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Measured Full-scale Dynamic Lateral Pile Responses in Clay and in Sand

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Measured Full-scale Dynamic Lateral Pile Responses in Clay and in Sand

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SYNOPSIS: In order to design machine foundations and to examine interaction between pile and soil, versatile horizontal dynamic loading tests were done to piles. In the tests both stiffness and damping values of piles were measured in overconsolidated clay and in earthfill sand. The stiffness of piles was analyzed by Winkler's spring method and the damping of piles with Gazetas' and Dobry's method. The measured and calculated values were almost the same when stiffness was considered. In damping the measured values were about 40...70 % of the calculated values. Very important in the calculation is to know which is the gapping between pile and soil. In these tests the gapping was not measured.

INTRODUCTION

Because of the strict deformation requirements and the small allowable amplitudes caused by the dynamic loads the machine foundations often have to be put on piles.

When designing piled machine foundations, the dynamic analysis is made to find out the systems amplitudes related to excitation frequencies and excitation forces. In the dynamic analysis the combined piles/foundation/subsoil system has an effect on the systems stiffness and damping properties and thus on the magnitude of the amplitudes. In reality, machines often have to be run in some of their many resonance regions, in which case damping is required in order to maintain the machines defendability and to keep the amplitudes within allowable limits. In the optimal design of this kind of machine foundations the knowledge or right damping degrees is of crucial importance.

Generally it is more difficult to plan piled machine foundations for horizontal than for vertical forces. One reason for this is that often horizontal stiffness of piles is much smaller than vertical stiffness.

There are many theoretical solutions in the pile dynamics. These theoretical solutions are often based on visco-elastic theory in the half-space. Unfortunately the soil deposits are not homogeneous. In reality soil deposits have several layers of different soils. On the other hand the visco-elastic theory presumes that the displacements are linear with force. However near the surface of soil deposits there is the gapping phenomenon which is very difficult to measure and calculate accurately.

One other difficulty is to define the interaction between piles because stiffness and damping are dependent on frequency, especially in pile groups. Only few published articles of dynamic loading test of piles can be found so far. That is why it is important to verify theory by tests.

GENERAL ASPECTS

The horizontal dynamic loading test of piles were done in summer 1989, in order to examine interaction between piles and soils. The tests were carried out in Järvenpää at the area of Valmet Paper Machinery in Finland.

In the pile tests four single piles and a pile group of four piles were loaded with a dynamic force. The frequency was between 2...20 Hz. The amplitudes were limited to the linear area. The amplitudes in the ground were usually less than 80 um. The single piles were two driven reinforced concrete piles 300 x 300 mm^2 and two driven steel piles ø 273 x 9,3. The steel piles were filled with concrete. The piles of pile group were driven reinforced concrete piles 300 x 300 mm^2.

One single reinforced pile and one single steel pile were both in clay and in earthfill sand. The depth of the compacted earthfill was two meters. Single piles were measured with four different masses. With different masses it was possible to observe natural frequencies in wider range.

SOIL INVESTIGATIONS

The versatile soil investigations were made both with static and dynamic methods. The dynamic parameters were investigated by resonant column method in laboratory and with down-hole method in situ. In figures 1 and 2 results from some of these soil investigations can be found.

The original soil in test area was to the depth of 4.5 meter overconsolidated clay. The first 1.5 meters of the soil was a layer of dense, dry crust and it was taken away before tests.

Under the clay there were layers of silt and sand. The undermost layer on the rock was till. The thickness of the whole soil layer was about 7...10 meters. The soils in the test area are Quaternary glacial or postglacial deposits which are sedimented during or after last ice age.

MEASUREMENTS

The test loading was carried out as a mode measurement. The piles were loaded with random and sinusoidal excitation. In figures 3 and 4 the arrangements of tests are shown.

From the response of random excitations, the natural frequencies, natural modes and damping values were analyzed. With sinusoidal excitation also amplitudes of constant force in different frequencies were measured. In fig. 5 the typical frequency response function of random excitation is shown. Besides of dynamic loading tests, also static tests were carried out.

ANALYSIS

General

In the analysis of the tests the measured and calculated results were compared with each other. The calculations were done using results from site investigations.

The results of calculations were very much dependent on the separation in the upper part of soil layers near the surface. In the tests the gapping was not measured. In the analysis it was assumed that separation was 400 mm in single piles and 200 mm in pile group.

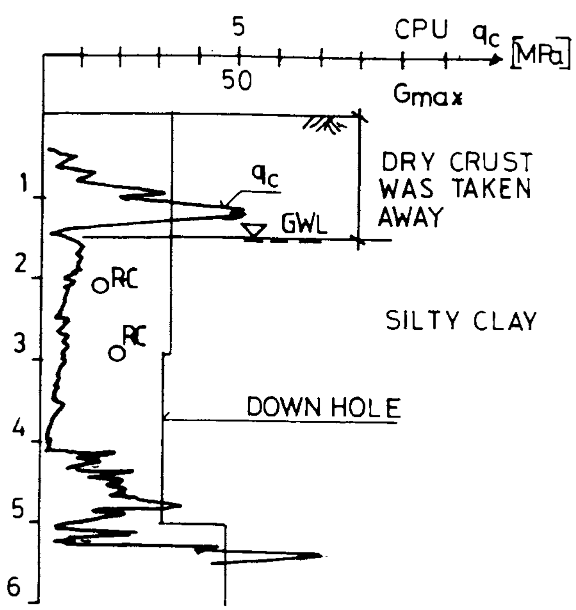


Fig. 1 Soil Investigations in Clay

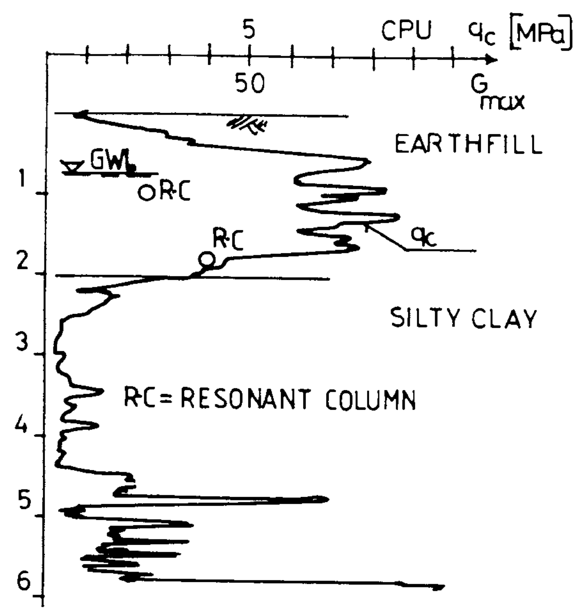


Fig. 2 Soil Investigations in Earthfill Sand

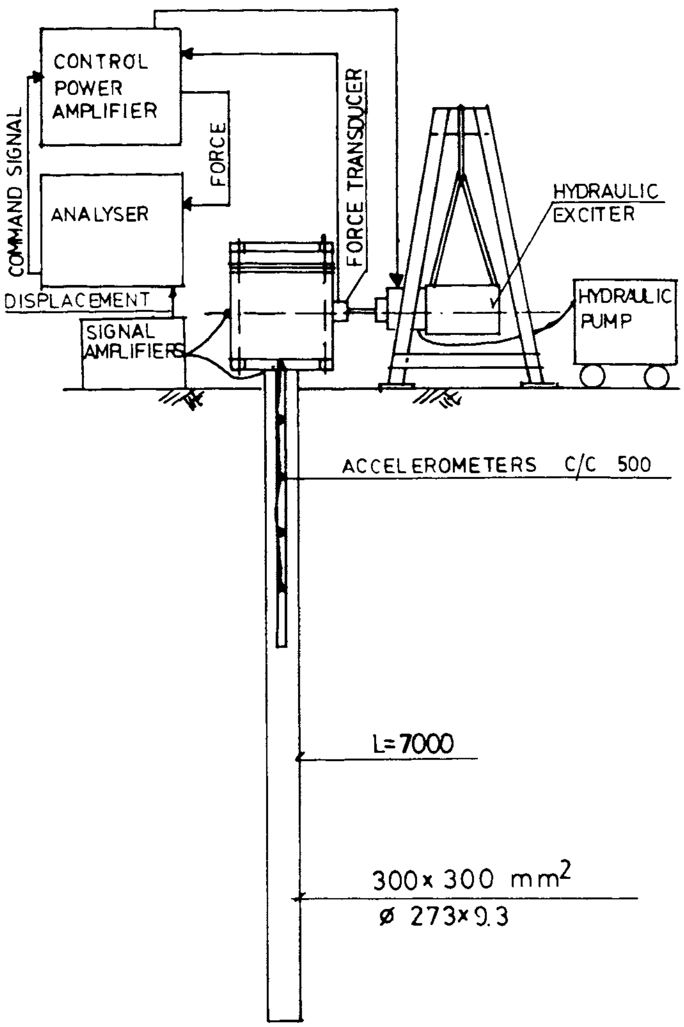


Fig. 3 The Arrangement of the Loading of a Single Pile

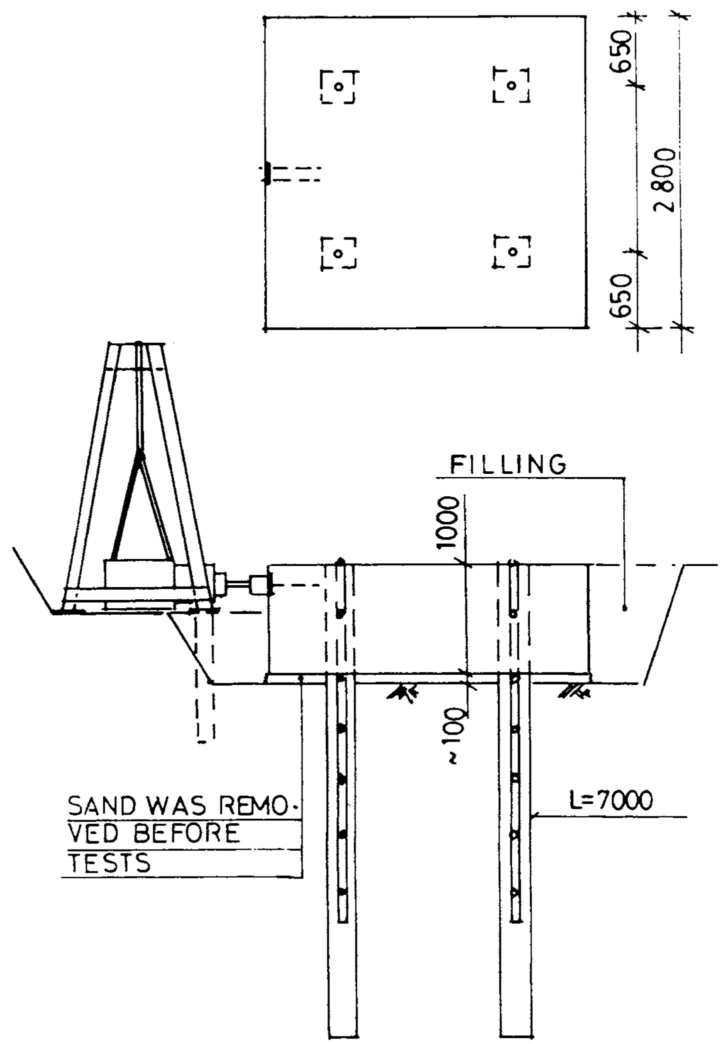


Fig. 4 The Arrangement of the Loading of the Pile Group

The single piles

Stiffness

The horizontal stiffness was measured with natural frequencies. The horizontal stiffness was calculated by using Winkler's spring model. This method don't describe the damping realistically and with this method you cannot calculate the frequency dependent stiffness. The model of Winkler was used because of simplicity. It is also written in many papers, for example Novak (1974) that the stiffness of single pile is not dependent on frequency in the area of low frequencies. The spring values were calculated with subgrade module given by Francis (1964). The methods to calculate subgrade modules for pile tests are many in litterature. The variation of these methods is quite large. In reality the response of horizontal loaded pile is more dependent on separation of pile and soil than the exact values of spring constants.

When comparing the measured values with the calculated ones it was found out that the stiffness is not dependent on frequency in the area of 2...20 Hz in this test. In fig. 6 the measured and calculated natural frequencies are shown. With supposed separation the measured and calculated stiffness are nearly same. In fig. 7 a typical natural mode is shown.

The stiffness of piles depends very little on the size of amplitudes. The unlinearity of soil in large amplitudes is balanced by linear quality of piles. The stiffness of piles in static tests were nearly the same as in dynamic tests.

Damping

Damping was measured from random excitation and from sinusoidal excitation by dynamic response curve in resonance. In analyses damping was calculated with the Gazetas' and Dobrys' (1984) method. In calculations pile mode and the results of site investigation was utilized. The measured and calculated values were different. Usually with sinusoidal excitation measured damping values were about 40...70 % of the calculated values. Without the supposed separation the calculated values would have been much higher. In fig. 8 the measured and the calculated damping is shown. The damping values of mode measurements were smaller than values of sinusoidal measurements. The growth of damping was similar to that in visco-elastic theory. Generally damping began to grow more strongly when the loading frequency was over 10 Hz. According to the visco-elastic theory the radiation damping will develope when the loaded frequency is over the natural frequency of soil layers. This calculated natural frequency was about 4...6 Hz.

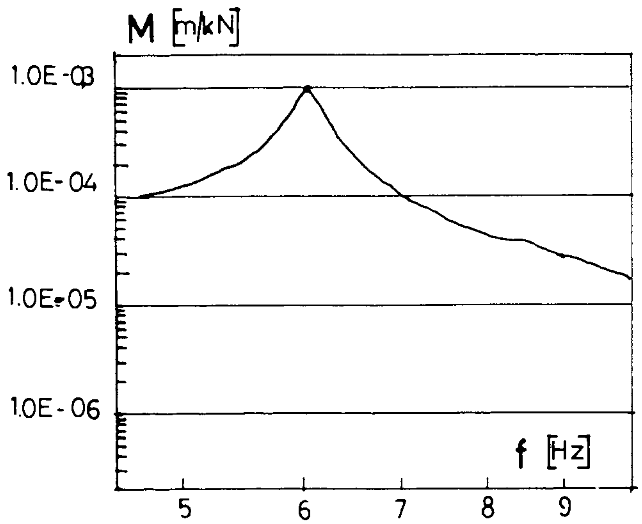


Fig. 5 Typical Frequency Response Function

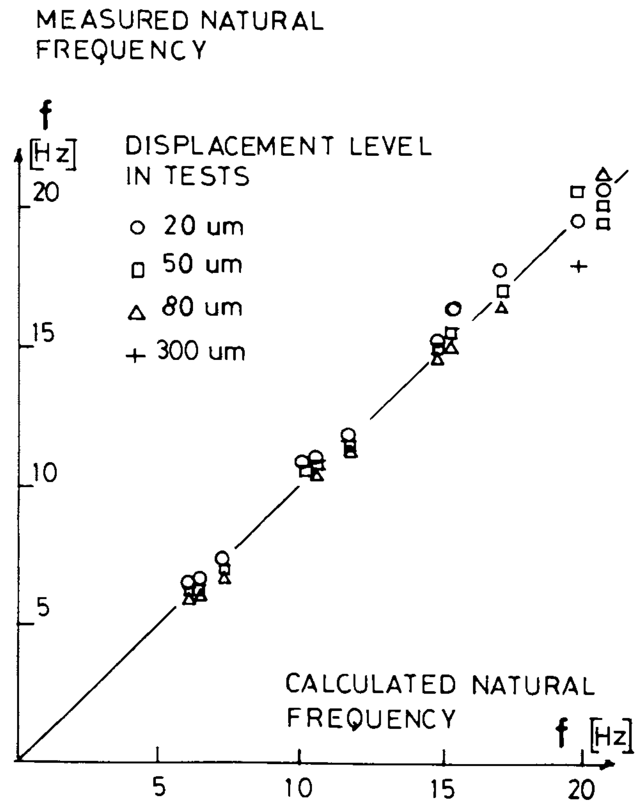


Fig. 6 Measured and Calculated Natural Frequencies

Gapping

The gapping has a very great significance to stiffness and damping. The gapping can also be partial. In calculation it is possible to get the same measured and calculated stiffnesses with different gapping assumptions by changing the spring values in calculation model.

In the pile tests the gapping could not be measured. The gapping was visually seen in the piles which were driven in sand. In addition to this the gapping could be seen or detected when excavating soil away around the piles or with comparing measured stiffnesses. The gapping in sand depended clearly on the loading time. In sands the gapping will happen when the piles are loaded. Gapping which will develop during driving of piles can be avoided by compacting soil around piles after driving. In sands the effect of gapping is decreased by the small stiffness of soil near the surface.

In clay the gapping developed probably before loading. During pile driving the "pile funnel" developed around pile near surface. There is no doubt that in clay the soil is disturbed also further away from pile. This degree of disturbance is difficult to measure because phenomen is so local.

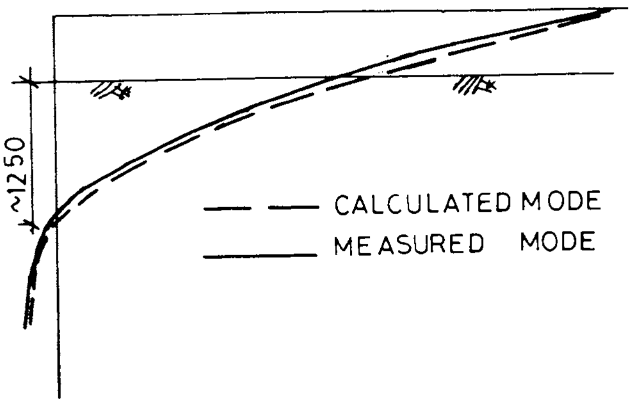


Fig. 7 Typical Natural Mode of a Single Pile

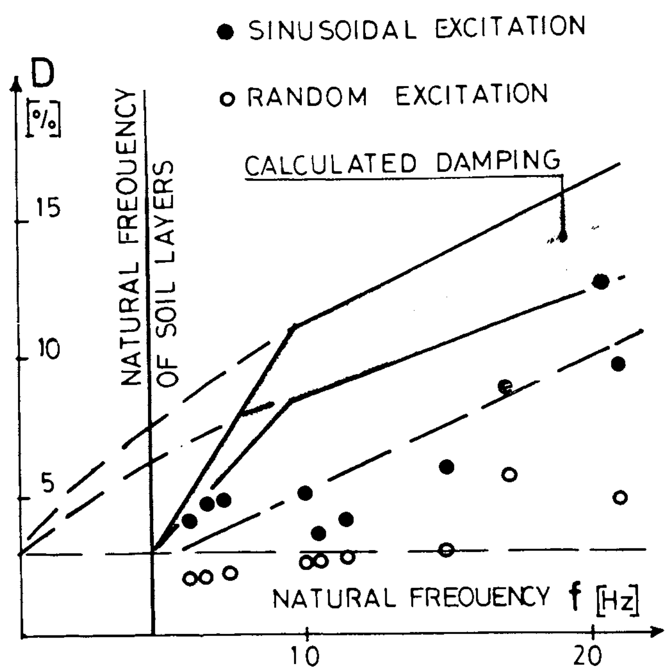
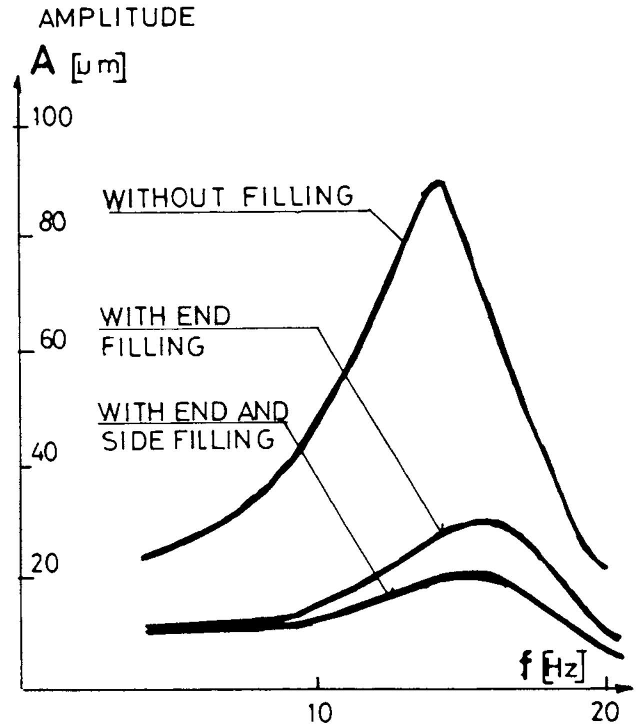


Fig. 8 Measured and Calculated Damping Values of Single Piles



	WITHOUT FILLING	WITH END FILLING	WITH END AND SIDE FILLING
STIFFNESS [MN/m]	160	210	220
DAMPING COEFFICENT C [Mg/s]	360	615	1 050
RELATIVE DAMPING D	0.10	0.15	0.25

Fig. 9 The Response of the 3 kN Sinusoidal Force Acting on the Pile Group

Pile group

The pile group was loaded three ways, without filling, with end filling and with side- and end filling. The end filling could not be made symmetric because of loadingsystem.

In fig. 9 the response of the system from 3 kN sinusoidal force is shown. In this figure there are also the damping values measured.

Measured and calculated stiffnesses were near each other when calculating stiffness with pile group coefficent 0.6. The effect of fillings were negletted.

The damping values were probably higher than the sum of damping values of single piles. However this could not be directly concluded from the results, because of different modes of the group of piles.

The fillings increased stiffness only little. The effect on damping value was bigger.

CONCLUSIONS

It would be very important to do fullscale pile tests in order to verify theories. When carrying out loading tests it is not so important to know how wide and deep the gapping is. The stiffness and damping of single pile is rather easy to measure. However, there will be difficulties in generalizing these measurements to pile groups. Also the effect of embedment around pile cap can be difficult to analyze.

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