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Development of hybrid experiments for nonlinear seismic soil-structure interaction

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ABSTRACT: The online test system that combines nonlinear restoring force characteristics of ground-foundation-structure system and numerical analysis has been developed using hydraulic actuators with electro-servo control by a micro computer. Using this technique in a developed method, frequency dependent dynamic characteristics were taken into account, introducing a new time domain numerical integration scheme. We abbreviate our new unique method as HENESSI standing for Hybrid Experiment on Nonlinear Earthquake induced Soil-Structure-Interaction. Earthquake responses of three types of rigid foundations different in size and depth of embedment, and flexible pile group foundations were studied.

1 INTRODUCTION

In the dynamic design of large-scale, important structures such as long-span suspended bridges and nuclear power plants, dynamic interaction effects are being taken into consideration nowadays. However it is difficult to express the interaction effecfs in a generalized, simple form. These effects depend not only on geometry and conditions of contact plane between ground and structure, but also on mechanical characteristics of their own. Because of the significant nonlinearity present in near field, it is difficult to model restoring force characteristics for the combined system. Also, we can not use observed data of severe earthquake motions because of insufficient data. Hybrid experiment can afford the weaknesses of model vibration test or forced vibration tests. Displacements obtained by solution of equations of motion of a lumped mass system are imposed to the structural test model system.Static developed restoring forces are input to the numerical algorithm. The restoring forces developed in the system are not postulated but measured at each integration time-step, directly from the test at the proper time. Repeating this computation and measurement, the earthquake response of the system can be obtained. Hybrid experiment is a numerical analysis utilizing the experimental information on the analyzed system's restoring force characteristics, which often are the most difficult properties to model. The concept of the hybrid experiment was originated in 1972 by Hakuno et al. They analyzed a coefficient of subgrade reaction of a single degree of freedom system (a sand-model pile system) using an electro magnetic actuator controlled by an analog on line computer. The idea, i.e. the earthquake response simulation without using a shaking table device, was extremely informative, but the obtained response was rather poor because of lack of accuracy and control limitations of the hardwares available at that time. Later, Takanashi et al. (1986) adopted a hybrid experiment to study a ground-surface footing (length 2m, width 2m, height 0.6m) - model steel frame system employing two actuators attached to a reaction wall. Although the test was successful for understanding the nonlinear interaction effects of ground-foundation-structure system, one of the most remarkable behavior concerning frequency dependency of dynamic interaction between ground and foundation was not considered.

The hybrid experimental method is a new technique and there are not so many studies on implementation of the idea to the practical use of the earthquake response analysis of ground-foundation-structure systems. The on line test system that combines nonlinear restoring force characteristics of ground-foundation-structure system and numercal analysis has been developed using hydraulic actuators with electro-servo control by a micro computer. Using this technique in a developed method, frequency dependent dynamic characteristics were taken into account, introducing a new time domain numerical integration scheme. We abbreviate

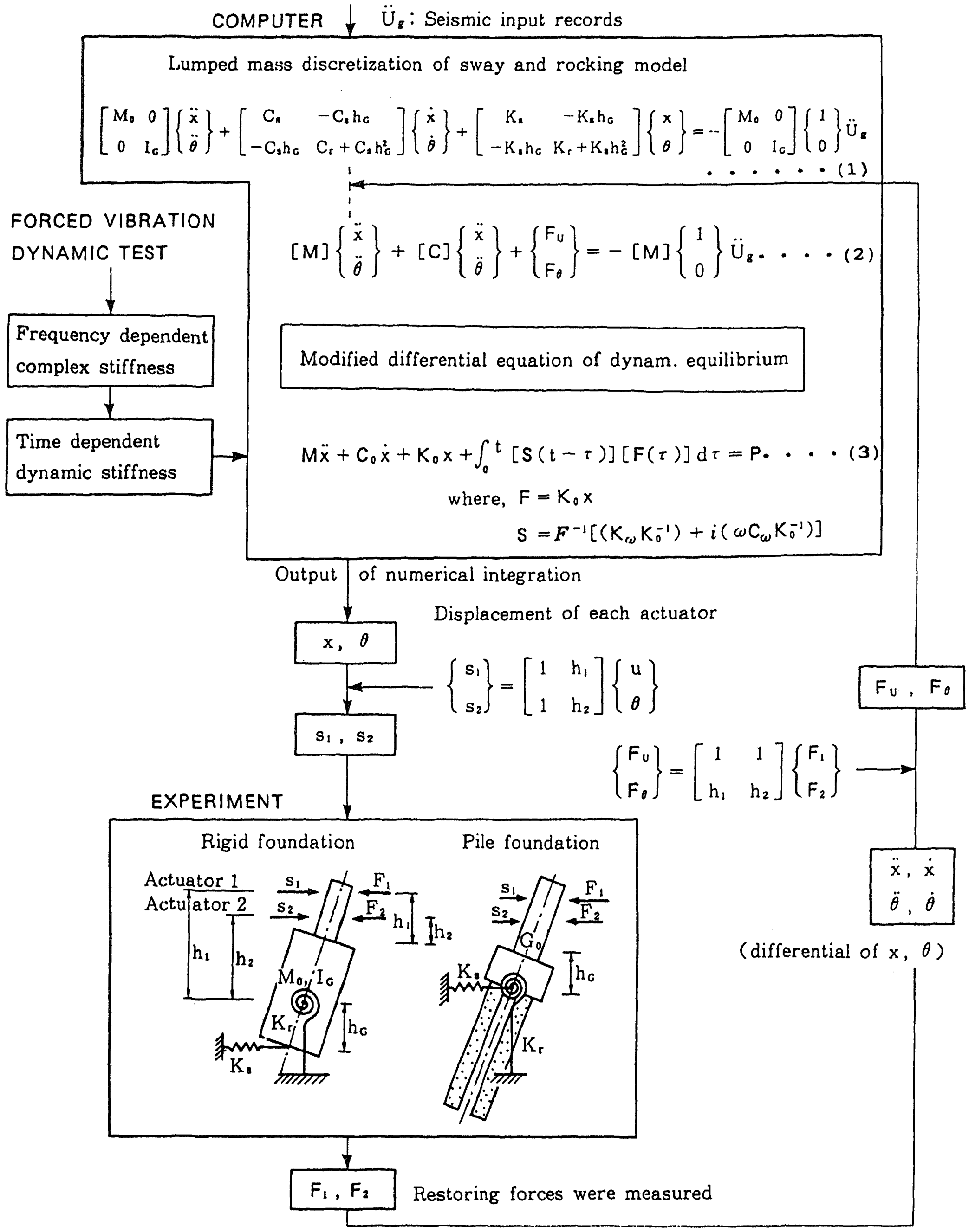


Fig. 1 Conceptual flow of hybrid test

our unique method as HENESSI.

Is our study, earthquake response of three types of foundations different in size and depth of embedment, and flexible pile group foundations were studied by comparing three cases of complex stiffness models for interaction. Static and dynamic mechanical characteristics of the ground-foundation-structure models were determined by static and forced vibration dynamic tests.

2 TEST EQUIPMENTS OF HENESSI

The analytical model in our study is a two deqrees of freedom system concerning sway and rocking model as shown in Fig. 1. Since it is impossible for one actuator to

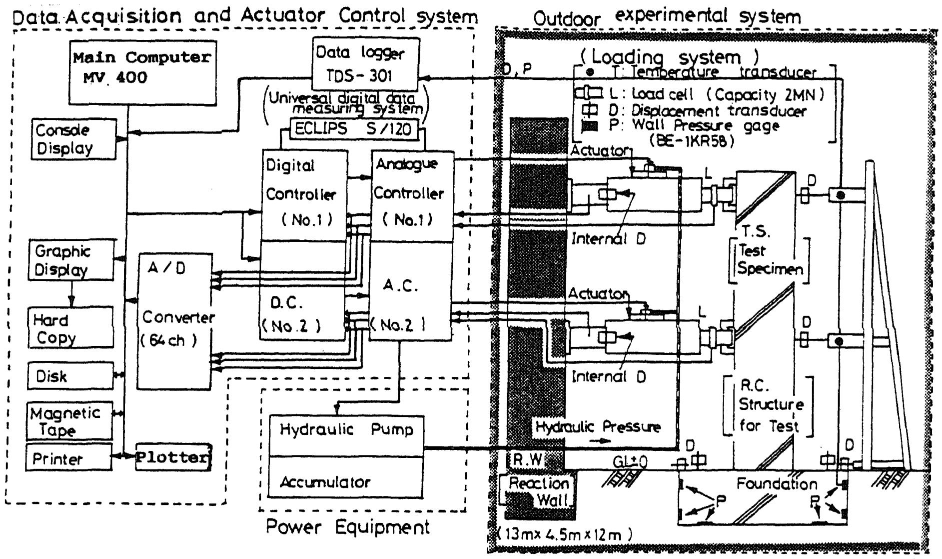


Fig. 2 Hybrid experimental system (HENESSI)

simulate both sway and rocking modes, two paralleled hydraulic actuators with electro-servo control were attached to a reaction wall and excite the foundation independently as is shown in Fig. 2, where data acquisition system, actuator controller and loading system are figured schematically. Equipments used in HENESSI are two analog controllers, two digital controllers, a 32 bit main mini computer (MV4000), two 12 bit binary D/A (digital to analog) converters, a data logger and measurement transducers for displacement and wall pressure gages. Natural ground was replaced by sand with shear velocity Vs of about 100m/s in order to clarify the dynamic properties and ignore velocity dependency of shear modulus and damping constant of the ground. The effect of underground water was ignored because it was lower than the foundation. The displacements of actuators at each step of the input seismic motion are computed by solving the dynamic equation of motion. The main mini computer (MV4000) commands a predicted displacement to the D/A converters (S/120) for controlling actuators shown in Fig. 2. This process is repeated four times at most until the foundation is moved to the desired (computed) displacement level. At this point the actuator motion is paused, the displacement, the reactional force, the earth pressure of the rigid foundation and the strain of pile foundation are measured by either of transducers. By sharing the work between the main computer (MV4000) and D/A converters (S/120), the rates of loading are speeded up in quasi-statical test algorithm. The main computer analyzes the equations of motion and dictates the D/A converters to control the actuators.

In this system, the radiation damping effect as well as the additional mass effect must be treated as the frequency dependent characteristics. Complex stiffness depending on frequency in the lumped mass model can not be obtained in quasi-statical test because they are present only in the real practice. Frequency dependent dynamic characteristics that have been obtained by the vibration test are taken into account in formulating dynamic equations of motion. Our method hybridizes frequency dependent and nonlinear restoring force characteristics of ground-foundation system in an analytical-experimental process. A new time domain numerical integration scheme which is based on Hilbert Transformation includes a time dependent term that provides frequency dependency of dynamic characteristics of the ground-foundation system shown in Fig. 1.

3 PURPOSE AND EXPERIMENTAL PROCEDURE

Three kinds of rigid foundations are studied : Surface Footing, Shallow Embedded Foundation (both as 2m diameter and 75cm height) and Caisson (diameter 2m, height 3m) shown in Fig. 3. Rigid superstructures (height about 3m) were used to transmit the actuator loads. The wall pressure gages, the type of load cell (BE-1KR58, diameter 10cm) were adopted as the earth pressure gage to take off the influence of bending moment by the pressure plate. Before the experiments, each of the wall pressure gages were adjusted to the earth pressure at rest from the back of the gages. Single, 2-, 3- and 9-pile group models are used as shown

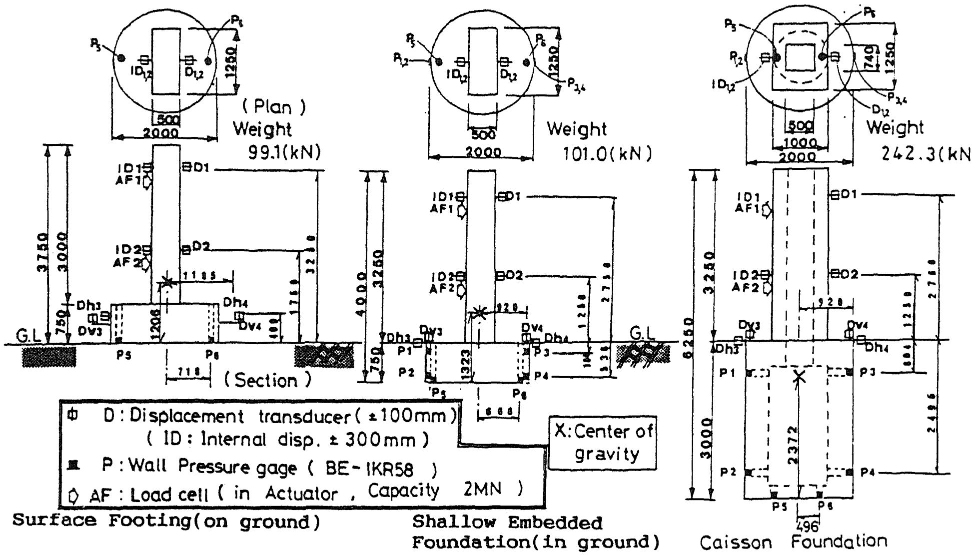


Fig. 3 Outline of ground-rigid foundations

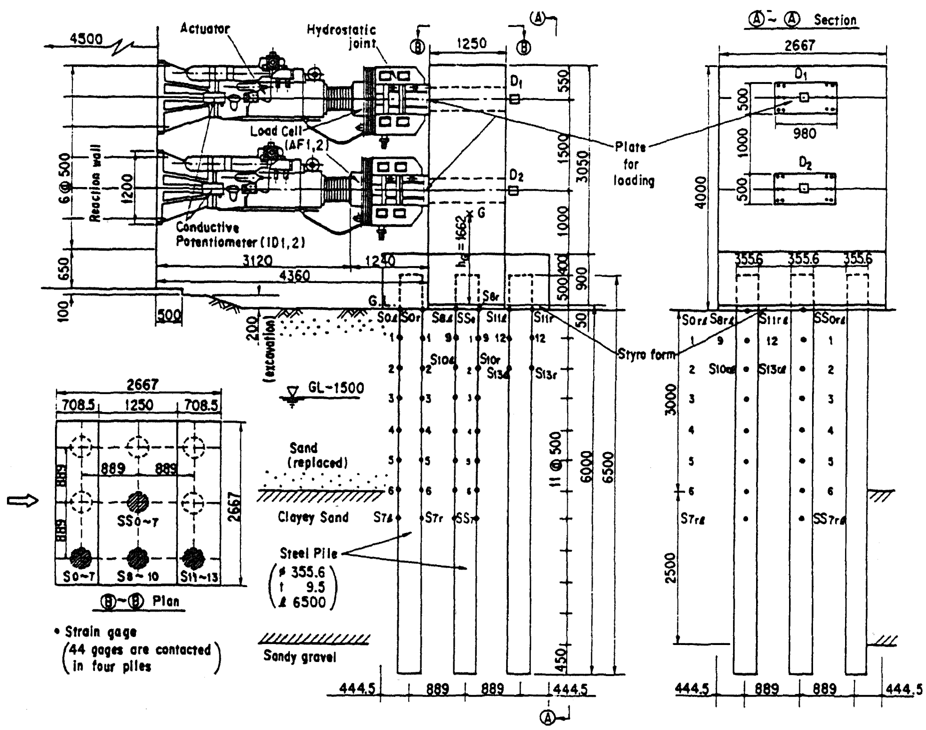


Fig. 4 Outline of ground-pile foundations

representativelly 9-pile group in Fig. 4. The spacing between the piles were set to provide a spacing-diameter ratio of 2.5. This ratio, according to the Japanese Seismic Code, is believed to minimize the pile-soil-pile interaction and allows the neglection of the grouping effect in pile group foundations design. The pile heads were rigidly connected (fixed) to the caps, to isolate the systems from any probable cap-soil interactions. Displacement pickups and strain gages were fixed along the pile shafts.

The main purpose of this study is to

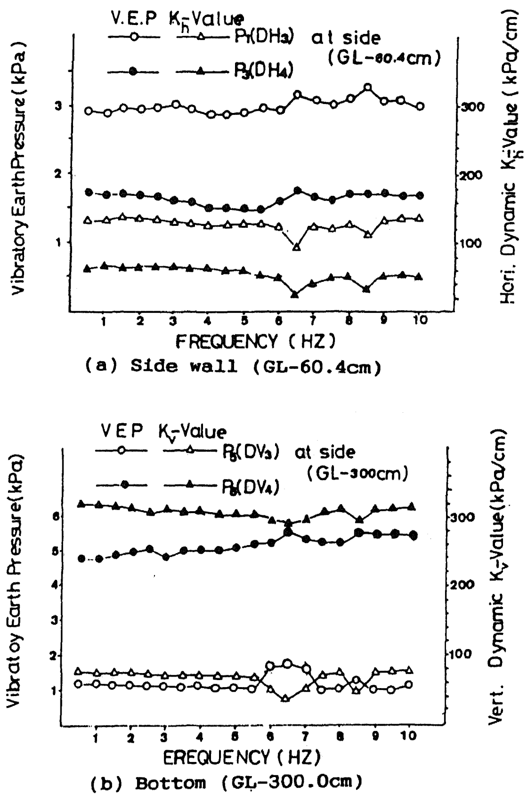
obtain seismic nonlinear soil-structure interaction, that is, on how many the influences of adjacent ground have the dynamic characteristics of foundations.

4 RESULTS OF EXPERIMENTS AND DISCUSSIONS

Frequency response curves of phase delay and magnification (displacement or angle was divided by the reaction of actuator) were obtained by the forced vibration dynamic tests concerning Caisson. Frequency dependent curves of vibratory earth pressure and horizontal and vertical dynamic K-values are shown in Fig. 5 (a)(b), which are obtained on either sides of foundation (P_1, P_3 at G.L.-60.4cm) and at bottom (P_5, P_6 at G.L.-300cm). Dynamic K-values are obtained from the maximum vibratorv earth pressure divided by the maximum response displacement. Vibratory earth pressures on both sides of wall and bottom show the peak value at the resonant frequency about 6.5 Hz. On the contrary, the dynamic K-values decrease at the resonant frequency. Time histories wave form of both vibratory earth pressure at the bottom of S.F. and vertical response displacement in Taft with 180 cm/s² are shown in Fig. 6 to obtain dynamic K-value. Surface Footing vibrates in rocking mode because vertical displacements and vibratory earth pressures at the opposite to the center of bottom show a reverse phase. It is found that both wave forms vibrate differently from the center line after about 2 or 3 seconds. Plastic deformation was seen as soon as the maximum acceleration was introduced.

Considering the restoring force hysteresis behavior, pile group stiffness increases as the number of pile in group does. The restoring force characteristics of 2-pile and 3-pile groups by complex stiffness A models are shown respectively in Fig.7. Comparing pile group drop rate of stiffness ((initial tangential stiffness - secant stiffness)/ initial tangential stiffness), the drop rate of 3-pile groups stiffness is smaller than that of 2-pile groups. 3-pile groups looks to vibrate more linearly in both the sway and rocking modes than 2-pile groups.

Considering the contributions from individual piles, the response of each pile is different in the axial strain and bending strain. Each strain responses of 9-pile groups by the HENESSI test results in the complex stiffness model A at the point of G.L.-1m are shown in Fig.8 to 9. Comparing the wave forms of ②, ③, ④ piles, the phases of the axial strains in ②, ④ piles are reverse. On the other hand, am-



(a) Side wall (GL-60.4cm)

(b) Bottom (GL-300.0cm)

Fig. 5 Vibratory earth pressure and dynamic K-value (forced vibration dynamic test of caisson)

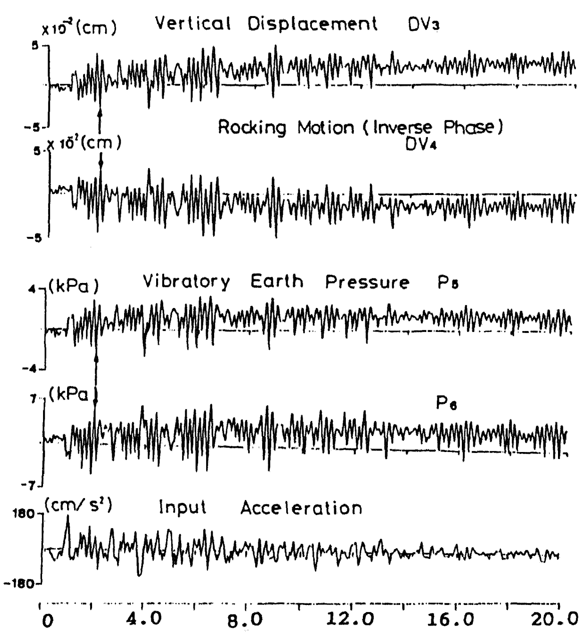


Fig. 6 Time series wave form of vibratory earth pressure (Surface Footing, Taft, 180 cm/s²)

plitude of pile is small, therefore ③ pile is the center of rocking mode. Axial strain is caused by the bending moment. The phase of the bending strain in②, ③, ④ piles are almost the same, therefore bending strain is caused by the horizontal force. The response amplitude of axial strain by the continuous swept wave motion is about 2times, and those of bending strains are about 4times larger than those of Taft with the maximum acceleration of 240 cm/s² . The resonant frequency 4.5 Hz can be obtained from the maximum response of 9-pile groups by the continuous swept wave motion. The behaviors of the continuous swept motion provide emphasised, suggestion for the study of the pile group effects.

5 CONCLUSION

By using HENESSI which has been developed for hybrid experiments, earthquake response characteristics of large scaled models can be tested in order to study nonlinear seismic soil-structure interactions. Three large scale Surface, Shallow-Embedded, Caisson, and four single, 2, 3 and 9-pile group foundation models were used. For each, three different stiffness models for the half-space were established from results of static and forced-vibration dynamic tests. The important results obtained in this study are summarized as follows.

(1) Frequency dependent vibratory earth pressures show the peak value at the

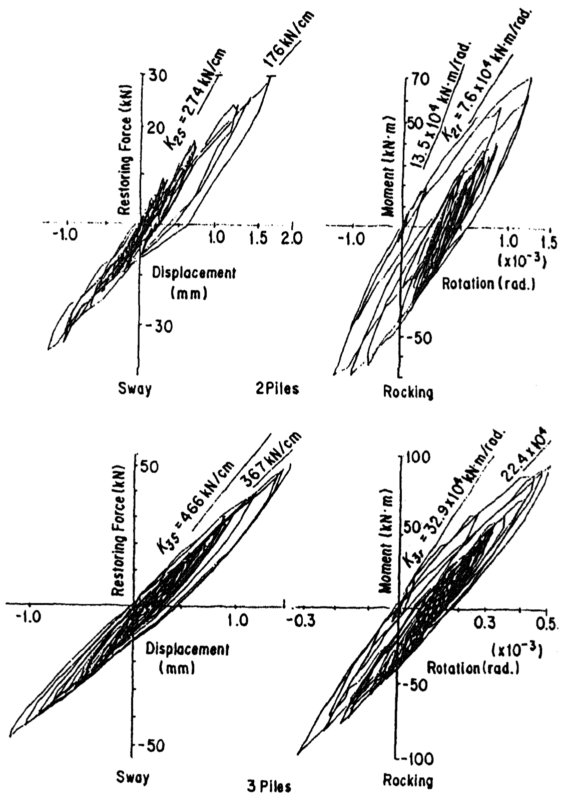


Fig. 7 Restoring force characteristics (SW part of Ibaraki,180cm/s²)

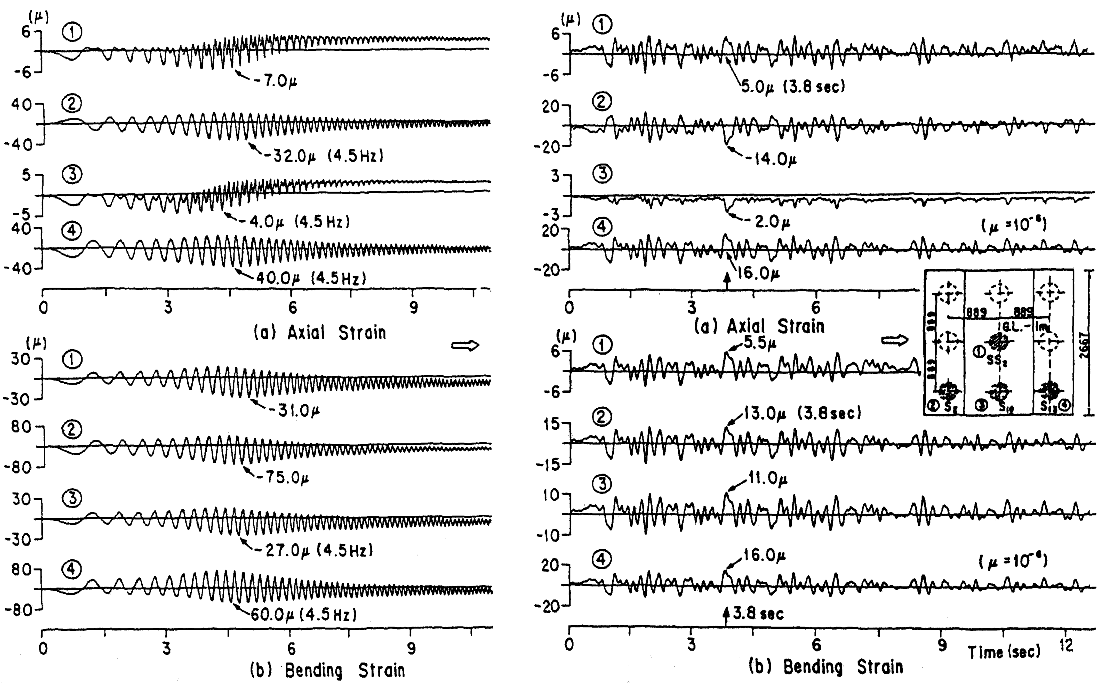


Fig. 8 9-pile group strain (Taft 240 cm/s², at G.L.-1m) resonant frequencies of rigid foundations. On the contrary, the dynamic K-values decrease at that frequency.

(2) Vibratory earth pressures increase and dynamic K-values decrease corresponding to increase in input acceleration.

(3) Axial strain is caused by the bending moment. Bending strain is caused by the horizontal force, compared to the strain distribution of individual piles.

(4) The behavior by the continuous swept motion provides emphasised, helpful suggestion for study of the pile group effects, depending mainly on the number of piles.

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