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SOIL-STRUCTURE INTERACTION IN DYNAMIC ANALYSIS OF THE SUPERCALENDER

L'INTERACTION SOL-STRUCTURE DANS L'ANALYSE DYNAMIQUE DE LA SUPERCALANDRE

Matti Hakulinen

South-Carelia Polytechnic
Lappeenranta, Finland

SYNOPSIS: Paper machines like supercalenders often have a great number of rolls which are different in size. Although being balanced they cause dynamic forces within a wide frequency area. The machine itself, the concrete foundation and the subsoil together form the machine-foundation-soil system, which usually cannot be designed outside the resonance area. In order to keep the amplitudes within permitted limits, the foundation system operating within this resonance area needs damping. The damping of the system can be obtained by means of transferring the waves from the foundation slab to the subsoil. As to small amplitudes, the behaviour of the subsoil can be explained according to the elastic theory. In this article, the primary attention has been focused on the problems caused by applying the elastic theory in practice. Because of the many uncertainties, the exact resonance area and damping value cannot be determined. In practical design work these uncertainties must however be considered. The efficient radiation damping of the foundation system demands that the unity of the machine and foundation is rigid enough.

INTRODUCTION

A supercalender is a machine which give the paper a better surface finish for printing. While calendering, a full roll of paper is reeled trough the supercalender to the another paper roll. As the requirements for paper quality have increased, also the requirement for safe and reliable running of the machine have grown. One supercalender and its foundation is presented in figure 1.

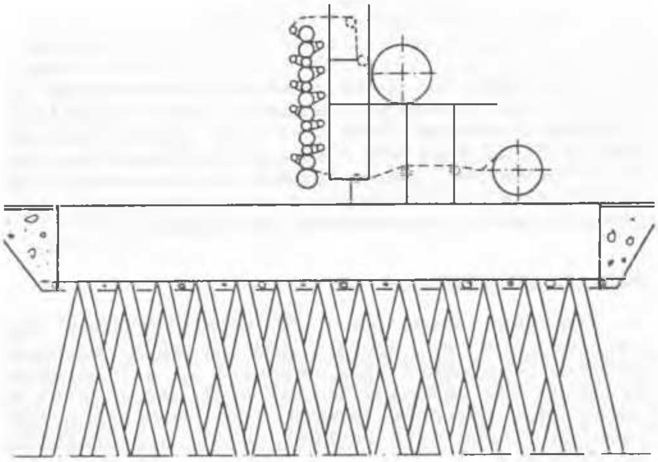

Fig. 1. Supercalender and its foundation (Hakulinen 1991b).

The eccentricities in different size of rolls cause dynamic forces to the foundation system. In figure 2 the excitation frequencies of the different rolls of a supercalender are presented during travelling speed. In figure 2 the lowest natural frequency of the machine without the foundation and the lowest natural frequency of the whole foundation system are presented. When considering the machine and the foundation, the flexibility of the system grows and the lowest natural frequencies are lower, usually within the resonance area. In figure 3 there is the lowest mode of the supercalender foundation system. Usually the lowest mode depends on horizontal motion.

The amplitudes caused by dynamic forces must be small, usually smaller than 150 μm and the vibration velocity under 4.5 mm/s in the reference point of the machine (Valmet 1989). These small values are required in order to quarantee the safe running of the machine and to prevent disturbancies spreading to the surroundings. The vibrations of the foundation slab are usually only 5...10 % of the vibrations in the reference point.

In the resonance area it is the damping forces which mainly resist dynamic loads. The damping can be obtained by material and radiation damping of the foundation system. The material damping is very small, about 1...2 % from the critical damping value. A greater damping can be obtained by means of transferring the waves from the foundation slab to the subsoil. Theoretically, the radiation damping can be analyzed by applying the elastic theory.

The elastic theory in the designing of machine foundations has been discussed by Novak (1987,1991), Gazetas (1983) and Wolf (1985) among others.

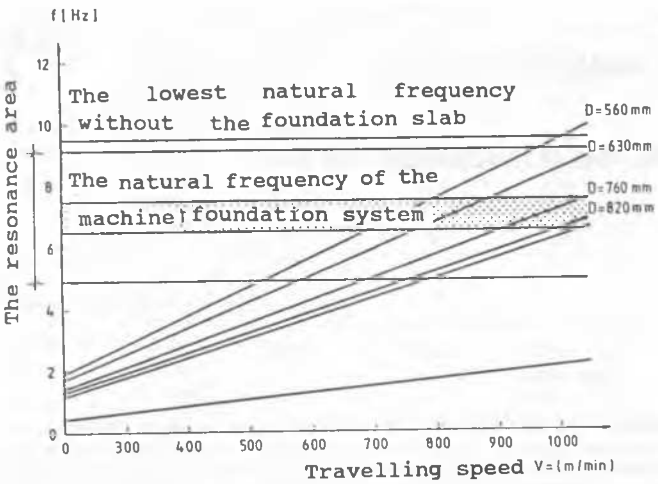

Fig.2. The excitation frequencies of the rolls of a supercalender during varying travelling speed (Hakulinen 1991b).

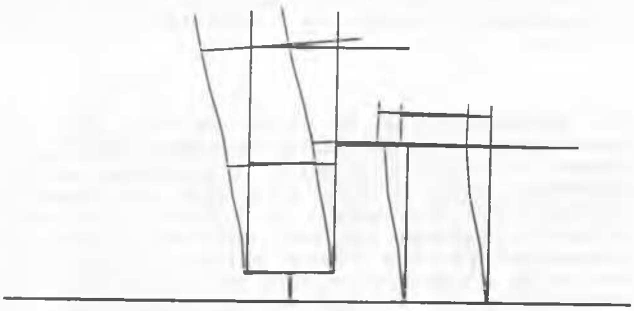

Fig.3. The lowest mode of a supercalender (Hakulinen 1991b).

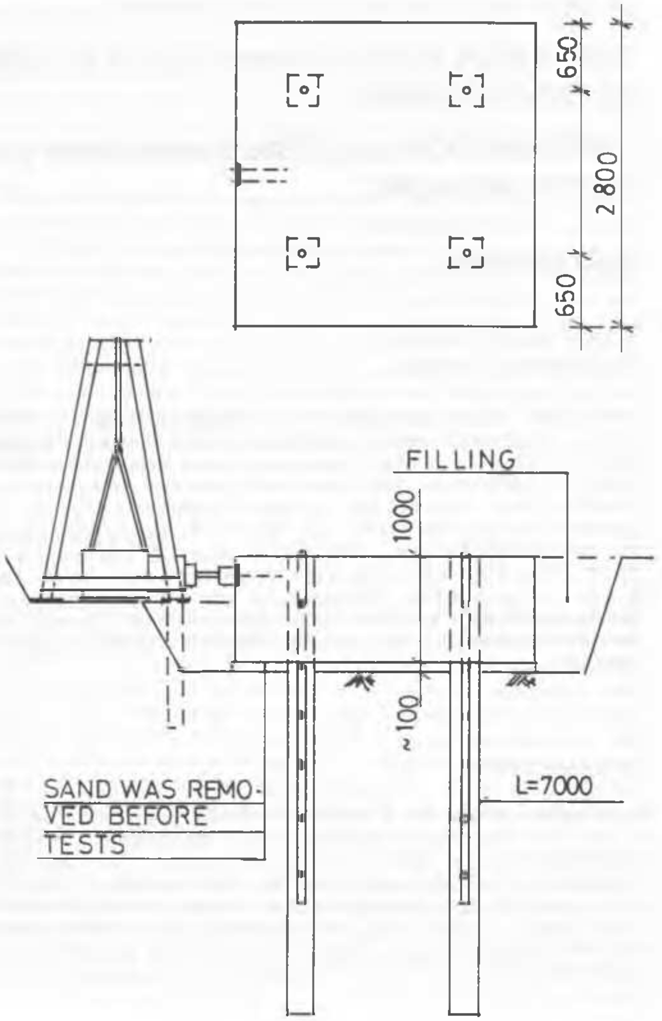

Fig.4. The arrangement of the pile test (Hakulinen 1991a).

In this article, the possibilities of utilizing the radiation damping in design of a supercalender foundation system is discussed. In order to test radiation damping in natural conditions dynamic pile test has been done.

THE PILE TEST

In order to test the elastic theory for designing work a pile test was done in summer 1989. The test was carried out in Valmet Paper Machinery's factory area in Järvenpää, Finland.

A pile slab was chosen for to be the test foundation because machine foundations are usually founded on piles. A pile foundation is usually needed to keep static settlements small or to keep the dynamic amplitudes within allowable limits. When bigger and more efficient machines are built the allowable differential settlements between different parts of the whole machine usually become smaller and thus the foundations are often founded on piles.

In the test the pile slab of four piles was loaded by dynamic forces. The excitation frequency varied from 2 Hz to 20 Hz and the amplitude in soil was < 80 µm. The concrete piles of 300*300 mm^2 were driven to the clay. The lenght of the piles were 7 m. The arrangement of the pile slab is presented in figure 4.

Site Investigations

In the test area the site investigations were carried out by static and dynamic methods. Dynamic parameters were measured in a laboratory by using the Resonant Column test and in situ by using the Downhole method. The most important results of the site investigations are presented in figure 5.

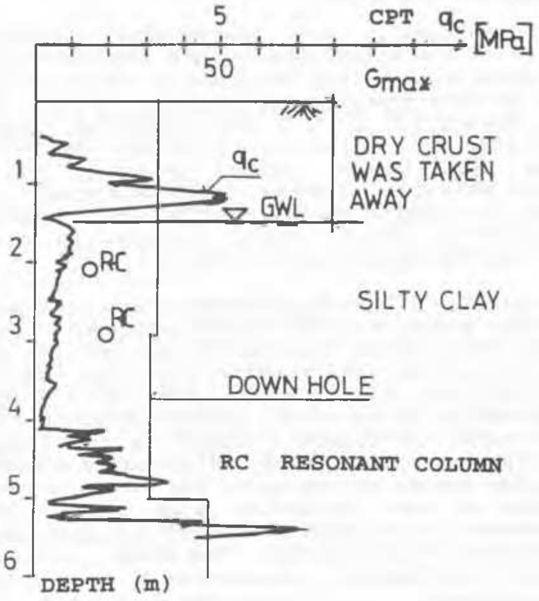

Fig.5. The results of the site investigations (Hakulinen 1991a).

Measurements

The test loadings were carried out as mode measurements. The pile slab was loaded with random and sinusoidal excitation. From the response of the random excitations, the natural frequencies, natural modes, frequency response functions and damping values were analyzed. The sinusoidal excitation amplitudes of a constant force in different frequencies were also measured. The damping values were measured in the resonance area from the response curve of the sinusoidal excitation. The pile slab was loaded without and with embedment. The earthfill was middle coarse sand. The sand was compacted in 0.3 m layers. The end filling could not be made symmetric because of the loading system. It was estimated that the stiffness due the unsymmetric embedment was only about 40% of that in full embedment.

Analysis and results

The pile slab was analyzied with a DYNA computer program. DYNA has been developed in the University of Western Ontario in Canada. The responses of both rigid pile foundations and the rigid shallow foundations can be analyzed with the DYNA program according to the elastic theory (Novak et al 1988).

In figures 6,7 and 8 there are the results of these analysis. The measured values could only be found in the resonance area.

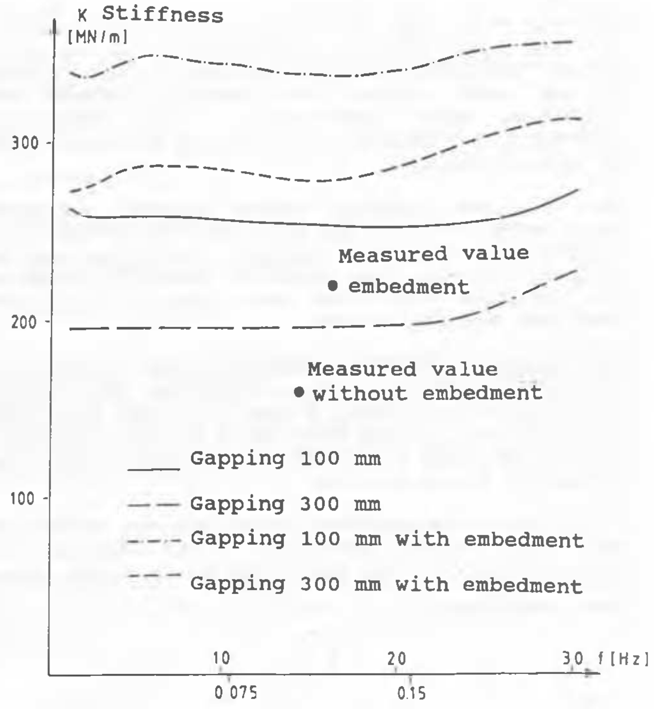

Fig. 6. The stiffness of the pile slab analysis and measurements (Hakulinen 1991b).

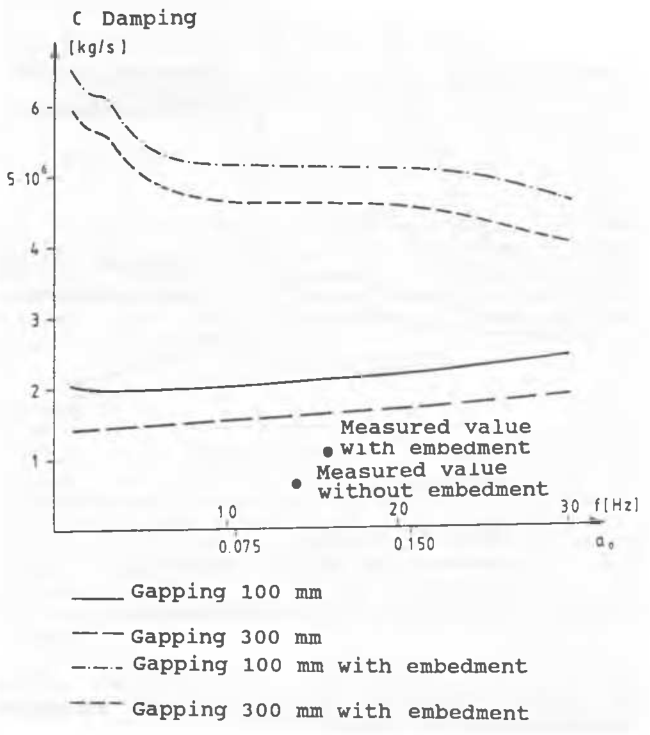

Fig.7. The damping values of the pile slab analysis and measurements (Hakulinen 1991b).

When the pile separation assumption was 300 mm , the analyzed stiffness values were about 25 % greater than the measured stiffness values. In the analysis, the embedment was not separated as end and side filling. According to the measured values the side filling increased the stiffness values very little. The damping values were increased more remarkably. The separation between the concrete slab and the soil could not be seen visually.

The measured damping values without embedment were about 40 % of the analyzed values when the separation assumption between the piles and the soil was 300 mm. The measured damping values of the embedded pile slab were about 25 % of the analyzed damping values.

The measured relative damping value D was 10 % without embedment in the sinusoidal excitation. With the side filling D was 15 % and with both side and end filling D was 25 % in the sinusoidal excitation. The frequency of the soil layers was estimated to be 4..6 Hz.

In figure 8 the analyzed, high damping values can be seen during embedment. The damping is overcritical. In the test this could not be seen.

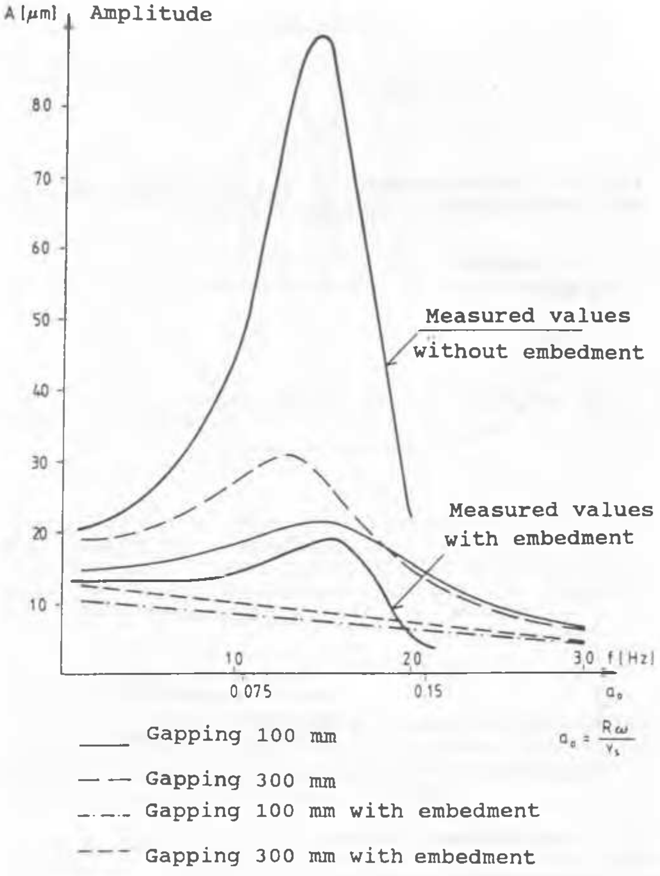

Fig.8. The responses of the pile slab analysis and measurements (Hakulinen 1991b).

THE FOUNDATION OF THE SUPERCALENDER IN THE RESONANCE AREA

The vibration analysis

In the following, the approximate vibration analysis of the supercalender has been done in the resonance area. The analysis is based on the lowest natural frequency and lowest natural mode of the foundation system. The foundation system is analysed as a vibrator of single degree of freedom. The lowest natural frequency of a flexible structural system can be analyzed as a vibrator of single degree of freedom (Clough & Penzien 1975). Other natural frequencies would change the following values little.

The foundation of the supercalender has generally been built rigid. The aim has traditionally been to get the lowest natural frequency of the foundation without the machine itself as near to 20 Hz as possilble. This kind of a rigid foundation is difficult to build elsewhere than on the rock. In figure 9 there is the lowest horizontal natural frequency of the supercalender foundation system according to the lowest natural frequency of the foundation slab itself. The upper curve 1 is an approximate natural frequency of a typical supercalender. The other curves 2 and 3 are the natural frequencies of more rigid supercalenders.

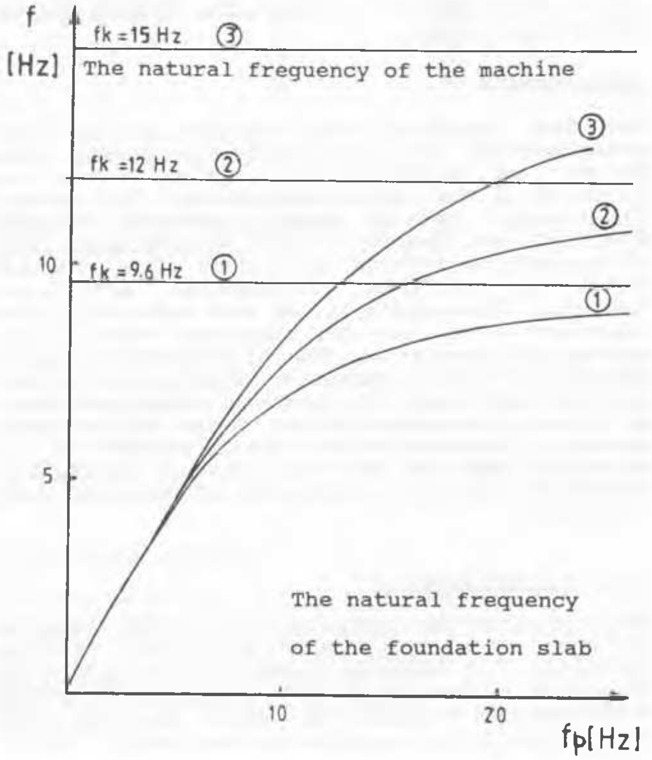

Fig.9. The lowest natural horizontal frequency a supercalender foundation system according the lowest natural frequency of the foundati slab (Hakulinen 1991b).

The results which are presented in figure 9 are based on equation (1) (Wolf 1985).

$$\frac{1}{f^2} = \frac{1}{f_k^{\,2}} + \frac{1}{f_p^{\,2}} \qquad (1)$$

f the natural frequency of the foundation system

f_k the natural frequency of the supercalender machine

f_p the natural frequency of the foundation slab

In figure 10 the damping values of the supercalender foundation system and the relative amplitude of the reference point of the supercalender are presented in the resonance area. The excitation force is the centrifugal force. Curve 1 presents the values of a typical supercalender foundation system.

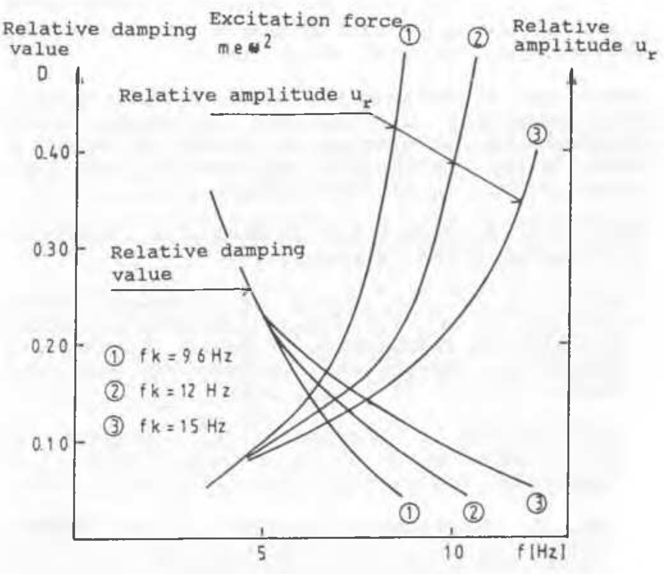

Fig.10. The damping values of a supercalender foundation system and the relative amplitude of the reference point in the resonance area (Hakulinen 1991b).

The damping values in figure 10 are analyzed according to equation (2) (Wolf 1985):

$$D = \frac{f}{f_k} D_k + 1 - \frac{f}{f_k} D_m + \frac{f}{f_p} D_p \qquad (2)$$

D_k the material damping value of the supercalender machine

D_m the material damping value of the soil

D_p the damping value of the foundation slab

The damping value of the foundation slab depends generally on the radiation damping, when the frequency is over the natural frequency of soil layers.

The relative amplitude in the resonance area are based on equation (3):

$$F = ku \qquad (3)$$

F force

k spring value

u amplitude/displacement

ω angle frequency

In case of the centrifugal excitation the force depends on frequency $F = m_h e \omega^2$ and the magnification factor of the dynamic excitation. In the resonance area the magnification factor is $K_d = 1/2D$. Spring value k can be calculated according to equation 4.

$$k = \omega^2 m \qquad (4)$$

By combinating equations 3 and 4 the relative amplitude in the reference point is based on equation 5.

$$u_r = \frac{m_h e \omega^2}{2D\, \omega^2\, m} \qquad (5)$$

$$= C/2D$$

m_h the mass of the excitation

e eccentricity

m the generalized mass of the foundation system

C coefficient $m_h e/m$

The value of the radiation damping of the foundation c is 40 10^6 kg/s in the analysis. The material damping value of the both soil and machine has been 2 %. The values of the material damping have little influence on the greater values of relative damping.

DISCUSSION

According to figures 2 and 9 it is concluded that it is not possible to design a typical supercalender foundation system as high tuned. In spite of a great rigididy of a foundation slab, the lowest natural frequency can not be designed higher than the excitation frequency. The foundation system is in the resonance area and the excitation force is opposed by damping forces.

In the resonance area, the necessity of damping is emphazised because of the difficulties in defining the resonance. Especially the stiffness of the pile foundations can vary very much according to the frequency.

In figure 11 the variations of the stiffness and the damping values of a piled supercalender foundation slab is presented. The values have been calculated with DYNA.

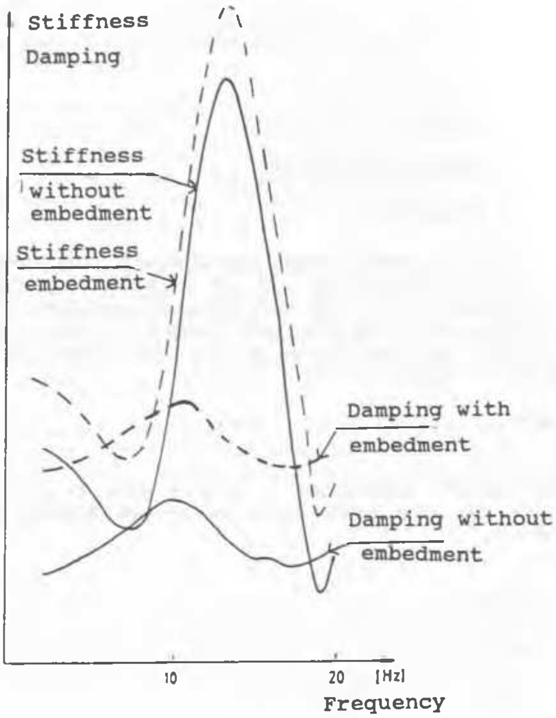

Fig.11. The variations of the horizontal stiffness and damping values of a piled supercalender foundation slab (Hakulinen 1991b).

In the dynamic analysis of a foundation system the exact resonance cannot be calculated because of the uncertainty of stiffness values. This uncertainty depends on inaccuracies of site investigations, modelling and analysis of the foundation (fig. 5 and fig.11).

In the analysis the most probable excitation frequencies in the resonance area must be calculated. The sensitivity of the foundation system to variation of frequency must be realized. In the analysis the stiffness of the foundation system must be defined so that the natural frequency is the same as the excitation frequency. The analysis must cover all the excitation forces in the resonance area.

Although the radiation damping of the foundation slab were high, the damping of the whole foundation system can be low. The radiation damping of the foundation slab is not utilizied effectively for the flexible supercalender machine. When good soil stiffness and damping properties are utilizied effectively, the machine itself must be rigid enough. In these kind of systems the high tuned foundation system can sometimes be designed. At least the resonance area is reached in higher excitation frequencies, making realization of the radiation damping more probable.

Secondly, the damping values can be increased by developing a foundation slab. The damping is greater when the area which radiates energy is larger. Smaller amounts of measured damping values in reference to theoretical values can make the possibilities of increasing the damping values more difficult. The measured damping values were much lower than the calculated values in the pile test (fig.7). Same kind of results have also been measured in other tests (Novak 1984,1987a,1991, Gazetas 1983,Wolf 1985, Kobori et al 1991). The most probable reason for that are nonhomogenous soil layers. There are variations in soil layers, which is difficult to investigate. Even the weight of the soil itself varies in the soil layers. In addition, there are probable gapping phenomena between the foundation slab or the piles and soil according to excitation. Also the building, especially the piling, can cause some kind of variation near the foundation slab and piles, which makes the radiation damping smaller.

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