass cannot be accounted for, should therefore be suitable only for comparing paths which are very similar in terms of geometry and material properties (Dai et al., 2002). Continuum fluid mechanics models utilize the conservation equations of mass, momentum and energy that describe the dynamic motion of debris, and a rheological model to describe the material behavior of debris. Continuum models compared to distinct element models experience faster computational times and are better suited to model viscous flows and pore pressure effects. On the other hand, distinct element models can better model large strain particle movement and active and passive pressures (Prochaska et al., 2008).

Gerolymos, Gazetas (2007) and Gerolymos (2010), in an effort to address the complex issue of triggering and post–failure travel distance of violent landslides, have recently developed a multi-block numerical model to interpret the sliding process, considering two mechanically coupled substructures: the accelerating deformable body of the slide, and the rapidly deforming shear band at the base of the slide. The model combines features of an extended Savage-Hutter approach for the sliding soil body, with (a) a Mohr–Coulomb failure criterion, (b) Bouc–Wen hysteretic stress–strain relationship, and (c) the Voellmy's rheology for the deformation of the material within the shear band, and exploits the concept of grain crushing-induced instability. The model has been validated with few large landslide cases in Japan.

No analytical solution, regardless its complexity, can be relied on without being calibrated against field observations. In general, rheological relationships defining the equivalent fluid should be simple with few changeable parameters that can be easily constrained. It is also recommended that each calibration study should use more than one landslide of a given type, in order to properly constrain the model (Hungr et al., 2005).

With the use of the correct input parameters, dynamic numerical models have the potential to provide accurate run-out lengths. They also provide additional information, such as the flow velocity along the run-out path, the area of flow and the peak discharge. However, these models also require the most sophistication during data collection and analysis in order to estimate appropriate input parameters. The cost of these detailed analyses may not be warranted for preliminary hazard assessments.

4. REFERENCES

Agliardi F., Crosta G. 2003. *High resolution three-dimensional numerical modelling of rockfalls*. Int. Journal of Rock Mechanics and Mining Sciences, 40: 455-471.

Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) 2008. *Guidelines for Legislated Landslide Assessments for Proposed Residential Developments in BC*

Ausilio, E., Costanzo, A., Silvestri, F., Tropeano, G. 2008. Prediction of seismic slope displacements by dynamic stick-slip analyses. Proceed. Seismic Engineering Int. Conf. (MERCEA'08), Reggio Calabria and Messina

Ayala, F.J., Cubillo, S., Álvarez, A., Domínguez, M.J., Laín, L., Laín, R., Ortíz, G. 2003. *Large scale rockfall reach susceptibility maps in La Cabrera Sierra (Madrid) performed with GIS and dynamic analysis at 1:5,000*. Natural Hazards, 30: 325-340

Baum, R.L., Savage, W.Z. and Godt, J.W. 2000. *TRIGRS – A FORTAN program for transient ranfall infiltration and grid-based regional slope-stability analysis*. US Geological SurveyOpen-File Report 02-0424

Baum, R.L., Savage W.Z., Godt, J.W. 2008. *TRIGRS-A Fortran program for transient rainfall infiltration and grid-based regional slope-stability analysis, version 2.0*. US Geological Survey Open-File Report 2008–1159; Available via: http://pubs.usgs.gov/of/2008/1159/

Bourdeau, C., Havenith, H. B. 008. *Site effects modelling applied to the slope affected by the Suusamyr earthquake (Kyrgyzstan, 1992)*. Engineering Geology, 97(3-4): 126-145

Bray, J.D. 2007. *Simplified seismic slope displacement procedures*. Earthquake Geotechnical Engineering. K. D. Pitilakis ed. Springer

Bray, J.D., Travasarou, F. 2007. *Simplified Procedure for Estimating Earthquake-Induced Deviatoric Slope Displacements*. Journal of Geotechnical and Geoenvironmental Engineering, 133: 381

Bray, J.D., Rathje, E.M. 1998. *Earthquake-induced displacements of solid-waste landfills*. Journal Geotechnical and Geoenvironmental Engineering, ASCE, 124(3): 242–253

Bozzolo, D., Pamini, R. 1986. *Simulation of rock falls down a valley side*. Acta Mechanica, 63: 113-130

Cannon, S. H. 1993. *An empirical model for the volume-change behaviour of debris flows*. Proceed. ASCE National Conference on Hydraulic Engineering, San Francisco, CA.: 1768-1773

Chang, K.J., Taboada, A., Chan, Y.C. 2005. *Geological and morphological study of the Jiufengershan landslide triggered by the Chi-Chi Taiwan earthquake*. Geomorphology 71(3-4): 293-309

Cheng, Y.M., Lansivaara, T., Wei, W.B. 2007. *Two-dimensional slope stability analysis by limit equilibrium and strength reduction methods*. Computers and Geotechnics 34(3): 137-150

Copons, R., Vilaplana, J.M. 2008. *Rockfall susceptibility zoning at a large scale: from geomorphological inventory to preliminary land use planning*. Engineering Geology 102: 142–151

Corominas, J. 1996. *The angle of reach as a mobility index for small and large landslides*. Canadian Geotechnical Journal, 33: 260-271.

Crosta, G. B., Imposimato, S., Roddeman, D. 2009. *Numerical modeling of 2-D granular step collapse on erodible and nonerodible surface*. Journal Geophysical Research, 114, F03020

Crosta, G.B., Imposimato, S., Roddeman, D.G., Chiesa, S., 2004. *The 2001 Las Colinas landslide, El Salvador: from geology to numerical modeling*. Proc. 9th Int. Symp. On Landslides, Rio de Janeiro

Dai, F.C., Lee, C.F., Ngai, Y.Y. 2002. *Landslide risk assessment and management: an overview*. Engineering Geology 64(1): 65-87

Devoli, G., De Blasio, F. V., Elverhøi, A., Høeg, K. 2009. *Statistical Analysis of Landslide Events in Central America and their Run-out Distance*. Geotechnical and Geological Engineering, 27(1): 23-42

Domaas, U. 1994. *Geometrical methods of calculating rockfall range*. Norwegian Geotechnical Institute. Report 585910-1. 21 pp., unpublished.

EC8 2004. *Eurocode 8: Design of structures for earthquake resistance, Part 5: Foundations, retaining structures and geotechnical aspects*. CEN-ENV, Brussels

Evans, S.G., Hungr, O. 1993. *The assessment of rockfall hazard at the base of talus slopes*. Canadian Geotechnical Journal, 30: 620-636.

Fannin, R.J., Wise, M.P. 2001. *An empirical-statistical model for debris flow travel distance*. Canadian Geotechnical Journal, 38: 982-994

Fell, R., Bonnard, C., Cascini, L., Leroi, E., Savage, W. 2008. *Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning*. Engineering Geology 102: 99–111

Finlay, P.J., Mostyn, G.R., Fell, R. 1999. *Landslide risk assessment: prediction of travel distance*. Canadian Geotechnical Journal, 36: 556-562

Gerolymos N. 2010. *Numerical modeling of seismic triggering, evolution, and deposition of rapid landslides: Application to Higashi–Takezawa*. International Journal for Numerical and Analytical Methods in Geomechanics 34 (4): 383–407.

Gerolymos N., Gazetas, G. 2007. *A model for grain-crushing-induced landslides—Application to Nikawa, Kobe 1995*. Soil Dynamics and Earthquake Engineering, 27: 803–817

Han, Y., Hart R. 2010.*Seismic analysis of the reservoir-earth dam-pore fluid system using an integrated numerical approach*. Proceed. 5th Int. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, California

Harp, E.L., Jibson, R.W. 1995. *Inventory of landslides triggered by the 1994 Northridge,California earthquake*. US Geological Survey Open File Report, 95–213

Harp, E.L., Jibson, R.W. 1996. *Landslides triggered by the 1994 Northridge, California earthquake*. Bulletin of the Seismological Society of America 86(1B), S319–S332

Hasegawa, S., Dahal, R.K., Nishimura, T., Nonomura, A., Yamanaka, M. 2009. *DEM-Based Analysis of Earthquake-Induced Shallow Landslide Susceptibility*. Geotechnical and Geological Engineering 27(3): 419-430

Hsü, K.J. 1975. *Catastrophic debris stream (sturzstroms) generated by rockfalls*. Geological Society of America Bulletin, 86: 129-140

Hungr, O. 1995. *A model for the runout analysis of rapid flow slides, debris flows and avalanches*. Canadian Geotechnical .Journal, 32: 610-623

Hungr, O., Evans, S.G. 1988. *Engineering evaluation of fragmental rockfall hazards*. Proceed. 5th Int. Symp. on Landslides, Lausanne, Bonnard ed., A.A. Balkema, 1: 685-690

Hungr. O., Corominas, J., Eberhardt, E. 2005. *Estimating landslide motion mechanisms, travel distance and velocity*. Proceed. Int. conf. on Landslide Risk Management, O. Hungr, R. Fell, R. Couture and E. Eberhardt eds.: 99-128, Taylor and Francis, London

Hunter, G. Fell, R. 2003. *Travel distance angle for rapid landslides in constructed and natural soil slopes*. Canadian Geotechnical Journal, 40(6): 1123-1141

Hutchinson, J.N. 1971.*Undrained loading, a fundamental mechanism of mudflows and other mass movements'*, Géotechnique 21(4): 353-358

Hutchinson, J.N. 1986. *A sliding-consolidation model for flow slides* Canadian Geotechnical Journal, 23: 115-126

Hutchinson, J.N. 1988. *Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology*. In Bonnard (ed.), Proceed. 5th Int. Symp. on Landslides, Lausanne, Switzerland. A.A. Balkema, 1: 3-35.

Iverson, R.M., 2000. *Landslides triggering by rain infiltration*. Water Resources Research, 36(7): 1897-1910

Iverson, R.M., Denlinger, R.P. 2001. *Flow of variably fluidized granular masses across three-dimensional terrain: Part I: Coulomb mixture theory*. J. Geophys. Res., 106: 537-552

Iverson, R.M., Schilling, S.P., J.W., Vallance 1998. *Objective delineation of lahar-inundation hazard zones*. Geological Society of America Bulletin, 110: 972–984

Jaboyedoff, M., Labiouse, V. 2003. *Preliminary assessment of rockfall hazard based on GIS data. ISRM 2003–Technology roadmap for rock mechanics*. South African Institute of Mining and Metallurgy: 575.578

Jibson, R.W., Jibson, M.W. 2003. *Java programs for using Newmark's method and simplified decoupled analysis to model slope performance during earthquakes*. US Geological Survey Open File Report: 03-005

Jibson, R.W. 1993. *Predicting earthquake-induced landslide displacements using Newmark's sliding block analysis*. Transportation Research Record 1411, 9–17

Keefer, D.K. 1984. *Landslides caused by earthquakes*. Geological Society of America Bulletin, 95: 406- 421

Keefer, D.K. 2002. *Investigating landslides caused by earthquakes - A historical review*. Surveys in Geophysics, 23: 473-510ù

Kokusho, T., Ishizawa, T. 2005. *Energy approach to slope failures and a case study during 2004 Niigata-ken Chuetsu earthquake*. Proceed. of Geotechnical Earthquake Engineering Satellite Conference Osaka, Japan, ISSMGE, 255-262

Kokusho, T., Ishizawa, T., Hara, T. 2009. *Slope failures during the 2004 Niigataken Chuetsu earthquake in Japan*. Earthquake Geotechnical Case Histories for Performance-Based Design - Kokusho ed., Taylor & Francis Group, London

Konagai, K., Orense, R.P., Johansson, J. 2009. *Las Colinas landslide caused by the 2001 El Salvador Earthquake*. Earthquake Geotechnical Case Histories for Performance-Based Design-Kokusho ed., Taylor & Francis Group, London

Lagaros, N.D., Tsompanakis, Y., Psarropoulos, P.N., Georgopoulos, E.C. 2009. *Computationally efficient seismic fragility analysis of geostructures*. Computers & Structures 87(19-20): 1195-1203

Laigle, D., Coussot,P. 1997 *Numerical Modelling of Mudflows*. Journal Hydrology Engineering, ASCE, 123: 617-623

Latha, G.M., Garaga, A. 2010. *Seismic Stability Analysis of a Himalayan Rock Slope*. Rock Mechanics and Rock Engineering: 1-13

Leroueil, S., Vaunat, J., Picarelli, L., Locat, J., Lee, H., Faure, R.M. 1996. *Geotechnical characterization of slope movements*. Proceed. 7th Int. Symp. on Landslides, Trondheim, 1: 53-74

Li, T. 1983. *A mathematical model for predicting the extent of a major rockfall*. Zeitschrift für Geomorphologie 24: 473- 482

McDougall, S, Hungr, O. 2004. *A model for the analysis of rapid landslide motion across three-dimensional terrain*. Canadian Geotechnical Journal 41(12):1084–1097

Michael-Leiba, M., Baynes, F., Scott, G. and Granger, K. 2003. *Regional landslide risk to the Cairns community*. Natural Hazards, 30: 233-249

Miles, S.B., Keefer, D.K. 2009. *Evaluation of CAMEL--comprehensive areal model of earthquake-induced landslides*. Engineering Geology 104(1-2): 1-15

Montgomery, D.R., Dietrich, W.E. (1994). *A physicall based model for the topographic control on shallow landsliding*. Water Resources Research 30: 1153-1171

Morgan, G.C., Rawlings, G.E., Sobkowicz, J.C., 1992. *Evaluating total risk to communities from large debris flows*. Procede. 1st Canadian Symp. on Geotechnique and Natural Hazards. BiTech Publishers, Vancouver, BC: 225-236.

Newmark, N.M. 1965. *Effects of earthquakes on dams and embankments*. Geotechnique 15, 139-160

Nicoletti, P.G., Sorriso-Valvo, M. 1991. *Geomorphic controls of the shape and mobility of rock avalanches*. Geological Society of America Bulletin 103: 1365-1373

Olivares, L., Tommasi, P. 2008. *The role of suction and its changes on stability of steep slopes in unsaturated granular soils*. Proceed. 10th Int. Symp. on Landslides and Engineered Slopes, Xi'an, China, Chen Z., Zhang J., Li Z. Wu F. Ho K. eds., Taylor&Francis, London, 2: 203-215

Paolucci, R. 2002. *Amplification of earthquake ground motion by steep topographic irregularities*. Earthquake Engineering and Structural Dynamics 31(10), 1831–1853

Papadopoulos, G.A., Plessa, A. 2000. *Magnitude-distance relations for earthquake-induced landslides in Greece*.Engineering Geology 58(3-4): 377-386

Pastor, M., Haddad, B., Sorbino, G., Cuomo, S., Drempetic, V. 2009. *A depth integrated coupled SPH model for flow-like landslides and related phenomena*. Int. Journal Numerical and Analytical .Methods n Geomechanics, 33(2): 143-172

PEER strong ground motion database http://peer.berkeley.edu/smcat/index.html

Peng, W.F., Wang, C.L., Chen, S.T., Lee, S.T. 2009. *Incorporating the effects of topographic amplification and sliding areas in the modeling of earthquake-induced landslide hazards, using the cumulative displacement method*. Computers and Geosciences 35(5): 946-966

Pfeiffer, T.J., Bowen, T.D., 1989. *Computer simulation of rockfalls*. Bulletin of the Association of Engineering Geologists, 26(1): 135–146.

Prochaska, A. B., Santi, P.M., Jerry, D., Higgins, J.D., Cannon, S.H. 2008. *Debris-flow runout predictions based on the average channel slope (ACS)*. Engineering Geology 98(1-2): 29-40.

Quecedo, M., Pastor, M., Herreros, M.I. 2004. *Numerical modelling of impulse wave generated by fast landslides*. Int. Journal Numerical Methods. In Engineering, 59: 1633-1656

Rathje, E.M., Bray, J.D. 2000. *Nonlinear coupled seismic sliding analysis of earth structures*. Journal of Geotechnical and Geoenvironmental Engineering 126(11): 1002–1014

Rickenmann, D. 1999. *Empirical relationships for debris flows*. Natural Hazards, 19: 47–77

Savage, W.Z., Godt, J.W., Baum, R.L. 2004. *Modeling time-dependent areal stability*. Proceed. 9th Int. Symp. on Landslides, Rio de Janeiro, Lacerda W.A., Erlich M., Fontoura S.A.B., Sayao A.S.F. eds., 1:23-36

Savage, W.Z., Hutter, K. 1991. *The dynamics of avalanches of granular materials from initiation to runout. Part I: Analysis.* Acta Mechanica 86: 201-223

Scheidegger, A. 1973. *On the prediction of the reach and velocity of catastrophic landslides*. Rock Mechanics, 5: 231-236

Sorbino, G., Sica, C., Cascini, L. 2010. *Susceptibility analysis of shallow landslides source areas using physically based models*. Natural Hazard 53: 313-332

Sousa, J., Voight, B. 1995. *Multiple-pulsed debris avalanche emplacement at Mount St. Helens in 1980: Evidence from numerical continuum flow simulations*. Journal of Volcanology and Geothermal Research, 66(1-4): 227-250

Taiebat ,M., Kaynia, A. 2010. *A practical model for advanced nonlinear analysis of earthquake effects in clay slopes*. Proceed 5th Int. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, California

Terzaghi, K. 1950. *Mechanics of landslides*. Engineering Geology (Berkeley) Volume. Geological Society of America

Takahashi, T., 1991. *Debris Flows*. A. A. Balkema, Brookfield, Vt., 165 pp

Travasarou, T. 2003. *Optimal ground motion intensity measures for probabilistic assessment of seismic slope displacements*. Ph.D. Dissertation, U.C. Berkeley

Travasarou, T., Bray, J.D. 2003. *Optimal ground motion intensity measures for assessment of seismic slope displacements*. Proceed. 2003 Pacific Conf. on Earthquake Engineering, Christchurch, New Zealand

Tsukamoto, Y., Ishihara, K. 2005. *Residual strength of soils involved in earthquake–induced landslides*. Proceed. of Geotechnical Earthquake Engineering Satellite Conference on Performance Based Design in Earthquake Geotechnical Engineering: Concepts and Research, ISSMGE, Osaka, 117-123

Van Westen, C.J., Castellanos, E., Kuriakose, S.L. 2008. *Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview*. Engineering Geology 102(3-4): 112-131

Wang, H., Wang, G., Wang, F., Sassa, K., Chen, Y. 2008. *Probabilistic modeling of seismically triggered landslides using Monte Carlo simulations*. Landslides 5(4): 387-395

Yin, Y., Wang, F., Sun, P. 2009. *Landslide hazards triggered by the 2008 Wenchuan earthquake, Sichuan, China*. Landslides 6(2): 139-152

Zania, V., Psarropoulos, P. N., Karabatsos, Y., Tsompanakis, Y. 2008. *Inertial distress of waste landfills*. Computers & Structures 86(7-8): 642-651