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Stability and Run-out Analysis of Earthquake-induced Landslides

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1. Introduction

A large number of landslides can be caused by a strong earthquake and they have been the source of significant damage and loss of people and property. Therefore, it is very important to predict the stability of slope and the movement behaviors of a potential landslide under an earthquake loading, i.e., stability and run-out analysis (Figure 1).

Earthquake-induced landslides have been the source of significant damage and loss of people and property. One of the most serious event is the 1970 Peru earthquake. This event caused a huge rock avalanche that killed almost 54,000 people and buried two cities [143]. Another example is, in the 1920 Haiyuan earthquake, a large number of landslides caused widespread damage to infrastructure and buildings and killed at least 100,000 people, almost half of the total earthquake deaths [82].

Therefore, it is very important to predict the earthquake-induced landslides and to take countermeasures for potential landslides.

Main topics of earthquake-induced landslides are the following:

1. Investigation of recent and historical earthquake-induced landslides and their impacts so as to produce inventories of historical earthquake-induced landslides
2. Prediction of potential earthquake-induced landslides, including (i) failure mechanism and stability analysis of seismic slopes, (ii) movement mechanism and behaviours of earthquake-induced landslides, and (iii) Instrumentation and monitoring technologies for potential earthquake-induced landslides or post-earthquake landslides.
3. Preventive countermeasures for earthquake-induced landslides, including (i) Stabilization and disaster mitigation of earthquake-related landslides, (ii) risk assessment and

management of earthquake-related landslides, and (iii) hazard map and early warning system for earthquake-related landslides

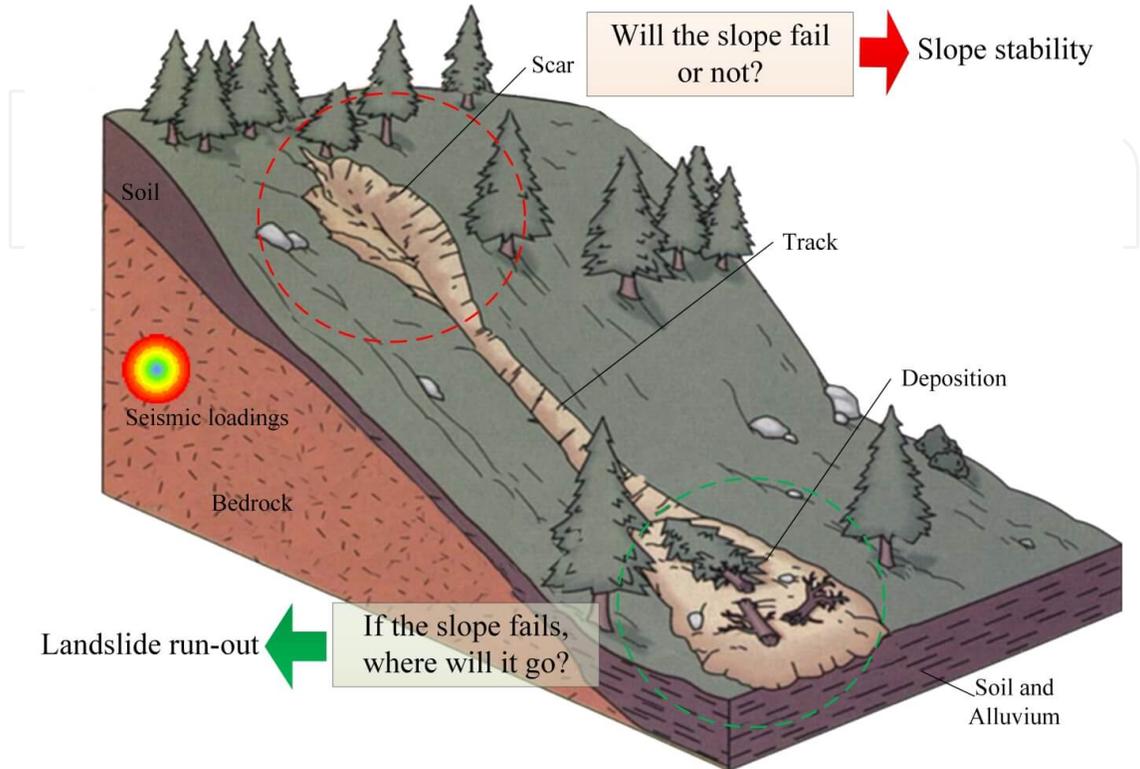


Figure 1. Stability and run-out analysis of earthquake-induced landslides

This chapter focuses on the prediction of potential earthquake-induced landslides. The prediction of potential landslide can be carried out using detailed geotechnical investigations and stability calculations. (i) Failure mechanism and stability analysis of seismic slopes, i.e. seismic slope stability analysis and (ii) movement mechanism and behaviours of earthquake-induced landslides, i.e. landslide run-out analysis are outlined firstly, and then the merits and demerits of each method are clarified in this chapter.

2. Seismic slope stability analysis

So far, methods developed to analyze the stability of earthquake slopes can be divided into three types: (1) pseudo-static methods, (2) dynamic sliding block methods, and (3) stress-strain methods. These three types of methods can be applied in different cases due to each of them has merit and demerit [73].

2.1. Pseudo-static methods

[166] first presented the pseudo-static method, which is a simple method for evaluating of seismic stability of a slope. This type of method can be used to man-made or natural slopes

based on either analytical method or numerical method. The earthquake force, acting on the an element or whole of the slope, is written by a horizontal force and/or a vertical volum force equal to the gravitation force multiple a coefficient k , called the pseudo-static coefficient as shown in Figure 2 and Equation (1).

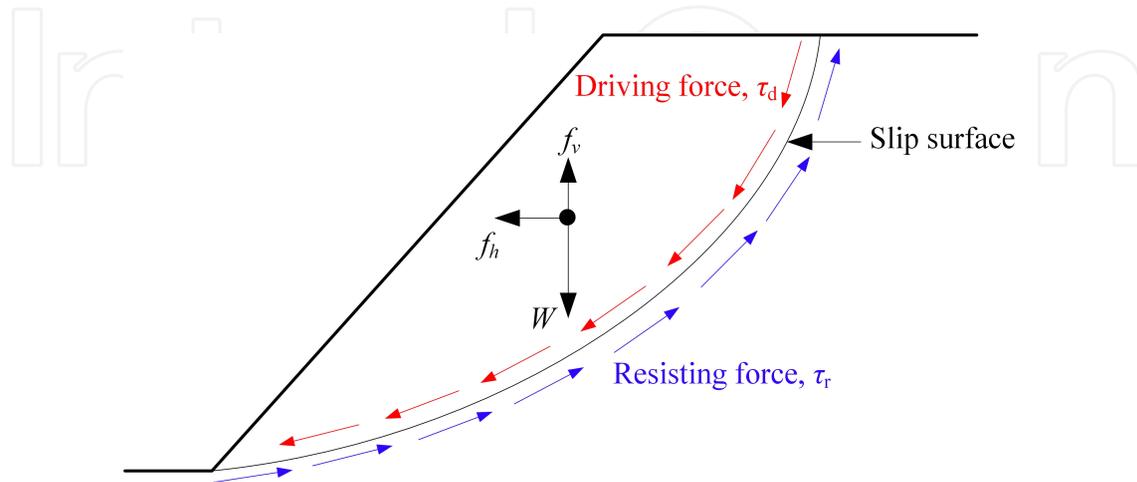


Figure 2. Forces acting on a slope in pseudo-static slope stability analysis

Thus, k times the gravitational acceleration g , i.e. $a=kg$ forms the assumed seismic acceleration a . The assumed pseudo-static forces acting on a potential sliding mass of weight W will be

$$\begin{aligned} f_h &= \frac{a_h W}{g} = k_h W \\ f_v &= \frac{a_v W}{g} = k_v W \end{aligned} \tag{1}$$

where a_h and a_v are horizontal and vertical pseudo-static accelerations, respectively, k_h and k_v are horizontal and vertical pseudo-static coefficients, respectively. The factor of safety(FOS) is represented as the ratio of the resisting force to the driving force, Equation (2).

$$\text{FOS} = \frac{\tau_r}{\tau_d} \tag{2}$$

From Equation (1), the pseudo-static force is determined by the seismic coefficient. The key problem for the pseudo-static procedure is how to select an appropriate seismic coefficient under an acceptable FOS. There have been studies for determining the most appropriate pseudo-static coefficient by a matter of experience and judgment.

[166] classical paper made the original suggestion to use of $k_h=0.1$ for severe earthquakes, $k_h=0.2$ for violent and/or destructive earthquakes, and of $k_h=0.5$ for catastrophic earthquakes.

[103] presented a minimum pseudo-static FOS of 1.5 based on a slope material strength reduction factor (SRF) of 0.8 and the following acceleration values associated with two different earthquake magnitudes M . The same values of seismic coefficients for magnitude 6.5 and 8.25 earthquakes are recommended by [154], but with an acceptable FOS of 1.15.

$$\begin{aligned} a &= 0.1g \text{ for } M = 6.5 \text{ implying } k = 0.1 \\ a &= 0.15g \text{ for } M = 8.25 \text{ implying } k = 0.15 \end{aligned} \quad (3)$$

[137] also presented the pseudo-static coefficient related to earthquake magnitude. In detail, for an 8.25, 7.5, 7.0 and 6.5 magnitude earthquakes, if the seismic coefficients equal to 1/2, 1/3, 1/4 and 1/5 of the PGA, respectively, the computed FOSs are larger than 1.0, the accumulated displacements of slope are likely to be acceptably small.

In the report published by the International Commission of Large Dams (ICOLD), [154] shows a list of the minimum FOS value and horizontal seismic coefficients for 14 large dams worldwide, in which the minimum FOSs range from 1.0 to 1.5 and the horizontal earthquake coefficients range from 0.1 to 0.15. The Corps of Engineers Manual recommended a earthquake coefficient of 0.1 or 0.15 for areas where major and great earthquake threats are estimated, respectively, and a FOS of no larger than 1.0 for all magnitude earthquakes.

Some references related the earthquake coefficient value to the peak ground acceleration (PGA) [10, 67, 108]. [108] related a pseudo-static coefficient of 1/3 to 1/2 of the PGA at the top of a double-side slope (a dam in the source reference), whereas [67] related a pseudo-static coefficient of 1/2 of the PGA of bedrock (PGA_{rock}) with a FOS of no larger than 1.0 and a SRF of 20%. And, [10] recommended the pseudo-static coefficient of 0.6 or 0.75 times of the PGA of bedrock (0.6 or $0.75PGA_{rock}$). It should be noted that the value given by [10] is conservative because the original study is designed for solid-waste landfills, where the allowable deformation are relatively small. [89] pointed that although engineering judgment is required for all cases, the criteria of [67] should be appropriate for most slopes.

[91] suggested one-half of PGA to use in an area of low seismicity (peak acceleration $<0.15g$) for the stability of earth embankments. This can be obtained from the peak horizontal motion (mean) from Modified Mercalli Intensity (MMI), magnitude-distance attenuation and the probability of a 50-year, 90% nonexceedance. However, in an area of moderate to strong seismicity ($0.15g \leq PGA \leq 0.40g$), PGA is obtained from the peak horizontal motion, from MMI, magnitude-distance attenuation and probability of 250-year, 90% nonexceedance.

[76] suggested a minimum FOS of 1.0, also based on a slope material SRF of 0.8 and the following values of pseudo-static coefficient: a equals to $0.17PGA$ or $0.5PGA$ for the dynamic response analysis is to be performed for the slope or earthquake structure or not.

[163] developed an expression for the earthquake coefficient in terms of characters of ground motion and magnitude of earthquake based on the data of [10].

It is almost common that only the horizontal acceleration is considered in evaluating the stability and deformation of a slope because the horizontal acceleration is the principal destabilizing force that acts on earth structures as well as the principal source of damage observed in earthquakes [4].

From Figure 2, the horizontal force clearly increases the driving force and decreases the FOS. The vertical pseudo-static force generally has less influence on the FOS than the horizontal pseudo-static force does because the vertical pseudo-static reduces both the driving and resisting forces. Hence, the effects of vertical seismic loading are frequently omitted in pseudo-static analysis [89].

Several investigators performed some analyses and have shown that the inclination of seismic loading have a significant influence on the seismic stability of slope by coupling the vertical and horizontal components of seismic force [20, 100].

In summary, pseudo-static method can be simply and directly used to identify the FOS and the critical seismic coefficient k_c . In addition, performance of slope is closely related to permanent displacement, but the results of pseudo-static method are difficult to interpret the performance of slope after a seismic event because this method provides no information about permanent displacement. Because the pseudo-static analysis method provides only a rough assessment of seismic slope, it should be only used for the preliminary procedures. More accurate methods can be used to the followed process [73, 163, 170].

2.2. Dynamic sliding block methods

Displacement-based dynamic sliding block method is another alternative approach to evaluate the seismic slope stability, as permanent displacement is a useful index of slope performance, especially for those man-made slopes constructed for special purposes such as dams, embankments et al. This method has been widely used in earthquake geotechnical engineering.

In 1965, [119] proposed the dynamic sliding block method for estimating the permanent displacement of embankment affected by a seismic loading. In this method, sliding would be induced once the seismic loading exceed the critical seismic force of a potential failure surface as shown in Figure 3. The sliding would be accumulated until the end of seismic loading. We can evaluate the accumulated permanent displacement to assess the seismic stability of a slope.

Newmark's method shows that the yield acceleration of a potential block is a function of the FOS and slope angle, as:

$$a_c = (\text{FOS} - 1)g \sin \alpha \quad (4)$$

where a_c is in terms of the gravity acceleration g ; FOS is the static factor of safety; and α is the slope angle.

Since then, the method has been numerous extensions and applications. The section 2.2.1 and section 2.2.2 will give reviews for these two aspects, respectively. In addition, a regional scale application of the dynamic sliding block method is reviewed in section 2.2.3.

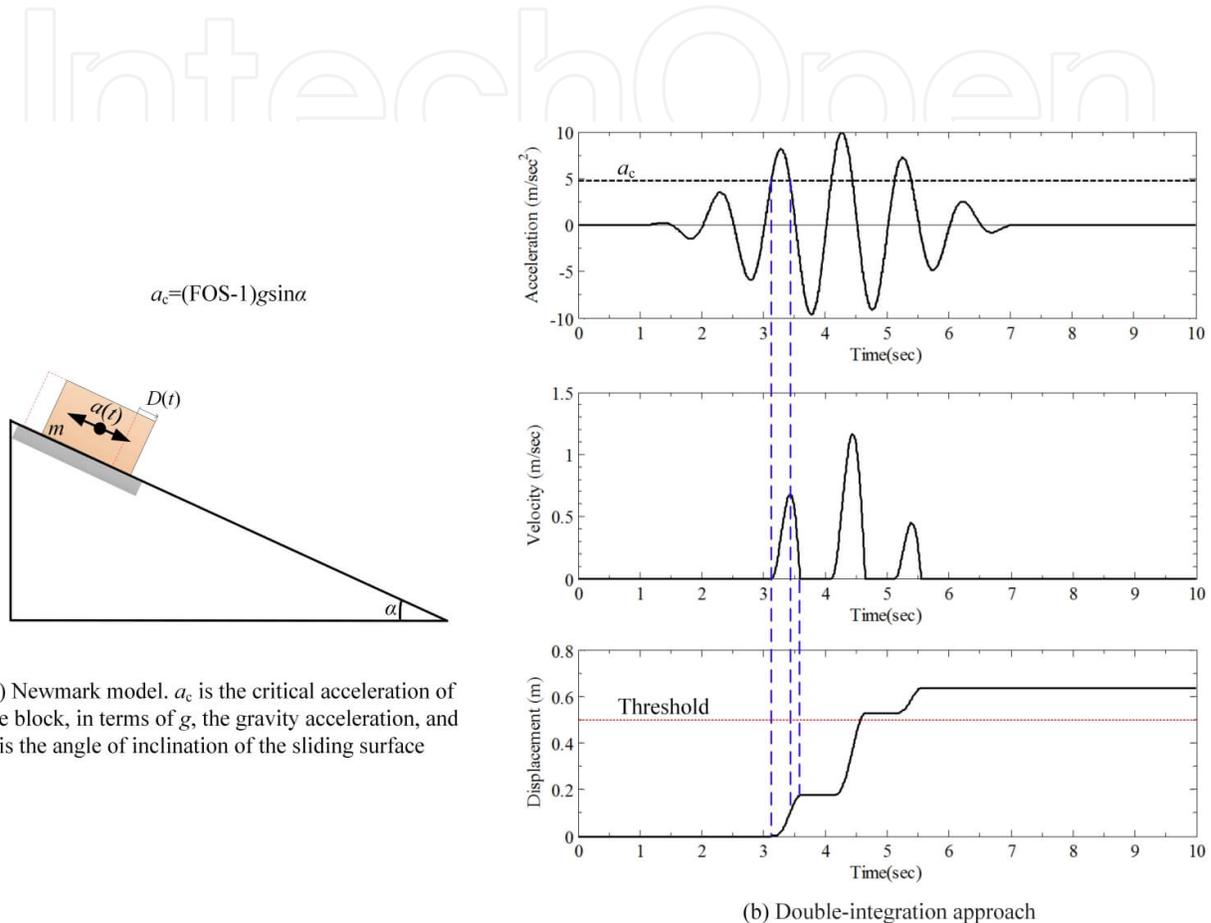


Figure 3. Illustration of the original Newmark's method

2.2.1. Extensions

More attention has been focused over the last decades on developing methods to more accurately analyze the seismic stability of a slope for dams, embankments or other important structures by modeling the dynamic response of a slope more rigorously.

After the first dynamic sliding rigid block method, [155 and 97] published more sophisticated methods to account for the un-rigid block. Similar studies also given by [103]. As the classification given by [73], methods for estimating the permanent displacement of a sliding system induced by earthquake loading can be grouped into: (1) rigid-block model [119], (2) decoupled model [10, 104], and (3) coupled model [11, 97, 139].

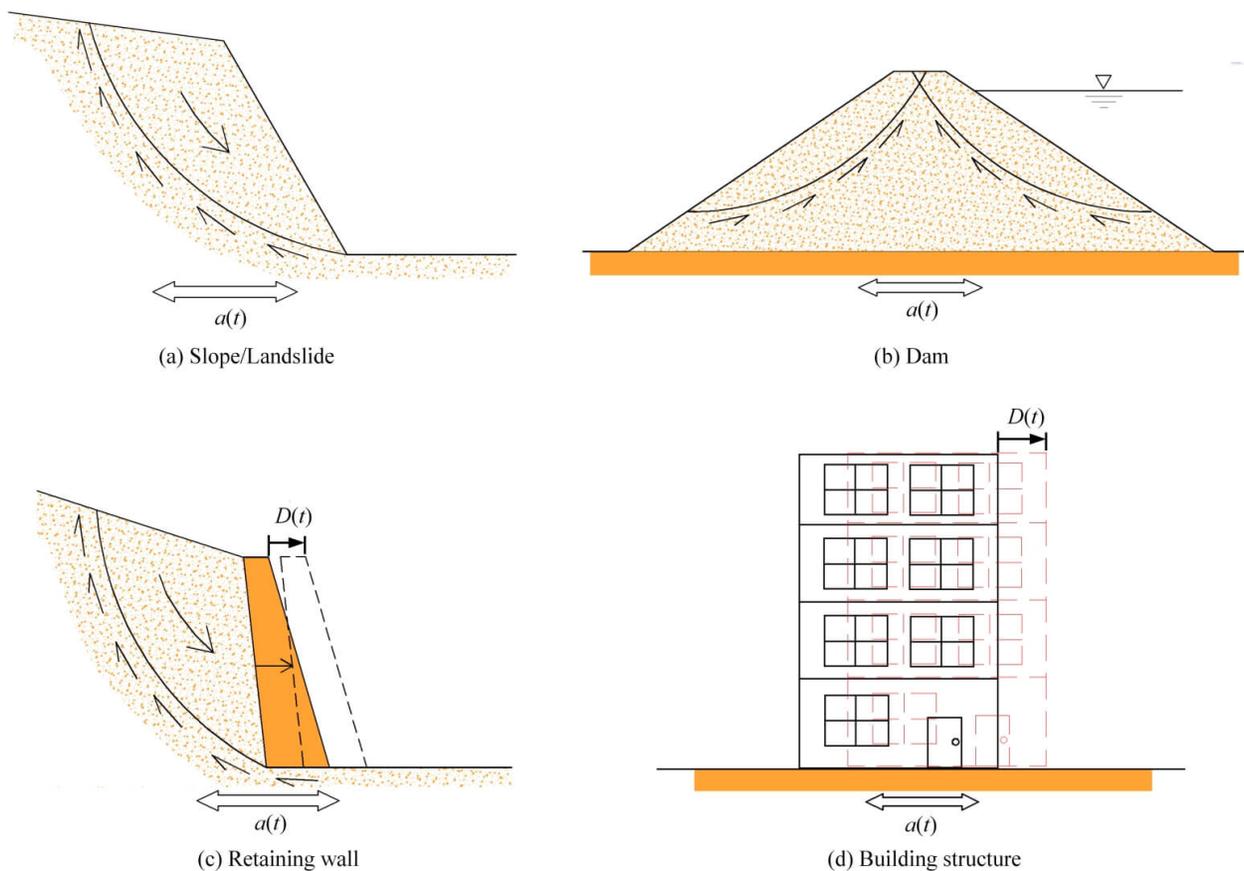


Figure 4. Applications of dynamic sliding block method in geotechnical engineering

2.2.2. Applications

Since the rigid-block method was published in 1965 by Newmark, it has seen numerous applications, four of which are shown in Figure 4. The applications in recent years include (1) the seismic deformation analysis of earth dams and embankments [1, 22, 48, 49, 89, 90, 97, 103, 138, 144, 145, 150, 155, 179, 180]; (2) the displacements associated with landslides [34, 53, 70, 171]; (3) the seismic deformation of landfills with geosynthetic liners [10, 181]; (4) the seismic settlement of surface foundations [141]; and (5) the potential sliding of concrete gravity dams [32, 47, 95]. The extension of the analogue by [140] to gravity retaining walls has met worldwide acceptance, and has found its way into seismic codes of practice. Several other generalised applications have also appeared (e.g. [2, 3, 45, 99, 139, 162, 169]).

2.2.3. Regional scale analysis

Except a single slope analysis, where the landslides are likely to occur and what kind of seismic conditions will cause it failure are two important topics in seismic hazard assessment, i.e. regional scale analysis [59].

For a regional scale analysis, slope stability analysis methods will be not suitable [143, 168]. With the development of Geographic Information Systems (GIS) tools in recent years, regional

scale analyses by the dynamic sliding block method have been proposed, in which ground shaking characteristic parameters, geotechnical material and topographic data are considered (e.g. [34, 71, 75, 106, 114, 151, 155]).

The Newmark analysis (which combines slope stability calculations with seismic ground-motion records) is widely used to evaluate the potential for landslides that could be triggered by earthquake shaking [70, 71, 72, 74, 113].

2.3. Stress-strain methods

With the developments of the simulation approach and computer technology in recent years, the stress-strain method is becoming increasingly used in seismic slope stability analysis. These methods can be grouped into continuous methods, e.g. finite element method (FEM) [21], finite difference method (FDM) [116], boundary element method (BEM) [12], and discontinuous methods, e.g. rigid block spring method (RBSM) [77; 80], discontinuous deformation analysis (DDA) [159, 160] and discrete element method (DEM) [31].

2.3.1. Continuous methods

[21] developed and named FEM of engineering analysis, in which the studied system is meshed into small many elements. This method can be applied to estimate the slope stability including dynamic stability analysis.

Some applications of the continuous methods have been proposed, e.g. [89, 94, 153] and [156]. Recently, nonlinear in-elastic soil models have been developed and implemented in two-dimension (2-D) and three-dimension (3-D) models (e.g., [42, 50, 135, 164]). In addition, [93] and [183] studied the seismic slope stability by using FDM.

2.3.2. Discontinuous methods

For the analysis of a potential failure mass consisting of multiple blocks as shown in Figure 5, the discontinuous methods are more applicable [120]. Some applications of RBSM and DEM can be found in some literature (e.g. [8, 52, 77, 79, 80, 85, 121, 127, 128, 129, 130, 131, 136, 182]).

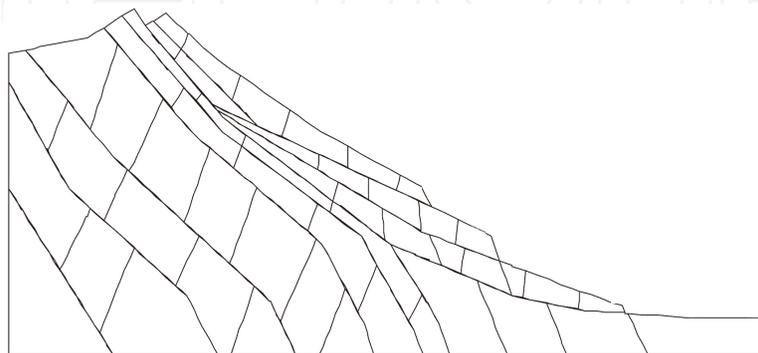


Figure 5. A jointed rock slope (modified from Bhasin and Kaynia, 2004)

DDA is also a discontinuous method developed for the modeling of the behaviors of multiple block systems. Since the novel formulation and the numerical code of DDA were presented, DDA draws more and more attention and many extensions and modifications to the original method have been proposed to overcome some limitations [19, 37, 38, 81, 87, 98] and make it more suitable, practical and efficient to seismic slope stability.

The DDA can be used both to static rock slope engineering (e.g. [17, 81, 102, 123, 176, 187]) and the seismic rock slope stability analysis [56, 57, 54].

In summary, stress-strain method represents a powerful alternative approach for seismic slope stability analysis which is accurate, versatile and requires fewer a priori assumptions, especially, regarding the shape of failure surface.

3. Landslide run-out analysis

It is important to estimate the movement behaviour of a potential landslide. For example, the movement distance is an important parameter in risk assessment and measure design. There are many run-out analysis methods, which can fall into four categories: (1) experimental methods, (2) empirical methods, (3) analytical methods, and (4) numerical simulation methods. The states of the art of these methods are reviewed in the following four subsections 3.1 - 3.4.

3.1. Experiment methods

Physical modelling typically involves using scale models to capture the motion of landslides. Physical experiments are usually preferred to models because models require more assumptions than direct measurements. But for landslides, direct experiment is difficult, dangerous, expensive, and of limited utility. Based on laboratory experiments and filed investigation data, there are many different available models developed for calculating run-out zones.

Some full-scale direct experiments with artificial landslides have been completed [118, 122, 124, 125, 126] and others). However, since landslides are frequently heterogeneous and single event cannot be repeated carefully through adjusting only one factor, direct experiment is difficult, dangerous, expensive and of limited utility. And observing conditions are complicated by the danger of being in close proximity to a landslide and the difficulty of measuring a material with properties that change when observed in-situ or when isolated for measurement. But laboratory experiments are still the first qualitative and quantitative observations on the obtained results became fundamental for a better understanding of movement runout behaviour.

3.2. Empirical methods

Several empirical methods for assessing landslide travel distance and velocity have been developed based on historical data and on the analysis of the relationship between parameters characterizing both the landslide, e.g. the volume of the landslide mass, and the path, e.g. local

morphology, and the distance travelled by the failure mass [65]. Regression model-based methods and geomorphology-based methods are two kinds of common methods.

3.2.1. Regression model-based methods

The regression model-based methods are developed on an apparent inverse relationship between landslide volume and angle of reach (also called as *fahrböschung* by [58]). Several linear regression equations have been proposed [25, 96, 153]. Introduced by [58], the angle of reach is the inclination of the line connecting the crest of the source with the toe of the deposit, as measured along the approximate streamline of motion. The angle of reach is considered an index of the efficiency of energy dissipation, and so is inversely related to mobility. Similar correlations between volume and other simple mobility indices have been proposed [33, 60, 142]. Given estimated source location, volume and path direction, these methods provide estimates of the distal limit of motion [111].

Improved empirical model notable performing regressions on subsets with varying scopes were presented by [13, 25, 69] and others.

Regression model-based models play a valuable role in landslide run-out analysis due to the regression model-based methods are simple. But the regression model-based methods are difficult to apply in practice with a high degree of certainty. For example, the correlation coefficients for some of regression models are 0.7-0.8, while a value of larger than 0.95 generally indicates a strong correlation. And it is difficult in this method to take account of influences of the ground condition, the micro-topography, the degree of saturation of the landslide mass and et al. For this point, geomorphology-based method is another alternative approach to predict the run-out of landslide.

3.2.2. Geomorphology-based methods

Field work and photo interpretation are the main sources of the geomorphological analysis for determining the travel distance of landslides [65]. The outer margin of the landslide deposits give an appraisal of the maximum distances that landslides have been able to reach during the present landscape (Figure 6). Several authors have provided these studies (e.g. [23, 24, 26, 88]).

The geomorphological approach does not give any clue of the emplacement mechanism. Furthermore, the slope geometry and the circumstances responsible for past landslides might have changed. Therefore, results obtained in a given place cannot be easily exported to other localities.

In summary, empirical methods, both regression model-based methods and geomorphology-based methods, typically predict travel distances, while the deformation characteristics or the slide velocities of the landslide are not predicted. These models may be applied to establish initial hazard characteristics for preliminary run-out analysis, which may be later refined by other models.



Figure 6. Boundary of the potential rockfall run-out area in Santa Coloma (Principality of Andorra), defined by the line that links the farthest fallen blocks observed in the field [24]. Arrows indicate historical rockfall paths and solid circles are large fallen boulders [65]

3.3. Analytical methods

In contrast to empirical methods, analytical methods are based on mechanics and involve the solution of motion equations [111]. The simplest analytical model is the classical sliding block model as shown in Figure 7, which is based on work-energy theory [6, 9, 43, Müller-Bernet in 58, 63, 83, 84, 132, 147]. Internal deformation and its associated energy dissipation are neglected and the landslides is treated as a lumped mass. At any position along the path, the sum of the energies including the potential energy, kinetic energy and net energy loss equals the initial potential energy. This energy balance can be visualized using the concept of energy grade lines, as shown in Figure 9. The concept of energy grade lines is useful for visualizing the energy balance. v is the velocity of the block, g is the vertical acceleration due to gravity and $v^2/2g$ is known as the velocity head, which is the kinetic energy of the block normalized by the product of its mass and g . The same normalization of net energy loss is known as head loss. Note that the positions of the energy lines are referenced to the centre of mass of the block and that the true energy line and mean energy line do not necessarily coincide. Given the initial position of the center of mass and a suitable relationship to approximate the energy losses, the position and velocity of the block can be determined at any given time.

Three-dimensional analysis for investigating runout of a slope were also proposed [36, 40, 51, 92 and 109]. These models require a high resolution Digital Elevation Model (DEM).

Generally speaking, the use of analytical methods is somewhat motivated by the limitations of purely empirical methods, as the unique geometry and materials involved in each case can be accounted for explicitly and a statistically-significant database of previous events is not

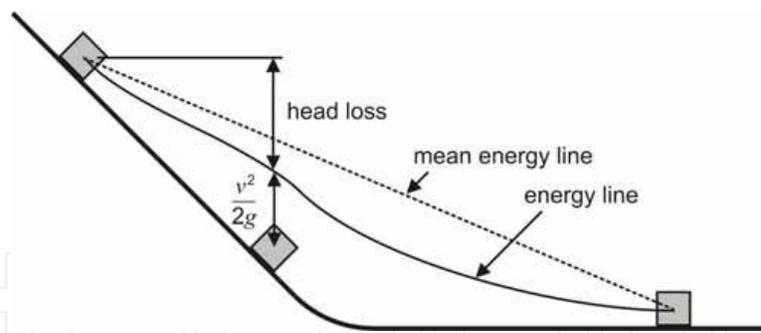


Figure 7. The classical sliding block model, based on work-energy theory [111]

necessarily required. The simplicity of a lumped mass allows analytical solutions, fast and effectively [66]. However, because the landslide is reduced to a single point, lumped mass models cannot provide the exact maximum runout distance, but only the displacement concerning the centre of mass [44, 62].

3.4. Numerical simulation methods

The single-block model should be only applied to the motion of the center of mass of a rigid body, but more complex continuum deformable mass or multi-block system is often appeared in practice. Some numerical simulation methods have been developed to account explicitly for deformation during motion.

3.4.1. Continuous methods

When considering that the dimensions of a typical particle is much smaller than the depth and length of the debris, the debris mass is treated as continuum. According to depth averaged Saint Venant approach, the material is assumed to be incompressible and the mass and momentum equations are written in a depth-averaged form. Many numerical methods now exist to investigate the run-out process of landslide (e.g. [18, 27, 28, 29, 30, 35, 62, 111, 112, 133, 149, 161, 165]). These methods are usually based on continuum mechanics and assume that the avalanche thickness is very much smaller than its extent parallel to the bed, i.e. thin layer depth-averaged models. The primary differences are their representation of basal resistance force and the constitutive relations describing the mechanical behaviour of the considered material. These models can accurately take account of detailed topography effects, shown to be significant, with a reasonable computational time, making it possible to perform sensitivity studies of the parameters used in the model. They can provide effective properties that make it possible to roughly reproduce not only the deposit shape but also the dynamic as shown in [46] and [117] for examples. However, conventional continuum approaching models, which neglects the contact between rocks, makes it impossible to trace the position of individual rock during a landslide.

3.4.2. Discontinuous methods

When the landslide mass consists of large fragments and boulders, the run-out mass is modelled as an assembly of blocks moving down a surface. Some authors take circular shape

models in their run-out analysis to evaluate maximum runout and final deposit position of past or potential events (e.g., [134]). Although polygonal shapes have the disadvantages due to the complexity of the contact patterns and penalty in computational time, methods using non-circular shapes will be required for more real-world problems. It is more appropriate when problems are limited in finite blocks. Discontinuous numerical simulation methods are powerful tools in simulation of failure and run-out process of rock avalanche controlled by weakness surface. DEM [31] and DDA [159, 157] are two of the most commonly used methods.

Both DEM and DDA employ the equations of dynamic motion which are solved at finite points in time, in a series of time steps, but there are some subtle but significant differences in their formulations of the solution schemes and contact mechanics. In the solution schemes, equations of motion in DDA are derived using the principle of minimization of the total potential energy of the system, while the equations of motion as implemented in DEM are derived directly from the force balance equations, which still resultant unbalanced force after a time step and damping is necessarily used to dissipate energy. In the contact mechanics, the DDA used a penalty method in which the contact is assumed to be rigid. No overlapping or interpenetration of the blocks is allowed as the same as real physical cases, whereas soft contact approach is used in DEM. The soft contact approach requires laboratory or field measured joint stiffness, which may be difficult to obtain in many cases. Many comparisons of basic models (sliding, colliding and rolling models) between the DEM and DDA were carried out and show that the results from DDA are more close to the analytical values than that from DEM [188]. Compared to DEM, DDA has a simpler and more straightforward physical meaning [172].

Applications of DEM can be found in some literatures, such as [85, 128, 129, 131, 136, 182].

DDA can be used for estimating the affected area of an earthquake-induced landslide.

[55] first validated the applicability of DDA for the dynamic behaviour of block sliding on a slope. Based on the same inputs model of seismic loadings, [7576886105, 158, 167, 178] studied the dynamic response or/and stability analysis of tunnel, slope, dam, foundation or ancient masonry structure by using DDA. Alternatively, the seismic loadings also can be applied to the base block [146, 147], which is different from the original DDA. Later, [173, 174, 175, 177] applied DDA to simulate the kinematic behavior of sliding rock blocks in the Tsaoling landslide and the Chiu-fen-erh-shan landslide induced by the 1999 Chi-Chi earthquake. Recently, [184] applied newest DDA program to simulate the largest landslides induced by the 2008 Wenchuan earthquake.

4. Comparisons of various methods

The studies in the field of the earthquake-induced landslides are generally reviewed. Two parts of contents, i) seismic stability analysis and ii) run-out analysis are reviewed and compared. Some conclusions can be drawn:

1. Three categories methods can be used to analyse the seismic stability of a slope. Each of these types of methods has strengths and weaknesses and each can be appropriately applied in different situations. In detail, pseudo-static methods can simply and directly determine the FOS and the critical coefficient k_c of a slope, while the widely used Newmark's methods and its extensions can determine the co-seismic deformation of a slope. And the Newmark's methods can be used to estimate where earthquake-induced landslides are likely to occur and what kind of shaking conditions will trigger them based on the GIS technology. More sophisticated analysis for real dynamic process of a seismic slope should be carried out by stress-strain methods, including both continuous methods and discontinuous methods.
2. Four kinds of methods can be used to analyse the run-out of a landslide. In detail, experiment method can provide the qualitative and quantitative observations on the obtained results although this method is difficult, dangerous, expensive and of limited utility. Empirical method can be directly used for assessing landslide travel distance and velocity based on historical data and on the analysis of the relationship between parameters characterizing both landslide and the path. Analytical method can be more directly used without the need of statistically-significant database of previous events. Numerical simulation method can be used to provide more information for the landslide composed by the complex continuum deformable mass or multi-blocks.

5. A case study: The Daguangbao landslide [185, 186]

5.1. Background

The Daguangbao landslide is located in the hanging wall only 6.5 km away from the Yingxiu-Beichuan fault. It is a typical bedding landslide.

Figure 8 gives a pre- and post-earthquake 3-D topographies, from which cross-section of the Daguangbao landslide can be obtained (Figure 9). The extent of the damage caused by the Daguangbao landslide is reflected in the following statistics [61]:

1. The affected area covered 7.3~10 km²;
2. The accumulation body width is 2.2 km;
3. Estimated volume of collapsed rock mass is 750~840 million m³;
4. The failure zone is more than 1 km;
5. The failure mass moved about 4.5 km;
6. Formed a 600m high landslide dam.

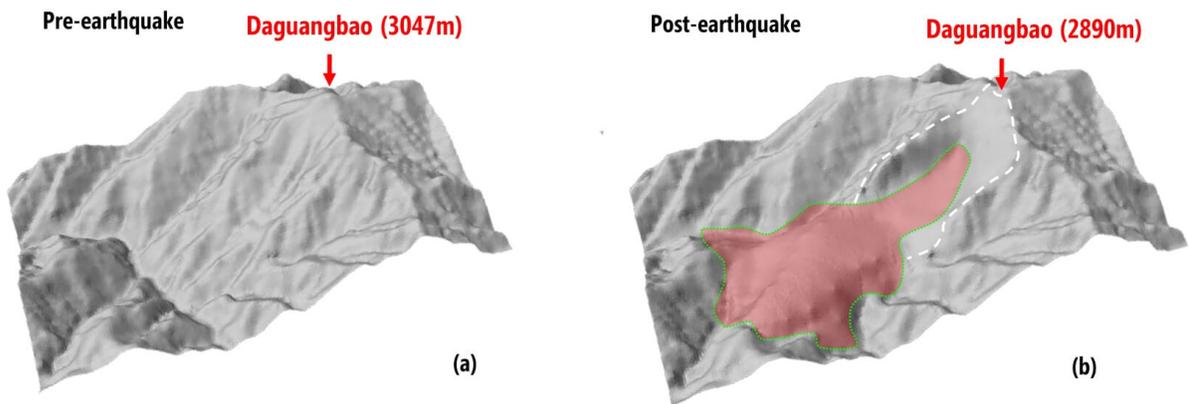


Figure 8. Pre- and post-earthquake 3-D topographies of the Daguangbao landslide

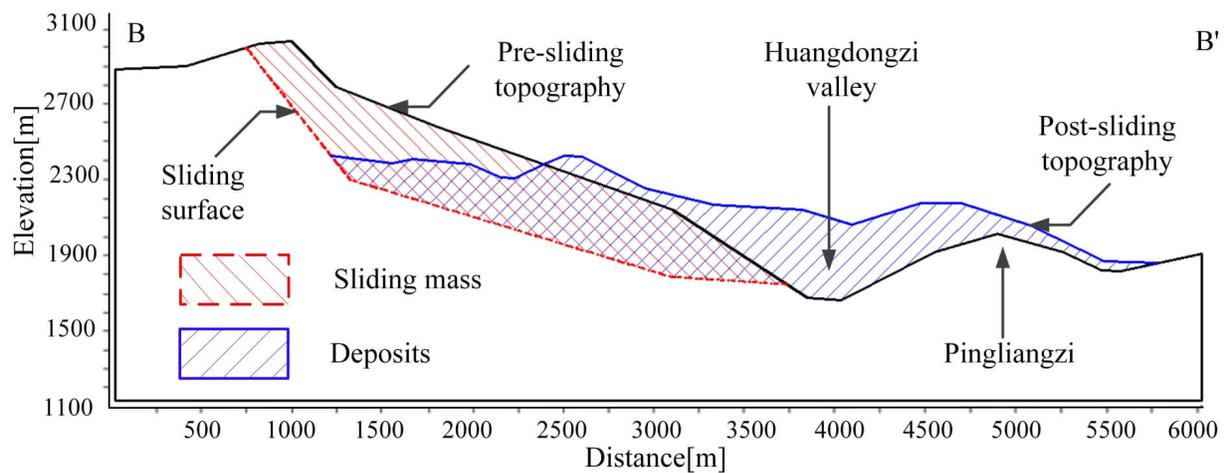


Figure 9. Cross-section of the Daguangbao landslide before and after the Wenchuan earthquake.

5.2. Material properties and ground motion

5.2.1. Material properties

The Daguangbao landslide is so huge that the size effect must be considered. To account for this discrepancy, experience equations based on Hoek-Brown failure criterion, which size effect can be considered, is used to back calculate the material strength. Table 1 lists the material properties of the Daguangbao landslide.

| | Material 1 | Material 2 | Material 3 | |
|---|------------|------------|--------------------|--------|
| | | | FLAC ^{3D} | DDA |
| Density (ρ): g/cm ³ | 2.5 | 2.6 | 2.6 | 260000 |
| Unit weight of rock (γ): kN/m ³ | 25 | 26 | 26 | 0 |
| Elastic modulus (E): Gpa | 1.86 | 2.63 | 14.76 | |
| Poisson's ratio (ν) | 0.2 | 0.2 | 0.1 | |
| Friction angle of discontinuities (φ): ° | 10.8 | 12.18 | 23.53 | |
| Cohesion of discontinuities (c): Mpa | 1.276 | 1.576 | 4.052 | |
| Tensile strength of discontinuities (σ_t): kPa | 12 | 32 | 556 | |

Table 1. Material properties of the Daguangbao landslide in FLAC^{3D} and DDA

5.2.2. Ground motion

The horizontal earthquake wave is the projection combination in the main sliding direction (N60°E) use the MZQP acceleration records in E-W and N-S directions as Equation (5). The inputted vertical earthquake wave is the MZQP acceleration records in U-D direction.

$$a_H = a_{E-W} \cdot \sin 60^\circ + a_{N-S} \cdot \cos 60^\circ \quad (5)$$

Figure 10 shows the input combined acceleration records. Velocity and displacement time histories can be obtained by first and second integration from acceleration record. The duration of earthquake wave is 60s.

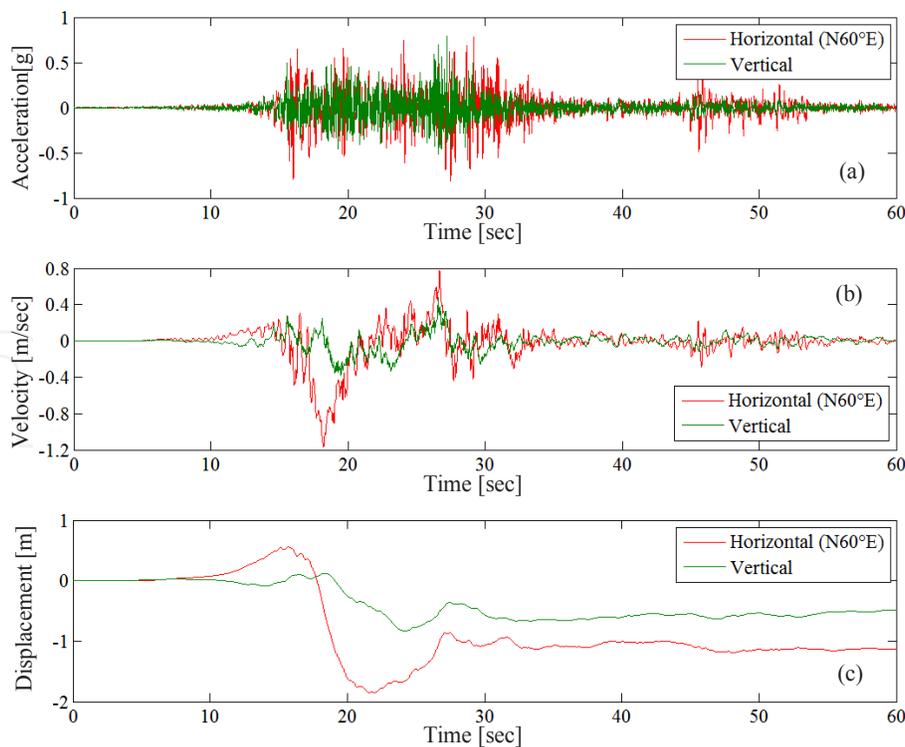


Figure 10. Input post-corrected horizontal and vertical ground records projected to N60°E direction

5.3. Numerical simulations-Run-out analysis

Seismic DDA can successfully simulate the movement of earthquake induced landslide. Two main features determine the Daguangbao landslide is a unique case, one is near-fault location (≈ 6.5 km) and the other one is huge scale ($\approx 800 \times 10^6$ m³). The near-fault location determines the Daguangbao landslide must be shocked by the extreme ground motion from the strong Wenchuan earthquake. And the Daguangbao landslide located on the meizoseismal area where the vertical seismic component is very large. In addition, the landslide is so huge that the size effects must be considered. The friction coefficient measured in the laboratory is no longer suitable for stability and run-out analysis.

To these two features, the Daguangbao landslide is simulated by the newest seismic DDA code in which multi-direction seismic forces can be applied in the base block directly, and experience equations based on Hoek-Brown failure criterion is applied to back-calculate the material strength by trying to consider the size effect.

| Parameter | Value |
|--|------------------------|
| Assumed maximum displacement ratio (g_2) | 0.001 |
| Total number of time steps | 20,000 |
| Time step (g_1) | 0.005s |
| Contact spring stiffness (g_0) | 5.0×10^8 kN/m |
| Factor of over-relaxation | 1.3 |

Table 2. Control parameters for DDA

5.3.1. Geometry of sliding blocks

The main sliding direction of the Daguangbao landslide, N60°E, is selected as analysis profile. The DDA model is depicted in Figure 11. In this simulation, based on the shape of failure surface and the character of slope topography, the whole slope is divided into three parts: base block, upper sliding mass, and lower sliding mass. Then two sliding masses are divided into the smaller discrete deformable blocks based on pre-existing discontinuities.

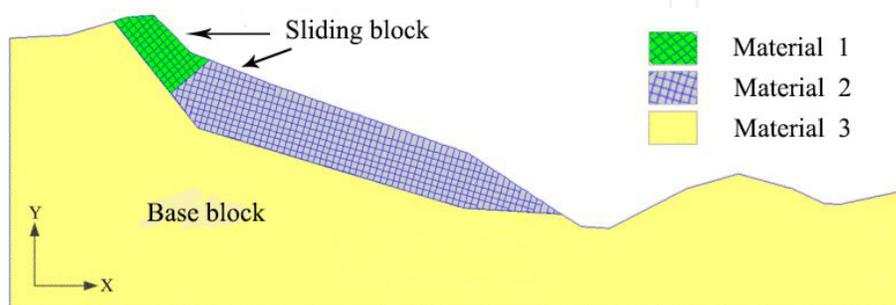


Figure 11. DDA model of the Daguangbao landslide

5.3.2. Results

Figure 15 shows the post-failure behavior of the Daguangbao landslide simulated by the seismic DDA code. Simulated results show that the sliding blocks climb over the Pingliangzi. After overlapping the final step of DDA calculation with the topographic cross-section at the Daguangbao landslide, the deposit pattern of the simulated Daguangbao landslide under horizontal-and-vertical situation coincides well with local topography.

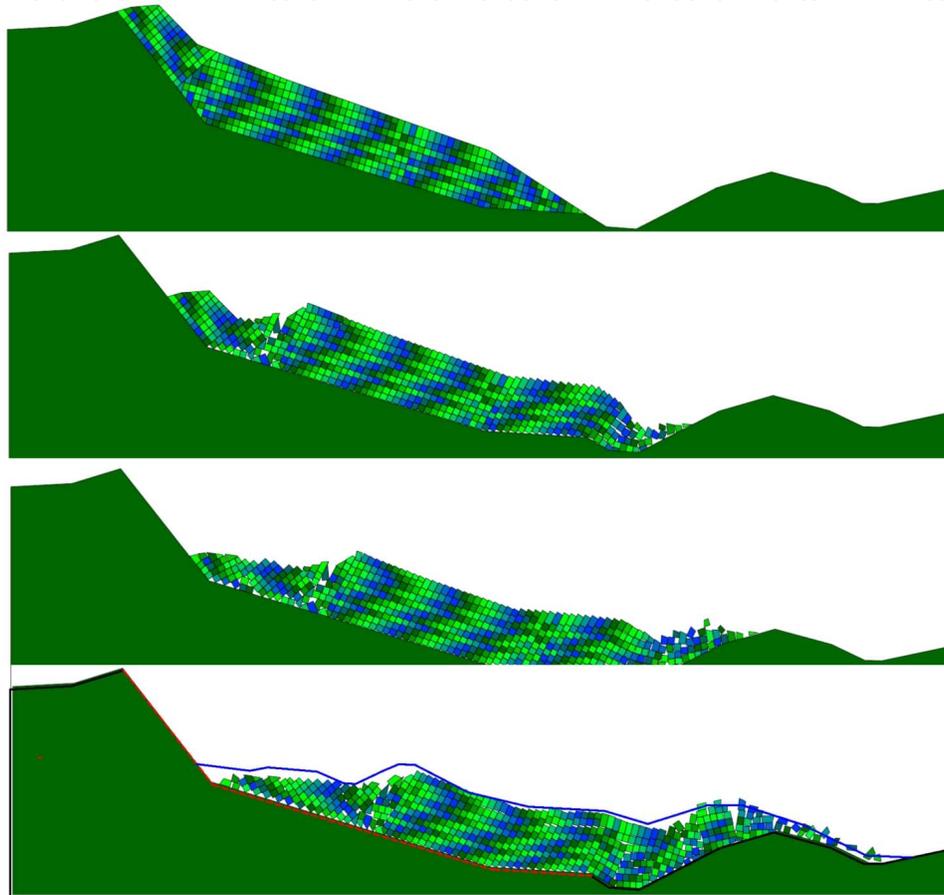


Figure 12. Simulation results of the Daguangbao landslide

6. Conclusions

Five cases are performed using finite difference program $FLAC^{3D}$, under the real seismic waves near the study site. The results show that the seismic conditions cause a significant reduction in factor of safety than static situation. It also found that the vertical seismic has a significant influence on tension failure of block, although it has an insignificant influence on change of the factor of safety. Another important conclusion is the effect of vertical seismic force on relative displacement of potential sliding mass is significant. In addition, large area of tension

failure caused by the combined seismic forces at back edge of the slope applies the evidence of effect of vertical seismic force on failure mechanism of slope stability.

A comparison of simulation results from three situations, static, only-horizontal and horizontal-and-vertical, is carried out. Seismic force has a significant influence on the arrival distance, and shape of post-failure. Arrival distance from horizontal-and-vertical situation is larger than that from only-horizontal situation. In addition, the deposit pattern of the simulated Dag-uangbao landslide under horizontal-and-vertical situation coincides well with local topography. The vertical seismic force should be considered for landslide assessment and management, especially in the situation that the studied site located on the meizoseismal area during the earthquake.

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References

- [1] Ambraseys, N., and Sarma, S. 1967. The response of earth dams to strong earthquakes. *Geotechnique*, 17(3): 181-213.
- [2] Ambraseys, N., and Menu, J. 1988. Earthquake-induced ground displacements. *Earthquake Engineering & Structural Dynamics*, 16(7): 985-1006.
- [3] Ambraseys, N., and Srbulov, M. 1994. Attenuation of earthquake-induced ground displacements. *Earthquake Engineering & Structural Dynamics*, 23(5): 467-487.

- [4] Anderson, D., and Kavazanjian Jr, E. 1995. Performance of landfills under seismic loading. In Proc., 3rd Int. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics. Univ. of Missouri Rolla, MO, Vol.3, pp. 277-306.
- [5] Army, U.C.o.E. 1960. Stability of Earth and Rockfill Dams, EM 1110-2-1902.
- [6] Azzoni, A., La Barbera, G., and Zaninetti, A. 1995. Analysis and prediction of rock-falls using a mathematical model. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. Elsevier, Vol.32, pp. 709-724.
- [7] Bakun-Mazor, D., Hatzor, Y., and Glaser, S. 2012. Dynamic sliding of tetrahedral wedge: The role of interface friction. International Journal for Numerical and Analytical Methods in Geomechanics, 36(3): 327-343.
- [8] Bhasin R, Kaynia AM. 2004. Static and dynamic simulation of a 700-m high rock slope in western Norway. Engineering Geology, 71(3-4): 213-226.
- [9] Bozzolo, D., and Pamini, R. 1986. Simulation of rock falls down a valley side. Acta Mechanica, 63(1-4): 113-130.
- [10] Bray, J.D., and Rathje, E.M. 1998. Earthquake-induced displacements of solid-waste landfills. Journal of Geotechnical and Geoenvironmental Engineering, 124(3): 242-253.
- [11] Bray, J.D., and Travasarou, T. 2007. Simplified procedure for estimating earthquake-induced deviatoric slope displacements. Journal of Geotechnical and Geoenvironmental Engineering, 133(4): 381-392.
- [12] Brebbia, C.A., and Wrobel, L. 1980. The boundary element method. Computer methods in fluids.(A 81-28303 11-34) London, Pentech Press, Ltd., 1980: 26-48.
- [13] Cannon, S.H. 1993. An empirical model for the volume-change behavior of debris flows. In Hydraulic Engineering '93, San Francisco.
- [14] CDCDMG:California Department of Conversation, Division of Mines and Geology, 1997. Guidelines for evaluating and mitigating seismic hazards in California. CDMG Special Publication.
- [15] Chang, K.-T., Lin, M.-L., Dong, J.-J., and Chien, C.-H. 2011. The Hungtsaiping landslides: from ancient to recent. Landslides, 9(2): 205-214.
- [16] Chen, L., and Zhao, W. 1979. Longling earthquake, 1976. Earthquake press, Beijing.
- [17] Chen, G., and Ohnishi, Y. 1999. Slope stability analysis using Discontinuous Deformation Analysis method. Rock Mecganics for Industry: 535-541.
- [18] Chen, H., and Lee, C. 2000. Numerical simulation of debris flows. Canadian Geotechnical Journal, 37(1): 146-160.
- [19] Cheng, Y.M. 1998. Advancements and improvement in discontinuous deformation analysis. Computers and Geotechnics, 22(2): 153-163.

- [20] Chopra, A.K. 1966. The importance of the vertical component of earthquake motions. *Bulletin of the Seismological Society of America*, 56(5): 1163-1175.
- [21] Clough, R.W. 1960. The finite element method in plane stress analysis. In 2nd Conference on Electronic Computation, Pittsburgh, PA.
- [22] Constantinou, M., and Gazetas, G. 1987. Probabilistic seismic sliding deformations of earth dams and slopes. In *Probabilistic Mechanics and Structural Reliability (1984)*. ASCE, pp. 318-321.
- [23] Copons, R., and Vilaplana, J.M. 2008. Rockfall susceptibility zoning at a large scale: From geomorphological inventory to preliminary land use planning. *Engineering Geology*, 102(3): 142-151.
- [24] Copons, R., Vilaplana, J.M., Corominas, J., Altimir, J., and Amigó, J. 2004. Rockfall Risk Management in High-Density Urban Areas. The Andorran Experience. *Landslide hazard and risk*: 675-698.
- [25] Corominas, J. 1996. The angle of reach as a mobility index for small and large landslides. *Canadian Geotechnical Journal*, 33(2): 260-271.
- [26] Costa, J.E. 1984. Physical geomorphology of debris flows. In *Developments and applications of geomorphology*. Springer. pp. 268-317.
- [27] Crosta, G., and Agliardi, F. 2003a. A methodology for physically based rockfall hazard assessment. *Natural Hazards and Earth System Science*, 3(5): 407-422.
- [28] Crosta, G., and Frattini, P. 2003b. Distributed modelling of shallow landslides triggered by intense rainfall. *Natural Hazards and Earth System Science*, 3(1/2): 81-93.
- [29] Crosta, G.B., Frattini, P., and Fusi, N. 2007. Fragmentation in the Val Pola rock avalanche, Italian Alps. *Journal of Geophysical Research: Earth Surface (2003–2012)*, 112(F1).
- [30] Crosta, G., Imposimato, S., Roddeman, D., Chiesa, S., and Moia, F. 2005. Small fast-moving flow-like landslides in volcanic deposits: the 2001 Las Colinas Landslide (El Salvador). *Engineering Geology*, 79(3): 185-214.
- [31] Cundall, P. 1971. A computer model for simulating progressive, large scale movements in blocky rock system. In *Symposium of International Society of Rock Mechanics*, Nancy, France, pp. 11–18.
- [32] Danay, A., and Adeghe, L. 1993. Seismic-induced slip of concrete gravity dams. *Journal of Structural Engineering*, 119(1): 108-129.
- [33] Davies, T.R. 1982. Spreading of rock avalanche debris by mechanical fluidization. *Rock Mechanics*, 15(1): 9-24.

- [34] Del Gaudio, V., Pierri, P., and Wasowski, J. 2003. An approach to time-probabilistic evaluation of seismically induced landslide hazard. *Bulletin of the Seismological Society of America*, 93(2): 557-569.
- [35] Denlinger, R.P., and Iverson, R.M. 2001. Flow of variably fluidized granular masses across three-dimensional terrain: 2. Numerical predictions and experimental tests. *Journal of Geophysical Research: Solid Earth (1978–2012)*, 106(B1): 553-566.
- [36] Descoedres, F., and Zimmermann, T. 1987. Three-dimensional dynamic calculation of rockfalls. In 6th ISRM Congress.
- [37] Doolin, D.M. 2005. Unified displacement boundary constraint formulation for discontinuous deformation analysis (DDA). *International Journal for Numerical and Analytical Methods in Geomechanics*, 29(12): 1199-1207.
- [38] Doolin, D.M., and Sitar, N. 2004. Time Integration in Discontinuous Deformation Analysis. *Journal of Engineering Mechanics*, 130(3): 249-258.
- [39] Dorren, L.K. 2003. A review of rockfall mechanics and modelling approaches. *Progress in Physical Geography*, 27(1): 69-87.
- [40] Dorren, L., and Heuvelink, G.B. 2004. Effect of support size on the accuracy of a distributed rockfall model. *International Journal of Geographical Information Science*, 18(6): 595-609.
- [41] Dreyfus, D., Rathje, E.M., and Jibson, R.W. 2013. The Influence of Different Simplified Sliding-Block Models and Input Parameters on Regional Predictions of Seismic Landslides Triggered by the Northridge Earthquake. *Engineering Geology*.
- [42] Elgamal, A.-W.M., Scott, R.F., Succarieh, M.F., and Yan, L. 1990. La Villita dam response during five earthquakes including permanent deformation. *Journal of Geotechnical Engineering*, 116(10): 1443-1462.
- [43] Evans, S., and Hungr, O. 1993. The assessment of rockfall hazard at the base of talus slopes. *Canadian Geotechnical Journal*, 30(4): 620-636.
- [44] Evans, S., Hungr, O., and Enegren, E. 1994. The Avalanche Lake rock avalanche, Mackenzie mountains, northwest territories, Canada: description, dating, and dynamics. *Canadian Geotechnical Journal*, 31(5): 749-768.
- [45] Fardis, M.N. 2009. *Seismic design, assessment and retrofitting of concrete buildings: based on EN-Eurocode 8*. Springer.
- [46] Favreau, P., Mangeney, A., Lucas, A., Crosta, G., and Bouchut, F. 2010. Numerical modeling of landquakes. *Geophysical Research Letters*, 37(15): L15305.
- [47] Fenves, G., and Chopra, A.K. 1986. *Simplified analysis for earthquake resistant design of concrete gravity dams*. Earthquake Engineering Research Center, University of California.

- [48] Franklin, A.G., and Chang, F.K. 1977. Permanent displacements of earth embankments by Newmark sliding block analysis.
- [49] Gazetas, G., and Uddin, N. 1994. Permanent deformation on preexisting sliding surfaces in dams. *Journal of Geotechnical Engineering*, 120(11): 2041-2061.
- [50] Griffiths, D., and Prevost, J.H. 1988. Two-and three-dimensional dynamic finite element analyses of the Long Valley Dam. *Geotechnique*, 38(3): 367-388.
- [51] Guzzetti, F., Malamud, B.D., Turcotte, D.L., and Reichenbach, P. 2002. Power-law correlations of landslide areas in central Italy. *Earth and Planetary Science Letters*, 195(3): 169-183.
- [52] Hamajima, R., Kawai, T., Yamashita, K., and Kusabuka, M. 1985. Numerical analysis of cracked and jointed rock mass. In the 5th International Conference on Numerical Methods in Geomechanics, Nagoya, Japan, pp. 207-214.
- [53] Harp, E.L., and Jibson, R.W. 1995. Inventory of landslides triggered by the 1994 Northridge, California earthquake. US Geological Survey.
- [54] Hatzor, Y.H. 2003. Fully Dynamic Stability Analysis of Jointed Rock Slopes. In Proceedings of the 10th ISRM Congress, pp. 503-514.
- [55] Hatzor, Y.H., and Feintuch, A. 2001. The validity of dynamic block displacement prediction using DDA. *International Journal of Rock Mechanics & Mining Sciences*.
- [56] Hatzor, Y.H., Arzi, A.A., and Tsesarsky, M. 2002. Realistic dynamic analysis of jointed rock slopes using DDA. In 5th Int. Conf. on Analysis of Discontinuous Deformation - Stability of rock structures, Abingdon, Balkema, Rotterdam, The Netherlands, pp. 47-56.
- [57] Hatzor, Y., Arzi, A.A., Zaslavsky, Y., and Shapira, A. 2004. Dynamic stability analysis of jointed rock slopes using the DDA method: King Herod's Palace, Masada, Israel. *International Journal of Rock Mechanics and Mining Sciences*, 41(5): 813-832.
- [58] Heim, A. 1932. *Bergsturz und Menschenleben*, Zurich: Fretz and Wasmuth Verlag.
- [59] Hsieh, S.-Y., and Lee, C.-T. 2011. Empirical estimation of the Newmark displacement from the Arias intensity and critical acceleration. *Engineering Geology*, 122(1-2): 34-42.
- [60] Hsü, K.J. 1975. Catastrophic debris streams (sturzstroms) generated by rockfalls. *Geological Society of America Bulletin*, 86(1): 129-140.
- [61] Huang, R., Pei, X., Fan, X., Zhang, W., Li, S., and Li, B. 2012. The characteristics and failure mechanism of the largest landslide triggered by the Wenchuan earthquake, May 12, 2008, China. *Landslides*, 9(1): 131-142.
- [62] Hungr, O. 1995. A model for the runout analysis of rapid flow slides, debris flows, and avalanches. *Canadian Geotechnical Journal*, 32(4): 610-623.

- [63] Hungr, O., and Evans, S. 1988. Engineering evaluation of fragmental rockfall hazards. In Proceedings of the Fifth International Symposium on Landslides, Lausanne, AA Balkema, Rotterdam, Netherlands, pp. 685-690.
- [64] Hungr, O., and Evans, S. 2004. Entrainment of debris in rock avalanches: An analysis of a long run-out mechanism. *Geological Society of America Bulletin*, 116(9-10): 1240-1252.
- [65] Hungr, O., Corominas, J., and Eberhardt, E. 2004. Estimating landslide motion mechanism, travel distance and velocity.
- [66] Hürlimann, M., Rickenmann, D., Medina, V., and Bateman, A. 2008. Evaluation of approaches to calculate debris-flow parameters for hazard assessment. *Engineering Geology*, 102(3): 152-163.
- [67] Hynes-Griffin, M.E., and Franklin, A.G. 1984. Rationalizing the seismic coefficient method. Defense Technical Information Center.
- [68] Ishikawa, T., Sekine, E., and Ohnishi, Y. 2002. Shaking table tests of coarse granular materials with discontinuous analysis. Proc. of ICADD-5, BALKEMA: 181-187.
- [69] Jakob, M., and Hungr, O. 2005. Debris-flow hazards and related phenomena. Springer.
- [70] Jibson, R.W. 1993. Predicting earthquake-induced landslide displacements using Newmark's sliding block analysis. *Transportation Research Record*: 9-9.
- [71] Jibson, R. 2000. A method for producing digital probabilistic seismic landslide hazard maps. *Engineering Geology*.
- [72] Jibson, R.W. 2007. Regression models for estimating coseismic landslide displacement. *Engineering Geology*, 91(2-4): 209-218.
- [73] Jibson, R.W. 2011. Methods for assessing the stability of slopes during earthquakes—A retrospective. *Engineering Geology*, 122(1-2): 43-50.
- [74] Jibson, R.W., and Jibson, M.W. 2003. Java programs for using Newmark's method and simplified decoupled analysis to model slope performance during earthquakes. US Department of the Interior, US Geological Survey.
- [75] Jibson, R.W., Harp, E.L., and Michael, J.A. 1998. A Method for Producing Digital Probabilistic Seismic Landslide Hazard Maps: An Example from the Los Angeles, California, Area.
- [76] Kavazanjian, E., and Consultants, G. 1997. Design Guidance: Geotechnical Earthquake Engineering for Highways. Design Principles. Federal Highway Administration.

- [77] Kawai, T. 1977. A new discrete analysis of nonlinear solid mechanics problems involving stability, plasticity and crack. In the Symposium on Applications of Computer Methods in Engineering, Los Angeles, USA, pp. 1029-1038.
- [78] Kawai, T. 1978. New discrete models and their application to seismic response analysis of structures. *Nuclear Engineering and Design*, 48(1): 207-229.
- [79] Kawai, T., Takeuchi, N., and Kumeta, T. 1981. New discrete models and their application to rock mechanics. In ISRM International Symposium.
- [80] Kawai, T., Kawabata, Y., Kumagai, K., and Kondou, K. 1978. A new discrete model for analysis of solid mechanics problems. *Numerical methods in fracture mechanics*: 26-37.
- [81] Ke, T.C. 1996. The issues of rigid-body rotation in DDA. In First international forum on discontinuous deformation analysis (DDA) and simulations of discontinuous media, Berkeley, USA, pp. 318-325.
- [82] Keefer, D.K. 2000. Statistical analysis of an earthquake-induced landslide distribution –the 1989 Loma Prieta, California event. *Engineering Geology*, 58(3): 231-249.
- [83] Kirby, M.J., and Statham, I. 1975. Surface stone movement and screen formation. *Journal of Geology*, 83(3): 349-362.
- [84] Kobayashi, Y., Harp, E., and Kagawa, T. 1990. Simulation of rockfalls triggered by earthquakes. *Rock Mechanics and Rock Engineering*, 23(1): 1-20.
- [85] Komodromos, P., Papaloizou, L., and Polycarpou, P. 2008. Simulation of the response of ancient columns under harmonic and earthquake excitations. *Engineering Structures*, 30(8): 2154-2164.
- [86] Kong, X., and Liu, J. 2002. Dynamic failure numeric simulations of model concrete-faced rock-fill dam. *Soil Dynamics and Earthquake Engineering* 22(9–12): 1131–1134.
- [87] Koo, C.Y., and Chern, J.C. 1998. Modification of the DDA method for rigid block problems. *International Journal of Rock Mechanics & Mining Sciences*, 35: 683-693.
- [88] Kostaschuk, R. 1987. Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. *Debris flows/avalanches: process, recognition, and mitigation*, 7: 115.
- [89] Kramer, S.L. 1996. *Geotechnical earthquake engineering*. Prentice-Hall Civil Engineering and Engineering Mechanics Series, Upper Saddle River, NJ: Prentice Hall, 1996, 1.
- [90] Kramer, S.L., and Smith, M.W. 1997. Modified Newmark model for seismic displacements of compliant slopes. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(7): 635-644.

- [91] Krinitzsky, E.L. 1993. *Fundamentals of earthquake-resistant construction*. Wiley.com.
- [92] Lan, H., Derek Martin, C., and Lim, C. 2007. RockFall analyst: A GIS extension for three-dimensional and spatially distributed rockfall hazard modeling. *Computers & Geosciences*, 33(2): 262-279.
- [93] Latha, G.M., and Garaga, A. 2010. Seismic Stability Analysis of a Himalayan Rock Slope. *Rock Mechanics and Rock Engineering*, 43(6): 831-843.
- [94] Lee, K.L. 1974. *Seismic permanent deformation in earth dams*, University of California, Los Angeles, CA.
- [95] Leger, P., and Katsouli, M. 1989. Seismic stability of concrete gravity dams. *Earthquake Engineering & Structural Dynamics*, 18(6): 889-902.
- [96] Li, T. 1983. A mathematical model for predicting the extent of a major rockfall. *Zeitschrift Fur Geomorphologie*, 24: 473-482.
- [97] Lin, J.S., and Whitman, R.V. 1983. Decoupling approximation to the evaluation of earthquake-induced plastic slip in earth dams. *Earthquake Engineering & Structural Dynamics*, 11(5): 667-678.
- [98] Lin, C.T., Amadei, B., Jung, J., and Dwyer, J. 1996. Extensions of discontinuous deformation analysis for jointed rock masses. *international Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 33(7): 671-694.
- [99] Ling, H.I. 2001. Recent applications of sliding block theory to geotechnical design. *Soil Dynamics and Earthquake Engineering*, 21: 189-197.
- [100] Ling, H., and Leshchinsky, D. 1998. Effects of vertical acceleration on seismic design of geosynthetic-reinforced soil structures. *Geotechnique*, 48(3): 347-373.
- [101] Lomnitz, C. 1970. Casualties and behavior of populations during earthquakes. *Bulletin of the Seismological Society of America*, 60(4): 1309-1313.
- [102] Luan, M., Li, Y., and Yang, Q. 2000. Discontinuous deformation computational mechanics model and its application in stability analysis of rock slope. *Chinese Journal of Rock Mechanics and Engineering*, 3: 006.
- [103] Makdisi, F.I., and Seed, H.B. 1977. Simplified procedure for estimating dam and embankment earthquake-induced deformations. In ASAE Publication No. 4-77. *Proceedings of the National Symposium on Soil Erosion and Sediment by Water*, Chicago, Illinois, December 12-13, 1977.
- [104] Makdisi, F.I., and Seed, H.B. 1978. Simplified procedure for estimating dam and embankment earthquake-induced failures. *Journal of the Geotechnical Division, ASCE*, 104: 849-861.

- [105] Makris, N., and Roussos, Y. 2000. Rocking response of rigid blocks under near-source ground motions. *Geotechnique*, 50(3): 243-262.
- [106] Mankelow, J.M., and MURPHY, W. 1998. Using GIS in the probabilistic assessment of earthquake triggered landslide hazards. *Journal of Earthquake Engineering*, 2(4): 593-623.
- [107] Marcuson, W. 1981. Moderator's report for session on Earth Dams and Stability of Slopes under Dynamic Loads. In *Proceedings, International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Vol.3*, p. 1175.
- [108] Marcuson III, W.F., and Franklin, A.G. 1983. *Seismic Design, Analysis, and Remedial Measures to Improve Stability of Existing Earth Dams*, DTIC Document.
- [109] Masuya, H., Amanuma, K., Nishikawa, Y., and Tsuji, T. 2009. Basic rockfall simulation with consideration of vegetation and application to protection measure. *Natural Hazards and Earth System Science*, 9(6): 1835-1843.
- [110] McDougall, S. 2006. A new continuum dynamic model for the analysis of extremely rapid landslide motion across complex 3D terrain, University of British Columbia.
- [111] McDougall, D. 2006. The distributed criterion design. *Journal of Behavioral Education*, 15(4): 236-246.
- [112] McDougall, S., and Hungr, O. 2004. A model for the analysis of rapid landslide motion across three-dimensional terrain. *Canadian Geotechnical Journal*, 41(6): 1084-1097.
- [113] Meunier, P., Hovius, N., and Haines, A.J. 2007. Regional patterns of earthquake-triggered landslides and their relation to ground motion. *Geophysical Research Letters*, 34(20).
- [114] Miles, S.B., and Ho, C.L. 1999. Applications and issues of GIS as tool for civil engineering modeling. *Journal of Computing in Civil Engineering*, 13(3): 144-152.
- [115] Miles, S.B., and Keefer, D.K. 2000. Evaluation of seismic slope-performance models using a regional case study. *Environmental & Engineering Geoscience*, 6(1): 25-39.
- [116] Mitchell, A.R., and Griffiths, D.F. 1980. *The finite difference method in partial differential equations*(Book). Chichester, Sussex, England and New York, Wiley-Interscience, 1980. 281 p.
- [117] Moretti, L., Mangeney, A., Capdeville, Y., Stutzmann, E., Christian Huggel, C., Schneider, D., and Francois Bouchut, F. 2012. Numerical modeling of the Mount Steller landslide flow history and of the generated long period seismic waves. *Geophys. Res. Lett.*, 39(L16402).
- [118] Moriwaki, H., Yazaki, S., and Oyagi, N. 1985. A gigantic debris avalanche and its dynamics at Mount Ontake caused by the Nagano-ken-seibu earthquake, 1984. In *Proc. 4th Int. Conf. Field Workshop on Landslides*, pp. 359-364.

- [119] Newmark, N.M. 1965. Effects of earthquakes on dams and embankments. *Géotechnique*, 15: 139-159.
- [120] Ning, Y., and Zhao, Z. 2012. A detailed investigation of block dynamic sliding by the discontinuous deformation analysis. *International Journal for Numerical and Analytical Methods in Geomechanics*: 1-21.
- [121] Niwa, K., Kawai, T., Ikeda, M., and Takeda, T. 1984. Application of a new discrete method to fracture analysis of brittle materials. In the 3rd International Conference on Numerical Methods in Fracture Mechanics, Swansea, U.K., pp. 13-27.
- [122] Ochiai, H., Okada, Y., Furuya, G., Okura, Y., Matsui, T., Sammori, T., Terajima, T., and Sassa, K. 2004. A fluidized landslide on a natural slope by artificial rainfall. *Landslides*, 1(3): 211-219.
- [123] Ohnishi, Y., Chen, G., and Miki, S. 1995. Recent development of DDA in rock mechanics. *Proc. ICADD*, 1: 26-47.
- [124] Okura, Y., Kitahara, H., and Sammori, T. 2000. Fluidization in dry landslides. *Engineering Geology*, 56(3): 347-360.
- [125] Okura, Y., Kitahara, H., Sammori, T., and Kawanami, A. 2000. The effects of rockfall volume on runout distance. *Engineering Geology*, 58(2): 109-124.
- [126] Okura, Y., Kitahara, H., Ochiai, H., Sammori, T., and Kawanami, A. 2002. Landslide fluidization process by flume experiments. *Engineering Geology*, 66(1): 65-78.
- [127] Pal, S., Kaynia, A.M., Bhasin, R.K., and Paul, D.K. 2011. Earthquake Stability Analysis of Rock Slopes: a Case Study. *Rock Mechanics and Rock Engineering*.
- [128] Papaloizou, L., and Komodromos, P. 2009. Planar investigation of the seismic response of ancient columns and colonnades with epistyles using a custom-made software. *Soil Dynamics and Earthquake Engineering*, 29(11-12): 1437-1454.
- [129] Papantonopoulos, C., Psycharis, I.N., Papastamatiou, D.Y., Lemos, J.V., and Mouzakis, H.P. 2002. Numerical prediction of the earthquake response of classical columns using the distinct element method. *Earthquake Engineering & Structural Dynamics*, 31(9): 1699-1717.
- [130] Pekau, O.A, and Yuzhu, C. 2004. Failure analysis of fractured dams during earthquakes by DEM. *Engineering Structures*, 26(10): 1483-1502.
- [131] Pekau, O.A, and Yuzhu, C. 2004. Seismic collapse behaviour of Damaged dams. In 13 WCEE: 13 th World Conference on Earthquake Engineering Conference Proceedings.
- [132] Pfeiffer, T.J., and Bowen, T. 1989. Computer simulation of rockfalls. *Bulletin of the Association of Engineering Geologists*, 26(1): 135-146.
- [133] Pirulli, M. 2005. Numerical modelling of landslide runout. A continuum mechanics approach, Politecnico di Torino.

- [134] Poisel, R., Preh, A., and Hungr, O. 2008. Run Out of Landslides—Continuum Mechanics versus Discontinuum Mechanics Models. *Geomechanics and Tunnelling*, 1(5): 358-366.
- [135] Prevost, J.H. 1981. DYNA-FLOW: a nonlinear transient finite element analysis program. Princeton University, Department of Civil Engineering, School of Engineering and Applied Science.
- [136] Psycharis, I., Lemos, J., Papastamatiou, D., Zambas, C., and Papantonopoulos, C. 2003. Numerical study of the seismic behaviour of a part of the Parthenon Pronaos. *Earthquake Engineering & Structural Dynamics*, 32(13): 2063-2084.
- [137] Pyke, R. 1991. Selection of Seismic Coefficients for Use in Pseudo-Static Slope Stability Analyses. http://www.tagasoft.com/Discussion/article2_html.
- [138] Rathje, E.M., and Bray, J.D. 1999. An examination of simplified earthquake-induced displacement procedures for earth structures. *Canadian Geotechnical Journal*, 36(1): 72-87.
- [139] Rathje, E.M., and Bray, J.D. 2000. Nonlinear coupled seismic sliding analysis of earth structures. *Journal of Geotechnical and Geoenvironmental Engineering*, 126(11): 1002-1014.
- [140] Richards, R., and Elms, D.G. 1979. Seismic behavior of gravity retaining walls. *Journal of the Geotechnical Engineering Division*, 105(4): 449-464.
- [141] Richards, J., Elms, D., and Budhu, M. 1993. Seismic bearing capacity and settlements of foundations. *Journal of Geotechnical Engineering*, 119(4): 662-674.
- [142] Rickenmann, D. 1999. Empirical relationships for debris flows. *Natural Hazards*, 19(1): 47-77.
- [143] Rodriguez, C.E., Bommer, J., and Chandler, R.J. 1999. Earthquake-induced landslides 1980-1997. *soil Dynamics and Earthquake Engineering*, 18: 325-346.
- [144] Sarma, S.K. 1975. Seismic stability of earth dams and embankments. *Geotechnique*, 25(4): 743-761.
- [145] Sarma, S.K. 1981. Seismic displacement analysis of earth dams. *Journal of the Geotechnical Engineering Division*, 107(12): 1735-1739.
- [146] Sasaki, T., Hagiwara, I., Sasaki, K., Ohnishi, Y., and Ito, H. 2007. Fundamental studies for dynamic response of simple block structures by DDA. In *In Proceedings of the eighth international conference on analysis of discontinuous deformation: fundamentals and applications to mining & civil engineering*, Beijing, China, pp. 141-146.
- [147] Sasaki, T., Hagiwara, I., Sasaki, K., Yoshinaka, R., Ohnishi, Y., and Nishiyama, S. 2004. Earthquake response analysis of rock-fall models by discontinuous deformation analysis. In *In Proceedings of the ISRM international symposium 3rd ARMS*, Kyoto, Japan, pp. 1267-1272.

- [148] Sassa, K. 1988. Motion of Landslides and Debris Flows: Prediction of Hazard Area: Report for Grant-in-aid for Scientific Research by Japanese Ministry on Education, Science and Culture (project No. 61480062). Disaster Prevention Research Institute.
- [149] Savage, S., and Hutter, K. 1989. The motion of a finite mass of granular material down a rough incline. *Journal of Fluid Mechanics*, 199(1): 177-215.
- [150] Sawada, T., Chen, W.F., and Nomachi, S.G. 1993. Assessment of seismic displacements of slopes. *Soil Dynamics and Earthquake Engineering*, 12: 357-362.
- [151] Saygili, G., and Rathje, E.M. 2009. Probabilistically based seismic landslide hazard maps: An application in Southern California. *Engineering Geology*, 109(3): 183-194.
- [152] Scheidegger, A.E. 1973. On the prediction of the reach and velocity of catastrophic landslides. *Rock Mechanics*, 5(4): 231-236.
- [153] Seed, H.B. 1973. Analysis of the Slides in the San Fernando Dams During the Earthquake of Feb. 9, 1971: Report to State of California Department of Water Resources, Los Angeles Department of Water and Power, National Science Foundation. College of Engineering, University of California.
- [154] Seed, H.B. 1979. Considerations in the earthquake-resistant design of earth and rock-fill dams. *Geotechnique*, 29(3): 13-41.
- [155] Seed, H.B., and Martin, G.R. 1966. The seismic coefficient in earth dam design. *Journal of Soil Mechanics & Foundations Div*, 92(Proc. Paper 4824).
- [156] Serff, N. 1976. Earthquake induced deformations of earth dams. College of Engineering, University of California.
- [157] Shi, G.-H. 1988. *Discontinuous Deformation Analysis A New Numerical Model for the Statics and Dynamics of Block Systems*, University of California, Berkeley.
- [158] Shi, G. 2002. Single and multiple block limit equilibrium of key block method and discontinuous deformation analysis. In *Proceedings of the 5th International Conference on Analysis of Discontinuous Deformation*. Rotterdam: AA Balkema, pp. 3-43.
- [159] Shi, G.-H., and Goodman, R.E. 1985. Two dimensional discontinuous deformation analysis. *International Journal for Numerical and Analytical Methods in Geomechanics*, 9: 541-556.
- [160] Shi, G.-H., and Goodman, R.E. 1989. Generalization of two-dimensional discontinuous deformation analysis for forward modelling. *International Journal for Numerical and Analytical Methods in Geomechanics*, 13: 359-380.
- [161] Sousa, J., and Voight, B. 1991. Continuum simulation of flow failures. *Geotechnique*, 41(4): 515-538.
- [162] Stamatopoulos, C. 1996. Sliding system predicting large permanent co-seismic movements of slopes. *Earthquake Engineering & Structural Dynamics*, 25(10): 1075-1093.

- [163] Stewart, J.P., Blake, T.F., and Hollingsworth, R.A. 2003. A Screen Analysis Procedure for Seismic Slope Stability. *Earthquake Spectra*, 19(3): 697.
- [164] Taiebat, M., Kaynia, A.M., and Dafalias, Y.F. 2011. Application of an Anisotropic Constitutive Model for Structured Clay to Seismic Slope Stability. *Journal of Geotechnical and Geoenvironmental Engineering*, 137(5): 492.
- [165] Takahashi, T., Momiyama, A., Hirai, K., Hishinuma, F., and Akagi, H. 1992. Functional correlation of fetal and adult forms of glycine receptors with developmental changes in inhibitory synaptic receptor channels. *Neuron*, 9(6): 1155-1161.
- [166] Terzaghi, K. 1950. *Theoretical Soil Mechanics*.
- [167] Tsesarsky, M., Hatzor, Y., and Sitar, N. 2005. Dynamic displacement of a block on an inclined plane: analytical, experimental and DDA results. *Rock Mechanics and Rock Engineering*, 38(2): 153-167.
- [168] Varnes, D.J., Landslides, t.I.A.E.G.C.o., and Slopes, O.M.M.o. 1984. *Landslide hazard zonation: a review of principles and practice*.
- [169] Wartman, J., Asce, M., Bray, J.D., and Seed, R.B. 2003. Inclined Plane Studies of the Newmark Sliding Block Procedure. *Journal of Geotechnical and Geoenvironmental Engineering*, 129(8): 673-684.
- [170] Wasowski, J., Keefer, D.K., and Lee, C.-T. 2011. Toward the next generation of research on earthquake-induced landslides: Current issues and future challenges. *Engineering Geology*, 122(1-2): 1-8.
- [171] Wilson, R.C., and Keefer, D.K. 1983. Dynamic analysis of a slope failure from the 6 August 1979 Coyote Lake, California, earthquake. *Bulletin of the Seismological Society of America*, 73(3): 863-877.
- [172] Wu, J.-H. 2003. *Numerical analysis of discontinuous rock masses using discontinuous deformation analysis*, Kyoto University, Kyoto, Japan.
- [173] Wu, J.-H. 2010. Seismic landslide simulations in discontinuous deformation analysis. *Computers and Geotechnics*, 37(5): 594-601.
- [174] Wu, J.-H., and Chen, C.-H. 2011a. Application of DDA to simulate characteristics of the Tsaoiling landslide. *Computers and Geotechnics*, 38(5): 741-750.
- [175] Wu, J.-H., and Tsai, P.-H. 2011b. New dynamic procedure for back-calculating the shear strength parameters of large landslides. *Engineering Geology*.
- [176] Wu, A., Ren, F., and Dong, X. 1997. A study on the numerical model of DDA and its preliminary application to rock engineering. *Chinese Journal of Rock Mechanics and Engineering*, 16(5): 411-417.

- [177] Wu, J., Lin, J., and Chen, C. 2009. Dynamic discrete analysis of an earthquake-induced large-scale landslide. *International Journal of Rock Mechanics and Mining Sciences*, 46(2): 397-407.
- [178] Yagoda-Biran, G., and Hatzor, Y.H. 2010. Constraining paleo PGA values by numerical analysis of overturned columns. *Earthquake Engineering & Structural Dynamics*, 39(4): 463-472.
- [179] Yegian, M.K. 1991a. Seismic risk analysis for earth dams. ASCE.
- [180] Yegian, M.K., Marciano, E.A., and Ghahraman, V.G. 1991b. Earthquake-induced permanent deformations: probabilistic approach. *Journal of Geotechnical Engineering*, 117(1): 35-50.
- [181] Yegian, M., Harb, J., and Kadakal, U. 1998. Dynamic response analysis procedure for landfills with geosynthetic liners. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(10): 1027-1033.
- [182] Zhang, C., Pekau, O.A., Jin, F., and Wang, G. 1997. Application of distinct element method in dynamic analysis of high rock slopes and blocky structures. *soil Dynamics and Earthquake Engineering*, 16: 385-394.
- [183] Zhang, Y., Chen, G., Zheng, L., Wu, J., and Zhuang, X. 2012a. Effects of vertical seismic force on the initiation of the Daguangbao landslide induced by the Wenchuan earthquake. In *The 8th Annual Conference of International Institute for Infrastructure, Renewal and Reconstruction*, Kumamoto, Japan, pp. 530-539.
- [184] Zhang, Y., Chen, G., Zheng, L., and Li, Y. 2012b. Numerical analysis of the largest landslide induced by the Wenchuan earthquake, May 12, 2008 using DDA. In *International Symposium on Earthquake-induced Landslides*, Kiryu, Japan.
- [185] Zhang, Y., G. Chen, L. Zheng, Y. Li and J. Wu. 2013. Effects of near-Fault Seismic Loadings on Run-out of Large-Scale Landslide: A Case Study. *Engineering Geology* 166, 216-236.
- [186] Zhang, Y., G. Chen, L. Zheng, Y. Li, X. Zhuang. 2014. Effects of vertical seismic force on initiation of the Daguangbao landslide induced by the 2008 Wenchuan earthquake, *Soil dynamics and earthquake engineering* (In press).
- [187] Zhao, S.L., Salami, M.R., and Rahman, M.S. 1997. Discontinuous Deformation Analysis Simulation of Rock Slope Failure. In *9th International Conference on Computer Methods and Advances in Geomechanics*, Wuhan, China
- [188] Zheng, L. 2010. Development of new models for landslide simulation based on discontinuous deformation analysis, *Kyushu University*, Fukuoka, Japan.