INVESTIGATING THE DYNAMIC MECHANICS OF SATURATED SOFT SANDSTONE USING ANISOTROPICALLY CONSOLIDATED CYCLIC TRIAXIAL TEST

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ABSTRACT

In anisotropic consolidation, the normal and shear stresses of a sample at the plane 45° from horizontal can be controlled by axial and confining stresses. Therefore, we carry out anisotropic consolidation on Kuanmiao sandstone and conduct static and dynamic triaxial tests to evaluate the static and dynamic mechanism of saturated soft sandstone at the plane 45° from horizontal. In static triaxial tests, soft sandstone undergoes shear contraction, indicated by the excess pore pressure generation, then later turns to shear dilatation since the pressure is then decreases to negative. The cyclic triaxial test results show that the sample becomes unstable when excess pore pressure and axial strain starts to accumulate. The specimen promptly fails when the axial strain reaches 1%, even when the stress state is still below the static failure envelope. Increasing the number of load cycles to failure, N_f, increases the accumulated displacement but decreases the shear modulus, while the damping ratio increases obviously once the sample approaches failure state.

Key Words: Soft rock, Anisotropic consolidation, Shear modulus, Damping ratio

INTRODUCTION

There were many important engineering projects held next to the western foothills areas in recent years, such as tunnel excavations, and highway bridges. However, those areas are mostly consisted of Neogene clastic sedimentary rock with relatively short rock-forming period, which produces porous and poorly cemented soft rock. The strength and consolidation properties of soft rock are usually between soil and rock, making it unsuitable to be simply analyzed by theorems regarding to soil or ordinary rock; thus, before proceeding an engineering design in this area, we need first to understand the stress-strain behavior, mechanical properties, and strength parameters of the soft rocks.

Currently, numerous researches have been done on soft rock in Taiwan with plenty of outcomes, such as “A Study on the Relationship of the Deformation Behavior and the Lithology of Tertiary Period Sandstone” by M.C. Weng, F.S. Jeng, T.H. Huang and L.S. Tsai (2001); and “A Study on the Deformation Behavior of Mushan Formation Sandstone under

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Different Stress Path" by L.S. Tsai, F.S. Jeng and M.L. Lin (2001), which are mainly focused on the deformation behavior of sandstone generated in the tertiary period. Furthermore, C.A. Chen (1994) has done another research on the mechanical behavior of Mushan sandstone under different stress path, when W.Y. Hsieh (1995) did a research on the mechanical behavior of mudstone under various temperatures and pressures. H.M. Lin, Y.F. You and C.J. Liao (2004) studied the mechanical characteristics of Kuanmiao sandstone. C.Y. Chang (1998) and C.Z Su (2000) separately investigate thoroughly on the strain mechanism of soft sandstone from Dakeng area in Taichung, and the in-situ mechanics and hydraulic properties of soft rock of Toukoshan formation at Hsinchu; and T.C. Kao (2000) discussed the bearing behavior of pile driven in the soft rock.

The active earth crust movement around Taiwan produces a lot of earthquakes. Most fault lines are distributed around the western foothills and eastern Taiwan, and strong earthquakes could induce disaster such as ground subsidence, soil liquefaction, slope collapse, landslide and debris flow, but despite of the thorough researches regarding to the mechanical behavior of soft rock in Taiwan, the researches on dynamic behavior of soft rocks are still unpopular.

Thus, we will try to proceed dynamic triaxial tests to probe the dynamic behavior of soft rock during earthquake. Samples of porous soft sandstone are taken from Longci in Tainan, and the laboratory tests are mainly proceeded under anisotropic consolidation to simulate the initial stress condition of soft sandstone on the slope. Dynamic loading is brought by shear stress path method to probe the dynamic behavior of saturated porous soft sandstone under earthquake. The stress path variation of soft sandstone under dynamic loading and its volume variation in shear condition could be calculated from the excess pore pressure variation. Besides, its shear modulus and damping ratio variation under cyclic loading could be found by the theory of elasticity.

THE CONCEPT OF ANISOTROPICALLY CONSOLIDATED DYNAMIC TRIAXIAL TEST

Anisotropic consolidation

By consolidation method, dynamic triaxial test can be separated to be isotropically consolidated and anisotropically consolidated. The former is used to simulate soil layer under ground surface without initial static shear stress (before earthquake), and the latter is generally used to simulate soil layer with initial static shear stress on the failure surface of slope or foundation. In isotropic consolidation, the axial stress σ_1 is similar to the confining stress σ_3. The specimen is evenly consolidated at the plane 45° from horizontal without initial shear stress. In anisotropic consolidation, the axial stress will be larger than the confining stress, and the initial static shear stress τ can be obtained at the plane 45° from horizontal. The difference between the two methods is displayed in Fig.1. Usually, the cyclic shear-stress ratio ($Kc=\sigma_1/\sigma_3$) is used to determine the consolidation state of specimen. When Kc=1 the specimen is isotropically consolidated, and when Kc>1 it is anisotropically consolidated with initial static shear stress. The larger is the ratio, the larger is the initial shear stress.

Stress control method in dynamic triaxial test

Because of the difficulty of test and the limitation of apparatus in normal dynamic triaxial test, confining stress is usually preserved; while, axial stress is changed to simulate the effect of

cyclic shear stress. As shown in Fig.2(a), cyclic shear stress $\Delta\tau=\Delta\sigma_d/2$ is produced at the plane 45° from horizontal when the cyclic axial stress $\Delta\sigma_d$ is loaded on the specimen, but the normal stress $\Delta\sigma_d/2$ which is simultaneously produced at the specified plane, which is different from the actual condition.

Therefore, to preserve the increase of cyclic shear stress $\Delta\tau$ at the plane 45° from horizontal but unchanged stress state in the normal direction, the confining stress will be controlled by server, which enable axial and confining stress to simultaneously change to simulate the actual mechanical behavior of soil layer under cyclic shear stress. Fig.2(b) shows the loading method in the dynamic triaxial test in this research, which is similar to the stress control method for ideal dynamic triaxial test mentioned by Seed & Lee (1996).

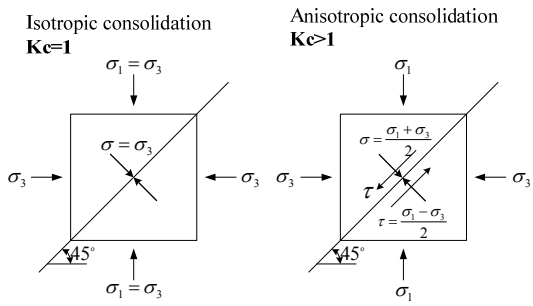

Fig. 1 The stress condition of specimen in triaxial test under isotropic and anisotropic consolidation

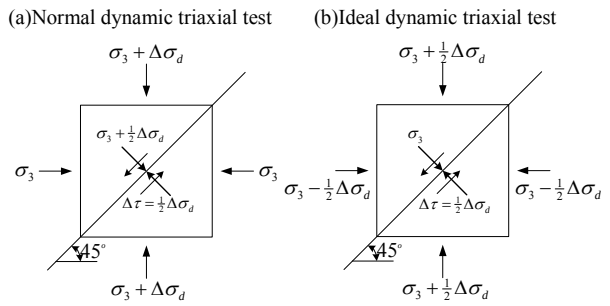

Fig. 2 The stress loading method on normal and ideal dynamic triaxial test under isotropic consolidation

Calculation method of stress condition

In this research, dynamic triaxial tests are mainly anisotropically consolidated to simulate the dynamic behavior of saturated porous soft sandstone slope under earthquake, which will be shown in Fig.3. Fig.3(a) is an unlimited slope with potential sliding surface at depth H. The initial normal stress σ_o' and initial shear stress τ_o at the sliding surface are separately calculated by equations (1) and (2).

Once the initial condition at potential sliding surface is defined, we proceed anisotropic consolidation by adding different axial stress σ_1 and confining stress σ_3 to let the stress state at the plane 45° from horizontal similar to those formed at potential sliding surface, where initial static shear stress exists. The magnitude of axial and confining stress can be calculated by the relationship shown in Fig.3(b). Fig.3(c) shows the axial and confining stresses loaded to cylindric specimen, where cyclic shear-stress ratio Kc can be calculated from the relationship of both stresses.

$$\sigma_o^{'} = \frac{W\cos^2\theta}{b} = \left[\gamma_d(H-H_w)+(\gamma_{sat}-\gamma_w)H_w\right]\cos^2\theta \tag{1}$$

$$\tau_o = \frac{W\sin\theta\cos\theta}{b} = \left[\gamma_d(H-H_w)+\gamma_{sat}H_w\right]\sin\theta\cos\theta \tag{2}$$

Where:

γ_d is the dry unit weight of soft sandstone

γ_{sat} is the saturated unit weight of soft sandstone

H_w is the groundwater depth, and

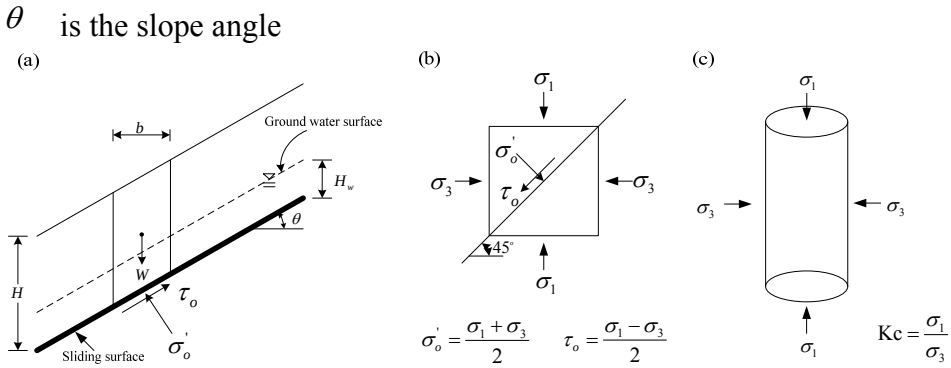

Fig. 3 The stress condition design for anisotropically consolidated dynamic triaxial test

TEST MATERIAL AND METHOD

Test material

The porous soft sandstone taken from Longci area in Tainan is investigated in this research. The geological map proposed by W.P. Keng (1981) shows that the rock belongs to the Kuanmiao formation, which is comparable to Toukoshan formation in northern Taiwan. Kuanmiao formation is integrated over Nanhua mudstone, which mainly ranges from lumpy fine sand to sandy quartzitic sandstone, with few alternations of sandstone and mudstone. Its thickness is between 5m to 20m, which often become a syncline slope along its inclination angle. The loose structure is due to the short rock-forming period, making it similar to silt or silty sand when it is disturbed or softened by water. Fig.4 is the geological map drawn by the National Geological Survey, MOEA, and the red dot in the figure shows the sampling area of this research, which is located at a slope of county highway No.182 at 22.5K. Field investigation showed that the strike direction is N16E with dip angle between 26° to 34°.

The basic properties of samples used in this research are shown in Table 1, which were porous soft sandstone as shown by void ratio e=0.39. Hydraulic conductivity k=5.9×10^{-5}(cm/sec) indicates good permeability, and from the aspect of slaking index Id_1=0, which is classified as rock with very low durability (Gamble, 1971). Therefore, the slope could be sensitive to weathered and eroded, which could eventually lead to failure. Besides, water content is also an important factor for soft sandstone, where the uniaxial compressive strength for saturated specimen decreases about 20% of those of dried specimen. According to the results of uniaxial compressive strength, the Kuanmiao formation sandstone is classified as soft rock(ISRM, 1981)

Table 1 Properties of soft sandstone

Properties		Value
Field wet unit weight, γ_t(kN/m^3)		20.5
Field water content, w(%)		9.0
Dry unit weight, γ_d(kN/m^3)		18.8
Specific gravity, G_s		2.61
Void ratio, e		0.39
	Sand, (%)	63
Grain-size distribution	Silt, (%)	36
	Clay, (%)	1
Hydraulic conductivity, k(cm/sec)		5.9×10^{-5}
Slaking Index, Id_1(%)		0
Uniaxial compressive strength on air dried specimen, (MPa)		1.98
Uniaxial compressive strength on saturated specimen, (MPa)		0.36

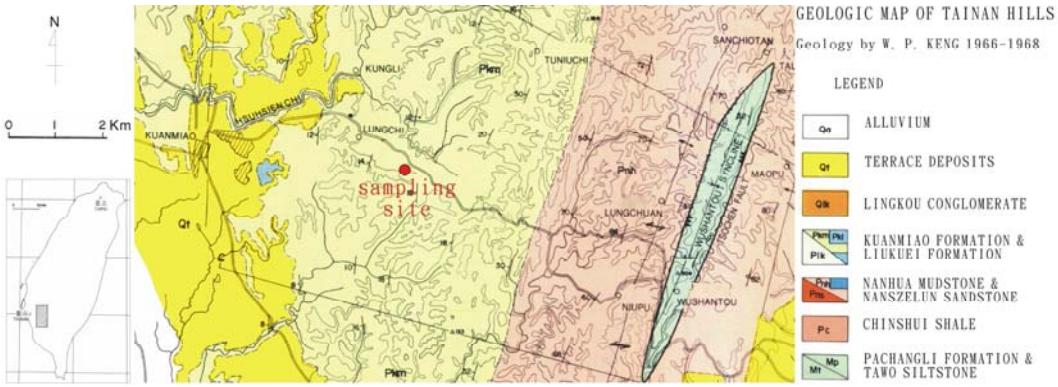

Fig. 4 The geological map of the hills area around east side of Tainan (referred from National Geological Survey, MOEA)

Test method

1. Isotropically consolidated - undrained static triaxial test
Soft sandstone is easily loosen by water, thus, cylindric specimen will be made by pneumatic drill with the ratio of length/diameter=2.0. The drilled specimen is placed into test apparatus and water is added to saturate the specimen and eliminate air bubbles. Consolidation step could be started once B value reaches 0.9, with previously loaded confining stress. Valves at the top and bottom of apparatus are used as drainage path in consolidation process, and the consolidation is completed when excess pore pressure decreases to zero or there is no more volume change in specimen. Valves will be closed when the consolidation completes, and axial stress in rate of 0.2mm/min will be loaded to proceed undrained static triaxial test. The variation of stress-strain relationship curve will be observed, and loading should be stopped once the deviator stress and excess pore pressure become static. The volume change of specimen after test can be measured from the record on volume strain tube.

2. Anisotropically consolidated - undrained static triaxial test
Before anisotropic consolidation is proceeded on the specimen, both axial and confining stresses are loaded to initial value to simulate the initial normal and shear stresses at the plane 45° from horizontal. Confining stress should be loaded before it is followed by axial stress, then the valves can be opened to process consolidation. Once excess pore pressure and volume change of specimen are static, valves are closed and the loading stage is started. This test will be compared to the dynamic triaxial test; therefore it will be performed through pure shear stress path. Rate of 0.05MPa/min is used to conduct axial compression and lateral extension until the specimen fails.

3. Anisotropically consolidated - undrained dynamic triaxial test
This research aims to probe the dynamic behavior of soft rock during earthquake, and it is conducted under anisotropic consolidation to simulate initial stress condition of soft sandstone in a slope. Cyclic loading of axial and confining stresses are controlled by server to probe mechanical behavior and dynamic parameters variation of specimen under pure cyclic shear stress, therefore, both axial and confining stresses should be loaded to initial value on saturated specimen to conduct anisotropic consolidation and to simulate the initial normal and shear stresses at the plane 45° from horizontal. Once the consolidation finishes, valves are closed to start cyclic loading with 0.1Hz sine wave. The angle between axial and confining stress is 180°, and the cyclic loading continues until the specimen fails. Fig.5 shows the cyclic axial and confining stress used in this research.

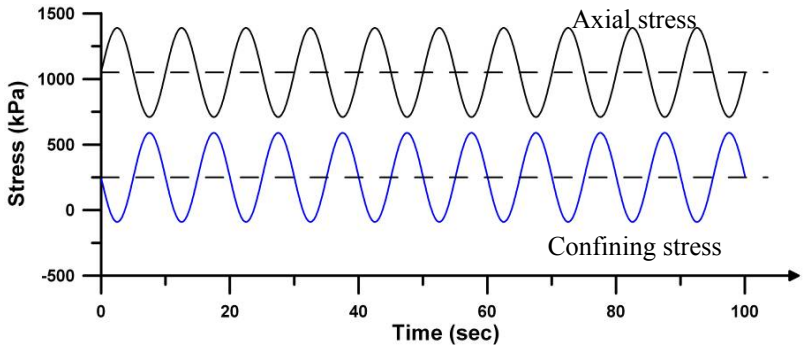

Fig. 5 Cyclic loading in the anisotropically consolidated - undrained dynamic triaxial test

TEST RESULTS AND DATA ANALYSIS

Isotropically consolidated - undrained static triaxial test

Isotropically consolidated – undrained triaxial test is done on porous soft rock specimen to understand its mechanical behavior under static loading, and the test is combined with different confining stresses to probe its stress-strain relationship. The shear behavior of specimen is acquainted from excess pore pressure variation. Fig.6 shows the stress-strain curve and excess pore pressure variation curve of the isotropically consolidated - undrained static triaxial test, from which, we can see that specimen strength is increased along with the increment of confining stress, but strain-softening exhibits when the confining stress is lower than 2MPa, and it is then ended with brittle failure. From excess pore pressure variation curve, the specimen undergoes shear contraction in initial shear stage with positive excess pore pressure. Excess pore pressure reaches the maximum value when axial strain increased around 0.5% to 0.8%, before later turned to negative. At the same time, specimen undergoes shear dilatation. Maximum negative value is reached when the specimen fails, and contraction degree is raised along with the increment of confining stress.

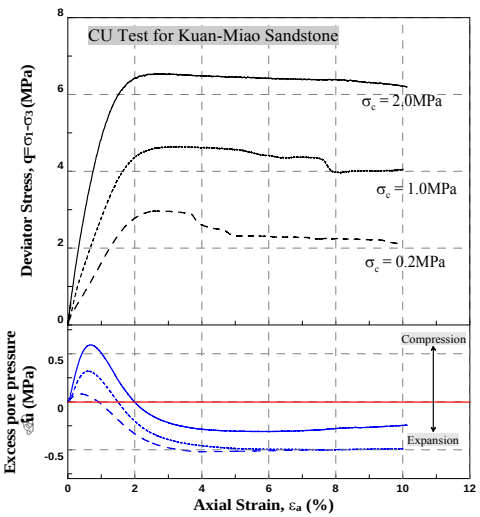

Fig. 6 The stress-strain relationship and excess pore pressure variation curve of the isotropically consolidated - undrained static triaxial test

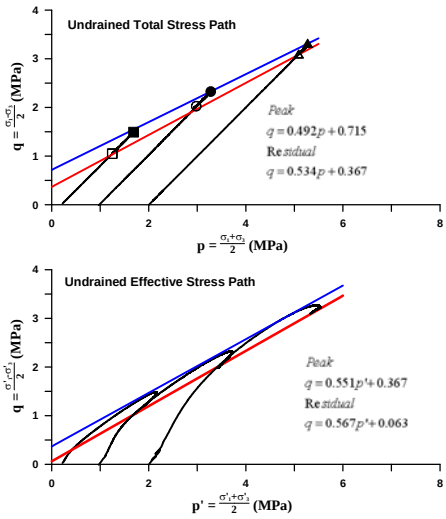

Fig. 7 Total stress path and effective stress path of the isotropically consolidated - undrained static triaxial test

From the effective stress path (Fig.7), the effective stress rises continuously once the specimen is sheared, and after it reaches maximum value, the specimen fails and the effective

stress decreases to the residual condition. Shear dilatation is obvious when the confining stress is under 2MPa, which is similar to the behavior of dense sand. Regression line equation as shown in Fig.7 is obtained by regressing the peak and residual stresses. Table 2 shows the shear strength parameters in Mohr-Coulomb failure criterion $\tau = c + \sigma \tan\phi$ which is obtained by proceeding linear regression over Mohr stress circle drawn by the test results.

Table 2 Shear strength parameters obtained from the isotropically consolidated - undrained static triaxial test

Confining stress, σ'_C (MPa)	c_p (MPa)	ϕ_p (°)	c_r (MPa)	ϕ_r (°)	c'_p (MPa)	ϕ'_p (°)	c'_r (MPa)	ϕ'_r (°)
0.2-2.0	0.82	29.5	0.43	32.3	0.44	33.4	0.08	34.5

Anisotropically consolidated - undrained static triaxial test

Anisotropic consolidation is proceeded on rock specimen to produce initial shear stress at the plane 45° from horizontal to simulate the initial stress condition of the soft sandstone slope to probe its stress-strain behavior, excess pore pressure and effective stress path under pure shear stress. In the terms of consolidation stress, assume the slope is 45 m high with 30° inclination, with groundwater located 39.5m below ground surface, which result in initial normal stress σ_o'=0.65MPa and initial shear stress τ_o=0.4MPa, so the consolidation is proceded with σ_1=1.05MPa and σ_3=0.25MPa. Once the consolidation finishes, the test will be proceeded with rate of 0.05MPa/min.

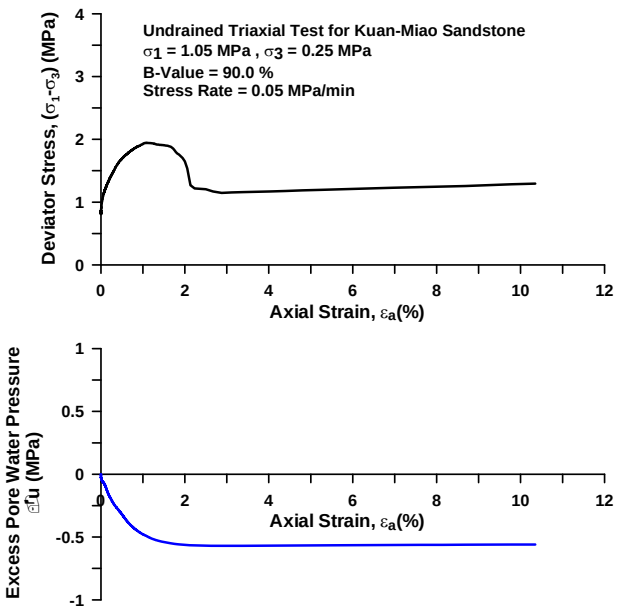

Fig. 8 The stress-strain relationship and excess pore pressure variation curve of the anisotropically consolidated - undrained static triaxial test

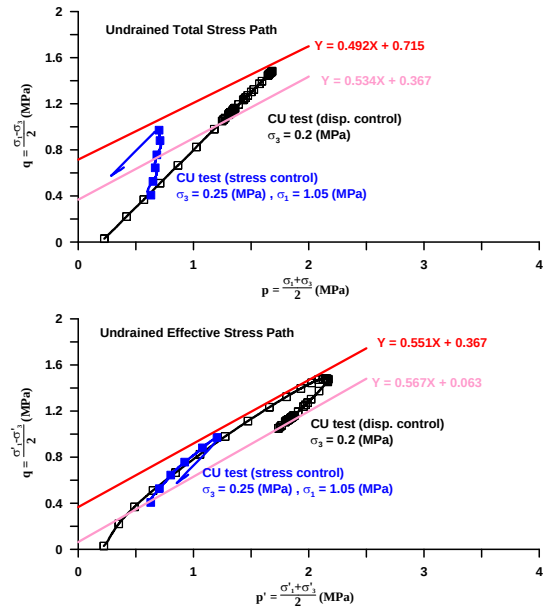

Fig. 9 Stress path of the undrained static triaxial test (comparison between isotropic and anisotropic consolidation)

Fig.8 shows the stress-strain curve and excess pore pressure variation curve obtained by the test, from which the strain-softening exists and the failure mode is brittle. Excess pore pressure continues to accumulate in negative value along with the increment of axial strain before later become stable. In Fig.9 we compare the stress path of this test with the confining stress 0.2MPa in isotropically consolidated test. The total stress path in anisotropic consolidation has already failed when it approaches to the failure line, while the residual stress approaches the residual line. The effective stress path of the test is almost reduplicating those of isotropically consolidated, where it has also failed when it approaches the failure line

and eventually decreases the effective stress. This is expected to be caused by partial cracks on specimen produced when the axial stress is larger than confining stress in anisotropic consolidation process.

Anisotropically consolidated - undrained dynamic triaxial test

Anisotropically consolidated dynamic triaxial test is proceeded to probe the dynamic behavior of porous saturated soft sandstone slope during an earthquake, where cyclic loading of axial and confining stresses are controlled to maintain the pure shear stress condition. Dynamic behavior is acquainted by measuring the variation of excess pore pressure and axial strain. At the same time, the variation of dynamic parameters can be acquainted by calculating the relationship of shear modulus G and damping ratio D with the number of load cycles.

Table 3 The results of the anisotropically consolidated - undrained dynamic triaxial test

Specimen No.	Water content (%)	K_c	σ_1 (kPa)	σ_3 (kPa)	σ'_o (kPa)	τ_o (kPa)	τ_{cyc} [a] (kPa)	$\triangle u_{max}$ [b] (kPa)	N_f [c]
D-1	18.0		1050	250			370	250	72
D-2	18.3	4.2	1050	250	650	400	340	195	327
D-3	18.0		1050	250			310	190	195

a) Cyclic shear stress
b) Maximum excess pore pressure
c) Load cycles to failure

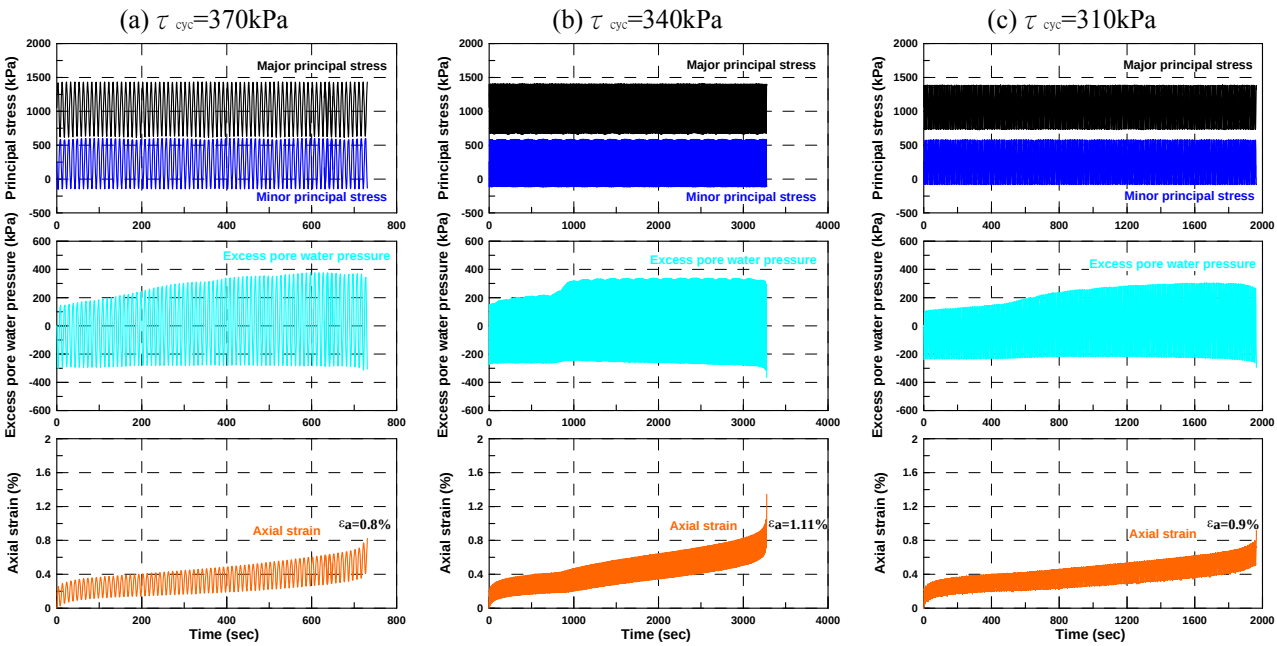

Fig. 10 The results of the anisotropically consolidated - undrained dynamic triaxial test (Kc=4.2)

Anisotropic consolidation is again proceeded with σ_1=1.05MPa and σ_3=0.25MPa (Kc=4.2). The cyclic loading is proceeded under 0.1Hz sine wave. Table 3 and Fig.10 show the results of the anisotropically consolidated - undrained dynamic triaxial test. There is obvious accumulation of excess pore pressure before failure, which decreases the effective stress of specimen and gradually increases the axial strain, and the specimen promptly fails once the axial strain is around 1%.

Accumulated excess pore pressure is increased along with the increment of cyclic shear stress. By observing the variation of axial strain, excess pressure accumulation is separated into 3

stages. Accelerated accumulation in the first stage is followed by the stable second stage, while the rapid increment in third stage starts when there is obvious accumulation of the excess pore pressure. This shows the obvious influence of excess pore pressure accumulation to soft sandstone, since the effective stress decreases and axial strain increase continuously once the excess pore pressure is obviously accumulated.

Dynamic parameters variation

To probe the dynamic parameters variation of porous saturated soft sandstone under cyclic loading, the loop of number of cycles in each stress-strain variation curves is calculated to obtain the variation of shear modulus G and damping ratio D. Elastic modulus needs to be found before calculating the shear modulus by the theory of elasticity such as shown in equation (3). Damping ratio is calculated by Kelvin-Voigt model, which relationship with loop cycle is shown in Fig.11; and the damping ratio of each loop can be obtained by equation (4). In which, △W indicates the energy lost during each loop, and W is the maximum strain energy stored within an object.

$$G = E / 2(1+\upsilon) \tag{3}$$

$$D = \frac{1}{4\pi}\frac{\Delta W}{W} \tag{4}$$

Fig.12 shows the relationship between shear modulus and the number of cycles, from where the initial shear modulus G increases together with the number of cycles N, which happens since the initial cyclic loading presses the void inside porous soft sandstone and makes it denser, but excess pore pressure accumulates under cyclic shear stress which slowly destroys the cementation of the rock, which rapidly decreases the shear modulus G when the sample fails. Fig.13 shows the relationship between damping ratio and the number of cycles, from where the damping ratio tends to decrease until it becomes stable along with the increment of the number of cycles, but then contrarily increases when the sample approaches to failure, which happens since the energy lost when the specimen is softening due to cyclic loading continues to increase. The damping ratio increases, then rapidly deforms.

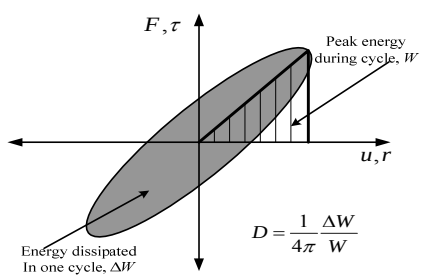

Fig. 11 The relationship of loop cycle and damping ratio

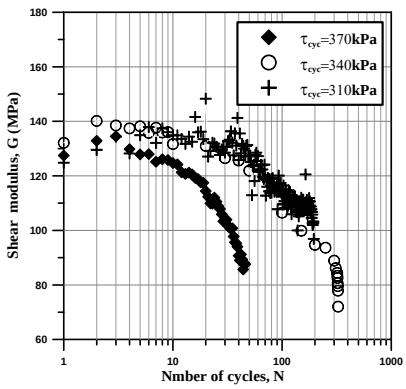

Fig. 12 The relationship between shear modulus and the number of cycles

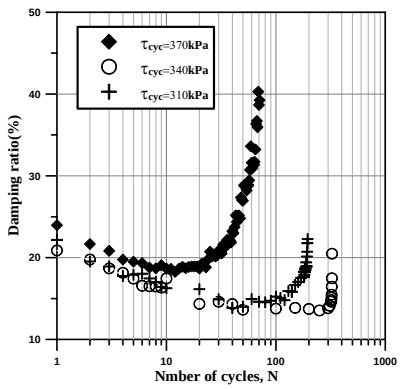

Fig. 13 The relationship between damping ratio and the number of cycles

CONCLUSIONS

From the excess pore pressure variation under confining stress between 0.2 and 2.0MPa in isotropically consolidated – undrained static triaxial test, the soft sandstone undergoes shear contraction in the initial shear stage, but turns to shear dilatation when the excess pore pressure reaches maximum value. The maximum negative value of excess pore pressure is approached when the deviator stress is maximized, and, at the same time, the shear dilatation degree of specimen is also maximized.

The result of anisotropically consolidated – undrained dynamic triaxial test of saturated Kuanmiao sandstone shows obvious accumulation of excess pore pressure which decreases the effective stress of specimen before it fails under cyclic shear stress when the accumulated strain is around 1%, with failure surface produced around 45° to 60° from horizontal.

The dynamic parameters variation shows that shear modulus of soft sandstone obviously decreases when it approaches to failure, while damping ratio tends to be stable before increases in the end. Thus, the failure surface of saturated soft sandstone slope during earthquake is influenced by cyclic shear stress. Accumulated excess pore pressure decreases the effective stress and destabilizes the slope. Decreasing shear modulus and increasing damping ratio eventually result in slope failure.

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