Paper No. 370. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

CYCLIC DEFORMATION AND STRENGTH OF DASHIHE MINE SLIME

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ABSTRACT

The undrained cyclic behavior of saturated mine slime was examined by means of dynamic triaxial apparatus. The deformation, pore water pressure and strength were studied under diverse stress conditions. Dynamic strength correction factors K_α and K_σ were discussed. The residual strength after cyclic loading was investigated in detail.

KEYWORDS

Mine slime; undrained cyclic response; initial consolidation stress; residual strength; cyclic trixial test.

INTRODUCTION

A tailings dam has become a critical component of modern mining operation. Generally it is a major soil structure that demands considering effect of earthquake loading on its stability. According to the construction method, a tailings dam is fallen into three categories: a upstream dam, a downstream dam and a centerline dam. In early practice, tailings dams, most of which are still under service, were almost constructed by the upstream method. That is mainly because this method is simple, economic and easy to construct. Following its procedure, each stage embankment is directly constructed on the previously deposited slime which is finer part of tailings and is usually at loose, saturated and unconsolidated condition during the life of the impoundment. Therefore the performance of the slime under shaking loading influences greatly upon seismic response and stability of the upstream tailings dam. Writers pain more attention into the effect of the slime upon the response and liquefaction of dams while investigating two major Chinese tailings impoundments using state-of-the-practice analysis technique (Xin and Wang, 1989). It was found that the slime deposit reduced or unamplified the acceleration response of the dam under design earthquake motions from Chinese Code. It was thought that the development of larger plastic deformation may contribute to this response. That is to say, the soft slime layer maybe absorb a large amount of engine when seismic waves with higher amplitude propagate upward through it.

Except investigation of Ishihara et al. (1980), studying on mine slimes was rarely reported, at least to the writer' knowledge. Researching about natural cohesive soils and marine clay has made known that the performance of soft clay is much distinguished from that of sands under cyclic loadings (Andreasson, 1980; Idriss, et al., 1978; Lee and Focht, 1976; Seed and Chen, 1969; Sun, et al., 1988; Zen and Higchi, 1984). The actual ground responses of Tianjin area during the 1976 Tangshan earthquake and Mexico City area during the 1985 Mexico City earthquake are two excellent cases that indicate some role of the soft clay in seismic site response.

It can been seen that understanding of the dynamic behavior of the slime is one of key factors to estimate the performance of the upstream tailings dam during earthquake. A more comprehensive laboratory testing program, financed by IDRC of Canada, was therefore conducted at Central Research Institute of Building and Construction, MMI, China to investigate the dynamic characteristics of the slime under cyclic loading. These tests and results are described in this paper as follows.

SLIME TESTED AND TEST PROCEDURES

Slime Properties

The slime investigated were retrieved from the 1990 site investigation on Dashihe Tailings Dam, which experienced sandboil, cracks and residual deformation during the 1976 Tangshan earthquake. Based on the stratigraphy of the dam, Dashihe slime was classified into three soil types: silt, loam and clay. The grain size distribution curves for these three soils are shown in Figure 1. The basic indexes of these soils are given in Table 1. According to USCS, the tailings silt belongs into sandy clay and both loam and clay are silty clay.

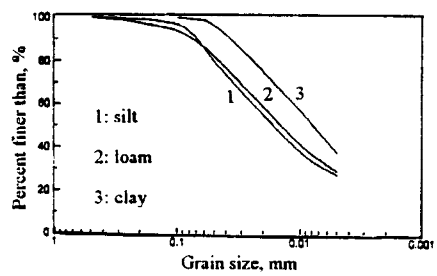

Figure 1 Grain size distribution curves.

Table 1 Index properties of slime tested

Index	Silt	Loam	Clay
Specific gravity	2.83	2.77	2.86
Liquid limit (%)	24.8	26.9	40.9
Plast. index (%)	8.6	11.0	20.4

Note: the liquid limit was determined from fall cone test.

Table 2 Consolidation conditions

σ'_3	K_c=1.0	K_c=1.1	K_c=1.5	K_c=2.0
100	-	T-2	T-2	T-2
300	T-1	T-2	T-2	T-2
450	-	T-2	T-2	T-2

Note: T-1=Modulus and damping ratio, and T-2=Strength test.

Sample Preparation and Test Procedures

Test specimens 5 cm in diameter and 10 cm in higt were prepared at a dry density of 14.5 kN/m^3, by a procedure that has come to be known as moist tamping. Following this procedure, moist soil was tamped into a membrane mold in six layers.

A stress-controlled cyclic triaxial apparatus made in Japan, model SUM-1, was uses in this research. The specimens were fully saturated in triaxial chamber by applying an appropriate back pressure, magnitude of 150 kPa or 250 kPa. Skempton's B-value was greater than 0.98.

After each sample has been saturated, it was isotropically consolidated under a desired effective confining pressure, 100 *k*Pa, 300 *k*Pa or 450 *k*Pa. *U*-value, degree of consolidation, not was less than 95%. In anisotropical condition, the sample was then consolidated under an axial deviator stress corresponding to desired consolidation stress ratio, K_C, which was defined as ratio of effective maximum principal stress, σ_1', to effective minimum principal stress, σ_3'. Table 2 lists the consolidation stresses that the specimens encountered.

When a sample was fully consolidated in the pressure cell, the drainage valves were all closed, and cyclic axial loading was applied using a sine wave at a cyclic frequency of 1 Hz. The axial stress, axial strain and dynamic pore water pressurs were measured by appropriate transducers and captured by micro-computer.

RESULTS OF DYNAMIC LOADING TESTS

Shear Moduli and Damping Ratio

In this investigation the shear moduli and damping characteristics of the slime were determined from the hysteretic stress - strain relationshipe determined by cyclic undrained triaxial test. For each loading cycle, a hysteresis loop was plotted. The equivalent modulus was obtained from the secant modulus which represented the average modulus of the loop. The equivalent damping factor at a shear strain level was determined from the area inside the hysteresis loop using standard procedures (Seed and Idriss, 1970). It was considered that the shear modulus and damping ratio at the 7th cycle fom 10 cycles represent average of soil which suffered from earthquake of magnitude 6 or 7 (Seed et al., 1984).

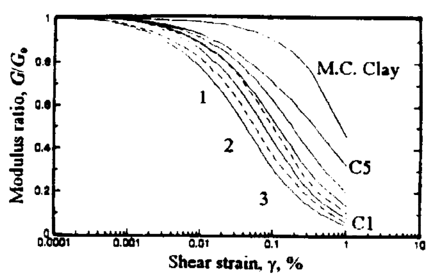

Fig. 2. Noralized modulus reduction relationship with different plasticity indices.

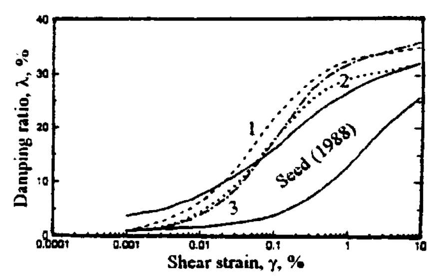

Fig. 3. Strain dependent damping ratios.

Figure 2 shows the normalized modulus reduction curves of the slime. in which the reduction curves of clay soils are also plotted proposed by Sun et al.(1988). It is clear that the modulus reduction of the slime decreases with increasing the plasticity index and its behavior looks similar to that of clay soils. The strain dependent damping ratios are shown in Figure 3. The solid lines in this Figure are after Seed and Idriss (1977) on clayer soils. It clearly indicates the damping ratio characteristics with shear strain of the slime displays like that of the clayer soils.

Dynamic Strength

A consolidated undrained cyclic triaxial test was performed to understand cyclic shear strength. Failure was defined at 5% amplitude cyclic axial strains in this research. A total of 99 cyclic loading tests were carried out into reconsolidated samples. Table 3 summarizes the basic properties of each specimen before cyclic loading.

The records of typical cyclic loading tests on sample are given in Figure 4. It is noted that: 1.) An axial strain gradually increases with number of cycles and the higher consolidation ratio, the faster developed permanent deformation.; 2.) Cyclic pore water pressure fluctuated in large and within former cycles a 'suction pore pressure' was induced when the sample was extended, with total pore pressure being lower than the static equilibrium pore pressure before cyclic loading. And it is observed that the higher the consolidation stress ratio and plasticity index, the longer appeared this response.; 3.) On the first cycle a pore pressure developed greatly, but the residual porepressure did not develop up to the initial effective confining pressure when axial strain reached to 5%.

Table 3 State of specimen after consolidation

Soil		σ'_3 kP_a	γ_d kN/m^3	ω %	Hc cm	B
	Kc=1.1	100	15.3	30.5	9.687	0.982
		300	15.7	28.4	9.694	0.990
		450	16.1	26.8	9.662	0.997
Silt	Kc=1.5	100	15.3	30.0	9.589	0.983
		300	15.7	28.4	9.467	0.982
		450	16.2	26.4	9.432	0.990
	Kc=2.0	100	15.4	29.4	9.275	0.980
		300	15.8	28.0	9.215	0.988
		450	16.4	25.6	9.130	0.992
	Kc=1.1	100	15.0	30.8	9.812	0.984
		300	15.6	28.0	9.701	0.994
		450	16.0	26.6	9.611	0.993
Loam	Kc=1.5	100	15.2	29.7	9.702	0.983
		300	15.6	28.0	9.645	0.984
		450	16.1	26.0	9.496	0.999
	Kc=2.0	100	15.3	29.3	9.434	0.982
		300	15.9	27.0	9.403	0.979
		450	16.2	25.6	9.318	0.990
	Kc=1.1	100	15.1	31.0	9.777	0.987
		300	15.6	29.1	9.536	0.983
		450	16.2	26.8	9.405	0.984
Clay	Kc=1.5	100	15.3	30.3	9.583	0.980
		300	15.8	27.8	9.317	0.980
		450	16.4	26.0	9.298	0.987
	Kc=2.0	100	15.4	30.0	9.260	0.980
		300	16.3	26.4	9.035	0.982
		450	16.5	25.6	9.017	0.987

Note: σ'_3 = effective cell pressure,
γ_d = dry density after consolidation,
ω = water content after consolidation,
Hc = height of sample after consolidation,
B = Skempton's value.

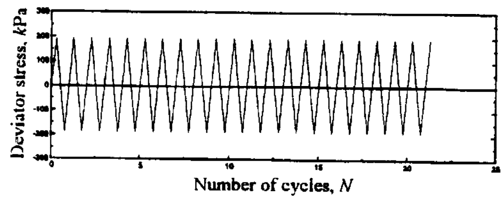

Fig. 4.a Record of deviator stress.

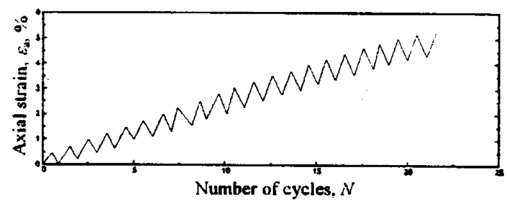

Fig. 4.b Record of axial strain.

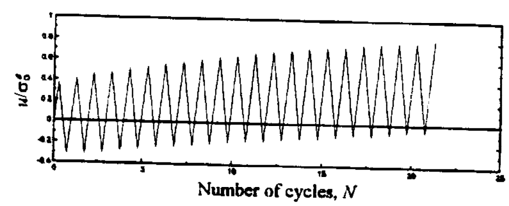

Fig. 4.c Record of WPW ratio.

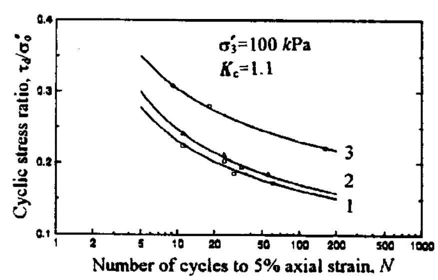

Fig. 5 Variation of Cyclic ratios with Plasticity indices.

Figure 5 depicts the relationship between the cyclic stress ratio, τ/σ_o, and number of cycles required to cause 5% axial strain to Dashihe mine slime with K_c=1.1 and σ'_3=100 kPa. It describes that the increase of finer content and plasticity index increases the cyclic strength of the slime. Moreover it can been seen from Figure 5 that the strength attenuation curve of the slime turns flatter with increasing plasticity.

Effects of effective confining pressure and driving stress on dynamic strength have been paid to more attention on sands (Castro & Christian, 1975; Rollins & Seed, 1988; Seed, 1983; Seed & Harder, 1990; Vaid

& Finn, 1979). Investigations have shown that the normalized dynamic strength tends to decrease as the effective cell pressure increases and the influence of the static shear stress on the resistance against cyclic loading depends on relative density of sand. When sand is at loose condition (D_r<40%), the strength decreases with increasing the initial static shear stress and the strength tends to increase with the driving shear stress when sand is at dense condition (D_r>55%). The correction factors K_α and K_σ proposed by Seed (1983) make it easier to understand the effects of the initial static stress on the cyclic strength. Figure 6 shows the factors K_α and K_σ of the mine slime, in which the factors K_α and K_σ given by Seed and Harder (1990) on sand are also drawn in corresponding Figure, respectively. Figure 6 reveals that effect of the initial static stress on the cyclic strength of the slime is not so strongly as that of sand. The factors of Dashihe slime can be assessed by Equations as follows.

$$K_\alpha = 1.0 - 0.470\alpha \quad (1)$$

$$K_\sigma = 1.0 - 0.023(\sigma_3' - 1.0) \quad (2)$$

where α is initial effective shear stress ratio and σ_3' is effective confining pressure in kg/cm^2.

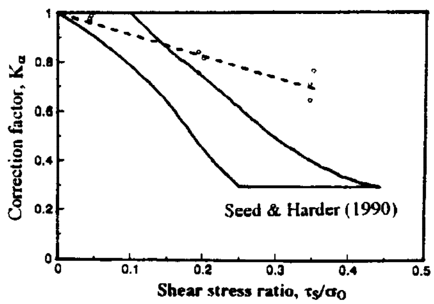

Fig. 6.a Initial static stress ratio versus factor K_α

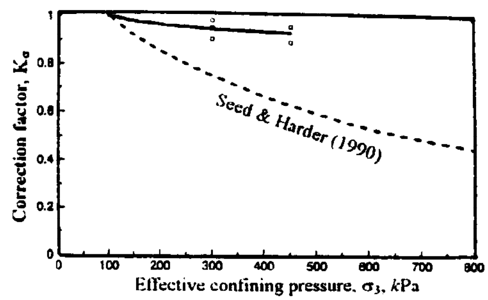

Fig. 6.b Effective confining pressure versus factor K_σ

Residual Strength

The residual, ultimate or steady state strength is a major factor controlling post-earthquake behavior of soil structure. Because real undisturbed sample is too difficult to obtain, the steady state strength cannot be determined directly by undrained shear tests. Seed (1987) recommended that the shear resistance determined by static compression test after cyclic loading was taken as the residual strength of soil. It order to evaluate the strength remaining after earthquake loading, cyclic loading is stopped as soon as the axial strain reaches to 5%. Following that, the static compression tests were carried out. In this procedure, without any additional consolidation after cyclic loading, the sample was then loaded to failure like monotonic shear test.

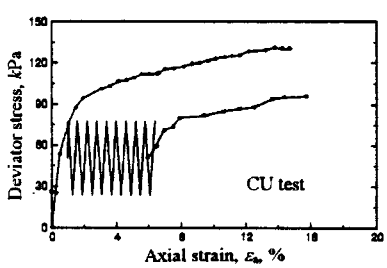

Fig. 7. Stress-strain curve after cyclic loading.

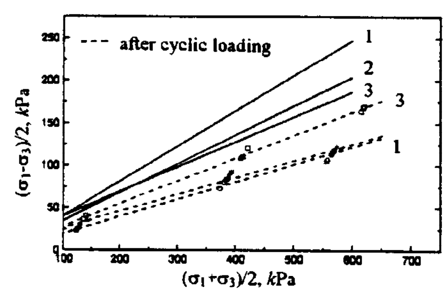

Fig. 8. Strength renaiming after cyclic loading.

The typical monotonic stress-strain curve after cyclic loading is betrayed in Figure 7. The curve obtained from undrained monotonic test is drawn in Figure 7, too. It indicates that the stress-strain relationship of the slime experienced cyclic loading was still of hysteretic but only were the secant moduli and the strength reduced in some degree. Figure 8 summarizes the residual strength of slime tested. For comparison, results from noncyclic loading static consolidated-undrained tests are also drawn in this Figure. It is clear that the strength loss due to cyclic loading decreases with increasing plasticity index. Figure 9 depicts variation of strength ratio, strength remaining after cyclic loading over original static strength, with strain ratio, peak cyclic strain over failure strain in static test. The Figure suggests that the strength remaining after cyclic loading of the slime is about 50% - 70% of the initial static strength. This ratio is lower than the average proposed by Thiers and Seed (1969) on clay soils. The difference may be mainly caused by soil structure. Undisturbed specimens were used in Thiers and Seed's investigation.

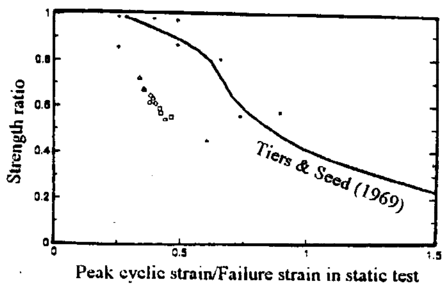

Fig. 9. Variation of strength after cyclic loading

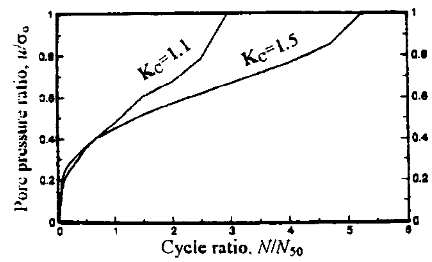

Fig. 10. Normalized pore pressure curves.

Dynamic Pore Water Pressure

A significant factor in seismic stability studies of slope and dams is the development of pore water pressure under earthquake loading. During dynamic loading two kinds of pore water pressures are generated in saturated materials: transient and residual. The transient pressures are due primarily to changes in the applied mean normal stresses during cyclic excitation. Since they balance each other, the effective stress regime in soil remains largely unchanged and therefore the stability and deformability of soil is unaffected. The residual pore water pressures are owing to plastic deformations in the soil skeleton. They exert a major influence on the strength and stiffness of the soil skeleton.

It is observed from test records that loam and clay, especially clay, developed little residual pore water pressure corresponding to 5% axial strain under cyclic loading. Owing to this fact, residual pore pressure is only analyzed to slit. The generation of the pore water pressure is given in Figure 10 based on the model developed by Finn, et al. (1980). In addition, the results showed that the pore water pressure corresponding to 5% axial strain did not developed up to 50% of initial effective stress when specimen was consolidated under K_c=2.0.

CONCLUSIONS

The following conclusions are drawn based upon the results of this investigation.

1. Modulus reduction of the mine slime decreases with increasing finer content and plasticity index. It is found that plasticity has little effect on damping ratio of the slime. The behavior of the slime looks similar to that of clay soils under cyclic loading.

2. Cyclic strength of the mine slime tends to increase as plasticity increases. In addition, the mine slime with higher plasticity has a lower rate of the strength reduction with number of cycles.

3. Initial static shear stress decreases the resistance againsg earthquake of the slime. It means that the correction factor K_α is less than 1.0. This performance of the slime looks like that of loose sand. But K_α has less effect on mine slime than on sand.

4. As the effective confining pressure increases, the cyclic stress ratio of the mine slime tends to decrease. That is to say, the correction factor K_σ is less than 1.0. This response of mine slime is similal to that of sand but reduction rate of the slime is lower.

5. The mine slime exhibits a great fluctuation in pore water pressure under cyclic loading. Within former cycles a 'suction pore pressure' is induced when the sample is extended and the higher the consolidation stress ratio, the longer appears this suction pressure.

6. The strength remaining after cyclic loading of mine slime is about 50% - 70% of original static strength. The strength reduction decreases with increasing plasticity index somewhat.

ACKNOWLEDGMENT

This research was supported by International Development Research Centre, Canada. This support is greatly acknowledged.

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