第2回構造物の破壊過程解明に基づく
地震防災性向上に関するシンポジウム論文集　2001年3月

INFLUENCE OF PARTIAL SATURATION OF SOIL ON GROUND STRAIN INDUCED BY EARTHQUAKES

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1995年兵庫県南部地震の際にポートアイランドの鉛直アレイで観測された地震動の加速度記録は、土の飽和度が地震動に大きな影響を及ぼすことを明かにした。この研究では、液状化の可能性のある不飽和地盤における地震動の水平成分と鉛直成分が土の飽和度によってどのような影響を受けるかを数値解析により明らかにすることを目的としている。解析結果から、地盤内の動的ひずみと蓄積される過剰間隙水圧に及ぼす不飽和度の影響の大きいことが明らかになり、この原因を説明するための簡単な力学モデルを提示した。また、地盤震動を評価するためには地盤の不飽和度を的確に推定することが重要であること示唆した。

Key Words: *partial saturation, ground response, ground strain, pore pressure, earthquakes*

1. INTRODUCTION

The downhole array observations on strong ground motions at the Port Island, Kobe, during the Hyogo-ken Nanbu earthquake of 1995 showed a unique feature: while the amplitudes of both horizontal components of ground motion were reduced when seismic waves traveled from bottom to surface, the vertical motion was significantly amplified. The resultant vertical-to-horizontal ratio of peak acceleration was as large as 2, substantially exceeding the value commonly used in engineering practice. Comprehensive analyses of this case history have been conduced [1), 2)], which indicate that the characteristics of both horizontal and vertical ground motions at the array site were closely related to the shallow liquefied soils; in particular, the saturation conditions of the shallow layers played a key role in the amplification of vertical motion. Learning from the Port Island case history, a great interest arises in the further study of the effect of partial saturation on the response of liquefiable sites.

In this study, a series of numerical tests of a liquefiable sand deposit subjected to either horizontal shaking only or the simultaneous action of horizontal and vertical motions are performed. Special attention is paid here to the influence of partial saturation of subsoil on the induced shear and volumetric strains as well as the buildups of pore pressures in different loading conditions. The mechanisms for the new findings from the numerical tests are also proposed.

2. SETUP OF NUMERICAL TESTS

(1) Sand deposit for testing

A hypothetical sand deposit of a thickness of 18 m, as illustrated in Fig. 1, is used in the numerical tests. The deposit is assumed to rest on a rigid bedrock that is impermeable. The water table is specified at 1m depth below the ground surface, at that depth the pore water is free draining. The shear wave velocity of the sand is considered to vary linearly with depth. The basic properties of the sand are given in Fig. 1, and the cyclic behavior of the sand under undrained conditions is shown in Fig. 2.

(2) Constitutive model and numerical procedure

The well reproduced cyclic behavior is obtained with an advanced hypoplasticity bounding surface model [3)]. This model is capable of realistically simulating the soil behavior under a wide range of loading conditions, from simple monotonic to complex cyclic, at different amplitudes and directions. This model has been incorporated into a fully coupled finite element procedure for earthquake ground response, whose predictive capability has been verified using the three-dimensional field observations of the moderate and strong level of earthquakes [4), 2)] and using the centrifuge test data [5)].

(3) Input motions

Two typical loading conditions are considered in the numerical tests: one is the case of horizontal shaking only and the other is the case of the combination of horizontal and vertical earthquake loading. The original acceleration records in horizontal and vertical components used in the tests are shown in Fig. 3, together with their response spectra at 5% damping. The predominant period is about 0.85 sec for the horizontal motion while 0.25 sec for vertical motion. These records are taken from the actual near-field acceleration records in east-west and up-down directions at a depth of 32 m at the Port Island downhole array site. In numerical tests, the original motions in the horizontal component are scaled to peak acceleration of 100 gal and the vertical motions are scaled correspondingly.

(4) Test cases

In order to investigate the influence of saturation on the response of the deposit, two typical cases of saturation are considered: one is referred to as the full saturation case in which the sand below the water table is conventionally treated to be fully saturated; the other is the partial saturation case in which the sand below the water table is assumed to be partially saturated with the degree of saturation of 99%. In either the case of full saturation or the case of partial saturation, two loading conditions as described previously are applied. Thus, there are four cases to be investigated, as listed in Table 1, where "H" and "H+V" denote "horizontal input motion only" and "the combination of horizontal and vertical motions".

In the present study, observation is conducted of the strain and pore pressure response at a depth of 4.5 m, while observation of the acceleration time histories is made at the surface of the deposit.

Table 1 Test cases

Case	Saturation condition	Loading condition
Case A	full	H
Case B	full	H+V
Case C	partial	H
Case D	partial	H+V

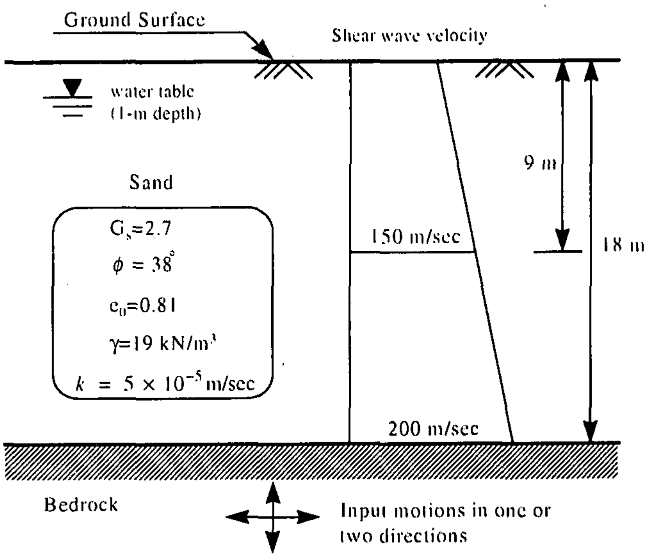

Fig. 1 A hypothetical sand deposit used in numerical tests

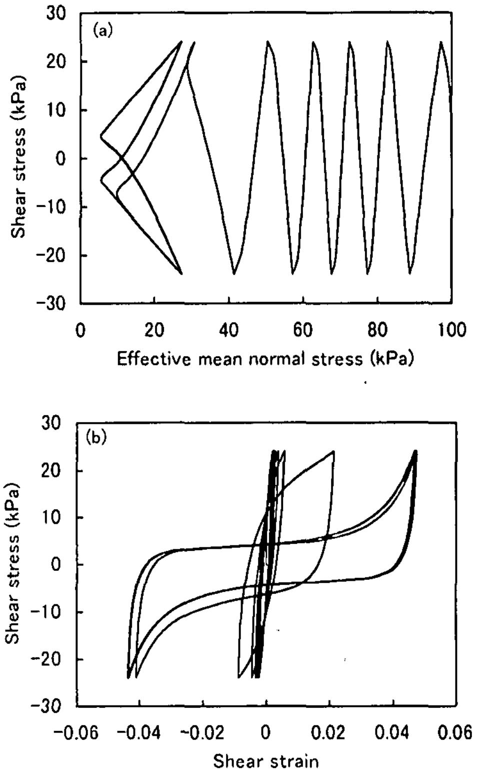

Fig. 2 Undrained cyclic behavior of the sand

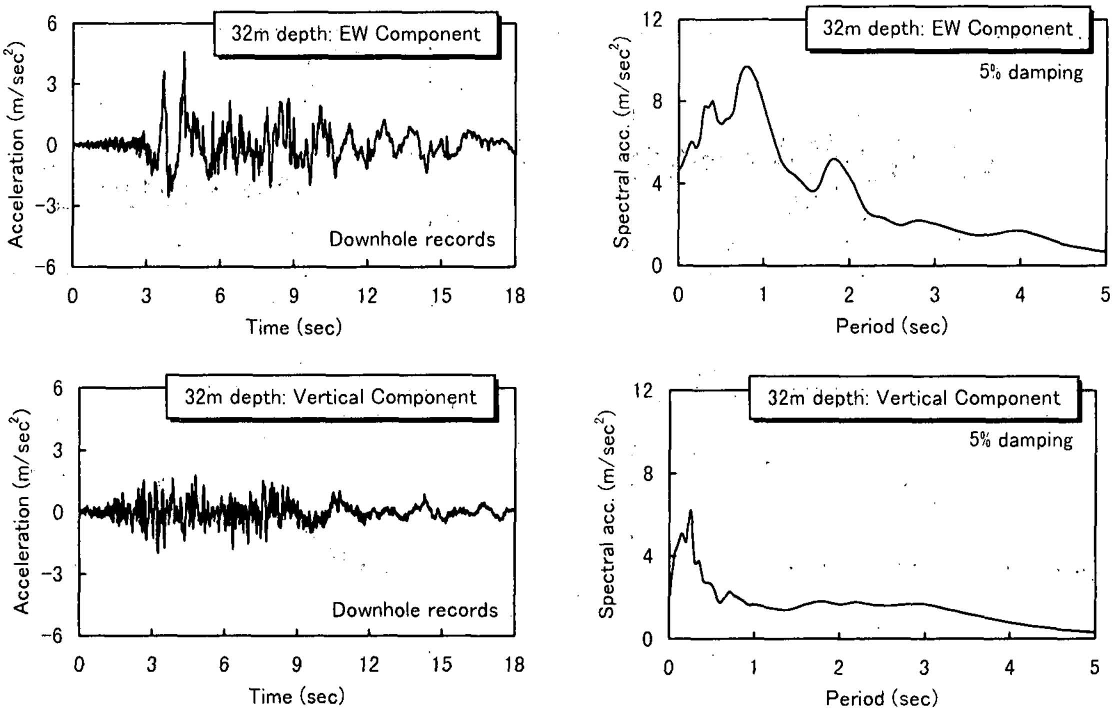

Fig. 3 Acceleration records employed in tests

3. RESULTS AND ANALYSES

(1) Effect of partial saturation on ground strain

Fig. 4 shows the time histories of shear and volumetric strains in sand at the depth of 4.5 m in Case A and C. The time histories of ground strains in Case B and D are shown in Fig. 5.

The results indicate that, in either the case of horizontal input motion only or the case of combination of horizontal and vertical motions, the influence of saturation of the sand is substantial on the volumetric strain. A slight decrease of full saturation may lead to a much greater volumetric strain. This reasonable performance is considered to be associated with the change in the compressibility of the pore fluid. At full saturation conditions, pore fluid is water only, whose bulk modulus is about 2200 GPa. But at partial saturation conditions, pore fluid is the mixture of pore water and air, whose compressibility can be increased substantially with even a very small amount of air inclusions [1].

As far as the shear strain is concerned, it is noted that, when the deposit is subjected to horizontal shaking only, a decrease of full saturation may cause a lower level of shear strain. But if the deposit is subjected to the simultaneous action of horizontal and vertical motions, the influence of partial saturation on the shear strain becomes small. This performance is also reflected by the shear stress-shear strain histories shown in Fig. 6.

(2) Effect of partial saturation on pore pressure

Fig. 7 shows the time histories of excess pore pressure ratio generated in the sand at the depth of 4.5 m in Case A, B, C and D. A comparison of Fig. 7a and b indicates that, at full saturation conditions the inclusion of vertical motion has a minor affect on the residual pore pressure, aside from causing some high-frequency oscillations in the response. This performance has been supported by available shaking table tests. On the other hand, by comparing Fig. 7a and c, it is found that, when the sand deposit is subjected to the horizontal shaking only, a decrease of full saturation causes a lower liquefaction potential. This behavior agrees very well with the laboratory observations on cyclic triaxial tests [6], which showed that a decrease of B-value of the samples leads to an increase of liquefaction resistance. Corresponding to the lower level of pore pressure, the induced shear strain is at lower level, consistent with the results shown in Fig. 4a.

It is of interest to note the significant difference between the Case C and D shown in Fig. 7, which suggests that the inclusion of vertical motion may cause a large affect on the development of the

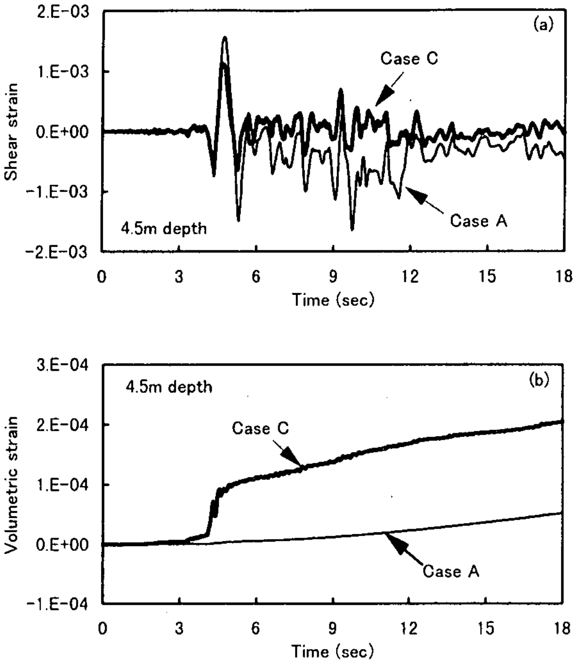

Fig. 4 Time histories of shear and volumetric strains: Case A and Case C

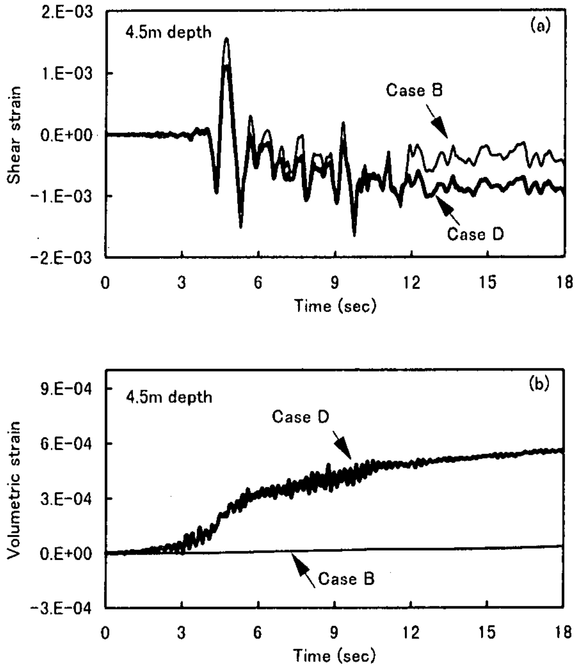

Fig. 5 Time histories of shear and volumetric strains: Case B and Case D

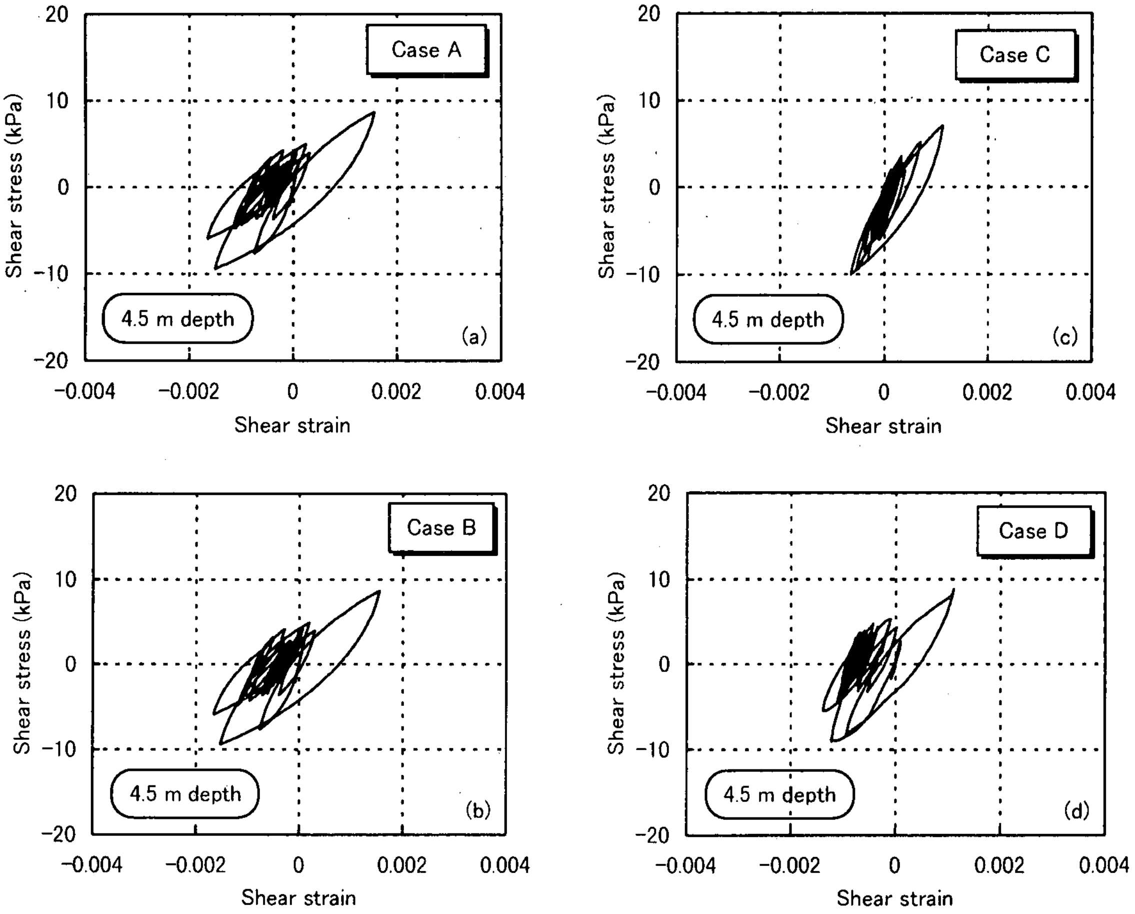

Fig. 6 Stress-strain histories at 4.5m depth in different cases

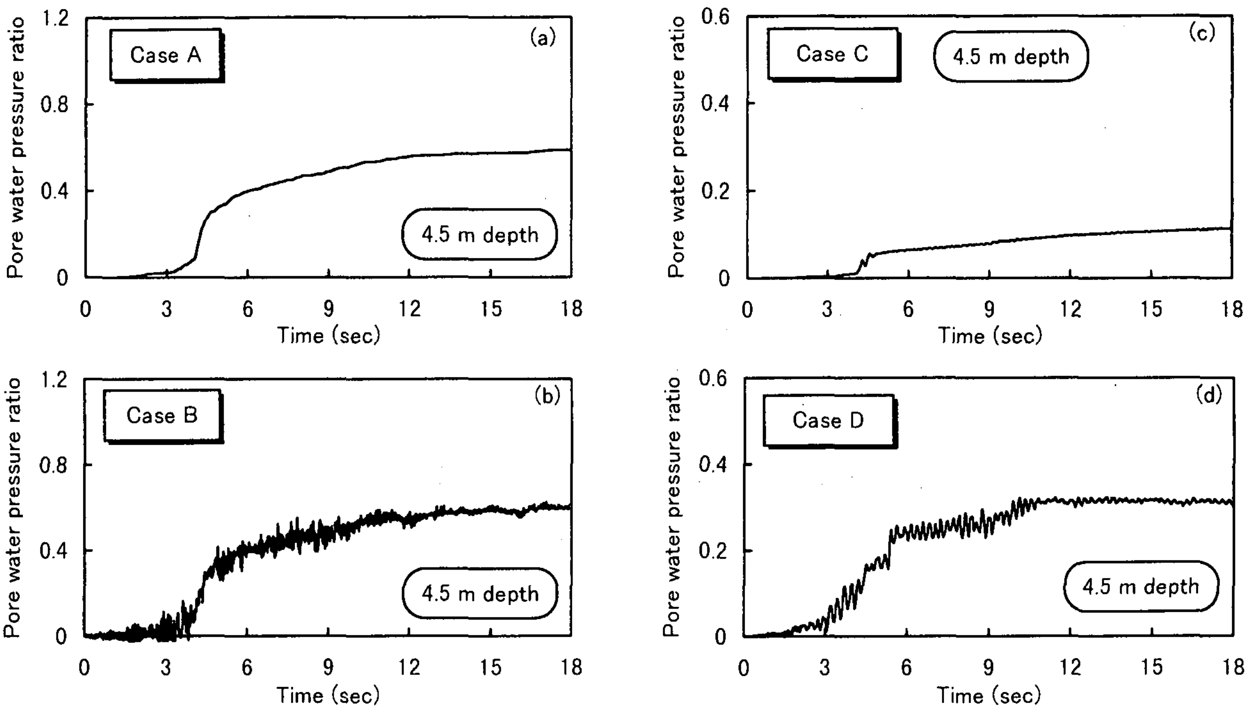

Fig. 7 Pore pressure response at 4.5m depth in different cases

liquefaction. Since this observation implies that the common understanding that the effect of vertical motion is negligible on site liquefaction may not always hold true, a mechanism is desirable to explain this new finding.

It is considered that the vertical motion may be mainly related to compressional waves. In the free-field condition, the horizontal stress σ_{dh} and the vertical stress σ_{dv} in a soil element induced by the propagation of compressional waves are related by

$$\sigma_{dh} = \frac{\nu}{1-\nu}\sigma_{dv} \qquad (1)$$

where ν is the Poisson's ratio of soil. When the soil is fully saturated, ν is close to 0.5 and therefore the deviatoric stress $(\sigma_{dv} - \sigma_{dh})$ induced by compressional waves is almost equal to zero. As a consequence, the inclusion of vertical motion has a minor affect on the development of liquefaction. However, when the soil is not fully saturated, its Poisson's ratio may be significantly lower than 0.5, as discussed by Yang and Sato [1]. Fig. 8 shows the effect of degree of saturation on the Poisson's ratio for the sand at the depth of 4.5 m. Since the Poisson's ratio at partial saturation conditions is below 0.5, a deviatoric stress can be induced and hence make a contribution to the development of liquefaction.

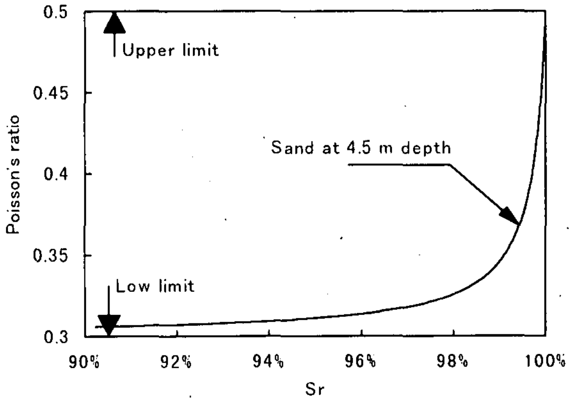

Fig. 8 Effect of partial saturation on Poisson's ratio

(3) Effect of saturation on ground motion

The ground motions in both horizontal and vertical directions at the surface are shown in Fig. 9 for the case of full saturation (Case B). The corresponding results for the case of partial saturation (Case D) are shown in Fig. 10. It is found that the influence of partial saturation is significant on the vertical motion. When the sand is not fully saturated, a much greater amplification takes place in the vertical motion, accompanied by a period lengthening. This is mainly because that partial saturation may reduce the velocity of compressional waves, as well demonstrated by Yang and Sato [1), 7)].

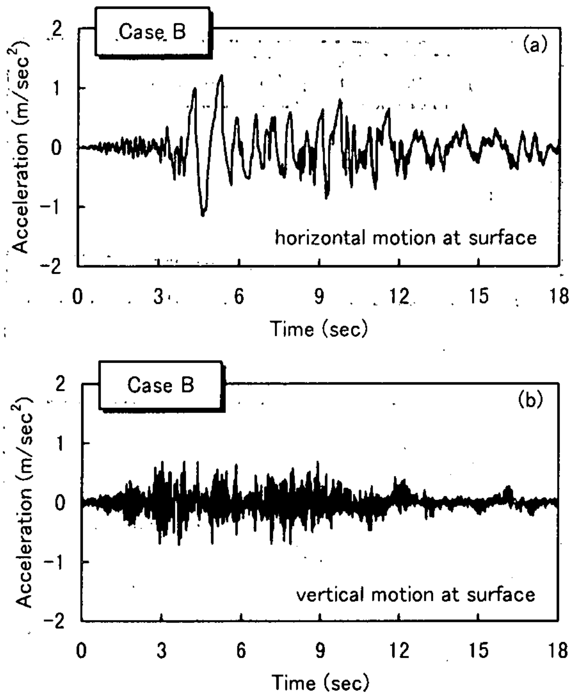

Fig. 9 Acceleration time histories at ground surface in Case B

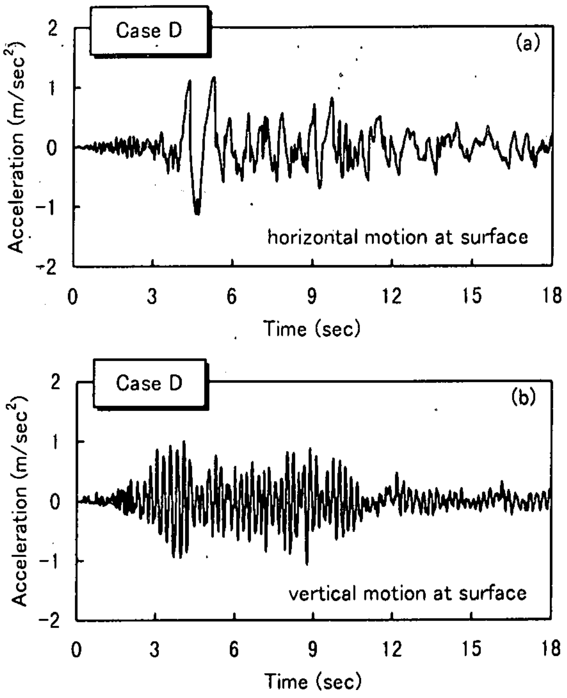

Fig. 10 Acceleration time histories at ground surface in Case D

As for the horizontal ground motion, the influence of saturation is relatively small.

4. CONCLUSIONS

Based on a series of numerical tests, this paper has presented some interesting results of the effects of partial saturation on earthquake ground response, which can be summarized as follows:

(1)A decrease of full saturation of subsoil may cause a lower level of shear strain and pore pressure when the deposit is subjected to the horizontal input motion only. However, when the vertical motion acts simultaneously, this effect may be reduced.

(2)The inclusion of vertical motion has a minor affect on soil liquefaction if the soil is fully saturated. But when the soil is not fully saturated, the inclusion of vertical motion may have a significant affect on the development of liquefaction. One possible mechanism is that the propagation of vertical motion may induce a deviator stress rather than only a pure compression in the full saturation condition.

(3)The effect of saturation is substantial on the volumetric strain in either the case of horizontal shaking only or the case of combination of horizontal and vertical motions. A decrease of full saturation may cause a larger volumetric strain. This is mainly due to the increase in the compressibility of pore fluid.

(4)At partial saturation conditions the vertical ground motion can be amplified more greatly than at full saturation conditions.

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