Landslide Failure Process Simulation with Automatic Remeshing in FLAC3D

Aiwu Cao\textsuperscript{1,2}, Weijiang Chu\textsuperscript{1,2}, Rongfu Wang\textsuperscript{3}, Jiayao Wu\textsuperscript{1,2}, and Liuke Huang\textsuperscript{4,5}

1 Hydro-China Itasca R&D Center, Hangzhou 311122, Zhejiang, China
2 PowerChina Huadong Engineering Co., Ltd., Hangzhou 311122, Zhejiang, China
3 Yilihe Power Plant of Huadian Yunnan Power Generation Co., Ltd., Qujing 654200, Yunnan, China
4 State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, Hubei, China
5 Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China

Abstract: Landslide is a serious geologic disaster, which remarkably influences the safety of lives and engineering activities. Numerical simulation is the most universal method to analyze the stability and influence of landslides. For the continuous mechanical modeling of deformation based on a mesh, most landslide deformation failures of a slope are based on the small strain mode instead of the large strain mode to avoid mesh distortion. However, the failure process and the morphological characteristics of different stages cannot be reflected. In this study, an automatic remeshing technology in Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC3D) is developed to overcome this problem. With the built-in Python in FLAC3D, the mesh of the landslide is automatically updated with deformation. The strain and stress of the adjusted mesh are remapped from the old mesh to maintain the consistency of results. This method is extended to simulate the extremely large deformation in FLAC3D for the landslide failure process. With this strategy, 3D slopes with and without a large strain mode and automatic remeshing technology are compared to understand the failure process and eliminate or reduce threats of a landslide.

1. Introduction
Landslides are difficult and dangerous physical and geological processes in the form of a massive downslope soil displacement; landslide processes are the most common, difficult, time-consuming, and multifactorial events that cause considerable economic losses (Tymchenko O., 2016). Landslides occur abruptly and have complex influencing factors, such as earthquakes, rainfall, and excavation. Therefore, further studies should provide a basis for designing protective measures based on the correct understanding of landslide movement.
Landslides have been widely explored. They considerably influence the environment, engineering activities, lives, and other aspects (Luo et al., 2019; Dhakal S. et al., 2020; Xu et al., 2021). Landslide processes have been analyzed with the discrete element method; furthermore, the initiation and development of landslides can be described intuitively with 3DEC or PFC (Ju et al., 2018; Wang et al.,...
2019; Li et al., 2019). Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC3D) is commonly used to evaluate landslide stability and support (Yin et al., 2015). In this study, a new method with automatic remeshing technology is developed with built-in Python in FLAC3D to describe the failure processes of landslides. This method is then used to analyze the failure processes and mechanisms of a 3D slope.

2. Problems without automatic remeshing in large deformation analysis in FLAC3D

FLAC3D is widely used for geotechnical analyses. It utilizes an explicit finite volume formulation that captures the complex behavior of models that consist of several stages, show large displacements and strains, present a nonlinear material behavior, or exhibit instability (Itasca Consulting Group, 2020). During the analysis with FLAC3D in a large strain mode, several problems can occur and affect calculation without remeshing technology.

2.1. Small and large strain modes in FLAC3D

The default calculation mode of FLAC3D is a small strain with an unchanged gridpoint. Stress and strain are calculated using the original shape of the zones. In the large strain mode, positions are frequently updated, yielding a potentially more accurate solution. Large strain simulations are a more accurate representation of actual conditions.

2.2. Simulation termination in FLAC3D in the large strain mode

When FLAC3D is run in the large strain mode, the grid may become distorted to such an extent that the simulation becomes terminated, and an “illegal geometry” error message is issued (Itasca Consulting Group, 2017; Cardozo N. et al., 2008). In Figure 1, boundary movement in tectonic evolution was analyzed, and the detachment layer and covers slipped under an external force. When the amount of the movement was 5.85% of length, zone 795 became the “illegal geometry,” which stopped the calculation. The shape of zone 795 transformed from a square into a triangle (Figure 2). Therefore, its maximum principal strain was extremely large.

![Figure 1. Model of boundary movement in tectonic evolution](image)

2.3. Slope stability analysis with a small strain mode

A slope with a cross-section in Figure 3 is used to evaluate the slope stability with a small strain mode in FLAC3D, and the parameters are shown in Table 1.

The slope is unstable (with parameters in Table 1). After 100,000 steps in FLAC3D are solved, the displacement is shown in Figure 4. The displacement continuously increases with more calculation steps, but this increase is unreasonable because displacement never stops.
Figure 2. Simulation termination in FLAC3D in the large strain mode (a: Initial mesh; b: mesh when simulation stops; and c: maximum principal strain increment when simulation is terminated)

Figure 3. Sketch of the slope (unit: m)

Table 1. Parameters of the slope

| Mesh size (m) | Unit weight (kN/m³) | Cohesion (c) (MPa) | Friction angle (φ) (degrees) | Young's modulus (E) (MPa) | Poisson ratio (μ) |
|---------------|---------------------|--------------------|----------------------------|--------------------------|-----------------|
| 0.5–1.0       | 20.0                | 0.0                | 30.0                       | 500.0                    | 0.35            |

Figure 4. Displacement of the slope with a small strain mode after 100,000 steps are solved
2.4. Slope stability analysis with a large strain mode

For the same slope in Figure 3, the slope is analyzed in the large strain mode, an “illegal geometry” error appeared after 30,051 steps are solved. Therefore, the geometry of zone 3932 becomes distorted, and the calculation is terminated (Figure 5).

Figure 5. Simulation termination for slope stability analysis in a large strain mode

The analysis based on a large strain mode is more actual, but the “illegal geometry” error stopped the calculation. If the mesh could be updated to avoid the error, the calculation could be continued, and the failure process of a landslide could be described.

3. Automatic remeshing technology implementation in FLAC3D

According to the analysis above, the calculation stops in FLAC3D in the large strain mode with the “illegal geometry” error. Therefore, a technology is developed to avoid a distorted mesh, and strain and stress are mapped from an old mesh.

3.1. Steps in automatic remeshing technology

The flow chart of automatic remeshing technology is shown in Figure 6. The remeshing and mapping of strain and stress are the most crucial parts of this technology.

3.2. Remeshing in FLAC3D

The latest version of FLAC3D 7.0 has a built-in Python 3, which is used to adjust the mesh by changing the position of a gridpoint to make a more coordinated geometry of the zone. The adjustment of the gridpoint is shown in Figure 7.

Figure 6. Flow chart of automatic remeshing technology
Figure 7. Adjustment of the gridpoint in 2D (a: before and b: after the adjustment)

During adjustment, gridpoints, such as gridpoints 11 and 16, are fixed in the vertices of the outer contour. For the other gridpoint $G_{i,j}$, the adjustment for the $x$-position in the outer contour is calculated with Equation (1):

$$x'_{i,j} = \frac{x_{i-1,j} + x_{i,j} + x_{i+1,j}}{3}.$$  (1)

The updated $x$-position of the gridpoint inside is calculated with Equation (2):

$$x'_{i,j} = \frac{x_{i-1,j} + x_{i,j} + x_{i+1,j} + x_{i,j-1} + x_{i,j+1}}{5}.$$  (2)

For the $y$- and $z$-positions, the adjustment principles of the gridpoint position are the same. The adjustment effect is shown in Figure 8.

Figure 8. Adjustment process of the gridpoint in 3D (a: before and b: after the adjustment)

3.3. Mapping of strain and stress in FLAC3D

The gridpoint of a zone can be updated in accordance with the adjustment principle, and the most important step is to maintain the consistency of results before and after mesh adjustment. Interpolation functions in NumPy with Python are used to map the strain and stress from the old mesh. The displacement and stress before and after remeshing are shown in Figure 9. Therefore, strain and stress are also the same.
3.4. Comparison of simulated results with and without automatic remeshing technology

Automatic remeshing technology overcomes the shortcoming of FLAC3D in a large strain mode, indicating that the application scope of FLAC3D is expanded.

Geological conformation movement is simulated to show the advantage of remeshing technology. The numerical model is shown in Figure 10. In the exogenous process in two directions, the overlying strata become continuously compressed. The results of geological conformation movement are shown in Figure 11. Without automatic remeshing technology, the simulation is terminated with element distortion, and the decrease in the overlying strata is only 3.62%. With automatic remeshing, the overlying strata are continuously compressed, with a compression of 20%. Several fault systems are detected, and this finding is consistent with the results of Boyer and Elliott (1982).

Figure 9. Mapping results before and after remeshing (a: x-displacement of zone before and b: after the adjustment; c: minimum principal stress of zone before and d: after the adjustment)

Figure 10. Geological conformation movement simulation model of FLAC3D
4. Landslide failure process simulation with automatic remeshing in FLAC3D

For the model in Figure 3, the automatic remeshing technology is used to analyze the landslide failure process, and remeshing is performed for every 10,000 calculation steps (Figure 12). Compared with the landslide stability analysis in Figure 4 with a small strain mode and Figure 5 with a large strain mode, this method with automatic remeshing technology shows the displacement propagation in different parts of the landslide, especially in the slope foot. Failure starts from the top of the slope; as the landslide proceeds, the influence range in the slope foot appears and moves further.

Figure 12. Landslide failure process simulation with automatic remeshing technology

5. Conclusions

For a landslide analyzed in FLAC3D, displacement cannot be convergent with increasing displacement in a small strain mode, or calculation is terminated by an “illegal geometry” error for a distorted mesh in a large strain mode. In this study, an automatic remeshing technology is developed to avoid these problems and analyze the failure process of landslides with the built-in Python in
FLAC3D. After the position of gridpoints is updated and the strain and stress from the old mesh are mapped, the failure process of landslides can be more reasonably described in FLAC3D. With this method, the application scope of FLAC3D is expanded. Although the automatic remeshing technology is still based on a relatively regular hexahedral mesh, a more general remeshing solution for a common mesh should be explored.

6. References

[1] Tymchenko O, Ugnenko E and Makovyye R 2016. *Analysis of Methods of Landslide Processes Forecasting on Highways*. (Procedia Engineering) pp146-152.

[2] Luo H Y, Zhang L L and Zhang L M 2019. *Progressive failure of buildings under landslide impact*. (Landslides 16) pp1327-1340.

[3] Dhakal S, Cui P, Rijal CP and et al 2020. *Landslide characteristics and its impact on tourism for two roadside towns along the Kathmandu Kyirong Highway*. (Journal of Mountain Science) pp1840-1859.

[4] Xu L, Yan D and Zhao T 2021. *Probabilistic evaluation of loess landslide impact using multivariate model*. (Landslides 18) pp1011-1023.

[5] Ju Y, Sun H, Xing M and et al 2018. *Numerical analysis of the failure process of soil-rock mixtures through computed tomography and PFC3D models*. (International Journal of Coal Science & Technology) pp126-141.

[6] Wang Y, Wu L Z and Gu J 2019. *Process analysis of the Moxi earthquake-induced Lantianwan landslide in the Dadu River, China*. (Bulletin of Engineering Geology and the Environment), 2019.

[7] Li D Y and et al 2021. *Numerical Simulation on the Longitudinal Breach Process of Landslide Dams Using an Improved Coupled DEM-CFD Method*. (Frontiers in Earth Science).

[8] Yin Y, Li B and Wang W 2015. *Dynamic analysis of the stabilized Wangjiayan landslide in the Wenchuan Ms 8.0 earthquake and aftershocks*. (Landslides 12) pp537-547.

[9] Itasca Consulting Group Inc 2020. *FLAC3D User’s Manual*.

[10] Itasca Consulting Group Inc 2017. *FLAC User’s Manual*.

[11] Cardozo N and Cuisiat F 2008. *Fault propagation folding modeling in FLAC*. (Continuum and Distinct Element Modeling in Geo-Engineering)

[12] Boyer S E and Elliott D 1982. *Thrust systems*. (American Association of Petroleum Geologists Bulletin) pp1196-1230.