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Proposal of torsional hollow cylindrical test data utilization method for validation of liquefaction analysis

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ABSTRACT: Since the ground is regarded as a continuum comprised of inhomogeneous materials, numerical analyses are indispensable for evaluating the actual behavior of foundations and soil structures in a detailed designing process. However, no comprehensive method or procedure has been established to check the calculated results systematically and objectively. In this paper, a series of torsional shear tests were conducted from the view of validating a numerical analysis results related to the liquefaction problem in level ground. In particular, the influence of initial stress conditions and loading wave patterns on the excess pore pressure accumulating process was investigated. The relationship between the accumulative shear strain and the accumulated excess pore water pressure was utilized to develop the method to evaluate the results of an effective stress analysis.

1 INTRODUCTION

Although the soils are aggregate comprised of inhomogeneous materials, the ground can be regarded as a continuum, and it enables to employ numerical analyses, e.g. FEM, in the design process to evaluate the detailed behavior of the foundations and soil structures. While it is important that the results of these analyses are systematically checked for accuracy, no comprehensive method or procedure has been established. In this paper, a series of torsional shear tests were conducted to test the validity of the numerical analysis results of a numerical analysis for a liquefaction problem in level ground. In particular, the influence of initial stress conditions and loading wave patterns on the excess pore pressure ratio (referred to as 'EPPR' hereafter) accumulating process was investigated. Then, a unique relationship between the specially treated shear strain, which will be explained together with the experimental results, and the accumulated EPPR independent of the above mentioned experimental conditions was found in order verify numerical element responses. The extent of reliability is expected to be quantified as the relationship is used.

Azeiteiro et al. (2017) found the relationships between the dissipated energy per unit volume normalized by the post-consolidation isotropic effective stress and the ratio of residual EPPR build-up. They mentioned that not only did the normalized dissipated energy at the onset of liquefaction appear to be independent of the loading pattern used in each test, but also that a unique relationship was obtained between the pore pressure ratio and the normalized dissipated energy for the entire loading history. In many earlier research works in the literature, the focus was on the reconsolidation volumetric strain after the dissipation of excess pore pressure. For example, Sento et al. (2004) studied the relationship between liquefaction-induced reconsolidation volumetric strain and the undrained shear loading history by using a hybrid online testing technique and concluded that the relationship between the accumulated shear strain and the reconsolidation volumetric strain was closer than that with the maximum shear strain and the normalized dissipated energy. Unno et al. (2012) also confirmed this relationship through a series of 1-G shaking table tests and, further, found a kind of compensating relationships between the reconsolidated volumetric strain and the residual shear strain. This was consistent with findings of earlier work which showed the influence of initial shear stress on the post-liquefaction behavior of sand, as investigated by Unno & Tani (2008). Despite the usefulness of the results drawn by the above- mentioned research works, they were utilized for very specific purposes only, like conducting approximate evaluations of the likelihood of liquefaction damage using SPT or some other sounding results, or providing better but still approximate evaluations using a calculated earthquake response done by an equivalent linear analysis.

Using the equivalent linear analysis for the evaluation of liquefaction related problems presents a theoretical problem: it is not clear how the response of the potentially liquefiable layers above the earlier-liquefied layer shown in Figure 1 should be accurately estimated. An equivalent linear analysis can deal only with a linear response, which means that no effect or material property change during an earthquake motion analysis can be taken into consideration, and the responses after the onset of liquefaction by the analysis method are useless. While the authors acknowledge usefulness of the evaluation method when a combination of laboratory test results and the equivalent linear response is used to evaluate the likelihood of liquefaction in practice, the use of the equivalent linear method has clear theoretical limitation and cannot be considered "correct responses". The results obtained by it are merely vague indices, not actual responses. That is, the evaluation method, or the chart based on it, are suitable for use on multiple sites to roughly determine whether each site has a higher risk of liquefaction or not, but it cannot provide a detailed estimate of the actual responses of an important site. In addition, it is also theoretically inadequate to utilize the equivalent linear response analysis to the problems related to migration of excess pore pressure mentioned by Cubrinovski et al. (2017) and Sinatra & Foti (2015) or the problems implying multi directional shearing as reported by Su & Li (2008).

In order to estimate the earthquake responses for an important construction site, an effective stress analysis must have potential to deal with the complexities of the task at hand. However, it is difficult to judge the validity of the calculated results of the theoretically sophisticated and rather complicated constitutive model implemented in the effective analysis code. One of the aims of this study is to assess the validity of the results obtained by effective stress by utilizing the knowledge acquired from extensive laboratory test results, like those mentioned above, without the requirement of input from an experienced expert. This might lead to the general use of an effective stress analysis and, perhaps, to automatic design by AI in the future.

In this study, a series of torsional shear tests were conducted under various experimental conditions, e.g. the initial normal stress ratio of horizontal to vertical, the input wave form and the relative density. Accumulated shear strain, which is shown in Figure 2, was adopted as an index to express the process of excess pore pressure generation sheared by various loading patterns. The influence of the initial stress conditions and loading wave patterns on the EPPR accumulation process was investigated. The method to evaluate the results of an effective stress analysis proposed in this report makes use of the relationship between the accumulative shear strain and accumulated EPPR. The advantage of this approach is that the strain history throughout the

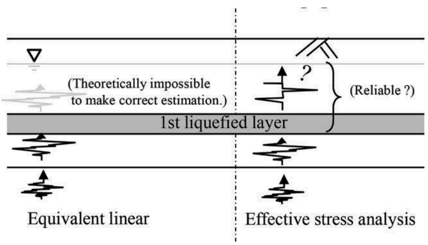


Figure 1. Problems related to numerical analysis methods.

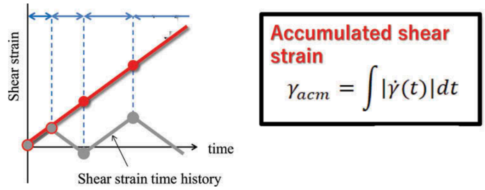


Figure 2. Accumulated shear strain.

duration of the earthquake motion can be evaluated regardless of the loading wave pattern. Further, since this approach uses only strain, it may be able to avoid the combined errors while using both strain and stress as the dissipated energy. The authors acknowledge that using the dissipated energy during undrained cyclic shearing in order to predict the likelihood of liquefaction appears promising, but the main purpose of this paper is to propose a objective evaluation framework to validate the reliability of the results of numerical analysis and the relationships between an index and the characteristics of liquefaction can be switched afterward, therefore, as a trial, the above mentioned accumulated shear strain is used in this paper.

2 TORSIONAL SHEAR TESTS

A series of torsional shear tests was conducted using Toyoura sand with a mean diameter of 0.3 mm, a specific gravity of 2.668, and e_{max} and e_{min} values at 0.964 and 0.631. The test conditions are shown in Table 1. Cyclic torsional shear was applied by strain waves as shown in Figure 3 under the undrained and plane strain condition with the stresses of two horizontal components maintained to coincide during the shear. Typical test results of Case 2 are shown in Figure 4. As shown in this figure, in all the tests except for that for Case 12, shear strain was controlled to reach the prescribed strain amplitude denoted by the wave forms shown in Figure 3, and the stress amplitudes were therefore different in each cycle. A line was drawn to connect the maximum values in each cycle: this was adopted as an index to represent the accumulated EPPR.

2.1 *Influence of the initial stress ratios*

Figure 5 shows the results from Case1 to Case6 to confirm the influence of the initial stress ratio of the horizontal stress to the vertical stress on the EPPR accumulations. As shown in the left-hand side figure, the relationships between the accumulated shear strain and the EPPR remained within a rather narrow range. This may be in part due to the method to realize plain strain conditions: because the two horizontal stresses were kept the same during the whole process of shearing

Table 1. Torsional shear test cases.

Case #	K_0	Wave form No.	Case #	K_0	Wave form No.	Case #	K_0	Wave form No.	Case #	K_0	Wave form No.
1	1.0		**4**	0.4		**7**		2	**10**		5
2	0.8	1	**5**	1.5	1	**8**	1.0	3	**11**	1.0	6
3	0.6		**6**	2.0		**9**		4	**12**		Earthq.

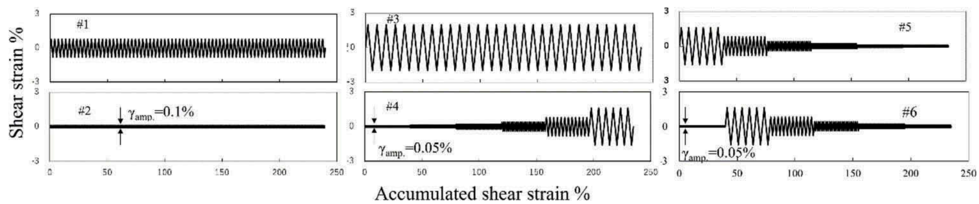


Figure 3. Applied wave forms.

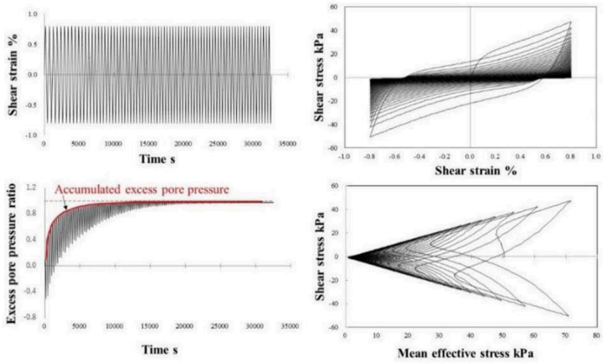


Figure 4. Typical torsional test results (Case2).

in this investigation, the stress differences vanished at the early stage of the shearing in all cases, then after a 5 % accumulated shear strain, the stress ratio in every case became unity. That is, the stress conditions were kept same in this series of experiments for the majority of the shearing.

This problem can be resolved by controlling the inner and outer cell pressure independently to allow the strain horizontal and parallel to shearing direction to occur while maintaining the strain horizontal and perpendicular to shearing direction at zero. Since the main target of this paper is not to find an excellent unique relationship between the accumulated shear strain and EPPR but to propose how an effective stress analysis can be validated, this was left as a problem to be solved in the future.

2.2 *Influence of the loading patterns*

While the initial stress had little effect on the relationship between the accumulated shear strain and the EPPR, the influence of the loading patterns was significant, as shown in Figure 6(a). The EPPRs of Case9 and Case11, which had the smallest strain amplitude at the initial loading stage, are much smaller than those of the other cases. That of Case7 is also slightly smaller. Figure 6(b) shows the EPPRs at the accumulated shear strain of 40 %: the amplitude of shear strain was kept constant before this for every case. As shown in Figure 6 (b), the contributions of the accumulated shear strain to increase EPPR become smaller when the cyclic shear strain amplitudes become smaller. Therefore, in order to evaluate the contributions of the accumulated shear strain on EPPR appropriately, a coefficient f calculated from Equation (1) was adopted to adjust the contribution of shear strain on accumulations of excess pore pressure so that the effect of the smaller strain is smaller. The following equation (2) depicts a modification factor from passing i $_{\text{th}}$ peak strain $\gamma_{peak,i}$ to the next peak strain (f=1.0 before the first shear strain peak, $\gamma_{peak,1}$).

$$\gamma_{acm,m} = \sum f \cdot |\Delta\gamma| \tag{1}$$

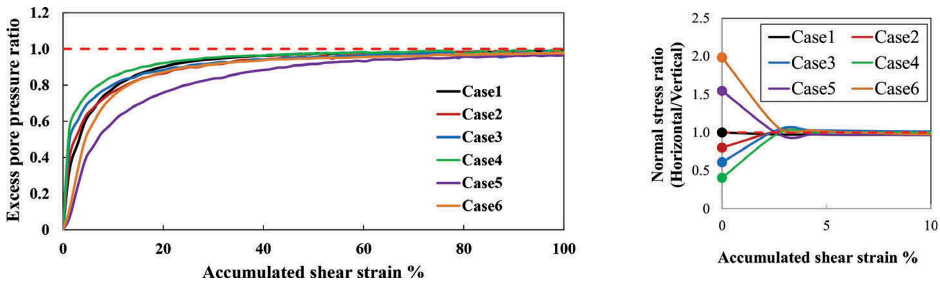
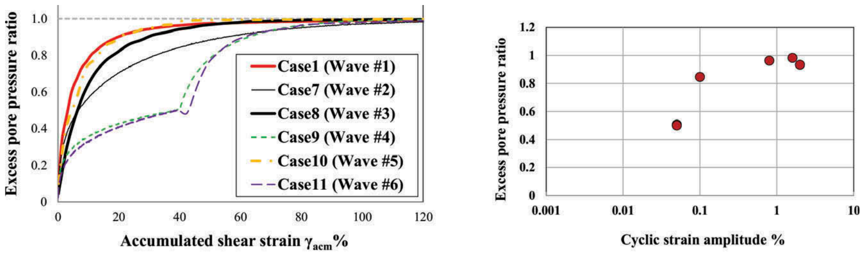


Figure 5. Influence of the initial stress ratios (Case1 - Case6).



(a)The realtionships between $\gamma_{acm.}$ And EPPR. (b)Results at γ_{acm} = 40%.

Figure 6. Influence of the loading patterns (Case1, Case7 -Case11).

$$f = \frac{1}{1 + \left(a + c\left|\gamma_{PT} - \gamma_{peak,i}\right|\right)\left(\gamma_{acm} - \gamma_{acm,i}\right)^{b}} \tag{2}$$

Where $\gamma_{acm,m}$ = modified accumulated shear strain; $\Delta\gamma$ = shear strain increment; $\gamma_{acm,i}$ = accumulated shear strain at $\gamma_{peak,i}$;; γ_{PT} = shear strain when reaching phase transformation stress; and *a, b, c* = fitting parameters to be identified from laboratory experiments.

(a)The realtionships between $\gamma_{acm.}$ And EPPR. (b)Results at γ_{acm} = 40%.

Figure 7 shows the relationships between the modified accumulated shear strain and the EPPR for every case using a different loading wave form, and those were gathered within a narrow range. The fitting parameters used are shown in Table 2. In this table, since the behaviors of the sand were totally different between before and after passing the transformation line as mentioned by former research works about sands in general, e.g. Ishihara et al. (1975), Alarcon-Guzman et al. (1988), and so on, two values of parameter *c* are shown for before/after passing the phase transformation line.

The authors acknowledge that this is not an essential finding but merely a superficial transformation. However, to use these kind of findings from laboratory tests to validate the element responses calculated from a rather complicated analytical method like an effective stress analysis, gathering the results within a narrow range is both important and convenient. Using a representative unique curve, like averaged curve for a narrow range, is the key concept of the proposed method to validate the element responses in the next section.

Table 2. Parameters to calculate coefficient *f*.

	before PT	after PT
γ_{PT} %	0.2	
a	0.4	
b	0.3	
c	18	0.03

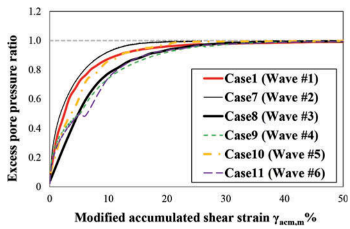


Figure 7. Relationships between the modified accumulated shear strain and EPPR.

3 PROPOSAL OF A NEW VALIDATION METHOD FOR ELEMENT RESPONSES CALCULATED FROM A NUMERICAL ANALYSIS BY UTILIZING THE RESULTS FROM LABORATORY TESTS

3.1 *Relationships between a torsional test result conducted by using an irregular wave form and the reference range obtained by uniform or semi-irregular wave form loading*

A torsional shear test was conducted by using an irregular wave form in order to confirm the suitability of using the relationships between the accumulated shear strain and EPPR as a reference curve for validations of element responses of a numerical result. The irregular wave form used and the results are shown in Figure 8. The results are summarized as the relationship between the accumulated shear strain and the maximum EPPRs in each cycle of shearing. As shown in Figure 8, even by the irregular shearing, the curve is located within the narrow band obtained in the previous chapter. This fact indicates that all the element responses obtained by a numerical analysis for a level liquefiable ground must be in and/or near the band. In the next section, a method with regard to evaluate the validity of numerical responses is proposed.

3.2 *A new validation method for element responses calculated from a numerical analysis by utilizing the results from laboratory tests*

As mentioned in the previous section, all the element responses obtained by a numerical analysis for a level liquefiable ground must be in and/or near the band obtained by the laboratory tests using the same material. It is, therefore, practical to use the flow shown in Figure 9 as the validation method. This is comprised of the three steps of data processing and the final judgement.

First, in order to prepare the reference curve for validation, at least two laboratory tests must be conducted, and the relationship between the accumulated shear strain and the EPPR for each result must be obtained by data processing. If needed, the parameters γ_{PT} *a, b* and *c* to obtain the modified accumulated shear strain in Eq. (1) are identified to make those two curves closer, and then those two curves form a narrow range. Another index besides the (modified) accumulated shear strain, like the dissipated energy per unit volume proposed by Azeiteiro et al. (2017), can be used as long as it allows to represent various experimental results in a unique relationship for convenience for use in the next step. Further, besides the relationship between γ_{acm} and EPPR, other element responses can be calibrated as long as a unique experimental curve has been acquired. Needless to say, it is same in the later process.

Second, calculate the modified accumulated shear strain of all the elements by using those parameters, then summarize the final values, and then collect the maximum values of EPPR for each element. Note that because the EPPR represents the peak values of each cycle, as shown in Figure 4, and because the relationships shown in Figure 8 and the other related figures only represent the peak values of each loading cycle, it is meaningless to compare a whole response of each element with the reference curve. It is adequate when the maximum or peak values of each cycle of EPPR time history are checked in the following third step.

In the third step, the task is to make a reliability contour. To do this, quantify the reliability of element responses with regard to the process of pore pressure generation (using all peaks)

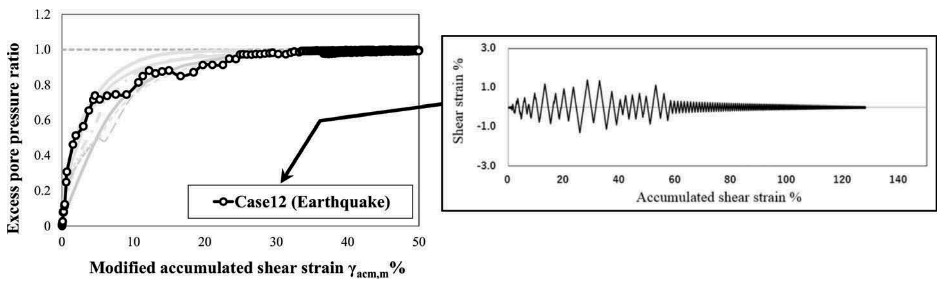


Figure 8. Comparison the results obtained by an irregular wave loading like an element response during an earthquake and the narrow band in the previous chapter.

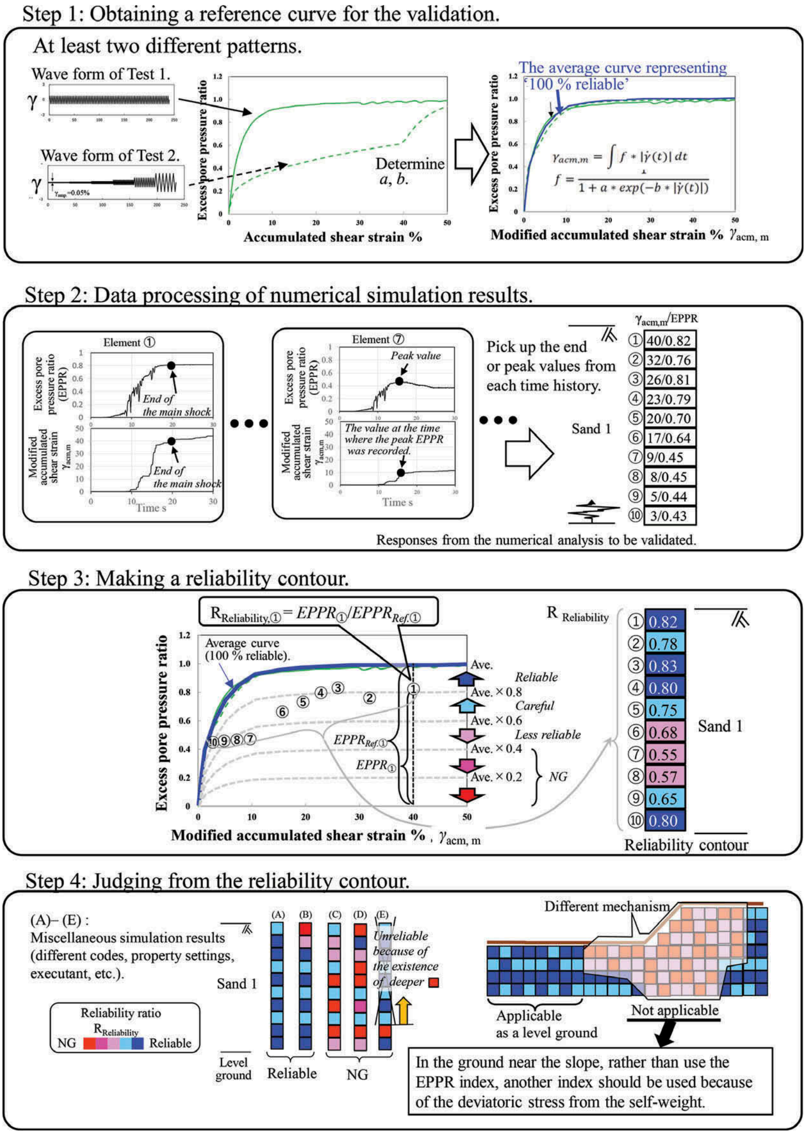


Figure 9. A proposal of systematic validation method for effective stress analysis.

or the maximum value of EPPR using the ratio of the obtained EPPR to the point on the reference curve at the same modified accumulated shear strain.

Finally, based on the obtained reliability contour, a total judgement should be made. Since the experimental results used to obtain the reference curve are likely limited, that is, at first the experimental conditions do not cover all conditions expected in situ, and because those results might contain some unidentified errors, it is not reasonable to expect that all the element responses will score a reliability of 1.0 or close to it. Therefore, a proper reliability value, for which the element response (EPPR) is reliable without any further check, should be determined first. Then, if it exists, check the extent of influence of the lower reliability area on the total response in question. The existence of lower reliability area does not always mean the failure of the numerical analysis.

When the lower reliability area is located at the important part for estimating the total response, there are two major possibilities: it may indicate the failure of the numerical analysis or, perhaps, it is a clue suggesting the need for further detailed investigation if the stress changes are beyond the scope of those conditions of the laboratory test conducted to obtain the reference curve. In such case, additional laboratory tests should be conducted. If it is difficult to impose those conditions on the specimen even by sophisticated torsional shear test apparatus, a shaking table test should be used by modeling the target ground with measuring instruments specially arranged to investigate the response against those specific conditions.

4 SUMMARY

The results of the series of experiments carried out in this research indicate that the initial value of the coefficient of earth pressure and the existence of initial shear stress have little influence on the relationship between accumulated shear strain and excess pore pressure ratio (EPPR). On the other hand, it was found that the process of increasing the excess pore pressure differs for each loading wave pattern. By focusing on the relationships between the excess pore water pressure and the loading wave patterns, it was found that the magnitude of the strain level affect the excess pore water pressure at the same accumulated shear strain. Therefore, a correction factor to modify accumulated shear strain was proposed to obtain a unique relationship between the modified accumulated shear strain and EPPR so that it can be used as a convenient reference curve to validate element responses in a numerical analysis.

After showing the potential of the reference curve by comparing with the response of an experiment conducted using an irregular wave form loading, a concept of the systematic validation method for numerical simulation results is demonstrated using the reference curve of the relationship between the modified accumulated shear strain and the EPPR obtained by a series of torsional shear tests. Although the authors acknowledge that this is only a concept and it is far from perfect, this type of systematic validation is indispensable for common use of an effective stress analysis in practice. That is, a comprehensive method which employs the vast knowledge based on the experimental results shown in the literatures is needed to promote a reliable usage of sophisticated numerical analysis method in practical design work. The concept used in this method no doubt can be improved by conducting further investigations designed to find various relationships from the perspective of validating the element responses in a numerical analysis. The point is to have a method whereby systematic judgments can be made based on the reliability contour, ideally with a related check list.

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