Simulating seismic response of unsaturated sand layers inside a geotechnical centrifuge

Simulation de la réponse sismique de couches de sable non saturées à l'intérieur d'une centrifugeuse géotechnique

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ABSTRACT: Dynamic properties of partially saturated soils may differ from those in dry condition, which may lead to different seismic site response. A set of degree of saturation-controlled centrifuge seismic models were tested to assess the seismic site response of partially saturated sands. Steady state infiltration technique was used to control and obtain uniform profiles of degree of saturation along the specimen depth. The results demonstrate higher surficial acceleration amplification in partially saturated sand than the ones in dry layers. The amplification factors, however, were found to be depth-dependent showing lower values for partially saturated sand. Partial saturation led to higher intensity amplification reflected by higher values of Arias intensity in the unsaturated layers. The changes of frequency content were negligible as a result of low suction range in the sand. Seismic settlement of partially saturated sand with higher stiffness was lower than the one in dry condition.

RÉSUMÉ : Les propriétés dynamiques des sols partiellement saturés peuvent différer de celles en conditions sèches, ce qui peut entraîner des réponse sismiques différentes. Un ensemble de modèles sismiques à centrifugation contrôlés par saturation a été testé pour évaluer la réponse sismique du site des sables partiellement saturés. La technique d'infiltration à l'état stationnaire a été utilisée pour contrôler et obtenir des profils uniformes de degré de saturation selon toute la profondeur de l'échantillon. Les résultats démontrent une plus grande amplification de l'accélération superficielle dans le sable partiellement saturé que ceux dans les couches sèches. Les facteurs d'amplification, cependant, se sont révélés dépendants de la profondeur, montrant des valeurs plus faibles pour le sable partiellement saturé. La saturation partielle a conduit à une amplification d'intensité plus élevée reflétée par des valeurs plus élevées de l'intensité d'Arias dans les couches non saturées. Les variations en terme de fréquence étaient négligeables en raison de la faible plage de succion dans le sable. Le séisme du sable partiellement saturé avec une rigidité plus élevée était plus faible que celui de l'état sec.

KEYWORDS: Seismic Site Response, Unsaturated Soils, Centrifuge Modeling.

1 INTRODUCTION

Seismic waves travel through soil layers prior to reaching the ground surface (except when an outcrop motion is recorded). As a crucial step in structural seismic design, the effects of local site conditions are often assessed using “site response analysis” procedures given the bedrock motion. The significance of the influence of local site conditions on site response was highlighted during the past recorded earthquakes (e.g. Borcherdt and Glassmoyer 1994 and Boore et al. 1994) as well as through laboratory physical modeling experiments (e.g. Adaalier and Elgamal 2001). Degree of saturation is among the site parameters that influence the seismic response (Ghayoomi et al. 2013, Mirshekari and Ghayoomi 2017). Matric suction in partially saturated soils increase the contact effective stresses (Lu and Likos 2006) which, in turn, leads to different soil dynamic properties including small-strain and strain-dependent shear modulus and damping (Mancuso et al. 2002, Mendoza et al. 2005, Khosravi et al. 2010, Hoyos et al. 2015, Ghayoomi et al. 2016). Consequently, wave propagation mechanisms would differ in partially saturated soils (Yang 2006) which results in a different seismic site response (D’Onza et al. 2008, Ghayoomi et al. 2013, Mirshekari and Ghayoomi 2015, 2017).

Although the effect of partial saturation on site response has been demonstrated in previous research, this topic has received less attention. This was due to the experimental challenges of physical modeling of unsaturated soils (Caicedo et al. 2014, Mirshekari and Ghayoomi 2016) and assuming lower intensity amplification and seismic deformations in unsaturated soils because of their higher stiffness. Considering this assumption, the response of dry or saturated soils could be conservatively used for the sites where the soil layers seasonally become partially saturated. According to novel numerical and experimental studies on site response of partially saturated soils, however, this assumption was demonstrated to be inappropriate depending on the design criteria (Ghayoomi and Mirshekari 2014, Mirshekari and Ghayoomi 2015, 2017). This paper presents the results of a set of degree of saturation-controlled centrifuge seismic models to investigate the site response in partially saturated soils. The effects of partial saturation in terms of various motion characteristics including acceleration time history, Peak Ground Acceleration (PGA) amplification, Arias intensity, Fast Fourier Transform (FFT), and seismic settlement are presented and discussed.

2 BACKGROUND

2.1. *Site response analysis*

The effects of local site conditions on seismic site response are commonly evaluated through simplified procedures regulated by seismic provisions or more complex site-specific ground response analysis for sensitive seismic designs. Current seismic design provisions (e.g. NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, ASCE/SEI 7-10, International Building Code, and Minimum Design Loads for Buildings and Other Structures) regulate 5%-damped design acceleration spectrum to represent seismic events at ground surface. The parameters influencing design spectrum include the seismic hazard level on the bedrock, the effect of local site conditions, and the intensity of ground motion. The seismic hazard level for any region in the United States is estimated using mapped spectral ordinates of the bedrock motion for short periods (S_s) and mid-periods (S_1). The other two parameters are taken into account using low-period and mid-period amplification factors (F_a and F_v) that are functions of local site conditions and intensity of bedrock motion (Dobry et al. 2000). The local site condition is reflected through site classification systems. According to provisions after 1997, different sites could be categorized based on a weighted average shear wave velocity of the top 30 m of the soil profile (V_s), an average SPT blow-count number (N), or a representative undrained shear strength (S_u). In addition, according to NEHRP Provisions for assessing liquefaction potential and soil strength loss, mapped PGA values have to be multiplied by PGA amplification factors (F_{PGA}) to obtain the PGA associated with the design Maximum Considered Earthquake (MCE). The same values are used as F_a and F_{PGA} coefficients in NEHRP Provisions. The site-specific ground response can also be evaluated numerically considering the soil nonlinearity through equivalent or nonlinear stress-strain relationships (e.g. Hashash et al. 2016).

In spite of substantial advances in numerical codes, to date, the influence of partial saturation could not be directly assessed in site response analysis using commercial programs. An indirect simulation of seismic response of unsaturated soils could be achieved by manually varying unit weight and dynamic properties of soil layers (Ghayoomi and Mirshekari 2014, Mirshekari and Ghayoomi 2015). However, to promote the site response analysis in unsaturated soils and to validate potential improvement to site response numerical codes, data from physical modeling experiments simulating the seismic response of unsaturated soil layers would be imperative.

2.2. *Steady state infiltration technique*

Different approaches could be followed to conduct centrifuge modeling on partially saturated soils. They include compacting wet, fine soil with a target water content prior centrifugation (Deshpande and Muraleetharan 1998), water drainage during high-g experiments from an initially saturated condition (Ng et al. 2014), capillary rise from a set water table level (Esposito 2000), and steady state infiltration to achieve a uniform degree of saturation throughout the depth (Ghayoomi and McCartney 2011, Mirshekari and Ghayoomi 2017). For sands, however, the first three scenarios would yield to very low degrees of saturation within the unsaturated zone. Moreover, amongst the mentioned methods, steady state infiltration is the most suitable when controlled-suction fields are needed. Steady state infiltration has been traditionally incorporated in centrifuge permeameters to streamline measurement of hydraulic properties of unsaturated soils (e.g. Nimmo et al. 1987, Dell'Avanzi 2004, McCartney and Zorenberg 2010). This technique, lately, was successfully implemented in larger centrifuges to study different Geotechnical aspects of unsaturated soils (Ghayoomi and McCartney 2011, Mirshekari and Ghayoomi 2017).

3 EXPERIMENTAL PROGRAM

3.1. *Experimental Setup*

The experiments were conducted using a 5 g-ton centrifuge facility at the University of New Hampshire. The steady state infiltration setup comprised of inflow and outflow tanks, water spraying nozzles, and drainage valves, which all served to obtain different uniform profiles of degree of saturation ranging from 32% to 68% depending on the applied discharge. A laminar container, that was modified to facilitate the water drainage, was used to avoid adverse boundary effects. The specimens were fully instrumented using accelerometers, LVDTs, and capacitance moisture sensors to record acceleration, displacement, and Volumetric Water Content (VWC), respectively. A schematic of an instrumented specimen is shown in Figure 1.

3.2. *Material Properties*

F-75 Ottawa sand was used in this study as a fine silica sand that can retain water up to 10 kPa of matric suction before it reaches the residual water content. However, it is yet permeable enough to allow the infiltration using the current system. The physical and hydraulic properties of the sand are listed in Table 1.

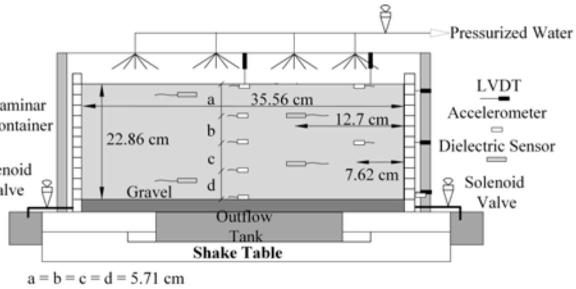

Figure 1. Schematic of the infiltration setup and a fully instrumented specimen (after Mirshekari and Ghayoomi 2017)

Table 1. Physical and Hydraulic Properties of F-75 Ottawa Sand

Parameter	value
Coefficient of curvature, C_c	1.71
Coefficient of uniformity, C_u	1.01
Specific gravity, G_s	2.65
D_{50} (mm)	0.182
Void ratio limits, e_{min}, e_{max}	0.49, 0.80
φ (deg)	40
Poisson's ratio (υ)	0.38
van Genuchten parameter, α_{vG}	0.25
van Genuchten parameter, N_{vG}	9
Residual VWC, θ_r	0.07
Saturated VWC, θ_s	0.392

3.3. *Testing Procedure*

In order to prepare the specimens, the sand was dry pluviated to reach the relative density of 45%. While preparing the specimen, the instrumentations were placed at different levels as illustrated in Figure 1. The specimen was, then, saturated from the bottom through the provided holes in the base plate followed by locating the side and top LVDTs. The applied pressure at high-g, was assumed, to generate an initial fully saturated condition acting as a back pressure. Thereafter, the centrifuge was spun to the acceleration level of 50g at the middle of the specimen and various spraying discharges were applied simultaneously as free drainage occurred leading to different degrees of saturation. The Several dry and unsaturated soils (denoted with the letter U followed by the degree of saturation) were tested during this set of experiments. A scaled Northridge earthquake motion with the prototype PGA of 0.3g, then, was imposed to the specimens with uniform profiles of degree of saturation and the response was captured in terms of displacement and acceleration time histories. More details on the experimental setup and testing procedure can be found in Mirshekari and Ghayoomi (2017).

4 RESULTS AND DISCUSSION

The captured data comprised of arrays of displacement and acceleration time histories at different levels for the dry and unsaturated tests. The time histories were post processed to investigate the effect of partial saturation on frequency content of the motion as well as accumulated energy. The results of three experiments, including one dry and two unsaturated tests (degrees of saturation of 38% and 66%, U38 and U66) are presented herein. The corresponding matric suction values of the specified tests are 4.67 and 3.91 kPa for the tests U38 and U66, respectively. All the results are presented in prototype scale unless specified.

Since the PGA of the imposed motion varied slightly among different tests (as a result of a small nonlinearity of the in-flight shake tables and different weight of the specimens), the acceleration values of time histories were normalized with respect to PGA_{base}. Normalized acceleration time histories along with F_{PGA} equals to $PGA/\ PGA_{base}$ in different levels are illustrated in Figure 2 for the selected tests.

Consistent with the results of simplified numerical analysis (Mirshekari and Ghayoomi 2015), the time histories indicate a higher acceleration amplification at the ground surface for unsaturated tests comparing with the dry one. The amplification ratio was higher for the test with lower degree of saturation (higher matric suction), U38, than the one in U66. In addition, the amplification ratio was lower within unsaturated sand layers than that in the dry specimen at other levels showing a depth-dependent influence of partial saturation on site response. The PGA amplification is inversely proportional to strain-dependent shear modulus and damping both of which are affected by partial saturation. In unsaturated conditions shear modulus is increased (Khosravi et al. 2010, Ghayoomi and McCartney 2011) leading to lower PGA amplification; however, damping decreases as a function matric suction (Hoyos et al. 2015) resulting in higher amplification ratios. The captured acceleration response demonstrates that despite the increased stiffness of unsaturated soils, their seismic response might show higher surface acceleration levels as a result of depth-dependent interaction between shear modulus and damping values. It should be noted that the slight variation of PGA_{base} amongst the tests causes an additional effect on F_{PGA} (e.g. see Idriss 1991, Silva et al. 2000, Stewart et al. 2003) that should be considered in the interpretation process (Mirshekari and Ghayoomi 2017).

Arias intensity is a well-known measure of the cumulative energy buildup during a seismic event, which was selected in this study to shed light on the accumulated energy level in unsaturated conditions. Arias intensity time histories of the selected tests are shown in Figure 3 (a) demonstrating a higher energy level in unsaturated condition than the dry test. In order to assess the effect of partial saturation on frequency content of the motion, FFT amplitude of the recorded surface motion was obtained and shown in Figure 3 (b). Although the degree of saturation changes significantly between the tests, the corresponding matric suction variation is not substantial for this sand. This causes a minimal change in the effective stress due to partial saturation, which explains the negligible observed difference in terms of frequency content between the tests.

Seismic settlement time histories of the tests, measured by the middle LVDTs, are shown in Figure 3 (c). In spite of the observed trend of higher acceleration amplification in unsaturated sand, seismic settlement decreased as a result of higher shear modulus in unsaturated conditions which was similarly observed in Ghayoomi et al. (2011).

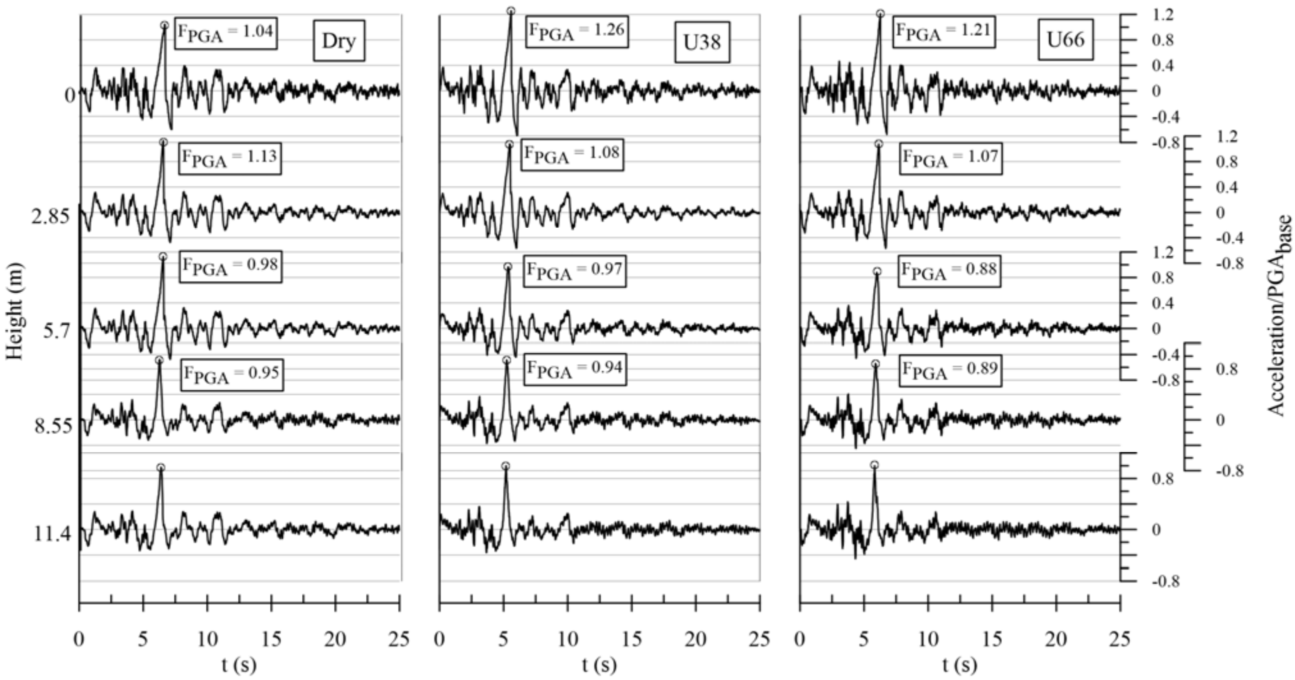

Figure 2. Selected Arrays of Acceleration Time Histories

Figure 3. (a) Arias Intensity Time Histories (b) FFT Amplitude (c) Settlement Time Histories of the Tests

5 CONCLUSION

The effect of partial saturation on seismic site response was studied through a set of degree of saturation-controlled centrifuge tests where the degree of saturation was controlled using steady state infiltration technique. The results of seismic modeling were presented in terms of normalized acceleration, settlement, and Arias intensity time histories as well as PGA amplification factor and FFT amplitude of the motions for one dry and two unsaturated specimens. In contrast with the previously-believed assumption, surface-to-base PGA amplification factor was found higher for unsaturated conditions especially for the test with lower degree of saturation. Similarly, more energy was accumulated within the sand layers during the earthquake in unsaturated tests. However, lower seismic settlement was captured for the unsaturated sands due to their increased stiffness. The change in frequency content due to partial saturation was negligible as a result of low matric suction limit of the tested sand.

6 ACKNOWLEDGEMENTS

The authors would acknowledge funding of this project by the National Science Foundation through the NSF CMMI grant No. 1333810.

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