Post-cyclic shear behavior of clayey soil – effects of pore water pressure build-up and reconsolidation

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1 Introduction

The 2024 Noto Peninsula earthquake and subsequent tsunamis caused significant damage to the eastern breakwater at Iida Port, Suzu City, Japan [1]. The breakwater was constructed on a soft marine clay layer approximately 60 years ago or earlier. Although detailed construction records are not available, it is presumed that no ground reinforcement was applied to the underlying soft clay at the time of construction. The thickness of the clay layer varies along the breakwater and increases toward the head section; past geotechnical survey data indicate that the thickness at the most severely damaged section is approximately 5–7 m [2].

The observed failure mode was distinct from the typical tsunami-induced overturning of coastal structures toward the port side. In contrast, the eastern breakwater at Iida Port tilted toward the seaward side (Figure. 1). Because the failure occurred approximately 30 minutes after the earthquake, when the tsunami struck the breakwater, this unusual behavior was probably attributed to the build-up of excess pore water pressure (EPWP), defined as the excess pore water pressure normalized by the initial vertical effective stress, in the clayey foundation soil [2]. Centrifuge model tests further demonstrated that cyclic loading during the earthquake significantly softened the clayey soil, which subsequently underwent large deformation under tsunami-induced loading (Figure. 2) [3].

Despite its importance for the stability of coastal structures, the post-cyclic shear behavior of clayey soil has not been well understood. In particular, quantitative evaluation of shear stiffness and strength after cyclic loading, considering both the magnitude of EPWP build-up and subsequent reconsolidation, remains limited in the existing literature.

This study therefore aims to quantitatively investigate the effects of pore water pressure build-up and reconsolidation on the post-cyclic shear behavior of clayey soil through a series of triaxial tests.

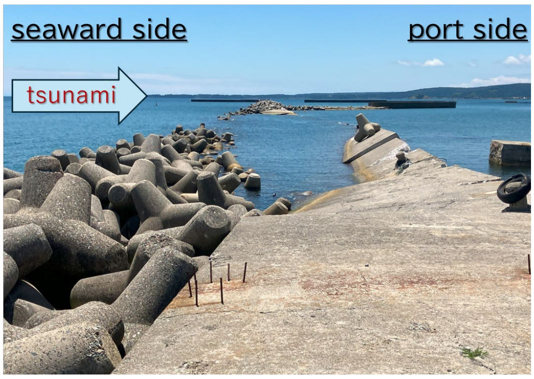

Figure 1. Failure mode of the eastern breakwater at Iida Port caused by the 2024 tsunami [2].

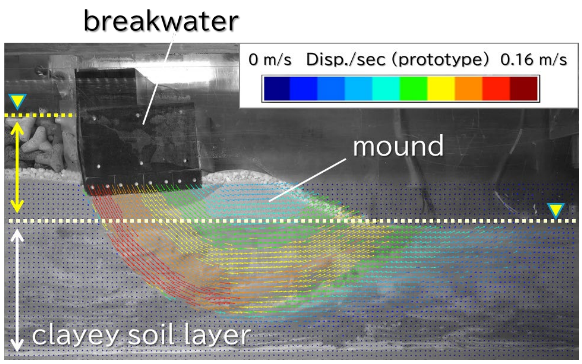

Figure 2. Centrifuge model test result showing deformation of the breakwater subjected to static tsunami loading after seismic shaking [3].

2 Test method

Because in-situ sampling of the clay beneath the damaged breakwater was difficult, an analogue clayey soil with a similar particle size distribution (PSD) was prepared by mixing kaolin clay and non-plastic silt at a dry mass ratio of 8:2. The resulting PSD is shown in Figure. 3 and falls within the range of clayey soils collected at Iida Port during past geotechnical surveys. Although the plastic and liquid limits of the in-situ clay have not been reported, those of the analogue soil were 25.7% and 47.6%, respectively, giving a plasticity index (PI) of 21.9%.

A series of triaxial tests was conducted with cyclic loading and subsequent reconsolidation stages, as illustrated in Figure. 4 and Table 1. The soil was mixed with water and poured into a metal mould, after which one-dimensional preconsolidation was applied under a vertical stress of 80 kPa. Two types of specimens were prepared: normally consolidated (NC) and over-consolidated (OC) clays. After demoulding, each specimen was set in a triaxial cell and subjected to an isotropic confining pressure of 100 kPa. For the OC specimens, the isotropic stress was first increased to 200 kPa and then reduced to 100 kPa after consolidation, resulting in an over-consolidation ratio (OCR) of 2.

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To simulate the generation of EPWP during earthquake loading, sinusoidal cyclic deviator stresses were applied under undrained conditions at a loading frequency of 0.1 Hz. The deviator stress (q) amplitudes were set to 27 kPa for OCR = 1 and 46 kPa for OCR = 2, such that the EPWP ratio, r_u, reached approximately 0.95 after 20 loading cycles for both NC and OC specimens. Typical cyclic responses of the NC clay are shown in Figure. 5, where gradual stiffness degradation is observed. According to Vucetic and Dobry (1991) [4], cohesive soils with higher plasticity indices generally exhibit more gradual stiffness degradation during cyclic loading; this behavior can partially explain the key differences in failure mechanisms between sandy and clayey soils subjected to an earthquake followed by a tsunami.

The r_u values were monitored during undrained cyclic loading, and loading was terminated when the q reached zero during the compression phase after attaining the target r_u, as indicated by the star symbols in Figure. 5. For the NC clay (Figure. 5), the number of cycles required to reach each target r_u (0.4, 0.6, 0.8, and 0.95) were 5, 10, 13, and 18, respectively (Table 1). The post-cyclic axial strain was then manually returned to zero under undrained conditions at a quasi-static rate to eliminate residual deformation and ensure consistent specimen geometry across the test cases, as highlighted in Figure. 5(a), and sufficient time was allowed for the pore water pressure variation to cease. It should be noted that during this relaxation process, the r_u values increased due to additional pore water pressure generation associated with returning the axial strain under undrained conditions, and the r_u value immediately before the subsequent monotonic compression was defined as r_u^* (Table 1). Subsequently, undrained monotonic compression was performed at a strain rate of 0.05 %/min up to 15% axial strain to evaluate the post-cyclic shear behavior. For the reconsolidation cases, the accumulated r_u, which once exceeded 0.95, was fully dissipated by allowing drainage (i.e. r_u^* = 0), after which monotonic compression was applied in the same manner. The void ratio value at the onset of monotonic compression was defined as e^* (Table 1).

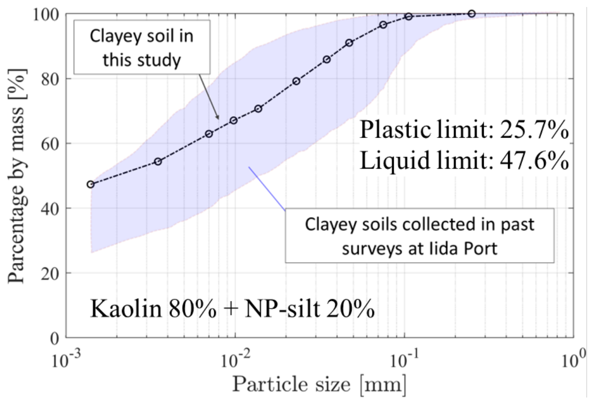

Figure 3. Particle size distribution of the analogue clayey soil.

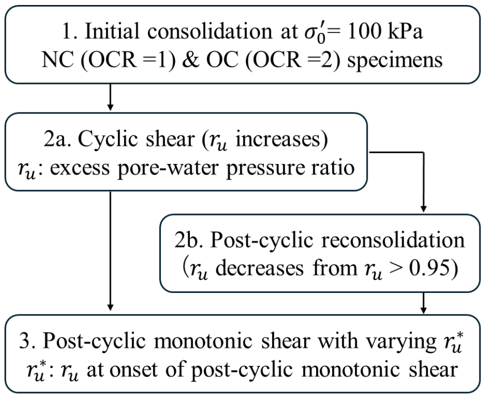

Figure 4. Schematic illustration of the triaxial test procedure.

Table 1. Test cases and specifications.

ID	OCR	e^*	CSR**	Target r_u	No. of cycles	r_u^*	Re-consol
NC, Reference	1	1.076	No cyclic loading applied (intact)				
NC, No consol	1	1.205	0.135	0.40	5	0.40	no
	1	1.173	0.135	0.60	10	0.67	no
	1	1.203	0.135	0.80	13	0.87	no
	1	1.180	0.135	0.95	18	0.97	no
NC, Re-consol	1	1.008	0.135	0.95	21	0.00	yes
OC, Reference	2	1.027	No cyclic loading applied (intact)				
OC, No consol	2	1.196	0.230	0.60	14	0.67	no
	2	1.196	0.230	0.80	19	0.93	no
	2	1.198	0.230	0.95	22	0.95	no
OC, Re-consol	2	1.079	0.230	0.95	22	0.00	yes

**Cyclic stress ratio (CSR) was defined as 0.5 times the single-sided cyclic stress amplitude / the initial confining stress.

3 Results and discussion

Figure 6 compares the undrained monotonic stress–strain response of intact clay (reference case without cyclic loading) with the post-cyclic stress–strain responses obtained at different excess pore water pressure ratios at onset of post-cyclic monotonic compression (r_u^*). For both normally consolidated (NC) and over-consolidated (OC) clays, the initial shear stiffness and large-strain shear strength clearly decrease with increasing r_u^*. The degradation becomes pronounced when

r_u^* exceeds approximately 0.8. This behavior is attributed to the reduction in effective stress and the weakening of the soil structure induced by cyclic loading.

Although the reference (intact) OC specimen exhibited a much stiffer response than the NC specimen, a similar degradation trend with increasing r_u^* was observed for both soil conditions (Figures. 6(a) and 6(b)). This result supports the failure mechanism inferred from field observations and centrifuge model tests, in which cyclic softening of the clayey foundation soil contributed to the deformation of the breakwater under subsequent tsunami loading [2, 3]. As discussed above, unlike clean sand, the clayey soil did not exhibit a sudden loss of stiffness, but instead retained a certain level of stiffness during cyclic loading, which may have allowed the superstructure to remain stable during the earthquake.

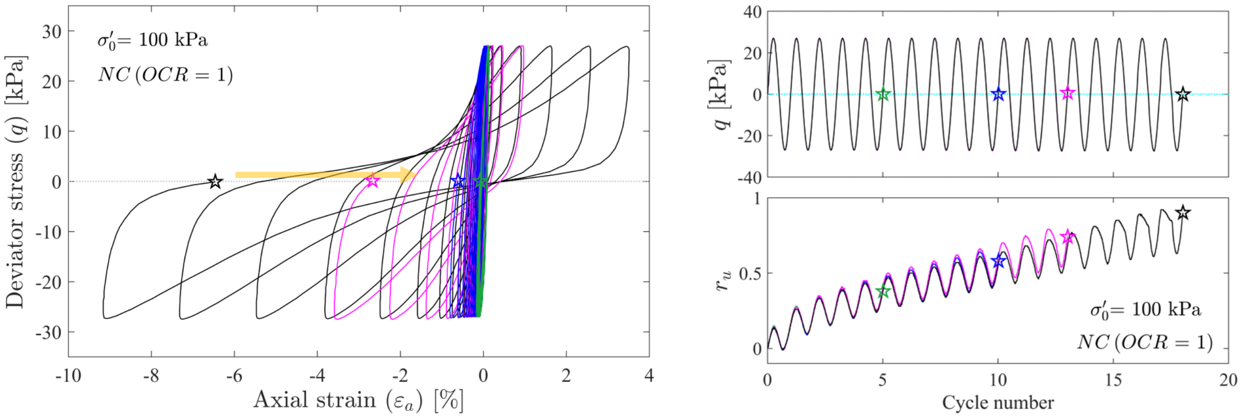

Figure 5. Cyclic shear response of the clayey soil with OCR = 1: (a) undrained stress–strain relationship and (b) mechanical responses (deviator stress q and excess pore water pressure ratio r_u) with respect to the number of loading cycles. Star symbols indicate the points at which cyclic loading was terminated.

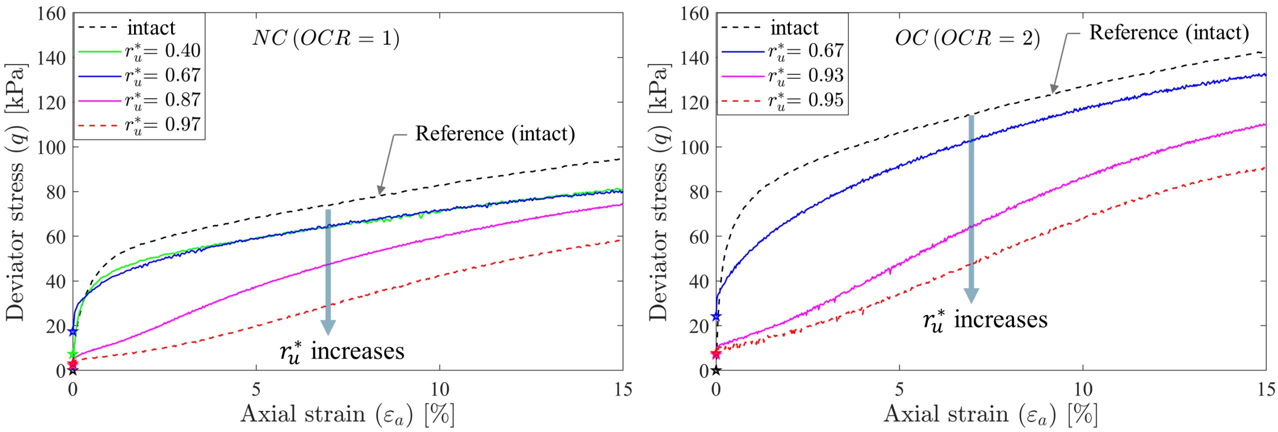

Figure 6. Influence of excess pore water pressure ratio on post-cyclic shear behavior: (a) normally consolidated (NC) specimens with OCR = 1 and (b) over-consolidated (OC) specimens with OCR = 2.

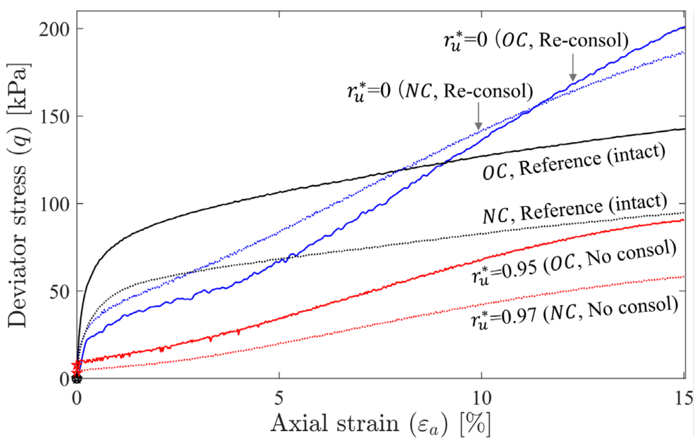

Figure 7. Post-cyclic shear behavior after full reconsolidation for NC specimens (OCR = 1) and OC specimens (OCR = 2).

Considering that the tsunami struck the eastern breakwater at Iida Port approximately 30 minutes after the earthquake, the excess pore water pressure at the site was likely maintained at a high level with limited dissipation. Nevertheless, it is also important to examine the mechanical behavior after reconsolidation. Figure. 7 shows the undrained monotonic stress–strain responses after full reconsolidation ($r_u^* = 0$). The results indicate that the stiffness and strength reduced by pore water pressure build-up can largely recover once drainage is allowed and excess pore water pressure dissipates, likely due to soil structure recovery [5] as well as densification. As a result of reconsolidation, the void ratio of the NC specimen decreased from 1.125 to 1.008, whereas that of the OC specimen decreased from 1.182 to 1.079.

Interestingly, the large-strain shear strength after full reconsolidation exceeded that of the specimen without prior cyclic loading (Figure. 7). In addition, the post-reconsolidation stress–strain responses of the NC and OC clays became similar, particularly at large strains, where both the stiffness degradation behavior and the shear strength converged to comparable levels. This indicates that the influence of over-consolidation with OCR = 2 diminished due to cyclic loading in which r_u once exceeded 0.95 prior to reconsolidation. Although the present study employed an artificial analogue clay with a relatively low PI value, similar trends have been reported for natural marine clays in Japan [6].

4 Summary and conclusions

Motivated by the rare failure mode observed at the eastern breakwater at Iida Port, this study investigated the effects of excess pore water pressure build-up and subsequent reconsolidation on the post-cyclic shear behavior of normally and over-consolidated clayey soils through triaxial tests using an analogue clay. Based on the experimental results, the following conclusions can be drawn.

- The undrained shear stiffness and strength of clayey soil after cyclic loading decrease with increasing the excess pore water pressure ratio at the onset of monotonic compression (r_u^*), primarily due to the reduction in effective stress.
- Unlike clean sand, the tested clayey soil with a plasticity index (PI) of 21.9% does not exhibit a sudden loss of stiffness during cyclic loading, which may have allowed the superstructure to remain stable during the earthquake.
- The degradation in stiffness and strength caused by excess pore water pressure build-up can largely recover after full reconsolidation, likely due to soil structure recovery and densification.
- Although over-consolidated clay shows stiffer responses than normally consolidated clay at equivalent r_u^*, the mechanical responses of the two soils become similar after reconsolidation following significant cyclic disturbance, particularly at large strains, where both stiffness degradation and shear strength converge to comparable levels (see Figure. 7).

These findings indicate that pore water pressure build-up and subsequent reconsolidation play a key role in controlling the short- and long-term stability of clayey soil foundations subjected to earthquake and tsunami loading, highlighting the importance of considering post-cyclic soil behavior when external loading occurs before full dissipation of excess pore water pressure.

It should be noted that the findings of this study are based on a clayey soil with relatively low plastic and liquid limit values; therefore, the applicability of the observed post-cyclic behavior to highly plastic or natural marine clays requires further investigation.

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