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Sensitivity analysis of LEAP soil liquefaction tests

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ABSTRACT: An analysis is conducted to assess the sensitivity of 17 replicas of a saturated sloping deposit tests conducted within the 2017 Liquefaction Experiments and Analysis Projects (LEAP). A difference analysis is first used to quantify the dissimilarities between recorded input acceleration time histories. This analysis provided a unique decomposition of the differences in terms of phase, frequency-shift, amplitude at 1 Hz, and amplitude of frequency components higher than 2 Hz (2+Hz). A kriging analysis was used to evaluate the sensitivity of the deposit response accelerations to differences in input motion amplitude at 1Hz and 2+Hz and cone penetration resistance. The analysis showed a response that is more sensitive to variations in cone penetration resistance values than to amplitude of the input 1Hz and 2+Hz motion (frequency) components.

1 INTRODUCTION

The response and liquefaction of saturated soil systems during earthquakes and extreme loading conditions remain a challenge to the geotechnical community. Centrifuge testing of reduced scale soil models constitutes a valuable source of information in this regard. However, the results of these tests are marked by variability and experimental uncertainty. Centrifuge tests conducted at different experimental facilities produce, for instance, input motions with some dissimilarity due to variability in setup and procedures, along with other uncertainties. Thus, there is need for an analysis to appraise the effects of these dissimilarities on the measured or observed response.

The reproducibility of tests at different centrifuge facilities provides the means to assess the experimental uncertainties and evaluated the sensitivities of the experimental results to these uncertainties. A sensitivity analysis is the study of the relative effects of different input factors and initial conditions on a physical system (or model of the system) response, and provides information to determine which factors and conditions contribute most to response variability (McCullough, et al., 2017).

The Liquefaction Experiments and Analysis Projects (LEAP) are an ongoing series of international collaborations to produce high quality (centrifuge) experimental data of saturated soil systems and to use this data to validate the constitutive models and numerical tools used in soil liquefaction analyses (Manzari, et al., 2018). In 2017, the LEAP exercise involved repeating the same centrifuge test of a sloping deposit at nine experimental facilities; namely Cambridge University in UK, Ehime University and Kyoto University in Japan, Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR) in France, KAIST University in Korea, National Taiwan University in Taiwan, Rensselaer Polytechnic Institute and University of California, Davis in USA, and Zhejiang University in China.

This article provides an overview of a number of analyses that were conducted to assess the differences between the input motions and evaluate the sensitivity of the experimental results to variability in input motion and deposition.

2 THE 2017 LEAP TESTS

The LEAP 2017 centrifuge model is a deposit of Ottawa F-65 sand sloping at an angle of 5° and having a height of 4 m at mid-slope (Fig. 1). The sand was deposited through pluviation in a level rigid container. The achieved mass densities of the 2017 tests had a mean value of about 1650 kg/m^3 (Kutter, et al. 2019), as displayed in Fig. 2. The deposits were saturated with a viscous fluid to achieve the same prototype permeability at the nine facilities. The models were instrumented with an extensive array of accelerometers, as shown in Fig. 1 (with AH1-AH10 to

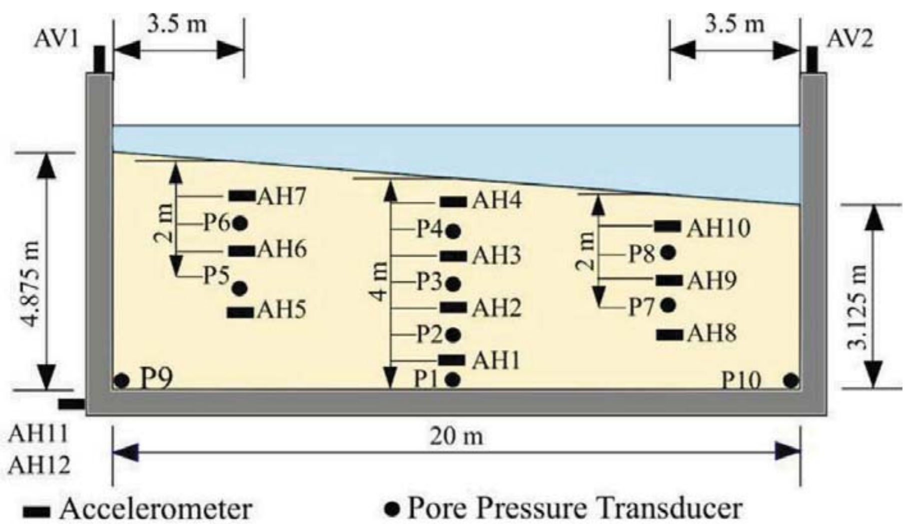

Figure 1. Schematic of the LEAP 2017 Centrifuge Model (dimensions are in prototype units).

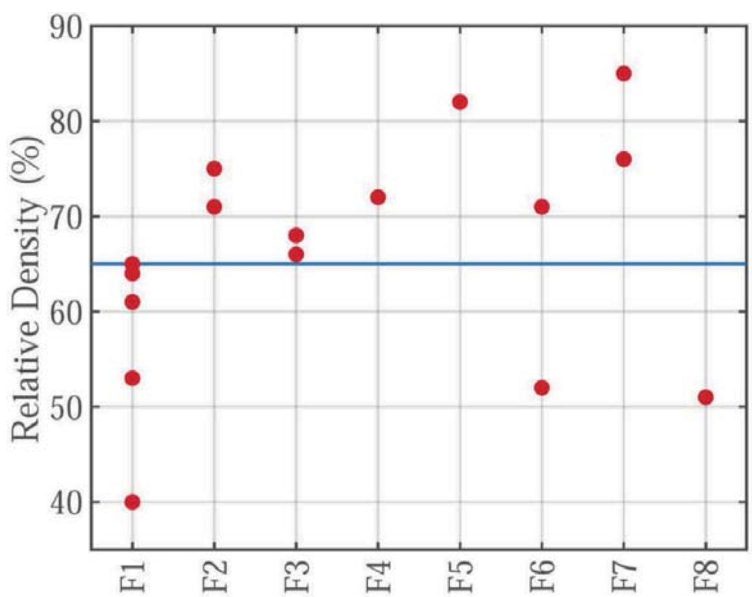

Figure 2. Achieved relative densities of the analyzed 17 LEAP tests (conducted at centrifuge different facilitiestermed F1 to F8).

measure the soil horizontal accelerations and AH11 and AH12 to monitor the input motion at the base of the model). A CPT (cone penetration test) was used during most of the centrifuge tests to characterize the deposit conditions before and after shaking. A comprehensive description of the model and experimental conditions is given by Kutter, et al., (2019).

A total of 25 centrifuge test replicas of the sloping deposit were conducted at the nine centrifuge facilities during LEAP 2017 (Carey et. al. 2019, Escoffier and Audrain 2019, Hung and Liao 2019, Kim et. al. 2019, Korre et. al. 2019, Liu et. al. 2019, Madabhushi et. al. 2019, Okamura and Nurani Sjafruddin 2019, Vargas Tapia et. al. 2019). A total of 17 tests were selected for the sensitivity analysis reported below. The selection was based on consistency among the associated stress-strain responses, as reported in Goswami (2019). The relative densities that were achieved during these 17 tests are shown in Fig. 2.

The centrifuge models were subjected to inputs that achieved base accelerations with different levels of closeness to a prescribed reference motion (Fig. 3). A qualitative assessment of the recorded motions reveals that the obtained input accelerations have different levels of similarities and differences. These differences are due to variability in equipment (e.g., shaker actuators) along with other unknown uncertainties, and lead to dissimilarities in input amplitude, phase and frequency contents. The recorded soil accelerations also showed a significant level of variability among the different centrifuge tests, as illustrated by the AH4 motions in Fig. 3. In addition to the dispersion in input motions, the response accelerations were also affected by the variability in properties and characteristics of the analyzed soil deposits (such as the relative density, as shown in Fig. 2).

3 DIFFERENCE IN INPUT MOTION

A number of metrics may be used to assess the differences among accelerations time histories (see Zeghal et al. (2018) for a brief overview). Herein, the difference d_{ij} between two corresponding acceleration time histories $a_i = a_i(t)$ and $a_j = a_j(t)$ of two different test replicas i and j is quantified using a normalized mean squared deviation:

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

in which t is time and W is length of a time window of interest. This metric is normalized so that it varies between 0 and 1. A d_{ij} metric approaching zero means that the two accelerations are essentially the same, whereas a metric of 1 is obtained, for instance, when two pure sinusoidal motions are 180 degrees out of phase with each other.

An analysis was conducted to assess the dissimilarities between the reference acceleration and the input motions that were recorded during the selected 17 centrifuge tests. These dissimilarities were quantified in terms of 4 differences in the amplitude of the dominant component at 1 Hz, amplitude for the 2+Hz components, phase angle and a shift in frequency at 1 Hz (referred to as $\Delta A_{ij}^{1Hz}, \Delta A_{ij}^{2+Hz}$, $\Delta\Phi_{ij}$ and ΔF_{ij}, respectively). Figure 4 shows the quantitative values of the differences $\Delta A_{ij}^{1Hz}, \Delta A_{ij}^{2+Hz}$, $\Delta\Phi_{ij}$ and ΔF_{ij}between the accelerations. The differences in phase angle $\Delta\Phi_{ij}$ and frequency $\Delta F_{ij}$are minor from a relative practical perspective. The $\Delta A_{ij}^{1Hz}$and ΔA_{ij}^{2+Hz}were more significant (especially for a set of about 8 input motions).

4 SENSITIVITY ANALYSIS

A kriging analysis was employed to assess the sensitivity of the observed response accelerations. Kriging provides an effective means to estimate response quantities, and corresponding derivatives and integrals, over a domain of associated input parameters using only noisy observations or measurements for a limited irregularly-spaced set of these parameters (Chilès

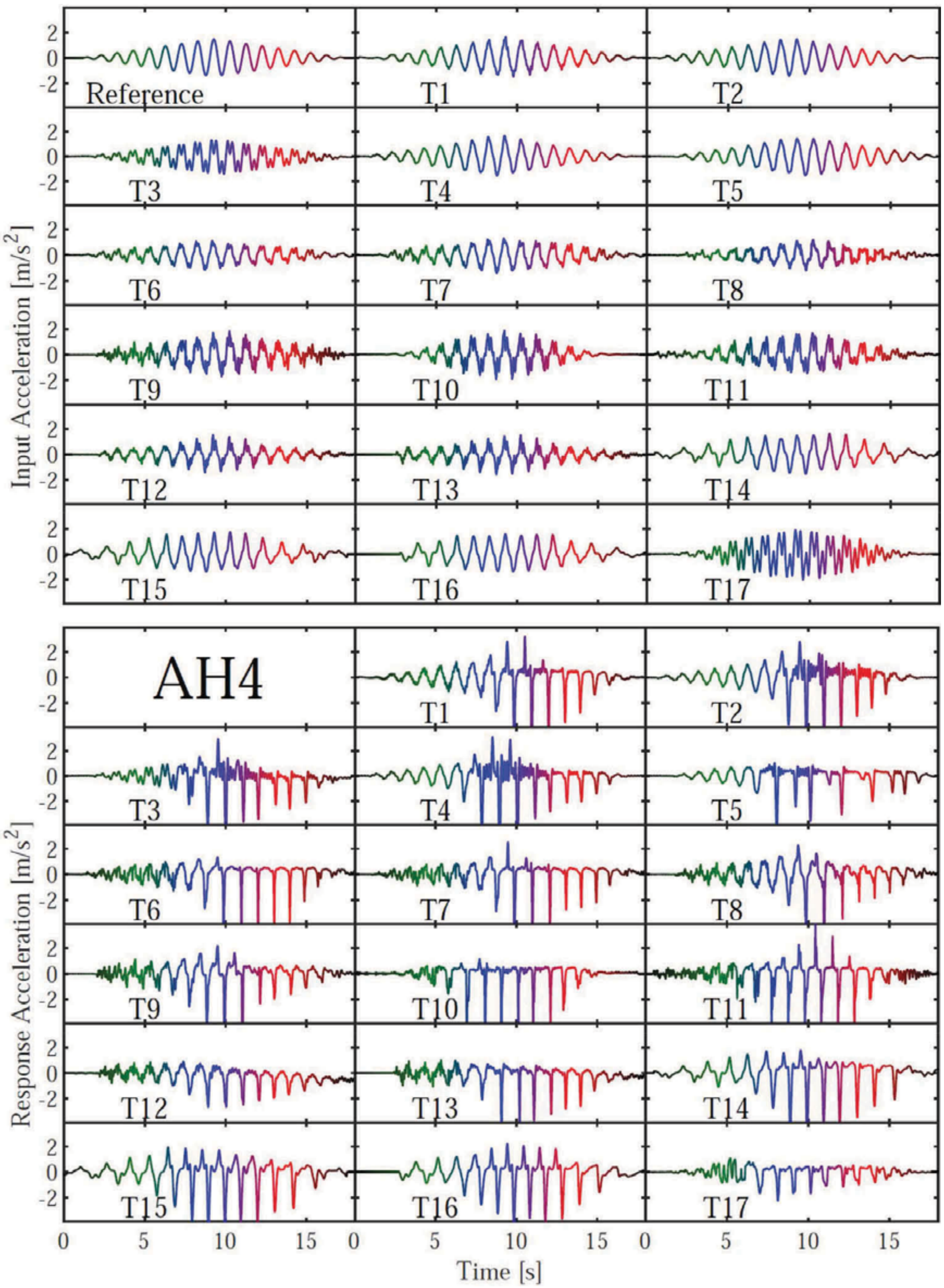

Figure 3. Accelerations of the analyzed 17 centrifuge tests (termed T1 to T17): (a) reference and achieved input (AH11) accelerations, and (b) recorded AH4 soil accelerations.

and Del ner, 1999; McCullough, et al., 2017). The difference analysis above showed that $\Delta A_{ij}^{1Hz}$and ΔA_{ij}^{2+Hz} are the two main input motion parameters that varied during the selected 17 centrifuge tests of LEAP 2017. The tested soil models had also variability in soil deposition. An average over depth of the CPT (Cone Penetration Test) tip resistance (hereafter referred to

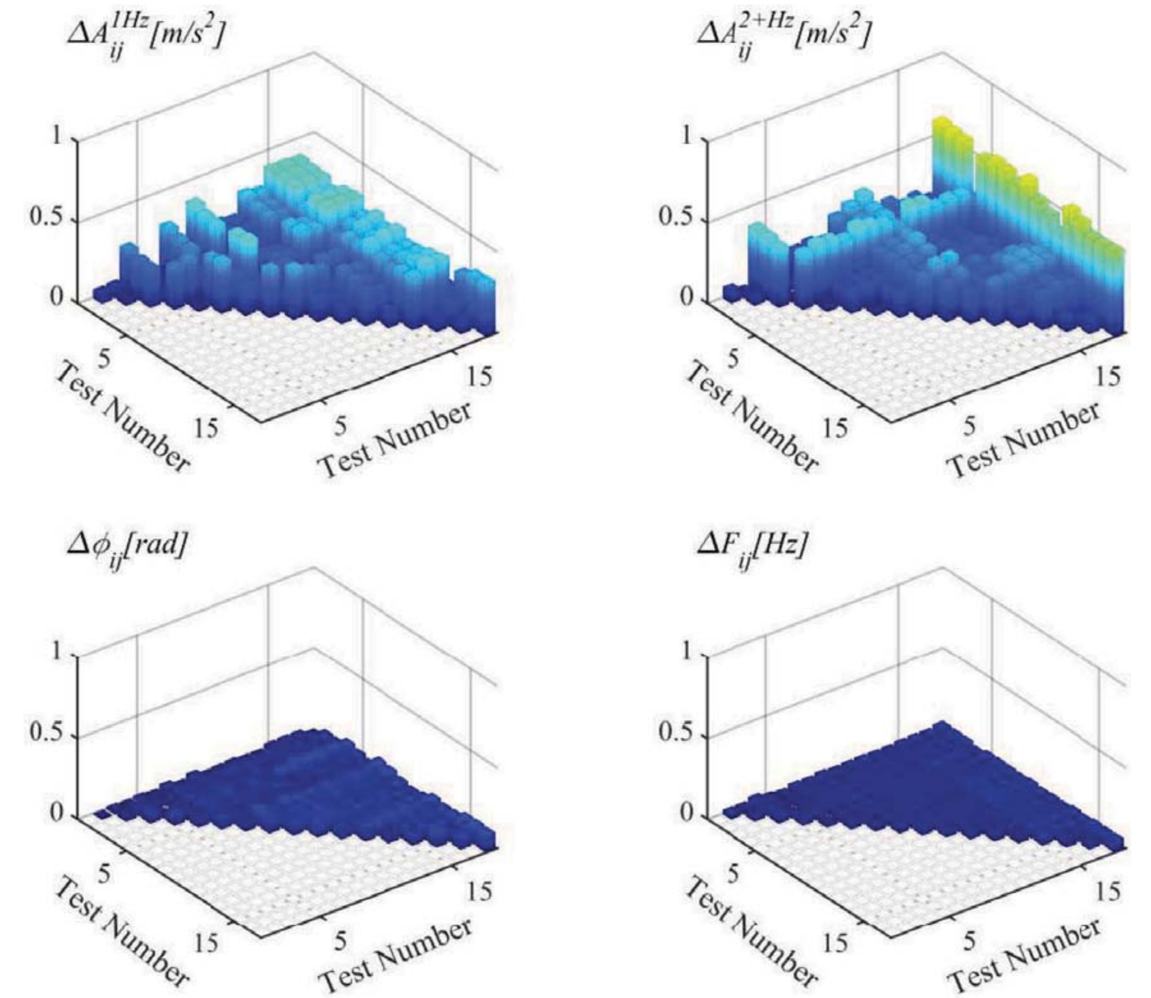

Figure 4. The four difference components ΔA_{ij}^{1+Hz}, ΔA_{ij}^{2+Hz}, $\Delta \Phi_{ij}$ and $\Delta \Phi_{ij}$ of the dissimilarities between the reference and input accelerations of the analyzed 17 tests.

as $q_{c\text{-}avg}$) is deemed herein to provide a good measure deposit initial fabric and packing conditions (better than relative or mass densities, for instance).

The conducted sensitivity analysis is based on an estimate of the variations of the difference measures d_{ij} of the recorded accelerations at AH1 to AH4 as a function of ΔA_{ij}^{1Hz},ΔA_{ij}^{2+Hz} and $q_{c\text{-}avg}$. Specifically, the analysis provided a kriging response surface representing d_{ij} (for each of AH1 to AH4) as a function of the variables, ΔA_{ij}^{2+Hz} and $q_{c\text{-}avg}$ (over the domain associated with these variables, as show in Fig. 5). Note that the differences among the tests in input motions, ΔA_{ij}^{1Hz} and ΔA_{ij}^{2+Hz}, and in response difference metrics, d_{ij}, (at AH1 to AH4) had to be computed with respect to a common reference, which was selected to be test T1 of Fig. 3.

Three sets of discrepancy surfaces are employed herein to visualize the obtained kriging results, as displayed in Fig. 5. The obtained results show that the AH1 accelerations have comparable sensitivities to variations in $\Delta A_{ij}^{1Hz}$and ΔA_{ij}^{2+Hz}. In contrast, the response at AH4 is about two times as sensitive to a as to ΔA_{ij}^{1Hz}. The discrepancy metrics for AH1 to AH4 show a sensitivity that increased from the bottom of the deposit to the free surface. The sensitivities for AH2 and AH3 had values that varied between those of AH1 and AH4. The difference metric surfaces as a function of ΔA_{ij}^{1Hz} and $q_{c\text{-}avg}$, and ΔA_{ij}^{2+Hz} and $q_{c\text{-}avg}$, were employed to explore the effects of the observed variation in CPT resistance. The obtained metric surfaces show a response that is significantly more sensitive to a decrease in $q_{c\text{-}avg}$ than an increase. This is explained by the fact that lower values of $q_{c\text{-}avg}$ are associated with a looser more

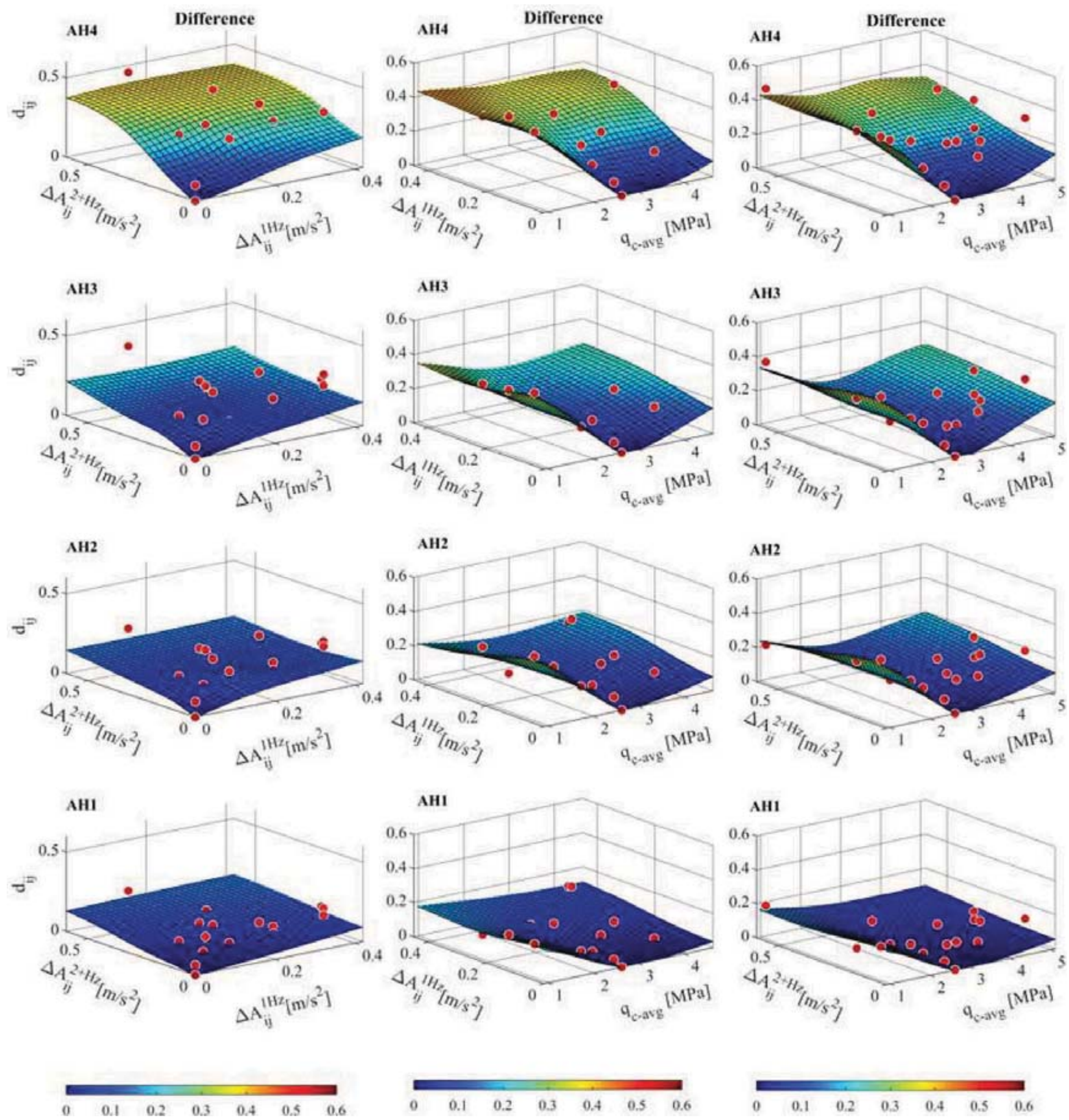

Figure 5. Variation of the difference metric d_{ij} of the recorded accelerations (at AH1 to AH4) obtained using a kriging analysis: (1) as a function of ΔA_{ij}^{1+Hz} and ΔA_{ij}^{2+Hz} for $q_{c\text{-}avg}$ =2.7 MPa, (2) as a function of ΔA_{ij}^{1+Hz} and q_c for $\Delta A_{ij}^{2+Hz} = 0$, and (3) as a function of ΔA_{ij}^{2+Hz} and $q_{c\text{-}avg}$ for $\Delta A_{ij}^{1+Hz} = 0$; the red dots correspond to the analyzed 17 tests.

contractive soil with a response that contrasts substantially with the target dilative deposit with a *Dr* of about 65%. In contrast, larger $q_{c\text{-}avg}$ values are indicative of a denser soil that is only slightly more dilative and has a response that is only somewhat different. Generally, the sensitivity values increased from AH1 to AH4, and the sensitivities with respect to $q_{c\text{-}avg}$ were significantly larger than those associated with ΔA_{ij}^{1Hz}andΔA_{ij}^{2+Hz}.

5 CONCLUSIONS

This article presented a sensitivity analysis of the acceleration time histories of test replicas of a saturated sloping deposit conducted during LEAP (Liquefaction Experiments and Analysis Projects) 2017. A normalized mean squared deviation is used as difference metric to quantify the dissimilarities between recorded acceleration time histories. The differences between input motions were found to be associated mostly with variation in amplitude of the dominant component at 1 Hz and the components with frequencies higher than 2 Hz (2+Hz). A kriging analysis was used to assess the sensitivity of the deposit response acceleration to differences in input motion amplitude at 1Hz and 2 +Hz and average CPT (Cone Penetration Test) resistance (used as a measure reflecting deposit fabric condition and initial grain packing). The analysis showed that the deposit accelerations are relatively more sensitive to variations in CPT resistance than to the input motion and that this sensitivity is larger for a decrease in resistance compared to an increase.

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