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Stability and Run-out Analysis of Earthquake-induced Landslides

Yingbin Zhang

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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

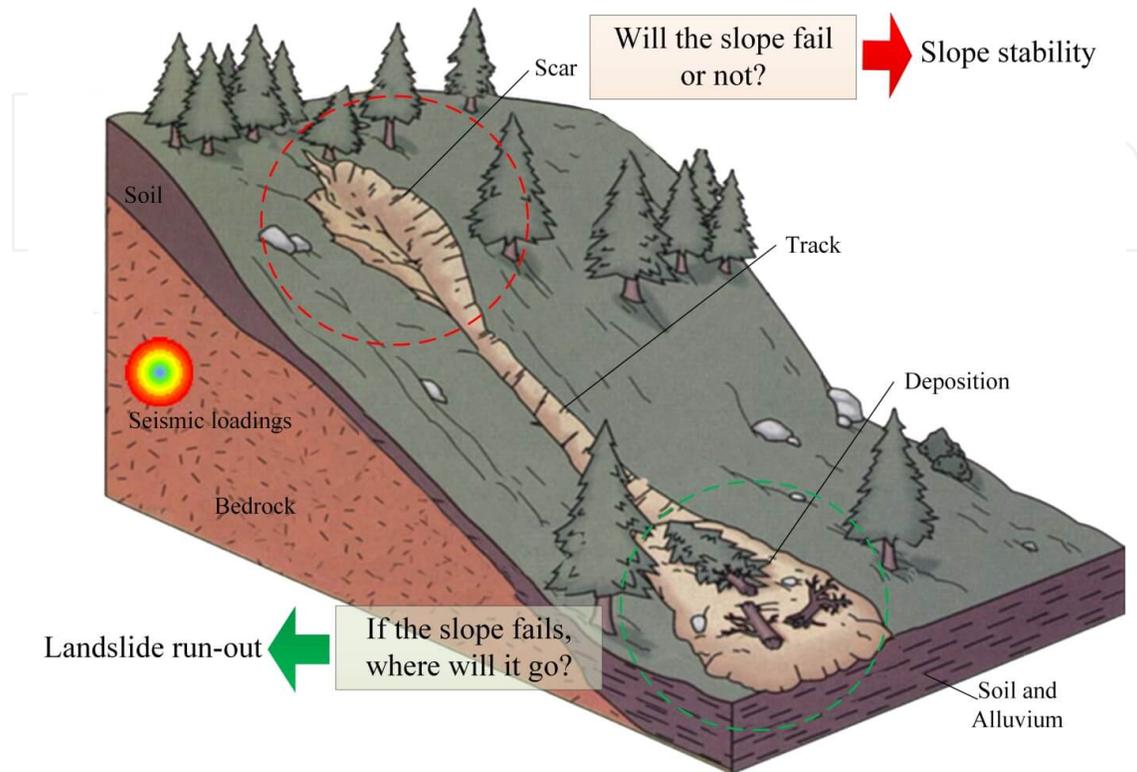


Figure 1. Stability and run-out analysis of earthquake-induced landslides

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).

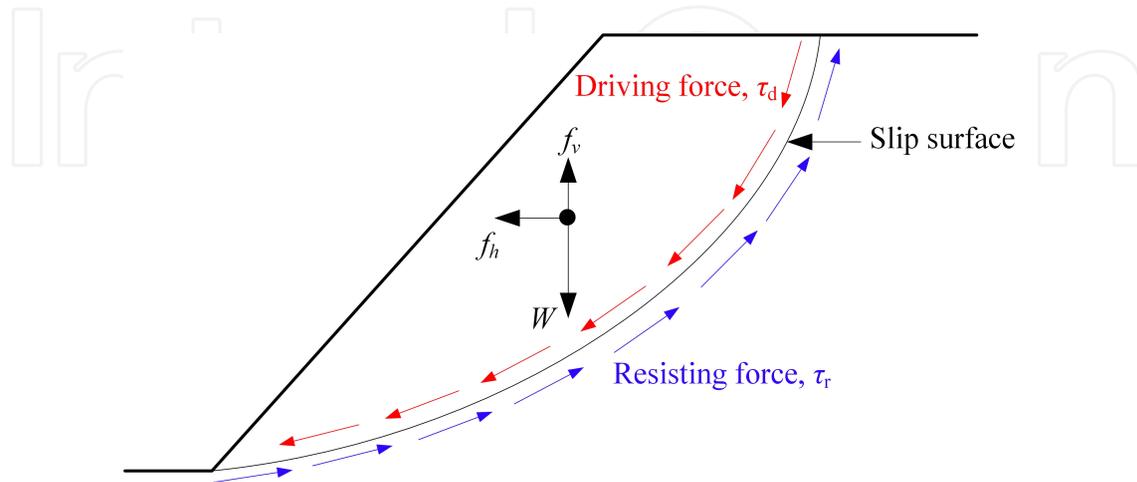


Figure 2. Forces acting on a slope in pseudo-static slope stability analysis

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 $0.75PGA_{\text{rock}}$). 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.

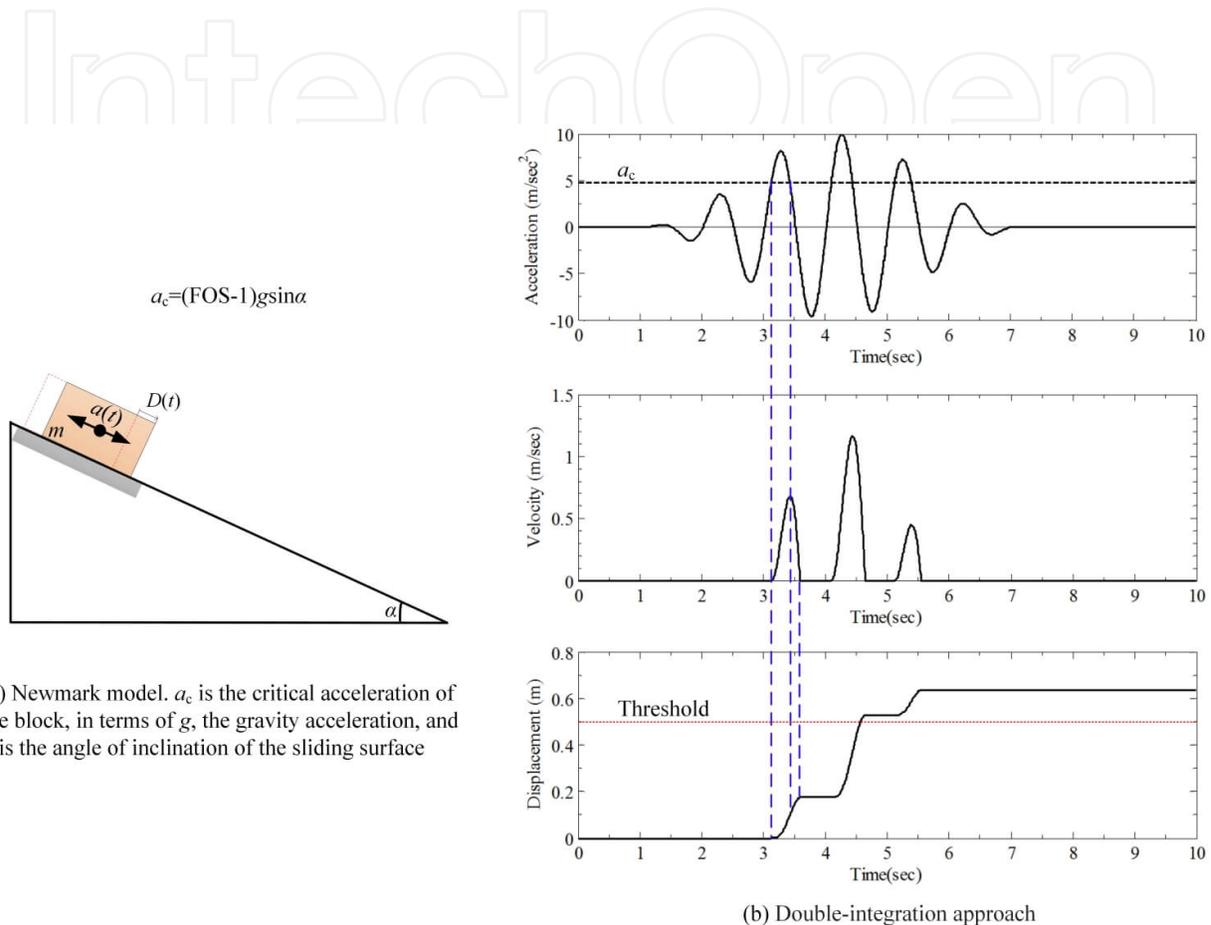


Figure 3. Illustration of the original Newmark's method

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].

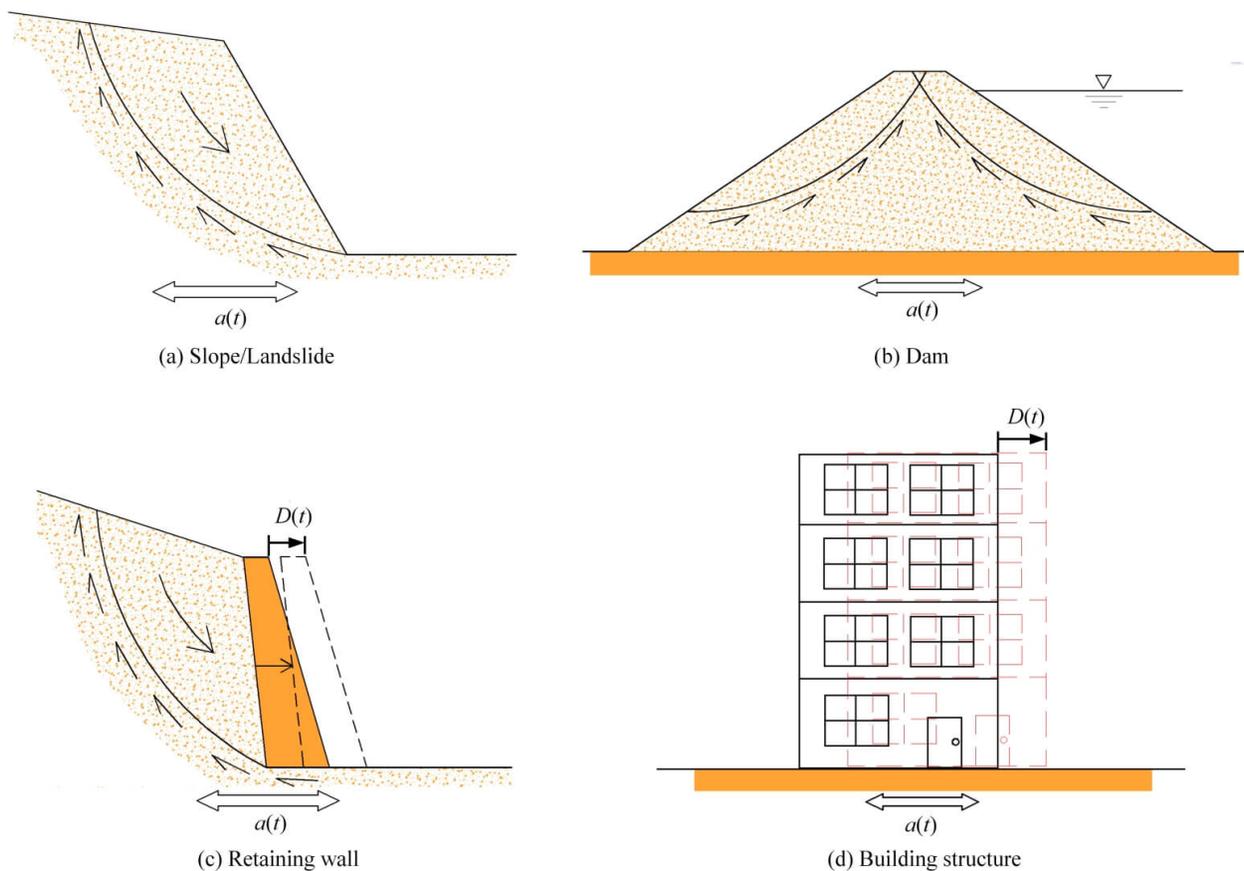


Figure 4. Applications of dynamic sliding block method in geotechnical engineering

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]).

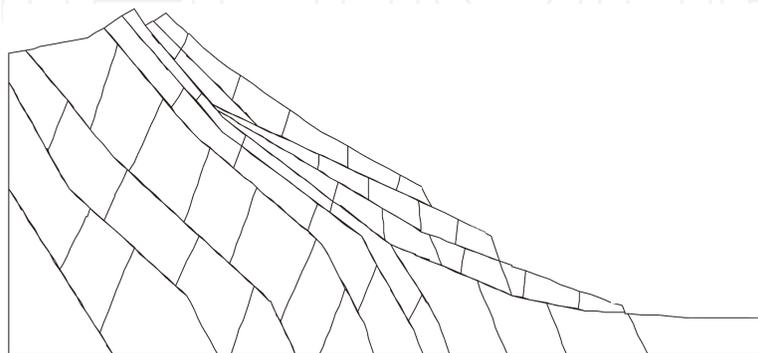


Figure 5. A jointed rock slope (modified from Bhasin and Kaynia, 2004)

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

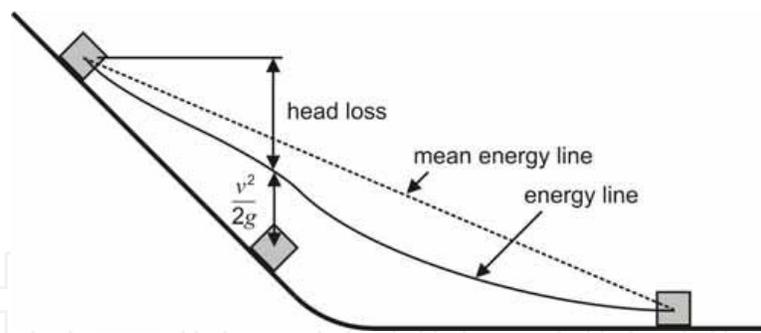


Figure 7. The classical sliding block model, based on work-energy theory [111]

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.

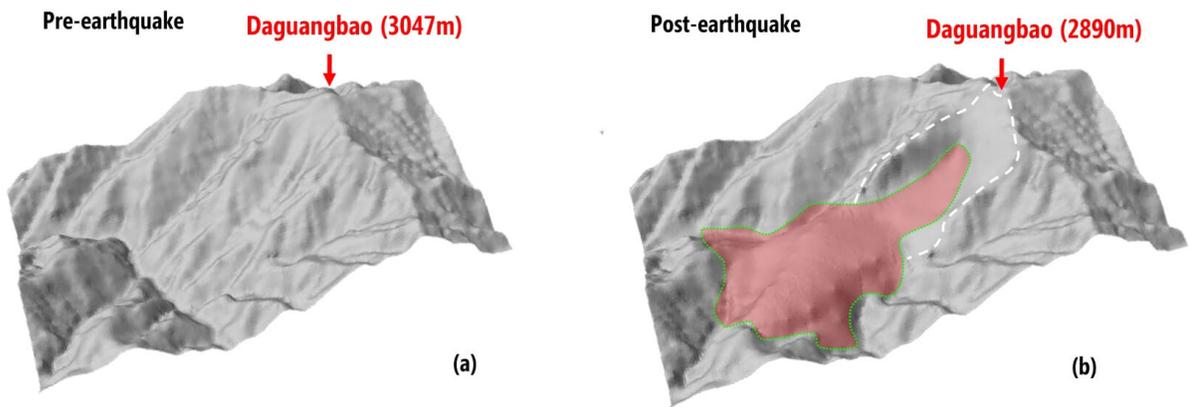


Figure 8. Pre- and post-earthquake 3-D topographies of the Daguangbao landslide

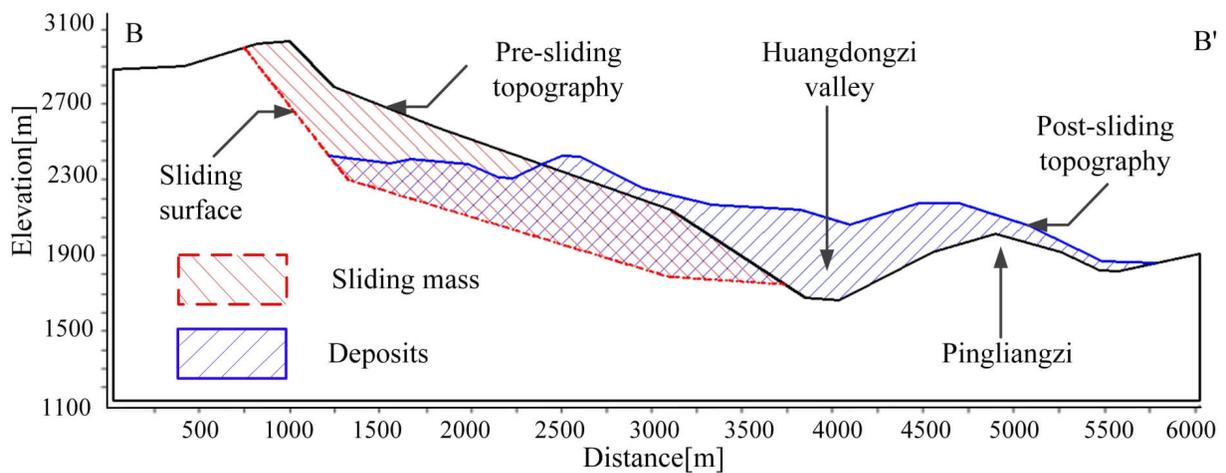


Figure 9. Cross-section of the Daguangbao landslide before and after the Wenchuan earthquake.

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.

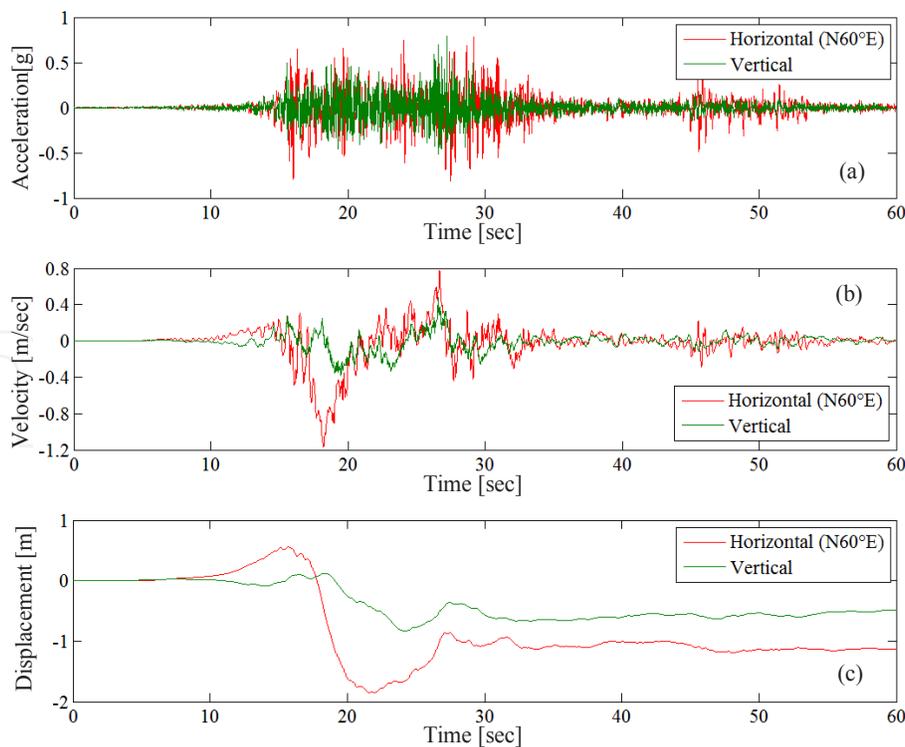


Figure 10. Input post-corrected horizontal and vertical ground records projected to N60°E direction

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.

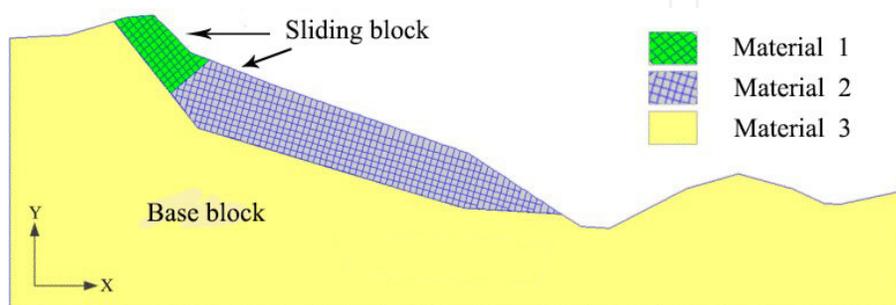


Figure 11. DDA model of the Daguangbao landslide

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.

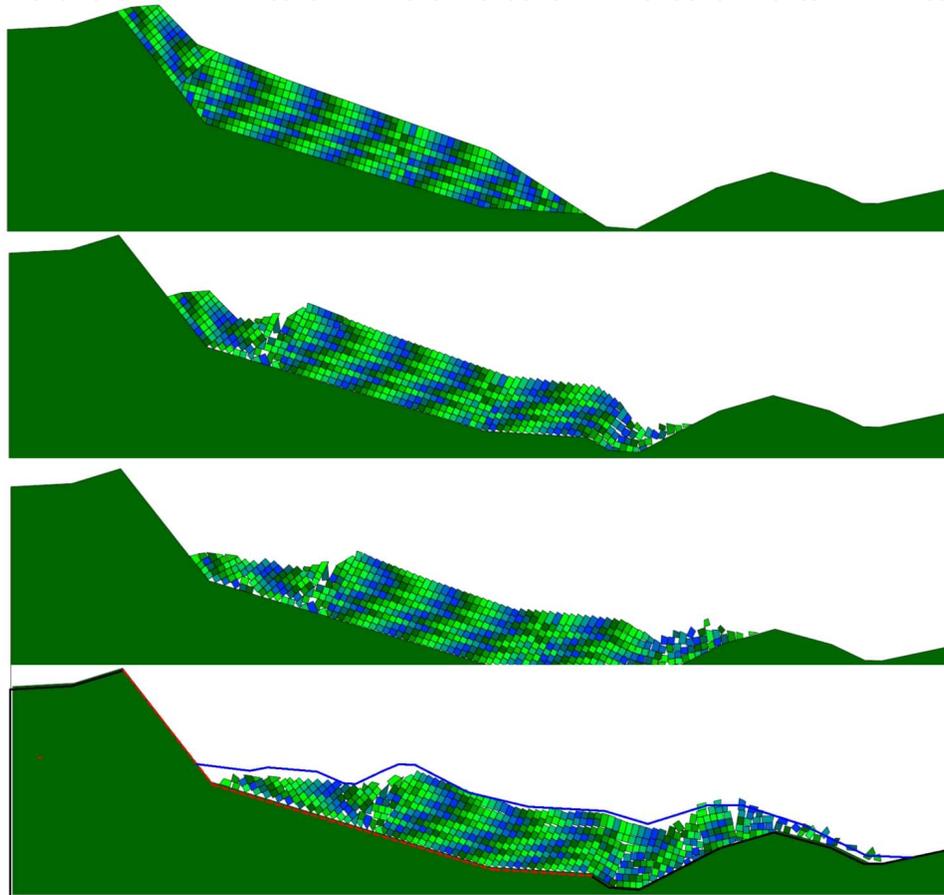


Figure 12. Simulation results of the Daguangbao landslide

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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Author details

Yingbin Zhang*

Address all correspondence to: yingbinz516@126.com

Department of Geotechnical Engineering, School of Civil Engineering, Southwest Jiaotong University, Chengdu, China

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