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EXPERIMENTAL STUDY ON EFFECT OF VERTICAL GROUND MOTIONS UPON GROUND AMPLIFICATION AND DAMAGE TO LIFELINES IN LIQUEFIED AREA

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ABSTRACT

To observe the effects of vertical ground motions on liquefaction of saturated sand layers and buried pipelines during earthquakes, a series of tests have been performed on saturated sand stratum and buried pipelines by means of 2-D shaking table. It is shown that a added vertical shaking does promote the rise of excess pore water pressure and the settlement of ground. The dynamic strains of buried pipelines are also affected by the added vertical shaking. It is suggested that the vertical ground motions should be considered in design criteria.

KEYWORDS

Vertical ground motion; liquefaction; pipeline; shaking table; small scale test.

INTRODUCTION

The 1995 Hyogoken Nambu earthquake has produced strong motions where the vertical accelerations have been greater than the other two orthogonal horizontal acceleration components in liquefied area. A large-scale liquefaction of ground occurred in Kobe city and it caused a great deal of damages to buried pipelines. Therefore , it is necessary, for design purposes, to understand how vertical ground motions affect the extent of liquefaction of saturated ground and damage to buried pipelines by means of experimental methods. Kawakami *et al.* (1965) measured the change of excess pore water pressure by making a cylindrical sand box drop freely from a certain height. Goto *et al.* (1976) used a horizontal shaking table and a vertical vibration generator to investigate the liquefaction and the settlement of the structural foundation under two directional shaking. Such studies have shown that the vertical shaking may cause the rise of excess pore water pressure though their conclusions were limited by their imperfect equipments. To estimate the effects of strong vertical ground motions on ground amplification and damages to buried pipelines in liquefied ground, a shaking table which can simultaneously shake in horizontal and vertical directions is used in this paper. The experimental results indicate that a added vertical shaking can promote the rise of excess pore water pressure and result in liquefaction of saturated sand ground. It is interesting that the added propagation of p-wave can change the amplification of propagation of s-wave. It is also found that the dynamic strains of buried pipelines are affected by the added vertical shaking.

EXPERIMENTS ON LIQUEFACTION AND SETTLEMENTS OF GROUND

Test Apparatus and Test Method

The sand used in the tests was easy to liquefy under shaking. Fig.1 shows the grain size accumulation curve of the sand. A saturated sand stratum with being 2000 mm in length, 900 mm in width and 420 mm in depth was made in sand box by water-pouring method as shown in Fig.2. Two water pressure meters were established in the centre of sand box in the positions of 120 mm and 320 mm, respectively, from the surface of ground. In order to measure input accelerations in both horizontal and vertical directions, two accelerometers were established under the shaking table (maximum weight 2,000 kgf, maximum acceleration 2 G). Another two accelerometers, which were waterproofed, were embedded in the position of 120 mm from the surface of model ground to measure the response accelerations in both horizontal and vertical directions.

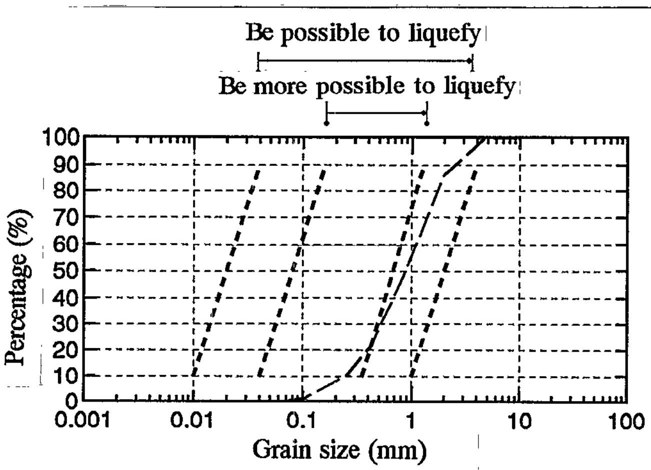

Fig.1. Grain size accumulation curve of sand

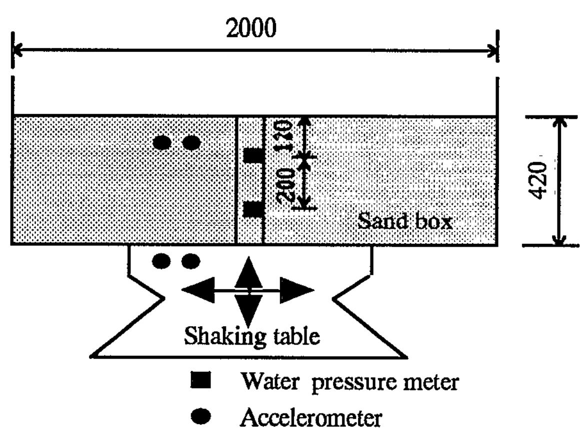

Fig.2. Experimental equipment for saturated sand ground

Both horizontal and vertical input waves were sinusoidal waves and their frequencies were fixed in 10 Hz which corresponded to predominant shaking of sand box and sand stratum. The shaking time during each case of test was 4 seconds. Following items were measured in the tests. 1) Horizontal and vertical input accelerations; 2) Horizontal and vertical response accelerations in model ground; 4) Excess pore water pressures in the positions of 12 cm and 32 cm from the surface of model ground; 5) Model ground settlements after shaking.

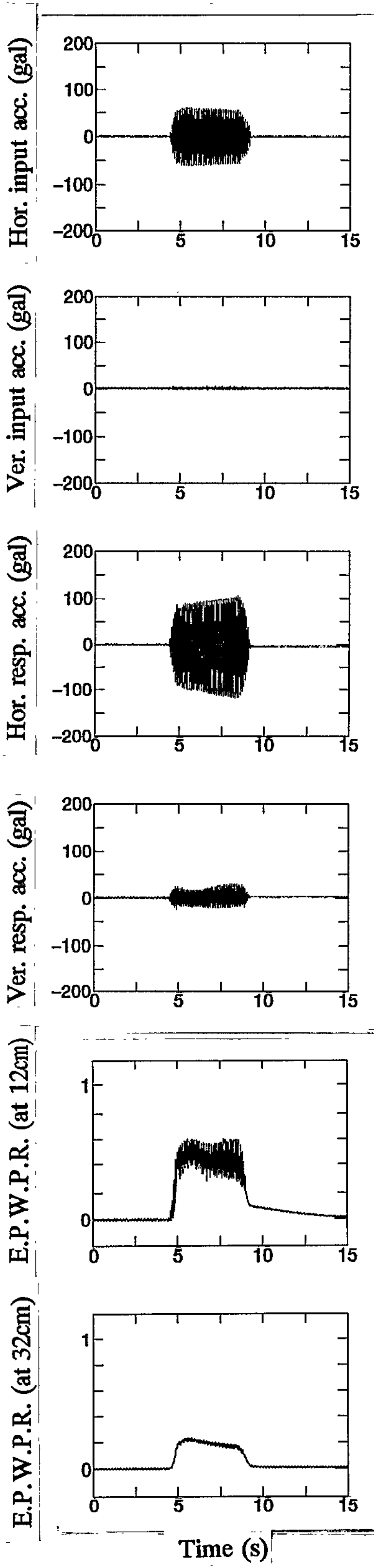

Fig.3. Horizontal shaking only (60 gal)

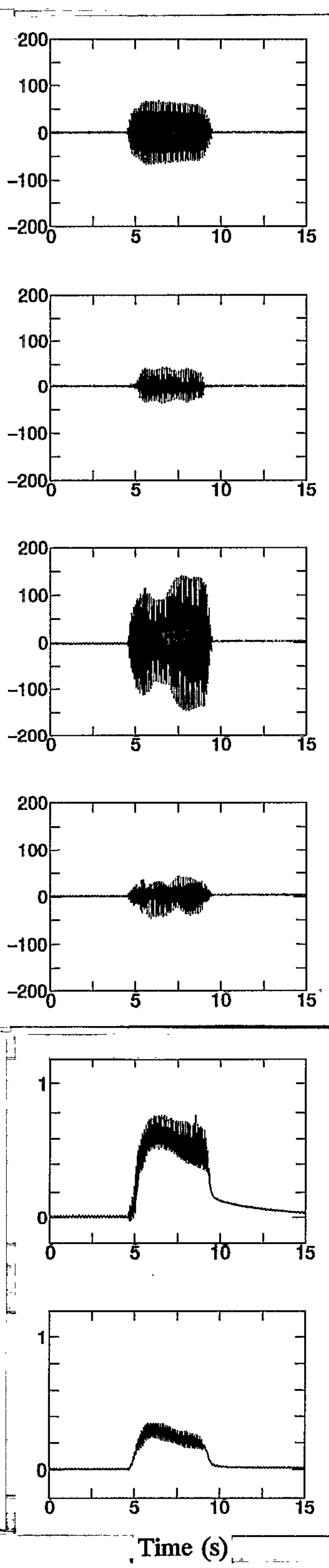

Fig.4. Two directional shaking (Hor. 60 gal + ver. 40 gal)

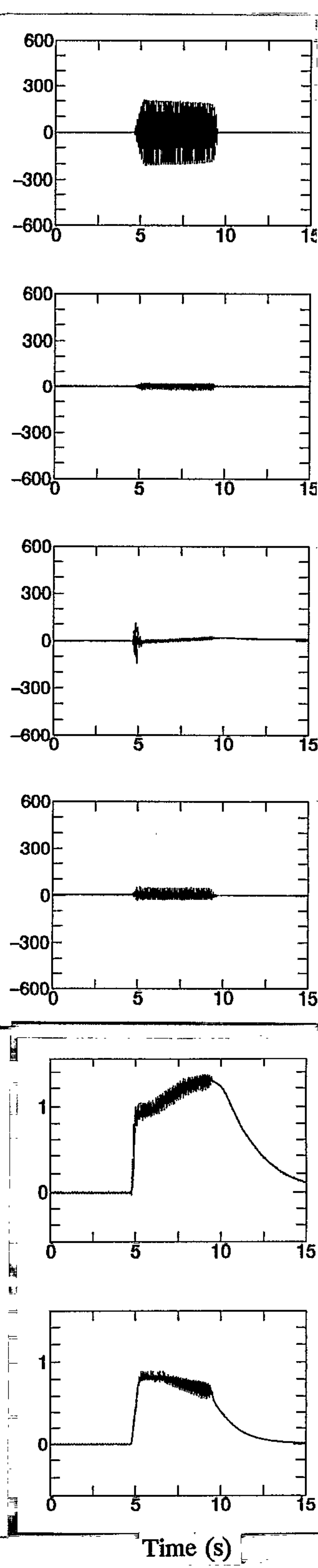

Fig.5. Horizontal shaking only (200 gal)

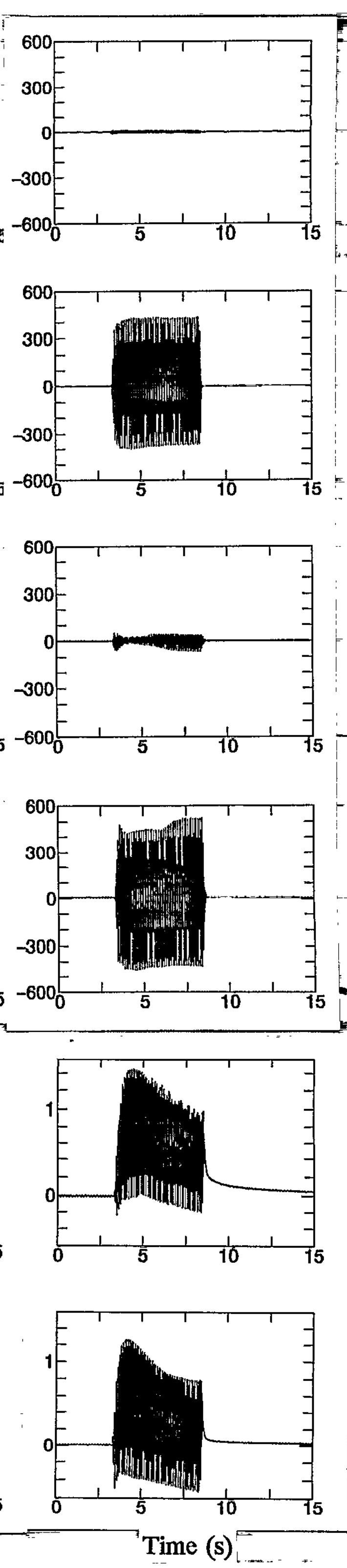

Fig.6. Vertical shaking only (400 gal)

Test Results and Observations

Figs.3~6 show the input accelerations, response accelerations, excess pore water pressure varying with the shaking time. Fig.3 and Fig.5 are the cases that input accelerations are only horizontal accelerations of 60 gal and 200 gal, respectively. In the case shown in Fig.3, the excess pore water pressure ratio (at 12 cm) reached about 0.5, the model ground had not been completely liquefied. It can be found that the response acceleration, that is, the shear wave amplified in the ground without any damping. Meanwhile, as shown in Fig.4, when a vertical acceleration of 40 gal was added to the case shown in Fig.3, the excess pore water pressure ratio (at 12 cm) was promoted to 0.7. In this case the propagation of *s*-wave behaved differently in time-history: firstly, it was more amplified as the excess pore water pressure rose; secondly, it was dampened; then, it was much more amplified as excess pore water pressure dissipated. Fig.5 shows the case that only horizontal acceleration of 200 gal was as the input shaking. In this case the sand stratum was completely liquefied. It is found from Fig.5 that shear wave could not propagate in completely liquefied ground. Fig.6 is the case that only vertical acceleration 400 gal was as the input shaking. It indicates that a only vertical shaking could also cause the rise of excess pore water pressure in saturated sand ground. Being different from that caused by horizontal shaking, the excess pore water pressure cyclically increases and decreases intensely during the dissipation, and even in liquefied ground *p*-wave was able to propagate and be amplified.

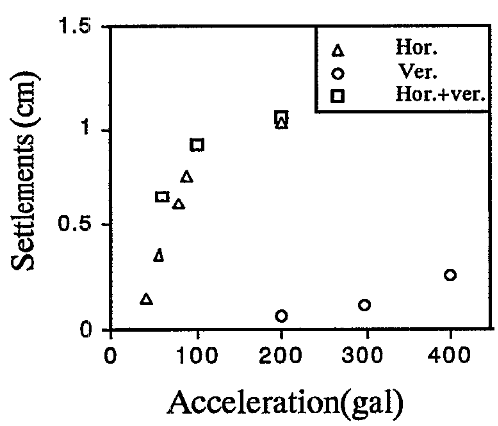

Fig.7. Ground settlements under hor., ver., hor.+ver. shaking

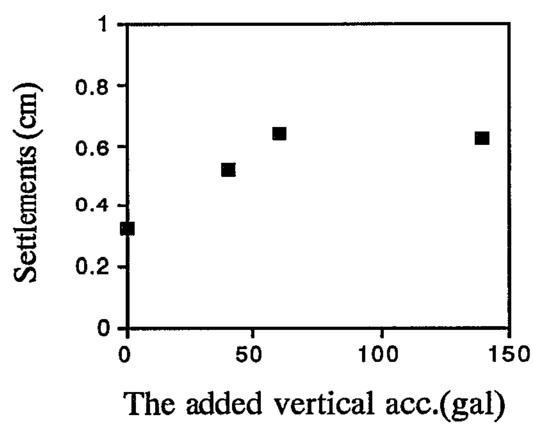

Fig.8. Ground settlements under two directional shaking (Hor. acc. is fixed to 60gal)

Figs.7~8 show the settlements of ground in various cases. Fig.7 indicates the relations between settlements of ground and input accelerations in the cases of only horizontal shaking, only vertical shaking and two directional shaking. The settlements of ground increased while input accelerations increased for all cases. The settlement caused by horizontal shaking was much bigger than that caused by vertical shaking, but two directional shaking caused it the biggest.

EXPERIMENTS ON BURIED PIPELINE RESPONSE IN LIQUEFACTION PROCESS

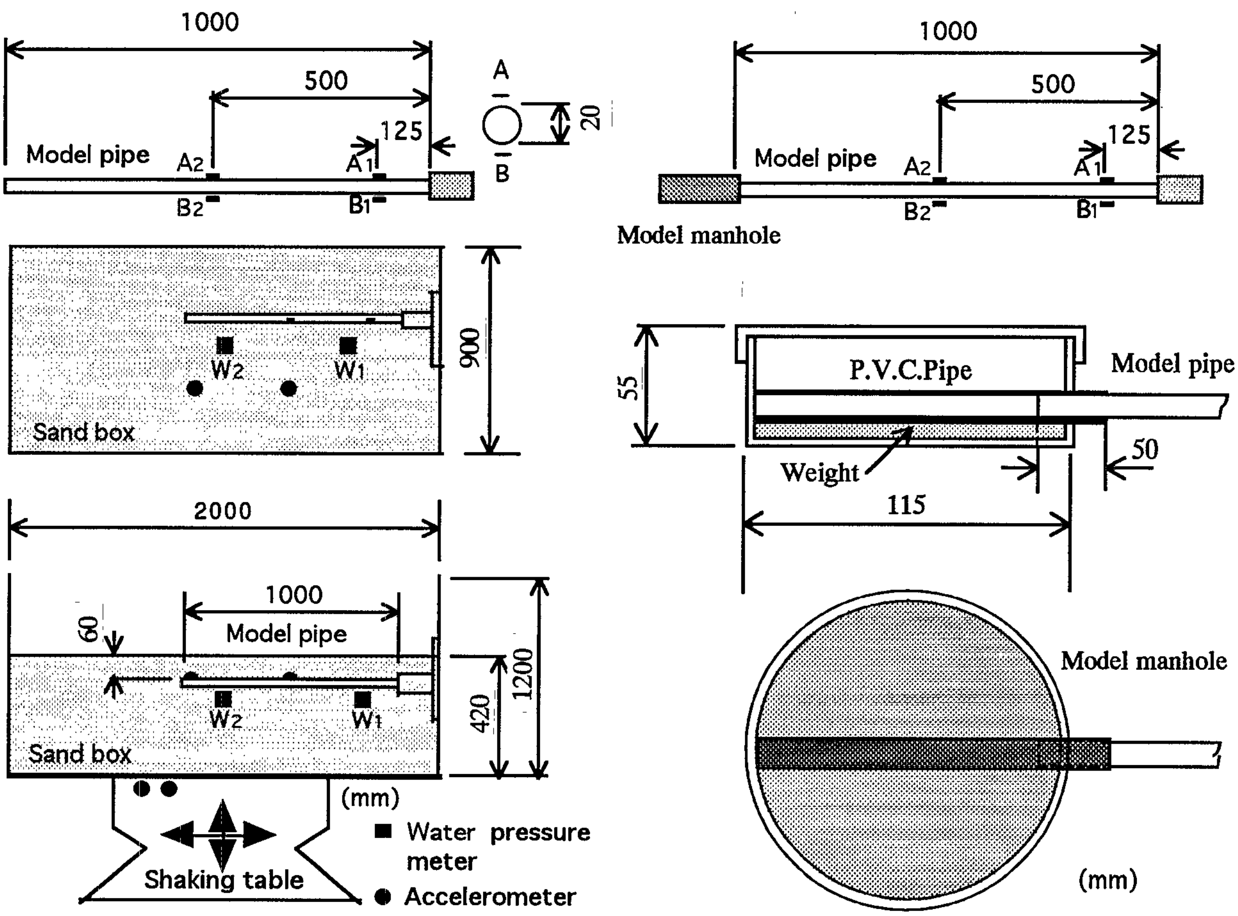

Fig.9. A general view of experimental equipments for pipeline buried in saturated sand ground

Test Procedure

A general view of experimental apparatus is shown in Fig.9. The model saturated sand stratum was as same as mentioned above. The model pipe was simulated by a rubber rod with 20 mm in diameter and 1000 mm in length. Its elastic modulus was 79.4 Mpa and its weigh per unit volume was 11.2 KN/m^3. The strain gauges and accelerometers were waterproofed. Two accelerometers and two water pressure meters were embedded at the same depth as that of the model pipe in sand stratum and another accelerometer was installed on the manhole. The pipe was buried into the model sand stratum in two conditions. The first condition was that one end of model pipe was fixed to sand box and the other end was free, the second condition was that one end of model pipe was fixed to sand box and the other end was connected with the manhole as shown in Fig.9. The strain gauges were utilized on the upper and lower sides at the center and 125 mm from the fixed end of the pipe. The upper and lower strain gauges were named as A and B. Suffix 1 and 2 indicate the end and center of the model pipe, respectively. Both horizontal and vertical input waves were sinusoidal waves and their frequencies were 3 Hz, 5 Hz and 10 Hz. The shaking time during each case of test was 20 seconds.

Characteristics of Response Strain

Records of excess pore water pressure and pipe strains of 10 Hz excitations in the first condition and 3 Hz excitations in the second condition are shown in Figs.10 and 11, respectively. The input accelerations in the first condition were horizontal 200 gal, horizontal 200 gal and vertical 200 gal, respectively. The input accelerations in the second condition were horizontal 200 gal, horizontal 200 gal and vertical 100 gal, respectively. The vibration and accumulated residual strains of pipeline introduced here are defined as the vibration strain amplitude and the drift of the neutral axis in the strain record due to pipe bending. The tensile strain is positive and the compressive strain is negative. It can be seen from Fig.10 that the vibration strains, in both only horizontal shaking and two directional shaking conditions, took peak values as the excess pore water pressure rose and fell. These agreed to the results of other frequencies. There was no notable difference of vibration strains between one and two directional shaking because the model pipe was so soft and its section was so small that the propagation of added vertical shaking could not obviously affected its vibration. Nevertheless, as seen from the accumulated residual strains shown in Fig.10, the added vertical shaking caused a different behavior of bending deformations of the model pipeline. A tensile accumulated residual strain occurred at A_1 under two directional shaking condition was greater and maintained longer time than that under only horizontal shaking condition, but the eventual compressive accumulated residual strain at A_1 was smaller under two directional shaking condition than that under only horizontal shaking. At A_2 the pipe bending deformations under only horizontal shaking were in three stages: firstly, the accumulated residual strains were tensile in the shaking of nearly 8 seconds, then became compressive, at last remained tensile. Meanwhile, the accumulated residual strains under two directional shaking were compressive almost in the whole shaking time. It is thought that the added vertical shaking which promoted the excess pore water pressures as can be seen in Fig.10 led to a bigger and faster buoyancy and hastened the consolidation of sand stratum so that the bending deformations at A_1, A_2 were different from those under only horizontal shaking.

Fig.11 shows the case that a model manhole was connected with the free end of model pipe. Input accelerations were 200 gal under only horizontal shaking condition, horizontal 200 gal and vertical 100 gal under two directional shaking condition, respectively. As observed above, the added vertical shaking led to the effects on pipe response strains as similar as the case shown in Fig.10. The velocity of float of manhole under two directional shaking was a little more quickly than that under only horizontal shaking. It was found in the experiments that the shallow-buried manhole was hastened to float out under both shaking conditions. In comparison with those under only horizontal shaking the greater tensile and smaller compressive accumulated residual strains occurred at A_1 under two directional shaking were considered to be due to the more intense excess pore water pressure and greater settlement of sand stratum. As to those occurred at A_2, the greater buoyancy under two directional shaking led to the end of pipe with which the manhole was connected to float more quickly. It resulted in, therefore, the greater compressive strains at A_2 remaining nearly for seven seconds. Then, the dead weight of manhole which floated out caused the smaller tensile strains at A_2 as can seen in Fig.11.

CONCLUSIONS

This paper has presented some experimental studies on the effects of vertical ground motions on liquefaction, settlements of saturated sand ground and the characteristics of strains of pipelines buried in saturated sand ground. From the results of experiments, the following conclusions have been derived.

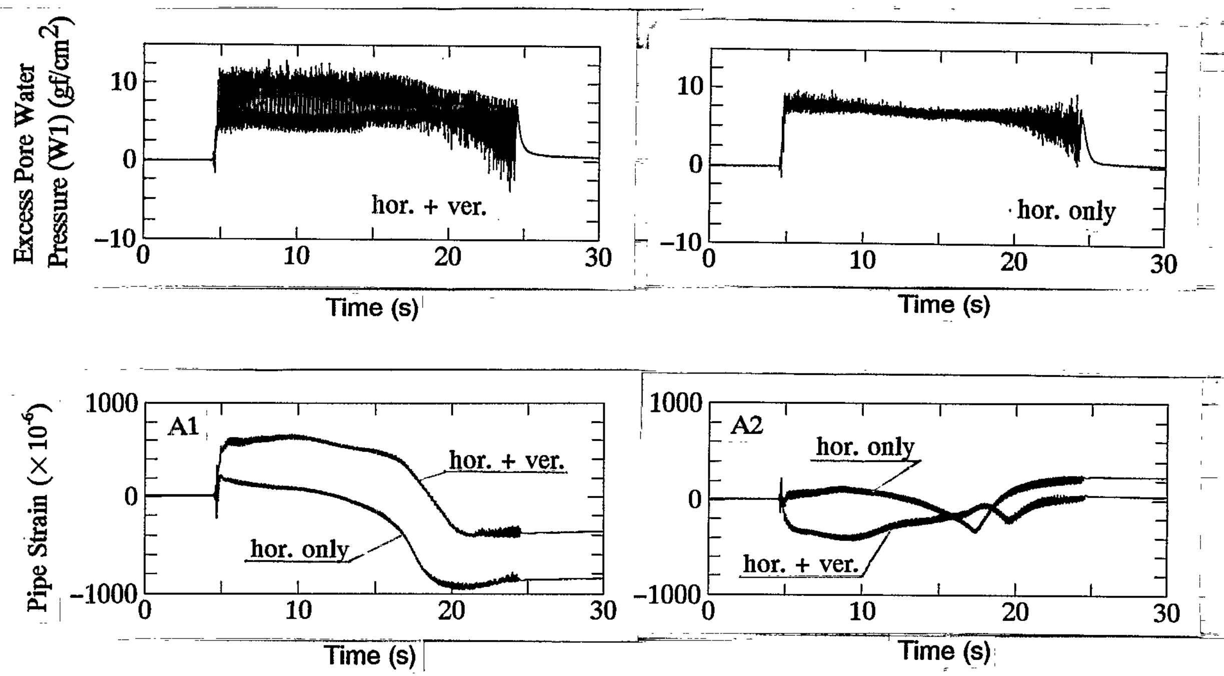

Fig.10. Time-hostories of excess pore water pressures and pipe strains under horizontal and two directional shaking. (one-end-fix and one-end-free)

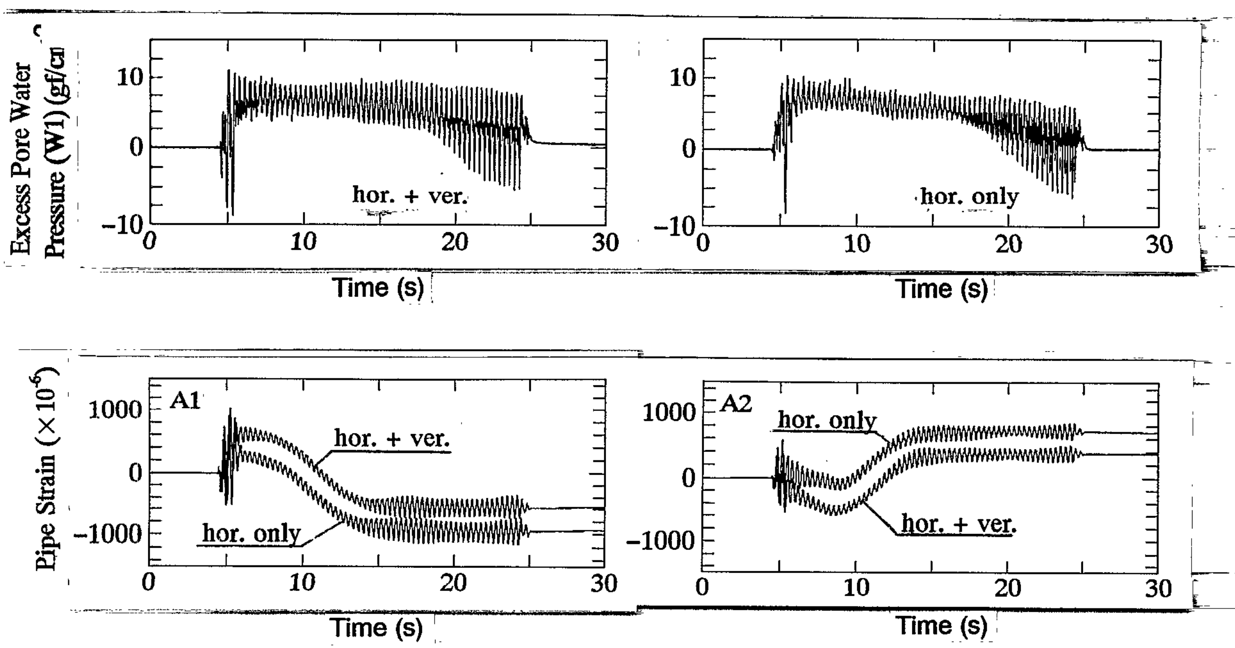

Fig.11. Time-hostories of excess pore water pressures and pipe strains under horizontal and two directional shaking. (one-end-fix and one-end-manhole)

1) When vertical ground motion is added to horizontal ground motion, it can promote the rise of excess pore water pressure and lead to liquefaction of saturated sand ground.
2) Vertical ground motion only can also result in the rise of excess pore water pressure, but it cyclically increases and decreases intensely during the dissipation.
3) *S*-wave does not propagate, but *p*-wave propagates and is amplified in completely liquefied ground.
4) The settlements caused by horizontal shaking are much greater than those caused by vertical shaking, but two directional shaking causes greater settlements of ground than those caused by horizontal shaking only.
5) The effects of a added vertical shaking on pipelines buried in saturated sand stratum were observed to due to, mainly, the stronger excess pore water pressure and greater settlements of ground. The propagation of *p*-wave in saturated ground seemed not to be a main factor to affect the actions of pipelines in the experiments.

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