Centrifuge Evaluation of the Impact of Partial Saturation on the Amplification of Peak Ground Acceleration in Soil Layers

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ABSTRACT

The seismic response of partially saturated soils differs from that of dry or water saturated soil deposits. However, available site response analysis methods ignore the influence of partial saturation. As a soil changes in degree of saturation, the corresponding changes in matric suction will have an effect on the effective stress and small strain shear modulus. Further, the unit weight of the soil will change, altering its inertial response. As a result, the distribution of degree of saturation with depth affects the propagation of seismic waves and the peak ground acceleration amplification factor. This paper involves a centrifuge modeling approach to assess the impact of partial saturation on shear wave velocity and the peak ground acceleration amplification factor of partially saturated sand layers.

INTRODUCTION

Partially saturated soils have a different seismic response compared to dry or water saturated soils (Ghayoomi et al. 2011). Except in regions of the country where the water table is at the ground surface, shallow soils are typically partially saturated. Suction in partially saturated soils increases the effective stresses (Lu and Likos 2006), which impacts key soil dynamic properties such as the small strain shear modulus, shear wave velocity, nonlinear soil response, damping ratio, and unit weight. As a result, the degree of saturation and effective stresses are expected to significantly influence the propagation of seismic waves through the soil deposit and the resulting accelerations.

According to current provisions (e.g., 2009 NEHRP Recommended Seismic Provisions for New Buildings and Other Structures) the design Maximum Considered Earthquake (MCE) for soil sites is estimated through amplification of MCE at the bedrock using surface-to-base spectral ratios or by performing site-specific equivalent linear or nonlinear seismic analyses. This paper focuses on evaluating the surface-to-base amplification factor by studying the effect of partial saturation. Since the current state of practice for evaluating site-specific ground motions relies on procedures that
assume dry conditions, the proposed correction factors may affect considerably the estimated ground motions and hence, soil response and the design of engineered facilities. The insight gained from this study will enable the earthquake engineering community to better evaluate and mitigate the potential seismic hazards facing critical engineered facilities and sets the path for future research into incorporation of the effect of partial saturation in site response analysis.

Although a comprehensive data set of field case histories on the impact of partial saturation on site response is not available, a recent series of centrifuge model experiments performed by Ghayoomi et al. (2011) confirms the impact of the degree of saturation. As part of a centrifuge physical modeling testing plan for evaluating the seismic compression of partially saturated sands, the acceleration time history was measured through the depth of partially saturated sand layers. These data were used to evaluate the effect of partial saturation on Peak Ground Acceleration (PGA) amplification factors.

**BACKGROUND**

**Code-Based Site Response Analysis**

In practice, code-based design spectra are typically constructed from spectral accelerations developed using Probabilistic Seismic Hazard Analysis (PSHA) or Deterministic Seismic Hazard Analysis (DSHA) methods for a generic site category. Ground motion prediction equations (GMPE; also known as the Next Generation Attenuation relationships) are also used in seismic hazard analysis. The commonly used guidelines to account for site effects in seismic hazard analysis are the 2010 Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10, or the 2009 NEHRP Recommended Seismic Provisions for New Buildings and Other Structures, FEMA P-750. However, most design scenarios involve site conditions that are different from a generic site class used in the code-based approach. For sensitive projects, more advanced site response analyses are used to obtain site-specific estimates of likely ground motions.

In practice, the site may be classified generically according to ASCE/SEI 7-10 or FEMA P-750 ranging from A-F. The main parameter used in classifying the site in a code-based approach is the average shear wave velocity at the top 100ft (30m) of the soil (Vs-30) as in Table 1.

<table>
<thead>
<tr>
<th>Site Class</th>
<th>Material</th>
<th>( V_s ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hard rock</td>
<td>&gt;1524</td>
</tr>
<tr>
<td>B</td>
<td>Rock</td>
<td>762 to 1524</td>
</tr>
<tr>
<td>C</td>
<td>Very dense soil</td>
<td>365 to 762</td>
</tr>
<tr>
<td>D</td>
<td>Stiff soil</td>
<td>182 to 365</td>
</tr>
<tr>
<td>E</td>
<td>Soft soil</td>
<td>&lt;182</td>
</tr>
<tr>
<td>F</td>
<td>Sensitive soil</td>
<td>Specific soils</td>
</tr>
</tbody>
</table>

Table 1. Site Classification (ASCE/SE 17-10)
The average shear wave velocity is determined using the following equation:

\[ \bar{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{v_{si}}} \]  

(1)

where \( v_s \) is the average shear wave velocity, \( v_{si} \) is the shear wave velocity of each layer, \( d \) is the depth of each layer, and \( i \) is the number of layer ranging from 1 to \( n \).

Peak Ground Acceleration is a major representative of intensity of motion in seismic design analysis of geotechnical and structural systems. In current provisions the PGA measured or estimated at the bedrock should be adjusted based on site conditions. Consequently, an amplification factor was introduced and implemented as in the following equation:

\[ PGA_M = F_{PGA} \cdot PGA \]  

(2)

where PGA is the peak ground acceleration, \( PGA_M \) is the modified peak ground acceleration, and \( F_{PGA} \) is the site specific amplification factor. The values of amplification factor for different site classes and PGAs are shown in Table 2 (ASCE/SEI 7-10). However, dynamic site specific response analyses are commonly performed analytically for sensitive sites using computer programs (e.g. SHAKE, Idriss and Sun 1992; FLAC, Itasca 2005; etc.).

<table>
<thead>
<tr>
<th>Site Class</th>
<th>PGA ≤ 0.1</th>
<th>PGA = 0.2</th>
<th>PGA = 0.3</th>
<th>PGA = 0.4</th>
<th>PGA ≥ 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>C</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>E</td>
<td>2.5</td>
<td>1.7</td>
<td>1.2</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Site specific analysis is needed</td>
</tr>
</tbody>
</table>

**Impact of Partial Saturation on Shear Modulus and Shear Wave Velocity**

In general, most studies on the impact of partial saturation on the dynamic response of soil have been focused on the measurement of the small strain shear modulus, \( G_{max} \). \( G_{max} \) can be considered constant with shear strain for strain amplitudes less than about \( 10^{-4}\% \) (Hardin and Richart 1963; Hardin and Drnevich 1972). \( G_{max} \) is well known to be correlated to the shear wave velocity \( (v_s) \) through the following equation:

\[ G_{max} = \rho v_s^2 \]  

(3)

Several factors may influence \( G_{max} \) of partially saturated soils. Previous experimental studies have emphasized the important effect of void ratio \( (e) \) and mean effective stress \( (\sigma'_m) \) on \( G_{max} \) (Hardin and Black 1968; Hardin and Black 1969; Hardin and Drnevich 1970; Hardin and Drnevich 1972; Iwasaki et al. 1978; Stokoe et al. 1995) as shown in the following equation:
$G_{\text{max}} = AF(e) \left( \frac{\sigma_n}{P_a} \right)^m$  \hspace{1cm} (4)

where $F(e)$ is a function of void ratio, $P_a$ is atmospheric pressure, and $A$, $m$ are constant fitting parameters.

Several experimental studies have defined trends between $G_{\text{max}}$, net normal stress $\sigma_n$ (i.e., the difference between the total mean stress, $\sigma$, and pore air pressure, $u_a$, i.e., $\sigma_n = \sigma - u_a$), and matric suction $\psi$ (i.e., the difference between pore air pressure and pore water pressure $u_w$, i.e., $\psi = u_a - u_w$) using bender element technique or resonant column tests (Sawangsuriya et al. 2009, Ng et al. 2009; Ghayoomi and McCartney 2011; Khosravi et al. 2010; Khosravi and McCartney 2011). In general, previous studies on partially saturated sands have shown an increase in $G_{\text{max}}$ up to a certain degree of saturation during drying, after which the value of $G_{\text{max}}$ starts to decrease. Ghayoomi and McCartney (2011) presented the results of a series of bender element tests performed on loose sand in the centrifuge during steady-state infiltration as shown in Figure 2(a) in terms of the shear wave velocity $V_s$ along with density variation line and in Figure 2(b) in terms of the small strain shear modulus. Shear wave velocity has its highest value at low degrees of saturation.

A modified version of Bishop’s effective stress equation for partially saturated soils to combine the impacts of net normal stress and matric suction in defining a unified relationship for $G_{\text{max}}$ was proposed by Lu et al. (2010) as follows.

$$\sigma' = \sigma_n + \frac{\psi}{(1 + (\alpha \psi)^N)^{(N-1)/N}}$$  \hspace{1cm} (5)

where $\alpha$ and $N$ are van Genuchten (1980) fitting parameters. Ghayoomi and McCartney (2010) indicated that Equation (5) could be incorporated into the $G_{\text{max}}$ equations developed for dry and saturated soils (Hardin and Drnevich 1972) and also proposed a similar equation specific to partially saturated Ottawa sand at 45% relative density, as follows:
$G_{\text{max}}(\text{MPa}) = 92.6 \left(\frac{\sigma'_m}{P_a}\right)^{0.5}$ (6)

**AMPLIFICATION FACTOR MODIFICATION**

The shear wave velocity is affected to some extent by the degree of saturation as shown in Figure 2(a). This change leads to different site response due to seismic shakings. Although the change in the shear wave velocity due to partial saturation may not be enough for affecting the code-based amplification factor, but, in fact, it can affect the site response meaningfully. Either a site specific response analysis for partially saturated soil layers, field measurement during seismic events or physical modeling tests can clarify this effect.

One practical way to account for the effect of partially saturated soil on PGA amplification factor (i.e. $F_{\text{PGA}}$) is to introduce a typical modification factor depending on the degree of saturation, similar to the following equation,

$$F_{\text{PGA-m}} = F_{\text{PGA}} \cdot MF$$ (7)

where $F_{\text{PGA}}$ is the code-based amplification factor, $F_{\text{PGA-m}}$ is the modified amplification factor for partially saturated soil, and $MF$ is the modification factor.

In field conditions, suction or degree of saturation profile through the depth of a soil layer could be more complicated. Consequently introducing a unique equation needs extensive field data or measured experiments. However, assuming a uniform suction profile will provide a useful insight in interpreting the effect of degree of saturation. In addition, it is possible to study the effect of the degree of saturation on amplification factor with different uniform suction profiles both analytically and experimentally where this system was successfully tested for centrifuge physical modeling (Ghayoomi et al. 2011). However, even a complicated suction profile can be later represented by an average or effective degree of saturation value.

**CENTRIFUGE PHYSICAL MODELING**

**Testing System**

Ghayoomi et al. (2011) developed a steady state infiltration system to model sand layers with uniform degree of saturation. They investigated the effect of partial saturation on seismic compression of sand layers after application of cyclic loads, and measured seismically induced accelerations at different depths in the soil layer. A 15.87 cm depth loose sand layer was prepared by dry pluviation to reach 45% relative density. The specimen was saturated with de-aired water. Then, the centrifuge was spun up to the target g-level (either 40 or 30g). Infiltration was applied by spraying water on the top surface and free drainage from the bottom. The soil water content was controlled using dielectric sensors until a steady state condition was achieved. The soil was then subjected to cyclic loads with two different shaking amplitudes representing induced accelerations of 0.65g and 0.55g at the soil surface (PSA) in prototype scale. The schematic of model system is shown in Figure 2 while a detailed explanation is available in Ghayoomi et al. (2011).
Acceleration Measurements

During the application of cyclic loading to the sand layers with different degrees of saturation, the induced accelerations were measured at the surface, 7.5 cm depth and also at the bottom of the sand layer. The variation of the peak induced accelerations with the degree of saturation is shown for the accelerometers at the surface and 7.5 cm depth in Figure 3. The acceleration amplitudes are scattered for different degrees of saturation while there is a general decreasing trend by increasing the degree of saturation. This was due to shake table performance and also the weight of the container.
Figure 4. Peak induced acceleration due to cyclic load while (a) \( N=40g \) and \( PSA=26g \); (b) \( N=40g \) and \( PSA=22g \); (c) \( N=30g \) and \( PSA=19g \);

ANALYSIS

Based on the measured accelerations from the centrifuge tests the amplification factors are calculated using Equation (7). The ratio of the peak acceleration induced at the surface to the peak acceleration induced at the depth of 7.5 cm for different degrees of saturation is shown in Figure 5(a). Further, the ratio of peak acceleration induced at the surface to the peak acceleration induced at the base for different degrees of saturation is shown in Figure 5(b). The figures includes the data for three different testing conditions: (1) tests performed at 40g centrifugal acceleration while the target PSA was 26g (0.65g in prototype scale); (2) tests performed at 40g centrifugal acceleration while the target PSA was 22g (0.55g in
prototype scale); and (3) tests performed at 30g centrifugal acceleration while the target PSA was 19g (0.55g in prototype scale).

Figure 5. Side view schematic of the infiltration system

An overall increase in F_{PGA} in partially saturated specimens with low degrees of saturation can be observed. The test results for saturated specimens are not presented because the response mechanism is expected to be different due to liquefaction. Also, the data for surface to base amplification factor is limited since the suction is more through the depth of the sand layer and gets close to saturated condition near the base.

Using Equation 1, an average shear wave velocity (geometric mean) can be calculated based on the data in Figure 2(a) for the centrifuge tests at 40g. 15.87 cm sand layer was divided into two layers while a shear wave velocity of 170 m/s and 133 m/s associated with dry specimens were assumed for the depths of 3.51 and 11.11 cm. The average shear wave velocity was obtained to be about 150 m/s. This value is representing site class E according to Table 1. Then, F_{PGA} is 0.9 for a PGA greater than 0.5. However the calculated shear wave velocity is corresponding to 15.87 cm sand layer in model scale at 40g centrifugal acceleration (6.35 m in prototype scale) while the code is set for the to 30 m of sand layer. Estimating G_{max} from Equation 6 for the case of dry sand and then calculating V_s from the Equation 3, a shear wave velocity of 366 m/s was obtained at the 30m depth. This shear wave velocity would result in a geometric mean shear wave velocity of between 182 and 365 m/s which categorizes the site as class D with an amplification factor of 1.0.

The amplification factors estimated from the centrifuge tests at 40g level and a target prototype PSA of 0.65g are shown in Figure 6. Both surface to 7.5cm depth acceleration ratio and surface to base acceleration ratio are shown together with code-based amplification factors. The bottom line is for the case where only the 6.35m prototype depth was considered (F_{PGA}=0.9) while the top line is for the case where a hypothetical 30m soil depth was considered (F_{PGA}=1.0).
Figure 6. Comparison of code-based and centrifuge test amplification factors

The surface to base acceleration ratio estimated from the centrifuge tests results are in closer agreement with code-based amplification factors. However, a higher amplification factor for the case of partially saturated sand with low degree of saturation (high suction) is obvious. This indicates a meaningful influence of degree of saturation on site response. Consequently, the value of MF in Equation 7 is expected to be more than one. According to the scattered data in Figure 6 the amplification factors of partially saturated specimens are less than 20% higher than of dry specimens. Accordingly the value of MF can reach up to 1.2 in case of high suction or low degree of saturation. Although this value may be different or different soils with different depths, it still provides useful insight in considering the effect partial saturation on site response. Ignoring this effect may result in designing the geotechnical or structural systems for lower design acceleration demand, which could be unsafe.

CONCLUSIONS

The centrifuge results presented in this study indicate that partially saturated soil conditions affect the shear wave velocity and the site response to seismic shaking. Peak surface acceleration as a measure of shaking intensity depends on site condition and peak ground acceleration at the bedrock. The current state of practice is based on application of an amplification factor to obtain peak surface acceleration from the peak ground acceleration at the bedrock. The induced accelerations from a set of centrifuge physical modeling tests of a partially saturated sand layer due to cyclic load were measured. Steady state infiltration was used in centrifuge testing implemented so that sand layers with uniform degree of saturation profiles could be evaluated. PGA amplification factors were estimated based on the measured induced accelerations. Higher amplification factors were observed in partially saturated sand layer while the highest values happened in lower degrees of saturation (high suctions). A modification factor for the acceleration amplification value was
proposed. A maximum 20% increase in amplification factor with respect to dry condition was found to lead to a modification factor of 1.2 in the case of partially saturated soil. This increasing factor provides a very useful insight to geotechnical engineers in their site response analysis, where the presence of partially saturated soil condition can meaningfully affect the seismic demand in design of geotechnical and structural systems.

REFERENCES


