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Fan Yongbo[a], Oyediran Ibrahim Adewuyi[bc] & Feng Chun[a]

[a] Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China

[b] Key Laboratory of Engineering Geomechanics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, People's Republic of China

[c] Department of Geology, Faculty of Science, University of Ibadan, Ibadan, Federa`l Republic of Nigeria
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Strength characteristics of soil rock mixture under equal stress and cyclic loading conditions

Fan Yongbo[a]*, Oyediran Ibrahim Adewuyi[b,c] and Feng Chun[a]

[a]*Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China;* [b]*Key Laboratory of Engineering Geomechanics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, People's Republic of China;* [c]*Department of Geology, Faculty of Science, University of Ibadan, Ibadan, Federa'l Republic of Nigeria*

Soil rock mixture (SRM) is a special geological material with non-uniform rock distribution, non-continuous cementation between rock and soil, and size effect structural characteristics, hence, possessing mechanical properties different from rock or soil. Field survey indicated that the surface layer of SRM above the rock slope was almost unstable under cyclic loading; however, at the same time, the slope itself was stable. This phenomenon exceeded initial judgments, thus it was important to study the mechanical characteristics of SRM under cyclic loading. Numerical simulation using continuum-based discrete element method was employed to study the strength degradation and failure mechanism of SRM under different frequencies, dynamic stress amplitudes and durations. Results show that the peak stress gradually increased with the increasing dynamic stress amplitude and frequency, but decreased with the increasing percentage of rock because the stiffness decreased greatly under cyclic loading. At the same time, the elasticity modulus decreased gradually with the dynamic stress amplitude and increasing frequency.

Keywords: cyclic loading; dynamic elasticity modulus; frequency; dynamic stress amplitude; CDEM; strength degradation

1. Introduction

The 12 May 2008 Wenchuan earthquake with the highest magnitude (Cao, LeslieYoud, & Yuan, 2011) involved 50,000 landslide collapse and debris flows as a result of its long duration and strong vibration response. The destructive event had a large proportion of the landslides (Figure 1) being soil rock mixture (SRM) landslides (Chigira, Wu, Inokuchi, & Wang, 2010; Fan et al., 2012; Gorum et al., 2011; Huang, 2009; Zou, Xu, Kong, Liu, & Zhou, 2013). As a special geological material, the mechanical property of SRM (non-homogeneous materials) is different from those of either rock or soil. Through model tests undertaken by Zhao, Feng, Li, AI, and Liu (2012), major damage phenomenon of colluvial landslide triggered by earthquake was observed to be shallow collapse, consistent with the result of Wenchuan earthquake phenomenon, which indicated that the type of colluvial slope failure under earthquake loading was not subjected to the slip band, but the strength of SRM at the surface of the slope. Several research works have been carried out (Araei, Razeghi, Tabatabaei, & Ghalandarzadeh, 2012; Jiang, Wang, & Lu, 2013; Liu, Huang, & He, 2012) to study the behavior of rock subjected to dynamic loading and fatigue (cyclic) loading. Results show that the elastic modulus gradually decreased with the increase of the dynamic stress amplitude; the axial strain at failure increased at the same frequency as the confining pressure increased. Furthermore, other researchers (Fuenkajorn & Phueakphum, 2010;

Toufigh & Ouria, 2009) investigated materials such as sand, salt and clay under cyclic loading conditions. With respect to salt, elastic modulus was observed to decrease slightly during the first few cycles and tends to remain constant until failure. Experiments on sand (Lee & Seed, 1967; Seed & Idriss, 1967; Seed & Lee, 1966) revealed that the higher the cyclic stress, the smaller the number of stress cycles. Equally of note are studies on the mechanical properties of SRM under equal stress loading conditions by laboratory and *in situ* tests. Fan, Li, and Feng (2013) conducted the stress boundary loading test of SRM and determined that the strength parameters of SRM were about 20% lower than the strength parameters under the equal displacement boundary conditions. Also, Ouyang, Li, and Dai (2010) and Li, Liao, He, and Chen (2007) undertook the equal stress loading experiment by flexible emulsion and obtained the strength parameters. However, the strength parameters of SRM under cyclic loading conditions have not been reported. Thus, obtaining the strength degradation characteristics of SRM under cyclic loading has theoretical value and practical significance.

2. Numerical experiment scheme

2.1. Rock percentage and size

In order to reasonably determine the percentage of rock and size for numerical simulation, 407 colluvial slopes

*Corresponding author. Email: ybfan@imech.ac.cn

Figure 1. The landslide of BeiChuan middle school (quoted from Huang Runqiu).

Figure 2. The curve of the dynamic stress amplitude versus time ($t = 0.05\,\mathrm{s}$).

analyzed (Li, 2010) (Table 1) were taken into consideration. The percentage of rock of almost 90% of the slope was less than 40% with more than half of the slopes being less than 25%. Furthermore, Rücknagel, Götze, Hofmann, Christen, and Marschall (2013) selected 10%, 20%, 30% and 40% as rock percentage. Hence for this work, rock percentage less than 40% (10%, 15%, 20%, 25%, 30% and 35%) was therefore selected for all cases as the percentage of rock in the SRM samples. With respect to rock size, Xu, Xu, and Hu (2011) indicated rock size between 2 and 20 cm based on the observations of the Xiazari colluvial slope composition. Furthermore, gravel particle size in SRMs should not be larger than 1/5 to 1/6 of the compaction mould diameter (Donaghe & Torrey, 1994). Thus, for this experiment 2 cm was selected as the rock size for the 300 mm diameter SRM sample.

2.2. Experiment scheme

All of the numerical calculations were implemented using the continuum-based discrete element method (CDEM), a numerical method that can simulate continuous or discontinuous deformation and asymptotic failure under static or dynamic loading conditions. To obtain the strength parameters of the degradation degree of SRM, a series of initial parameters are assumed as follows: cycle time (0.05, 0.1 and 0.2 s), dynamic stress amplitude (100–200 kPa, with 20 kPa interval) and confining pressure (0.1 MPa). The curve of dynamic stress amplitude versus time is illustrated in Figure 2 while with respect to initial parameters, parameters of rock and soil including density,

Young's modulus, Poisson's ratio, cohesion and angle of internal friction are all listed in Table 2. The numerical model (Figure 3) shows the top and bottom of the model with x and y direction constraint, with application of the confining pressure around the model and cyclic loading (sine curve) at the top of the model.

2.3. Introduction of CDEM

CDEM (Feng, Li, Liu, & Zhang, 2014; Li, 2013; Wang, 2013), the method, which couples finite element method (FEM) and discrete element method (DEM) carries out FEM calculation in a single block and carries out DEM calculation on the interface of two blocks. It can model continuous and discontinuous deformation and kinetic characteristics, as well as the asymptotic process from continuum to discontinuum while it also includes block and contact model. Block model consists of Linear elastic model, Plastic model, Block cutting model, Drucker–Prager model, Mohr–Coulomb model, Failure model, Creep model, etc. while Contact model consists of Linear elastic model, Brittle fracture model, Strain softening fracture model and Fracture flow model. CDEM has been widely used in geotechnical engineering, mining engineering, structural engineering, water resources and hydropower engineering and so on.

Table 1. The characteristics of percentage of rock distribution.

Percentage of rock (%)	< 25	25–40	40–70	> 70
Proportion (%)	57.3	32.9	8.1	1.6

Table 2. Physical and mechanical parameters of rock and soil.

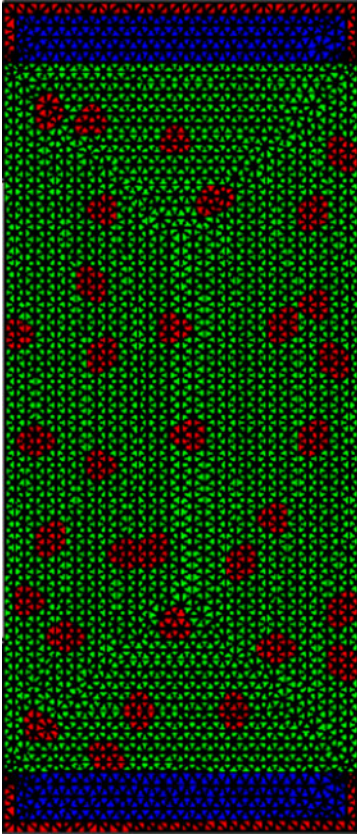| Material name	Density (kg m^{-3})	Young modulus (Pa)	Poisson's ratio	Cohesion (Pa)	Angle of internal friction (°)
Rock	3000	1.3e^{11}	0.25	6e^6	45
Soil	1580	1.5^6	0.35	1.5^4	25

Figure 3. The SRM sample with equivalent diameter 2-cm rock.

3. Results and discussion

3.1. Characteristics of stress–strain curve

The stress–strain curve (Figure 4) was divided into three stages: initial linear elastic stage (compression between soil particle), hysteresis loop stage (dislocation between rock and soil, short and decentralized crack appeared) and plastic stage (shear crack incorporated).
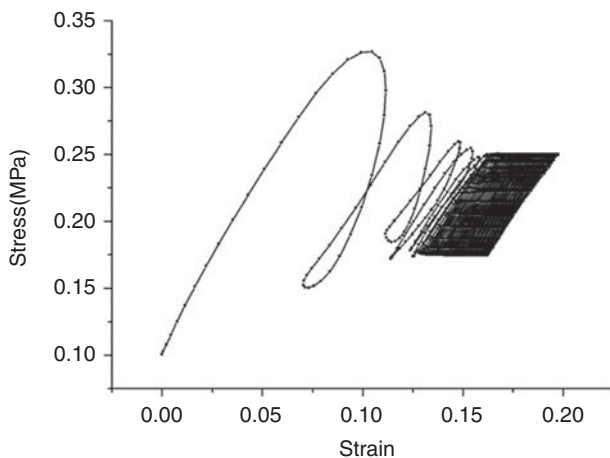

Figure 4. Stress–strain curve of SRM under cyclic loading conditions.

3.2. Failure type and characteristic

The type of failure observed was similar to those with static loading. So many short and decentralized cracks appeared with the increasing cyclic loading. Continuous loading resulted in the incorporation of shear crack, generation of single crack, and eventually appearance of shear failure.

3.3. Factors influencing strength degradation characteristic

The relationship between peak stress, amplitude, cycle and percentage of rock is displayed in Figure 5. The results of the numerical simulation showed that the peak stress gradually increased with the increasing dynamic stress amplitude under the same frequency loading condition (Figure 5(a)). With the same dynamic stress amplitude, it was noted that the peak stress gradually decreased with the increasing percentage of rock. Comparing the three graphs (Figure 5(a–c)), it could also be seen that peak stress gradually increased with the same dynamic stress amplitude when frequency increased. Moreover, peak stress gradually increased with the frequency increasing (Figure 5(b)), which indicated that the SRM sample would fail under a higher stress. Meanwhile, peak stress gradually decreased with the increasing percentage of rock under the same frequency, particularly when dynamic stress amplitude was higher. This tendency became more and more obvious and was not consistent with observations under static loading conditions. Because under cyclic loading conditions, with the increasing percentage of rock, the contact surfaces between the soil and rock increased, sliding failure occurred easily, leading to decreased force, and thereby, the sample would become loose. Thus, the stiffness decreased accordingly. A comparison of the graphs showed that the peak stress gradually increased with the same frequency when dynamic stress amplitude increased. Furthermore, peak stress gradually increased with the increasing dynamic stress amplitude under the same percentage of rock conditions (Figure 5(c)). At the same time, the higher the frequency, the greater the peak stress. Under the same frequency loading conditions, peak stress gradually decreased with the increasing percentage of rock. The graphs showed clearly that peak stress gradually decreased with the increasing percentage of rock under the same frequency.

3.4. Deformation characteristics

The curve of elasticity modulus subjected to the frequency, dynamic stress amplitude and percentage of rock (Figure 6) showed that the elasticity modulus decreased gradually, with the increasing dynamic stress amplitude under the same frequency, while, the higher the percentage of rock, the bigger the elasticity modulus. In all cases, elasticity modulus gradually decreased with the
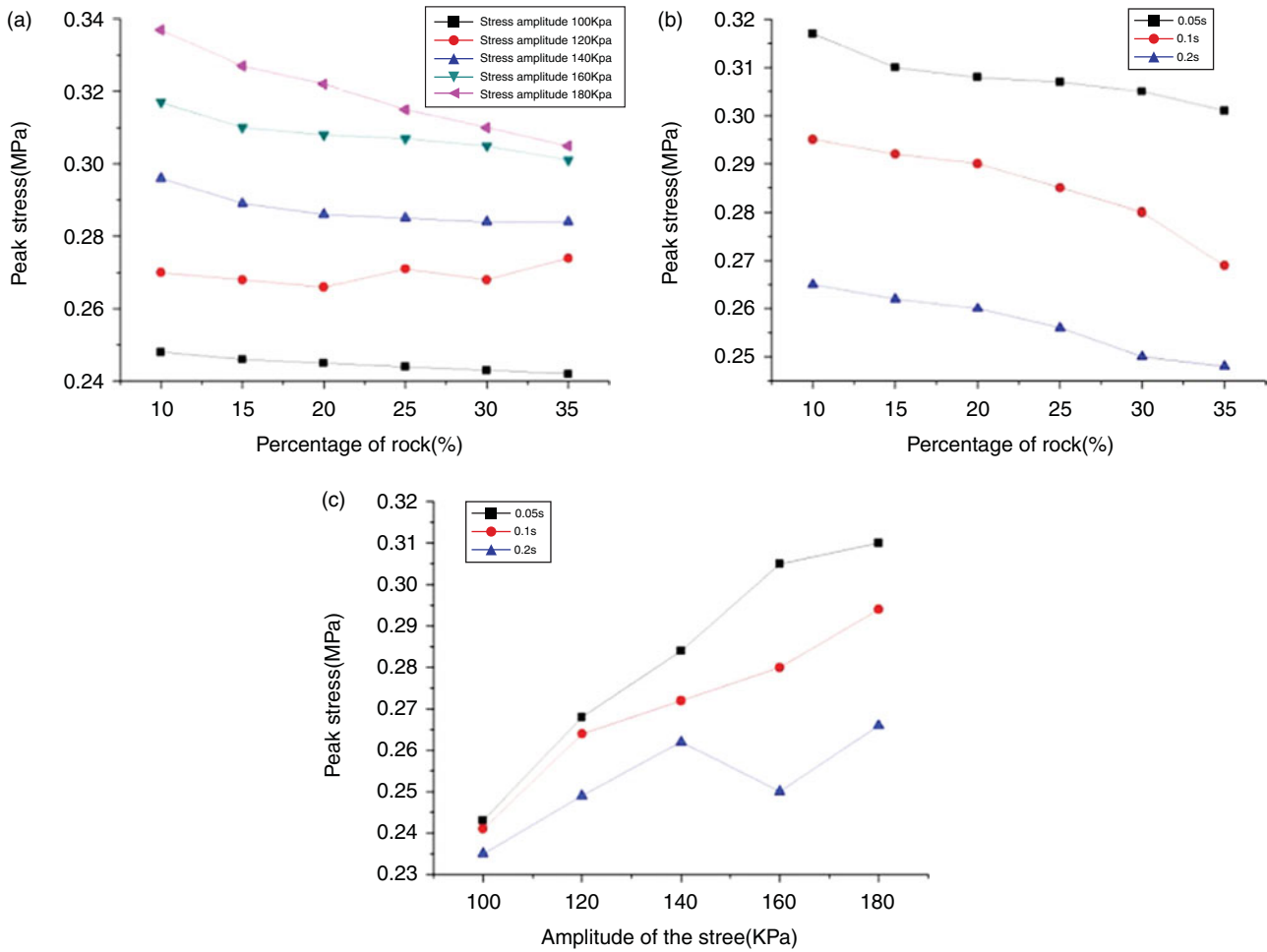
Figure 5. The relationship between peak stress, amplitude, cycle and rock percentage.
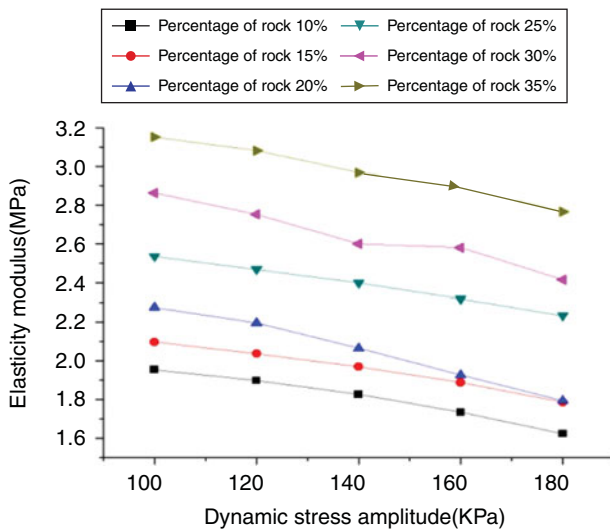

Figure 6. Elasticity modulus curve with amplitude ($t = 0.1$ s).

increasing frequency under the same dynamic stress amplitude loading conditions.

4. Conclusions

Numerical simulation about SRM under equal stress and cyclic loading conditions assessed a series of mechanical characteristics of SRM. The results indicated that peak stress gradually increased with the increasing dynamic stress amplitude and frequency, but decreased with the increasing percentage of rock because the stiffness decreased greatly under cyclic loading, as higher loading frequencies imply less time for hysteresis loop energy dissipation, so they produce more damage to tested materials. The obtained results corroborated this trend. At the same time, the elasticity modulus decreased gradually with the increasing dynamic stress amplitude and frequency, with higher loading frequency and dynamic stress amplitude implying much more com-

pression unit time. Thus, internal damage would be larger and elasticity modulus would be decreased.

Some elementary knowledge obtained from the numerical experiment about the SRM showed the complexities involved with the following three aspects deemed necessary. First, the diameter distribution of stone should be considered; second, three-dimensional numerical models would exactly reflect the mechanical characteristics of SRM and third, comparison with experimental data with the same loading conditions is necessary.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Araei, A. A., Razeghi, H. R., Tabatabaei, S. H., & Ghalandarzadeh, A. (2012). Loading frequency effect on stiffness, damping and cyclic strength of modeled rockfill materials. *Soil Dynamics and Earthquake Engineering*, *33*, 1–18.5.

Cao, Z., LeslieYoud, T., & Yuan, X. (2011). Gravelly soils that liquefied during 2008 Wenchuan, China earthquake, Ms=8.0. *Journal of Soil Dynamics and Earthquake Engineering*, *31*, 1132–1143.

Chigira, M., Wu, X., Inokuchi, T., & Wang, G. (2010). Landslides induced by the 2008 Wenchuan earthquake, Sichuan, China. *Journal of Geomorphology*, *118*, 225–238.

Donaghe, R. T., & Torrey, V. H. (1994). A compaction test method for soil-rock mixtures in which equipment size effects are minimized. *Geotechnical Testing Journal*, *17*, 363–370.

Fan, X., van Westen, C. J., Korup, O., Gorum, T., Xu, Q., Dai, F., ... Wang, G. (2012). Transient water and sediment storage of the decaying landslide dams induced by the 2008 Wenchuan earthquake, China. *Journal of Geomorphology*, *171–172*, 58–68.

Fan, Y. B., Li, S. H., & Feng, C. (2013). A study of the failure mechanism of rock and soil associate under different boundary conditions. *Journal of Hydrogeology and Engineering Geology*, *40*, 48–51 (in Chinese).

Feng, C., Li, S. H., Liu, X., & Zhang, Y. N. (2014). A semi-spring and semi-edge combined contact model in CDEM and its application to analysis of Jiweishan landslide. *Journal of Rock Mechanics and Geotechnical Engineering*, *6*, 26–35.

Fuenkajorn, K., & Phueakphum, D. (2010). Effects of cyclic loading on mechanical properties of Maha Sarakham salt. *Engineering Geology*, *112*, 43–52.

Gorum, T., Fan, X., van Westen, C. J., Huang, R., Xu, Q., Tang, C., & Wang, G. (2011). Distribution pattern of earthquake-induced landslides triggered by the 12 May 2008 Wenchuan earthquake. *Journal of Geomorphology*, *133*, 152–167.

Huang, R. (2009). Mechanism and geomechanical modes of landslide hazards triggered by Wenchuan 8.0 earthquake. *Chinese Journal of Rock Mechanics and Engineering*, *28*, 1239–1249 (in Chinese).

Jiang, H., Wang, B., & Lu, X. (2013). Experimental study on damage behavior of reinforced concrete shear walls subjected to cyclic loads. *Journal of Earthquake Engineering*, *17*, 958–971.

Lee, K. L., & Seed, H. B. (1967). Cyclic stress conditions causing liquefaction of sand. *Journal of Soil Mechanics and Foundation Division, Proceedings of ASCE*, *93*, No. SM1.

Li, S. H. (2013). Progressive failure constitutive model of fracture plane in geo-material based on strain strength distribution. *International Journal of Solids and Structures*, *50*, 570–577.

Li, X. (2010). *Geo-mechanics classification and related parameters research of slope* (The Report of Knowledge Innovation Project of Chinese Academy of Sciences, in Chinese) Chinese Academy of Sciences, 1–50.

Li, X., Liao, Q., He, J., & Chen, J. (2007). Study of in-situ tests of mechanical characteristics on soil-rock aggregate. *Chinese Journal of Rock Mechanics and Engineering*, *26*, 2377–2384 (in Chinese).

Liu, E., Huang, R., & He, S. (2012). Effects of frequency on the dynamic properties of intact rock samples subjected to cyclic loading under confining pressure conditions. *Rock Mechanics and Rock Engineering*, *45*, 89–102.

Ouyang, Z., Li, S. H., & Dai, Z. S. (2010). On the influence factors of mechanical properties for soil-rock mixture. *Journal of Experimental Mechanics*, *25*, 61–67 (in Chinese).

Rücknagel, J., Götze, P., Hofmann, B., Christen, O., & Marschall, K. (2013). The influence of soil gravel content on compaction behavior and pre-compression stress. *Geoderma*, 226–232.

Seed, H. B., & Idriss, I. M. (1967). Analysis of soil liquefaction, Niigata earthquake. *Journal of Soil Mechanics and Foundation Division, Proceedings of ASCE*, *93*, No. SM3.

Seed, H. B., & Lee, K. L. (1966). Liquefaction of saturated soils during cyclic loading. *Journal of Soil Mechanics and Foundation Division, Proceedings of ASCE*, *92*, No. SM6.

Toufigh, M. M., & Ouria, A. (2009). Consolidation of inelastic clays under rectangular cyclic loading. *Journal of Soil Dynamics and Earthquake Engineering*, *29*, 356–363.

Wang, L. X. (2013). A GPU-based parallel procedure for nonlinear analysis of complex structures using a coupled FEM/DEM approach. *Mathematical Problems in Engineering*, *61*(8), 1–15.

Xu, W., Xu, Q., & Hu, R. (2011). Study on the shear strength of soil-rock mixture by large scale direct shear test. *International Journal of Rock Mechanics and Mining Sciences*, *48*, 1235–1247.

Zhao, A., Feng, C., Li, S., AI, C., & Liu, Y. (2012). Experimental research on seismic failure mode and supporting for slope of bedrock and overburden layer. *Journal of Rock and Soil Mechanics*, *33*, 515–523 (in Chinese).

Zou, D., Xu, B., Kong, X., Liu, H., & Zhou, Y. (2013). Numerical simulation of the seismic response of the Zipingpu concrete face rockfill dam during the Wenchuan earthquake based on a generalized plasticity model. *Journal of Computers and Geotechnics*, *49*, 111–122.