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Uncertainty quantification of the seismic behavior of liquefiable sloping ground

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ABSTRACT: To provide a quantitative assessment of prediction techniques for liquefaction, we performed multiple centrifuge model tests on the seismic behavior of liquefiable sloping ground, targeting a unique prototype, as well as effective stress analyses for each test result. In comparison of experimental and/or analysis results, uncertainty quantification framework was introduced to estimate the variations and validate the computational model: an error measure called EARTH, in which a total error is given as a sum of phase, magnitude, and slope errors, was used to quantify discrepancy between time histories of experimental or analysis results. By directly comparing the time histories using the error measure, the variation in numerical simulations was assessed in a quantitative manner, as well as that in centrifuge experiments; this suggests that the validity of computational techniques can be evaluated in an objective way by considering both experimental and analytical variations.

1 INTRODUCTION

Seismic behavior of soil-structure systems is in general nonlinear. For evaluating the complex behavior, centrifuge model tests are often used as well as effective stress analyses. Following major earthquakes (e.g., Niigata and Kobe earthquakes in Japan), many findings about the experimental and analytical methods have been accumulated through continuous elaborate research. However, it is considered that the precision of the seismic behavior prediction strongly depends on experimenters and analysts, and it is not yet possible to guarantee the validity of prediction methods in an objective way. This may be because conventional research and practice rarely discusses the experimental variation (or repeatability) under the same test condition. Additionally, another reason may be that the validity of analytical methods is generally confirmed by a subjective judgement of analysts through comparison of just a pair of analytical and experimental results, without considering the uncertainty in experimental and analytical methods. To overcome the problem and to improve the objective reliability and credibility of the seismic behavior prediction of soil-structure systems by experimental and analytical methods, the idea of V&V (Verification and Validation) has attracted attention (ASME, 2006). V&V is characterized by the requirement of uncertainty quantification (UQ) in both experimental and analytical results.

Based on these backgrounds, researches are under way to evaluate the variation and reliability of the results of centrifuge model tests and effective stress analyses (Arulanandan and Scott, 1994; Kutter et al., 2018; Manzari et al., 2018). However, a quantitative evaluation method has not yet been concretely presented. Therefore, to raise the objective validity of ground behavior prediction, we attempted in this study a more quantitative evaluation for a series of centrifuge experimental results on a liquefiable sloping ground during earthquakes and its simulations based on effective stress method. It is a feature of using the idea of comparing time histories instead of instantaneous values (e.g., peak value) as an evaluation method of the results.

2 CENTRIFUGE MODEL TESTS

2.1 *Brief summary of centrifuge model tests*

We used a geotechnical beam centrifuge with a 2.5-m effective radius at the Disaster Prevention Research Institute, Kyoto University. Model cross section in prototype scale is shown in Figure 1. We conducted shaking experiments on a 1/40 model of the prototype (see Figure 1) under a 40 G centrifugal acceleration. Ottawa sand (F65) was used as a ground material, and the ground was prepared with a target void ratio of 0.6 using the air pluviation method. A viscous fluid, called Metolose, with a viscosity of 40 cSt was used for the pore fluid. As shown in Figure 1, eight pore water pressure transducers and seven accelerometers were installed, but we will pay attention in this paper to the responses at AH0 through AH4 and PWP1 through PWP4.

In the experiments, a total of four cases were considered as shown in Table 1. A ramped sinusoidal wave with a frequency of 1 Hz and a duration of 40 s was used as the input motion, and a maximum amplitude of 330 Gal was set as the target. However, the achieved value listed in Table 1 is slightly larger than the target value in Case 2 and slightly smaller in Case 4. As shown in Table 1, there were slight variations in the void ratio, the degree of saturation, and the viscosity of the pore fluid, but it is considered difficult to rigorously satisfy the target values (i.e., a void ratio of 0.6, the degree of saturation of 100%, and a viscosity of 1.0 cSt in prototype scale).

2.2 *Experimental results*

Figure 2 shows the input accelerations at AH0 and the response accelerations at AH4 near the ground surface as an example. Although a difference of about 20 Gal exists between Cases 1 and 2 with regard to the maximum amplitude shown in Table 1, the Arias Intensities in the both cases are nearly identical as shown in the left column of Figure 2. As for Case 4, both the maximum amplitude and the Arias Intensity are smaller than in the other cases. The response accelerations at AH4 show negative spikes arising from positive dilatancy in either case, but the degree is different from case to case. When trying to judge the difference (or similarity) between cases from only the shape of waveforms, we must rely on the subjective judgement of experimenters.

The time history of excess pore water pressure (EPWP) at PWP1 through PWP4 is shown in Figure 3. In all cases, the qualitative tendency is almost the same: the occurrence of liquefaction

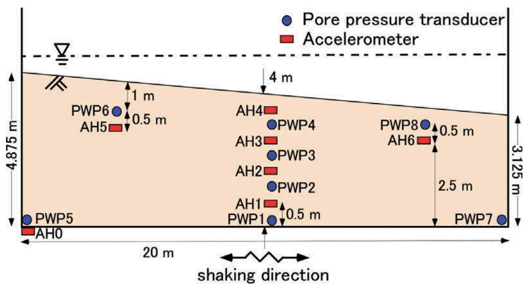


Figure 1. Cross-section diagram in centrifuge model tests.

Table 1. Test cases.

Case	D.A. input (Gal)	ρ_d (kg/m^3)	e	Sr (%)	Viscosity (cSt)
1	334	1658	0.60	97.5	1.11
2	354	1646	0.61	100.0	0.99
3	333	1643	0.61	99.6	0.95
4	284	1663	0.59	100.0	0.90

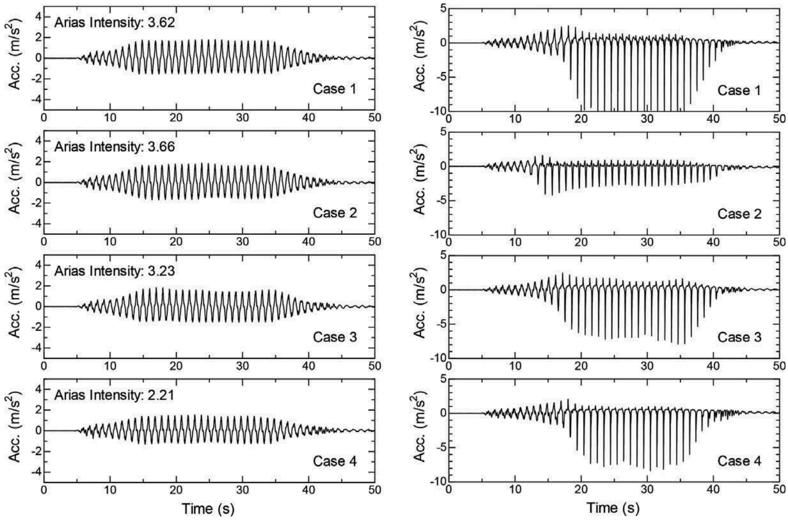


Figure 2. Time histories of input and response accelerations (left: AH0, right: AH4).

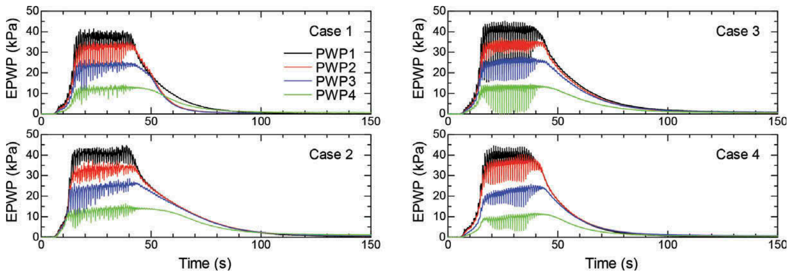


Figure 3. Time histories of excess pore water pressure.

during shaking and the dissipation of EPWP after shaking are commonly observed. However, some variations exist in the dynamic amplitude during shaking and the dissipation rate after shaking. It is considered difficult to objectively and quantitatively evaluate the degree of variation between cases only from the visual observation of the time history as is the case for accelerations.

Figure 4 shows the time history of lateral displacements at the center of the ground surface. A clear difference between cases can be recognized. The residual value is the most important in general design with regard to displacements, so the instantaneous value (the residual value in this case) is available for comparison unlike acceleration and EPWP. However, when it is necessary to pay attention to the dynamic displacement during shaking, an objective methodology for quantitative evaluation based on the time history is considered to be required.

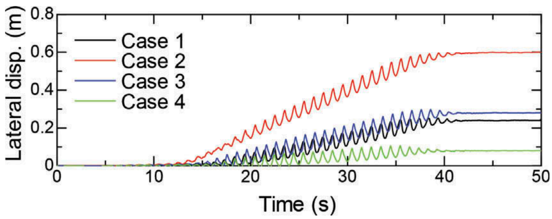


Figure 4. Time histories of lateral displacements.

3 EFFECTIVE STRESS ANALYSES

3.1 *Brief summary of analyses*

For the centrifuge model tests described in the previous chapter, we carried out two-dimensional finite element analyses using 3,600 elements (including pore water elements). The degree of freedom in the horizontal and vertical directions were fixed at the base and the lateral boundary was set to the vertical roller. For the liquid phase, the bottom and side boundaries were set as an impermeable boundary. The analyses were carried out in two stages: a self-weight analysis and a subsequent earthquake response analysis.

In this research, a finite element program, called "FLIP", was used for dynamic effective stress analysis of the sloping ground during earthquakes, and a strain space multiple mechanism model (Iai et al., 2011) was selected as a constitutive model for liquefiable soils. Note that a qualitative methodology proposed in the next chapter does not put a restriction on the type of constitutive models for effective stress analyses. Model parameters related to dynamic deformation characteristics and dilatancy in Table 2 were determined referring to laboratory experimental data (Kutter et al., 2018) with the aid of the simplified method for parameter identification (Mikami et al., 2011); G_{ma}, ϕ_f, and h_{max} are the shear modulus under the confining pressure of 100 kPa, the internal friction angle, and the upper bound for hysteretic damping factor, respectively. All parameters in Table 2 were common among the cases because the void ratio in the experiments was almost the same among the cases as shown in Table 1.

3.2 *Analysis results*

Computed accelerations and EPWP are shown in Figures 5 and 6, respectively, with corresponding experimental results. The analyses appropriately reproduce the response accelerations with negative spikes and the build-up and dissipation processes of EPWP in the centrifuge experiments. However, the computed dynamic amplitude of EPWP during shaking is evaluated somewhat larger than the experiments. It is considered difficult to quantitatively evaluate the

Table 2. Model parameters of the strain space multiple mechanism model.

			Dilatancy parameters									
G_{ma} (kPa)	ϕ_f (deg.)	h_{max}	ϕ_p (deg.)	ε_d^{cm}	$r_{\varepsilon dc}$	$r_{\varepsilon d}$	q_1	q_2	l_k	r_k	S_1	c_1
1.10×10^5	40.0	0.24	28.0	0.03	1.7	0.08	1.0	1.0	2.0	3.0	0.005	1.40

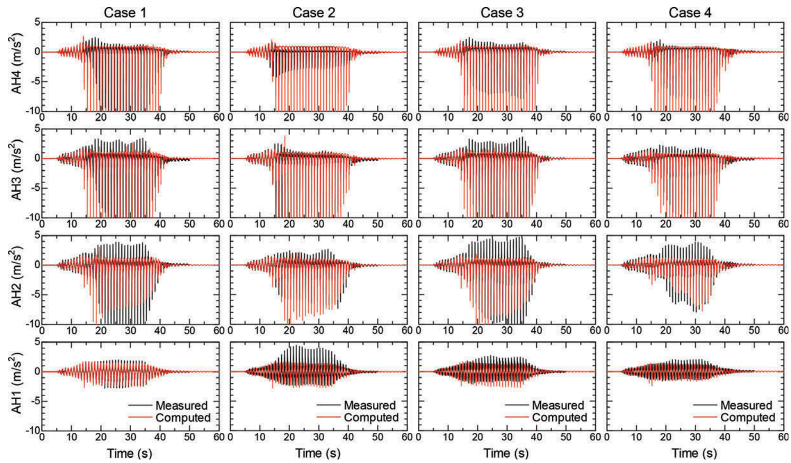


Figure 5. Comparison of computed accelerations with measurements.

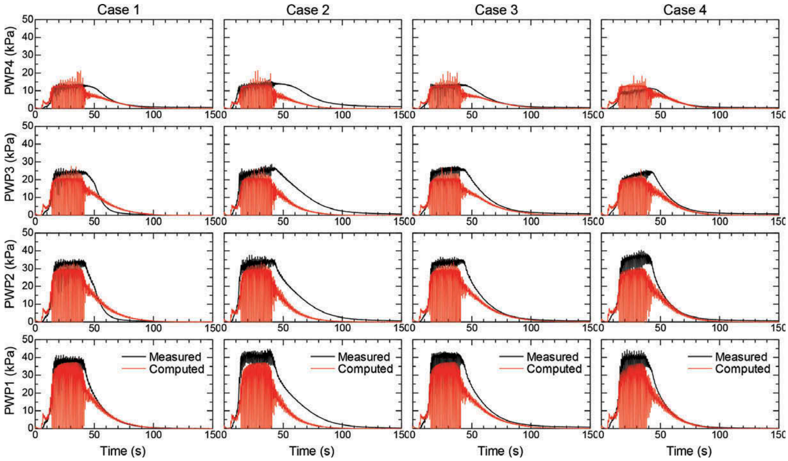


Figure 6. Comparison of computed excess pore water pressures with measurements.

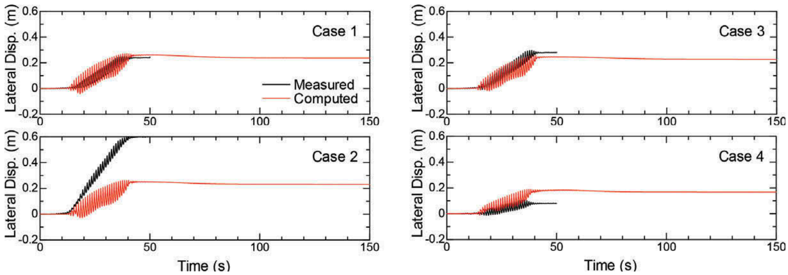


Figure 7. Comparison of computed lateral displacements with measurements.

difference between the experimental and analytical results through a simple comparison of the time histories.

Figure 7 shows a comparison of computed horizontal displacements at the center of the ground surface with corresponding measured time histories. In Cases 1 and 3, displacement waveforms almost equal to the experiments are obtained in the analyses, but the computed displacement in Case 2 is underestimated as compared with the experiment. On the contrary, the computed displacement is somewhat overestimated in Case 4, even when the difference in the input motions shown in Figure 2 is considered in the analyses.

4 UNCERTAINTY QUANTIFICATION

4.1 *Evaluation technique*

In this research, we adopted the error measure, called EARTH (Error Assessment of Response Time Histories) proposed by Sarin et al. (2010) in the field of automotive engineering. This is because the methodology can be applied to time series data in which response characteristics (e.g., amplitude, frequency) greatly change with the lapse of time. In EARTH, the difference between two time series data is divided into three components: Phase error, Magnitude error, and Slope (or frequency) error. If the target time history is represented by

$$y(t_i) = Y\cos(\omega t_i + \phi), \tag{1}$$

the difference in Y, ω, and ϕ corresponds the Magnitude, Slope, and Phase errors.

Each error can be evaluated as follow (refer to the original paper by Sarin et al. (2010) for details). First, the Phase error is calculated based on the result of the cross correlation between two time histories. However, the Phase error is basically equivalent to the total (or averaged) deviation of two waveforms, and can be reduced by aligning the starting time of shaking. Thus, we decided not to take into account the error in this research. Next, the Magnitude error is evaluated by the following equation applying a method called Dynamic Time Warping (DTW).

$$\mathrm{ERROR}_{\mathrm{madnitude}} = \left\| A^{[ts+w]} - B^{[ts+w]} \right\| / \left\| B^{[ts+w]} \right\| \tag{2}$$

where A and B are two time series vectors, and the superscript $[ts+w]$ indicates a time series vector with DTW applied after considering the overall phase shift. Finally, the Slope error was evaluated by the equation below.

$$\mathrm{ERROR}_{\mathrm{slope}} = \left\| A^{[ts+d+w]} - B^{[ts+d+w]} \right\| / \left\| B^{[ts+d+w]} \right\| \tag{3}$$

where the superscript $[ts+d+w]$ represents the process of considering the overall phase shift for the original data first, then calculating the time differentiation and finally applying the DTW.

4.2 *Results of uncertainty quantification*

First, the results of quantitative evaluation on the acceleration time histories are discussed. Figure 8(a) shows the results for the input accelerations at AH0, and Exp 1 through Exp 4 in the figure correspond to Cases 1 through 4 (see the left column in Figure 2) in the centrifuge

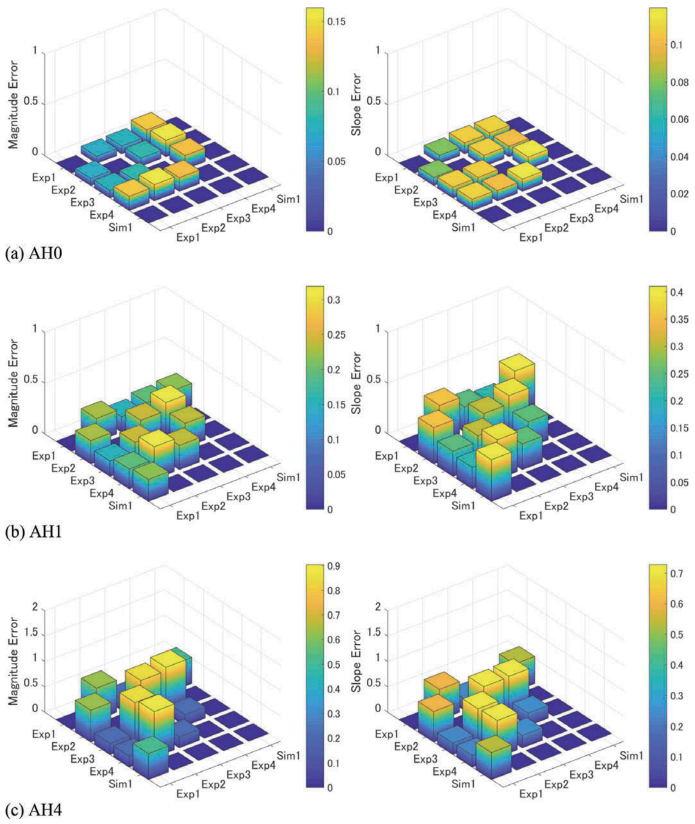


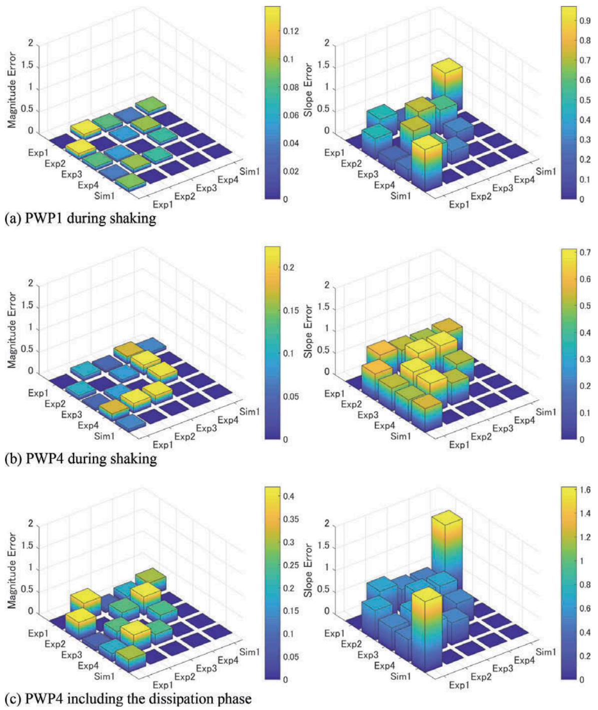
Figure 8. Results of quantitative evaluation for accelerations.

experiments. Following Goswami et al. (in press), bar graphs are used for the comparison. Since there is no clear meaning in comparing the results between the effective stress analysis for Case 1 (Sim 1 in the figure) and the other experimental cases (i.e., Exp 2 through Exp 4), a bar graph is not depicted for the combination. As shown in Figure 8(a), the Magnitude error is about 0.15 between Exp 4 and the other cases, which is slightly larger than the error between other pairs, whereas the Slope error is almost the same as around 0.1 regardless of the combination. This indicates that the difference between the cases is mainly due to the Magnitude error when it comes to the input acceleration.

Figure 8(b) and (c) show the results of quantitative evaluation on the response accelerations at AH1 and AH4. Both the Magnitude and Slope errors for AH1 are the largest between Cases 2 and 4 (0.3 for the former and 0.4 for the latter) in the experiments, and the same tendency is observed for AH4. However, when comparing its magnitude, the Magnitude error for AH4 is 0.9 and the Slope error is about 0.7; the both errors are larger than those for AH1. As shown in Figure 8, we can evaluate the error between cases with regard to the input and response accelerations in a quantitative and objective way by applying the EARTH methodology.

Next, when comparing the analysis result (Sim 1) with the experimental result (Exp 1), both the Magnitude and Slope errors are about 0.5 for AH4 (see Figure 8(c)), so the response in the centrifuge model tests has not been completely reproduced. However, the analytical result is considered to be included in the experimental variation because an error close to 1.0 occurred at the maximum even among Exp 1 through Exp 4, which were implemented to be a reproduction experiment. This suggests that the effective stress analyses carried out in this study was appropriate at least from the viewpoint of accelerations.

The results of error evaluation for EPWP at PWP1 and PWP4 are shown in Figure 9. Since the maximum amount of EPWP build-up is generally determined by the initial effective overburden stress, the Magnitude error remains at a relatively small value, particularly during shaking as shown in Figure 9(a) and (b). The Magnitude error between the analytical and experimental results for PWP1 and PWP4 in Case 1 is within the variation range of the error between the experimental cases. Thus, it is considered that the analytical method is valid from



(a) PWP1 during shaking

(b) PWP4 during shaking

(c) PWP4 including the dissipation phase

Figure 9. Results of quantitative evaluation for excess pore water pressure.

the viewpoint of the EPWP amplitude. On the other hand, the Slope error for PWP1 in Case 1 is about 1.0 and exceeds the range of the error variation between the experimental results, which is about 0.7 at maximum. This is why it is desirable to improve the analytical condition, including the readjustment of the input parameters, if we give emphasis to the Slope error. The results of the error evaluation for EPWP at PWP4 including the dissipation phase are shown in Figure 9(c). Compared to the Magnitude error, a large Slope error is recognized between the analytical and experimental results for Case 1. Thus, it may be necessary to readjust the model parameters for improving the analysis accuracy, if the response prediction including the dissipation phase is required.

5 CONCLUSIONS

To provide a quantitative assessment of prediction techniques for liquefaction, multiple centrifuge model tests on the seismic behavior of liquefiable sloping ground were performed followed by effective stress analyses for each test result. When comparing the experimental and/or analysis results, uncertainty quantification framework was introduced to estimate the variations and validate the computational model: an error measure methodology called EARTH, in which a total error is given as a sum of phase, magnitude, and slope errors, was used to quantify discrepancy between time histories of experimental or analysis results. By directly comparing the time histories using the error methodology, the variation in numerical simulations was assessed in a quantitative manner, as well as that in centrifuge experiments; this suggests that the validity of computational techniques can be evaluated in an objective way by considering both experimental and analytical variations.

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