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Model studies of dynamic pile response using hydraulic gradient shaking table tests

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ABSTRACT

A new method of shake table model testing of soil-pile interaction is presented. A unique feature of this method is the use of hydraulic gradient to increase the stress level in the models, as opposed to the centrifuge technique. The testing principle and procedure are discussed. A series of free and forced vibration tests on single piles are presented. It is shown that this new testing technique provides an easy and inexpensive way to model the seismic response of piles at the field stress condition using a conventional shake table.

INTRODUCTION

Pile foundations have suffered severe damage in past earthquake events (Fukuoka 1966, Margason 1975, Sugimura 1981). Several analytical methods have been proposed to analyze the seismic response of piles under earthquake loading. These methods vary from linear elastic (e.g. Novak et al. 1978) to nonlinear solutions (e.g. Matlock et al. 1978). However, because of the scarcity of well documented field pile response data under real earthquake events, the actual performance of a pile foundation under seismic loading is still poorly understood. Thus, model tests have often been performed to study the seismic response of pile foundation, and these tests form a data base against which analytical methods can be evaluated.

The shaking table has been by far the most commonly used equipment in examining earthquake effects on soils and soil-structure systems. Many research institutes and universities have used shaking table facilities to simulate earthquake loading. However, the application of shake table tests in soil-structure interaction, especially for pile foundations, is severely limited mainly due to the small size of the model which results in low stresses in the soil. Because the stress-strain response of soil is highly dependent on the stress level, the response of the prototype will be quite different than the model. Consequently, this type of modelling test is not appropriate, and has been severely criticized. Finn and Gohl (1987) have reported the results of dynamic model tests on pile in which the centrifuge was used to increase the self stresses in the model to the field condition. However, this is an expensive approach, requiring costly

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equipment and well trained personnel. In addition, the application of seismic loading during centrifugal flight is not that easy, involving specially built facilities (Whitman 1984). Thus, the existing body of test data available on seismic soil-pile interaction at field stress condition is still meagre. Generation of such data is very much needed to validate numerical procedures.

In this paper, an inexpensive alternative method to test models on conventional shake tables but at field stress level is presented. This method, called the Hydraulic Gradient Similitude method (HGS), employs a high hydraulic gradient which causes a seepage force within the granular soil and creates a high body force. This body force results in high stresses simulating field conditions. The testing principle and its application to seismic pile response are presented.

PRINCIPLE OF HYDRAULIC GRADIENT SHAKING TABLE TEST

Similar to the centrifuge modelling technique, the HGS method is just another way of increasing soil stresses in the model. The only difference is that the body force of the model soil is effectively increased by the seepage force through the porous material rather than by centripetal acceleration. This offers the advantage that the models with escalated stress field can be mounted on the usual shake table and readily subjected to prescribed input excitation, rather than in the seismic centrifuge testing where seismic inputs have to be supplied within the high stress environment during the centrifugal flight.

For a model test subjected to a controlled downward hydraulic gradient, seepage force will increase the unit volume body force of a soil element by an amount of $i\gamma_w$. This is equivalent to increasing the unit weight of the material by $i\gamma_w$. Hence the effective unit weight, γ_m, of the model soil is:

$$\gamma_m = i\gamma_w + \gamma' \qquad (1)$$

where i is the applied downward hydraulic gradient, γ_w is the unit weight of water if water is used in the test, and γ' is the submerged unit weight of soil. Thus, the vertical effective stress in the model soil has increased at any depth, z, below the surface is given by:

$$\sigma'_v = \gamma_m \cdot z \qquad (2)$$

and the HGS scale factor, N, is defined as:

$$N = \frac{\gamma_m}{\gamma_p} = \frac{i\gamma_w + \gamma'}{\gamma_p} \qquad (3)$$

where γ_p is the effective unit weight of the soil in the prototype, which could either be total or submerged unit weight depending upon the ground water conditions in the prototype soil. Thus, when the 1/n scaled model test is performed under a hydraulic gradient scale factor N=n, the stresses due to the self-weight of soils at homologous points of model and prototype will be the same, i.e., the scale factor for stress is unity. If the same soil is tested and the same stress path is followed in the model as in the prototype, the strains in the model and prototype will be the same (Roscoe 1968), i.e., the scale factor for the strain is unity, while the displacements of the prototype will be larger than the model by the factor n=N. Thus, the scaling laws for the HGS tests are expected to be the same as in the centrifuge tests.

However, in the actual testing the scaling laws related to the problems studied have to be verified experimentally, as many factors may not be scaled due to technical limitations. In centrifuge tests, the "modelling of models" technique is often used, in which an assumed prototype behaviour is simulated with different scaled models under different stress fields. In this paper, this same technique will be employed to examine the HGS scaling laws for testing dynamic pile response.

HGS has been successfully applied in some model testings (Yan and Byrne 1989, 1990, 1991). Herein, a model study of seismic response of single piles to the simulated earthquake loading is presented to illustrate the application of HGS technique to dynamic testing. Test program consists of free and forced vibration tests of single piles in dense sand.

TEST SET-UP AND PROCEDURES

A test device using HGS testing principle has been developed at the University of British Columbia. A schematic of the device is shown in Fig.1. Detailed description of HGS device is given by Yan (1990).

During a test, water is continuously pumped to the sand surface. The given hydraulic gradient is obtained by controlling the air pressure in air chamber and draining the water to a low pressure at the base. Thus, pore water pressure in the soil decreases with depth, giving escalated effective stresses that increase linearly with depth. This test device is mounted on the normal shaking table, and the model tests performed as usual shaking table tests.

The soil deposit is formed of uniform fine Ottawa sand using the "quick sand" sample preparation technique (Yan and Byrne 1989). The sand deposit is 323.6 mm in height, and 404x190 mm in plan with the larger dimension in the shaking direction. No soft material is used at soil container walls to simulate the free field condition as it is found that the "soft" boundary is not sufficient to simulate the simple shear mode of soil motion, rather it introduces active soil failures at the boundaries when the stress in the soil is increased by the hydraulic gradient, thus violating zero strain boundary conditions before earthquake loading. The effect of rigid boundary will be discussed later in light of experimental data.

Three model piles made of 6.35, 9.53, 12.7 mm O.D. alum. tubing were used in the test program. The 6.35 mm O.D. pile is instrumented with 8 pairs of foil type strain gauges along its length to measure the bending moments. Brass masses of different weights are clamped at the pile head to simulate different structure masses.

In the free vibration tests, after a given soil stress condition is established, the pile is pushed to a given displacement at the pile head, and then released quickly to undergo free vibration. Pile head acceleration and lateral displacement are measured respectively by a miniature accelerometer at the mass centre and two LVDTs. For the forced vibration tests, a sinusoidal motion is input through the shake table at the sand base to simulate earthquake excitation. A miniature accelerometer is installed at the surface about 16 pile diameter away from both boundary and pile to measure the free field response. Measurement is also made of the base input acceleration.

RESULTS AND DISCUSSIONS

Free Vibration Test

SYSTEM STIFFNESS AND DAMPING. Fig.2 shows a typical pile head acceleration response in the free vibration test at N = 30. This is a typical response of a under-damped system. The natural frequency of soil-pile system can be obtained from the period between acceleration peaks or FFT analysis of the acceleration response. Both methods have been used and found to give very similar results. The decay in the acceleration amplitude is a result of system damping, and an equivalent viscous damping can be obtained from the logarithmic decrement of the amplitude.

A series of pile free vibration tests were performed at different hydraulic gradients but at the same initial lateral displacement to evaluate the stress level dependency of the soil-pile natural frequency and damping. Fig.3 shows the relation between natural frequency, f_n, of the soil-pile system and the HGS scale factor, N. It is shown that as the hydraulic gradient increases the natural frequency of soil-pile system increases, and can be expressed as a power function of soil stresses. If the natural frequency, f_n, of the pile is normalized by the 1st natural frequency of the soil deposit, i.e. $f_n = V_s/4H$, where V_s and H are respectively the shear wave velocity and depth of soil deposit, the normalized soil-pile natural frequency appears to be independent of soil stress level, as also shown in Fig.3.

Fig.4 shows the equivalent viscous damping of soil-pile system determined at different soil stress levels. It is shown that the damping is nearly independent of soil stress levels, but appears to be a function of vibration amplitude. At the 1st cycle, large vibration amplitude gives a damping of about 8.6%, while at the 7th cycle smaller amplitude gives a damping of about 4%. The equivalent damping obtained from the logarithmic decrement of amplitude represents total damping of the system including material and geometric damping. The strong dependency of the measured damping with the vibration amplitude suggests that the major component of the measured damping results from material damping rather than geometric damping. Theoretical studies (Novak and Nogami 1977) have shown that material damping is the major source of system damping when the pile is vibrated in a frequency lower than the natural frequency of the soil deposit, as is the case for these tests (Fig.3). In the absence of radiation damping, the rigid boundary would have little effect on the free vibration test results.

EVALUATION OF SCALING LAWS. The scaling laws implied in the HGS test can be evaluated using the "modelling of models" technique. Three geometrically similar piles of different sizes were made, and tested in free vibration to examine the scaling law. These models were tested at the appropriate HGS scale factor, N, to produce the same prototype condition. According to the scaling laws, the natural frequencies measured in model tests, $(f_n)_m$, are related to the natural frequency of the assumed prototype, $(f_n)_p$, as in Eq.(4). This implies that the measured model frequency is proportional to HGS scale factor, N. As

$$(f_n)_m = N \cdot (f_n)_p \quad (4)$$

shown in Fig.5, the measured model frequency does vary linearly with N, indicating that in HGS tests the scaling laws are satisfied. This result also indicates that for our test conditions the effects of lateral boundaries are not significant.

Forced Vibration Test

Forced vibration tests on a given model pile were performed at a HGS scale factor of 60. The natural frequency of this model is about 18.5 Hz determined from a free vibration test. The peak base accelerations used are 0.51g and 0.43g at input frequency of 10 and 20 Hz, respectively. The input vibration frequency is changed to examine the pile response under or near the pile natural frequency.

Table 1 give a summary of peak base, free-field, and pile head acceleration values. It can be seen that for both input base accelerations a similar small amount of amplification occurs between the base and sand surface. However, this is not the case for pile head acceleration.

When the pile is vibrated under a base input frequency significantly less than its natural frequency, only a small amount of amplification from free field to pile head occurs. On the other hand, when the pile is vibrated under a base input frequency close to its natural frequency, significant amplification occurs at the pile head acceleration. At this resonant condition, the acceleration at the pile head is about 3 times higher than that in free field.

Such a high pile head acceleration produces a significant increase in the pile bending moment. Fig.6 shows a comparison of pile bending moment distributions between resonant and non resonant conditions. This bending moment distribution is very similar to that observed from centrifuge test (Finn and Gohl 1987). The maximum bending moment occurs at a depth of 3.5 pile diameter below the surface. It is seen from this figure that the maximum bending moment for the near resonant condition is about 4 times higher than that for the non resonant condition. Thus, it is important in the design to avoid resonant condition, and provide enough damping and ductility to control the amplification and prevent pile bending damage should resonance occur.

SUMMARY AND CONCLUSION

In this paper, a new method of performing seismic shake table tests at a field stress condition is presented. The unique feature of this method is the use of the hydraulic gradient to increase the stress level in the models. Scaling laws implied in dynamic HGS tests have been evaluated and found to be satisfied. A series of free vibration and forced vibration tests have been presented to illustrate the application. Relations between pile stiffness and damping with the soil stress level have been evaluated, and different pile response at resonant and non resonant conditions has been clearly demonstrated. From these test results it is shown that a conventional shake table in combination with HGS technique can provide a simple and inexpensive way of seismic model testing at the field stress condition. Such tests can enrich our data base from which the analytical methods can be checked.

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Table I SUMMARY OF FORCED VIBRATION ACCELERATION RESULTS

Base Motion	Free Field	Pile Head	Remarks
10Hz, 0.51g	0.69g	0.75g	Non Resonant
20Hz, 0.43g	0.53g	1.72g	Resonant

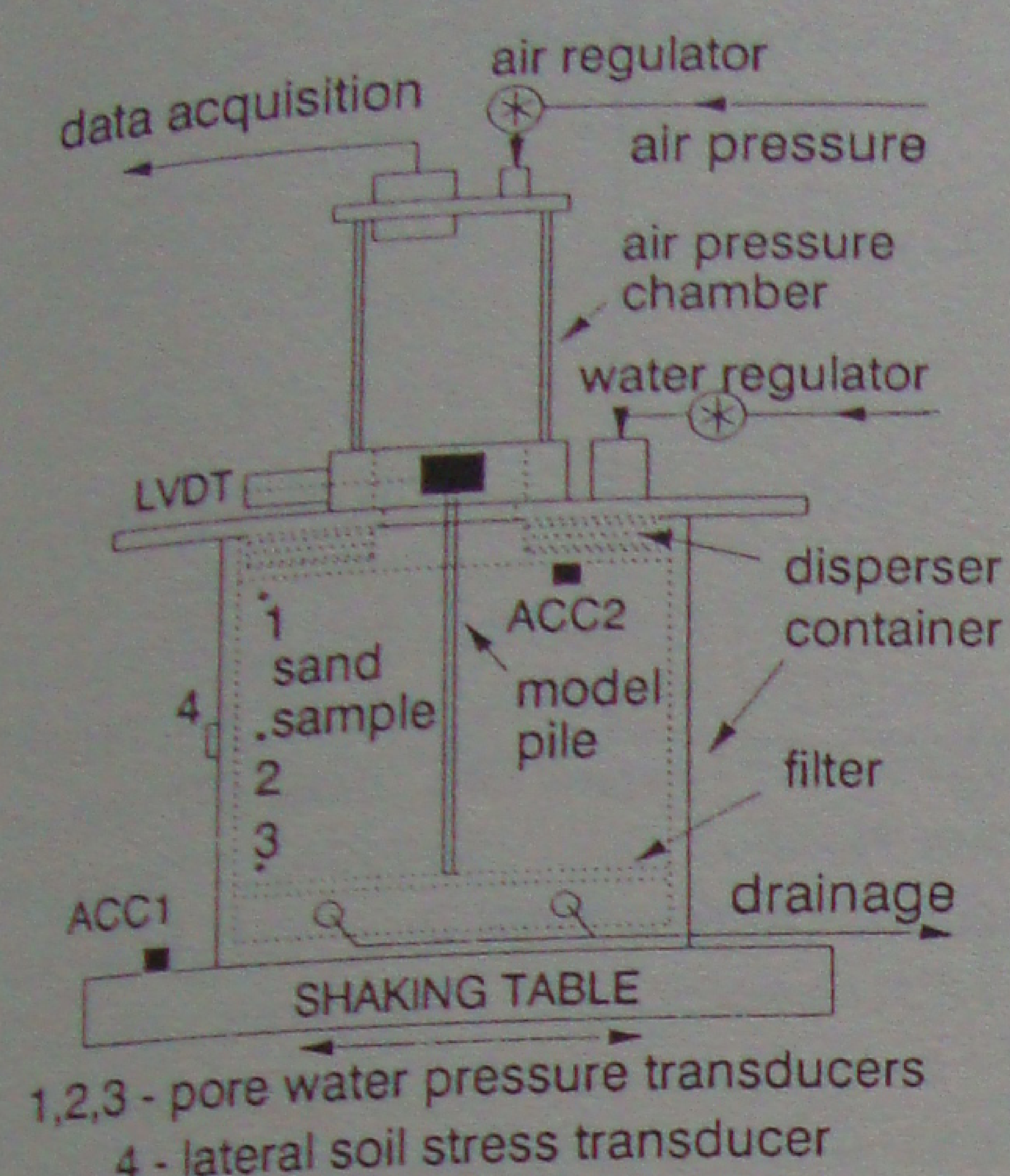

Figure 1 Schematic of HGS Shake Table Device

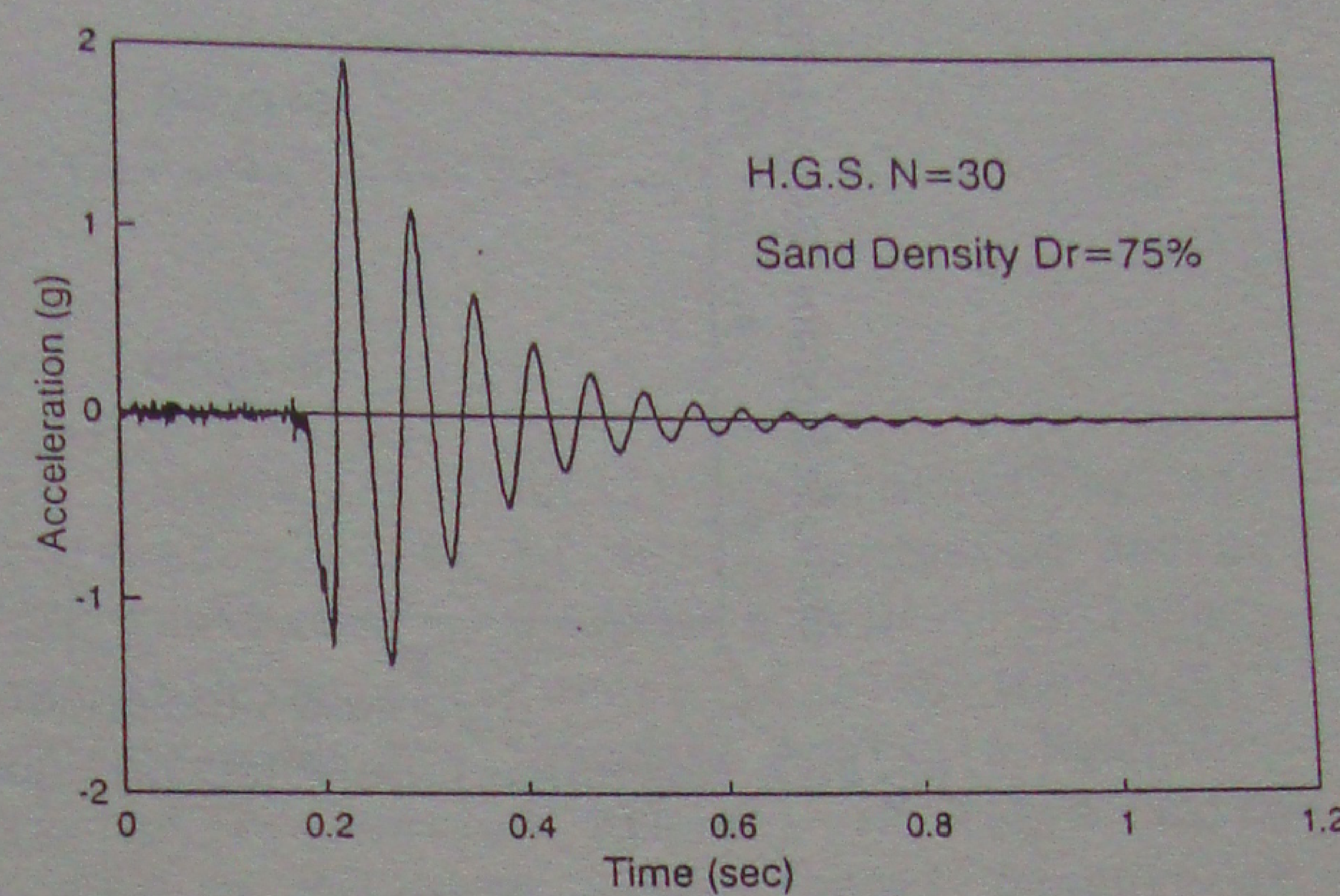

Figure 2 A Typical Acceleration Response of Free Vibration at Model Pile Head

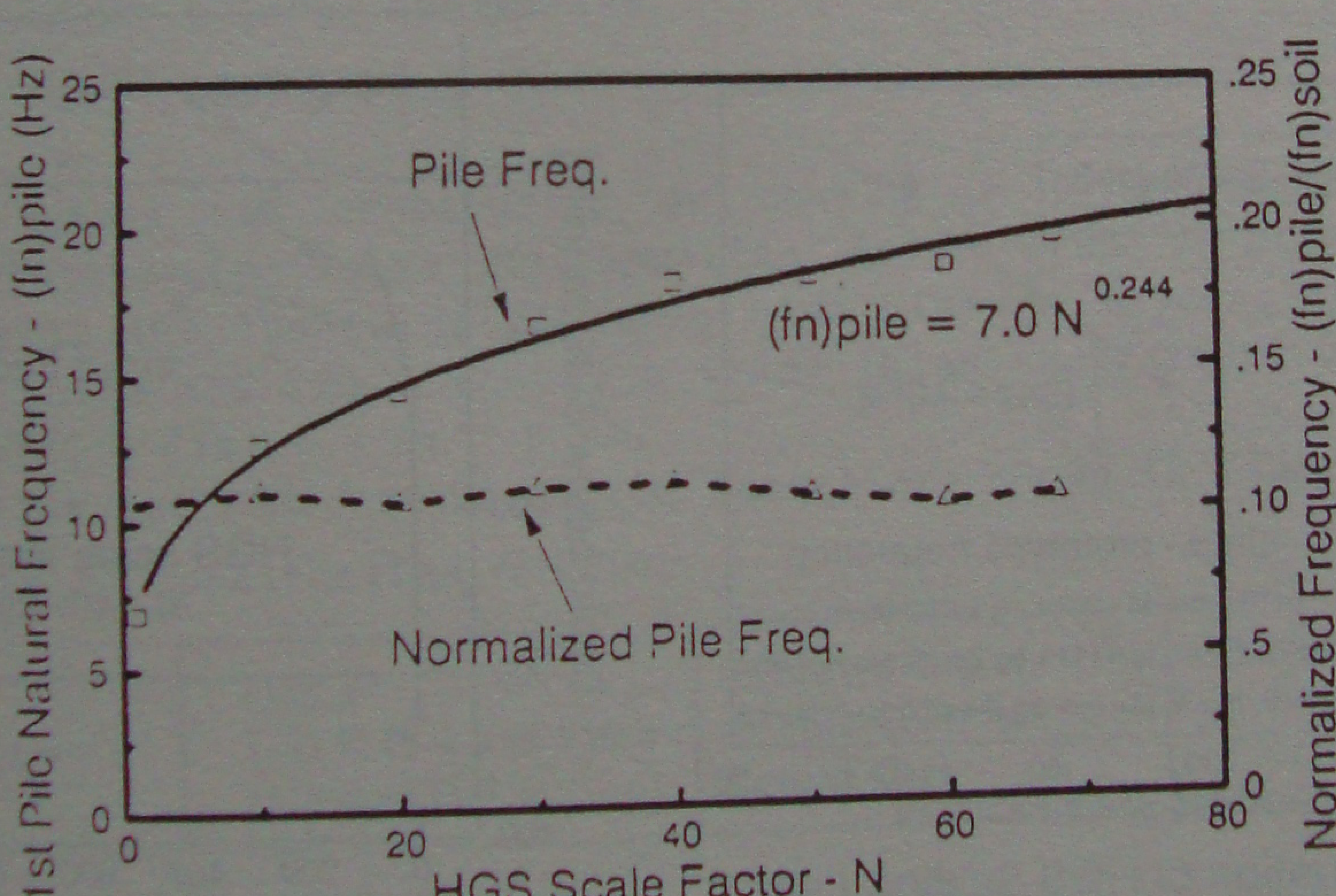

Figure 3 Soil Stress Level Effect on 1st Pile Natural Frequency

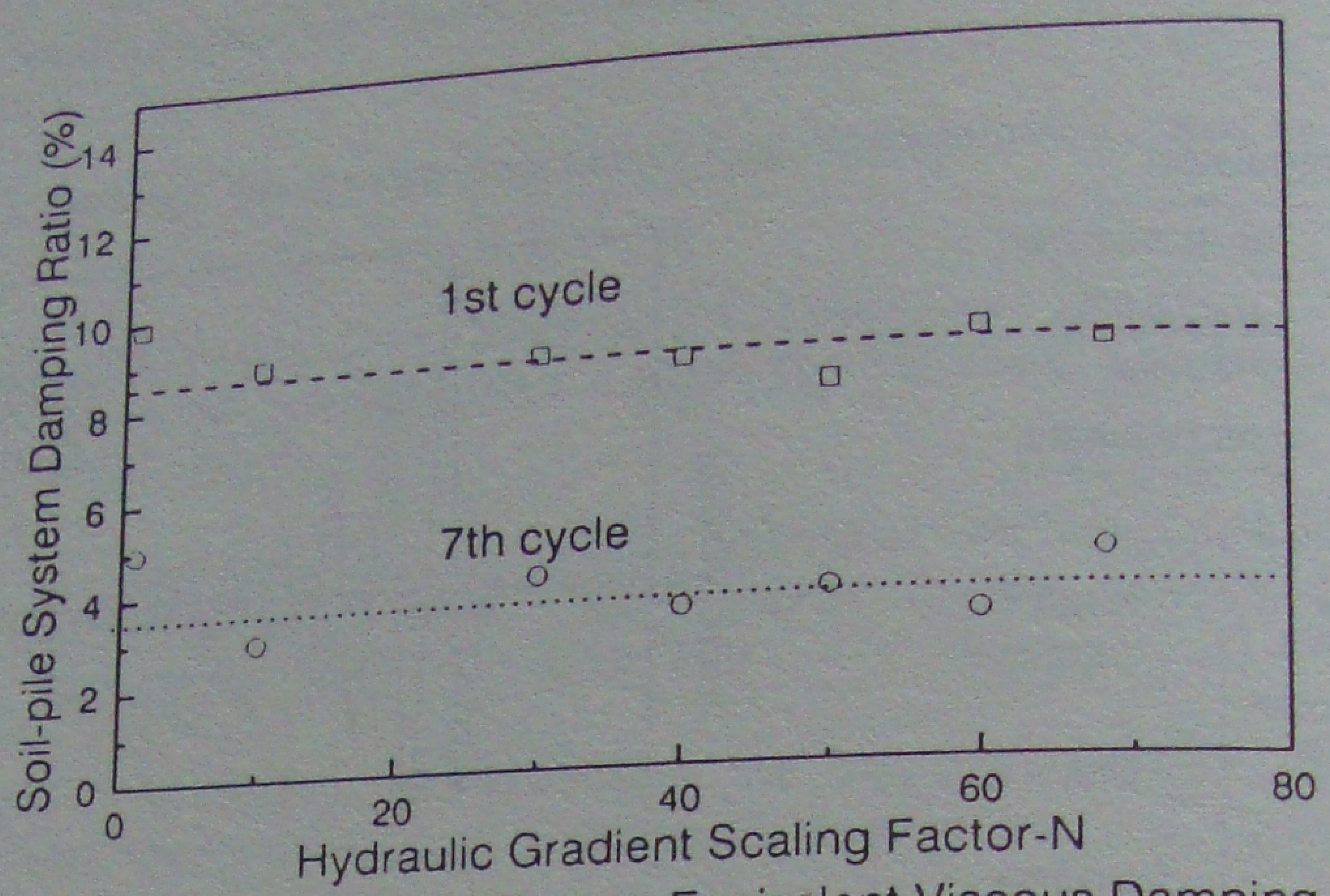

Figure 4 Soil Stress Level Effect on Equivalent Viscous Damping Ratio

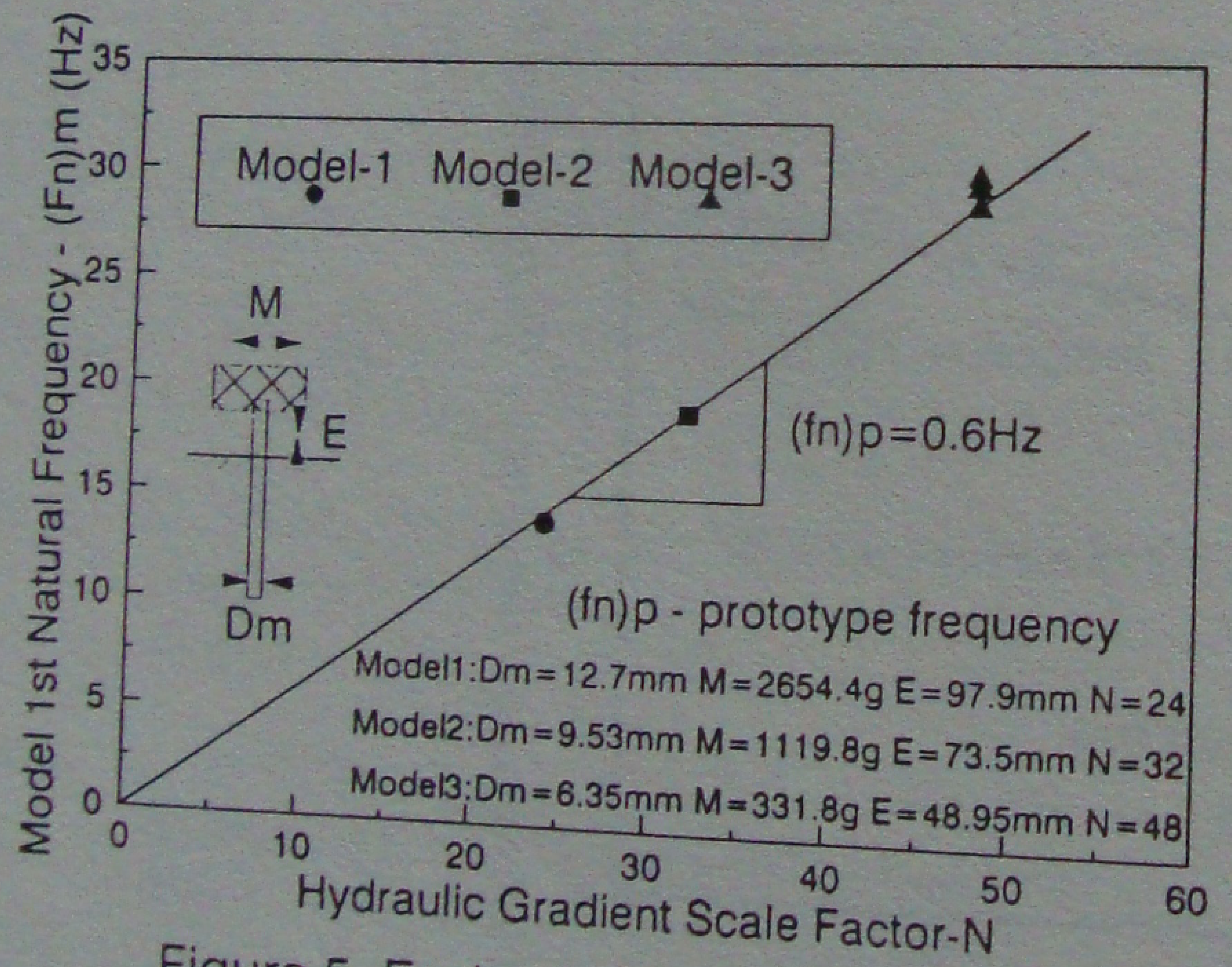

Figure 5 Evaluation of HGS Scaling Law

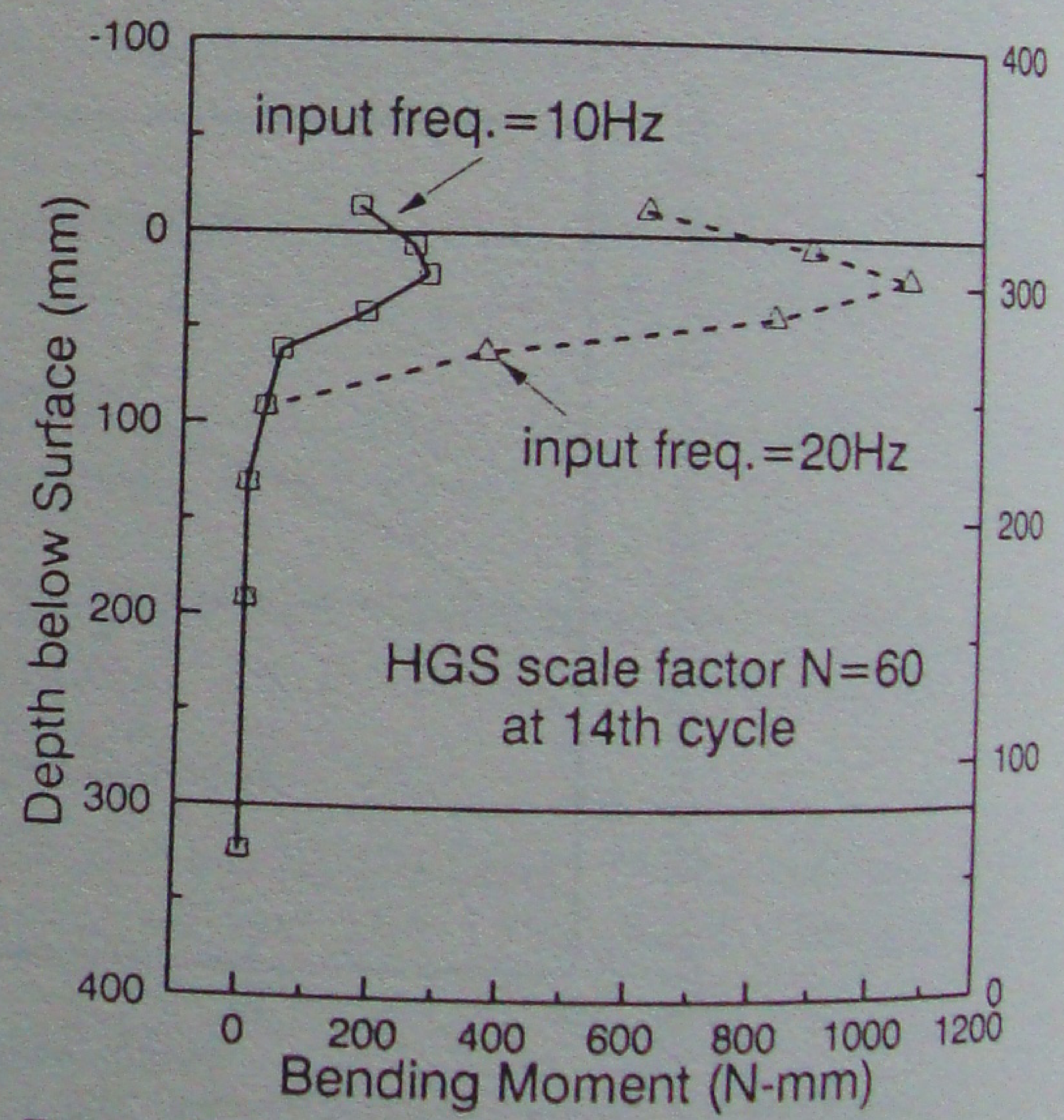

Figure 6 Comparison of Pile Bending Moment at Different Base Input Frequencies