MECHANICAL BEHAVIOR OF COASTAL SOFT CLIFF SUBJECTED TO WAVE EROSION

Shima KAWAMURA[1], Seiichi MIURA[2] and Masaki KURIBAYASHI[3]

[1]Member of ISSMGE, Assistant Professor, Faculty of Engineering, Muroran Institute of Technology
(27-1 Mizumoto-cho, Muroran 050-8585, Japan)
E-mail:skawamur@mmm.muroran-it.ac.jp
[2]Member of ISSMGE, Professor, Graduate school of Engineering, Hokkaido University
(Kita 13, Nishi 8, Kita-ku, Sapporo 062-8263, Japan)
E-mail:s-miura@eng.hokudai.ac.jp
[3]Member of JGS, Graduate student, Graduate school of Engineering, Muroran Institute of Technology
(27-1 Mizumoto-cho, Muroran 050-8585, Japan)
E-mail:s1521036@mmm.muroran-it.ac.jp

This paper aims at clarifying the deformation-strength properties for coastal soft cliff. A series of triaxial compression tests was performed on undisturbed specimens sampled from the coastal soft cliff in Hokkaido, Japan to obtain mechanical properties such as shear strength. From the triaxial test results, it was found that the effect of fabric anisotropy on the strength-deformation behavior could not be ignored for the coastal soft cliff. In addition to these laboratory tests, a series of 1g-model test to grasp the feature of slope failure due to wave erosion was conducted on the model cliff having the corresponding strength with that of the soft cliff. From the model test results, it was shown that such failure was affected by cliff strength, wave height and the number of wave cycles.

Key Words : *erosion, soft cliff, anisotropy, slope failure, model test*

1. INTRODUCTION

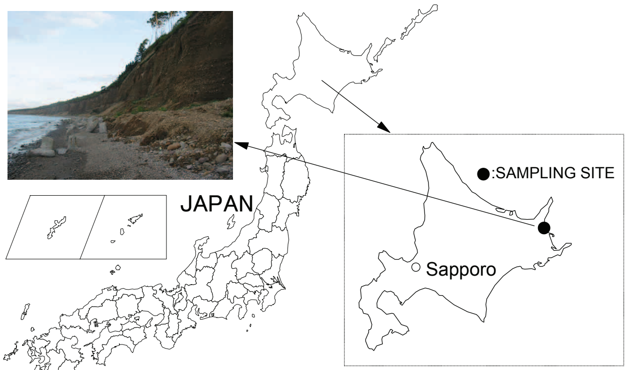
Frequent slumping and slope failure of soft cliff formed from glacial or volcanic sediments which has a tendency to rapid change has been reported in the United Kingdom, the United State, Canada and Japan (e.g. Hutchinson (1969)[1)], Sunamura (1983)[2)]). Since sea-level rise is thought likely to result from global warming produced by an enhanced greenhouse effect (Bray and Hooke (1997)[3)]), therefore, accurate estimate of erosion recession and of slope failure (or slumping) will be necessary for protecting the shoreline and land border in the future.

In numerous studies concerning such erosion phenomenon, the mechanism and recession ratio and historical development have been investigated, for example, Sunamura (1983)[2)] has described the state of the art of cliff erosion. However, the research on coastal soft cliff from the geotechnical engineering standpoint is extremely limited in comparison with other soils.

The purpose in the present study is to understand the mechanical behavior of coastal soft cliff and the mechanism of slope failure attributed to wave erosion. The mechanical behavior of undisturbed specimens sampled from the coastal soft cliff in Hokkaido, Japan was elucidated based on the results of element tests such as triaxial compression tests (CD, CU and UU tests). In particular, anisotropy in deformation-strength was described herein. Thereafter, a series of model test was performed on the model cliff having the corresponding strength with that of the soft cliff. The feature of slope failure and of erosion process was revealed. Based on the test results, the development process of erosion and the evaluation of slope stability due to wave erosion was discussed detailedly.

2. TEST MATERIALS AND TRIAXIAL TESTING PROCEDURES

Coastal cliff is roughly classified into two types of cliff as “Hard cliff” and “Soft cliff” by cliff materials



Sample name	ρ_s (g/cm^3)	$\rho_{d\ in\ situ}$ (g/cm^3)	D_{50} (mm)	U_c	F_c (%)
Shibetsu soil	2.77	1.40	0.67	3.7	4.5
Toyoura sand	2.68	---	0.15	1.3	0

Fig.1 Sampling site and physical properties of Shibetsu soil

(Damgaard and Dong (2004)[4]). In particular, the soft cliff formed from glacial deposits or volcanic sediments has a high potential on frequent slumping and landslips.

In this study, the soft cliff of east coast in Hokkaido, Japan was sampled as a test material. Sampling site is shown in Fig.1. This sample is hereafter referred to as Shibetsu soil. Physical properties of sample are also shown in Fig.1, compared to that of Toyoura sand.

Undisturbed specimens were taken using a block sampler. After sampling, undisturbed specimens were frozen in the insulated box and transported to a freezer (about -25^{o}C). Thereafter, a frozen specimen for triaxial shear testing was trimmed to 70mm in diameter, 150mm in height. Two kinds of undisturbed test specimen, which were specified according to the cutting directions, were prepared from the frozen blocks.

BV specimen: This was cut from the frozen block so that the direction of specimen coincided with the in situ vertical direction.

BH specimen: This specimen was prepared by cutting in the direction which differed from that of BV specimen by 90^o.

On the other hand, Toyoura sand specimens were prepared by the pluviation of sand through air. The relative density after consolidation was aimed to be *Drc*=77.5% and was controlled within ±2.5%.

After specimen was set up in the cell, the frozen specimen was allowed to melt under an effective confining pressure 19.6kPa for 2 hours. All specimen was saturated using the methods proposed by JGS (2000)[5]. A back pressure of 196kPa was, thereafter, applied to ensure the saturation of specimen. By this procedure, Bishop's *B* value of all specimen was equal to or larger than 0.96. For consolidated undrained (CU) and consolidated drained (CD) tests, all specimen was isotropically consolidated for 2 hours under an effective confining pressure σ_c' =49, 98 and 196kPa. A series of triaxial compression tests was performed under drained and undrained conditions with an axial strain rate of 0.25%/min.

3. TEST RESULTS AND DISCUSSIONS

(1) Mechanical behavior of coastal soft cliff

Geotechnical properties of the soft cliff formed from glacial deposits have been described by Kamphuis (1987)[6], Chapman et al.(2002)[7]. According to Kamphuis (1987)[6], the shear strength of foreshore sediments, which consisted of the same material as the cliff, was estimated as vane shear strength of 60 kN/m^2 based on the test results of twenty-two samples at some sites along the shore of the Great Lakes between the United state and Canada. On the other hand, the soil strength of bluffs composed of the glacial and lacustrine sediments for the region of lake of Michigan were ϕ' =29.3^o -31.2^o , c' =2.4 kN/m^2 -28.4 kN/m^2 (4 types of soil), and the slope angles were from 30^o to 50^o, occasionally, there were some places at greater than 70^o (Chapman et al. (2002)[7]). In this study, especially, the strength-deformation behavior of the coastal soft cliff formed from volcanic sediments was made clear.

Fig.2 shows the relationship between principal stress ratio ($\sigma_1'/\sigma_3'=\sigma_a'/\sigma_r'$) and principal strain ($\varepsilon_1=\varepsilon_a$, $\varepsilon_3=\varepsilon_r$) on BV specimen under undrained condition. From the test result, it can be pointed out that the stress-strain behavior for Shibetsu soil resembles that for dense sand. Fig.3 shows the stress-strain behavior of BH specimen under undrained condition. Comparison of the mechanical behavior of BV and BH specimens indicates that there is the difference in the strength-deformation behavior between both specimens (see Fig.2 and Fig.3). This experimental fact implies that BV specimen is by far more resistant to deformation than BH specimen. Such difference in deformation-strength behavior of Shibetsu soil is very similar to that of Toyoura sand. In general, it has been well known that anisotropy in deformation-strength properties such as that observed above is attributed to anisotropic fabric of in-situ ground (e.g. Miura and Toki (1984)[8]). Similarly, undrained compression strengths of the BV specimen and BH specimen for the UU test results were 187.8 kN/m^2 and 174.7 kN/m^2, respectively.

Fig.4 depicts the relationship between ϕ_d, ϕ' and effective mean principal stress at failure p_f'. It is apparent that there is a unique relationship between ϕ_d , ϕ' and p_f' under each condition. Furthermore, the difference in ϕ'-p_f' relationship between BV and BH

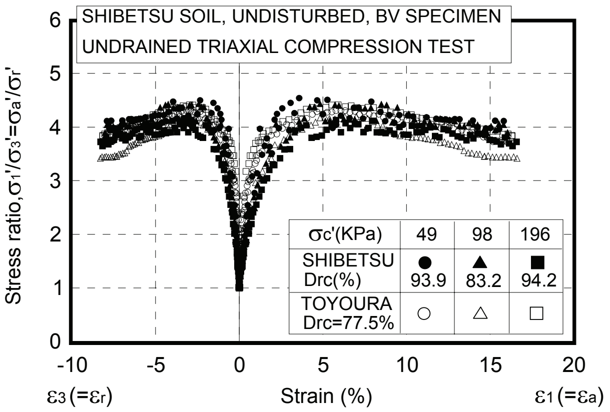


Fig. 2 Stress-strain relationship of BV specimen for CU test

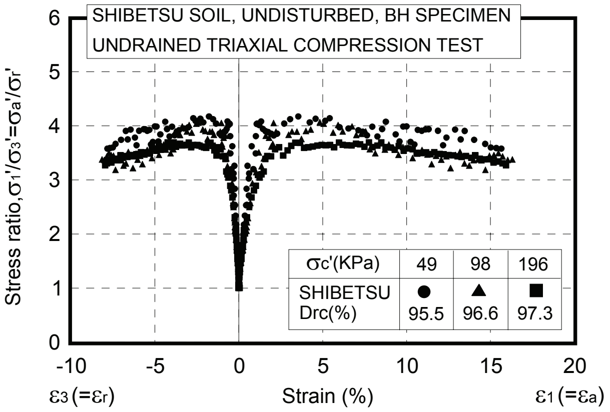


Fig. 3 Stress-strain relationship of BH specimen for CU test

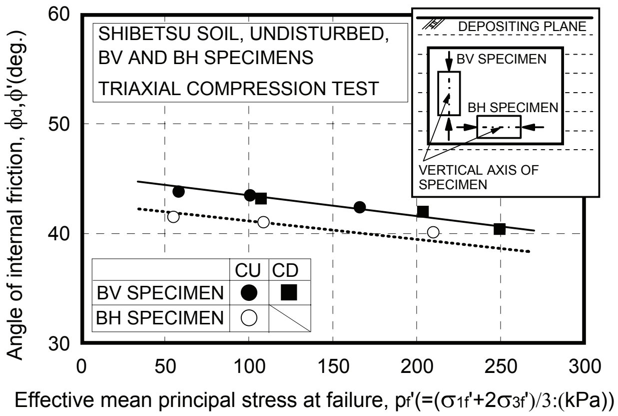


Fig. 4 ϕ_d, ϕ'-p_f' relationship at failure for BV and BH specimens

specimens can be clearly observed, for example, it was around 3°.

From these results, it can be said that the evaluation of stress dependency and of the anisotropy in strength is important for predicting cliff recession in coastal region.

(2) Model testing using wave-paddle system

In order to further grasp the failure mechanism of the soft cliff due to wave erosion, a series of 1g-model test was conducted using a wave paddle system. As mentioned above, since the cliff strength was thought to be a key factor for evaluation of failure, the model cliff having the corresponding strength with that of the soft cliff was used herein.

In the preliminary test (Kawamura et al.(2007)[9)]), unconfined compression strengths of the test specimens of the sand-cement materials, which were made to accord with ϕ' and c' reported by Chapman et al (2002)[7)], were from 40kN/m^2 to 90kN/m^2. In this study, the compression strength of 90kN/m^2 was tentatively adopted as a typical strength of soft cliffs.

Model materials to construct model cliff were Toyoura sand and a quick drying Portland cement. Because that the existence of granular soils in fluid has been a key factor for evaluating such erosion phenomenon (Sunamura (1983)[2)], Kamphuis (1987)[6)]).

Model scale of 1/30 (model/prototype) was adopted to suitably simulate such soft cliff for the model test apparatus. For the reason, the cement content (weight ratio of cement/sand) was set to 1.0% so that unconfined strength of model cliff became 1/30 of the in situ strength (Kawamura et al.(2007)[9)]).

These materials were put into the frame box (400mm in length, 600mm in width and 500mm in height) in the soil box (2000mm in length, 600mm in width and 700mm in height) and were uniformly tamped to the desired density (1.80g/cm^3±3.0%) up to the critical height (=433mm) to eliminate an influence of the model cliff height on test results. Thereafter, the cliff surface was carefully cut to the slope angle 60^o (relative to the horizontal) using a straight edge so as to free from disturbance of the surface. After constructed the cliff, the surface was covered with wet cloths for curing and was kept in normal temperature (18^{o}C) more than 48hours.

Pore water transducers were set into the model cliff at z =0mm and 25mm (z : the depth from water surface), furthermore, a wave-recorder was fixed at the position of wave crest. Before a series of model test, the model slope (100mm in height and 200mm in length) was also placed in front of the cliff to simulate foreshore. During the model tests, digital and video cameras were used to record and to calculate soil movements.

Standing wave was created using a flap paddle system at one end of the soil box, by which AC servomotor generated a rotational motion of crank wheel. The stroke of wave paddle can be varied by selecting any hole of the crank wheel, as shown in Fig.5.

Water depth and wave frequency were 180mm and 0.55Hz, respectively. Test conditions are

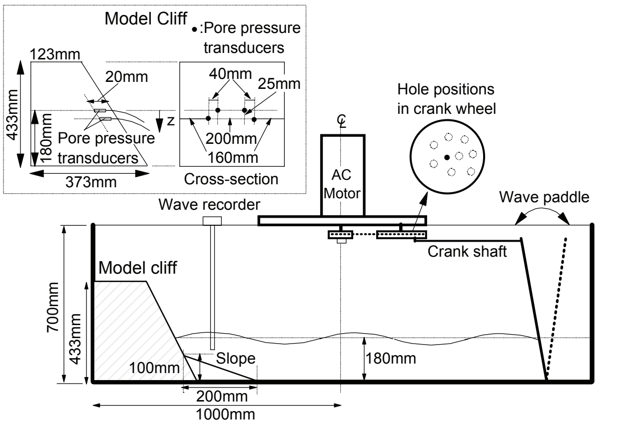


Fig. 5 Schematic of wave tank and model cliff

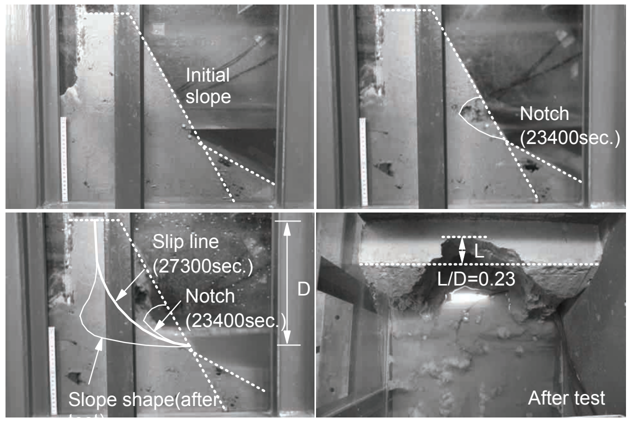


Fig. 6 Deformation behavior for model cliff under wave height of H=52mm

Table 1 Test conditions for 1g-model test

Test condition (Model scale 1/30)	
Cliff angle	60°
Cliff height	433mm
Cement content	1.0%
Wave height*(at peak)	52mm, 42mm, 18mm
Wave frequency	0.55Hz
Water depth	0.18m

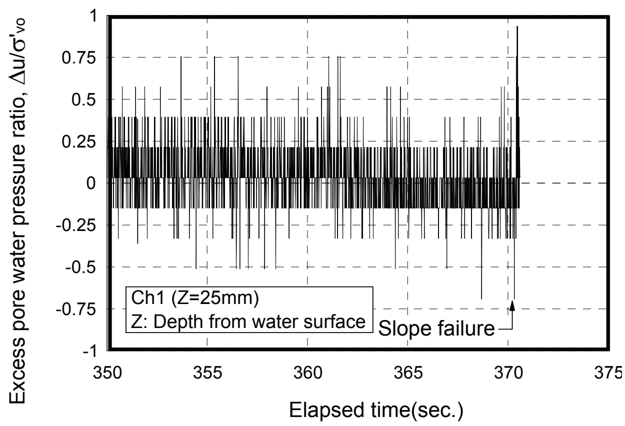


Fig.7 Behaviour of pore water pressure for model cliff under wave height H=52mm

summarized in Table 1. A series of model test was carried out until 3hours or slope failure. Since it was difficult to grasp progressive failure due to the development of erosion, the mechanical behavior at which the slip line developed until the crown of the model cliff was regarded as that at failure.

(3) Failure mechanism of model cliff and its evaluation

Fig.6 illustrates the deformation behavior for the model cliff at wave height of H=52mm. The notch was extended by wave actions, thereafter slope failure was caused rapidly. As the result, a considerable development of erosion distance was observed. This indicates that soft cliff has a potential having a tendency of the rapid recession and slope failure due to wave erosion. In addition, the failure mode appears to be surface slope failure, based on horizontal recession ratio (the horizontal distance /the depth of slip line; L/D) of 0.23. After collapsed, a steeper slope was formed with the development of erosion. This phenomenon, which the failure mechanism is due to notching and slumping, has been also observed at relative stiff dunes (Nishi and Kraus (1996)[10]). Therefore, the experimental results seem to be able to relatively explain such phenomena.

Fig.7 shows pore water pressure behavior. In this figure, Δu and σ_{vo}' are the excess pore water pressure and the initial overburden pressure, respectively. The pore water pressure periodically oscillated with wave actions, however its excess pressure did not reach to the initial liquefaction $\Delta u/\sigma_{vo}'$=1.0 (less than $\Delta u/\sigma_{vo}'$=0.80). Similar trend was obtained for other cases. Therefore, it is apparent that slope failure is not induced by liquefaction phenomenon but is caused by mainly wave loadings for such soft cliff. However, it has been reported that there is a possibility of liquefaction for the cliff composed of the material that behaves like sand (Newson et al. (2005)[11]). Therefore, the mechanical behavior of soft cliff should be investigated detailedly.

Fig.8 and Fig.9 depict the relationship between normalized erosion distance $x/(H\gamma_w/q_u)$ and the number of wave cycles Nc and the relationship between normalized wave height ($H\gamma_w/q_u$) at failure and the number of wave cycles, respectively, where x is erosion distance, H is wave height, q_u is unconfined compression strength and γ_w is unit weight of the fluid. The normalized erosion distance nonlinearly increased with increasing wave cycles,

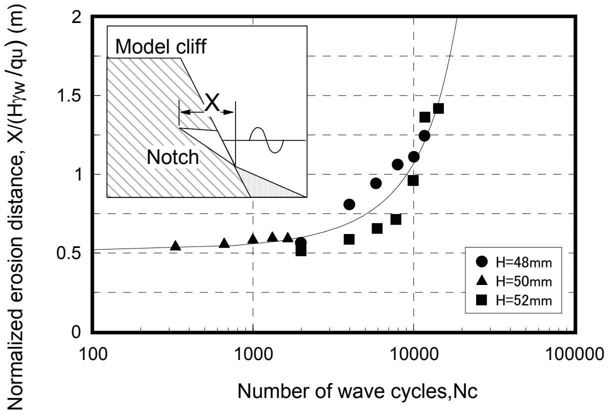


Fig.8 Relationship between erosion distance and number of wave cycles

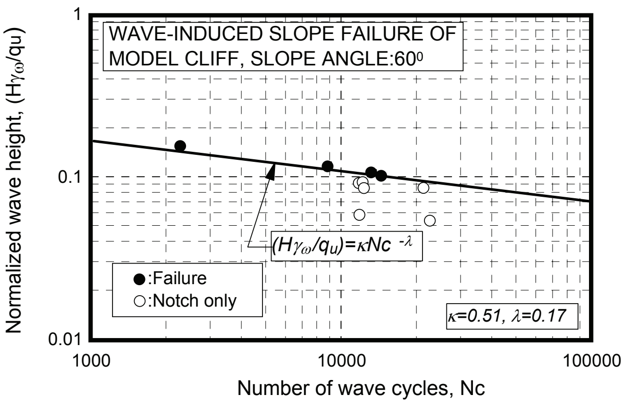


Fig. 9 Relationship between normalized wave height and number of wave cycles

irrespective of the magnitude of wave height. This fact means that the erosion distance is affected by the loading history of wave and may be more rapidly developed by the anisotropy effect. Sunamura (1983)[2] has indicated that there is a unique relationship between eroded distance and wave force which is normalized by cliff strength.

On the other hand, it is obvious from Fig.9 that a unique relationship between normalized wave height and wave cycles exists. The slope failure appears to be not induced in the lower domain from this line. For example, this relation can be expressed as follows;

$$\left(\frac{H\gamma_w}{q_u}\right) = \kappa \cdot N_c^{-\lambda} \qquad (1)$$

where κ and λ are coefficients, κ=0.51 and λ=0.17, respectively. Therefore, it is possible to evaluate the failure due to wave erosion if such a relation can be obtained for soft cliff.

4. CONCLUSIONS

On the basis of the limited number of triaxial tests on undisturbed specimens and 1g-model tests, the following conclusions were derived;

(1)Evaluation of stress dependency and of anisotropy in strength is very important for coastal soft cliff and should be considered into the stability analysis and the prediction of cliff recession.

(2) Erosion distance is affected by the loading history of wave. Furthermore, there is a possibility that is more rapidly developed by anisotropy effect.

(3) Slope failure of the model cliff is induced by not liquefaction phenomenon but by wave loadings and is affected by cliff strength, wave height and the number of wave cycles.

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