(81) SEISMIC NONLINEAR HYBRID EXPERIMENT ON PILE FOUNDATION SYSTEMS

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ABSTRACT

Seismic pile groups were studied by means of Hybrid Experiment in which nonlinear restoring forces were accounted for by Pseudo-Dynamic Tests while frequency dependent dynamic characteristics were introduced analytically in a new time domain integration scheme which is based on Hilbert Transformation. Full-size single, 2, 3(in a row) and 9(3x3) pile groups were used. Amplitude scaling technique was employed for seismic and harmonic input excitations. Pile group study was carried out through comparison of results from different experiments on foundations with different frequency dependent half-space and stiffness modelings.

INTRODUCTION The dynamic characteristics and the interaction of soil-structure systems have been well studied analytically for linear pile foundations. With the aid of digital computers, great efforts have been made with some success, to take account of nonlinearities. But, as the object of practical analysis is to predict the overall response of a large system composed of soil and a structure during an earthquake, it necessarily involves a number of assumptions about and limitations on wave propagation characteristcs, dynamic soil properties, mathematical modeling of soil-structure systems, equivalent linear idealizations, presumed nonlinear behavior, and the use of numerical techniques. An assessment of reliability can only be made by comparing the results of a sound experiment with the corresponding predicted values. To be able to do this, good experimental methods are necessary. Although a number of methods are known, they loose accuracy when test results of small models are interpreted for actual systems.

PROCEDURE Taking advantage of analytical idealization, a time domain numerical integration scheme, and large scale modeling, and using Pseudo-Dynamic Testing (PDT), we developed a hybrid method with which to study the seismic nonlinear behavior of soil-structure systems. We developed an algorithm in which we imply PDT in order to study the seismic nonlinear behavior of soil-structure systems and their frequency dependency. Our procedure, a flow-chart for which is shown in Fig.(1), is named HENESSI which stands for Hybrid Experiments on Nonlinear Earthquake-induced Soil-Structure Interaction. The procedure starts with large scale modeling following mathematical discretization of the soil-structure system. Lumped parameter discretization leads to a governing system of second-order ordinary differential equations for dynamic equilibrium. Static and forced vibration dynamic tests are carried out on these equations, from which the mechanical characteristics of the system are determined. Frequency-dependent dynamic characteristics are determined through the phase delay study of forced vibration tests. Using these results, we constructed the complex frequency-dependent stiffness matrix of the system in the frequency domain then, using Hilbert and inverse Fourier transformations, established a time-history-dependent pseudo-force that we used to decompose the equations of motion into equations for the initial, nonlinear and time-rate-dependent characteristics of the system[1].

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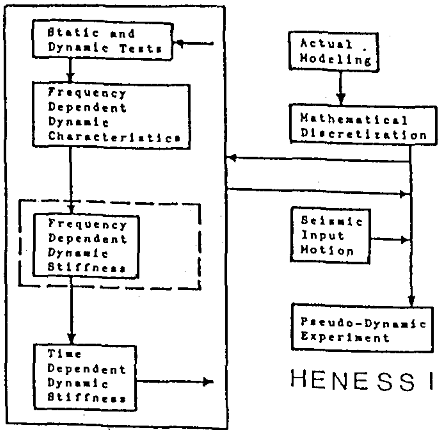

Fig.(1) : Flow of HENESSI

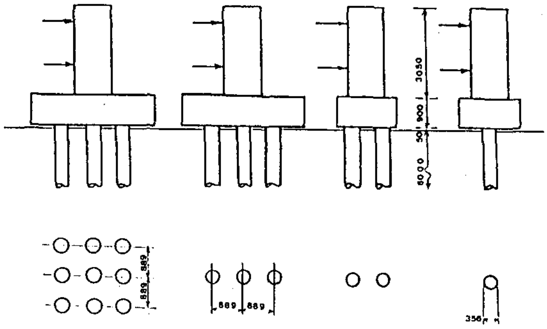

Fig.(2) : Test Set-Up

TEST SET-UP We used four pile foundation models; Single-Pile(1P), 2-Pile(2P), 3-Pile(3P) and 9-Pile(9P) Group foundations. Only two degrees of freedom were assigned for the systems. Although two actuators were used to impose deformations, and thus the degrees of freedom, we assumed the sway and rocking modes at the center of gravity of the system in our mathematical modeling. For these foundations, relative rigid super-structures were constructed to maintain dead weight and to transmit the forces applied by the actuators to the soil-structure interfaces, Fig.(2).

HYBRID STUDY In our hybrid analysis the structural system is considered an assembly of structural elements interconnected at foundation center of gravity where its mass is assumed to be concentrated, Fig.(3). The deformation state of this idealized discrete parameter system is determined by the sway and rocking modes chosen as the two degrees of freedom at the center of gravity. Given a discrete parameter model of the system, the equations of dynamic equilibrium can be deduced. By means of these equations static and forced vibration tests were performed. Results for dynamic tests on 1P and 2P are shown in Fig.(4). Using results from dynamic tests, frequency-dependent functions for stiffness and damping of the system in the sway and rocking modes are established. In considering frequency dependence, we have used two models to represent the dynamic stiffness of a soil-structure systems; a virtual mass model(VRL) for the parabolic frequency dependence of stiffness and a developed convolved stiffness model(CNV) which approximates the frequency dependence of the dynamic characteristics by utilizing a time-history-dependent stiffness function derived from the Hilbert transformation of the frequency-dependent part of stiffness. A constant stiffness and damping model(CNS) is used, in addition, for comparison. In performing a pseudo-dynamic test, the equations of motion are solved by direct, step-by-step numerical integration schemes. Electro-hydraulic actuators are used to impose the calculated structural dis-

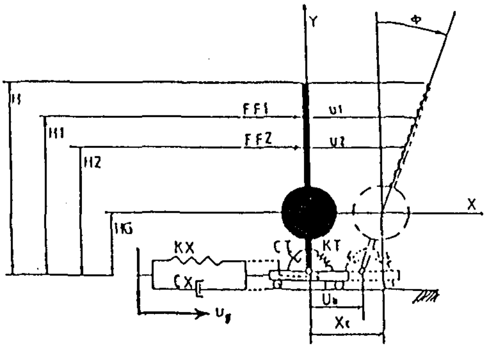

Fig.(3) : Mathematical Discretization

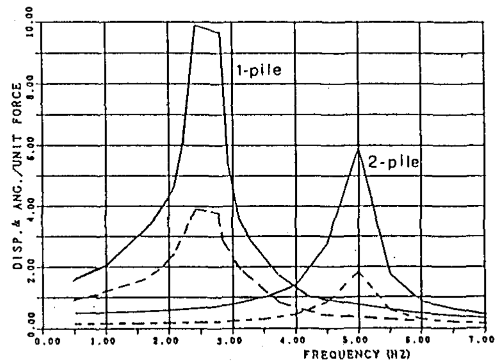

Fig.(4) : Dynamic Test Results

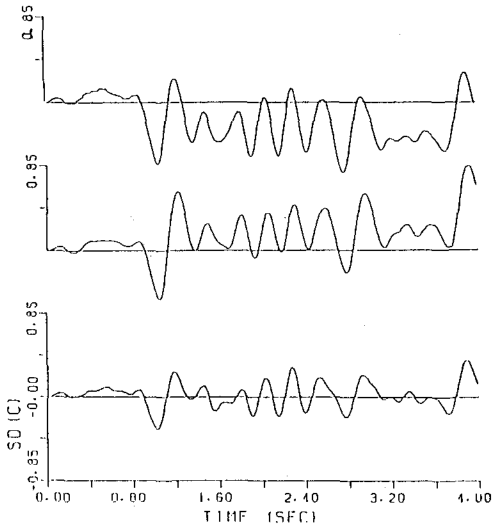

Fig.(5) : 2P-CNS, -VRL and -CNV under T-180(downwards)

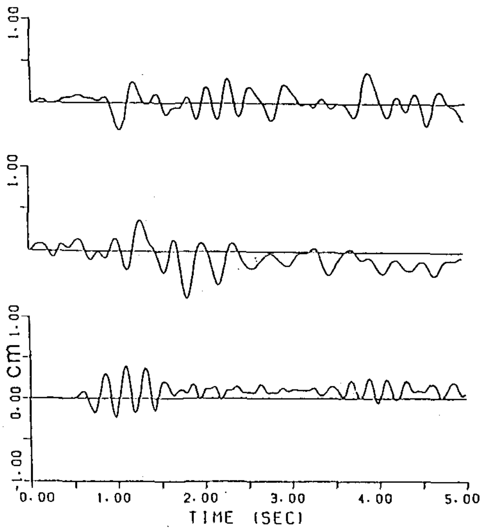

Fig.(6) : 2P-CNV under T-, H- and I-180(downwards)

placements on the system. The developed static restoring forces are measured and transformed to the sway and rocking forces at the center of gravity that are used in the next step of the numerical integration algorithm. We have utilized the Central Scheme of the Finite Difference Method, one of the most widely used explicit integration techniques for PDT. This scheme has been proven to be stable and accurate enough within our chosen range of frequency and time interval.

TESTS AND RESULTS Three different accelerograms; TAFT(S69E, Jul. 21, 1952), HACHINOHE(N00S, May 16, 1968) and IBARAKI(S90E, Jul. 12, 1987, observed at the site of experiments) were used in our hybrid study. For each of the inputs, we used an amplitude scaling technique by which we could excite the systems with different maximum acceleration amplitudes ranging from 120 to 300 gal. Hereafter, T,H and I denote TAFT, HACHINOHE and IBARAKI; for example, T-180 for TAFT with 180 gal peak acceleration and H-300 for HACHINOHE with 300 gal peak acceleration. Tests were performed for the 1P,2P,3P and 9P foundations with CNS, VRL and CNV modelings. Sway displacement responses of 1P- and 2P-CNV for T-120 through

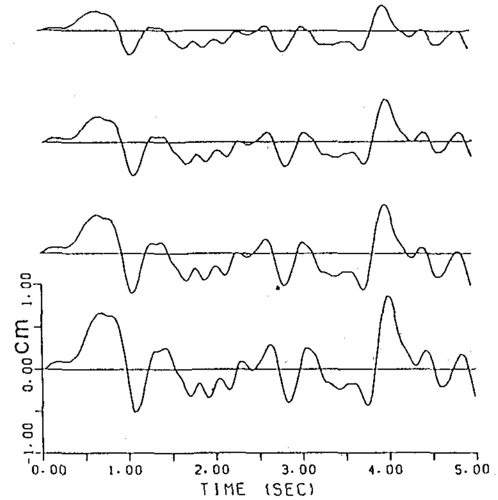

Fig.(7) : 1P-CNV under T-120 through -300 in Sway (downwards)

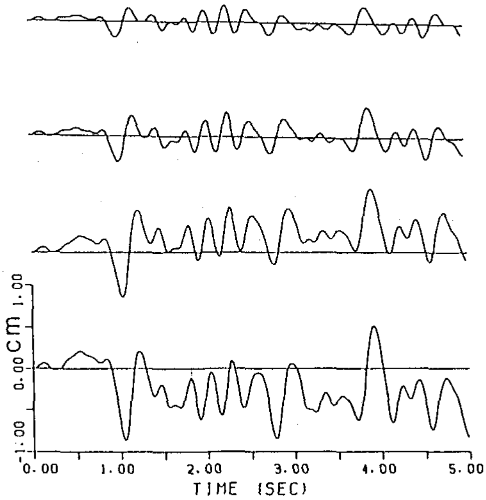

Fig.(8) : 2P-CNV under T-120 through -300 in Sway (downwards)

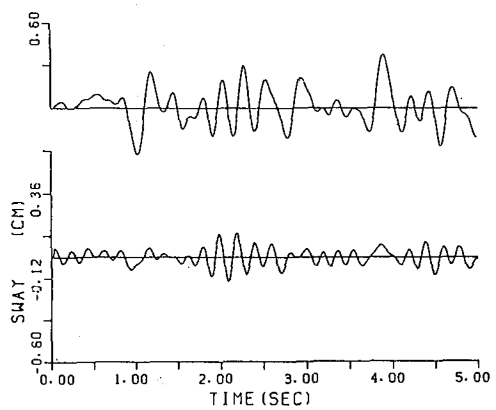

Fig.(9) : 2P-CNS under T-180; Test(upper), Linear Analysis(lower)

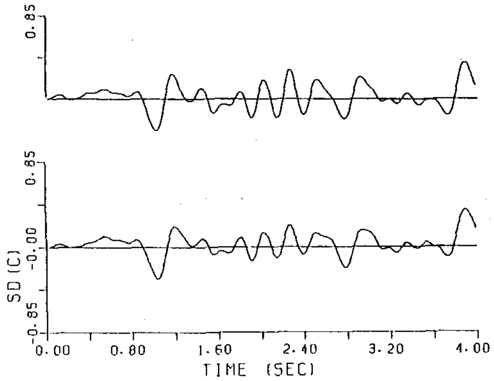

Fig.(10) : 2P-CNV under T-180 with Spring(upper) and Matrix(lower) stiffness

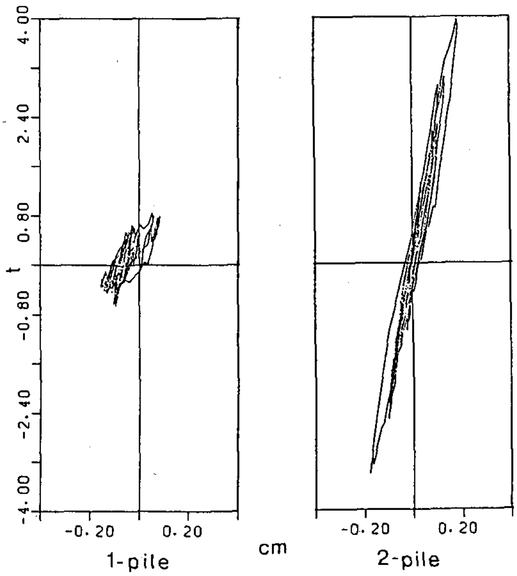

Fig.(11) : Hysteretic Restoring Force Characteristics; 1P- and 2P-CNV under T-180

-300 are shown in Fig.(7) and (8). Responses of 2P with CNS, VRL and CNV modelings for T-180 are shown in Fig.(5). Response of 2P-CNV under T-, H- and I-180 are presented in Fig.(6). In addition to the hybrid experiments we made linear analyses, using constant initial stiffnesses presented in Fig.(9) for 2P-CNS. In an another hybrid experiment we employed matrix modeling for stiffness in which we took into account nondiagonal coupling terms of system stiffness. Results are shown in Fig.(10) and compared with spring stiffness modeling. Hysteresis loops of restoring force characteristics of 1P and 2P in sway are shown in Fig.(11)

REFERENCE

1. Kenzo Toki, Tadanobu Sato, Junji Kiyono, Nozar Kishi Garmroudi and Masaaki Yoshikawa, "Development of Hybrid Experiment Method for Nonlinear Soil-Structure Interaction System", Annals of the Disaster Prevention Research Institutre, Kyoto University, No. 31 B-2, April 1988(in Japanese).