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EXCESSIVE VERTICAL FORCE EXERTED ON BURIED PIPE DUE TO LIQUEFACTION SETTLEMENT OF GROUND

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SUMMARY

This paper deals with the development of an air-lifted shaking table test apparatus that is to be used to carry out a small 1-g model experiment of liquefied ground and also presents a study on the buried pipe behavior in liquefied ground. The reliability of model test using the air-lifted shaking table apparatus was first examined by performing the liquefaction strength test of silica sand with the apparatus and the simple shear box filled with saturated silica sand was shaken under sinusoidal force. Then, an experiment of buried pipe in the liquefied ground was performed to study the force acting on the pipe joint at fixed end that examines the design problem of buried pipe joint to a stationary foundation structure.

INTRODUCTION

During the 1995 Kobe Earthquake, there were extensive damages on the lifeline facilities, such as buried pipelines of water and gas. The cause of damages are partly due to the very strong ground vibration during the earthquake, but also the liquefaction of ground is thought to have played a significant role in causing damages especially on those facilities located along the coast line of the Osaka Bay where loose deposits of Holocene Sand are frequently found. After the earthquake, various researches have been made on the design methods for buried pipe damages, and the use of aseismic joint, such as flexible joints, for buried pipes was promoted by Japan Water Works Association, (JWWA (1997)). Although the use of aseismic joints is promoted, the design method for such joint has not yet well established. In the view of such state of buried pipe joint designs, the authors have examined the performance of the buried pipe with flexible joint, Tanaka et al. (2000) & (2002). Although our previous works have shown some aspects of buried pipe behavior in the liquefied ground, there is still a strong need for examining the pipe and joint performances in liquefied ground under various seismic loading conditions.
For such complicated liquefaction problems involving both the liquefied soil and the buried structure as pipelines, it is most important to understand how the liquefied ground behaves

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and/or how it interacts with the structures that resist against the flowing ground. Here model experiments of ground and structure play an important role for grasping the real mode of ground behaviors and the interaction between the liquefied ground and the structure. To carry out such model experiments, it is the first consideration to select the size of experimental set-up. The larger the scale of the model becomes, the better the results of simulation results would be obtained. However, the cost of the experimental set-up and the cost of performing the experiment increase drastically with the increase of the model scale.
In order to perform the model experiment of ground liquefaction within a reasonable cost, an air-lifted shaking table was devised by eliminating costly oil-servo mechanism for shaking the table with heavy load of experiment model. This paper describes the experiments carried out to examine the performance of developed shaking table test apparatus. One of the experiments was to compare the liquefaction strength of soil as determined from the shaking table test with that obtained from the laboratory soil element tests. The other was to examine the behavior of buried pipe in the liquefied ground.

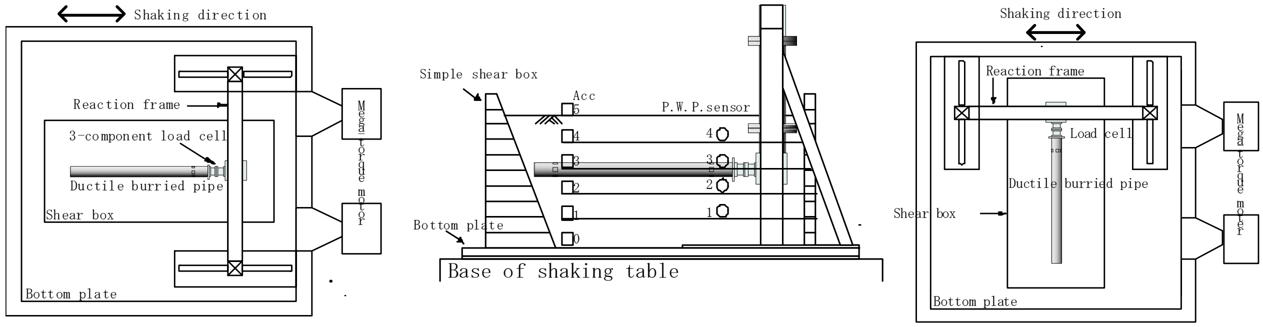
EXPERIMENTAL SET-UP OF SHAKING TABLE TEST APPARATUS

Shaking Table

Figure 1 shows the outline of shaking table test apparatus that is set-up for performing a model test on buried pipe in the ground. The base of shaking table which is constructed by a reinforced concrete has a size of 2m x 2m. The top of the base surface is covered by a stainless steel plate placed on framed steel members. Numerous air holes are provided on the surface plate that provides a lifting force to the shaking table in the form of pressurized air, and the pressurized air is carried through the framed steel below the surface plate. Maximum air pressure of 200kPa can be provided to lift the weight on the shaking table. The horizontal shaking force to the table is provided by two mega-torque motors, and the rotational force of the motor is converted into horizontal movement by using a screw gear. The motor movements are controlled by electric signals provided from a desktop computer.
The base plate of shaking table has a size of 2m x 2m and it is made of hollow structured steel plate of 30mm thick. On the top of base plate, a simple shear box with 150cm x 70cm x 70cm size was placed. The simple shear box consists of 10 laminated aluminum frames of 70mm thick, and between each frame, linear motion bearing plates are placed to provide the smooth movements. Fig.1 shows the experimental set-up for carrying out a buried pipeline test for which a reaction frame is placed on the base plate of shaking table so that a model buried pipe can be attached to the reaction frame.

Test Soil and Model Ground

Within the shear box, a rubber sheet is placed to keep water tightness of saturated model ground. Silica sand which is commercially available was used, and No.6 and 7 of Silica sand was mixed with equal weight to produce the test soil. Maximum grain size is 2 mm, and the average grain size of 0.21mm with specific gravity of 2.64. The model ground was constructed by pulverizing the sand into water, and the relative density of soil thus produced was about 50%.
In the model ground, accelerometers and pore water pressure sensors were placed and the location of these sensors are shown in Fig.1. The shaking of ground was controlled by adjusting the motor rotational speed, and usually sinusoidal wave of 1Hz in frequency was given for 30 seconds.



(a)Shaking table test in the direction of pipe alignment

(b)The location of accelerometers and pore water pressure sensors

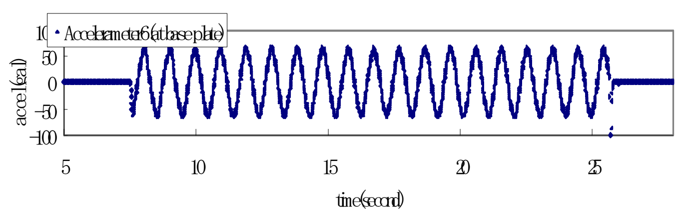
(c)Shaking table test in the direction normal to the pipe alignment

Fig.1 Shaking table test apparatus

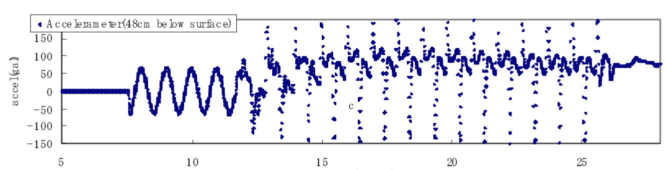
LIQUEFACTION STRENGTH TEST

Outline of Test Results

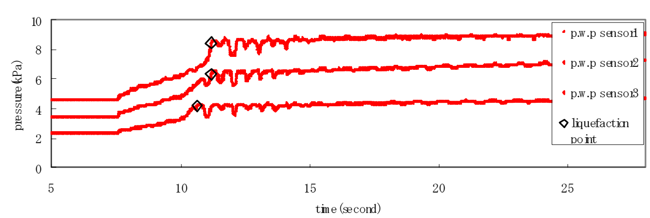
Three model tests were performed to examine the performance of shaking table test apparatus by examining the liquefaction strength as determined from the shaking table test. Figs.2 (a)(b)(c)presents a typical of measurements taken from the experiment and the response of shaking table, the ground response, and the pore pressure developments in the ground respectively. The acceleration record at base place (Fig.2 (a)) shows about 65gal of input motion, and the ground response at 12cm above the base plate is shown in Fig. 2(b). After 5 cycles of shaking, the ground response becomes very scattered that indicates the liquefaction of ground causing the accelerometer dislocations. The start of liquefaction in model ground is clearly depicted by the pore pressure measurements, and



(a) Input motion at the base plate



(b) Ground response at 12cm above the base plate



(c) Pore water pressures at 3 depths

Fig.2 Example of measurements during the liquefaction strength test all three sensors indicate the complete liquefaction after 5 cycles of shaking.

Analysis of Test Results

Acceleration records at 6 depths in the ground were used to compute the ground displacements at these elevations, and then the shear stress and the shear strain were computed based on these records. For each soil layers between the measurement points, an average shear stress, τ, and shear strain, γ, at mid-height of each layer was computed using the following equations;

$$\tau = \sum_{i=0}^{4} \left(\frac{\frac{\rho_{sat}\alpha_i}{10} + \frac{\rho_{sat}\alpha_{i+1}}{10}}{2} \right)(h_{i+1} - h_i) \qquad \gamma = \frac{\delta_4 - \delta_0}{h_4}$$

Where δ : displacements, α : accelerations, h: elevations of measuring points ρ_{sat}: saturated density of soil. It may be noted that in computing the displacement from the acceleration record, it is necessary to apply the base line correction, and 3rd order polynomial was used for the correction.

From computed shear stresses and shear strains at various stages of shaking cycles, the stress-strain relations in the ground can be depicted, as shown in Fig.3. From such stress-strain loop, the shear modulus, G, can be obtained for a given level of shear strain, γ. Fig. 4 presents the relationship between G and γ, and it can be seen that a unique curve of G vs. γ can be defined for all data of three different tests.

As to the liquefaction strength of soil, Fig. 5 presents the strength obtained from three experiments that is compared with the laboratory determined liquefaction strength curve. The laboratory tests involves a small size tortional hollow cylinder test with specimen size of 60mm & 100mm in inner and outer diameters respectively, and also a large hollow cylinder test with specimen size of 300mm & 500mm in inner and outer diameters respectively. The confining pressures used for these tests were 400kPa and 100kPa for the small and the large hollow cylinder tests, respectively. The comparison of the strength shows that the results from the shaking table test are higher than those from the

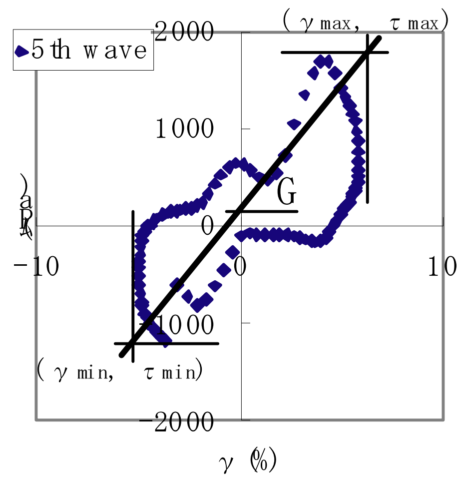


Fig.3 Shear stress and stress-strain relationship

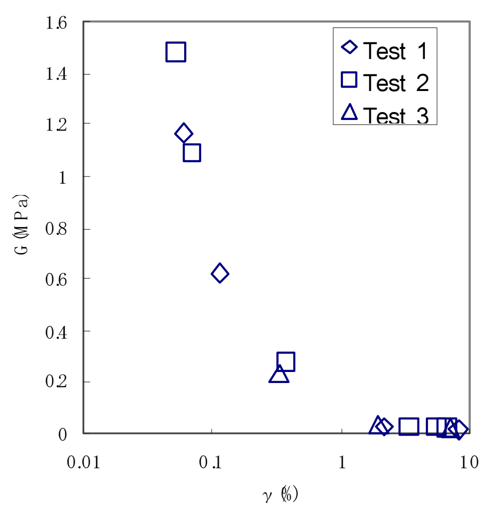


Fig.4 G vs. γ curve based on shaking table test

laboratory tests, but the difference is consistent. The difference of strength seems to be due to the different confining stress states used for the shaking table test and the laboratory tests. Tastuoka & Kozeki (1986) report that the liquefaction strength is higher under low confining stress based on their laboratory test results. Therefore the difference of the strength as shown in Fig.4 is probably due to the difference of confining pressure between the shaking table test and the laboratory tests.

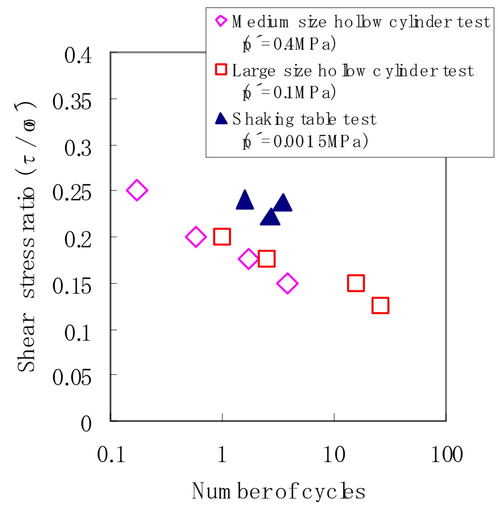


Fig.5 Liquefaction strength curve from the experiments

The effective stress path of model ground is depicted in Fig.6 that is produced by using the computed values of the shear stress and the effective vertical stress at each measurement points. It is clearly seen that the stress path is a typical of soil exhibiting the liquefaction.

Based on these test results as shown above, it can be concluded that the results of shaking table test is very satisfactory, and this apparatus can be used to model other type of liquefaction problems.

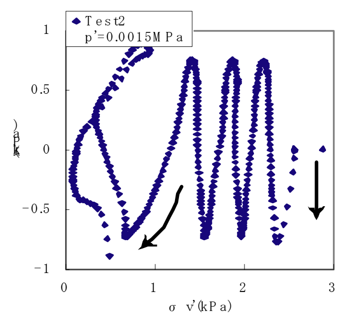


Fig.6 The effective stress path based on shaking table test

MODEL TEST ON BURIED PIPE IN LIQUEFIED GROUND

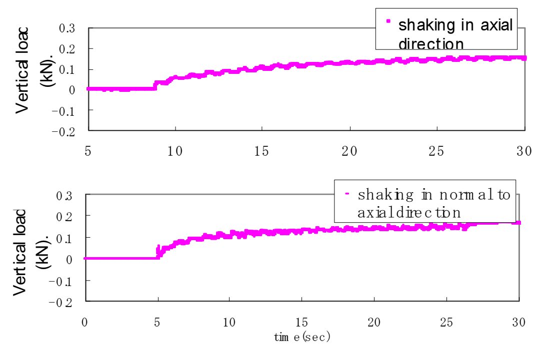
There were severe pipe damages due to the liquefaction of ground during the Great Hanshin Earthquake. The use of aseimic pipe joint is being promoted to increase the safety of buried pipeline against ground liquefaction. The design method of such aseismic pipe joint is however not yet well established, and therefore there is a strong need for understanding the difference of having standard joints and aseismic joints and to establish a proper design method for aseismic pipe joints.

A research using the air-lifted shaking table was initiated to investigate the behavior of buried pipe in liquefied ground with or without such aseismic joints, and, as a first stage of the investigation, the pipe without aseismic joints in liquefiable ground was studied by performing the model pipe test. The advantage of air-lifted shaking table is that the shaking of table is not limited in one direction as there is no mechanical connection between the base of shaking table and the base plate of the table. As can be seen from Figs.1 (a) & (c), the direction of shaking can be easily changed by rotating the shaking base plate by 90 degrees and changing the horizontal loading attachments to suitable location.

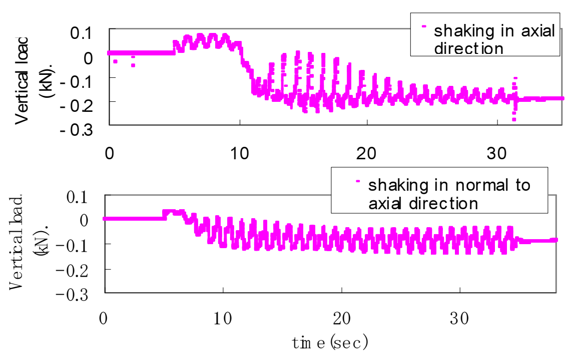
In the following, described is an example of shaking test on the model buried pipe of which one end is connected to a stationary reaction frame. This test arrangement simulates a situation of an underground pipe being connected a rigid structure that is fully resistant to liquefied ground movements. Such case would represent an extreme condition of constrains to the buried pipe, and thus the thrust force exerted on the pipe due to ground flow movement would be the maximum.

Experimental Set-up for Mode Pipe and Ground

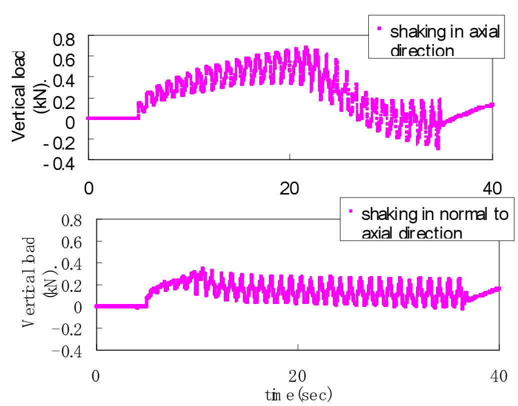
The model pipe used has an outside diameter of 60.5mm, and it is made of ductile steel. This model pipe was buried in the ground having the soil overburden depth of 22cm to the top of pipe while the total thickness of model ground was 60cm. Three different soil conditions were prepared for buried pipe; one was dry soil condition, second being completely saturated ground, and third was unsaturated ground in which the water level was kept 34 cm below the ground surface (i.e., about 10cm below the pipe center). The preparation of ground was the same as the case of liquefaction strength test and the relative density of soil was set to be 50%. The shaking of the pipe and ground was made twice for the each soil condition to ensure the repeatability of result, and the shaking was made in two different directions (i.e., one being along the axial direction of pipe, and the other direction in normal to the axial pipe direction). The instrumentations installed for the model test have been shown in Fig.1 (b). Measurements taken are the accelerations, pore water pressures, pipe stresses via strain gauges and vertical, axial, and horizontal thrust at the pipe end.



(a) Dry ground



(b) Saturated ground



(c) Partially saturated ground

Fig.7 Vertical loads at the fixed end of buried pipe

Test Results

The test results are shown in Figs. 7 (a), (b), (c) and Fig.8 for the vertical load at the pipe end, and the results of horizontal load are shown in Fig.9. Many other results of accelerations, and pore water pressures are not shown here although the measurements were successful. The purpose of presenting the pipe experiment data herein is to show that the shaking table test is useful in revealing how the buried pipe behaves in liquefied ground.

Vertical load at pipe end

As shown in Fig.7 (a), the vertical load for dry sand case show gradual increases with time as shaking progress. The magnitudes of vertical force measured were nearly the same irrespective of shaking direction. It can be argued that the increase of load would be due to gradual settlement of ground surrounding the pipe. The vertical load in case of saturated sand decreased as the shaking continues as shown in Fig.7 (b), and this decrease is thought to be caused by the increase of pore water pressure in the ground. This type of load changes was observed for the saturated ground irrespective of shaking direction. The negative value in load measurement indicates uplifting force acting at the end, and it matches with the calculated buoyancy force of the pipe in water. Although not shown here, the decreased vertical load during the shaking increased with time when the pore water pressure start to dissipate.Fig.7 (c) shows the measured vertical load in case of unsaturated sand, and the load initially increased slightly and then some decreases. After the shaking is terminated, the load starts to increase, and the increases of load after the shaking are shown in Fig.8. The trend of load changes with time was nearly the same irrespective of shaking directions. The slight decrease of the load is thought to be associated with the increase of pore water pressure similar to the saturated sand case. Since the pipe is not submerged, the vertical load for this case never becomes negative (uplift). Important observation among three ground condition would be that the vertical load at pipe end is largest in the case of unsaturated sand. Such large vertical load may be caused by the settlement of saturated zone beneath the pipe after the pore pressure dissipation, and more significantly the apparent cohesion in unsaturated zone has induced a large zone of soil cover over the pipe to exert vertical load on the pipe.

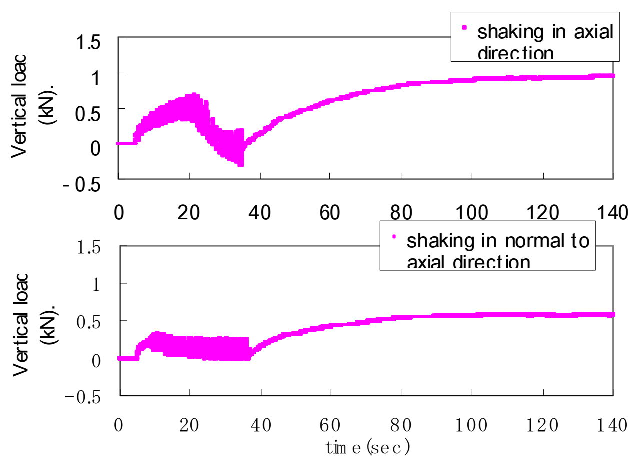


Fig.8 The long term change of vertical load at the fixed end of pipe

Horizontal Load

The horizontal load was measured only when the shaking was made in direction normal to the axial pipe direction. The horizontal loads in cases of saturated sand and unsaturated sand are shown in Fig.9, and it is to be noted that the input seismic motions between these two cases were different (i.e., 65gal for saturated sand, and 120gal for unsaturated sand) while the resulted horizontal loads were nearly the same. In order to understand the difference between the saturated and unsaturated sands, it seems useful to observe the pipe stress measurements as shown in Fig.10. Larger bending stress at fixed end is measured for the case of saturated sand, while smaller bending stress for the unsaturated sand case. These observations seem to indicate that for the case of saturated sand the liquefied ground exerted the flow type of pressure on the pipe. On the other hand, in the case of unsaturated sand, there may be some reaction resistance of soil in front of the pipe that has reduced the bending moment at the pipe end and also resulted in smaller horizontal load in comparison of larger input seismic motion.

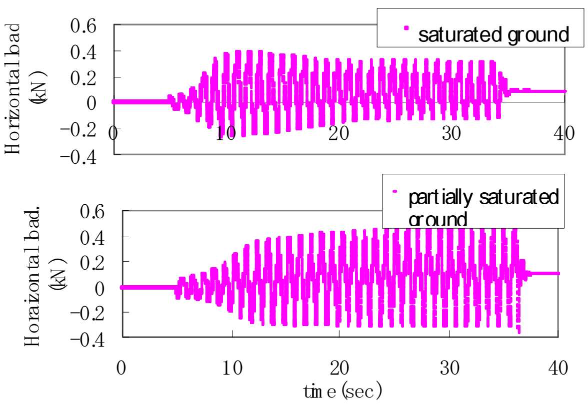


Fig.9 Horizontal loads at the fixed end of buried pipe

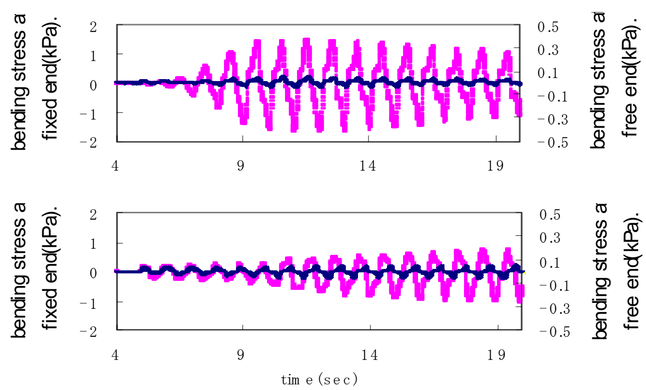


Fig.10 Measured pipe bending stresses

CONCLUSIONS

In this paper, the development of air-lifted shaking table has been described and its use for various ground liquefaction problems is discussed. Through the test results obtained herein, the following conclusions may be summarized.

1. Air-lifted shaking table test apparatus seems to perform well to simulate the ground shaking condition induced by earthquake and the consistency of liquefaction strengths obtained from the test supports the reliable performance of the shaking table test apparatus.
2. The liquefaction strength of sand as determined by the shaking table test yields slightly higher strength than those determined from laboratory testing. The strength difference seems to be due to the difference in confining stress, and in 1-g model testing of ground this aspect of strength difference should be considered.
3. The model test of buried pipe in liquefied ground yielded various interesting observations. When the pipe is buried in unsaturated zone above the liquefiable saturated sand, a large vertical load develops at the fix pipe end due to the settlement of liquefied sand beneath the pipe. The cause of such large vertical load seems to be the apparent cohesion of unsaturated sand above the pipe.

REFERENCES

Japan Water Works Association (1997): Earthquake Resistant Design Specification for Water Supply Facilities, (in Japanese)

Tanaka, Y., Kuruma, A., Asada, T. and Mizoguchi, Y. (2000): Dynamic Behavior of Buried Water Pipe With a Ball Type Flexible Joint in Liquefied Ground, Proc. ISOPE 2000, Vol.2, 381-385

Tanaka, Y., Kuruma, A., Asada, T. and Mizoguchi, Y. (2001): On the Forces Exerted On Buried Pipe in Liquefied Ground, Proc. ISOPE 2001, Vol.2, 160-165

Tatsuoka F., and Kozeki, J. (1986): Strength and Deformation Characteristics of Sand in Plane Strain Compression At Extremely Low Pressures, SOILS AND FOUNDATIONS, Vol. 26, No. 1, pp65-84