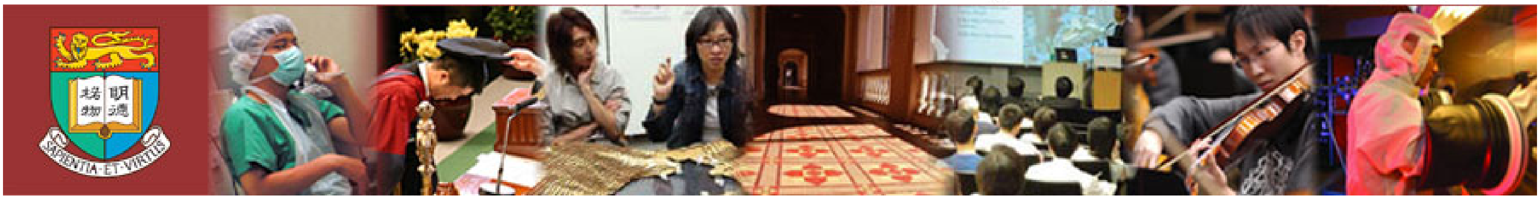

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Cyclic Loading Behavior of Saturated Sand with Different Fabrics

Comportement du sable saturé avec des structures différentes sous chargement cyclique

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ABSTRACT: The undrained response of saturated sand under cyclic loading has been a subject of long-standing interest. Although it has been recognized for long, the effect of fabric remians a critical problem that is not yet well understood. In this paper, cyclic triaxial test results from a strategically designed experimental program are presented to demonstrate how significant the effect of fabric can be on the undrained cyclic behavior of sand under different combinations of initial state and initial stress conditions. A significant finding of the study is that loose sand specimens, prepared by different reconstitution methods and thus having different initial fabrics, exhibit similar failure modes under the conventional symmetrical loading condition, but they show distinct failure patterns under the non-symmetrical cyclic loading condition. A qualitative explanation of the macroscopic observations is also proposed from a microscopic perspective, which sheds light on the mechanisms involved.

RÉSUMÉ : Le sujet de la réponse du sable saturé sous chargement cyclique non drainé a suscité de l'intérêt depuis longtemps. Cependant il est reconnu que l'effet de la structure reste un problème clef qui n'est pas encore bien compris. Dans cet article, les résultats d'essais triaxiaux cycliques faits dans le cadre d'un programme expérimental conçu spécialement sont présentés afin de démontrer la signifiance de l'effet de structure sur le comportement non drainé du sable soumis à différentes combinaisons d'état initial et contraintes initiales. L'un des résultats les plus importants est que les spécimens de sable lâche préparés par des méthodes différentes de reconstitution, et donc avec des structures initiales différentes, montrent les mêmes modes de rupture sous chargement symétrique, mais différents schémas de rupture sous chargement non symétrique. Une explication qualitative de ces observations faites à l'échelle macroscopique est donnée d'un point de vue microscopique, éclairant les mécanismes impliqués.

KEYWORDS: cyclic loading; fabric; failure; liquefaction; sand; soil behavior

1 INTRODUCTION

The understanding of cyclic failure behavior of soils plays a pivotal role in geotechnical earthquake engineering design against liquefaction and cyclic mobility types of damages. Complication of this subject lies in the fact that cyclic behavior is under the inter-related influences of various factors. Dominant ones such as soil density, overburden pressure and initial static shear stress have been assessed and discussed (e.g. Vaid et al. 2001, Yang & Sze 2011a & b). An important one, the fabric effect, has, nevertheless, been largely neglected.

Fabric is defined as the spatial arrangement of particles and voids. Since sand is a discrete granular material, how it behaves macroscopically is a result of the microscopic interactions between grains and voids. So far, most studies focused on the effect of fabric anisotropy on the monotonic behavior (e.g. Oda 1972a). Regarding the cyclic behavior, only cyclic strength is concerned (e.g. Mulilis et al. 1977). No particular effort has been placed on investigating how fabric takes effect on the cyclic failure pattern, which is of fundamental importance for understanding of cyclic loading behavior of soil.

In terms of the cyclic failure pattern, several studies (e.g. Yamashita & Toki 1993, Oda et al. 2001) have offered some valuable data. While these studies did shed light on this subject, they focused only on very dense sand with relative density over 80%, which is of less practical interest. Also, no concern was given on how the fabric effect might change as the initial state, in terms of soil density and effective confining pressure, shifts. Moreover, no attempt has ever been placed on relating it with the initial shear impact. The complicated inter-related effects of initial state and initial shear have already been demonstrated by Yang & Sze (2011a & b).

For long, fabric anisotropy of sand has been recognized but not being adequately taken into account in cyclic behavior study. A fundamental difficulty is the lack of well-organized laboratory test data to reveal more comprehensively the fabric effect on the cyclic failure response and how it possibly relates with other key factors. This study is thus prompted, by means of cyclic triaxial testing, to investigate thoroughly the fabric effect on the cyclic failure pattern of sand as well as its dependence on initial state and initial shear. The focus is on loose soil becasue its susceptibility to liquefaction is of the most concern.

In this paper: (1) details of the cyclic triaxial test program and sample reconstituion methods are described; (2) the observed cyclic failure patterns exhibited under various combinations of initial fabric, state and shear conditions are discussed; and (3) a qualitative explanation of the observed fabric effects is given from the micro-mechanical perspective aiming to shed light on the fundamental understanding of the role of fabric on the cyclic behavior of sand.

2 EXPERIMENTATION

All cyclic triaxial tests were carried out on Toyoura sand. The material properties are summarized in Table 1.

Table 1. Physical properties of the test material.

Mean grain size	Coeff. of Uniformity	Max. void ratio	Min. void ratio	Fines Content
0.175mm	1.5	0.977	0.605	0%

2.1 *Sample Reconstitution Methods*

Different initial fabric can be simulated by means of changing the sample reconstitution method in the laboratory (Mulilis et al. 1977). Depending on the methods of reconstitution, it is possible to mimic the fabric possession of in-situ soil deposit having different formation histories (Miura & Toki 1984).

Two common sample reconstitution methods, as moist tamping (MT) and dry deposition (DD), were strategically selected for this study. It takes advantages of their known different fabric possession and that they tend to mimic different in-situ fabric - MT simulates construction fill compaction; DD is representative of natural fill deposition. The procedures for each method are briefly illustrated in Figure 1.

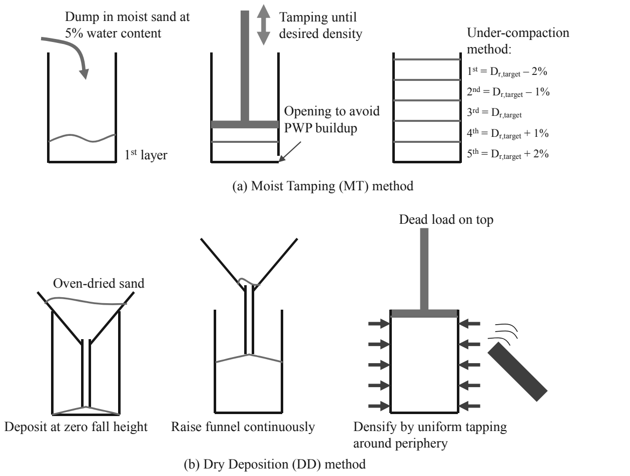

Figure 1. Sample reconstitution methods: (a) moist tamping; and (b) dry deposition.

2.2 *Control of Initial State and Initial Shear*

Specimens prepared by either method was brought to saturation through CO_2 flushing and then de-aired water flushing to achieve a B-value higher than 0.98. The stress state in terms of the effective normal stress σ_{nc}' and the initial static shear stress ratio α was attained through anisotropic consolidation such that

$$\sigma_{nc}' = q_s / 2 + \sigma_{3c}' \quad (1)$$

$$\alpha = q_s / 2\sigma_{nc}' \quad (2)$$

where q_s is the initial deviatoric stress and σ_{3c}' is the minor effective consolidation pressure. Undrained cyclic loading, in terms of cyclic stress ratio CSR_n,

$$CSR_n = q_{cyc} / 2\sigma_{nc}' \quad (3)$$

where q_{cyc} is the cyclic deviatoric stress, was then applied at a 0.01 Hz. Such a low frequency allowed more stable input and output signals and hence ensured the soil loading responses to be precisely represented and confidently examined.

2.3 *Test Program*

The cyclic triaxial test program is listed in Table 2. Loose sands with post-consolidation density D_{rc} at 20% and 35% were tested at various combinations of σ_{nc}' and α values. Test at each combination was repeated for MT and DD methods. Such step-wise varied test program allowed the examination of: 1) the fabric effect under otherwise identical conditions; and 2) the inter-relations of the fabric effect with both initial state and initial shear.

Table 2. Cyclic triaxial test program.

Reconstitution Method		D_{rc} (%)	σ_{nc}' (kPa)	σ_{3c}' (kPa)	q_s (kPa)	α
MT	DD	20	100	100	0	0
MT	DD	20	100	90	20	0.1
MT	DD	20	100	75	50	0.25
MT	DD	20	100	60	80	0.4
MT	DD	20	500	500	0	0
MT	DD	20	500	450	100	0.1
MT	DD	20	500	375	250	0.25
MT	-	20	500	300	400	0.4
MT	DD	35	100	100	0	0
-	DD	35	100	75	50	0.25
MT	DD	35	100	60	80	0.4
MT	DD	35	500	500	0	0
MT	DD	35	500	450	100	0.1
MT	DD	35	500	375	250	0.25
MT	DD	35	500	300	400	0.4
MT	DD	50	100	100	0	0

3 CYCLIC FAILURE BEHAVIOR

The cyclic loading responses of sand possessing a certain type of fabric have been found to be distinctive under different initial state and shear conditions (Yang & Sze 2011a & b). The test results from this study further reveal that sands possessing different initial fabric would exhibit differentiating failure patterns under otherwise identical conditions. This can be exemplified by the following four cases.

3.1 *Runaway Deformation (MT) vs Limited Deformation (DD)*

Very loose sand (D_{rc} = 20%) is found to exhibit runaway deformation when subjected to cyclic loading regardless of its initial state and shear stress conditions. This complete collapse phenomenon is exhibited consistently only in MT specimen. When initial shear is absent, DD specimen shows similar behavior. Yet, when shear stress is present, a distinctive failure pattern – limited deformation prevails with this type of fabric, even α is small. This is demonstrated in Figure 2.

Runaway deformation is featured by its sudden large abrupt strain gain associated with sudden build-up of excess pore water pressure (PWP) directly to σ_{3c}' resulting in a total loss of shear strength and stiffness of sand. On the contrary, limited deformation is featured with its sudden but limited or controlled axial strain and PWP gain resulting in partial collapse of soil structure. This partial collapse is followed by a rapid plastic strain accumulation at a strain rate over 1 % per loading cycle.

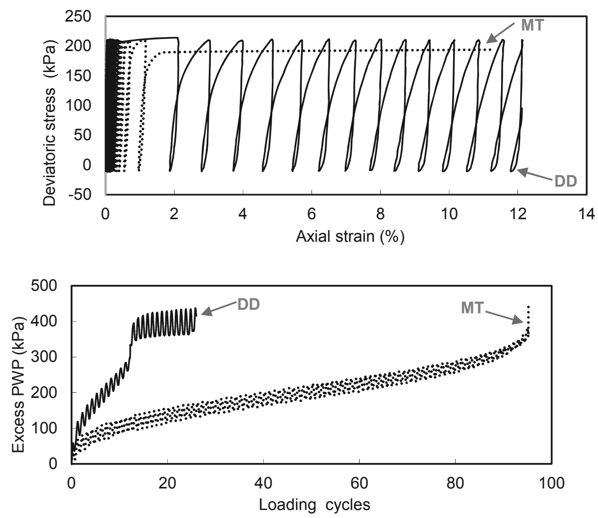

Figure 2. Runaway deformation (MT) & limited deformation (DD): [D_{rc}=20%, σ_{nc}'=500kPa, α=0.1, CSR_n=0.11]

3.2 *Cyclic Mobility (MT) vs Runaway Deformation (DD)*

A remarkable change in MT behavior is observed as soon as the soil density reaches D_{rc} = 35%. Cyclic mobility prevails in its failure mode when α = 0. Under otherwise identical condition, DD specimen is still liable to complete collapse i.e. runaway deformation. It is illustrated in Figure 3.

Here, cyclic mobility is featured by the progressive excess PWP build-up which eventually leads to transient softening of soil whenever the applied deviatoric stress reaches zero. When it is non-zero, the sand gains back strength and stiffness as a result of the temporary PWP reduction. Yet, once softening is first triggered, the associated deformation becomes excessive and keeps accumulating in double-amplitude.

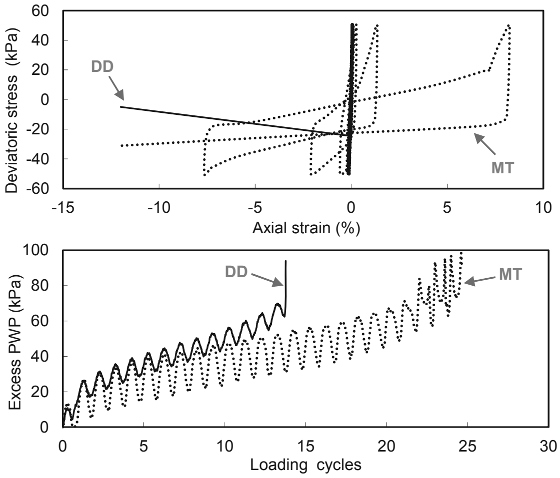

Figure 3. Cyclic mobility (MT) & runaway deformation (DD): [D_{rc}=35%, σ_{nc}'=100kPa, α=0, CSR_n=0.225(MT),0.125(DD)]

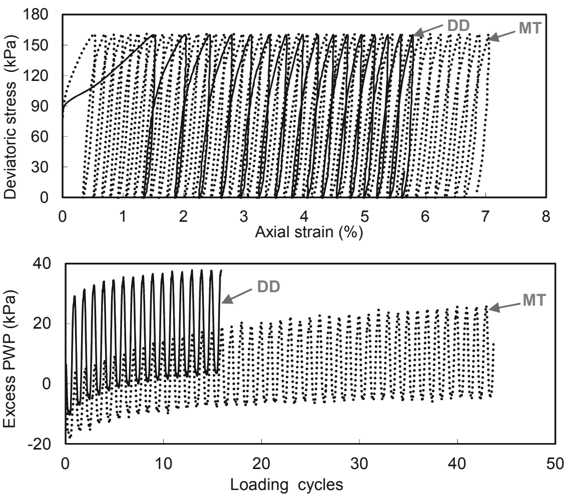

Figure 4. Plastic strain accumulation in single amplitude (MT & DD): [D_{rc}=35%, σ_{nc}'=100kPa, α=0.4, CSR_n=0.4]

3.3 *Plastic Strain Accumulation (MT & DD)*

By simply imposing initial shear stress (α = 0.4) to the test conditions presented in Section 3.2, the failure mode is abruptly changed into plastic strain accumulation in single-amplitude for both fabric types but obviously the rate of strain gain is different (Figure 4).

3.4 *Cyclic Mobility (MT) vs Limited Deformation (DD)*

The fabric effect has been observed remarkable at loose state. It is, therefore, of interest to explore how it might change at a denser state. A single series of tests has thus been conducted: D_{rc} = 50%, σ_{nc}' = 100kPa and α = 0 (Figure 5).

At such condition, another form of limited deformation is observed, again, only in DD behavior. Instead of being followed by a high pace of plastic strain accumulation, the partial collapse is succeeded by cyclic mobility. This failure mode is clearly different from the pure mobility exhibited by the MT specimen. Sudden and abrupt deformation and PWP build-up to the state of transient softening are triggered in the course of cyclic load application on the DD specimen. That on MT specimen is, on the other hand, progressive and controlled.

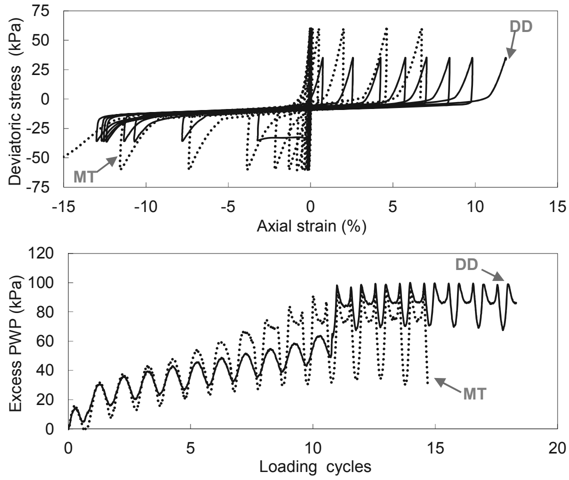

Figure 5. Cyclic mobility (MT) & limited deformation (DD): [D_{rc}=50%, σ_{nc}'=100kPa, α=0, CSR_n=0.25(MT),0.175(DD)]

4 MICROSCOPIC INTERPRETATION

It is attempted to offer an explanation to the above macroscopic observations from a microscopic perspective on a qualitative basis. It has been consistently observed that: 1) limited deformation prevails in DD behavior only; 2) DD and MT behaviors are distinctive only when α presents at loose state but when α is absent at dense state; and 3) both DD-induced excess PWP build-up pace and axial deformation rate are higher.

4.1 *Degree of Anisotropy*

Following the pioneering works by Oda (1972a), it is generally accepted that dry sand when deposited under gravity would have the contact normals aligning preferentially along the deposition direction because the particles tend to stop at the most stable position. This features the high degree of anisotropy induced in the DD specimen. On the contrary, initial moisture contributes suction which holds particles of MT specimen together. The orientation of grains is thus not controlled by gravity. Such random particle orientation results in a more isotropic structure, which is similar to the honeycomb structure suggested by Casagrande (1975). Figure 6 hypothetically shows these two distinct fabric structures. This difference in anisotropy is consistent with the quantitative study by Yang et al. (2008) who computed the average vector magnitude $\triangle$ of DD sample as 0.214, whereas that of MT is 0.091. $\triangle$ = 0 indicates isotropy.

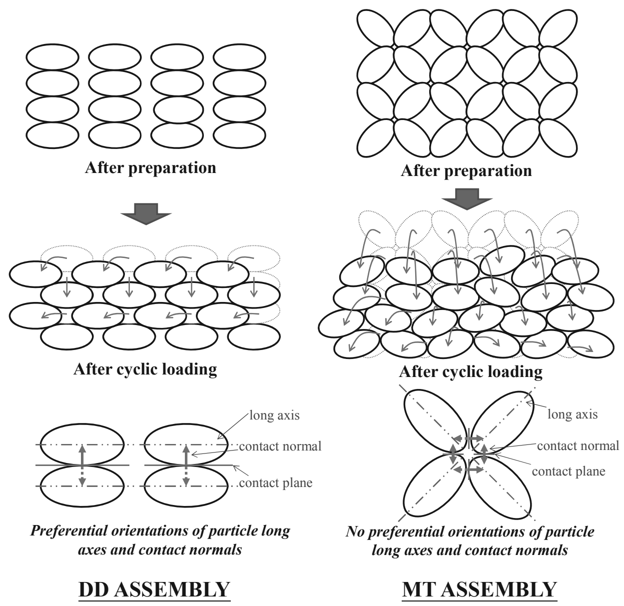

Figure 6. Schematic illustration of DD assembly and MT assembly before and after cyclic loading.

4.2 *Observation 1: Occurrence of Limited Deformation*

Shearing leads to fabric reconstruction which keeps increasing the degree of anisotropy (Oda 1972b) as a result of particle rearrangement. Assuming the ultimate anisotropy at failure of a granular structure is fixed, the change of anisotropy in the MT assembly is considered more significant than the DD one. It is because the change in MT is from "isotropic" to "anisotropic" but DD is from "anisotropic" to "more anisotropic". Therefore, the particle rearrangement involved in the process of changing anisotropy is higher in the former. Correspondingly, more substantial PWP build-up is resulted leading to complete collapse of the structure. As shown in Figure 6, the DD assembly apparently undergoes a lesser degree of collapse. Macroscopically, it is reflected by an axial deformation in a sudden but controlled manner. Right after the initial collapse, particles repack and the stable configuration is reconstructed. It thus leads to its subsequent post-collapse dilative stabilization.

4.3 *Observation 2: Distinctive Behavior under Differential Initial State & Stress Conditions*

The presence of preferential contact normal orientation gives rise to the higher compressibility nature of DD specimen especially when the major principal stress σ_1 is perpendicular to the contact normal (Yamashita & Toki 1993, Oda et al. 2001). Therefore, DD behavior is particularly contractive when subjected to cyclic loading with stress reversal. It explains why DD specimen exhibits collapse behavior even at a denser state (D_{rc} = 50%). But when initial shear presents such that the cyclic loading becomes non-symmetrical, DD behavior becomes less contractive due to the rotation of σ_1 away from its preferential particle orientation. It is evidenced by the occurrence of plastic strain accumulation in both DD and MT specimens (D_{rc} = 35%) at higher α level. On the other hand, D_{rc} = 20% results in a highly contractive state so both exhibit collapse behavior. Under non-symmetrical loading condition, the occurrence of limited deformation has been discussed above.

4.4 *Observation 3: Higher PWP Accumulation Rate*

Due to the higher contractiveness of DD specimen, the higher pace of PWP build-up as well as higher deformation rate become understandable. It hence results in higher cyclic failure potential usually observed with DD-induced fabric.

5 CONCLUSION

This experimental study offers crucial evidence on how initial fabric affects the cyclic behavior of sand under distinctive initial state and shear stress conditions. In the absence of initial static shear (i.e. under symmetrical loading), loose sand always exhibits a complete collapse behavior, featured by runaway deformation by the triaxial specimens, irrespective of the fabric. Dense sand, on the other hand, apart from performing the classic cyclic mobility, it would undergo a phenomenon of partial collapse if the fabric changes. In the laboratory, moist tamped specimens are responsible for the former behavior while the latter is featured by limited deformation by dry deposited specimens. When an initial shear stress is present (i.e. under unsymmetrical loading), the fabric effect is reversed. With a change of initial fabric, loosely deposited specimens always exhibit limited deformation whereas moist tamped ones maintain the runaway failure. Dense sand is free from fabric effect as it always behaves plastically under undrained cyclic loading. The important practical implication is that apart from accouting for the state and stress effect on design against cyclic failure of soil, there is a need to incoporate a fabric parameter into the design process.

6 ACKNOWLEDGEMENTS

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