Paper No. 386. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

EFFECTS OF LIQUEFACTION-INDUCED LATERAL FLOW ON A CONDUIT WITH SUPPORTING PILES

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ABSTRACT

The present study discusses the soil force of liquefaction-induced lateral flow on a conduit-pile system. For this purpose, the model shake table test and the static load test were conducted. The soil force on the pile is possible to estimate utilizing a drag force, though some difficulties exist in design practice. Despite this, normalized lateral earth pressure intensity and soil force on the pile are found to be correlated in direct proportion. It is stressed that the correlation enables us to determine the soil force of lateral flow.

KEYWORDS

liquefaction; earthquake resistant design; conduit; pile; lateral flow; liquefaction measures; model shake table test; foundation; soil

INTRODUCTION

The objective of the present study is to develop a soil force estimation on a conduit with supporting piles which sustains liquefaction-induced lateral flow. Pile support measures have been widely used to prevent vertical instability of above- and in-ground structures arising from soil liquefaction such as subsidence or floating. However, the measures validation for liquefaction-induced lateral flow has no been fully discussed so far. This is mainly due to the fact that the performance of in-ground structures subject to lateral flow has been unsolved. Then the author conducted experimental works by the following manner : (1) a model shake table test and (2) static load test.

Efforts to practice the pile support measures for a conduit have been paid partly in transmission power cable works. Fujinami and Koyama (1980) and Hinata (1984) investigated that friction pile, sheet pile and soil cement were effective among other measures in economic and construction work view point. Kawamura *et al.* studied the effectiveness of measures for conduit floating based on model shake table tests and employed pile support and gravel drain in construction practice. Thus a conduit with supporting piles gives satisfactory results. Nevertheless further efforts are essential to extend the measures against liquefaction-induced lateral flow.

TESTS

Model Shake Table Test

The model shake table test demonstrated that an actual conduit-pile system would suffer lateral flow in its general cross section. A model conduit was supported by two model piles. The model conduit was assembled by acrylic boards of 3 cm in thickness and its dimension was 30 cm in width, 20 cm in height and 40 cm in depth. Thereafter the word model will be dropped for brief in the present paper unless confusion arises. A model saturated sand deposit with the declined ground surface with two percent in gradient was constructed in a steel box having 300 cm in width, 100 cm in height and 100 cm in depth. This was because a gentle decline was proved the most significant cause of lateral flow in a steel box. Gifu sand whose unifomity coefficient and maximum particle size were respectively 1.59 and 0.84 mm was used for constructing the model ground. The conduit-pile system was installed in the steel box and the pile end was fastened to the box base.

Three piles were designed so that their flexural stiffness satisfied the similitude rule developed by Iai (1989). On the basis of the similitude rule, a scale factor was determined as 20 and a proto-pile was presumed as 30 cm in outer diameter and 6 cm in thickness. In addition, proto-pile materials were considered to be reinforced concrete (RC) and steel. To construct the piles, aluminum and stainless pipes having 2.5 cm in outer diameter were used. By adjusting their thickness, realized flexural stiffness were obtained as listed in Table 1. In the present study, Case 1, Case 2 and Case 3 refer to 5.91e+05 kg·cm^2, 6.38e+05 kg·cm^2 and 2.13e+06 kg·cm^2 in flexural stiffness, respectively.

Table.1 Pile model profile (unit : kg·cm^2)

Case	Proto-Type	Idealized Model	Realized Model	Note
1	1.21E+10	3.38E+05	5.91E+05	RC Pile
2	—	—	6.38E+05	—
3	7.26E+10	2.03E+06	2.13E+06	Steel Pile

Figure 1 illustrates measured points arrangement. Measured items were; acceleration, pore water pressure and lateral flow in the model deposit, and acceleration, lateral earth pressure and shear force of the conduit, and bending strain of the pile. As far as time history measurement of the lateral flow measurement was concerned, a specific method was introduced in the present test. Target plates with the same apparent specific gravity as liquefied sand were buried in the subsoil as shown in Fig. 1, and the horizontal movement of the plates was recorded using a roller-type displacement meter. A excitation by a shaking table was sine wave whose frequency and duration were 10 Hz and 2.6 seconds, respectively. Maximum acceleration amplitude was set to about 400 Gal.

Static Load Test

The static load test examined the effect of horizontal subgrade reaction in pre- and post-liquefaction on the pile. Tension force throughout a steel wire was applied to the upper face of the conduit. The static test included two stages : (1) without surrounding sand and (2) with surrounding sand. Measurement of the applied force and strains provided for the pile bending moment.

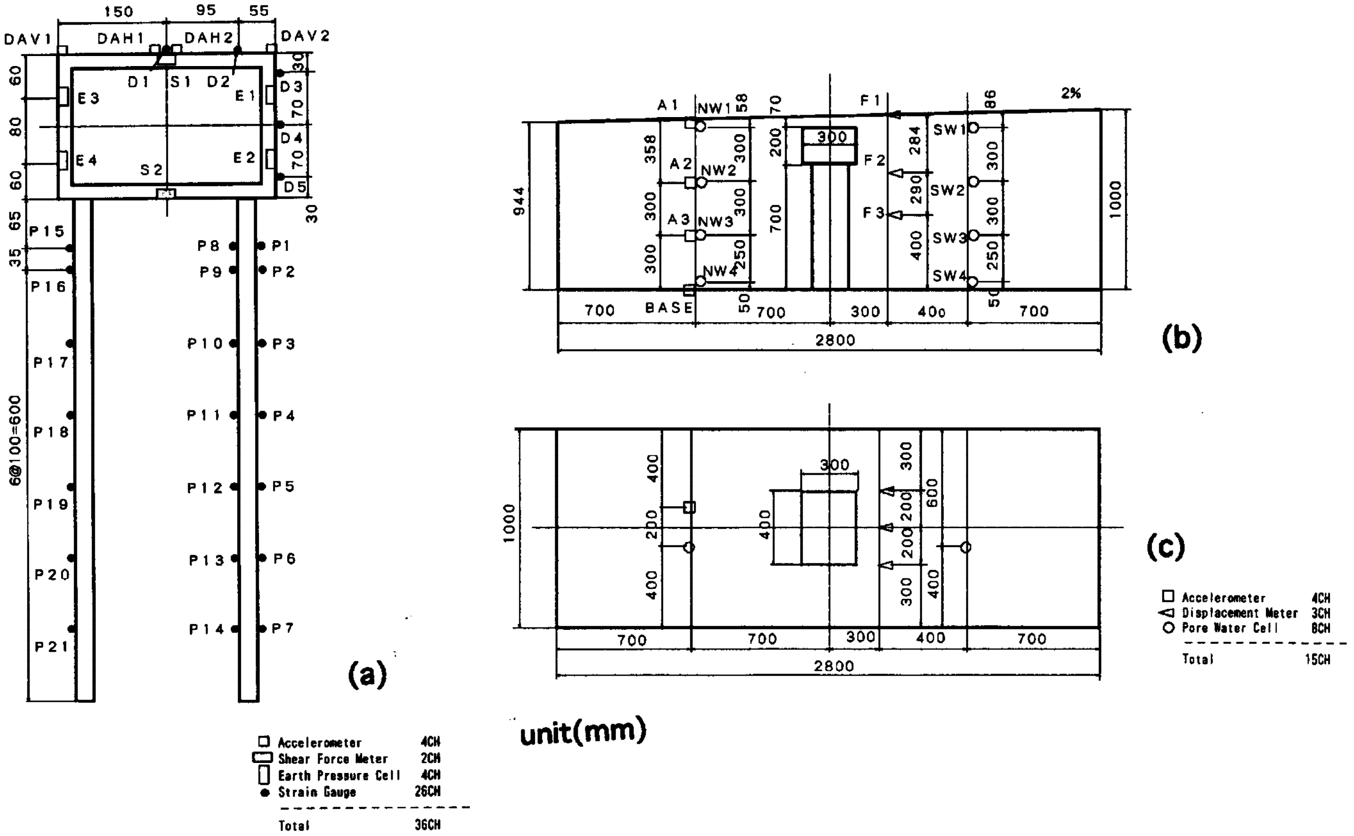

Fig. 1 Measured points arrangement (a) Pile and conduit, (b) Sand layer in cross section and (c) Sand layer in plan section

TEST RESULTS AND DISCUSSIONS

Soil Force on Pile

Maximum bending moment on the piles occurred at the time instant about 1.2 seconds after excitation in the model shake table test. The time instant bending moment distributions are shown in Fig. 2 for Case 1 and Case 2. The bending moment distributions obtained in the static load test are also plotted in Fig. 2. The static load test results provided a particular load step which caused approximately same degree of bending moment near the pile head.

Similar bending moment distribution is observed on the results of the model shake table test (solid line in Fig. 2) and the static load test without surrounding sand (dashed line in Fig. 2). On the contrary, the distribution pattern of the with surrounding sand (fine dashed line in Fig. 2) appears to be quite different from those two cases. The static load test without surrounding sand may roughly simulate to put a load on exposed pile, which leads most severest condition for horizontal bearing capacity of a pile. In this connection, the bending moment distribution obtained by the with surrounding sand test represents a typical form as supported with horizontal subgrade reaction. The fact observed in Fig. 2 therefore suggests that the horizontal subgrade reaction is extremely small when the pile sustained lateral flow.

Specification for Highway Bridge Part V, Earthquake Resistant Design (Japan Road Association, 1990) postulates the effect of liquefaction in the part of the earthquake resistant design of pile foundation. According to the design practice, soil constant of liquefiable subsurface layer is regarded as zero. While the present study reveals that the peak bending moment on the pile occurs when the horizontal subgrade reaction is extremely small as seen in Fig. 2. From this, the test results may verifies the specification design practice. Yet the specification involves still limitation for the effect of the lateral flow.

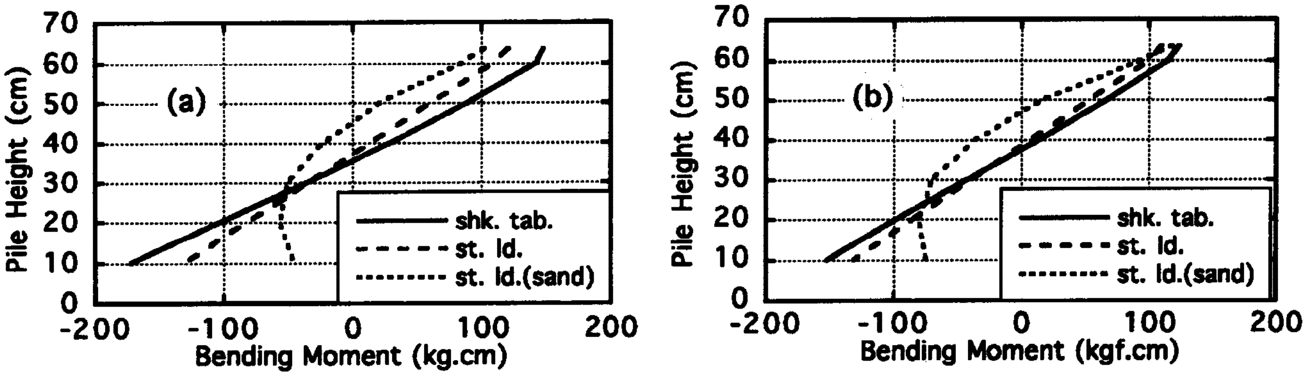

Fig.2 Maximum bending moment distributions (a) Case1 and (b) Case 2

Soil force and lateral flow velocity are examined in time history. The soil force can be estimated by a second order derivative on the bending moment along the pile axis. In doing so, discrete bending moment distribution was identified by a regression analysis. As clearly seen in Fig. 3, both peak values virtually harmonized at the same time instant. This implies that the soil force passing through the pile can be estimated utilizing a drag force which is proportional to square of flow velocity because liquefied sand performs like a muddy flow, or viscous fluid. As well as this, the drag force utilization for estimating the soil force has been verified by Ohtomo and Hamada (1994).

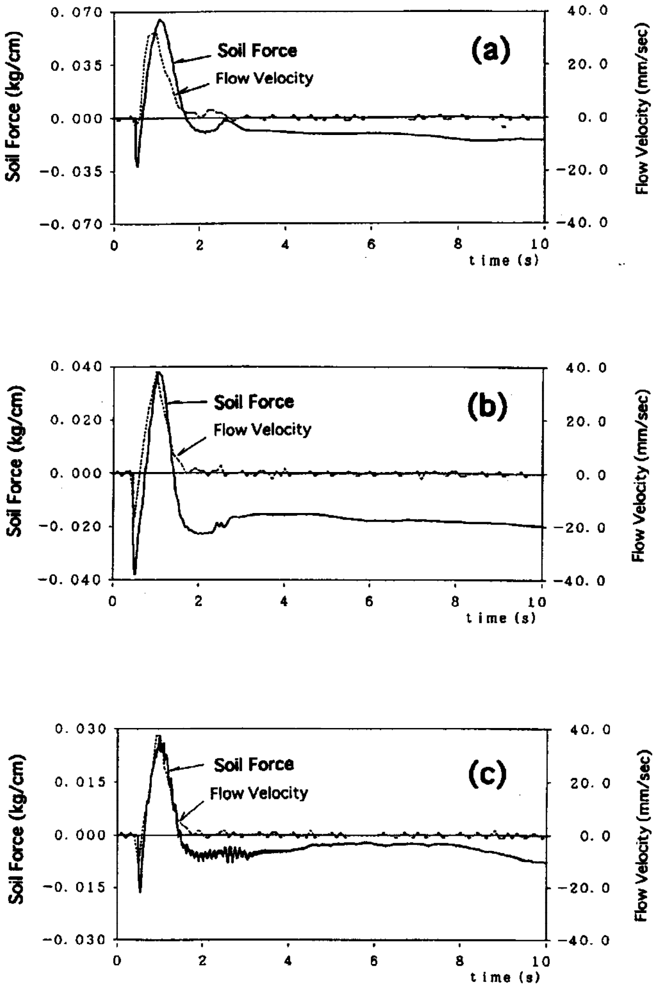

Fig. 3 Soil force and flow velocity (a) Case1, (b) Case 2 and (c) Case 3

Lateral Earth Pressure on Conduit

Lateral earth pressures on the side walls of the conduit develop with the increase of earth pressure coefficient during liquefaction process. However, the tendency is different from the upper and lower stream sides as clearly observed in Fig 4. Figure 4 shows four time histories from Case 1 as example : these are the lateral flow, the lateral earth pressures on upper and lower stream sides and the bending moment (See Fig. 1 regarding measured point location). The time histories indicate effective accumulation by eliminating vibration components. The lateral earth pressure discussed in the present study is defined as the sum of effective earth pressure and pore water pressure, i. e., total earth pressure.

When the lateral earth pressure at E2 and the bending moment P1 reach respective peak value, their time instant is identical as pointed by reverse solid triangles in Fig. 4. On the other hand, the lateral earth pressure at E4 decrease when the lateral flow is triggered. It continues to degraded until the bending moment P1 takes a peak value, subsequently it turns to increase. This observation implies that the lateral earth pressures are unbalanced loading on the conduit.

The bending moment time history no doubt expresses the pile head displacement. Hence the lateral earth pressure performance on the upper and lower stream sides highly depends on the lateral displacement of the conduit associated with the pile head movement. The lateral earth pressure will be further analyzed at the time instant at which the pile bending moment shows a peak value.

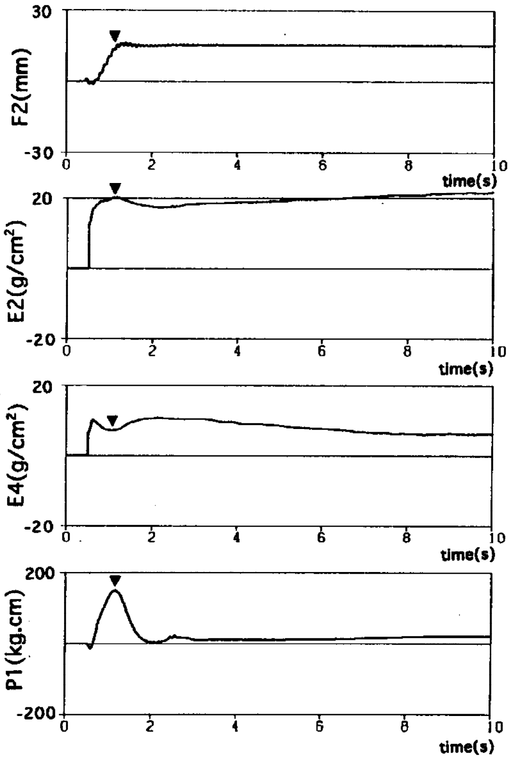

Fig. 4 Time histories of lateral flow, upper stream earth pressure, lower stream earth pressure and bending moment

The lateral earth pressure at rest, i. e., before excitation, was measured. Then it was added to the total earth pressure as earlier discussed in Fig. 4. Thus corrected total earth pressures were plotted in Fig. 5. In addition, dashed lines in Fig. 5 represent muddy earth pressure distribution, in which unit weight of saturated sand and earth pressure coefficient *K* were assumed as 1.8 g/cm^3 and 1.0, respectively. Major findings from Fig. 5 are : (1) Experiment values exceed the assumed muddy earth pressures on both stream sides. (2) The degree of the lateral earth pressure on the upper stream side is slightly larger than that of the lower stream side under the condition of unified pile flexural stiffness. (3) Totally, the degree of the lateral earth pressure grows with the lessening pile flexural stiffness. Though a triangle distribution with respect to depth may be valid for the lateral earth pressure discussed here, it is unlike the muddy earth pressure on a rigid wall, particularly in view of earth pressure intensity.

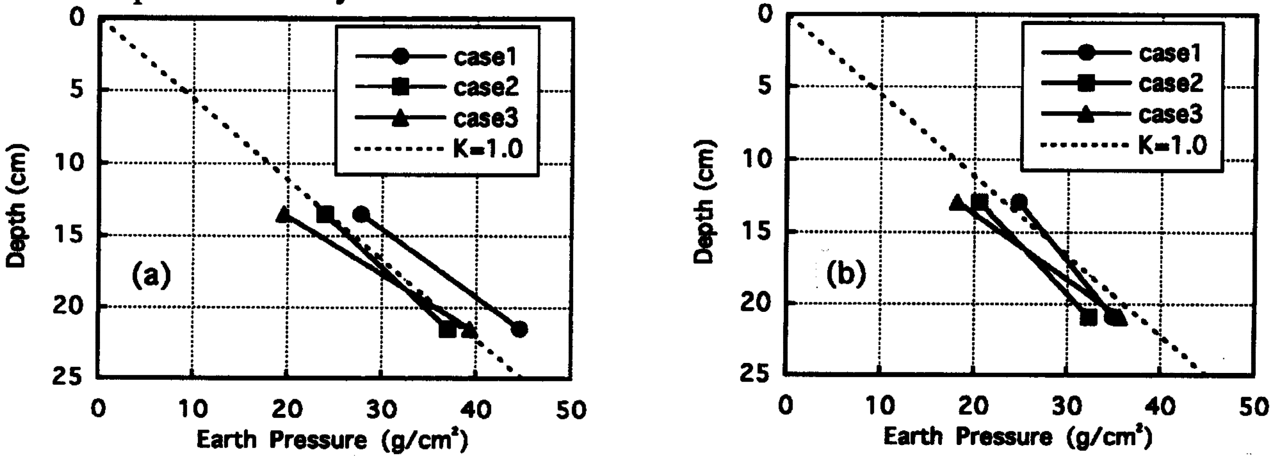

Fig. 5 Lateral earth pressure and muddy earth pressure (a) Upper stream side and (b) Lower stream side

To further analyze the observation of the lateral earth pressure performance in Fig. 4, a relationship between lateral earth pressure intensity P and pile flexural stiffness EI was examined. P is defined as

$$P = \int_0^H \{p_u(z) - p_l(z)\}\, dz \tag{1}$$

where $p_u(z)$ and $p_l(z)$ are the lateral earth pressure of upper and lower stream sides, respectively. They are assumed to change linearly along the conduit side wall. H indicates conduit height (20 cm) and z is vertical coordinate originated zero at the conduit upper face and positive in downward direction. As seen in Fig. 6, P and EI are found to be correlated with the following expression :

$$P = 870\ EI^{-0.4} \tag{2}$$

The effect of lateral load intensity P on pile section force, i. e., bending moment, is then evaluated by loading horizontally only P on the pile head. The pile was modeled as a fixed-end beam. A horizontal roller boundary condition is applied at the pile head. The vertical and rotation displacement components were prescribed. The bending moment developed by P is plotted in Fig. 7 and it accounts for about forty percent of the total bending moment, which is developed by excitation. This observation yields that the lateral earth pressure and the soil force on piles would be indispensable when pile section force becomes to be concerned for liquefaction induced lateral flow.

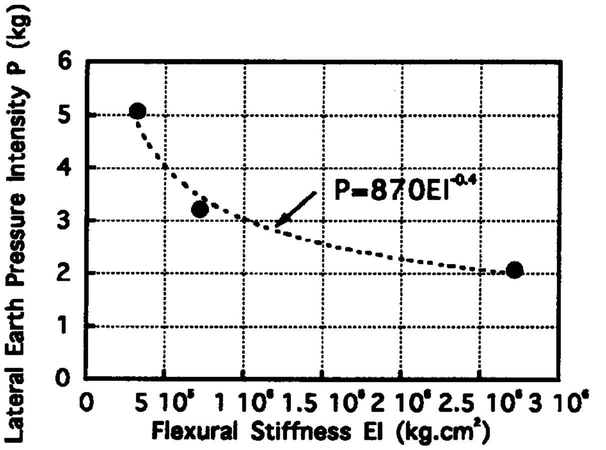

Fig. 6 Lateral earth pressure intensity and flexural stiffnesspressure

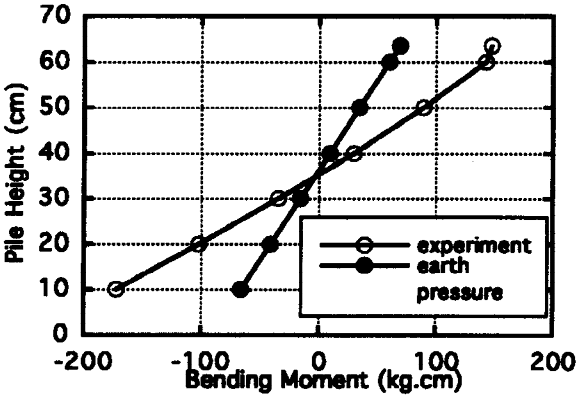

Fig. 7 Pile bending moment by lateral earth intensity

Substantial soil force q acting on the pile can be estimated by eliminating the degree of the bending moment developed by P. The bending moment developed only by q from Case 1 is plotted in Fig. 8. Second order polynomials regression analysis reveals good fitting with 0.999 in regression coefficient R. q is determined by a second order derivative of the regression formula along the pile axis. As a result, q is estimated as 0.058 kg/cm , 0.028 kg/cm and 0.014 kg/cm for Case 1, Case 2 and Case 3, respectively.

A set of normalized P and q, i. e., Pl^2/EI and ql^3/EI where l is pile length (70 cm) were plotted in Fig. 9. The correlation between Pl^2/EI and ql^3/EI is in direct proportion :

$$Pl^2/EI = 0.014\,(ql^3/EI) \tag{3}$$

This relationship is reasonable in view of the fact that no bending moment is developed unless the lateral flow is progressed as seen in Fig. 4. The correlation equation obtained here suggests that one can determine the soil force of liquefaction-induced lateral flow to conduit-pile system provided either P or q. On the basis of the present study, the lateral earth pressure can be estimated by appropriately correcting the earth pressure coefficient ; ideally more than 1.0. This procedure is easier than the direct estimation of the soil force on the pile. In fact, if a drag force is utilized the estimation, it requires information regarding flow velocity and viscosity of liquefied soil (Ohtomo and Hamada, 1994) . In general, these properties are quite difficult to predict in the current design practice.

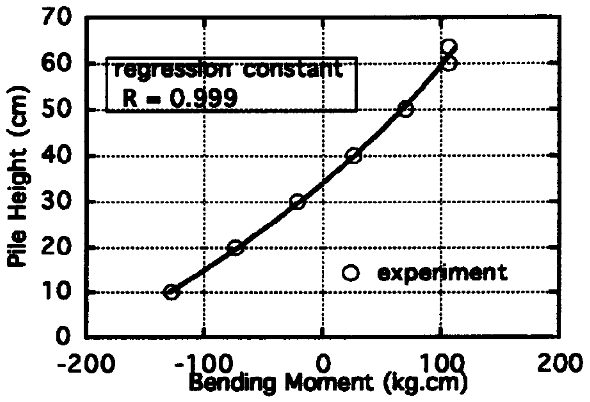

Fig.8 Regression analysis on bending moment

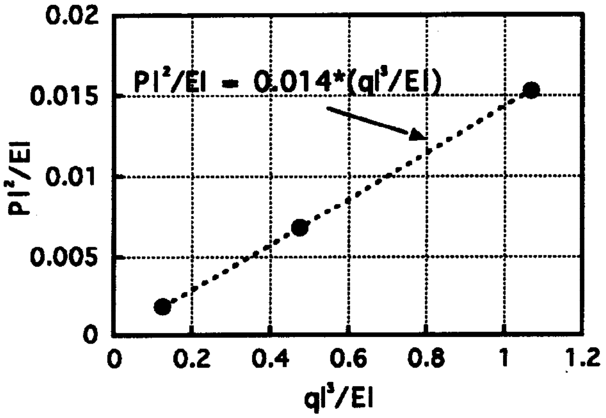

Fig. 9 Pl^2/EI and ql^3/EI

CONCLUDING REMARKS

The present study focused on the soil force of lateral flow on a conduit-pile system. For this purpose, the model shake table test and the static load test were conducted. On the basis of these test, soil force on the pile and the lateral earth pressure on the conduit were examined. The soil force on the pile is possible to estimate utilizing a drag force because liquefied sand performs as viscous fluid. However, a drag force utilization is rather difficult due to insufficient available data associated with fluid nature of liquefied sand. Despite this, normalized lateral earth pressure intensity and soil force on the pile are found to be correlated with direct proportion. Since the lateral earth pressure can be estimated by correcting earth pressure coefficient, this correlation enables us to determine the soil force of liquefaction-induced lateral flow.

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