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Discussions

Interactive comment on "Effects of relative density and accumulated shear strain on post-liquefaction residual deformation" *by* J. Kim et al.

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Most of all, we thank referee for the thorough review on the manuscript.

- 2/5. Residual shear strain only accumulated if some slope or free-face exists at a site. Under level-ground conditions, residual shear strain do not accumulated. Thus, this study only applies to sites that are susceptible to lateral spreading. This is not clearly articulated by the authors.

Takahashi et al. (2012) developed K0-controlled online seismic response experiment devices to evaluate earthquake-induced residual displacement at the ground level. They also examined the variation of volumetric strain and residual shear strain with different types of earthquake motions and OCR. As a result, they showed that residual

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shear strain is accumulated even under level-ground conditions. Therefore, additional text was inserted at page 4/line 24 as follows: "On the contrary, Takahashi et al. (2012) demonstrated that even level-ground residual shear strain was generated and accumulated in one direction by conducting a K0 online seismic response experiment."

Takahashi, H., Yoshida, J., Sento, N., Mori, T., Uzuoka, R. and Kazama M.: Evaluation of residual deformation after earthquake by means of K0 on-line seismic response experiment, Journal of JSCE, Division C, 68(2), 274-285, 2012.

- 2/12-13. In the 1980s, Dobry and his co-workers developed a very similar testing device that allowed stress-controlled cyclic torsional loading to liquefy a soil followed by stress-controlled monotonic loading. The device could apply equal all-around or Ko consolidation stresses. This device was used extensively to study the hydraulic ïňĄll materials from Lower San Fernando dam, as well as other sandy soils. Thus, the authors' device and test method is not novel, and the authors should review the work by Dobry and his co-workers to put their own work into proper perspective.

We have proposed a new test sequence (procedure) to evaluate the relationship between residual shear strain and residual volumetric strain, even if the test apparatus may be similar to that used for previous test sequences, as a reviewer pointed out. In other words, we have focused on the testing method rather than on the test apparatus. Furthermore, by their own account Dobry et al. (1982) developed an axial-torsional cyclic test, using a cylindrical specimen rather than a hollow cylindrical specimen. Applying torsional shear to a cylindrical specimen does not present a technical problem if we consider small deformation. However, when we consider the large shear strain level, the cylindrical specimen does not assure uniformity. For these reasons, we believe that our test method is in fact novel. Dobry, R., Vasquez-Herrera, A., Mohamad, R., and Vucetic, M. (1985):"Liquefaction flow failure of silty sand by torsional cyclic tests." Advances in the art of testing soils under cyclic conditions, Proceedings of a session sponsored by the Geotechnical Engineering Division in conjunction with the ASCE Convention in Detroit, Michigan, Khosla eds., 29-50.

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- What is “K0 drain”? Are the authors referring to reconsolidation?

“KÂň0 drain” is referred to as the reconsolidation. However, “K0” does not represent a normal consolidation. First, we have to explain the meaning of “K0” used in this study. “K0” in this study signifies the condition in which no lateral deformation takes place. So, the difference between reconsolidation and the aforementioned “K0 drain” is that the K0 drain only allows generation of vertical strain. Conversely, with normal reconsolidation axial strain and lateral strain are generated concurrently. But, in level-ground conditions, no lateral strain is generated during the reconsolidation.

- 2/15-16. Why would a Ko condition exist during cyclic loading that generates excess pore water pressure (leading to liquefaction)? Ishihara and his co-workers have shown that the coefïňĄcient of lateral stress, K, approaches unity as the excess pore water pressure approaches the effective vertical stress (i.e., as a soil approaches level-ground liquefaction). Therefore, it’s not clear why it is relevant or appropriate to maintain a Ko condition during cyclic loading, post-cyclic monotonic loading, and reconsolidation.

First, as explained above, “maintain K0 condition” doesn’t mean maintaining the coefficient of lateral pressure. As shown in Fig. 2, lateral stress and vertical stress approached the same value; namely, the coefficient of lateral pressure became unity (as you noted).

- 2/20. What are “restoration behaviors”?

Restoration means “recovery of effective stress”. To make it clear, “restoration” was replaced by “recovery of effective stress”.

- 2/22. What are “structure restoration characteristics”?

As is well known, the soil structure is broken during liquefaction and then starts to be restored with either drainage or monotonic shear. According to our test results, structural restoration is different depending on how excess pore water pressure is dissipated. We

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termed the differences that may arise as “structural restoration characteristics”.

- 3/16-22. Bray, Dashti, and their co-workers clearly have shown that a large percentage of shaking-induced settlement (including liquefaction-induced settlement) occurs during shaking because an undrained condition is not maintained for most soils during shaking. Post-shaking reconsolidation certainly does occur, but this may be a smaller fraction of the total shaking-induced volumetric strain. The authors appear to have missed this key aspect of soil behavior in their work.

Generally, it is assumed that an undrained condition is maintained due to earthquake motion that is too short to induce drainage. Thus, the settlement in sand deposits following liquefaction has been studied with the drainage following undrained cyclic loading (Lee and Albisa (1974), Tatusoka et al (1984), Nagase and Ishihara (1998), etc.). In addition, according to the results of Unno et al. (2006), the volumetric strain of the dry specimen after drained cyclic loading and the volumetric strain of the saturated specimen after undrained cyclic loading is the same given the same loading history. We agree that the undrained condition is not maintained during an earthquake of duration longer than 2 to 3 minutes, and that the drainage during cyclic loading would then have to be reconsidered. However, exploring this possibility is beyond the scope of this paper. Therefore, examining the residual volumetric strain using this method is proper.

Unno, T., Kazama, M., Uzuoka, R., and Sento, N.: Relation of volumetric compression of sand between under drained cyclic shear and reconsolidation after undrained cyclic shear, Journal of JSCE(C), 62, 757–766, 2006.

- 3/25. Stewart and his co-workers were focused on settlement of unsaturated soils during shaking. How does this relate to the current study?

This was pointed out by another reviewer, and we referred to some other papers.

- 3/26-27. Again, this statement is not consistent with the work done by Bray, Dashti, and co-workers.

To make it clear, we rewrote the sentence “Ground settlement generally occurs with the dissipation of excess pore water pressure caused by cyclic loading.” as “In saturated ground, post-liquefaction settlement generally occurs with the dissipation of excess pore water pressure caused by cyclic loading.”

- 4/11. What are “online testing techniques”?

Hakuno and Shidawara (1969) proposed the basic concept of the hybrid simulation method for the first time. They researched the nonlinear property of the resistance force of the beam subjected to seismic external force. In general, when performing nonlinear earthquake response analysis of a structure in the plastic region, the vibration equation will be solved step by step in a time domain. That is, if deformation at a certain moment is decided, the corresponding resistance force can be calculated from the constitutive model. However, they proposed that the resistance force property could be obtained from element tests instead of a constitutive model. That is to say, if deformation develops in a structure at a certain moment during an earthquake, the resistance force can be measured after giving the corresponding strain to the specimen. The numerical solution for the next time step can then be calculated from these measured values. Therefore, by repeating this process in the time domain, the analysis can proceed without a constitutive model. Because the experimental equipment must be controlled online, it has been called the “online test”.

- 5/11. At what rate are the liqueïňĄed specimens drained? Does the drainage rate affect the development of residual shear strains?

As you pointed out, the drainage rate affects the development of residual volumetric strain. So, the drainage rate was set to 0.05%/min by referring to JGS standard (JIS A 1227: 2009, Test method for one-dimensional consolidation properties of soils using constant rate of strain loading). They suggested 0.1%/min for a specimen in which the plasticity is under 10.

- 5/15-17. This statement is poorly written, and I don’t understand what the authors are trying to say. Why would the occurrence of lateral deformation be prevented under undrained conditions for horizontally stratiïňĄed soils?

We rewrote this sentence to read: “In level ground, the occurrence of lateral deformation is constrained (Ishihara, 1996).”

Ishihara, K.: Soil behaviour in earthquake geotechnics, Oxford science publications, 1996.

- 5/19. What are “indoor test programs”?

It should be “laboratory” test programs.

- 5/23-25. As noted above, residual shear strains only accumulate in sloping ground or near a free-face. As a result, the residual shear strain is a function of both the number of cycles as well as the static shear stress. That is, for a given number of cycles, the higher the static shear stress, the larger the residual shear strain. The authors appear to have neglected this key variable.

The external variable of accumulated shear strain, which is an indicator that reïňĆects the NUMBER OF CYCLES, was selected to reïňĆect the characteristics of earthquakes. “Accumulated shear strain was mobilized to indicate the cyclic loading history”.

- Figure 1. This ïňĄgure appears to illustrate an annular specimen. However, the authors earlier stated that the specimen is cylindrical. Please clarify the text and/or modify the ïňĄgure accordingly.

The word “cylindrical” should be changed to “hollow cylindrical”; we have revised throughout the manuscript.

- 6/6. The shear strain per pulse will be a function of the specimen height. Most commonly, this rotation per pulse is reported in radians (followed by a shear strain per pulse corresponding to a particular specimen height).

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It is 6.283×10-6 radian/pulse. It has been revised.

- 6/11. Again, this should be rotation, not shear strain.

We don't understand what the reviewer wants to say. As you pointed out, we control the rotation during the testing procedure. But this rotation develops shear strain to the hollow cylindrical specimen, and each value can be converted using simple equation. This is generally accepted in hollow cylindrical shear test.

- Figure 2. (a) needs a scale and an indication of the orientation of the photo. (b) is not needed.

We revised Fig. 2 as you pointed out; (b) was deleted.

- 6/24. Ko is the coefïňĄcient of earth pressure at rest, while K is the coefïňĄcient of lateral stress. Please clarify.

The meaning of K0 as used in this study is the lateral constrained condition for the cyclic and monotonic loading process. This K0 condition has been kept only during the consolidation and drainage process. Generally, in horizontally layered ground no lateral displacement occurs during either consolidation or during the earthquake; this is similar to the K0 condition. Although we used the expression because of this similarity, this expression leads to the misunderstanding. To avoid the confusion of readers, we modified the expression K0 to include lateral constrained.

âĂČ - Figure 3. This ïňĄgure is very difïňĄcult to follow since the authors don't include the cyclic loading history and measured pore water pressures with the plots. Does cyclic loading begin at t = 0 sec? If this is the case, a Ko condition is not maintained during cyclic loading as the authors indicated in the abstract. Clearly, during both sets of tests Ko approaches unity (presumably indicating liquefaction). That is not a constant Ko condition (nor should it be). Furthermore, on page 7, the authors indicate that liquefaction occurred completely (what is complete liquefaction?) at 12500 sec. This needs a pore water pressure plot (or some other clear data) to illustrate.

We added the time histories of pore water pressure ratio and shear strain. Figure 3 has been revised as attached pdf file.

Fig. 3. Time history by two types of control; (a) Laterally-controlled case, and (b) Vertically controlled case.

- 7/10-11. This statement is not clear. The “vertical control method is (adopted) to eliminate the effects of the Ko control method.” According to the authors, isn’t the vertical control method one type of Ko control. And I’m still not clear on how the authors are controlling K in this test.

To make it clear, we rewrote this statement as follows: “There are two different methods to maintain the K0 condition. One is vertical control that alters the deviator stress to constrain the vertical strain and adjusts lateral pressure (cell pressure) to keep the normal vertical stress constant. The other is lateral control, in which lateral pressure and deviator stress are used to control the vertical strain and constant normal vertical stress, respectively.”

- 7/15-17. This statement is not clear. How is the vertical stress changed to produce a constant total stress? Do the authors mean the “mean stress” is constant? This must be clariïňĄed.

In the vertical K0 control method, deviator stress is changed to constrain the vertical strain. Vertical stress also changed with varied deviator stress. The variation of lateral stress is also required to maintain the constant normal vertical stress.

- 8/11. What is “pre-consolidation”?

To make the specimen self-reliant, a negative pressure of 20 kPa was used. This negative pressure induces some vertical strain; this was termed “pre-consolidation.”

- 9/15. Figure 7 indicates that the cyclic load is applied at a rate of about 8 or 9 cycles / 1000 sec, or less than 0.01 Hz. What loading case is this intended to simulate. Because the load cycles are so slow, there is ample time for local void ratio change

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and creep to occur between load cycles because of the high permeability of the sand specimens. So, even though the global void ratio is unchanged (i.e., global undrained conditions are maintained), it is highly unlikely that local void ratio is unchanged. This could dramatically affect the test results.

We agree that the loading rate may affect the test results. However, in this study very slow loading was adopted to avoid the effect of frequency.

- Table 3. This is a key issue for this paper – six tests are FAR too few to recognize signiïňĄcant trends when there are multiple variables involved!

This study has developed a test program to evaluate residual strain characteristics. The effects of relative density and accumulated shear strain were examined. We focused on loading pattern B, and used patterns A and C for comparison. Since lateral displacement of loose to medium density induces the damage, the test cases have compositions of relative density between 40% and 60%. All test cases have been conducted at least twice to confirm data reproducibility, and representative data have been shown. Conducting more cases to verify this tendency would be worthwhile, but a great deal of labor would be required for each case. Over 20 experiments have been conducted with a precise control technique to evaluate the behavior of soil, and then 6 cases have been shown considering the test results comprehensively. This study has suggested the relationship we aim for between residual shear strain and residual volumetric strain, and provides meaningful findings in its conclusion as well. Given this, it is hard to agree with the idea that more cases are needed to achieve our objective. The authors feel that the data are sufficient to attain the conclusion given for the scope of research delineated during the introduction.

- Table 4. This is another key issue for this paper – the values of Ko used for testing are not reasonable for the sand. The table indicates that the consolidated relative densities range from 38% to 59%, yet the Ko values range from 0.53 to 0.57 (and do not show any trend with Dr). Using Jaky's equation, Ko values of 0.53 to 0.57 correspond to drained friction angles of 28 to 25. These friction angles are NOT consistent with sand specimens with relative densities of about 40 to 60%. Reasonable friction angles for this sand and these relative densities should be on the order of 33 to 36, corresponding to Ko values of 0.46 to 0.41. How do these unreasonable Ko values affect the authors' interpretations?

Jaky's equation is an empirical equation. So, the relation that Jaky suggested is not unique and depends on the sort of material used. According to the previous test results of Takahashi et al. (2012) who conducted K0 consolidation using same test mechanism and apparatus, K values of 0.4∼0.5 were achieved with a relative density of 50%. However, the material used in that test, Soma silica sand 5, is not the same material that we used. Given this difference, it is hard to say that the K0 values of this study are unreasonable.

- 11/1. Rate of strain, not strain speed

It was revised in the entire manuscript

- Figure 10 and related text. This ïňAgure shows that the excess pore water pressure builds more SLOWLY as the relative density increases, it does not build more QUICKLY as stated by the authors.

This was our miss; we changed it to "slowly".

- 11/16-17. Again, the excess pore water pressure ratio does NOT increase with increasing relative density. Figures 10, 11, and 12 clearly show that the rate of excess pore water pressure generation decreases with increasing relative density.

We rewrote this as "the tendency of excess pore water pressure ratio decreases with increasing relative density".

- 12/16-18. This statement is not well-supported. How is this shown in the ïňAgure?

According to Shamoto et al. (1997), shear stress-shear strain relations (mean effective stress-shear strain relation in this study) are nearly parallel to each other during monotonic shear conducted on a liquefied specimen. It can be concluded by referring to previous research that the slope of shear stress-shear strain relation is almost constant after a material starts to recover its rigidity (Shamoto et al. (1996 and 1997), Wang and Wang (2012)). In Fig. 13, thus, we can anticipate how much more sheer strain is needed to recover the rigidity of the specimen, with a relative density of 38% and accumulated shear strain 50%, to its initial condition. It looks like the initial rigidity is recovered at around 18%. It is apparent that the specimen of Dr=38% and accumulated shear strain 50% requires more than 8% of shear strain compared to the specimen of Dr=57% and accumulated shear strain 50%. So, slight increases of density would result in decreased generation of residual shear strain. ïĄň

- Conclusions. As a result of the numerous inconsistencies and questions throughout the study, it is impossible to comment on the reasonableness of the conclusions.

We are sorry that there are some vague explanations about the result of this study. We tried to make it clear throughout the manuscript.

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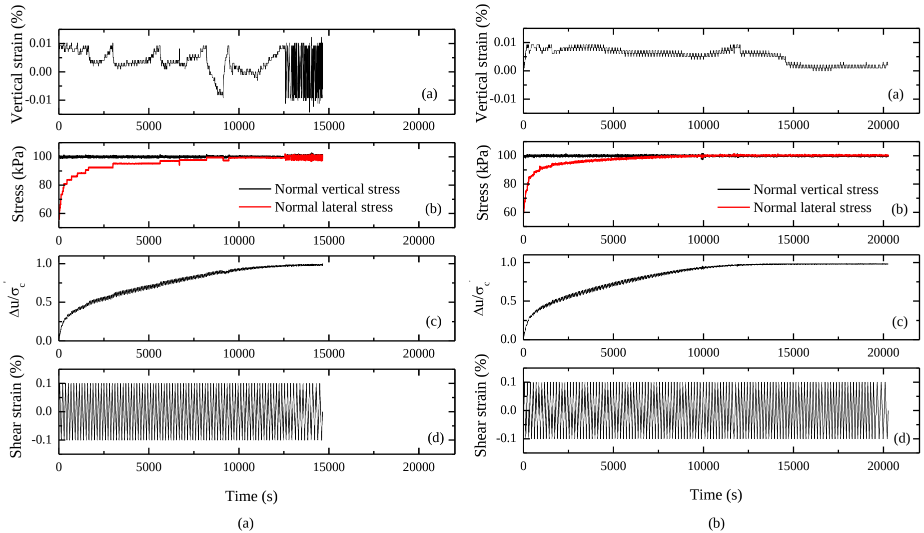

Fig. 3. Time history by two types of control; (a) Laterally-controlled case, and (b) Vertically controlled case.

Fig. 1.