Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

Characterization of a Reclaimed Site and Its Seismic Vertical Amplification

Jun Yang[1] and Tadanobu Sato[2]

Abstract

In this paper an analysis is presented for the field observation of large amplification in vertical motion at a reclaimed site subjected to the 1995 Kobe earthquake. The observation is considered to be associated with the amplification of *P*-waves caused by incomplete saturation of shallow soils. Saturation effects of soils on *P*-wave velocity and Poisson's ratio are discussed to show evidence of partial saturation in shallow layers at the array site. An analytical study is described to demonstrate substantial influence of saturation on the amplification of a soil layer to vertical earthquake excitation. Furthermore, a numerical simulation of the vertical motion at the realistic site considered is performed by incorporating saturation effects of shallow soils. The present study indicates that vertical motions may significantly be affected by saturation of surface soils, suggesting that one may need to carefully examine this soil condition in the study of vertical site amplification.

Introduction

During the Kobe earthquake of January 17, 1995, strong ground motions were recorded at the reclaimed Port Island, Kobe, by a borehole array which consisted of four triaxial accelerometers located at the surface and the depths of 16, 32 and 83 m. Figure 1 shows the three-component accelerograms at the surface and 83 m depth. Figure 2 depicts the distribution of peak accelerations with depth in three components. It is interesting to note that, while the peak accelerations in both horizontal directions were reduced as seismic waves traveled from the bottom to the surface, the motion in vertical direction was significantly amplified, resulting in the ratio of peak vertical and horizontal accelerations at the surface that largely exceeded the value of 2/3 commonly used in engineering applications.

[1] JSCE Senior Researcher, DPRI, Kyoto University, Kyoto 611-0011, Japan
[2] Professor, DPRI, Kyoto University, Kyoto 611-0011, Japan

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

So far considerable interest has been focused on the effects of the site on horizontal motions (e.g., Aguirre and Irikura 1997; Kokusho and Matsumoto 1999; Yang et al. 2000). Results of these studies indicate that substantial non-linearity associated with soil liquefaction resulted in the de-amplification of horizontal motions. On the other hand, available analysis of the observed vertical motion amplification is limited, that is surprising in view of its unusual feature as mentioned previously. One of the objectives of this study is, consequently, to present a reasonable explanation for this observation and to address the significance of shallow soil condition on vertical ground motion. In addition, the study possesses potential applications in site evaluation using a technique known as H/V, which involves the analysis of spectral ratios for horizontal and vertical components of ground motion (e.g., Theodulidis and Bard 1995; Konno and Ohmachi 1998).

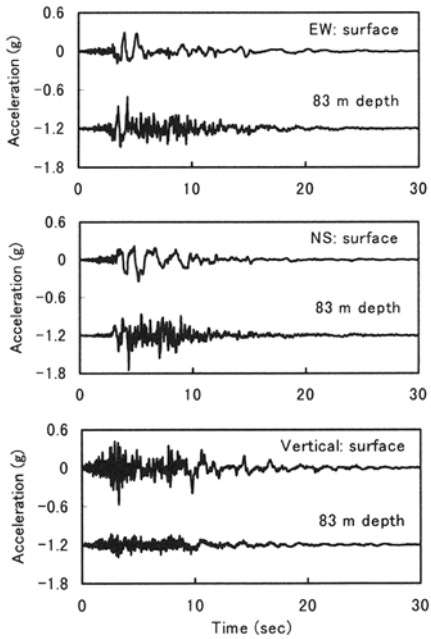

Figure 1. Three-component accelerograms at the surface and 83-m depth

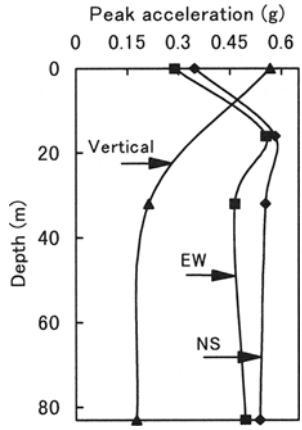

Figure 2. Distribution of peak accelerations with depth

In order to find the major contribution to the amplification in the vertical direction, spectral analyses have been performed for recorded motions in both vertical and horizontal directions. In Figure 3 the spectral ratios of surface motion to the motion at 83 m depth, which may well represent the transfer function for the site

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

considered, are given. It can be seen that peak amplification in vertical direction took place at frequencies around of 4.5 to 5.5 Hz, whereas seismic waves with such high frequencies in horizontal directions were substantially de-amplified due to non-linear effects. In addition, for most cases in engineering applications which concern the soil deposits within a relatively shallow depth (e.g., within 100 m below the ground surface), it is recognized that the conversion between *P*- and *SV*-waves may be negligible. The two facts described above suggest that the vertical amplification at the array site may mainly involve *P*-waves rather than long-period *SV* waves or surface waves due to local topography (Yang and Sato 2000). For this reason, it is considered herein that the observed large amplification in the vertical direction was caused by the characteristic of low *P*-wave velocity in surface layers, which was associated with incomplete saturation of soils, as will be demonstrated later.

To address this mechanism, first, the effects of saturation on *P*-wave velocity and Poisson's ratio are analyzed, which provides evidence that surface soils at the array site were not completely saturated. Secondly, an analytical study for a simple model is presented to show the influence of saturation on vertical motion amplification. Finally, a numerical simulation of the vertical motions at the realistic site considered is carried out to demonstrate the saturation effects of surface layers on vertical site amplification.

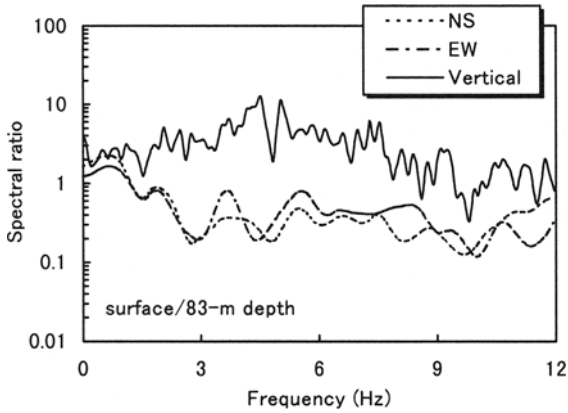

Figure 3. Spectral ratios of accelerations at the surface to 83-m depth

Characterization of Shallow Soils

The array site is located at Port Island, a reclaimed island on the south-west side of Kobe city. The soil profile in the borehole (provided by Kobe City Development Bureau) is shown in Figure 4. The reclaimed surface layers extend to the depth of 19 m and the water table was located at 2.4 m depth. The average *P*-wave velocity of the top layer (from the surface to 12.6 m depth) is very low, about

590 m/s, which is expected to be related to incomplete saturation of soils, because incomplete saturation is associated with the change of pore-fluid compressibility that has been found to significantly affect the velocity of compressional waves (Allen et al. 1980). In certain situations soils below the water table may not be fully saturated although the degree of saturation may be high. For example, incomplete saturation conditions can be caused by fluctuating water tables and recharge of ground water. It would be of value to address the relationships between *P*-wave velocity, Poisson's ratio and the degree of saturation for shallow soil layers, which may help to estimate in-situ saturation of soils as shown later.

P-wave Velocity

The typical case considered here is when the degree of saturation is sufficiently high (e.g., higher than 95%) so that the air is embedded in pore water in the form of bubbles. For this case the concept of homogeneous pore fluid may apply to the theory of two-phase media and the bulk modulus of the homogeneous fluid K_f can be approximately expressed in terms of the degree of saturation S_r as (Verruijt 1969)

$$K_f = \frac{1}{\frac{1}{K_w} + \frac{1 - S_r}{p_a}} \tag{1}$$

in which K_w=bulk modulus of water, p_a=absolute fluid pressure. From (1) it can be shown that even a very small amount of air in soil can drastically reduce the bulk modulus of fluid.

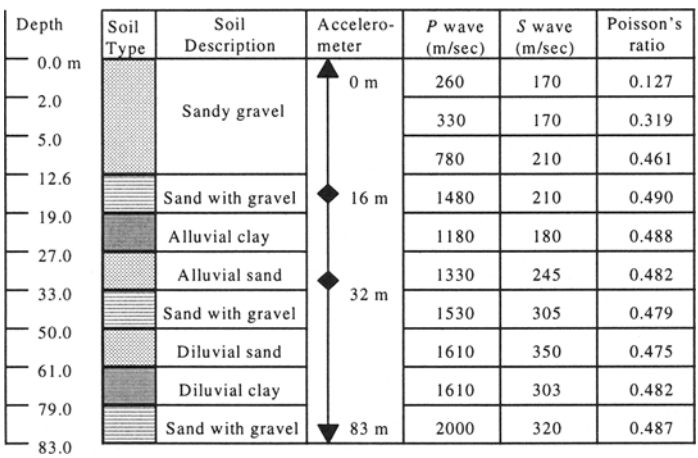

Figure 4. Soil profile at the borehole site (not to scale)

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

Introducing (1) into Biot's theory (Biot 1956) which takes into account the compressibility of constituents, and following similar procedures in Yang and Sato (1998a), one may obtain two types of compression waves traveling with different velocities (the fast and slow waves, respectively) and one shear wave. All the three types of waves are frequency-dependent and attenuated, and the influence of degree of saturation on each of them is different (Yang and Sato 1998b). In low frequency range, within which the frequencies used in most field dynamic tests fall, only the fast compression wave (referred to as *P*-wave) and shear wave (*S*-wave) exist. Their velocities can be given as

$$V_p = \sqrt{\frac{\lambda + 2G + \alpha^2 M}{(1-n)\rho_s + n\rho_f}} \qquad V_s = \sqrt{\frac{G}{(1-n)\rho_s + n\rho_f}} \tag{2}$$

in which

$$\alpha = 1 - \frac{K_b}{K_s} \qquad M = \frac{K_s^{\,2}}{K_d - K_b} \qquad K_d = K_s[1 + n(\frac{K_s}{K_f} - 1)] \tag{3}$$

and n =porosity, ρ_s = density of solid grains, ρ_f =density of pore fluid, λ, G =Lame constants of soil skeleton, K_s =bulk modulus of solid grains, K_b =bulk modulus of soil skeleton, K_f = bulk modulus of pore fluid, which depends on the bulk modulus of pore water, absolute fluid pressure and degree of saturation as described in (1).

Figure 5 shows the saturation effects on *P*-wave velocity for several types of soils in terms of stiffness using (2). As expected, the velocity of the *P*-wave decreases substantially with even a slight decrease below full saturation. The velocity reaches maximum in the case of full saturation, about 1500 m/s, while it drops to around 400 m/s when the degree of saturation is 98%. For *S*-wave, as indicated by (2), the influence of saturation is negligible.

Poisson's Ratio

It is known that Poisson's ratio for fully saturated soils is usually assumed to be close to 0.5 in engineering practice. However, due to the influence of saturation on *P*-wave, it is expected that Poisson's ratio may be affected by saturation as well. The evaluation of such influence is of interest because it may provide some additional information in identifying in-situ saturation states as shown below.

The Poisson's ratio for incompletely saturated soils with compressible constituents is given as (Yang and Sato 1999c)

$$\nu = \frac{1}{2}\frac{\alpha^2 M/G + 2\nu'/(1-2\nu')}{\alpha^2 M/G + 1/(1-2\nu')} \tag{4}$$

in which ν' =Poisson's ratio under drained condition, it depends on Lame constants of the skeleton. It can be readily shown that the range of ν is $\nu' \le \nu \le 1/2$. The

upper limit may be reached for incompressible constituents ($\alpha = 1, 1/M = 0$) and the lower bound is achieved when pore fluid is highly compressible ($K_f << G$). For the special case of saturated soils with incompressible grains, (4) can be simplified by considering that for most soils the condition $\lambda + 2G << K_w/n$ is satisfied:

$$\nu \approx \frac{1}{2}(1 - \frac{nG}{K_w}) \tag{5}$$

The relation shown above is the Poisson's ratio for fully saturated soils commonly used in geotechnical engineering (Ishihara 1996).

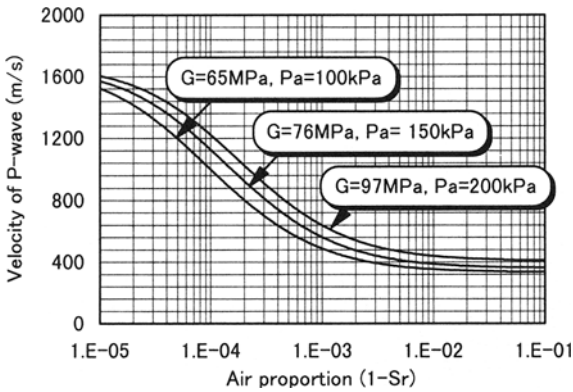

Figure 5. Effects of saturation on *P*-wave velocity

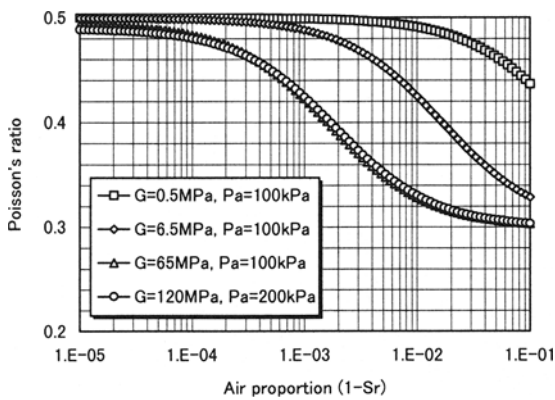

Figure 6. Effects of saturation on Poisson's ratio

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

Figure 6 shows the effects of degree of saturation on Poisson's ratio for several types of soils in terms of stiffness and absolute pore pressure, here v' is taken to be 0.3, a typical value for soils. It is seen that the influence of saturation on Poisson's ratio is significant and the influence depends on soil stiffness and absolute pore pressure. In general, Poisson's ratio decreases with the decreasing of degree of saturation. The upper limit of Poisson's ratio is 0.5, which may be reached for fully saturated soft soils, while the lower bound is v', which can be achieved in the relatively high air-saturation situation. Between the two limits, the variation of Poisson's ratio is little for soils with low stiffness, while the transition is large for soils with higher stiffness.

Variations of P-wave Velocity and Poisson's Ratio in Shallow Layers

Based on the previous discussion, a schematic illustration of possible structures of *P*-wave velocity and Poisson's ratio in shallow soil layers is given in Figure 7, by taking into account the variation of saturation in the vertical direction. With increasing depth, the saturation state of surface soils varies from low saturation to high saturation and finally to complete saturation at some depth. There exists a dramatic increase in *P*-wave velocity from incomplete saturation to full saturation. As for Poisson's ratio, due to the increase of degree of saturation, it also increases with depth until the soils reach the state of full saturation, for which case the value of Poisson's ratio is close to 0.5. After that Poisson's ratio tends to decrease with depth, because the stiffness of soils usually increases with depth gradually.

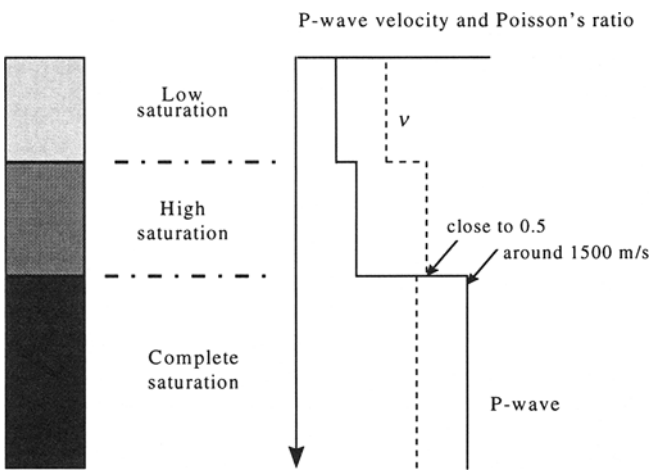

Figure 7. Schematics of variations of *P*-wave velocity, Poisson's ratio and saturation in shallow layers

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

The theoretical prediction for the variations of *P*-wave and Poisson's ratio with depth has been supported by some field test data (e.g., Kitsunezaki 1986). Especially, the soil profile in the borehole, as shown in Figure 4, provides clear evidence. It is seen that *P*-wave velocity shows a great increase with depth, from 260 m/s at the top to 2000 m/s at the bottom. In particular, at the depth of 12.6 m there is a dramatic transition in *P*-wave velocity, from 780 m/s to 1480 m/s. The soil layers with low *P*-wave velocity below the water table to that depth are believed to be incompletely saturated. In addition, it is noted that Poisson's ratio increases from the value of 0.127 at the top to 0.490 at the depth of 12.6 m, below which it gradually decreases. This tendency is in good agreement with the theoretical prediction.

Analytical Analysis of a Simple Model

The simple model corresponds to a soil layer subjected to vertical displacement excitations at the base. The surface of the layer is treated as pervious and stress-free whereas the bottom of the layer is assumed to be impervious. The soils are assumed to be incompletely saturated with a small amount of air inclusions. For this one-dimensional problem, the governing equations can be written as (Yang and Sato 2000)

$$(\lambda+\alpha^2 M+2G)\frac{\partial^2 u}{\partial z^2}+\alpha M\frac{\partial^2 w}{\partial z^2}=\rho\frac{\partial^2 u}{\partial t^2}+\rho_f\frac{\partial^2 w}{\partial t^2} \tag{6}$$

$$\alpha M\frac{\partial^2 u}{\partial z^2}+M\frac{\partial^2 w}{\partial z^2}=\rho_f\frac{\partial^2 u}{\partial t^2}+\frac{\rho_f}{n}\frac{\partial^2 w}{\partial t^2}+\frac{\eta}{k}\frac{\partial w}{\partial t} \tag{7}$$

in which u = displacement of solid phase, w = displacement of fluid with respect to solid phase, η = fluid viscosity and k = permeability with units of m^2.

The boundary conditions are given as

At bottom, $z=0$:

$$u=U_0 e^{i\omega t},\quad w=0 \tag{8}$$

At surface, $z=L$:

$$p_f=0,\ \sigma=0 \tag{9}$$

where p_f = pore pressure and σ = total stress. By enforcing the boundary conditions, analytic solutions for displacements, stresses and pore pressure can be derived. Details for the derivation and the effects of saturation on fluid displacements and pore pressures can be found in Yang and Sato (1998d). The interest of this study is focused on motion amplification, which is defined here as the ratio of solid displacements at depth to the base as follows

$$A_f=\frac{1}{\delta_1-\delta_2}\left(\delta_1\frac{\cos[k_1(L-z)]}{\cos(k_1 L)}-\delta_2\frac{\cos[k_2(L-z)]}{\cos(k_2 L)}\right) \tag{10}$$

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

Table 1. Soil properties used in the computation

Quantity	Value
Bulk modulus of solid skeleton	$K_b = 8.67\times10^7$ Pa
Bulk modulus of solid grains	$K_s = 3.6\times10^{10}$ Pa
Bulk modulus of water	$K_w = 2\times10^9$ Pa
Shear modulus of solid skeleton	$G = 6.5\times10^7$ Pa
Permeability	$k = 10^{-10}$ m^2
Viscosity	$\eta = 10^{-3}$ Pa s
Density of grains	$\rho_s = 2650$ kg/m^3
Porosity	$n = 0.37$

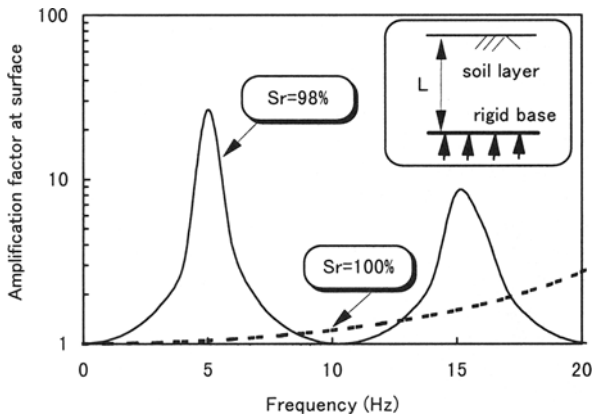

Figure 8. Effects of saturation on surface amplification factor

Figure 8 shows the variation of the amplitude of amplification factor at the surface with frequency. The soil properties, which are typical values of medium dense sands, are shown in Table 1. The thickness of the layer is assumed to be 15 m and the absolute fluid pressure p_a is assumed to be 150 kPa. Two cases of saturation, $S_r = 100\%$ and $S_r = 98\%$ are included to show the effects of saturation. It can be seen that, even if the degree of saturation is only slightly below full saturation, its impact on the amplification is significant. Both the amplitude and frequency content are strongly affected by saturation. Compared with the case of full saturation, the amplification in the case of incomplete saturation is much greater in the earthquake frequency range. In addition, it is noticed that the predominant frequency in the case of incomplete saturation is shifted towards the low frequency

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

end, in other words, the predominant period is lengthened due to partial saturation. This is reasonable, since partial saturation results in a dramatic decrease of *P*-wave velocity as seen in Figure 5.

If one treats the amplification function for the case of incomplete saturation as the one which reflects the true condition of the site, while the incorrect amplification function is the one presumably obtained without considering such soil condition. The above results indicate that at a certain frequency the two functions may yield the same amplification factor. For other frequencies the incorrect amplification function will not give right results, suggesting the need to carefully examine saturation conditions in the study of vertical site amplification. Of course, the model considered here is simplified. In the real case the site is a multi-layered system, there may exist more than one predominant frequency and the transfer function may also involve multiple vibration modes. However, the simple model does provide a direct picture of the saturation effects on the vertical motion amplification.

Numerical Simulation of Vertical Motion at the Borehole Site

In this section the study is completed by extending the simple model to the realistic site considered. A numerical simulation of the vertical motions at the borehole array site is performed by including the effects of saturation. The numerical procedure used here is a fully coupled finite element procedure for response analysis of layered sites under both horizontal and vertical earthquake loading (Li et al. 1998; Yang et al. 2000). In this procedure, wave motions in three components and transient pore fluid movement are coupled through the generalized Biot's formulation and inelastic soil models (e.g., Wang et al. 1990). Details of the procedure and integrated soil models may be found in the references mentioned above. Our intention here is to simulate the vertical motions at the array site by incorporating the effects of saturation into this procedure.

In conventional coupled site response analyses, soils below the water table are often assumed to be completely saturated. There remains difficulty in incorporating the effects of partial saturation. Based on previous analyses, an attempt is made here to investigate such effects on vertical amplification. In doing that, one key issue is to determine the degree of saturation of surface soils. For the array site considered, as indicated earlier, it is reasonable to assume that the soils below the water table (the depth of 2.4 m) are incompletely saturated to the depth of 12.6 m. Within this partially saturated range, soils are composed of two layers which have the average *P*-wave velocities of 330 m/s and 780 m/s, and Poisson's ratios of 0.319 and 0.461, respectively. Using the relationships established between the degree of saturation, *P*-wave velocity and Poisson's ratio, we may estimate that the average values of degree of saturation for the two layers are around 98% and 99.96%. Subsequently, the bulk modulus of pore fluid can be modified according to (1) and be incorporated into the numerical procedure. As for the soils above the water table, conventionally, they are approximately assumed as one-phase media (namely, dry state). The soils below the depth of 12.6 m can be treated as fully water-saturated (i.e. the compressibility of

water is used in the analysis).

The simulation is limited to the top 83 m of the deposit, in which the soils were characterized in detail and the accelerometers were also embedded. The model parameters selected for the deposit were described in Yang et al. (2000), which discussed the liquefaction-induced non-linear effects on the horizontal ground motions at the same site. The borehole acceleration records at the 83-m depth serve as the input motions. To compare with the incomplete saturation case, a conventional analysis is also conducted, which assumes that the soils immediately below the water table are fully water-saturated. In both cases, all input parameters are identical except for the degrees of saturation (or the compressibility of pore fluid) in reclaimed surface layers as indicated above. An illustration of different saturation zones used in the site response analyses for the two cases is shown in Figure 9 (the capillary zone is conventionally ignored in the analyses).

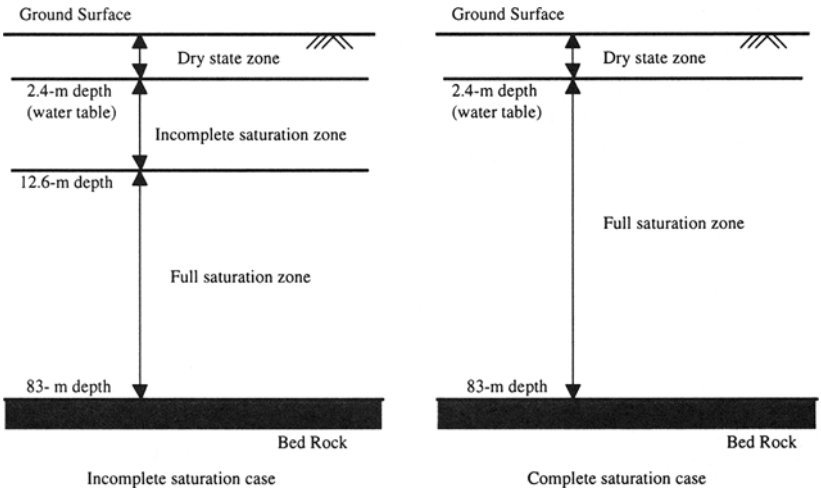

Figure 9. An illustration of saturation zones used in site response analyses

Figure 10 shows the computed vertical acceleration-time histories at the ground surface for the two cases of saturation (denoted as incomplete and complete saturation, respectively). The acceleration response spectra with a damping factor of 5% is shown in Figure 11 for these two cases. Figure 12 shows the computed distributions of peak accelerations with depth, together with the recorded ones. While both simulated surface motions are in general very similar to the field records, all the results clearly indicate that the incomplete saturation of surface soils, as expected, can cause a larger vertical site amplification. The simulated surface peak acceleration is 0.439 g in the case of complete saturation, whereas it increases to the value of 0.542 g even if very slight incomplete saturation exists in surface layers.

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

The discrepancy in peak acceleration response spectra is as large as 0.24 g, which takes place at periods around of 0.15 sec. Figure 13 shows the spectral ratios of vertical motions at the surface and 83-m depth in the case of incomplete saturation, as well as those for recorded motions. The simulation is in reasonable agreement with the field records, especially, the calculated ratios match the overall trend of the observed ones very well. Both simulated and recorded large vertical amplification took place at frequencies around of 4.5 to 5.5 Hz.

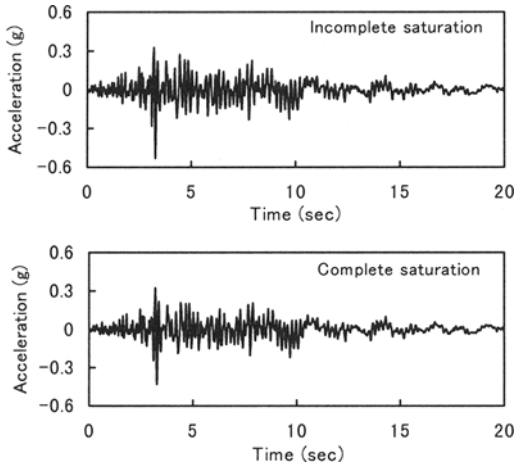

Figure 10. Simulated acceleration-time histories at the surface for two cases of saturation

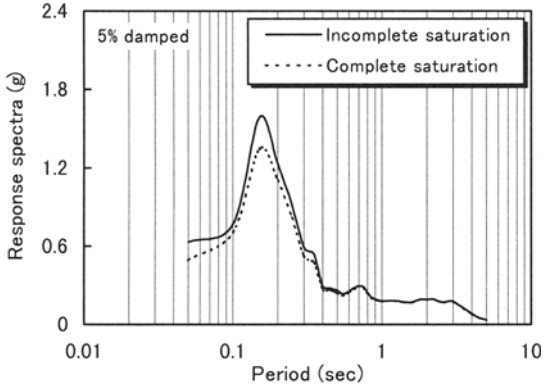

Figure 11. Ground surface response spectra for two cases of saturation

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.

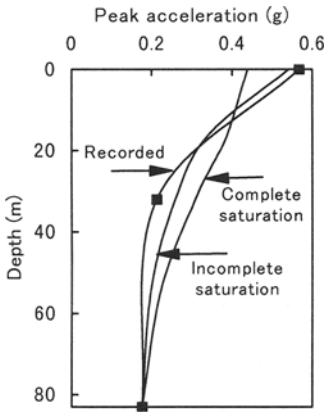

Figure 12. Distribution of peak accelerations with depth for two cases of saturation

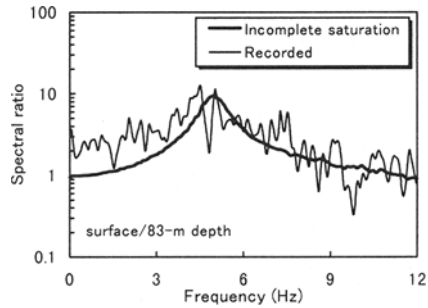

Figure 13. Simulated and recorded spectral ratios of vertical motions at the surface and 83-m depth

Conclusions

In this paper, an explanation is presented for the borehole array observation of vertical motion amplification at the reclaimed Port Island, Kobe. The explanation, amplification of *P*-waves caused by incomplete saturation of surface soils, is addressed by using Biot's theory and the concept of homogeneous pore fluid. The effects of saturation on *P*-wave velocity and Poisson's ratio of soils are briefly discussed to show evidence of partial saturation of shallow layers at the array site. The analytical study for a simple model clearly indicates that the degree of saturation may produce a substantial influence on vertical motion amplification. The numerical simulation for the realistic site by incorporating the effects of saturation, demonstrates the mechanism of large amplification caused by partial saturation of surface soils. The present study indicates that vertical motions may significantly be affected by saturation of shallow soils, suggesting that one may need to carefully examine the condition of saturation in the study of vertical site amplification.

Acknowledgments

The first author would like to acknowledge the financial support provided by Ministry of Education and Science, Japan via the Program of Center of Excellence, and the support by Japan Society of Civil Engineers via STA project during the course of the study. The careful reviews by two anonymous referees are also gratefully acknowledged.

Appendix. References

Aguirre, J., and Irikura, K. (1997). "Nonlinearity, liquefaction, and velocity variation of soft soil layers in Port Island, Kobe, during the Hyogo-ken Nanbu earthquake." *Bull. Seism. Soc. Am.*, 87, 1244-1258.

Allen, F.A., Richart Jr, F.E., and Woods, R.D. (1980). "Fluid wave propagation in saturated and nearly saturated sands." *J. Geotech. Engrg.*, ASCE, 106, 235-254.

Biot, M.A. (1956). "Theory of propagation of elastic waves in a fluid saturated porous solid." *J. Acoust. Soc. Am.*, 28, 168-191.

Konno, K., and Ohmachi, T. (1998). "Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor." *Bull. Seism. Soc. Am*, 88, 228-241.

Ishihara, K. (1996). "*Soil Behavior in Earthquake Geotechnics.*" Oxford University Press Inc., New York.

Kitsunezaki, C. (1986). "Velocity and attenuation of elastic waves in water-filled sand layers with partial gas saturation and their practical significance (in Japanese)." *Geophy. Exploration*, 39, 42-59.

Kokusho, T., and Matsumoto, M. (1999). "Nonlinear site amplification in vertical array records during Hyogo-ken Nanbu earthquake." *Soil and Found.,* Special Issue No. 2, 1-9.

Li, X.S., Shen, C.K., and Wang, Z.L. (1998). "Fully coupled inelastic site response analysis for 1986 Lotung earthquake." *J. Geotech. Geoenviron. Engrg.*, ASCE, 124, 560-573.

Theodulidis, N.P., and Bard, P.Y. (1995). "Horizontal to vertical spectral ratio and geological conditions: an analysis of strong motion data from Greece and Taiwan (SMART-1)." *Soil Dyn. Earthquake Eng.*, 14, 177-197

Verruijt, A. (1969). "Elastic storage of aquifers." *Flow Through Porous Media*, ed. R.J.M. de Weist, Acedemic Press, London.

Wang, Z.L., Dafalias, Y.F., and Shen, C.K. (1990). "Bounding surface hypoplasticity model for sand." *J. Engrg. Mech.*, ASCE, 116, 983-1001.

Yang, J., and Sato, T. (1998a). "Influence of viscous coupling on seismic reflection and transmission in saturated porous media." *Bull. Seism. Soc. Am.*, 88(5), 1289-1299.

Yang, J., and Sato, T. (1998b). "On the velocity and damping of elastic waves in nearly saturated soils." *Proc. 33rd Japan National Conference on Geotech. Engrg.*.

Yang, J., and Sato, T. (1998c). "On the variation of Poisson's ratio in shallow soil layers." *Proc. 53rd JSCE Annual Conference.*

Yang, J., and Sato, T. (1998d). "Seismic response of a partially saturated sand layer." *Proc. 10th Japan Earthquake Engrg. Symposium,* pp. 799-804.

Yang, J., and Sato, T. (2000). "Interpretation of seismic vertical amplification observed at an array site." *Bull. Seism. Soc. Am.*, 90(2), in press.

Yang, J., Sato, T., and Li, X.S. (2000). "Nonlinear site effects on strong ground motions at a reclaimed island." *Can. Geotech. J.*, 37(1), 1-14.

Downloaded from ascelibrary.org by Istanbul Universitesi on 06/08/13. Copyright ASCE. For personal use only; all rights reserved.