Mechanical properties of soft sedimentary rock under K_0 and isotropic cyclic loading conditionsYuhei Kurimotoⁱ⁾, Yuzuru Yamamotoⁱⁱ⁾, Hide Sakaguchiⁱⁱⁱ⁾, Feng Zhang^{iv)} and Yukimasa Saeda^{v)}ⁱ⁾ Ph.D. student, Department of Civil Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan.ⁱⁱ⁾ Senior scientist, Japan Agency for Marine-Earth Science and Technology, Showa-cho 3173-25, Kanazawa-ku, Yokohama 236-0001, Japan.ⁱⁱⁱ⁾ Principal research scientist, Japan Agency for Marine-Earth Science and Technology, Showa-cho 3173-25, Kanazawa-ku, Yokohama 236-0001, Japan.^{iv)} Professor, Department of Civil Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan.^{v)} Postgraduate student, Department of Civil Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan.

ABSTRACT

In this paper, unconsolidated siltstone is tested with static and cyclic loading that represents the dynamic force during an earthquake, under K_0 and isotropic conditions. Meanwhile, anisotropy of magnetic susceptibility (AMS) is conducted to check the changes in the internal textures of the specimen after these tests. As the results, no major fabric variation within the siltstone was confirmed based on AMS, in spite of substantial residual deformation occurred due to cyclic loading in all test cases. Furthermore, a phenomenon similar to fatigue fracture of metal was observed when the siltstone subjected to cyclic loading under K_0 condition. These results are exactly the same as the mechanical properties of décollement zone in which the internal texture remained unchanged but the density increased significantly. In other words, cyclic loading, such as the effective-pressure fluctuation, may become a possible reason for the formation of décollement zone.

Keywords: décollement zone, cyclic loading, anisotropy of magnetic susceptibility, soft sedimentary rock

1. INTRODUCTION

Initiation of the décollement zone in incoming sediments is crucial important to understand the mechanism of plate boundary faulting subduction zones and consequently it may help to clarify the mechanism of seismogenic zone. Near-future great earthquake in the Nankai Trough, a plate boundary faulting in the SW Japan is predicted, and therefore such studies are deadily needed. However, the basic mechanism and dynamics during the initiation and evolution of the plate boundary décollement zone remain poorly understood, because researches related to the great earthquake are mostly based the data from telemetry and the past geological records. Fundamental studies like laboratory tests and numerical tests related to the basic mechanical behaviour of the décollement zone then are needed.

Ocean Drilling Program (ODP) and Integrated Ocean Drilling program (IODP) are recently conducted to drill into the plate boundary fault. ODP Leg 190 successfully penetrated the Nankai accretionary prism off Muroto: the drilling sites are located at the prism toe (Site1174) and reference site (seaward of the prism, Site1173), respectively, as shown in Fig.1. Previous studies revealed that muddy materials in the proto-décollement zone (e.g. Site1173), could keep a relative high porosity, since the random fabric structures are maintained by the cementation due to

inter-granular bonding of authigenic clays, as shown in Fig.2. On the other hand, the cementation between the soil particles in the décollement zone (e.g. Site1174) collapsed and consequently formed a fault zone with denser material (Morgan and Karig, 1995; Ujiie et al., 2003). These results indicate that the cementation formed by inter-granular bonding in the proto-décollement zone was collapsed and the sediments shifted to high-density state during the décollement zone formation. The décollement zone is mainly composed of brecciated fragments with a size up to several centimeters, in which the random fabric structure remains alive, as shown in Fig.3. In other words, sharing is not the fundamental factor to make the denser state of the material within the décollement zone.

Fig.1. Location of ODP Leg 190 (solid circles).

Fig.2. Internal texture of brecciated fragments by SEM and distribution of CT bulk density at Site1174 (Ujiie et al., 2003).

Fig.3. Brecciated fragments and its internal texture by AMS from the décollement zone at Site1174 (Ujiie et al., 2003).

In geotechnical engineering, there is a general knowledge that the cementation/structure commonly observed in naturally deposited soils will collapse if it was subjected the shearing. The mechanical and physical properties inferred from the décollement zone, however, contradicted to this understanding. Transient fluctuation of fluid pressure apparently occurred in the décollement zone due to very low frequency earthquakes is reported (Davis et al., 2006), similar to a cyclic loading and may cause a large compression of weakly cemented soils (Asaoka, 2003). Based on the background, the authors here make a dramatic hypothesis different from the conventional idea. It is assumed that the cyclic loading both in isotropic and deviatoric stress due to stress wave propagation, especially P-wave, or fluctuation of fluid pressure and localized fracture failure during an earthquake, might cause a dramatic change in fabric and physical properties of sediments, as shown in Fig.4. Meanwhile, the authors have already verified the fact with numerical experiments that the possibility of the formation of extraordinary high density in the décollement zone due to the static shear has been denied. The numerical experiments were conducted using finite element method (FEM) based on a sophisticated constitutive model for geomaterials in finite-deformation scheme (Kurimoto et al., 2014). In order to verify the hypothesis, test apparatus that can apply cyclic loadings in both K_0 and isotropic conditions on rock sample were designed and developed to reproduce the above-mentioned external dynamic forces that may act on the rock in the décollement zone. Static and cyclic loading tests for the proto-décollement and the décollement samples are conducted to identify the macro-scale deformation

properties. These samples are taken by the Chikyu, a Japanese scientific drilling ship owned by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). SEM observation and anisotropy of magnetic susceptibility (AMS) before and after the tests are also conducted to evaluate the micro-scale behavior of the samples, such as the collapse of the cementation and random fabric structure during the formation process of the décollement zone. As the first step to identify formation mechanism of the décollement zone, unconsolidated siltstone is tested with static and cyclic loading that represents the dynamic force during an earthquake, under K_0 and isotropic conditions. Meanwhile, AMS is conducted to check if the internal textures of the specimen remain unchanged after the tests.

Fig.4. Sectional view of Nankai Trough and de-cementation process from the proto-décollement to the décollement.

2 DESCRIPTIONS OF TESTS

2.1 Test specimen

The unconsolidated siltstone was formed three million years ago at the Late Pliocene trench-slope basin in the Boso peninsula, central Japan. The reasons why using the unconsolidated siltstone in this experiment is that it is also a plate boundary faulting, the same as well as that at Nankai Trough. Additionally, its mechanical and physical properties are close to the sediments sampled from the Nankai Trough. The block samples with the fewest crevices/pockets and with best quality were chosen. The block was then bored in orthogonal direction to plane of stratification with a boring machine to produce a cylindrical specimen with a size of 25 mm in diameter and about 30 mm in height. Finally, by cutting and polishing both ends of the cylinder, the height of the specimens was adjusted to 20 mm, as shown in Fig.5. Because the mechanical behavior of unconsolidated siltstone will change a lot if the samples are open to air for a long time, the specimens were kept in vacuum state immediately after sampling and coring.

Some basic physical properties of the siltstone are given in Table 1. In spite of the unconsolidated siltstone

taken from the same sampling point, it can be seen that the physical properties of different pieces are different from each other across the tests. The reasons why this scattering occurs are that, firstly, the sampling season is different. Secondary, even though the block sample is taken in the same location, the deposition time may be different for several thousand years if the position is only different in several ten centimeters. Although these factors may affect the initial value of AMS, the aim of this experiment is to perceive continuously the variation of deformation properties and the internal texture/structure before and after the static and cyclic loading. The difference of the initial value of AMS is thought be no influential to the variation.

Fig.5. Unconsolidated siltstone specimen under the condition of (a) K_0 , (b) isotropic.

Table 1. Physical properties of unconsolidated siltstone.

	Unit	K_0 condition	Isotropic condition
Soil particle density ρ_s	g/cm ³	2.64	2.66
Dry unit weight γ_d	kN/m ³	14.4	11.9
Void ratio e	-	0.80	1.20
Moisture content w	%	25.9	43.2
Degree of saturation S_r	%	85.7	96.2

2.2 Test apparatus

Previous geological studies related to the décollement zone are greatly different from the current knowledge in geotechnical engineering. It is then suggested that there exist two ways to reduce dramatically the porosity of a granular material in the proto-décollement zone, that is, the shear deformation leading to a negative dilatancy of porous material, and the cyclic loadings both in mean stress and deviatoric stress under isotropic stress condition. To verify this hypothesis, test apparatus can be applied different loads under K_0 condition, representing the in-situ condition, and isotropic condition were newly designed and manufactured. Fig.6 and Table 2 show the cyclic loading apparatus that can apply static and dynamic loadings under K_0 and isotropic conditions and its performances.

Fig.6 (a) shows the cyclic loading apparatus under K_0 condition in which a rigid consolidation ring is used. In order to eliminate the friction generated between the consolidation ring and the specimen, two Teflon sheets with grease stuck between them were wrapped around the sample so as to then reproduce a strictly K_0 condition. In addition, porous metal plates were set on

both the ends of the specimen in order to drain water. Loading pattern can be selected not only with loading control but also constant rate control in the oedometer tests. On the other hand, Fig.6 (b) shows the cyclic loading apparatus under isotropic condition that can only apply isotropic cyclic loading, a device totally different from the conventional triaxial compression test apparatus. The static and dynamic loads (pressure) are supplied by an oil-pressure actuator with electric servo system with a maximum pressure of 20 MPa and within 10 Hz. By installing a spring to fasten the porous metal cap and the same, it is possible to prevent the fluctuation of non-contacting eddy current gap sensors under the cyclic loading test to obtain a stable measurement of displacement.

Fig.6. Cyclic loading apparatus under the condition of (a) K_0 , (b) isotropic.

Table 2. Performances of cyclic loading apparatus under K_0 and isotropic condition.

	Unit	K_0 condition	Isotropic condition
Vertical load	kN	50	-
Consolidation stress	MPa	-	20
Vertical displacement	mm	5	5
Pore water pressure	MPa	1	20
Displacement volume	ml	5	10
Load amplitude	kN	25	-
Load amplitude	MPa	-	10
Frequency	Hz	5	10
Rate of loading	mm/min	0.0001~0.1	-

2.3 Anisotropy of magnetic susceptibility

The elements tests under static and dynamic loads that will be described in detail later, are conducted to understand only the macro-scale deformation properties of the specimen. The internal texture/structure and the other physical properties such as anisotropy of magnetic susceptibility (AMS) are analyzed using the methods based on the lithology and geology. In this research, the AMS that is used extensively in geological field to observe the change of texture within the specimens is adopted to clarify micro-scale deformation properties of the specimen.

The magnetic susceptibility is the strength of a magnetic field obtained by an external magnetic field and its properties may be anisotropic in different direction due to the external magnetic field direction,

which is also called as the anisotropy of magnetic susceptibility (Graham, 1966; Hrouda, 1978). AMS is thought to be formed due to the variation of fabric within the geomaterials, subjected to stress history such as sedimentation processes and the cyclic loading, and its expression are given as,

$$F = \frac{K_{\text{int}}}{K_{\text{min}}}, \quad L = \frac{K_{\text{max}}}{K_{\text{int}}} \quad (1)$$

where, K_{max} , K_{int} , and K_{min} are the maximum magnetic susceptibility, the intermediate magnetic susceptibility and the minimum magnetic susceptibility, respectively. The value of L and F are correspondent to the degree of magnetic susceptibility, and also represent the shape of ellipsoid shown in Fig.7. The larger the F is, the more oblate the ellipsoid may be; the larger the L is, the more prolate the ellipsoid may be, as shown in Fig.7 in which the particle orientation in the specimen is foliation or lineation, respectively. If the value of F is equal to L , it means that the specimen is in a random particle orientation state, also called as random fabric structure. Although there are many different varieties of parameters expressing the degree of magnetic susceptibility, in this research, only L and F are used to discuss the AMS.

Fig.7. Shape of ellipsoid, (a) oblate ellipsoid, (b) prolate ellipsoid.

3 DESCRIPTIONS OF STATIC LOADING TESTS

3.1 Test conditions

Before conducting the cyclic loading tests, oedometer tests were carried out to investigate the pre-consolidation yield stress of the unconsolidated siltstone under K_0 and isotropic conditions and the influence of static loading on AMS. Oedometer tests with constant strain rate 0.01 %/min and a maximum 20 MPa in vertical stress under K_0 condition were conducted. Isotropic consolidation tests whose conditions are shown in Table 3, using incremental loading condition were also conducted. In both static and cyclic loading tests, the degree of saturation of unconsolidated siltstone is kept at the value from 80% to 90%, which means that siltstone is under unsaturated condition. This is because that the loading should be applied as an effective stress to the specimen.

Table 3. Loading condition of an oedometer test.

Loading/unloading condition: 60minutes/stage	
Loading: 0.2→0.4→0.8→1.6→3.2→6.4→12.8→16	
Unloading: 12.8→6.4→3.2→1.6→0.8→0.4→0.2→0.1	
Unit: MPa	

3.2 Results and discussions

Fig.8 shows the results of an oedometer test for the unconsolidated siltstone under K_0 condition and isotropic condition. It is clear from Fig.8 (b) that the void ratio is changed widely under the low confining pressure between 0.2 and 0.8 MPa. The reason caused this problem is not the variability in the mechanical behavior of the specimen, but the uneven displacements happened at the right and the left sides during the vibrated load under low confining pressure if the specimen size is 25mm in diameter and 20mm in height. From these results, consolidation yield stress of the unconsolidated siltstone is 5~6 MPa and 4~6 MPa under K_0 and isotropic conditions, respectively.

Fig.8. Oedometer tests under the condition of (a) K_0 , (b) isotropic.

4 DESCRIPTIONS OF CYCLIC LOADING TESTS AND ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

4.1 Test conditions

In order to investigate the influence of cyclic loading on AMS under both K_0 and isotropic conditions, cyclic loading tests using the unconsolidated siltstone were conducted. Here, K_0 cyclic loading test and isotropic cyclic loading test are respectively defined as the tests in which the specimen is subjected to cyclic loading under K_0 condition that corresponds to in-situ stress condition, and under isotropic condition that corresponds to hydraulic pressure. The test was conducted under drained condition in the static loading process to consolidation stress, while the cyclic loading was applied under undrained condition. The detailed cyclic loading conditions are designed based on the pre-consolidation yield stress obtained from the static test and are listed in Table 4. Cyclic loading test under K_0 and isotropic conditions were conducted under the same conditions listed in Table 4.

Fig.9 shows a type of stress path under isotropic condition. It is known from the Fig.9 that consolidation stress was accurately controlled under static and cyclic loading. The consolidation stress is held for one hour before the cyclic loading is applied. The reason doing this way is that if the cyclic loading test is conducted under an unstable displacement condition, it is difficult to distinguish whether the displacement generated by cyclic loading or static loading.

Fig.9. A type of stress path under isotropic condition.

Table 4. Test conditions of K_0 and isotropic cyclic loading.

Case	Consolidation stress (MPa)	Stress amplitude (MPa)	Frequency (Hz)	Number of vibrations (times)
A	5	1	0.5	1000
B		4		
C	10	1		

4.2 Results and discussions

Fig.10 shows the relationship between the vertical displacement and the number of vibrations under K_0 and isotropic conditions. The vertical axis indicates the relative vertical displacement starts just immediately

after cyclic loading. As shown in Fig.10 (a), particular attention is paid to the differences in the stress amplitude of Case A and Case B, the higher the stress amplitude is, the larger the amount of increase/decrease vertical displacement during cyclic loading and residual deformation will be. It can be also seen that vertical displacement increased abruptly after about 670 times in Case B. This is thought to be a phenomenon similar to the fatigue fracture of metal after a large number of cyclic loading. This phenomenon was confirmed in multiple times under the same test condition. If pay attention to the difference of the initial consolidation stress between Case A and Case C, we can find that the higher the initial consolidation stress is, the smaller the amount of increase/decrease vertical displacement during cyclic loading will be. The residual displacement, however, is on the contrary, that is, the higher the initial consolidation stress is, the larger the residual displacement will be. The reason of this tendency is now under investigation with cyclic loading test.

It is also known from the stress amplitude of Case A and Case B, as shown in Fig.10 (b), that the higher the stress amplitude is, the larger the amount of increase/decrease vertical displacement during cyclic loading and the residual displacement will be. The abrupt increase of displacement, however, cannot be observed under isotropic condition, in which the shear stress does not occur. If pay attention to the difference of the initial consolidation stress between Case A and Case C, we can find that the higher the initial consolidation stress is, the smaller the amount of increase/decrease vertical displacement during cyclic loading and residual deformation will be.

Fig.10. Relationship between vertical displacement and number of vibrations under the condition of (a) K_0 , (b) isotropic.

Fig.11 shows the diagrams of AMS before and after the static and cyclic loadings. From these results, it is found out that the specimen before cyclic loading has already developed the lineation due to the influence of sedimentation processes, but that the loading patterns does not contribute to a change of AMS in the siltstone.

Fig.11. Diagrams of AMS, (a) before loading, (b) after loading.

5 CONCLUSIONS

As the first step to identify if the cyclic loading both in isotropic and K_0 conditions due to stress wave propagation, especially P-wave during an earthquake, is one of the reasons that lead to the formation of the décollement zone, two cyclic loading tests on the unconsolidated siltstone were conducted. As the results, the major fabric variation within the siltstone was not confirmed based on AMS. Furthermore, a phenomenon similar to fatigue fracture of metal was observed when the unconsolidated siltstone subjected to cyclic loading under K_0 condition. These results are exactly the same as the mechanical properties of the décollement zone in which the internal texture remained unchanged but the density increased significantly. In other words, cyclic loading, such as the effective-pressure fluctuation, may become a possible reason for the formation of décollement zone. There is a very high possibility of uncovering a clue to the formation mechanism of

décollement zone, by using the test apparatus and procedure proposed in this research. On the other hand, there are also a few possible reasons that may cause AMS of the specimen being unchanged during the tests, that is, the specimen was initially at a relatively strong anisotropic state before loading while the deformation due to the cyclic loading was so small. In order to clarify these problems, static and dynamic tests using the remolded Fujinomori clay, which can be easily control the amount of deformation and initial degree of magnetic susceptibility, will be conducted in the late-coming works to verify the hypothesis. Meanwhile, static and cyclic loading tests using the proto-décollement and décollement samples drilled from Site1173 and Site1174 will be also conducted in reference to above-mentioned tests to clarify the process of cementation collapse within the sediments that strongly relates to the formation mechanism of the décollement zone.

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