Acceleration of ageing effect on liquefaction resistance of sandy soils by means of drained cyclic pre-shearing

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ABSTRACT

Experiences of seismic liquefaction during past earthquakes show that subsoil liquefaction occurs in young sandy soils significantly more frequently than in aged soils. This point was confirmed again during the 2011 Tohoku earthquake of Japan. It is, therefore, important that the age effect on liquefaction resistance of sand is understood and taken into account in engineering practice so that more reliable assessment may be made of liquefaction risk. The present study refers to past studies and supposes that minor earthquake shakings (pre-shearing) changes the granular structure of sand into more stable one and increases the liquefaction resistance with age. To propose a quantitative evaluation of the ageing effect, a series of laboratory tests were carried out in which 7 kinds of soils were studied by cyclic triaxial shear.

Keywords: liquefaction resistance, ageing effect, acceleration of ageing

1 INTRODUCTION

The liquefaction resistance of sandy soil is influenced by their grain size distributions and densities, but ageing effect changes the resistance more directly. Experiences of seismic liquefaction during past earthquakes show that subsoil liquefaction occurs in young sandy soils significantly more frequently than in aged soils. Laboratory liquefaction tests reported that liquefaction resistance of sandy soil is increased by applying long term confining pressure to the samples (Mulilis et al., 1977; Tatsuoka et al., 1984). However, the laboratory tests were unable to sustain the consolidation state for a long time, exceeding several months. Towhata et al. (2016) studied many cases of liquefaction during past earthquakes, and revealed that liquefaction resistance increases significantly after ageing of hundreds of years (Fig. 1).

Undisturbed samples of aged sand have higher liquefaction resistance than reconstituted samples, even if both samples have the same density and grainsize distribution (Yoshimi et al., 1984). Thus, ageing effect on liquefaction resistance of soil is caused not only by cementation but also by temporal stabilization of granular structure (fabric structure) of sand (Goto et al., 1992). Tokimatsu et al. (1989) showed that the micro fabric structure is stabilized by cyclic shearing history under drained condition. In this regard, the present study supposes that both long-term consolidation together with associating ageing effect and the cyclic shear history are equivalent with each other in the sense of stabilization of micro fabric structure. In other words, drained cyclic shear promotes the ageing effect.

Laboratory reproduction of ageing effect is useful for scientific studies because expensive undisturbed soil samples of high quality are replaced by reconstituted specimens (Goto, 1993). Obviously, the reproduction of ageing makes it possible to assess more accurately the in-situ liquefaction resistance in practice.

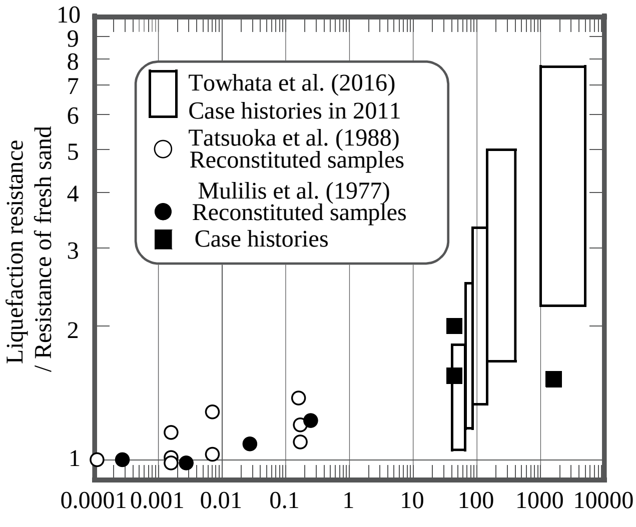

Fig. 1. Increasing of liquefaction resistance of soil with age.

Table 1. Cyclic shear history and liquefaction resistance of the sample tested.

Series	Sample contents		Virgin state		Index of Dynamic shear history			State after The Dynamic shear history	
	F_c%	Fines	Relative Density *Dr0 %*	Liquefaction Resistance *RL0*	Shear stress ratio *Rsm*	Number of cycles *Nsm*	Double amplitude Axial strain *DAsm*	Relative Density *Dr %'*	Liquefaction Resistance *RL'*
Toyoura-1~17	0	No fines	60~90	0.18~0.27	0.08~0.33	1~10,000	$1.0\text{x}10^{-04}$~$1.0\text{x}10^{-03}$	60~94	0.18-0.51
Kaorin-5~10	5~10	Kaolin	85~90	0.26~0.26	0.24~0.28	10,000	$1.0\text{ x}10^{-03}$	90	0.36-0.50
Clay-5~10	5~10	Marine clay of Tokyo Bay	70~90	0.15~0.22	0.05~0.26	1~10,000	$1.0\text{ x}10^{-04}$-$1.0\text{ x}10^{-03}$	72~83.5	0.15~0.42
Nclay-10~20	10~20		70~85	0.16~0.19	0.13~0.21	100-10000	$7.1\text{ x}10^{-04}$~$1.2\text{ x}10^{-03}$	70~90	0.19~0.31
Edogawa-1	15	Natural soil	65.6	0.18	0.16	100	$7.6\text{x}10^{-04}$	67.7	0.24
Edogawa-2	7		55.6	0.14	0.19	1,000	$1.2\text{ x}10^{-03}$	58.5	0.26
Kisarazu-1	21		80.4	0.23	0.08	100	$2.9\text{ x}10^{-04}$	80.6	0.23

This paper addresses the effect of drained cyclic shear (pre-shearing) on liquefaction resistance of sandy soil samples and then compares the increased resistance with the ageing effect in natural ground. The aim of this research is to develop equivalency between pre-shearing and long-term consolidation (ageing) in a quantitative manner.

2 LIQUEFACTION RESISTANCE INCREASED BY CYCLIC PRE-SHEARING HISTORY UNDER DRAINED CONDITIONS

2.1 Specimen preparation and liquefaction resistance increased by cyclic shear history

Toyoura sand and Toyoura sand mixed with kaolin or Tokyo Bay marine clay were used for specimens. Furthermore, specimens reconstituted from natural ground sample were also used for the test. Table 1 shows the properties of samples tested, such as fines content and indices of the drained cyclic pre-shearing.

After certain cyclic pre-shearing under drained condition (hereinafter called cyclic shear history), specimens were tested by undrained cyclic triaxial test to determine their liquefaction resistance.

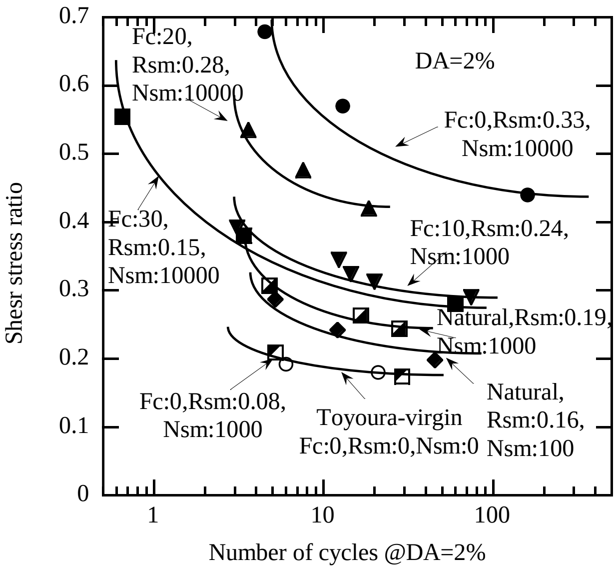

Fig. 2. Liquefaction test results of samples after the cyclic shear history.

Fig. 2 shows typical results of the liquefaction test on the specimens that experienced the cyclic shear history. Liquefaction resistance increased due to the cyclic shear history by at maximum about 2 times, although the relative density increased less than 5% during cyclic shear history. Noteworthy was that liquefaction resistance was not affected when shear stress ratio at the history (*R*sm) was 0.08 or less.

2.2 A simple model of increasing liquefaction resistance by the cyclic shear history

Fig. 3 shows a time history of volumetric strain (negative dilatancy) during the cyclic shear history. There are two components of dilatancy; the one is reversible dilatancy that varies with cyclic shear stress,

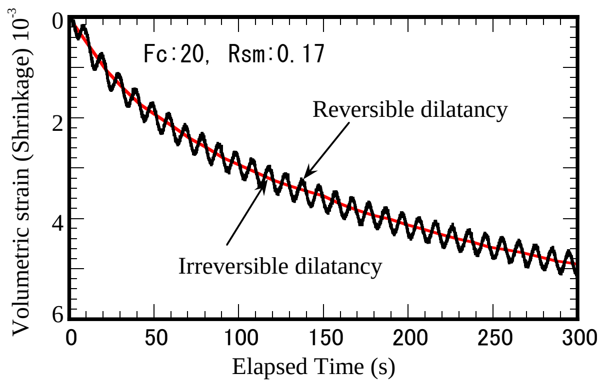

Fig. 3. Dilatancy on the cyclic shear history.

and the other is irreversible dilatancy that accumulates through the loading history (Shamoto et al., 1997).

Fig. 4 shows changes of the irreversible dilatancy during the cyclic shear history. The irreversible dilatancy increased with the progress of the cyclic shear history, but the rate of increase became smaller with the progress of cyclic shears. Because volumetric contraction of the specimen under drained condition is equivalent with the development of pore water pressure under the undrained

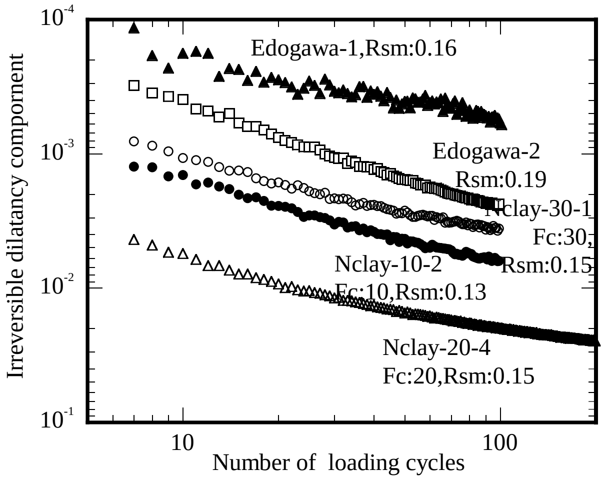

Fig. 4. Changes of irreversible dilatancy during the cyclic shear history.

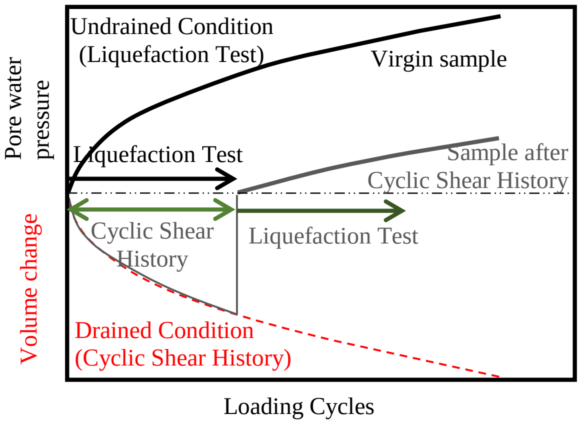

Fig. 5. Simple model of liquefaction resistance increasing due to cyclic shear history.

condition, the characteristics of irreversible dilatancy during drained shear history is profoundly related with the liquefaction characteristics.

A simple model was constructed of liquefaction resistance that increases during the cyclic shear history by referring to its equivalency with the volume change of sample during cyclic shearing; see Fig. 5. The idea is that the rate of negative dilatancy development after cyclic drained shear is less than that prior to cyclic shear, inferring that the excess pore water pressure in pre-sheared soil develops less rapidly than that without cyclic shear history.

2.3 Factors influencing liquefaction resistance after cyclic shear history

To evaluate the effects of cyclic shear history on improvement of liquefaction resistance, multiple regression analysis was carried out on all the test results. The number of analyzed tests was 45. Independent variables in the regression analysis were shear stress ratio at the history (*R*sm), the number of drained shear stress cycles (*N*sm), the fines content (*F*c), the relative density of soil (*D*r) before and after the cyclic shear

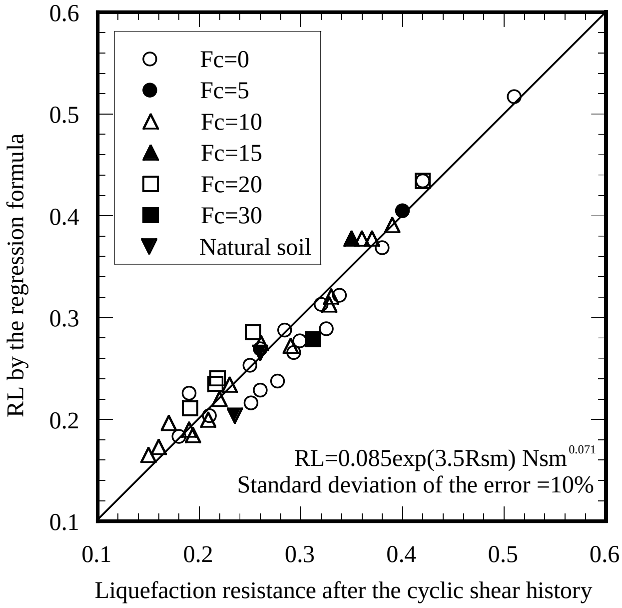

Fig. 6. Comparison between the test result of liquefaction resistance after the cyclic shear history and estimated values by the multiple regression formula.

history, the axial strain at the end of cyclic shear history (*D*Asm), liquefaction resistance *RL*0 in the virgin state, etc. Fig. 6 compares the liquefaction resistance obtained by tests after the cyclic shear history and the estimated resistance by the multiple regression formula. The regression formula is a product of an exponential function of *R*sm and a power function of *N*sm;

$$\mathrm{RL} = 0.085\exp(3.5Rsm)(Nsm)^{0.071} \qquad (1)$$

where the contribution ratio of other indices was neither significant nor negligible. The standard deviation of the estimation error by this multiple regression formula was about 10%.

3 LIQUEFACTION RESISTANCE IN AGED NATURAL GROUND AND CYCLICALLY SHEARED SAMPLES

The measured increase in liquefaction resistance of the cyclically sheared samples was plotted in Fig. 7 in a similar manner as in Fig. 1. Fig. 1 illustrated the relation between increase of liquefaction resistance and the consolidation time. Similarly, Fig. 7(a) uses the time that was elapsed from the sample preparation to the liquefaction test. However, evidently, the cyclically sheared samples demonstrated much greater liquefaction resistance than aged sand at the same consolidation time. This suggests that the cyclic shear history required additional time factor to be considered in this type of interpretation.

In Fig. 7(b), the test results were plotted using the newly-developed Consolidation Conversion Time (CCT) which attempts to evaluate the cyclic shear history as age

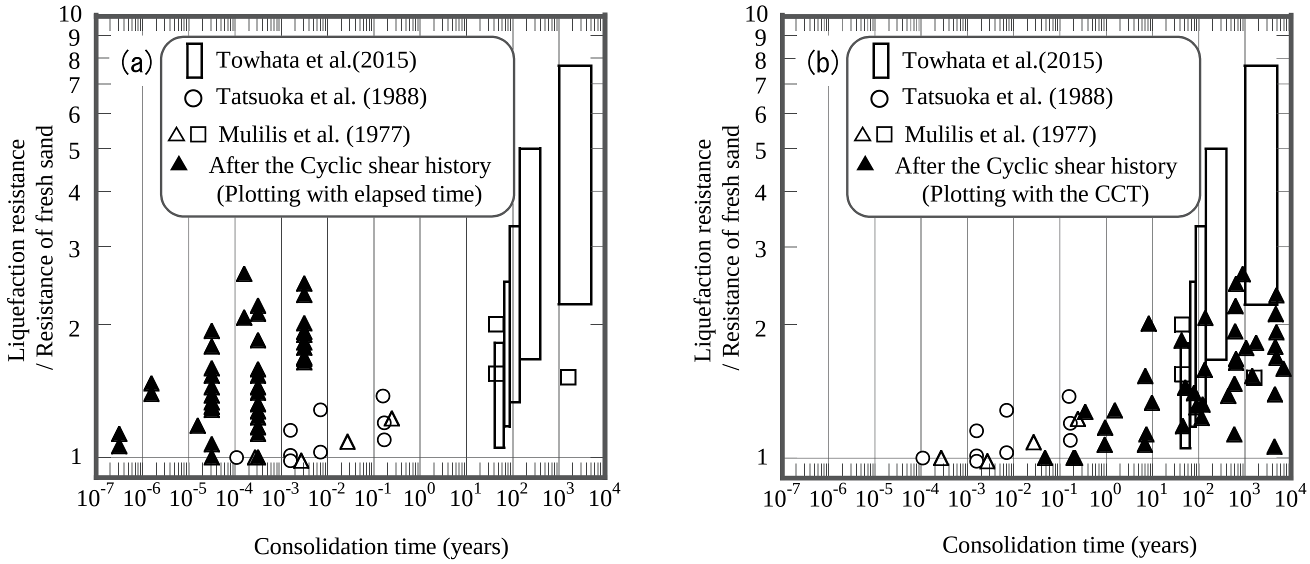

Fig. 7. Comparison of increasing of liquefaction resistance between ageing effect and the cyclic shear history

effect; see Eq. (2);

$$\mathrm{CCT}_{(\mathrm{year})} = 0.2\exp(50(\mathrm{Rsm}-0.08))(Nsm)^{0.01} \quad (2)$$

$$\text{where } \mathrm{Rsm} > 0.08,\ \mathrm{Nsm} \geq 1$$

The relationship between the liquefaction resistance ratio and the Consolidation Conversion Time of samples after the cyclic shear history shows good agreement with the originally obtained age effect in case histories. Based on this figure, it is reasonable to state that the liquefaction resistance increasing due to the cyclic shear history is equivalent with the ageing effect, being equivalent with several thousand years of consolidation time at maximum.

4 CONCLUSION

The characteristics of cyclic shear history under drained conditions (cyclic shear history) were evaluated. It was herein found that liquefaction resistance increase can be interpreted from the viewpoint of accelerating of ageing effect. The findings obtained are as follows.

1) The liquefaction resistance of sandy soil was increased by the cyclic shear history in the shear stress ratio of 0.09 to 0.33, even though the relative density of the samples increased only at most 5%.
2) The liquefaction resistances of the samples after the cyclic shear history were strongly governed by two indices; i.e. the shear stress ratio and the number of loading cycles of the history. This feature was modeled reasonably by the multiple regression model.
3) The cyclic shear history was converted into equivalent consolidation time and good consistency was obtained with the previously-obtained ageing effect. Effect of the cyclic shear history was equivalent with several thousand years of consolidation time at maximum in this test range.

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