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Centrifuge tests to assess seismic site response of partially saturated sand layers

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ABSTRACT

Seismic response of unsaturated soil layers may differ from that of saturated or dry soil deposits. A set of centrifuge experiments was conducted to study the influence of partial saturation on seismic response of sand layers under scaled Northridge earthquake motion. Steady state infiltration was implemented to control and provide uniform degree of saturation profiles in depth. The amplification of peak ground acceleration at the soil surface was inversely proportional to the degree of saturation, especially in low period range. The cumulative intensity amplification of the motion was also higher in unsaturated soils with higher suctions. The lateral deformation and surface settlement of partially saturated sand with higher stiffness were generally lower than that in dry soil. Although neglecting the effect of partial saturation in sand layers might be conservative with respect to seismic deformations, it may result in underestimating the surface design spectra.

1. Introduction

Seismic waves generated by earthquakes often travel through soils with different mechanical and hydraulic characteristics where they can be dramatically altered in terms of intensity, frequency content, and duration. This transition is commonly evaluated using "Site Response Analysis", which is a crucial step toward seismic design of soil-structure systems. Applications of site response analysis include development of design response spectra for surface structures, estimating seismically induced stresses, strains, and settlements, and liquefaction hazard assessment. Local site conditions such as soil density, plasticity index, stiffness, and damping can significantly affect seismic site response [1–8]. Thus, ignoring the effects of changes in the site conditions may lead to inaccurate assessment of the site response.

The role of local site condition and the intensity of rock motion in the site response have been highlighted using fully monitored and instrumented sites during past earthquakes [1,4–15]. In general, lower site amplification factors were observed during earthquakes with higher bedrock motion intensities [8,11–15]. This could be attributed to the nonlinear stress-strain behavior of soils and higher damping values as a result of higher induced strain levels. The motion amplification was, also, found inversely proportional to the square root of shear wave velocity as a representative measure of local site conditions [1,4–7,16]. Data obtained from instrumented sites under strong ground motions (e.g. [17,18]) as well as physical modeling experiments (e.g. [19,20]) can be used to develop guidelines for site response assessment. Traditionally, different methods have been employed to consider the effects of local site conditions and motion intensity in the surface motion evaluation, ranging from simplified procedures regulated by seismic provisions [21–23] to more complex site-specific ground response analysis for sensitive seismic designs using available software [24–29]. In current seismic provisions the local site condition is reflected through site classification system using an average shear wave velocity of the top 30 m of the soil profile ($\overline{V}_s$) (Table 1).

Degree of water saturation is among the parameters that influence the seismic response of soil layers [30]. Inter-particle suction in partially saturated soils increases the effective stresses on the grain skeleton [31]. This, in turn, yields to different soil dynamic properties including small-strain and strain-dependent shear modulus and damping [32–43]. As a result, seismic wave propagation mechanisms may vary in partially saturated soil layers [44] that would lead to a different seismic site response [30,45–49]. Soils in either dry or fully saturated conditions have been believed to result in more conservative solutions because matric suction in unsaturated soils increases the ground stiffness. Therefore, partial saturation has not been directly considered in the state-of-the-practice site response analysis. However, recent investigations on the site response in unsaturated soils showed that this assumption might not be always reasonable [47–49]. Further, the influence of the degree of saturation on seismic response analysis is often considered by incorporating the in-situ measured shear wave velocity of shallow unsaturated soil layers. However, the extent of this

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Table 1
Site classification (after *NEHRP Provisions* [21]).

NEHRP category	Description	Time-weighted average shear wave velocity ($\overline{V_s}$)
A	Hard rock	> 1500 m/s
B	Firm to hard rock	760–1500 m/s
C	Dense soil, soft rock	360–760 m/s
D	Stiff soil	180–760 m/s
E	Soft clays	< 180 m/s
F	Special study soils, e.g. liquefiable soils, sensitive clays, organic soils, soft clays > 36 m thick	

influence might be beyond the suction-dependency of the dynamic soil properties where the wave propagation mechanisms may vary [45]. In addition, soil properties may differ between the time of the construction and prior to the earthquake due to the seasonal fluctuation of water table. Thus, recognizing this difference would be essential in assessing the uncertainty in projected site response.

Yang [45] analytically studied the frequency-dependent amplification of inclined vertically propagated shear waves (SV waves) in soil layers overlying bedrock. The results indicated that a slight decrease in the degree of saturation of fully-saturated soil layers causes a dramatic difference in vertical amplification of the SV waves. Specifically, for regular earthquake frequencies, unsaturated soils may lead to a higher vertical amplification than saturated soil layers. D'Onza et al. [46] implemented the small-strain shear modulus and damping obtained from suction-controlled resonant column tests in a series of numerical site response analyses. Suction was found to significantly affect the natural frequency and Peak Ground Acceleration (PGA) amplification factor in clayey silt and silty sand layers. According to their numerical study, the natural frequency of the soil layers increased in higher suction values whereas PGA amplification factor was reduced. Ghayoomi et al. [30] studied seismically induced settlements in partially saturated sand by applying sinusoidal cyclic loads to sand layers in a set of suction-controlled centrifuge tests using steady-state infiltration technique [50]. The least amount of surface settlement occurred in middle range degrees of saturation due to the increase in shear modulus. Moreover, they observed a maximum 20% increase in PGA amplification factor in unsaturated sand with respect to the one in dry condition [47].

Recently, Ghayoomi and Mirshekari [48] and Mirshekari and Ghayoomi [49] numerically studied the seismic response of partially saturated sand and silt layers using site response software DeepSoil [24]. In the absence of any available numerical procedure to account for partial saturation, this influence was investigated by adjusting the soil unit weight and effective stress for any given degree of saturation. Changes of the effective stress in unsaturated soils, in turn, altered soil dynamic properties including small-strain and strain-dependent shear modulus and damping. Accordingly, partial saturation in the soil layers appeared to considerably influence the site response, where the extent of this effect was a function of soil type as well as induced motion characteristics. For example, partial saturation in sandy soils with low-range suction level (e.g. 10 kPa) resulted in higher amplifications and lateral deformations whereas in silty soils with high suction range (e.g. 70 kPa) led to lower amplifications and lateral deformations in comparison with those of dry soil layers.

Despite the proven influence of the degree of saturation on the dynamic soil properties and the site response, well-documented field or laboratory seismic site response data in partially saturated soils are still needed. Centrifuge physical modeling of free-field seismic ground response using a "degree of saturation-controlled" system is of a great value to validate this effect and to calibrate future numerical and analytical predictive models. This paper describes the adaptation and modification of an experimental setup to control the degree of saturation in a geotechnical centrifuge and its application to study seismic site response of partially-saturated soil layers. Furthermore, the effect of partial saturation on the site response of a sand layer is investigated and discussed in terms of different motion characteristics including PGA amplification factor (F_{PGA}), low-period and mid-period amplification factors (F_a and F_v, respectively), 5% damped spectral acceleration, Arias intensity (I_a), lateral deformation, and seismically induced settlements.

2. Suction control in geotechnical centrifuge

Modeling unsaturated soils under high gravitational acceleration is a challenging task where controlling suction or the degree of saturation is the key to any systematic investigation involving partially saturated soils. Centrifuge modeling of unsaturated fine-grained soils could be accomplished by using methods such as compacting soils with a target degree of saturation [51] or in-flight free drainage of an initially saturated specimen [52]. For sand layers, however, centrifugation along with free drainage leads to very low degrees of saturation due to their relatively higher permeability values. To address this problem, steady state infiltration was implemented in this study to generate uniform degree of saturation profiles inside a geotechnical centrifuge. This approach was devised from centrifuge permeameters [53–55], mainly used to streamline measurements of hydraulic parameters in unsaturated soils. Recently, similar steady state infiltration method was successfully incorporated in a laminar container inside a large arm centrifuge to study seismically induced settlements in partially saturated sand layers [50].

Dell'Avanzi et al. [56] analytically solved Richards' equation of water flow in unsaturated soils [57] for steady state infiltration, under higher gravitational field inside a geotechnical centrifuge. The suction profile along the depth of the specimen during steady state infiltration can be estimated using the following equations [56]:

$$\psi = -\frac{1}{a} ln\left[e^{\left(ln\left|\frac{v_m}{N_r k_{sat}} + e^{-a\psi_0}\right| - a\rho_w z_m \omega^2 \left(r_0 - \frac{z_m}{2}\right)\right)} - \frac{v_m}{N_r k_{sat}} \right] if \left(\frac{v_m}{N_r k_{sat}} + e^{-a\psi_0} \right) > 0 \tag{1a}$$

$$\psi = -\frac{1}{a} ln\left[-e^{\left(ln\left|\frac{v_m}{N_r k_{sat}} + e^{-a\psi_0}\right| - a\rho_w z_m \omega^2 \left(r_0 - \frac{z_m}{2}\right)\right)} - \frac{v}{N_r k_{sat}} \right] if \left(\frac{v_m}{N_r k_{sat}} + e^{-a\psi_0} \right) < 0 \tag{1b}$$

where a is the Gardner's hydraulic conductivity parameter in kPa^{-1} [58], e is the natural base of logarithms, v_m is the discharge velocity in m/s, z_m is height of any location in the specimen from its bottom in m, N_r is the g-level depending on z_m parameter, k_{sat} is the soil hydraulic conductivity in saturated condition, ψ_0 is suction at the bottom of the specimen defining the boundary conditions, and ρ_w is the density of water in kg/m^3. Then, the degree of saturation profiles could be obtained using hydraulic constitutive models relating the degree of saturation and matric suction; Soil Water Retention Curves (SWRC) (e.g. van Genuchten [59]). Applying steady state infiltration in higher g-levels results in a uniform suction with height with small transition zones. For example, profiles of the degree of saturation are illustrated in Fig. 1(a) and (b) for different discharge velocities and g-levels, respectively, during the centrifugation of a 22.86 cm of model Ottawa sand.

Dell'Avanzi et al. [56], also, determined suction scaling factor for steady state flow condition where a prototype infiltration is to be represented by a model with the length and discharge velocity scaling factors of 1/N and N, respectively. Comparison of prototype and model infiltration equations led to a suction scaling factor of unity for relatively uniform acceleration fields (i.e. ratio of centrifuge arm's length to the length of specimen is greater than 10). For the case of smaller centrifuges, however, the suction scaling factor becomes