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ANALYSIS OF SATURATED SAND-PILE INTERACTION UNDER EARTHQUAKE CONDITION BASED ON EQUIVALENT LINEAR METOD

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SUMMARY

In case a dynamic soil pile interaction is examined in case of the earthquake, it is the problem what kind of thing the foundation performance during earthquake. Many ways how to deal with the handling of the nonlinearity of the soil, the view of stress, the dimension to consider, and an element differs as a method of presuming the action of the foundation produced in case of an earthquake are proposed. The simplest technique in these is the linear equivalent total stress analysis technique. This method is represented by SHAKE developed in University of California, Berkeley in 1972.

This method can analyze the soil response which took the nonlinearity of the soils into consideration comparatively simply, and is a method currently widely used from having consistency well with the result of actual seismic observation being known on the multi-layer structure. However, since this method is total stress analyzing methods, in case the soil liquefied, it is made difficult to apply when the rigidity of the soil changes significantly.

When soil structure is complicated, the analysis technique which the 2-dimensional or 3-dimensional structure of the soil is needed, and the FEM analysis technique and the DEM analysis technique are used as such analysis. When using such analysis technique, it will be directly related to analysis accuracy how a soil model is actually real and can be created. Therefore, if the physical properties of the soils are not correctly modeled in case, an analysis result does not make a meaning.

There is the effective stress analysis technique when the rigidity of the soil changes extremely. This method is pursuing change of the effective stress in the soil for every moment, and calculating the rigidity of the soil, and distortion based on the effective stress.

It is verified that the validity of this method is effective of the liquefaction soil. It is necessary to decide the effective stress of the soil changes, in other words, the excess pore water pressure changes by this analysis technique. As this method, change of excess pore water pressure experimentally beforehand, and there is a method of analyzing using the constitution law which is the method of specifying change of effective stress by that result.

About a constitutive law, it is still in the region of research, and cannot waits for development of a steadfast thing to future fruits of work. Therefore, in the present condition, it can be said that the method of specifying change of effective stress by the element test result of the soil etc. is effective.

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About soil-pile interaction, the method of the soil act on a pile through a soil spring is comparatively simple, and it is verified on the static problem that is an effective method.

In the main subject, though it was comparatively simple, from a viewpoint which gropes for the high-precision analysis technique, the analysis technique based on the one dimensional equivalent alignment total stress analyzing method was proposed. In order to perform dynamic analysis of pile and on the basis of the method of the soil acting on a pile through a soil spring about interaction. A time domain analysis method is proposed.

INTRODUCTION

Earthquake-induced liquefaction of loose, saturated sandy soil is a major cause of damage to piles and deep foundations. Buildings, roads, bridges, port facilities and other civil engineering works are affected. Cracking and rupture of piles rupture of pile connections, and permanent lateral and vertical movements and rotations of pile heads and caps with impacts on the superstructure have been observed. A number of earthquakes in the last 37 years where deep foundations have been damaged by liquefaction. These include the 1964 Niigata Earthquake, 1964 Alaska Earthquake, 1983 Nihonkai-Chubu Earthquake, 1989 Loma Prieta Earthquake, 1991 Limon Earthquake, 1995 Hyogo-ken Nambu (Kobe) Earthquake, and the 1995 Manzanillo Earthquake.

Physical modeling has emerged in the US and Japan as a main tool to study the problem, understand and quantify the parameters involved, and provide guidance and calibration to both simplified engineering procedures and numerical simulation techniques. Active ongoing research combining physical modeling (centrifuge and 1g model testing with base shaking), and computational modeling techniques, are making significant progress toward understanding the main factors controlling this complex soil structure interaction problem. With the aid of 1g shake-table test models, it is now possible to obtain detailed measurements of soil and pile responses and to evaluate the importance of varying the earthquake characteristics (level of shaking, frequency content, and waveforms), soil profile characteristics, and pile characteristics.

Special features of the available experimental database discussed in this paper, include: experiment conducted under 2 different levels of input motion amplitude; high density of employed sensors deployed in the ground and pile, 190 sensors deployed for monitoring sand and pile behaviors in each test; or 570 time histories for the two shaking events; high resolution documentation of salient characteristics of soil-pile interaction during the process of increase of pore water pressure leading to larger bending moments induced along the pile. However, once the pore pressure reach the maximum (zero effective stress) and the sand is completely liquefied, the induced moments substantially decrease; and, monitoring of the sand stratum liquefaction-induced softening behavior. Two different levels of input motion (0.5, and 1.5 m/s^2) were applied and as the amplitude of the input motion increases the depth of liquefied sand increases accordingly. The amplitude of 1.5 m/s^2 causes the entire depth of the sand stratum to liquefy. This database is a significant complement to studies mainly based on limited field evidence, laboratory testing of soil elements.

This paper describes this experimental program conducted at NIED aimed at assessing the seismic interaction between a 2x1 pile group and liquefied sand, and discusses the analysis result of soil-pile interaction behavior based on equivalent linear method. About the case where it liquefies with the case where the soil does not liquefy as the analysis technique of the soil action in case of an earthquake, the validity of the one dimensional equivalent alignment total stress analyzing method and the one plane effective stress analyzing method is verified, and the analysis technique based on them is proposed, respectively.

EXPERIMENTAL PLAN

Experimental Setup:

The experiment (Fig. 1) aimed at studying the seismic interaction between a full-size 2x1 pile group and liquefied sand. The testing program encompassed three experiments with three different amplitudes of input motion, three shaking events were applied to the soil-pile-superstructure system. For excitation, the time history of the 1995 Kobe Earthquake record in Port Island at 28m underground was used. The shaking events were applied along the direction East-West, parallel to the longest dimension of the laminar container. Table I also indicates the global relative density for the sand before each shaking event. For these experiments, the total height of the soil was 4.0m using just 22 out of the total 28 laminates. To make the container waterproof, a 3mm-thick composite membrane made of neoprene and nylon was used.

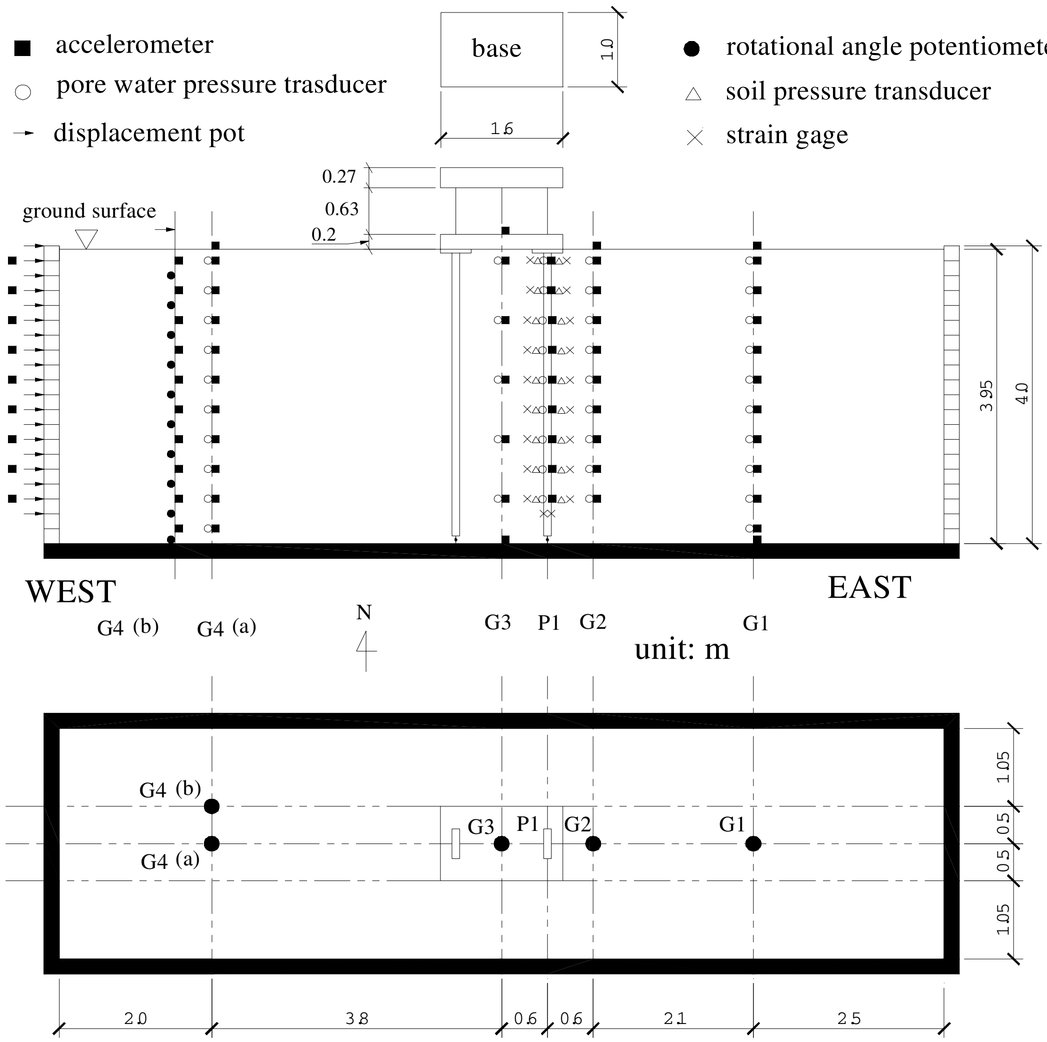

Fig. 1 Experimental setup

The material used for these experiments was the Kasumigaura-sand with average grain size D_{50} = 0.21mm, coefficient of uniformity C_u = 2.12, specific gravity G_s = 2.638, fine grain size content F_c = 5.8%, and maximum and minimum void ratios of 1.224 and 0.732 respectively. Using a large soil handling system, the sand stratum was formed using the water sedimentation method, and the degree of saturation was checked measuring P-waves. P-wave propagation speeds of 1500-1600 m/s were measured, which agree well with P-wave measurements in fully saturated sand samples in large-scale triaxial tests. The 2x1 pile group is composed of two 3.8m-long steel piles with rectangular, solid type cross-section, 0.10m thick and 0.40m wide (Young Modulus is E=21000 MPa, and EI=700 MN-m^2) .

The piles have hinged supports and bear a 3.6t mass simulating a superstructure. One of the two piles was heavily instrumented and the pile group was placed at the center of the soil container.

Curvature was calculated from the strain gauges placed on both sides of the pile. It is clearly observed that the amplitudes of acceleration and curvature increase as the depth decreases. At around 1s. The sand liquefies, and the accelerations at low frequencies increase in amplitude for about 1s. And then drastically decrease. Curvatures along the pile shows that at the moment of reaching the zero effective stress condition, there is a large pulse or large induced bending moment along the pile, and thereafter the magnitude of the curvature or bending moment gradually decreases. Liquefaction of the entire sand stratum is achieved at around 1s. Due to the rapid increase of pore pressure during the first second of shaking, thereafter pore pressure remains stable during the liquefaction phase.

REFINE ANALYSIS TOOLS

Soil Response Analysis

The main points of having looked again are having determined the expression of relations of G-gamma and beta-gamma according to the empirical equation of lshibashi&Zhang (1993), taking these relations changing by confined pressure into consideration etc. That is, it changes to a formula and G* is determined using a formula (1).

$$G^* = G\left(1 - 2\beta^2 + i2\beta\sqrt{1-\beta^2}\right) \qquad (1)$$

Moreover, the function in which analysis by the simultaneous input of two directions can be performed is added. Shear stress and strain which is used for calculation, is shown in formula (2).

$$\gamma_{eff} = \sqrt{{\gamma_{xy}}^2 + {\gamma_{yz}}^2} \qquad (2)$$

Soil-Pile Interaction Analysis

Presumption of the interaction of the soil-pile by a response displacement method is the method of making the displacement of the soil acting on a pile through the soil spring, depending on shear strength of the soil. This method is the analysis technique which started the instant with a dynamic interaction transposed to the static problem. The moment, pile stress serves as the maximum, supposing modification of a spring constant and the soil is right, the maximum stress of the pile consideration during the earthquake can be evaluated.

It is the moment deformation of the soil becomes the maximum, the moment, the stress of a pile becomes the maximum since it has the nonlinearity from shear modules of the soil. It is necessary to predict correctly the soil displacement.

As mentioned above, the displacement of presuming the stress of a pile using the response displacement method which is a static technique, it is rational to set up a soil spring, and soil displacement.

The method of analyzing the dynamic interaction which calculates the serial response of soil-pile is proposed.

The view of a response of a pile and soil is based on formula (1). However, γ is from equivalent to shear strain of soil

$$\gamma = (1+\nu)y/(fB) \qquad (3)$$

Shear stress which corresponding to shear strain of the soil.

$$\tau = G_s \gamma = G_{\max} F(\gamma / \gamma_r)\gamma \qquad (4)$$

From the force P of acting on a pile from the soil having nonlinearity,

$$p = 2 f \overline{\delta} B \tau_{ult} F(y^*) y^* + 2\rho_s B (V_s + V_p)\frac{dy}{dt} \qquad (5)$$

Shear stress of the soil at this moment, is express;

$$\tau_{ult} = A(\overline{\sigma}_v \sin\overline{\phi} + \overline{c}\cos\overline{\phi})/(1-\sin\overline{\phi}) \qquad (6)$$

On a static problem, only spring element is affected on a pile, affects to the stress of a pile, but it is necessary to consider the effect of damping on a dynamic problem. In other words, it can be said that the effect of the damping in a dynamic problem also combines the soil spring considered on a static problem. Soil-pile element which combined the damping element with the spring for the soil and a pile, here the joined model is used.

Here, it is soil-pile element. Force which acts on a pile is considered as follows.

$$f_p = \left\{2\rho_s \cdot B(V_s + V_p) + DMPRT \cdot \left[2\pi B^2 (1+\nu) G_{\max} \cdot \rho_p\right]^{0.5}\right\}\frac{dy}{dt} \qquad (7)$$

Here, DMPRT is a constant showing the effect of shear modules by damping, and the result of an element examination etc. determines it.

By using the same model as the pile model of a subterranean part also about super structure, this model can also calculate an interaction with super structure.

RESULTS OF EXPERIMENTS

Result of 50 gal shaking

Shaking of maximum input 50gal, carrying out. Although excess pore water pressure is rising a little from this shaking. Surface of the sand bed to the depth of about 2m, the soil has come to liquefy. It can be convinced that soil made by the underwater falling method, and pore pressure rises a little also by seismic-waves of 50 ga1 shaking from the relative density of the foundation having been about 45%, this time to some extent.

Since the data which can examine the soil-pile interaction of liquefaction does not occur.

Result of 150 gal Shaking

Shaking of maximum input 150 ga1 was carrying out. On this shaking, all layer liquefaction occurred. The fall of natural frequency and reduction of acceleration response amplitude appear in the response waveform under the influence of the excess pore water pressure which generated the acceleration response time history in each shaking according to acceleration in sand bed.

Adjustment of an experimental result and an analysis result

Adjustment of an experimental result, and an analysis result in case the soil does not liquefy

Although there was a rise of the excess pore water pressure in shaking which adjusted the maximum of input seismic waves to 50gal, and the soil, an excess-pore-water-pressure ratio is about 0.3 at the maximum, has come to liquefy.

The acceleration time history waveform obtained by the equivalent linearizing method analysis is conducted. Shear modules which called for analysis, equivalent is 80% to 60% of range of an initial value, and the ranges of this corresponding shear strain which equivalent are 0.001-0.005. This value is mostly adjusted with 0.005 of shear strain which is presumed from the measurement result of an experiment. Comparison of the measured value and analysis value of acceleration adjusts both in general well.

The correlation coefficient of the acceleration in the soil for every depth is 0.78 to 0.45.

Although the tendency both correlation decreases as depth becomes shallow of the correlation coefficient of the lowest in acceleration is 0.72, and even in this case, that both correlativity is high.

The soil displacement; both correlation as well as the case of an acceleration waveform was discussed. The same tendency as the case of acceleration is seen also in displacement, a correlation coefficient is at least 0.48 and correlativity can be referred to as being.

An experimental value in case the soil liquefies, and adjustment of an analysis result

It resulted in full liquefaction in about 2.0 seconds after shaking of maximum 150gal of input seismic waves.

Analysis was performed by the effective stress analyzing method after T.Kagawa. This analysis, the time for 0.01 seconds, the acceleration of the soil, and displacement, the response was calculated one by one.

When the soil liquefies, adjustment is not good, but an amplitude form is still the similar. Here, in order to argue about both adjustment objectives, the data of both time histories was made to correspond to 1:1 at this time, and evaluated using the technique of taking the correlation.

Correlativity is in the tendency which decreases as depth becomes shallow, even if the correlation coefficient of the lowest is 0.42 and it is this case, there is both correlativity, and correlativity is accepted in wave form.

Analysis result and measured value correlation as well as the case of an acceleration waveform were discussed. The same tendency as the case of acceleration is seen also about displacement, a correlation coefficient is at least 0.41 and correlativity can be referred to as being.

Verification of the dynamic interaction of the soil-pile system, and the proposal of a simple evaluation method

The action of the pile in the non-liquefying soil

It inquires using the experimental result at the time of maximum input acceleration 50gal shaking as an experimental results in case the soil does not liquefy. If it bends with inertial movement in shaking and modification is considered as an action of a pile, since examination corresponding to the action of the soil can be performed, it will bend about an acceleration response, and the curvature of a pile will be examined.

In order to obtain for a motion of a pile, the method of double integration of the output of the accelerometer attached in the pile is common, but the accuracy is not enough. The displacement of pile head was measured by laser sensor displacement meter also, we used this value for compare.

The modification by the force received by an interaction with the soil for a pile is bent. Then, a pile bends using the result of the pile having bent here and having direct measurement of the deformation.

Double differentiate of deformation as a method of presuming the horizontal force which acts on a pile, and the method of using the difference of the measured value by soil pressure meter attached in the both sides of a pile can be considered. However, double differentiating of deformation, a differentiation error is large and it is expected that the presumed accuracy of horizontal force becomes low. Moreover, in order that the method of depending on the measured value of soil pressure may also use the difference of the output of soil pressure meter attached in the both sides of a pile, it is expected that accuracy becomes low. Then, examination here is performed by bend and can be directly found from distortion bending, bending with modification and comparing the analysis value of modification.

A pile bends and modification analysis is performed by the method of making modification of the soil acting on a pile through the soil spring. The soil spring for analysis used the value corresponding to the rigidity according to shear deformation which the soil obtained as a result of performing response analysis by the equivalent linearizing method of the soil carry out. If the foundation spring constant used for analysis is appropriate, the measured value and analysis value of modification will be in agreement, and this analysis technique will be appropriate.

The action of the pile in the liquefied soil

It inquires using the experimental result at the maximum input acceleration 150gal shaking as an experimental results in case the soil liquefies. If it bends with inertial movement in shaking and modification is considered as well as the case of the non-liquefying soil as a behavior of a pile, since examination corresponding to the behavior of the soil can be performed, the curvature of a pile will be examined.

The displacement of pile head measured by laser displacement meter, they are from acceleration carried out direct measurement in total, and the displacement which double integrated, and calculated it. If the foundation liquefies, in order for shear modulus to fall extremely, the undamped natural frequency of the soil falls. Therefore, the oscillating ingredient of a low cycle stands high and an integration error increases further compared with the case where the soil does not liquefy. Therefore, compared with the result of displacement directly, accuracy is that which fell considerably. Moreover, also in case a pile bends, becoming similarly very low accuracy of the calculated value is expected. The soil spring used for analysis used the value corresponding to the rigidity according to shear strain which the soil obtained as a result of performing effective stress response analysis.

Adjustment of an experimental result and an analysis result

(1) The action of a pile and adjustment of an analysis result in the non-liquefying soil

In order to evaluate adjustment as well as the case of a response of the soil objective for both correlation coefficients, it was 0.79 in about 0.86. Although an analysis result is a little smaller than this result compared with the result of measurement, it is in agreement in general. The correlation coefficient of measured value and an analysis result is from 0.98 (pile bottom) to 0.79 (pile head), and there is a tendency to fall as pile head is approached. This tendency is the same as the case of a response of the soil, and is one of the same tendencies from the response analysis of a pile carrying out based on the response of the soil.

Both are in agreement in general. (Fig. 2)

(2) The action of a pile and adjustment of an analysis result in the liquefaction soil

The method of analyzing the interaction of a pile and soil is the same as that of the non-liquefying situation, and was based on the method of making modification of the soil acting on a pile through a spring and an attenuation element. Under the present circumstances, the result of an element tests determined a spring constant and attenuation.

In order to evaluate adjustment as well as the case of a response of the soil objective, both correlation coefficients was 0.72 in about 0.82 and the pile upper part. It can be said that there is an analysis result about as temporary correlativity as the result of measurement from this. The correlation coefficient of measured value and an analysis result has the tendency to fall as pile head is approached. This tendency is the same as the case in the non-liquefying soil.

If the soil liquefies, since soil rigidity becomes extremely small, this shows that a pile stops receiving horizontal force from the soil. The excess-pore-water-pressure ratio at the time becoming small to about 0.5, and the soil rigidity verified adjusts this mostly in the excess-pore-water-pressure ratio which falls rapidly.

If the foundation liquefies completely, shear modules of the soil fall extremely, that a soil spring became small. Therefore, on the soil of a full liquefaction state, the horizontal force from the soil which acts on a pile becomes very small. From this, it can be said that a stage until liquefaction is important for the examination about a pile in case the soil liquefies, and soil pile interaction.

Then, process, i.e., process until excess pore water pressure rises and an excess-pore-water-pressure ratio results in 0.5, until soil rigidity falls rapidly in an experiment is examined.

The measured value and analysis value of curvature of a pile are shown.

When it contains until after the soil carries out full liquefaction, it may compare the adjustment of the measured value in this portion, and an analysis value.

Presumed accuracy of response of a pile

In order to examine the dynamic soil-pile interaction about the case where it is not considered as the case where the soil liquefies, experiment was conducted. Comparison examination of the result of the analysis for presuming the response of the pile measured at the time of an experiment and the response of a pile was carried out, and the validity of the analysis technique was verified.

Consequently, it turned out that the soil-pile interaction can be presumed in high accuracy with the analysis technique proposed when the soil does not liquefy. Although presumed accuracy fell when, as for the presumed result by the analysis technique proposed when the soil liquefies, the soil did not liquefy, it turned out that the response of a pile can be presumed in a certain amount of accuracy. Especially the analysis result by the analysis technique proposed, is the case where the soil liquefied when the response of the liquefaction process considered being important. (Fig. 3, Fig.4)

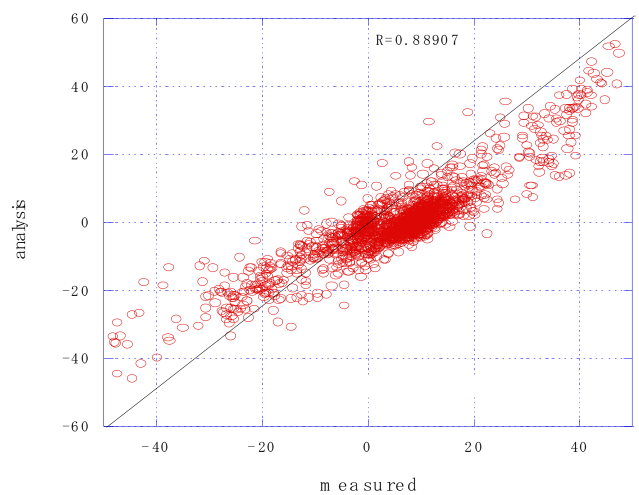

Fig.2 correlation between measured value and analysis value

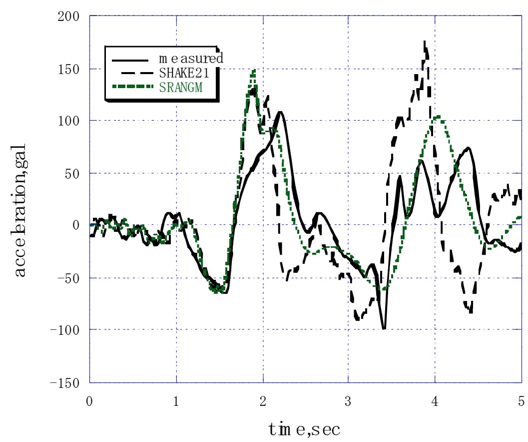

fig. 3 measured and analysis acceleration
GL-0.0m

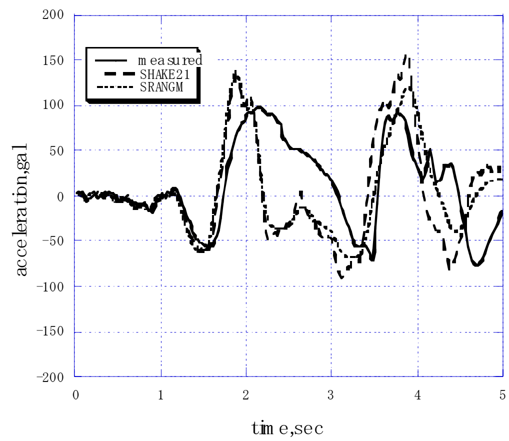

Fig. 4 measured and analysis acceleration
GL-2.0m

Conclusion

1 In order to presume the response of a pile, the analysis technique of the soil act on a pile through a soil spring and an attenuation element was proposed, and the response of a pile was analyzed by this method.

2 When the soil does not liquefy, it can presume in high accuracy with the analysis technique which inertial movement of a pile and deformation proposed.

3 When the soil liquefies, the presumed result by the analysis technique which inertial movement of a pile and deformation falls compared with the case where the soil does not liquefy. So greatly, in case a presumed error performs examination in the case of a design, it can be presumed in practically sufficient accuracy even in this case.

4 When the soil liquefies, the duration of liquefaction process in which the soil results in liquefaction that examination of the dynamic soil-pile interaction becomes important.

5 When the soil does not liquefy, it can presume in high accuracy by the analyzing method of connect the soil with a pile for the stress of a pile by the interaction of the soil, and the state of modification with a soil spring, and modification of the soil is made to act. Although assumption accuracy falls compared with the case where it does not liquefy, the stress of a pile by the interaction of the soil can be presumed in the accuracy considered to be enough practically.

By this method, sufficient accuracy can consider for the soil stress and deformation of the pile by soil-pile interaction and modification in a design soil.

REFERENCE

1)Per B. Schnabel,John Lysmer ,H. Bolton Seed (1972), SHAKE A COMPUTER PROGRAM FOR EARTHQUAKE RESPONSE ANALYSIS OF HORIZONTALLY LAYERED SITES, EERC

2)I .Ishibashi, X.Zang(1993): Unified Dynamic Shear Moduli and Damping Ratio of Sand and Clay, Soils and Foundations Vol.33,No.1, pp182-191
3) Yoshida,N.&Yoshinaka,R.(1972): A method to estimate modulus of horizontal subgrade reaction for a pile, Soils and Foundations, Vol.12, N0.3, pp.1-17.
4) Kagawa, T. and Kraft, L. M., Jr. (1981), "Lateral pile response during earthquakes," Journal, Geotechnical Engineering Division, ASCE, Vol. 107, No. GT12, 1713-1731 .
5) Chang,Y.L.(1937): Discussion on "Lateral pile loading tests" by Feagin, Transaction, ASCE,
6) Kagawa, T. (1996). SRANG - Site Response Analysis of Nonlinear Ground. A computer program for Slte Response Analysis, Wayne State University.
7) Kagawa T and Abe A (1996) : A new approach to site-response analysis, Proceedings, 2nd Annual Conference, Geotechnical Engineering Society of Japan.
8) Kagawa, T., Abe, A., Ogawa, N. and Minowa, C. (1997), "Shaking-table tests on a real-size pile foundation in liquefying sand,Proceedings, SMIRT 14 Conference, France.
9) Kagawa, T. and Kraft, L. M., Jr. (i98la), "Lateral pile response during earthquakes, Journal, Geotechnical Engineering Division, ASCE, Vol. 107, No. GT12, 1713-1731 .
10) Kimura.M.(1996): Damage statistics, Soils and Foundations, Special ISSUE on Geotechnical Aspects of the January 17th 1995 Hyogoken-Nambu Earthquake, pp.1-6.
11) Kubo,K.(1965): Experimental study of the behavior of laterally loaded piles, Proc. 6th ICSMFE, Vol.2, pp.275-279.
12) Kuwabara,F.,Aoki,H.&Kishida,H.(1993): Towards Limit State Design Standards for Pile Foundations, Proc. of Int. Limit State Design in Geotech. Eng., Danich Geotech. Inst., Copenhagen, Denmark, Vol.2/3, pp.523-532.
13) Lee,K.L.&Seed,,H.B.(1967): Drained strength characteristics of sands, Proc. ASCE, Vol.93, No.SM6, pp.117-141.
14) Li,Y.&Peter.M.B.(1992): Lateral pile response to monotonic pile head loading, Canadian Geotech., N0.29, pp.955-970.
15) Meyerhof,G.G.(1995): Development of geotechnical limit state design, Canadian Geotechnical Journal, Vol.32, pp.128-136.
16) Nishimura.A.,Haya,H.&Okumura,F.(1993): Limit state design application to railway foundation Design standard, Proc. of Int. Symp. Limit State Design in Geotech. Eng., Copenhagen, pp.543-550.
17) Scott,R.,F.(1980): Analysis of centrifuge pile tests: simulation of piles driving. (Cited in Murchison and O'Neill 1984). Research Report, American Petroleum Institute, OSAPR Project 13.
18) Terzaghi,K.(1955): Evaluation of coefficient of subgrade reaction, Geotechnique, Institution of Civ. Engrs., Vol.5, pp.297-326.
19) Wu,D.,Broms,B.B.&Choa,V.(1998): Design of laterally loaded piles in cohesive soils using p-y curves, Soils and Foundations, Vol.38, N0.2, pp.17-26.
20) Yoshida,1.&Yoshinaka,R.(1972): A method to estimate modulus of horizontal subgrade reaction for a pile, Soils and Foundations, Vol.12, N0.3, pp.1-17.