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TECHNICAL NOTE

Reappraisal of vertical motion effects on soil liquefaction

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KEYWORDS: dynamics; earthquakes; liquefaction; partial saturation; pore pressure

INTRODUCTION

Ground motion induced by an earthquake is in general characterised by a vector with its components along the vertical and two horizontal directions. In current practice and research, the effect of vertical ground motion is often disregarded while attention is focused mainly on the horizontal ground motion. Two primary reasons have been accepted for neglect of the vertical seismic motion. First, engineering structures are considered to have adequate resistance to dynamic forces induced by the vertical ground motion, which is generally much smaller than its horizontal counterparts. If the effect of vertical motion is explicitly included in design, it is typically assumed that the ratio of vertical to horizontal (V/H) response spectra will not exceed two-thirds (International Code Council, 1996). Second, the vertical ground motion is considered to have negligible influence on soil liquefaction because it induces almost purely compressive stresses, which cannot cause changes in the effective stress in the subsoil (Ishihara, 1996).

However, there are repeated observations from recent earthquakes, such as those in Northridge, California, in 1994 and Kobe, Japan, in 1995 (Bardet *et al.*, 1997; NCEER, 1997), that the rule-of-thumb ratio of two-thirds is a poor descriptor of vertical ground motions. The (V/H) spectral ratios may substantially exceed two-thirds in the near field of moderate and large earthquakes and at short periods. A typical case comes from the three-dimensional borehole array recordings obtained at Port Island, Kobe, during the 1995 Kobe earthquake (Yang & Sato, 2000), which indicated that the peak vertical acceleration was *twice* as high as the peak horizontal acceleration at the ground surface (Fig. 1). An integrated study of this case history (Yang & Sato, 2000; Yang *et al.*, 2000) has revealed that both the horizontal and the vertical ground motions were closely related to the liquefied soil layers and, particularly, the condition of partial saturation in the near-surface soils played a crucial role in the amplification of vertical motion. Partial saturation conditions may occur in certain situations as a result of fluctuating groundwater tables associated with natural or man-made processes. They may also exist in offshore sites or marine sediments. Thus considerable interest arises in reappraising the effect of vertical ground motion on soil liquefaction and, especially, in clarifying whether or not this effect is dependent on the saturation condition.

Aimed at this goal, analyses have been conducted by means of a verified, fully coupled numerical procedure for a model deposit subjected to a variety of combinations of loading and saturation conditions. A significant finding of the analyses is that the current understanding that the effect of vertical motion on liquefaction is negligible may not always hold true; rather, the effect is dependent on the saturation condition. This paper presents the main results and the related mechanisms. Implications of the results for dynamic model testing in the geotechnical laboratory are also addressed briefly.

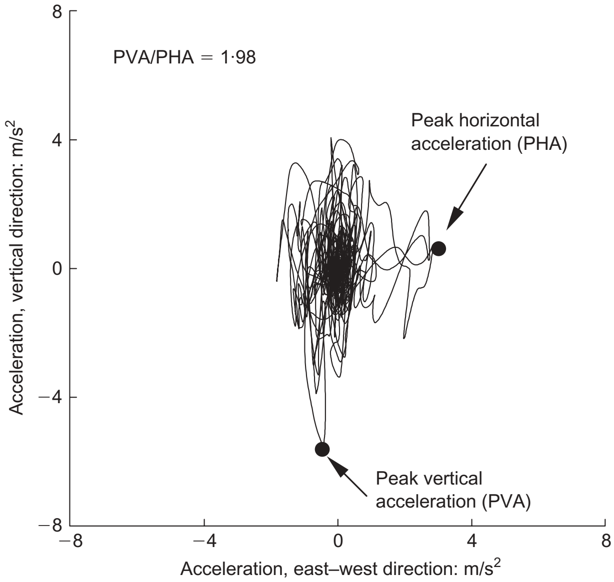

Fig. 1. Trajectory of recorded accelerations in vertical planes

METHOD OF ANALYSES

As an acceptable assumption in geotechnical engineering, site response to earthquakes may be regarded as the consequence of vertical propagation of shear and compression waves induced by multi-directional earthquake motions originating primarily from the underlying rock formation. The numerical procedure for analyses is formulated on the basis of vectored motion, effective stress, transient pore fluid movement, and generalised material stiffness (Li *et al.*, 1992). The constitutive model incorporated in the procedure is numerically robust yet sufficiently sophisticated (Wang *et al.*, 1990) to be capable of simulating the behaviour of soils under a wide range of loading conditions including, particularly, the rotational shear effects imposed by multi-directional earthquake motions. The procedure has been verified using laboratory centrifuge tests through the VELACS project (Arulanandan & Scott, 1993), by the use of shake table test results (Yang *et al.*, 2002), and by the well-documented case histories from the Lotung and Kobe earthquakes (Li *et al.*, 1998; Yang *et al.*, 2000). A complete description of the procedure is beyond the scope of this paper. For details the reader is referred to the given references.

To account for the partial saturation effect, the concept of

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homogeneous pore fluid, which assumes that the water/air mixture can be approximately treated as an equivalent homogeneous pore fluid that completely fills the pores with a pore pressure p_f, has been introduced (Yang & Sato, 2000, 2001). As a result, the compressibility of the pore fluid, K_f, is considered as a function of the degree of saturation, S_r, the compressibility of the pore water, K_w, and the absolute pore pressure, p_a:

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

and the effective stress equation is expressed in incremental form as

$$\Delta\sigma_{ij} = \Delta\sigma'_{ij} + \delta_{ij}\Delta p_f \tag{2}$$

in which Δp_f is related to the volumetric strain of the pore fluid $\Delta\varepsilon_{vf}$ by $\Delta p_f = K_f \Delta\varepsilon_{vf}$. This treatment has been demonstrated by the Kobe case history analysis to be simple yet effective (Yang & Sato, 2000).

Model deposit and input motions

The model deposit under consideration is shown in Fig. 2. The deposit is assumed to be composed of liquefiable sand, with the water table at 1 m depth below the surface. The shear wave velocity in the deposit is considered to vary linearly with depth, and the coefficient of earth pressure at rest is assumed as 0·7. The basic properties of the sand are given in Fig. 2. Two typical loading conditions are considered: one is horizontal shaking only, and the other is a combination of horizontal and vertical earthquake loading. The original acceleration records in the horizontal and vertical components employed in the analyses are shown in Fig. 3, together with their response spectra. The predominant period is about 0·85 s for the horizontal motion while that for the vertical motion is 0·25 s. These data are taken from the actual near-field acceleration records in the east–west and up–down directions at a depth of 32 m at the Port Island borehole array site. In the analyses the original motions in the horizontal direction are scaled to a peak acceleration of 1 m/s^2, and the vertical motions are scaled correspondingly.

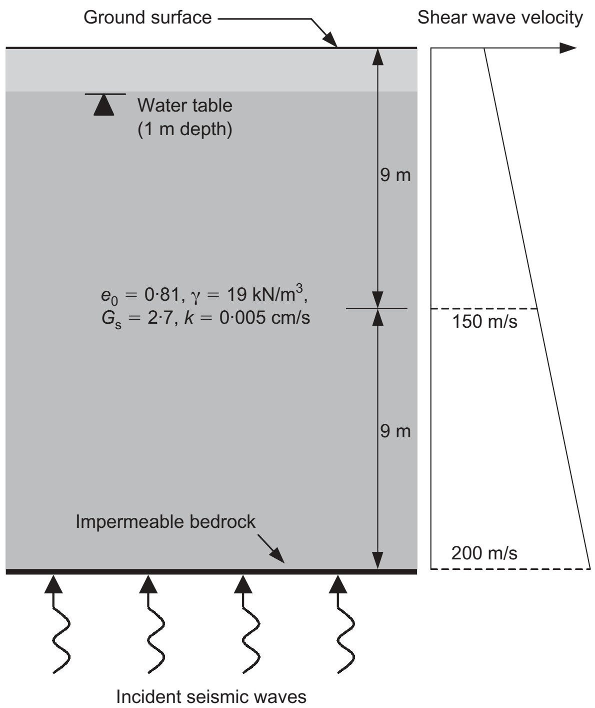

Fig. 2. Model deposit for analyses

In order to investigate simultaneously the influence of saturation on site response, two typical cases of saturation are considered under otherwise identical conditions. In one the sand below the water table is conventionally treated as fully saturated; in the other the sand below the water table is assumed to be partially saturated. To each case two loading conditions, as described earlier, are applied. Thus there are in total four typical cases under investigation.

RESULTS OF ANALYSES

Full saturation

Figure 4(a) shows the time histories of excess pore pressures at a depth of 4·5 m under two loading conditions: H denotes horizontal shaking only, and H + V combined horizontal and vertical excitation. Here the pore pressure is normalised by the initial effective vertical stress. It is clear from this graph that the influence of vertical motion on the build-up of pore pressure is slight. In both cases the generated residual pore pressure approaches about 60% of the initial effective vertical stress at the end of excitation. The inclusion of vertical excitation only causes some high-frequency oscillations in the response, but no change in the residual pore pressure. This performance is in good agreement with observations from recent shaking table tests (e.g. Mori *et al.*, 1996).

The lack of influence of vertical motion on the development of residual pore pressure is reasonable. For the case of level ground under consideration, the horizontal ground motion is associated with shear waves, which produce shear stress in the soil element, whereas the vertical motion is associated mainly with compression waves, which induce compressive stress, as illustrated schematically in Fig. 5. During the propagation of compression waves, normal stresses are induced in both the horizontal and vertical directions, thereby producing a triaxial mode of deformation in a soil element.

Assuming that the soil element is not allowed to deform in the horizontal direction, and based on the theory of elasticity, the induced horizontal stress, σ_{dh}, thus relates to the vertical stress, σ_{dv}, as

$$\sigma_{dh} = \left(\frac{\nu}{1-\nu}\right)\sigma_{dv} \tag{3}$$

in which ν is Poisson's ratio for the soil.

Under undrained conditions Poisson's ratio for a fully saturated soil is close to 0·5, and therefore equation (3) implies that the propagation of vertical motion associated with compression waves through saturated soils induces almost purely compressive stress, while the induced deviator stress ($\sigma_{dv} - \sigma_{dh}$) is nearly equal to zero. Because the compressive stress is transmitted mainly through pore water, there are only instantaneous changes in pore pressure, but no changes in residual pore pressure. This qualitative explanation has been widely accepted in geotechnical engineering, as documented in some textbooks (e.g. Ishihara, 1996). However, as will be shown later, when the soil is not fully saturated, the vertical motion may have quite a different influence.

Partial saturation

In this case the sand below the water table is assumed as incompletely saturated, with degree of saturation 99%. Fig. 4(b) shows the pore pressure response at a depth of 4·5 m

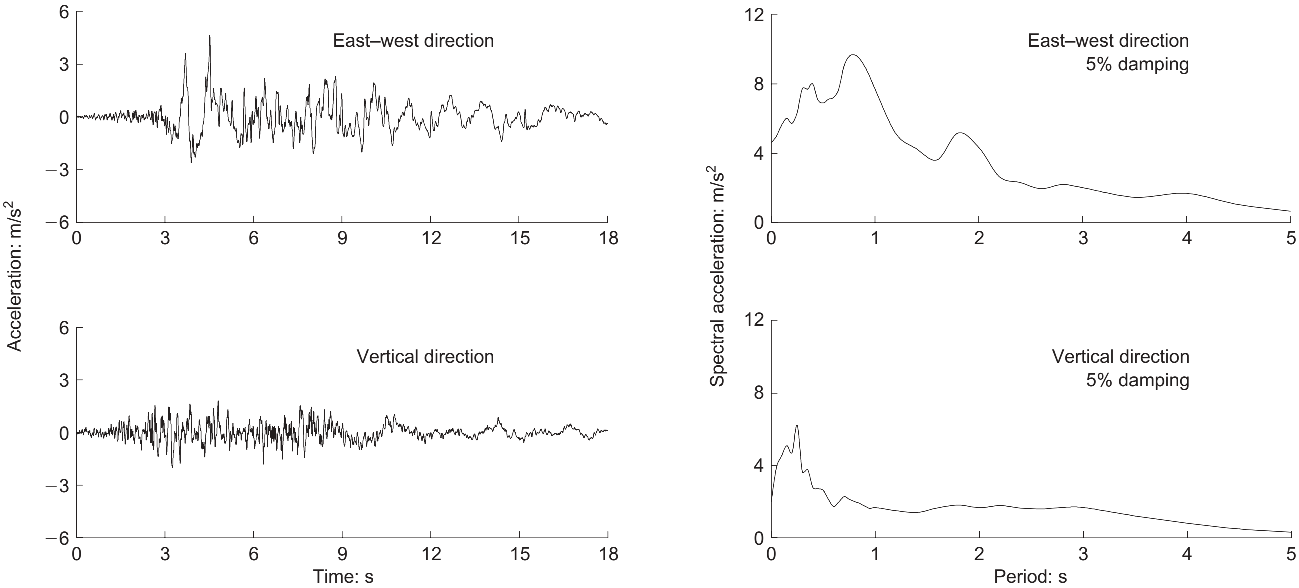

Fig. 3. Acceleration records employed in analyses

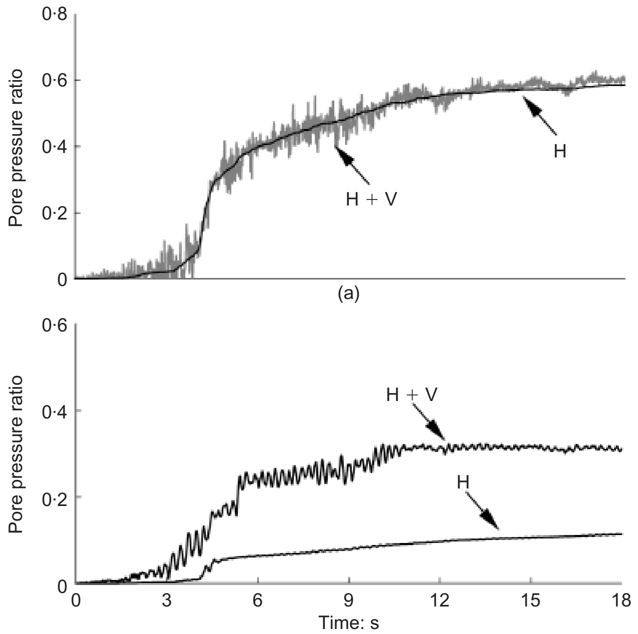

Fig. 4. Pore pressure response: (a) full saturation; (b) partial saturation (H, horizontal input motion only; H + V, combination of horizontal and vertical input motion)

under two loading conditions. It is interesting to note that, in contrast to the results for full saturation, the inclusion of vertical acceleration may, in addition to causing some oscillation in the response, produce a substantial influence on the residual pore pressure when the deposit is not fully saturated. The level of residual pore pressure ratio is increased by about 100% when horizontal shaking is combined with vertical excitation.

The results imply that the current understanding that vertical motion has a negligible effect on soil liquefaction may not always hold true; rather, the effect depends on the saturation condition of the subsoil. From a point of view that is similar to that discussed earlier for the case of full saturation, a qualitative explanation for this new finding is proposed as follows. Under the full saturation condition, as explained, vertical motion only induces a compressive stress in a level ground because the undrained Poisson's ratio is close to 0·5; however, when the soil is not fully saturated, its Poisson's ratio may be substantially below 0·5, and this will bring about a deviator stress.

Based on poroelasticity, Yang & Sato (2000) have derived the Poisson's ratio for an unsaturated soil with compressible constituents. If we ignore the compressibility of solid grains, as commonly accepted in soil mechanics, the Poisson's ratio is given by

$$\nu = \frac{1}{2}\left(1 - \frac{1}{a+b}\right) \tag{4}$$

in which

$$a = \frac{1}{n(G/K_w) + n(G/p_a)(1 - S_r)} \tag{5}$$

$$b = \frac{1}{1 - 2\nu'} = 1 + \frac{K_b}{G} \tag{6}$$

where G is the shear modulus, K_b is the bulk modulus of the soil skeleton, ν' is the Poisson's ratio of the soil skeleton, and n is the porosity. It is evident that for the specific case of fully saturated soil where $S_r = 100\%$, $K_w \gg K_b$ and $K_w \gg G$, equation (4) yields $\nu \approx 0{\cdot}5$.

Using equation (4) and assuming $\nu' = 0{\cdot}3$, Fig. 6 shows the Poisson's ratio as a function of saturation for the sand at depths of 4·5 and 13·5 m. It is clear from the graph that the Poisson's ratio may drop from 0·5 at full saturation to as low as 0·3 when a slight decrease of saturation occurs. According to equation (3), the propagation of vertical motion will then give rise to a deviator stress under partial saturation conditions. This deviator stress may contribute to the build-up of residual pore pressure and hence to the development of liquefaction. Though it is based on elasticity and is of a qualitative nature, the above discussion does provide a sound and consistent explanation for the results obtained by the present analyses.

By comparing the response of pore pressure under partial saturation conditions with that under full saturation conditions for the case of horizontal shaking only (i.e. the curves denoted by H in Fig. 4(a) and 4(b)), one can notice that

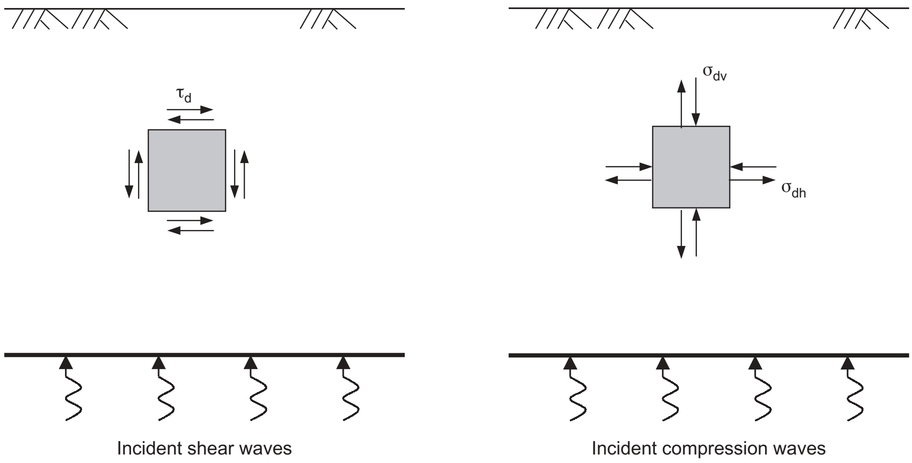

Fig. 5. Stresses induced by propagation of shear and compression waves

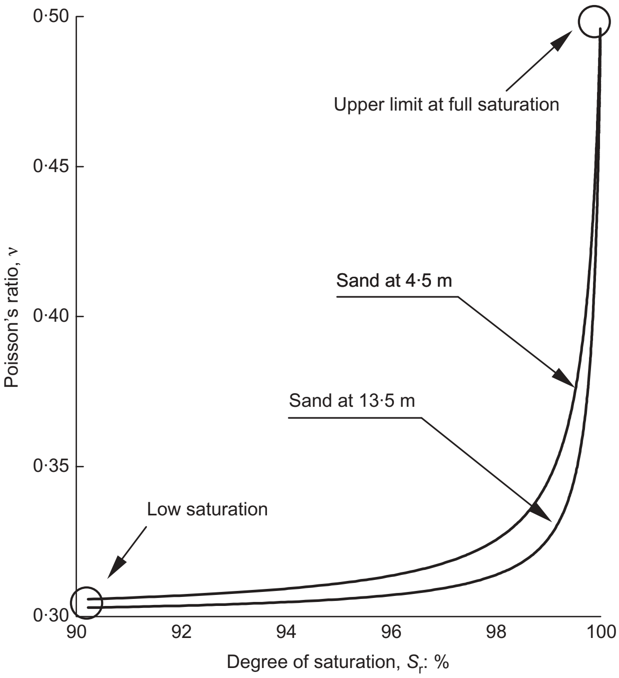

Fig. 6. Influence of saturation on Poisson's ratio

even a decrease of complete saturation may lead to a low pore pressure generated in the deposit and hence a high liquefaction resistance. This observation is confirmed by the available test results, as shown in Yang (2002).

Characteristics of ground motions

Figure 7 shows the time histories of horizontal and vertical accelerations at the surface for the two cases of saturation. It is apparent that although the horizontal ground motions in the two cases are very similar, the characteristics of vertical ground motions are quite different in terms of amplitude and frequency content. A much greater vertical amplification occurs under partial saturation conditions. The amplification is increased by as much as 50% when the degree of saturation changes from 100% to 99%, causing the ratio of peak vertical to horizontal acceleration at the surface to increase from less than 0·6 to about 0·9. Meanwhile, the slight decrease of full saturation causes a significant variation of the transfer function for the vertical ground motion, as shown in Fig. 8. A substantial shift of the peak frequency towards the low-frequency end, from about 20 Hz to 4·4 Hz, is observed.

It is believed that the change in both amplitude and frequency content of the transfer function is due mainly to the effect of saturation on the propagation of compression waves (i.e. P-waves), as confirmed by a rigorous solution obtained for a single soil layer model (Yang & Sato, 2001). Using the expression derived for the wave velocity in unsaturated soils, Fig. 9 shows the variation of the compression wave velocity with the degree of saturation for the sand at depths of 4·5 and 13·5 m. It can be seen that the compression wave velocity is over 1450 m/s at full saturation, whereas it drops dramatically to only 255 m/s at a degree of saturation of 99%.

IMPLICATIONS FOR DYNAMIC TESTING

Dynamic model testing in the geotechnical laboratory, such as the shake table and centrifuge testing, has increasingly been employed to gain insight into the complex response of soil structures under seismic loading. One key issue in the physical modelling is to ensure that the test results and interpretations are as reliable as possible, so that they can serve as useful reference solutions for verification and/or calibration. To date, in many shake table or centrifuge testing studies that involved saturated soil models, complete saturation of the soil models was not reliably verified, although it was often stated that the fully saturated condition was reached. Since even a very slight incomplete saturation may result in quite a different response and, consequently, quite a different interpretation, especially when the vertical excitation is included, the saturation condition must be carefully identified before testing in order to achieve a correct interpretation of the observations.

A reliable and effective method for identifying the saturation condition in these tests would be through measuring the compression wave velocity, because this is very sensitive even to a slight change in the degree of saturation, as shown in Fig. 9. The measurements can be made by means of bender elements or geophones embedded within the soil model. Effectiveness of the use of compression wave velocity in identifying in-situ partially saturated zones has been demonstrated by the borehole array site at Port Island (Yang & Sato, 2000). More recently, the application of compression wave velocity in interpreting laboratory test data for partially saturated sands and characterising their liquefaction resistance has been demonstrated by Yang (2002).

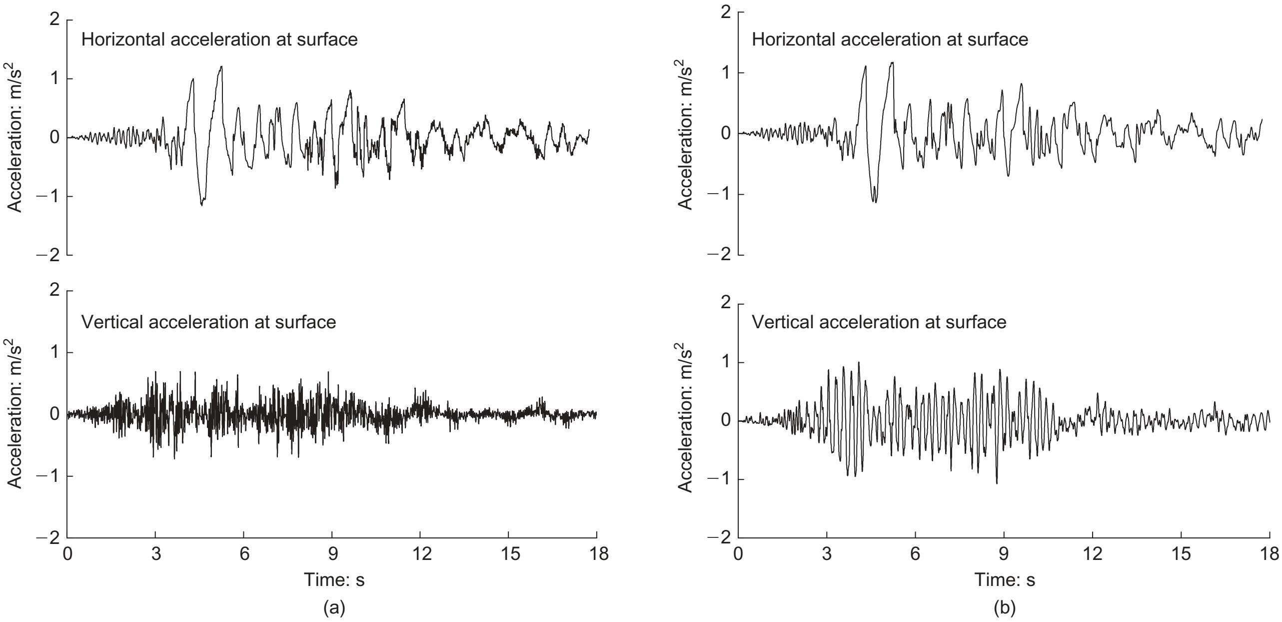

Fig. 7. Acceleration–time histories at surface: (a) full saturation; (b) partial saturation

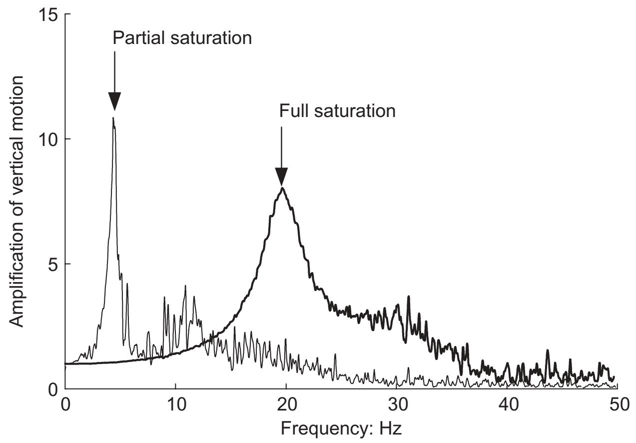

Fig. 8. Influence of saturation on transfer function for vertical ground motion

CONCLUDING REMARKS

The effect of vertical ground motion, which has traditionally been ignored in geotechnical earthquake engineering, is brought into focus in this study. The significant finding is that current understanding that the vertical motion effect on soil liquefaction is negligible may not always hold true; rather, the effect is dependent on the saturation condition of the soil. The main results are summarised as follows:

(*a*) The inclusion of vertical excitation has a minor influence on the build-up of pore pressure under full saturation conditions, apart from causing some high-frequency oscillation in the response. But under partial saturation, the inclusion of vertical motion may affect the development of liquefaction. An underlying mechanism is that the propagation of vertical motion can, under partial saturated, induce a deviator stress in the soil rather than a purely compressive stress under the fully saturated condition.

(*b*) The amplification of vertical ground motion is strongly affected by the saturation condition of the deposit. A much greater vertical amplification may occur under partial saturation than under full saturation, accompanied by a significant shift of the peak frequency in the transfer function towards the low-frequency end. This may cause a significant change in the spectral ratios between the vertical and horizontal ground motions.

(*c*) In dynamic model testing the saturation condition of soil models must be carefully identified in order to achieve correct interpretation of the experimental observations. A reliable and effective method for identifying the saturation condition would be through measurements of compression wave velocity in the soil models.

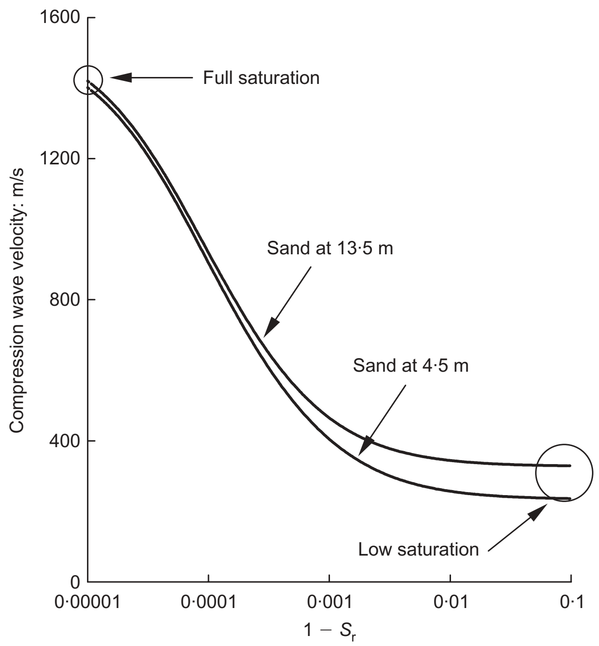

Fig. 9. Influence of saturation on compression wave velocity

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