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# Post-cyclic undrained shear behavior of marine silty clay under various loading conditions

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ABSTRACT

The post-cyclic undrained shear characteristics of marine silty clay was investigated by conducting a series of cyclic triaxial tests on undisturbed specimens. The effects of confining pressure, initial undrained shear stress ratio ($q_s/p_0$), cyclic stress ratio ($q_{cy}/p_0$) and number of cycles ($N$) on the post-cyclic undrained shear behavior were investigated. Results show that the post-cyclic shear strength decreases with the increase in $q_s/p_0$, $q_{cy}/p_0$ and $N$. The confining pressure has no apparent effect on the normalized post-cyclic monotonic undrained shear strength for the silty clay. During the post-cyclic shear, the specimens with small $q_s/p_0$ and $q_{cy}/p_0$ contract, while the cases with large $q_s/p_0$ and $q_{cy}/p_0$ dilate. Also, the terminal value of normalized post-cyclic shear-induced excess pore pressure decreases with $q_s/p_0$ or $q_{cy}/p_0$ increasing. The Equivalent Hvorslev Line (EHL) was proposed to form a failure envelop for the post-cyclic silty clay and the slope of EHL increases with the increase in $q_{cy}/p_0$ or $q_s/p_0$, regardless of the number of cycles. Moreover, a post-cyclic strength model, which could consider the influence of initial shear stress and previous cyclic loading history was proposed on the basis of Yasuhara model. This model demonstrates a good agreement with the test results.

## 1. Introduction

The behavior of marine silty clay subjected to cyclic loading, such as earthquakes and storm waves, is of great interest in the design of near-shore and offshore structures. Such soils with the characteristics of high water content, high void ratio and low strength are widely distributed in the coastal area of China, on which more and more coastal structures have been constructed. The marine silty clay beneath the coastal structures is subjected to wave load for a long time. One of the major issues in the design of such structures is the post-cyclic shear behavior of the clay.

When the clay is subjected to the undrained cyclic loading, the cyclic-induced pore pressure will gradually grow and the effective mean principle pressure of normally consolidated soil progressively decreased. If an undrained monotonic test on the specimen is followed, the clay after cyclic loading may behave similar to the overconsolidated specimen, which refers to the phenomenon of equivalent overconsolidation. The monotonic shear strength measured after cyclic loading is often lower than the strength of the soils without cyclic loading history. Many researchers also have investigated the degradation of post-cyclic strength for different types of soils by conducting different tests including cyclic triaxial tests and direct simple shear tests (Thiers and Seed, 1968; Andersen et al., 1980, 1988; Kaya and Erken, 2015; Wang et al., 2015b). Moreover, Yasuhara et al. (1992, 1994) studied the post-cyclic characteristics of the reconstituted Ariake clay and found that the post-cyclic undrained shear strength can be well evaluated by the cyclic-induced pore pressure based on the theory of equivalent overconsolidation. Wang et al. (2013) founded that the yield shear strength of the low-plasticity MRV silt were reduced with an increase in excess pore pressure ratio and the reductions were significant (about 80% for yield shear strength) when the excess pore pressure ratio was greater than 0.70. Above all, the post-cyclic strength degradation behavior is directly related to the development of pore pressure, which is identified as

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**Table 1**
Average index properties of tested silty clay.

| Natural water content/% | Unit weight/ (kN/m$^3$) | initial dry density $\rho_0$ | initial void ratio $e_0$ | Specific gravity | Liquid limit/% | Plastic limit/% | plasticity index $I_p$ | Compression index, $C_c$ | Swelling index, $C_s$ |
|---|---|---|---|---|---|---|---|---|---|
| 37.68 | 17.96 | 1.33 | 1.093 | 2.79 | 32.98 | 17.41 | 15.57 | 0.205 | 0.035 |

cyclic-induced pore pressure in previous studies. However, if a specimen is subjected to an initial undrained shear stress, a certain amount of initial shear-induced excess pore pressure can be produced and it can also affect the post-cyclic strength and critical characteristic of the soils. Therefore, to further clarify the effect of pore pressure developing in different stages on post-cyclic shear behavior, more researches are required.

The cyclic loading history can affect the shear strength characteristics after cyclic loading, but its effect on post-cyclic critical strength parameters is controversial. Li et al. (2011) concluded that although the post-cyclic shear strength decreases, the previous undrained cyclic loading seemed to have little influence on the critical strength property of the normally consolidated clay. Similar observations were made by Tavakoli et al. (2011) on mixture sand-clay and by Yasuhara (1982) on Ariake clay. However, Andersen et al. (1980) observed a higher post-cyclic cohesion intercept indicated in the test results for normally consolidated specimens and Moses et al. (2003) found a reduced value of cohesion intercept and internal friction angle instead. Wang et al. (2015a) concluded that the critical stress line is not unique for silts by carrying out a series of triaxial tests of MRV silts. The line can be changed with cyclic loading history as the excess pore pressure ratio reaches a value of 1.0. Above all, although many researchers have studied the critical post-cyclic strength characteristics, the effect of undrained cyclic loading history on the post-cyclic critical strength parameters exists significant differences. Therefore, the influence of cyclic loading history on critical strength parameters and the development of post-cyclic effective stress paths (ESPs) for silty clay are required additional efforts.

The model for evaluating the effect of cyclic loading on shear strength has been widely investigated. One type among these models developed based on the concept of degradation parameter ($t$) introduced by Idriss et al. (1978), such as the model of Zhou and Gong (2011) and Matasovic and Vucetic (1995), can predict the cyclic shear strength due to stiffness degradation, but cannot calculate the post-cyclic shear strength. Other types of models, such as the anisotropic elastic viscoplastic model (Li et al., 2011) and the anisotropic hardening model (Mroz et al., 1978), are not commonly used to evaluate the post-cyclic strength in practical application. Based on the concept of equivalent overconsolidation, Yasuhara et al. (2003) established another type of model to evaluate the post-cyclic strength of clay. The same type of models was also proposed by Wang et al. (2015a), Matsui et al. (1992) and Soroush and Soltani-Jigheh (2009) and so on. The model proposed by Yasuhara was easy to use and of explicit physical meaning. However, this model was developed on the basis of isotropic consolidation, without considering the effect of initial shear stress on post-cyclic strength. In actual engineering situation, the soil beneath the structures tends to be subjected to complicated combinations of initial shear stress and cyclic stress. According to the previous researches (Andersen et al., 1988; Hyodo et al., 1993; Sharma and Fahey, 2003), the initial shear stress is one of the most influential factors for the post-cyclic strength for soil, so the effect of initial shear stress should be taken into account. Moreover, the terminal excess pore pressure measured at the end of the cyclic stage is the only parameter to reflect the influence of previous cyclic loading in the Yasuhara model. However, this parameter cannot consider the effect of different previous cyclic loading conditions on the development of excess pore pressure during cyclic loading. Therefore, an excess pore pressure model is required to be developed for the silty clay to evaluate the post-cyclic shear strength with different previous cyclic loading history.

In this paper, a series of triaxial tests were performed to study the post-cyclic behavior of Yantai silty clay. First, the influences of confining pressure, initial undrained shear stress, undrained cyclic loading, and number of cycles on post-cyclic undrained shear behavior of the silty clay have been discussed. The developments of excess pore pressure and effective stress paths during post-cyclic monotonic shear under various loading conditions was also investigated. Then, the critical post-cyclic strength characteristic of the silty clay was studied based on the development of the post-cyclic ESPs. Finally, a post-cyclic strength model, which could consider the influence of initial shear stress and previous cyclic loading history was proposed on the basis of Yasuhara model and its validity and limitation was discussed.

## 2. Experimental program

### 2.1. Apparatus and materials

Triaxial tests were performed using the GDS Dynamic Triaxial Testing System. The undisturbed soil specimens employed in the present paper were taken from Yantai port of China below seabed level of 2~5 m. Related average index properties of the silty clay were listed in Table 1. The cylindrical silty clay specimens were 3.91 cm in diameter and 8.0 cm in height and saturated with vacuum pumping method to ensure the values of Skempton pore pressure parameter ($B$) at least 95% in all tests.

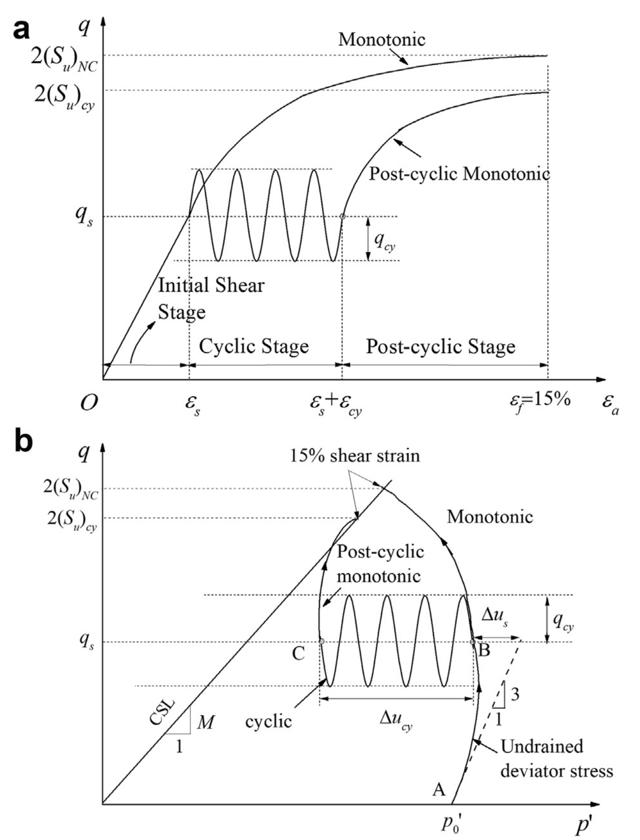


**Fig. 1.** Key sketch for testing procedure (a) schematic of stress-strain relationship (b) schematic of effective stress paths.