Performance of a Soil Liquefaction Model

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Abstract

The experimental results of two centrifuge test replicas of a sloping (saturated-soil) deposit are used to assess the predictions of the (open source) software OpenSees. The discrepancy between recorded and computed acceleration time histories is expressed as a unique aggregate of three measures associated with shape, phase and frequency-shift. This decomposition sheds light on the level of consistency between computed and recorded soil accelerations and the likely source of inaccuracies in the used model prediction.

INTRODUCTION

Granular soil liquefaction is a pervasive and costly problem during earthquakes. Significant liquefaction damage was observed during all recent major events, such as for instance the 2011 Christchurch, 1995 Hyogoken-Nambu and 1989 Loma Prieta earthquakes. Liquefaction (of a saturated granular soil) occurs when the pore water pressure reaches levels comparable to the confining stresses and leads to large strains and flow failure. Intensive efforts have been undertaken over the past thirty years by researchers towards the development of constitutive and numerical modeling tools to predict the dynamic response and liquefaction of granular soils (e.g., Elgamal et al. 2003; Dafalias and Manzari 2004). Significant advances were achieved, and current models are refined and sophisticated. However, the usefulness and applicability of these models remain limited without validation testing and assessment. The validation exercise requires a comparison between blind predictions and trusted experimental data sets (Manzari, et al. 2014), and the availability of metrics to quantify the outcome of this comparison.

A number of metrics have been used by researchers to assess discrepancies among dynamic time histories (e.g., accelerations), including vector norms, average residual and standard deviation, coefficient of correlation and cross-correlation, Sprague and Geers metric (Geers 1984), Russell's error measure (Russell 1997), normalized integral square error, root mean square error and the goodness-of-fit score (Anderson 2004). Dissimilarities were also assessed using Dynamic Time Warping (Sarin et al. 2010). The benefits and shortcomings of these different measures were briefly discussed by Goswami et al. (2017). This paper relies on a newly developed set of measures that quantify the phase, shape and frequency-shift discrepancies between recorded and predicted accelerations of a soil system response.

The following sections provide a brief overview of an international collaboration effort to validate soil liquefaction models, and present some details of a discrepancy analysis that was conducted towards the validation of the soil liquefaction model of the (open source) software OpenSees.

The 2015 LEAP AND CENTRIFUGE TESTS

The Liquefaction Experiments and Analysis Projects (LEAP) is an ongoing international effort to produce trusted experimental data using high-quality centrifuge tests and then undertake a systematic exercise to validate existing computational models of saturated granular soil response and liquefaction (Manzari, et al. 2014). A validation effort was undertaken in 2015 and used a reduced scale model of a benchmark sloping soil deposit that was tested at high *g* level at six different centrifuge facilities (Manzari, et al. 2017). Specifically, the centrifuge model was composed of a uniform Ottawa F-65 sand deposit, and corresponded to a prototype with a length of 20 m and a height decreasing from 4.875 m to 3.125 m or a 5^o sloping surface (Figure 1, note that all dimensions and response variables are presented in prototype units in this article). The deposits (at the six facilities) were saturated using viscous pore fluid to achieve the same prototype permeability and were equipped with an extensive array of accelerometers and pore pressure transducers (Figure 1). The models were subjected to a ramped-sine base motion corresponding to a target acceleration having a frequency of 1Hz and maximum amplitude of 0.15g (Figure 2).

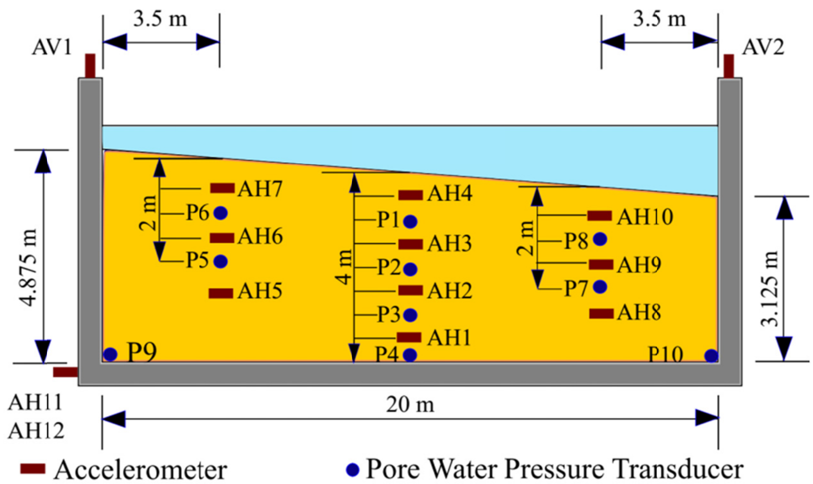

Figure 1. Schematic of the LEAP 2015 Centrifuge Tests.

The achieved (recorded) input motions at the six LEAP facilities had different levels of similarities and differences (Kutter, et al. 2017). Herein, focus is on the Rensselear Polytechnic Institute (RPI) and University of California, Davis (UCD) tests (Figure 2). The recorded RPI and UCD input motions were quite similar and consistent with the target acceleration. The main discrepancy was associated with the presence of high frequency components in the UCD motion. The corresponding soil response accelerations were also comparable. However, the RPI accelerations were marked by dilative acceleration spikes that were significantly larger than those at UCD. This discrepancy in spike magnitude is presumed to be associated with a difference in permeability between these two tests (Kutter, et al. 2017).

NUMERICAL PREDICTION

A numerical simulation of the conducted centrifuge tests was performed using the (open source) OpenSees code (Mazzoni et al. 2006). A two-phase elastic-plastic and pressure dependent model was employed to idealize the soil constitutive response (Yang, et al. 2003). The model is based on a multi-yield-surface plasticity formulation that incorporates soil liquefaction effects. The soil shear stiffness and dilatancy (shear-induced volume contraction or dilation) parameters were calibrated using the results of a series of soil sample tests. The simulations were conducted utilizing a two dimensional plane strain finite element analysis (consisting of 320 nine-node quadrilateral elements). The employed finite element model was subjected to the target input acceleration (Figure 2). Qualitatively, the obtained (simulated) response showed a strong consistency with the recorded accelerations at RPI and UCD (Zeghal, et al. 2017). For instance, clear dilative acceleration spikes were predicted in the downslope direction at the deposit shallow depths in agreement with the recorded responses. Nevertheless, theses spikes had amplitudes and occurred at time instances that were not fully consistent with the tests.

Performance and Discrepancy Quantification. Assessment of the similarities and differences in achieved input and target motions and in recorded and computed accelerations is fundamental to address the objectives of a validation exercise. A qualitative assessment, such as the one described above, is not sufficiently informative. Metrics are needed to quantify and qualify the consistency and discrepancy among the experimental replica results and numerical predictions.

The discrepancy d_{ij} between two acceleration time histories $a_i = a_i(t)$ and $a_j = a_j(t)$ (in which t is time) over a time window of length W may be quantified using a mean square deviation (MSD):

$$d_{ij} = \frac{\int_0^W (a_i - a_j)^2 dt}{2(\int_0^W a_i^2 dt + \int_0^W a_j^2 dt)} \tag{1}$$

This discrepancy is normalized so it varies between 0 and 1. The measure d_{ij} can be decomposed in terms of three specific fundamental components; namely phase, shape and frequency-shift discrepancies:

$$d_{ij} = d_{ij}^{phase} + d_{ij}^{shape} + d_{ij}^{F-shift} \tag{2}$$

The phase component d_{ij}^{phase} reflects discrepancies due to difference in acceleration phase angles. The shape component d_{ij}^{shape} quantifies the discrepancy associated with the geometrical shape (i.e., wave form and amplitude). The frequency shift component $d_{ij}^{F-shift}$ evaluates the discrepancy dealing with differences in frequency components. Goswami, et al. (2017) provide a full description of how to evaluate these different discrepancy measures. The relative values of the different metrics, d_{ij}^{phase}, $d_{ij}^{shape}$and d_{ij}^{Fshift} can be used as indicators to ascertain the discrepancy that prevails. These metrics were verified using simple synthetic signals with prescribed discrepancies and were found to be effective (discrepancy) quantification tools (the verification analysis is not presented herein because of space limitations and is discussed in Goswami et al. 2017).

An analysis was first conducted to assess the discrepancies among the target and achieved input motions at RPI and UCD. The computed total discrepancies d_{ij} (Figure 3) had low values varying from 0.02 to 0.06 and reinforce the basic qualitative visual appraisal of

Figure 2. The largest total discrepancy d_{ij} was between UCD input motion and the target and was due mostly to shape dissimilarities.

The discrepancies among predicted and recorded accelerations were found to increase in magnitude from the base to the surface of the deposit. At high depths, the total discrepancies were all of the order of 0.1, as shown in Figure 3 for the 2.5 m depth location along the central array. At this location, the discrepancy between the predicted and recorded motions was practically equal to the discrepancy between the recorded soil accelerations at RPI and UCD. Most of the discrepancy was associated with phase and may possibly indicate an inconsistency among the damping mechanisms of the actual soil deposits and the computational model. The discrepancies reached relatively large values near the surface, in spite of the relative good consistency between the input motions and the target. Nevertheless, the discrepancy between the recorded accelerations at RPI and UCD is lower than the discrepancies between the model prediction and each one the recorded motions. At this depth, there is a significant contribution associated with a frequency-shift in addition to a (larger) phase discrepancy. This frequency-shift discrepancy is due to the acceleration spikes of the predicted motion that occurred at time instants that are different from those of the recorded motions. In contrast, the shape discrepancies were relatively low at all depths.

Overall, the obtained results show that the model predictions provide reasonable estimates of the acceleration amplitudes. These predictions appeared to be affected by the employed damping and dilation mechanisms leading to relatively large phase and frequency-shift discrepancies at shallow depths. Further research is underway to confirm these findings.

CONCLUSIONS

This article presented an overview of the international collaborative effort to validate soil liquefaction models through LEAP (or Liquefaction Experiments and Analysis Projects). Two centrifuge tests and associated numerical prediction of a 2015 LEAP were briefly discussed. A new approach was used to assess the discrepancies among recorded and predicted acceleration time histories. The mean squared deviation of two specific histories is decomposed in terms of phase, shape and frequency components. These components showed that RPI and UCD centrifuge test results are rather consistent and that the conducted simulation predicts accelerations that have a larger discrepancy in phase and frequency-shift than in shape (especially for locations close to the surface).

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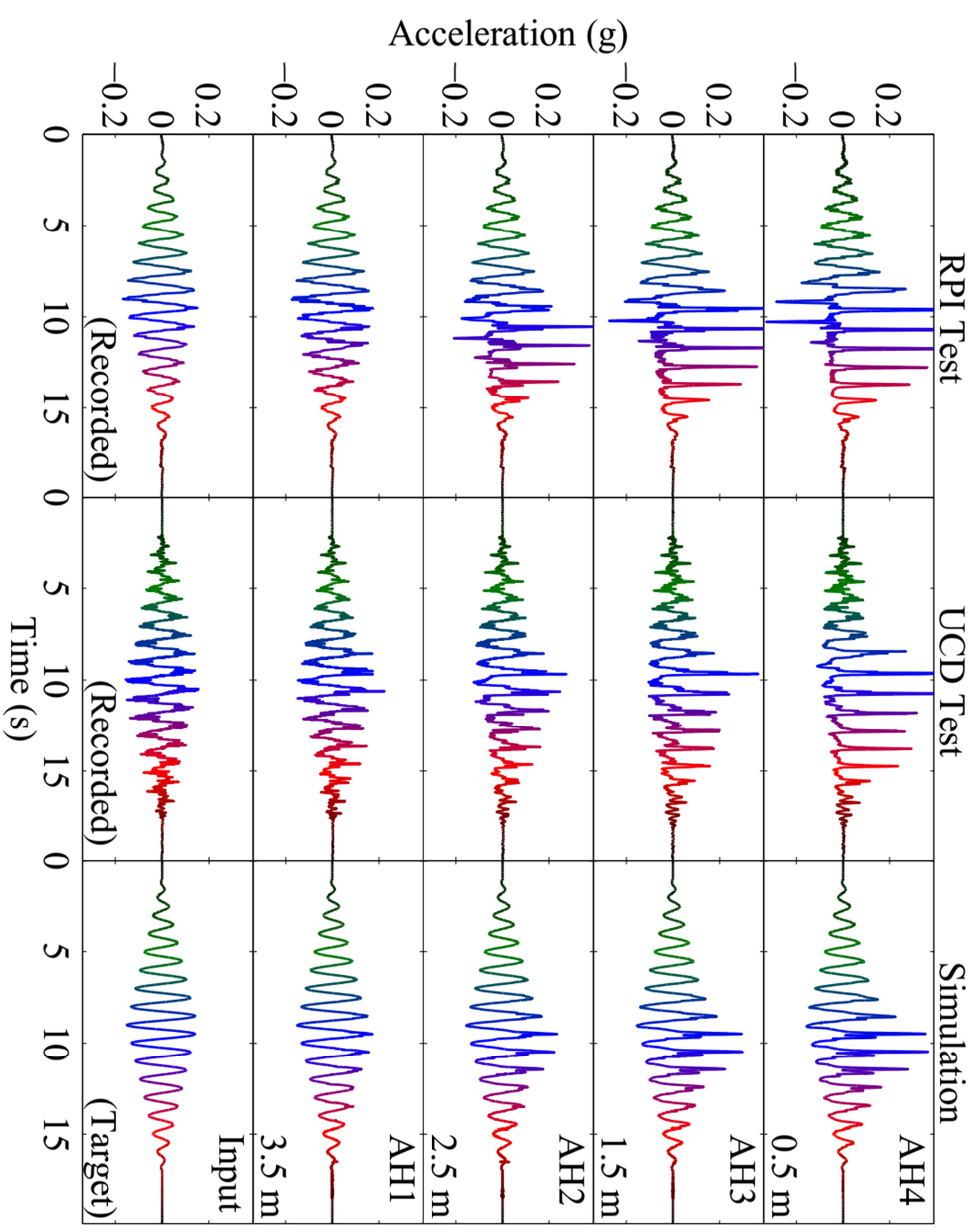

Figure 2. Acceleration time histories of the recorded RPI and UCD motions and corresponding OpenSees prediction.

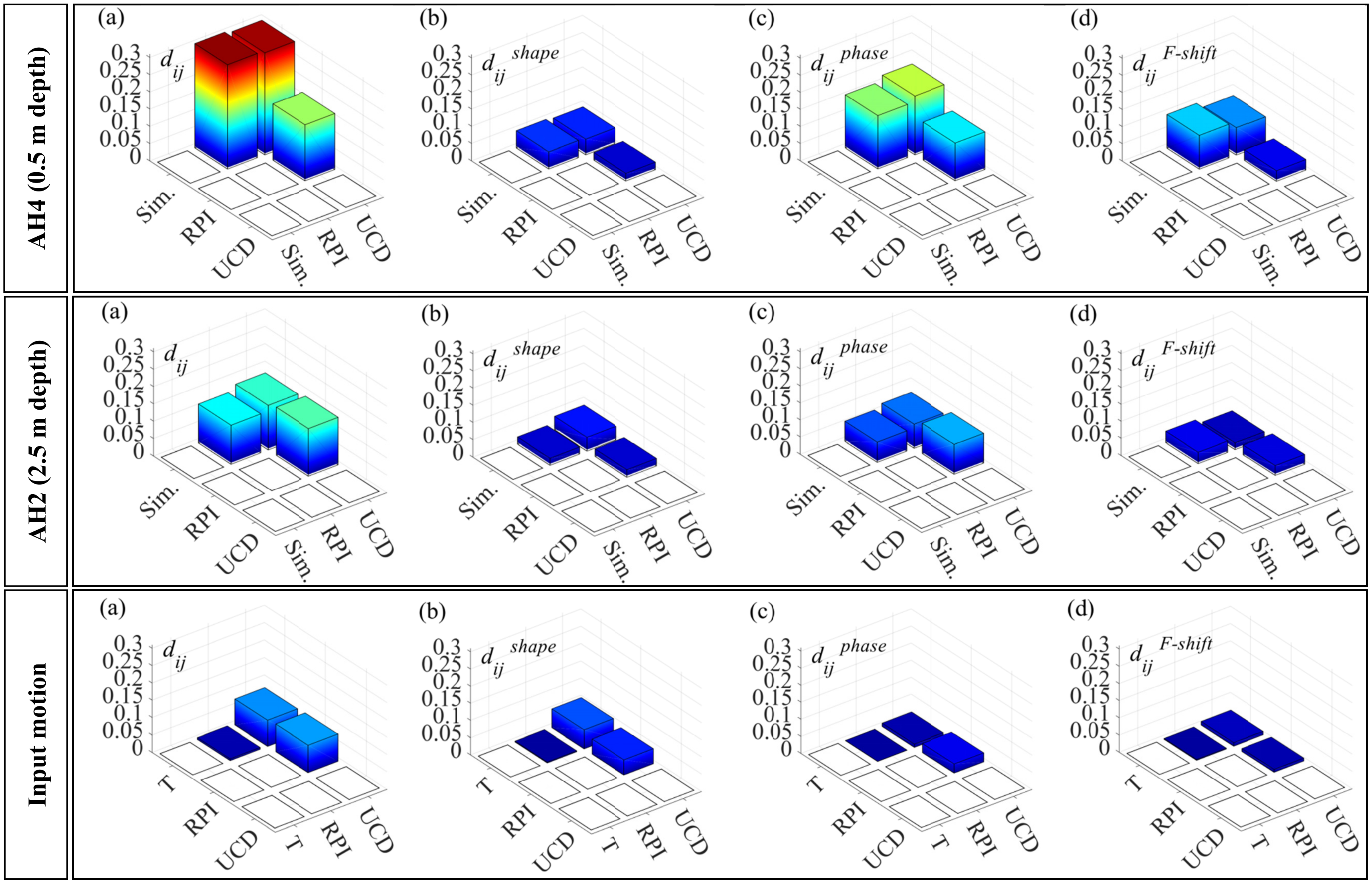

Figure 3. Discrepancy measures between: (1) recorded and target input motions, and (2) simulated and recorded accelerations at two selected depths ("T" refers to target input motion and "Sim" to predicted motion).

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