

Failure-mode analysis of loose deposit slope in Ya-Kang highway under seismic loading using particle flow code

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Abstract

PFC^{2D} (particle flow code in two dimensions) was used to investigate the dynamic processes and hypermobility mechanisms of the loose deposit slope in the Ya-Kang Highway case. The structure of loose deposit slope is simulated by numerous balls, which have different bonding strength. A trial-and-error calibration and biaxial models were applied to determine micro level parameters in PFC^{2D}. The parallel bonds between particles, the velocity vector diagram, the displacement vector diagram, the porosity and the stress in numerical models were analyzed. It can be concluded that deep sedimentary basins can have large effects on the slope surface. Three different slip patterns, which were identified by the sliding along the slope, the collision of rocks in the down-slope and break through sandstone, respectively, can be found. The velocity

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vector diagram indicates that at the start the particles may move by falling, toppling, and sliding, but over time begin to spread or flow. The location of particles is a critical factor in the stability of loose deposit slope. Particle displacement is smaller at the top and center than those at the bottom of the slope. The reason is that the collision interaction between the rock blocks involved the transfer of momentum, which caused the front of the mass to continue for a greater distance. The porosity of the surface slope generally increases with increasing seismic wave loading time, while the porosity of the inner slope remains constant. The stress on the slope surface is much larger than that on the inner layer of the slope. This indicates that seismic waves travel faster through hard rocks than through softer rocks and sediments.

Keywords Loose deposit slope · PFC^{2D} · Seismic wave · Microscopic · Failure process

1 Introduction

Loose deposit slope is special and complex geologic material slope. When there is the accumulation of seismic factors, to a certain extent, loose deposit slope can be inclined to serious and major geological hazards, especially in mountainous areas [18,19,20]. Sichuan is located in the Himalaya-Mediterranean seismic belt whose gigantic tectonic forces have created high mountains and number of loose deposit slopes. Wenchuan Earthquake (M7.9, May 12, 2008) that shocked the world was triggered by Longmen Shan fault, causing more than 87,000 people killed, 370,000 wounded and ¥1000 billion economic lost [9,19]. Sichuan is therefore, one of the loose deposit slope-hazard hotspots of the China [10]. Seismic stability of these kinds of slopes is one of these urgent issues induced by earthquake disaster. However, there is

comparatively little research about these loose deposit slopes [4,6,20]. More progress in forecasting and understanding of catastrophic loose deposit is needed to reduce casualties and property losses of reconstruction efforts in Sichuan after the Wenchuan Earthquake in 2008.

DEM was an important tool for modeling the failure behavior of granular geological materials through the time-stepping algorithms that have been developed over the past decade [15,16,17]. Particle flow code (PFC^{2D}) makes possible for the modeling of granular flow [8,17,22], fracture of intact rock, transitional block movements, dynamic response to blasting or seismic, and deformation between particles caused by shear or tensile forces, as described by Cundall and Strack [1]. The elements interact with each other via a force displacement law and can be of arbitrary shape, rectangular blocks and spheres being the most common ones.

This paper presents the results of a PFC^{2D} simulating the loose deposit slope based on a case study in the Ya-Kang Highway of Sichuan Province. The structure of loose deposit slope is simulated by numerous balls, which have different bonding strength. A trial-and-error calibration and biaxial models were applied to determine micro level parameters in PFC^{2D}. The parallel bonds between particles, the velocity vector diagram, the displacement vector diagram, the porosity and the stress curve in numerical models were analyzed. The failure modes of the loose deposit under seismic waves were also studied from a microscopic point of view.

2 Loose deposit slopes under seismic loading using PFC^{2D}

2.1 Loose deposit slope model

To simulate slope failure processes, the numerical modeling in this study was conducted with PFC^{2D}, developed by Itasca [7] based on the DEM. The cross section of PFC^{2D} models is selected according to the typical cross section of the loose deposit slope of the Ya-Kang Highway (from EK 43 + 00 to EK 43 + 100). Hills have slopes of 35° ~ 40° and heights of 120 ~ 130 m. Substances coating the sandstone to a certain thickness and highly and medium-weathered mudstone are the main features of this loose deposit slope.

Particle flow models were built according to the simplified geological results obtained in quake-hit regions in Sichuan Province. The different loose rocks are modeled as balls with different parallel bonds. The specimen-genesis procedure has two main steps, according to the PFC^{2D} user's manual. First, a box ($h = 140$ m, $l = 240$ m) with four walls is used to simulate the boundaries. The particles, simulated using 10000 balls of radii ranging from 0.72 m to 1.07 m, are generated randomly. Then the gravity is applied to the particles to reach an equilibrium state. Second, redundant balls are deleted according to the shape of the slope surface of the Ya-Kang Highway. A slope of length 193 m length and height 132 m and containing 4370 balls is obtained as shown in Fig. 1, where the blue balls represent sandstone, the green balls represent medium-weathered mudstone and the red balls represent highly weathered mudstone, respectively. For easier analysis, some particles were assigned numbers from 1 to 10. Nos. I and II represent the location of two measured circles. Three different values, 2.87×10^{11} , 1.9×10^{11} and 1.6×10^{11} N/m, were used for the parallel-bond strengths of sandstone, medium-weathered mudstone and highly-weathered mudstone, respectively.

The elastic contact model was chosen to simulate the contact force between rock masses. Tang et al. [16] established allow residual friction coefficient of 0.1. Here the author assumed that the residual friction is 0.1 during the earthquake.

2.2 PFC input parameter calibrations

The physical parameters of the loose deposit slope model obtained from Ya-Kang Highway survey data are shown in Table 1. However, in discrete element methods, the macroscopic behavior of the granular media depends on the contact mechanical properties and there is no straightforward solution relating these parameters. The micro-parameters of the PFC^{2D} models are derived from repeated calculations of the numerical tests (trial and error method). The flow chart of deriving the micro-parameters to construct a PFC^{2D} model is shown in Fig 2. Usually, the results from biaxial tests on a PFC^{2D} material are compared against actual results of the target material [7,11,13,21]. Therefore, to refine the calibration of PFC^{2D} input parameters in this paper, a series of PFC^{2D} biaxial models was designed to match the properties of soil of the Ya-Kang Highway. Different confining stresses (1, 5, and 10 MPa, as shown in Fig. 3) are applied to the assembly using a numerical servomechanism. The stress-strain curves and the volumetric stain-axial strain curves of biaxial tests under confining stresses of 1 MPa are shown in Fig. 4, from which the values for E and ν of sandstone, medium-weathered mudstone, and highly weathered mudstone were determined. The σ - τ curves obtained from a PFC^{2D} biaxial model under different confining stresses (1, 5, and 10 MPa, respectively). The value of c and ϕ of sandstone, medium weathered mudstone, and highly weathered mudstone can be determined using Mohr circles. The mathematical

expression is:

$$\sin \varphi = \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3 + 2ctg \varphi}$$

where σ is the mean effective stress, τ is the deviator stress, and σ_1 and σ_3 are the two principal stresses. The parameters E , ν , c and φ obtained from the PFC^{2D} biaxial model are summarized in Table 2. Comparison of Table 1 to Table 2 shows that the numerical parameters are a good match with the actual ones. Hence, the micro-mechanical parameters determined from the PFC^{2D} biaxial model can be used to analyze the macroscopic behavior of the real case. The PFC^{2D} input values used for the real model are listed in Table 3. Where, ρ , e , k_n , k_s , f_c , k_n^{pb} , k_s^{pb} , σ_c^{pb} , τ_c^{pb} , R_{pb} , R_{min} , R_{max} is the density, porosity, normal stiffness, shear stiffness, friction coefficient, normal stiffness of the parallel bond's, shear stiffness of the parallel bond's, normal strength of the parallel bond's, shear strength of the parallel bond's, the parallel bond's radius, the minimum radii and the maximum radii of all balls, respectively. With these PFC^{2D} input parameters and by applying gravity to the numerical model, a new equilibrium can be found.

2.3 Seismic loading

The acceleration-time curve of the Wenchuan Earthquake is shown in Fig. 5a. The peak seismic wave is 0.96 g. This seismic loading can be used to study the influence of earthquakes on the stability of loose deposit slope. However, because active loading only can be applied in velocities in PFC^{2D} model, the real acceleration-time curve of the Wenchuan Earthquake is integrated to the corresponding velocity-time curve, as in Fig. 5b. This corresponding velocity-time curve of the Wenchuan Earthquake is applied

on the boundary particles at far left and bottom.

3 Results and analysis

3.1 Parallel bonds between particles

The parallel bonds between particles of the loose deposit slope are used to analyze the slope failure processes. Fig. 6a-f illustrates the development of the broken parallel bonds under the seismic loading of the Wenchuan Earthquake. Fig. 6a shows the parallel bonds between particles of loose deposit slope at the initial state (time $t = 0$). Fig. 6b-f shows the parallel bonds between particles of loose deposit slope when the seismic loading of Wenchuan earthquake is applied 0.5 s, 1 s, 5 s, 50 s, and 70 s later, respectively. It can be observed from the figures that the stability of the slope varies with time. Fig. 7a-c illustrated the landslide photos after Wenchuan earthquake. Both in realistic and simulation, three different sliding patterns of landslide behavior can be found.

As shown in Fig. 6b, 0.5 seconds after the seismic loading, the broken parallel bonds in highly weathered mudstone (red line) and medium-weathered mudstone (green line) are clear to see. However, there are almost no broken bonds in sandstone (black line), indicating that at the start the main body of the granular mass behaves roughly as a rigid block. From Fig. 6c and d, 1 and 5 seconds after seismic loading, it can be seen that almost all the parallel bonds are broken in highly weathered mudstone and medium-weathered mudstone. In this case, it indicates that the sliding block becomes fragmented and the particles become free to roll and bounce. This is characteristic of earthquake-induced landslides and is associated with the intense

shaking at the top of the slope. In this case, the sliding along the slope is the major mechanism. We call it the first sliding pattern. This can be confirmed with the photo which was shown in Fig. 7a. Multiple shallow rock slides triggered by the earthquake can be seen in Fig. 7a. These are the slides originating from the top of the slope and extending all the way to the foot, as in the first failure mode. The shear loading induced by the movement of the landside bodies can be used to explain this phenomenon. Because the collision and friction between particles dissipated energy quickly, the deposition area would spread wider than those cases with higher bond strength.

In sandstone, the first significant increase in bond breakage occurs after about 5 s (Fig. 6e, blue dashed line). There is no significant difference in bond breakage over the period 5-30 s, indicating that the rocks in the down-slope are collide and accelerate in the down-slope direction as they slide, a stage we call the second sliding pattern. A second remarkable increase in break through fragmentation happens at about 50 s (red dashed line in Fig. 6e). In Fig. 7b, a zone of particularly shattered limestone is seen at the toe of slope, confirming the second failure mode as presented in Fig. 6d. The dust maybe caused by continuing landslide activity, probably due in part to aftershocks and in part to loosened material that continues to fail.

A third remarkable increase in break through fragmentation happens at about 70 s (green dashed line Fig. 6f). These break through fragmentations indicate that rock has naturally occurring fractures whose propagation can lead to failure of a rock mass. Huang et al. [6] also concluded that if the slip surface is planar and deep enough, the rock mass may behave essentially as a rigid body. This stage can be called the third

sliding pattern and can be confirmed by Fig. 7c. It can be seen that the failure of a slope cut into the weathering profile developed over sandstone in Fig. 7c (the solid red line).

3.2 The velocity vector diagram

There preventative particles shown in Fig. 8 were selected to study how a particle's velocity changes with time. Particles 1, 2, 5, 6, 10 represent, respectively, highly weathered sandstone at the top of the slope, highly weathered sandstone at the middle of the slope, medium-weathered sandstone at the center of the slope, medium-weathered sandstone at the toe of the slope, and sandstone. It can be found that particle 6 had maximum velocity (around 10.8 km/h), Tang et al. [16] state that the rock-mass velocity of many rockslide events remains below about 10 km/h, this confirmed that the micro parameters of PFC^{2D} in this study were deliberately chosen. The corresponding horizontal, vertical and resultant velocity vector diagrams were presented in Fig. 8a through c. It shows that there is no significant change in the velocity trend in highly and medium-weathered sandstone. The horizontal velocity was observed to increase with increasing time, while just the reverse occurred in vertical velocity. This phenomenon indicates that at the start the particles may move by falling, toppling, and sliding, but over time begin to spread or flow. The velocity of medium-weathered sandstone at the center (particle 5) is smaller than that at the toe of the slope (particle 6). The explanation is that the high initial velocity and the large difference in elevation between the cliff and the valley bottom induced the projectile motion. Meanwhile, particle elements impact the ground surface directly and caused the large velocity and large acceleration. The resultant velocity of particles on the surface increase with time

(particles 1, 2, 5, 6), indicating that the particles finally get enough energy to move apart when the vibrations become faster and broader. The conclusion can be confirmed by studies of sliding mass flows over a dilute layer of highly agitated particles [18]. However, compared to surface-layer particles (particles 1, 2, 5, 6), inner-layer high-strength particles (particle 10) may even remain stationary after sharp shaking. This phenomenon may be explained by considering that the vibrations are transferred outward from the origin of the quake. Deep sedimentary basins can have a large effect on ground motion above them, and seismic waves travel faster through hard rocks than through softer rocks and sediments.

3.3 Displacement vector diagram

Fig. 9 showing the variation of the slope displacement with time when the slope is subjected to seismic waves, indicates that all the displacement varies with time. Fig. 9a through c show that for all particle types, the displacements of particles in surface layers (1, 2, 5, 6) are larger than those of in inner layers (3, 4, 7, 8, 9). The displacement of particle 10, located in a high-strength inner layer, is almost 0. This phenomenon confirmed that particles of high strength in inner layers may not even be displaced after sharp shaking, as indicated in velocity vector diagram. The comparison between Fig. 9a and b shows that the horizontal displacement of the slope is more than the vertical displacement at all points. The horizontal displacements of particles located at center (particle 1 and 5) are nearly equal while located at bottom (particle 2 and 6) have a big difference. Meanwhile, the horizontal displacements of particles located at bottom are larger than those at center, whether in weathered mudstone slope (particles 1 and 2) or

medium-weathered mudstone slope (particles 5 and 6). This indicates that particle location is critical in the stability of loose deposit slope. Also, it can be seen that the horizontal displacement of the slope is maximum at the bottom of the slope (particle 6) as compared with the center (particle 1) or the top (particles 2 and 5). Looking at all the particles shows that the middle-bottom slope surface area provides maximum displacement both in highly weathered mudstone slope (particle 2, all red balls) or medium-weathered mudstone slope (particle 6, all green balls). Comparison between particles 2 and 6 also indicates that particle displacements smaller at the center of the slope (particle 2, all red balls) than at the bottom (particle 6, all green balls). The maximum horizontal, vertical and resultant displacements are 7 m, 4.5 m and 8.5 m, respectively. The values are consistent with those obtained from Wenchuan statistics. This phenomenon indicates that particles located at the top of slope can move by falling, toppling, and sliding from the origin of the quake but then come to rest and are buried. The momentum transfer model, i.e. an acceleration of the front blocks caused by increased collision [2,3,14], can be used to explain the displacement results presented here. In pace with the seismic loading, the rock mass was fragmented into relatively small blocks. Because of the restricted free movement and collisions occurred between rock blocks, rock blocks at the rear and bottom surfaces pushed rock blocks forward at the front and top surfaces. The collision interaction between the rock blocks involved the transfer of momentum, which caused the front of the mass to continue for a greater distance [3,5,12].

3.4 Porosity

We used the two measurement circles (I & II) shown in Fig. 1 to measure the porosity in the internal structure. Circle of radius 4.0 miles used to analyze the porosity of the surface of the slope, which is mainly composed of highly weathered mudstone. Circle II, of the same radius as I, can be used to analyze the porosity of the inner slope, which is mainly composed of sandstone. Fig. 10 presents porosity history curves of highly weathered mudstone and sandstone, respectively. Fig. 10a shows that the porosity of highly weathered mudstone generally increases with increasing seismic wave loading time, indicating that the highly weathered mudstone tends to be quite soft and easily broken into pieces under seismic loading. This conclusion is in accordance with the results in Fig. 6. However, it can also be seen that the porosity of sandstone did not change significantly. The porosity of sandstone decreases generally at the beginning and then tends to increase to a constant. The observation clearly confirmed that rock has naturally occurring fractures whose propagation can lead to failure. Despite this breakthrough fragmentation, however, the rock mass may behave essentially as a rigid body.

3.5 The stress history curve

Fig. 11 presents the stress history curve of measurement circles I and II, which represent the surface and inner layer of the slope, respectively, and shows that the particles located at the surface of the slope (circle I) undergo larger stress. The stress on the slope surface is 7 times that on the inner layer of the slope (circle II). This finding supports the idea that seismic waves travel faster through hard rocks than through softer rocks and sediments. As the waves pass from harder to softer rocks and slow down,

their amplitude must increase to carry the same amount of energy. Thus, shaking tends to be stronger at sites with softer surface layers, where seismic waves move more slowly.

4 Conclusions

In this paper, a situation in Ya-Kang Highway of Sichuan Province is simulated by a PFC^{2D} program. The failure modes of the landslide under seismic waves were studied from a microscopic point of view, and the parallel bonds between particles, the velocity vector diagram, the displacement vector diagram, the porosity history curve and the stress history curve were analyzed. The main conclusions are:

1. There are three different sliding patterns. The slides originate from the top of the slope, then continuing landslide activity, and finally the slope fails, cutting into the weathering profile.
2. Deep sedimentary basins can have a large effect on the slope surface. Shaking tends to be stronger at sites whose surface layers are softer compared to the inner slope.
3. The porosity of the surface slope generally increases with increasing seismic-wave loading time, while the porosity of the inner slope remains constant.
4. The displacement of some particles on the surface increases when increased seismic loading makes the stability of the slope become marginal in this area.

The location of particles is a critical factor in the stability of loose deposit slope.

Although the PFC^{2D} simulations still have limitations in modeling loose deposit, the work demonstrates that it can provide useful insights for mapping areas susceptible to potentially catastrophic slope failures.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Cundall, P.A., Strack, O.D.: A discrete numerical model for granular assemblies. *Geotechnique* **29**(1), 47-65 (1979)
2. Campbell, C.S.: Self-lubrication for long run out landslides. *J. Geol.* **97**, 653-665 (1989). 10.1086/629445
3. Cleary, P.W., Campbell, C.S.: Self-lubrication for long runout landslides: examination by computer simulation. *J. Geophys. Res [Solid Earth]*. **98**(5), 794-796 (1993). 10.1029/93JB02380
4. Dai, F.C., Xu, C., Yao, X., Xu, L., Tu, X.B., Gong, Q.M.: Spatial distribution of landslides triggered by the 2008 Ms 8.0 Wenchuan earthquake, China. *J. Asian Earth Sci.* **40**(3), 883-895 (2010). 10.1016/j.jseaes.2010.04.010
5. Deng, H.F., Zhou, M.L., Li, J.L., Sun, X.S., Huang, Y.L.: Creep degradation mechanism by water-rock interaction in the red-layer soft rock. *Arab. J. Geosci.* **9**(12), 601-615 (2016). 10.1007/s12517-016-2604-6
6. Huang, R.Q.: Mechanism and geomechanical modes of landslide hazards triggered by Wenchuan 8.0 earthquake. *Chin. J. Rock Mech. Eng.* **28**(6), 1239-1249 (2009). (in Chinese)
7. Itasca Consulting Group Inc. PFC2D-particle flow code in 2 dimensions, user's manual. Minneapolis: Itasca. (2008)
8. Kang, C., Chan, D.: Numerical simulation of 2D granular flow entrainment using DEM. *Granular Matter* **20**(13), 1-17 (2018) <https://doi.org/10.1007/s10035-017-0782-x>
9. Lee, G.: The 512 Wenchuan Earthquake of China: a preliminary report (2008). <http://mceer.buffalo.edu/research/reconnaissance/china5-12-08/chinaeq6-15-08.pdf>
10. Michael, D., Li, L.: Earthquake reconstruction in Wenchuan: Assessing the state overall plan and addressing the forgotten phase. *Appl. Geogr.* **31**(3), 998-1009 (2011). 10.1016/j.apgeog.2011.01.001
11. Meng, Y.W.: PFC2D simulation on stability of loose deposits slope in highway cutting excavation. *Geotech. Geol. Eng.* **35**(2), 897-902 (2017). 10.1007/s10706-016-0143-2
12. Okura, Y., Kitahara, H., Sammori, T., Kawanami, A.: The effects of rock fall

- volume on run out distance. *Eng. Geol.* **58**(2), 109-124 (2000). 10.1016/S0013-7952(00)00049-1
13. Potyondy, D.O., Cundall, P.A.: A bonded-particle model for rock. *Int. J. Rock Mech. Min. Sci.* **41**(8), 1329-1364 (2004). 10.1016/j.ijrmms.2004.09.011
 14. Schöpfer, M.P.J., Childs, C., Walsh, J.J.: Two-dimensional distinct element modeling of the structure and growth of normal faults in multilayer sequences: 1. Model calibration, boundary conditions, and selected results. *J. Geophys. Res.* **112** (B10), 1-15 (2007). 10.1029/2006JB004902
 15. Shi, C., Wang, S.N., Liu, L.: Research of avalanche disaster numerical simulation based on granular discrete element method of high-steep slope under seismic loads. *Chin. J. Rock Mech. Eng.* **32**(S1), 2798-2805 (2013). (in Chinese)
 16. Tang, C.L., Hu, J.C., Lin, M.L., Angelier, J., Lu, C.Y., Chan, Y.C., Chu, H.T.: The Tsaoling landslide triggered by the Chi-Chi earthquake, Taiwan: insights from a discrete element simulation. *Eng. Geol.* **106**(1-2), 1-19 (2009). 10.1016/j.enggeo.2009.02.011
 17. Tuitz, C., Exner, U., Preh, A., Grasemann, B.: The influence of particle orientation on the loading condition of pebbles in fluvial gravel. *Granular Matter.* **14**(5), 639-649 (2012). <https://doi.org/10.1007/s10035-012-0365-9>
 18. Wang, C., Tannant, D.D., Lilly, P.A.: Numerical analysis of the stability of heavily jointed rock slopes using PFC2D. *Int. J. Rock Mech. Min. Sci.* **40**(3), 415-424 (2003). 10.1016/S1365-1609(03)00004-2
 19. Yashinsky, M.: Performance of highway structures during the May 12, 2008 Wenchuan, China Earthquake. Technical Council on Lifeline Earthquake Engineering Conference. 1349-1358 (2009)
 20. Yin, Y., Wang, F., Sun., P.: Landslide hazards triggered by the 2008 Wenchuan earthquake, Sichuan, China. *Landslides.* **6**(2), 139-152 (2009)
 21. Zhang, L., Thornton, C.: A numerical examination of the direct shear test. *Geotechnique*, **57**(4), 343-354 (2007)
 22. Zhou, W., Lai, Z.Q., Ma, G., Yang, L.F., Chen, Y.: Effect of base roughness on size segregation in dry granular flows. *Granular Matter.* **18**(83), 1-14 (2016) <https://doi.org/10.1007/s10035-016-0680-7>