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Current Trends in Design and Analysis of Paper Machine Foundations

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SYNOPSIS: Current trends in the design and dynamic analysis of paper machine foundations to ensure satisfactory performance are presented in this paper. Space frame foundations for modern high speed paper machines are governed by the requirements to meet stringent alignment/deflection tolerances and dynamic stiffness requirements specified by the machine manufacturer. The current design approach considers the complete machine-foundation-soil interaction. The dynamic response analysis is commonly conducted using a suitable finite element computer code in which the soil is modelled by equivalent springs. Damping is also included in the response calculation. Appropriate stiffness and damping parameters to model the foundation soil or soil/pile system are obtained from complex, frequency-dependent impedance functions derived from analytical and numerical solutions of continuum foundation models. Two case histories are presented to illustrate the use of forced vibration testing to aid in the machine foundation design process.

INTRODUCTION

Recent innovations in paper machine design have resulted in faster and wider machines producing higher quality finished paper products. Today, paper machines have design speeds in the range of 1200 to 2000 m per minute and paper roll widths between 7.6 m and 8.2 m. These developments have increased the dynamic excitation forces causing vibration and at the same time decreased the allowable roll balancing tolerances. The increasing consumer demand for improved paper quality also requires tighter machine alignment tolerance and stricter vibration criteria which must be met. Consequently, the effects of vibration have to be checked for all sections of a paper machine including the headbox, former, press, dryers, coaters, calenders, and winders.

Current trends in the design and dynamic analysis of paper machine foundations to ensure satisfactory performance are presented in this paper. Two case histories are presented to illustrate the use of forced vibration testing to aid in the machine foundation design.

PAPER MACHINE AND FOUNDATIONS

Paper Machine Components

Figure 1 shows a schematic layout of a modern paper machine consisting of the headbox, formers, presses, dryers, calenders, reels and winders. At the headbox, the cellulose fibres in a water slurry enter the machine and pass onto moving wire or fabric screens called fourdriniers or formers. This forms the mat of fibres of the paper sheet. Next, the press rollers squeeze water out of the wet paper before it enters the long aluminum-hooded dryer section where it passes over a series of steam heated cylinders. The dryer section separates the so called "wet end" and "dry end" of the paper machine. The calender stack in the dry end consists of a series of vertical rollers which "iron" the dry paper to the desired thickness before finishing up in the reels and winders. For glossy product, the paper is further processed through a high speed coating section and supercalenders for the required finish.

The paper machine operating speeds are nowadays in the range of 1200 to 2000 m per minute. The paper speed in the winder section may be over 3000 m per minute. The excitation frequencies are typically between 3 to 15 Hz, depending on the diameter of the rollers.

The frame of the paper machine is made from welded steel sections and has the function of holding the components of the equipment in place. It supports the moving parts, linkages and other components of the machine. The frame must be sufficiently rigid to hold the machine in alignment under all loading conditions and to prevent unacceptable vibration.

Formerly, these frames were made of wrought iron in older machines and were inherently rigid because of very conservative designs. Modern machine frames are made of welded steel sections which are generally much more flexible in construction. The heavier loads and stricter alignment and vibration tolerances in modern machines compound the difficulties encountered in designing adequate machine support systems.

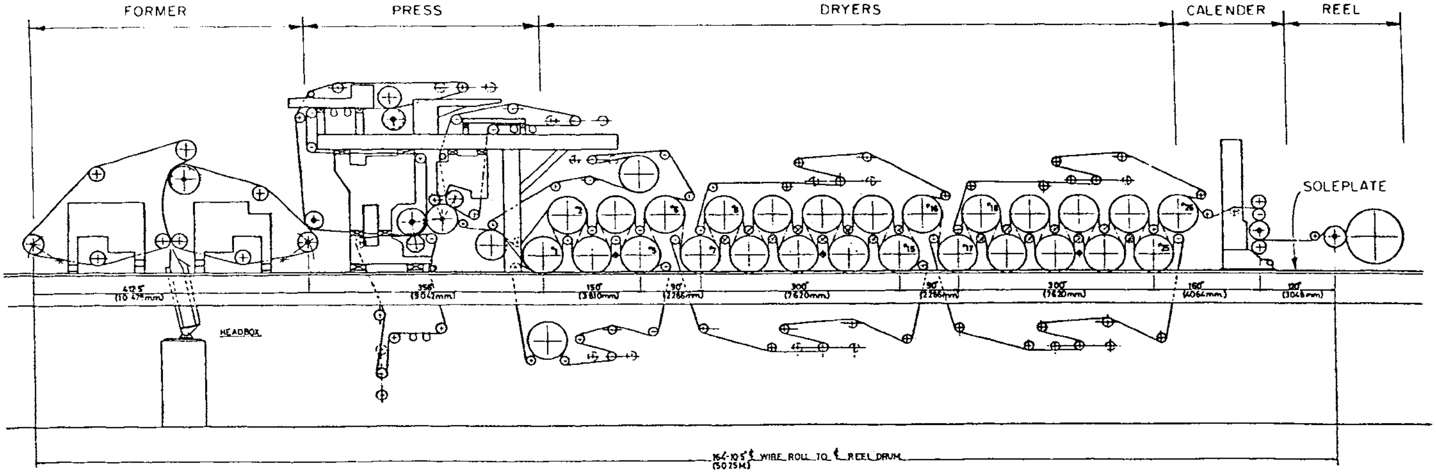


Figure 1 Typical Paper Machine Layout

Paper Machine Foundation

The steel support frame rests on the concrete foundation. The reinforced concrete foundation which supports the machine can take several forms. Rafts, strip footings and complete space frame structures are all employed depending on the design and the subsoil conditions. The principal function of the concrete foundation is to distribute the loading of the machine as evenly as possible onto the soils and to provide the required stiffness and strength for the machine being supported.

For the more competent soil conditions such as rock or heavily overconsolidated soils, spread footings and strip footings are used. In intermediate soil conditions, raft foundations are sometimes used. Where poor soils are encountered to depths that are uneconomic for removal and replacement with engineered fill, pile foundations are used. In such cases, the pile caps usually take the form of large rafts. Normally, paper machines are located on operating floors above the ground, so that a concrete space frame is used between the machine frame and the footings or pile caps. In the remainder of this paper, the term "foundation" refers to the complete machine support structure i.e. the space frame and its footings or pile caps.

The foundations for older machines were reinforced concrete cast monolithically with the building frame and building foundations. Modern paper machine foundations are isolated from the building frame and form independent foundations for each section of the machine. These isolated or "island-type" foundations are more straightforward to model in the analysis of each section of the machine, and they also have the advantage that vibrations from adjacent machinery and other equipment such as pumps are minimized. Because these foundations are now isolated, their effective stiffnesses in the horizontal directions are reduced, and the horizontal mode of vibration often becomes the critical consideration.

MACHINE FOUNDATION DESIGN

Design Criteria

The paper machine foundation has to meet both static and dynamic requirements for satisfactory performance. The static requirements are that the foundation should be safe against shear failure of the soils and that it should not settle or deflect excessively. The dynamic criteria are that:

1. Resonance should be avoided, i.e. the natural frequency of the machine-foundation-soil system should not coincide with the operating frequencies of the machine. Commonly, the natural frequency of the system is designed to be at least 1.2 times the principal excitation frequency.
2. The amplitudes of motion at the operating frequencies should not exceed the permissible values. These limiting amplitudes are specified by the machine vendor. Typically, machine beam deflection limits are set as 1 in 2000, and permissible vibration amplitudes under dynamic loads are not to exceed 0.013 mm at the wet end, 0.076 mm in the dryer section and 0.025 mm at the dry end.

Because of the strict deflection tolerances required for these machines, usually settlement and deflection considerations, rather than bearing capacity, govern the allowable foundation stresses on the subsoils. The layout and design of the machine foundation are usually governed by the dynamic requirements.

Design Approach

The inherent stiffness of the older paper machine frames and the smaller loads and forces that they were subjected to meant that there was a considerable safety factor built into the frame designs. Consequently, the machines were able to function satisfactorily with less stringent requirements for the foundation design. The stiffer frames and the lower speeds of the older machines also meant that excitation forces rarely were in resonance with the machine frame. Because of these two factors, it was sufficient in the past to perform independent analyses for the machine frame and the machine foundation, and not to consider the interaction of the two components.

This led to a convenient demarkation in design responsibility at the soleplate level (see Figure 1). In this approach, the machine vendor was responsible for the machine frame above the soleplates, and the foundation structural designer accepted responsibility for the foundation below the soleplates. The machine vendor specified deflection tolerances for the foundation under specified loading which the foundation design was required to satisfy. Designs on this basis included sufficient conservative factors that an analysis of the interaction of the two components was not required. For machines built up to 1980, this approach proved for the most part to be satisfactory.

Over the last decade, paper machine design has developed with the introduction of wider and faster machines. The introduction of lighter and more flexible welded steel machine frames has meant that an analysis of the complete system including the machine frame, foundation and soils, and which considers the interaction of each component of the system is now required for a satisfactory design.

The design of a paper machine foundation follows an iterative process involving the following main steps:

1. Determine the magnitude and characteristics of the dynamic loads and establish the foundation design performance criteria. These are specified by the machine manufacturer.
2. Determine the subsoil conditions and dynamic soil properties from in-situ and laboratory measurements.
3. Select the type and trial dimensions of the support structure and foundation.
4. Evaluate the static and dynamic response of the trial foundation.
5. Check whether the calculated deflections and response amplitudes meet the performance criteria. Otherwise, repeat steps 3 and 4 until a satisfactory foundation design is obtained.

The dynamic response analysis is the major component in the above design process. The analysis essentially involves the determination of the vibration characteristics of the machine-foundation-soil system, i.e. the natural frequencies and the amplitudes of vibration under the operating conditions of the machine. The response analysis is commonly conducted using a suitable finite element computer package such as STRUDL or IMAGES3D, in which the soil or pile/soil system is modelled by equivalent springs. Damping is also considered in the response calculation. Aside from the machine and structural foundation data, the soil stiffness and damping parameters form an important input in the dynamic analysis and will govern the computed response. A key step in the analysis is, therefore, the evaluation of the appropriate equivalent stiffness and damping parameters for the foundation soil or pile/soil system.

GEOTECHNICAL INPUT

Dynamic Impedance Functions

The dynamic loads produced by well balanced paper machines are relatively small compared to the combined weight of the machine and foundation. As mentioned above, the limiting dynamic displacement amplitudes are typically very small compared with the allowable foundation settlement under static load. Consequently, the deformations of the supporting soil are generally quasi-elastic, and the analyses to predict vibration amplitudes assume linear elastic or viscoelastic soil behaviour, with hysteretic soil damping to model energy losses at these small strain levels.

The appropriate stiffness and damping parameters are currently defined in terms of complex, frequency-dependent impedance functions derived from analytical and numerical solutions of the foundation vibration problems. For each harmonic excitation at a particular frequency, the dynamic impedance is defined as the ratio between the steady-state force (or moment) and the resulting displacement (or rotation) at the base of a rigid massless foundation. The dynamic impedance function can be expressed in complex notation as

$$K = K_1 + iK_2 = k + i\omega c \qquad (1)$$

in which K_1 and K_2 are, respectively, the real and imaginary parts of the complex stiffness K, $k=K_1$ is the dynamic stiffness and $c=K_2/\omega$ is the constant of equivalent viscous damping, ω = circular frequency of excitation and $i=\sqrt{-1}$. The constant c accounts for energy dissipation in soil stemming from wave propagation (geometric or radiation damping) and from soil hysteresis (material damping). The stiffness and damping constants, k and c, vary with frequency.

Impedance functions K_1 and K_2 have been evaluated for various foundation and idealized soil conditions, and are available in convenient charts, tables or simple formulas for estimation of frequency-dependent stiffness and damping parameters.

Shallow Foundations

The determination of the stiffness and damping parameters for shallow foundations should consider the following important factors: soil profile, shape of foundation, amount of embedment, soil inhomogeneity and machine operating frequency range. Gazetas (1983) presents an excellent and comprehensive compilation of characteristic numerical results for the dynamic impedances of massless rigid surface and embedded foundations for all possible (translational and rotational) modes of vibration. Results are presented for three categories of idealized soil profile: the halfspace, the uniform stratum on rigid base, and the layer on top of a halfspace. Most of the results are for the basic circular footing, with limited results for rectangular and two-dimensional strip footings. More results are presented in Dobry and Gazetas (1986) for arbitrarily shaped surface foundations on elastic halfspace.

The effect of footing embedment is to increase both stiffness and damping, but the increase in damping is more significant. Practical solutions to incorporate the effects of embedment are given in Novak (1974b).

For inhomogeneous soil profile, the practice is often to choose some equivalent, representative value of shear modulus. However, this representative modulus should be different for the various vibration modes. Based on a theoretical study of circular foundations resting on a halfspace with shear modulus increasing linearly with depth, Werkle and Waas (1986) suggested "representative depths" for different modes for calculation of representative shear moduli that can be used in the formulae for static stiffness of footings on homogeneous halfspace. They also suggested different "representative depths" for calculation of the shear moduli to obtain the dynamic coefficients for determination of the dynamic impedance functions.

Pile Foundations

For pile foundations, the key elements that must be considered are the single pile-soil interaction, pile-soil-pile interaction (or group effect) and pile cap-soil interaction (or embedment effect).

Novak and his co-workers at The University of Western Ontario have provided the most comprehensive and versatile solutions to the single pile problem for practical applications. Using plane strain soil reactions, Novak (1974a) developed an approximate continuum solution to the soil-pile interaction problem and presented his results in simple and useful charts. For the cases most commonly encountered in practice, Novak and El Sharnouby (1983) presented tables and charts for evaluation of single pile stiffness and damping covering homogeneous and parabolic soil profiles, fixed-headed and pin-headed piles, and end bearing and floating piles.

If piles are closely spaced, which is usually the case, they interact with each other and this pile-soil-pile interaction (or group effect) exerts considerable influence on the stiffness and damping of the group. The group effect stems from the fact that the displacement of one pile contributes to the displacements of the other piles. This effect is handled in practice by the use of the concept of interaction factors introduced by Poulos (1968) for static pile loading. Interaction factor charts appropriate for static or low frequency loadings are available in Poulos and Davies (1980) and El Sharnouby and Novak (1986). Frequency-dependent dynamic interaction factors have been proposed by Kaynia and Kausel (1982) as an extension to Poulos' static interaction approach, but only limited charts were presented. More recently, Dobry and Gazetas (1988) proposed simple analytical expressions for dynamic interaction factors for vertical and horizontal vibrations of floating pile groups.

Many pile foundations have partially or fully embedded pile caps. As a result, there are soil reactions acting on the vertical sides of the pile cap. The soil reactions acting on the base area are normally not considered as the contact may be lost due to soil settlement. The side reactions due to embedment result in increased stiffness and damping of the pile foundations, as for embedded footings. Impedance functions for pile cap embedment can be obtained from Novak (1974b) as for embedded footing. The impedance functions for side reactions are then added to those derived for the pile group to obtain the total impedance for the embedded pile foundation.

DYNAMIC RESPONSE ANALYSIS

For a complete system model, it is necessary that detailed computer models of the machine frame and the foundation be developed. Models of the machine frame are usually made available by the machine manufacturer. These include geometry definition, member properties, stiffnesses and masses of the machine frame. These models need to be sufficiently detailed to give a realistic representation of the dynamic behaviour of the machine. The information supplied is usually a simplified version of the computer models used in the machine design performed by the machine manufacturer. Damping in this section of the model is low but estimates have to be made by the analyst. Typically, values around 0.5 % of critical damping are used.

The foundation can be modelled as a two or three dimensional finite element model. Here, the stiffnesses and masses of the concrete sections are modelled. Estimates of damping of the concrete space frame have to be made. Typical damping values used are 1 to 2 % of critical.

Care has to be exercised in modelling the interface between the machine frame and the concrete foundation in order to ensure that modelling inaccuracies are avoided at the interface.

The machine-foundation-soil system is commonly analyzed by modal analysis which is performed in two steps. The first step of the analysis involves the determination of the undamped natural frequencies and the mode shapes of the system. The mode shapes provide useful information on the relative dynamic stiffnesses among the various parts of the system. The second stage of the analysis is a response calculation of the system caused by the dynamic forces. The computed natural frequencies and mode shapes are used to calculate steady state amplitudes from the specified forcing functions. Damping in the soil and the structural materials is included in this analysis to give the displacement, velocity and acceleration of the masses and also the internal forces in all members of the system. The mode shape information allows the designer to adjust vibration amplitudes at critical points by varying the stiffness, mass and damping characteristics of the system.

For systems with low damping, equivalent viscous damping may be assigned for each mode and response can be calculated as a summation of modal contributions. In systems where damping in excess of 20 % of critical is expected in significant modes, response analysis based on undamped mode shapes becomes inaccurate, and it is necessary to employ explicit formulations which include damping forces as the imaginary part of the complex variables. Because of the size and complexity of the models used for typical paper machine foundations, the complex formulation requires considerable computational capacity. Commercial programs are currently not available to do this type of analysis and such programs would have to be developed in-house.

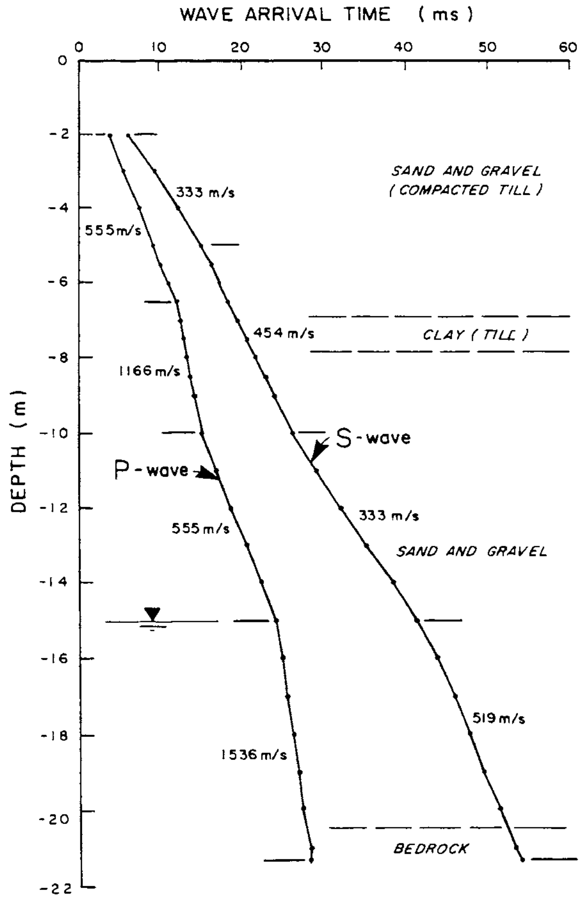


Figure 2 Soil and Seismic Velocity Profiles - Case History No.1

CASE HISTORIES

Two case histories are presented below in which forced vibration tests were used in the machine foundation design process. Each of these foundations is for a twin-wire former section where deflection and vibration tolerances are most stringent. The former is the critical section for paper formation and defects introduced here because of vibration will remain in the finished paper sheet.

Case History No. 1

Shallow foundations were used to support a new paper machine installed in Alberta, Canada. The spread footings were embedded 2 m into a 7 m thick compacted gravel fill pad placed above a 1 m thick layer of hard, overconsolidated clay till overlying very dense preglacial sand and gravel deposits. Figure 2 shows a typical soil profile at the site and in-situ shear and compressional wave velocities from downhole measurements. Based on the shear wave velocity results, "effective" shear moduli were selected as representative of the entire foundation soils and used to calculate stiffness and damping parameters as outlined earlier. Factors including footing size and shape, embedment, stratum over rigid base, and excitation frequency range were considered in the analysis.

In order to calibrate the computer model for the former section of this paper machine and to verify the soil parameters used in the analysis, dynamic testing was conducted on the partially constructed reinforced concrete foundation prior to installation of the machine. An electrodynamic shaker was used and steady state swept sine tests were performed with a maximum force amplitude of 1.56 kN. The shaker was positioned at several locations on the foundation in order to excite specific modes of vibration (see Figure 3). At Position (1), the shaker was located at the centre of the foundation and vertical excitation was applied to the foundation. The frequency response function

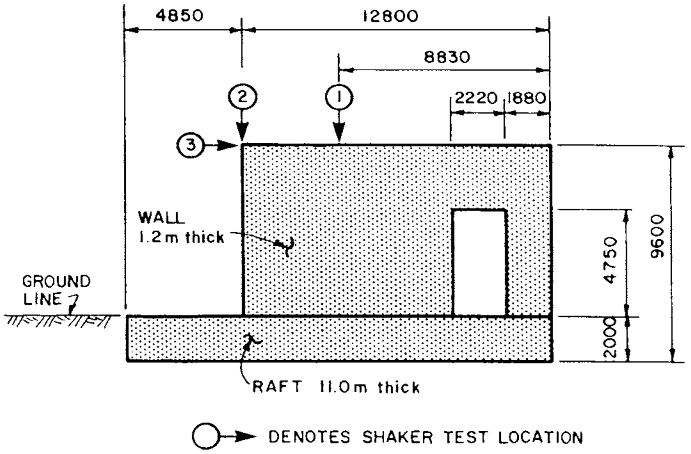


Figure 3 Shaker Locations on Former Foundation - Case History No.1

obtained from this test is shown in Figure 4. The predominant peak at 18.75 Hz is for the vertical mode of vibration. A second peak at 28.5 Hz corresponds to flexing of the raft and rocking of the wall. The shaker was located at position (2) for the second test and vertical excitation was again generated. From this test, the coupled rocking and vertical modes were excited at 20.75 Hz. In the third test, horizontal excitation was applied to the top of the wall. This test enabled the coupled horizontal and rocking modes to be established at 11.0 Hz.

Because of the large size of the former foundation as shown in Figure 3, it was found that the 1.78 kN force excitation system was taxed to its limit in order to produce reliable results.

Once the three or four lowest modes had been identified from the test results, the two-dimensional computer model of the foundation was "calibrated" to match the test results as closely as possible. In this process, the soil springs were adjusted until the computed natural frequencies were similar to the measured resonant frequencies for the identified mode shapes. It was found that the vertical pile/soil stiffnesses estimated by the procedure described above did not require any adjustment, but that the horizontal stiffnesses had to be reduced by 20 % to obtain the best match. Such adjustment is well within the normal uncertainty range of the stiffness estimates due to the simplified procedure and inherent soil variabilities within a large foundation area. Table 1 summarizes the results of the forced vibration tests and the computed natural frequencies and mode shapes for the final model.

Table 1. Measured Resonant Frequencies and Computed Natural Frequencies and Mode Shapes

Shaker Position No.	Measured Resonant Frequency (Hz)	Calculated Natural Frequency (Hz)	Mode Shapes
3	11.0	11.88	Horizontal Translation & Some Rocking
1	18.75	17.80	Vertical Translation & Some Rocking
2	20.75	18.78	Rocking
1	28.5	31.51	Flexing of Raft & Rocking of Wall

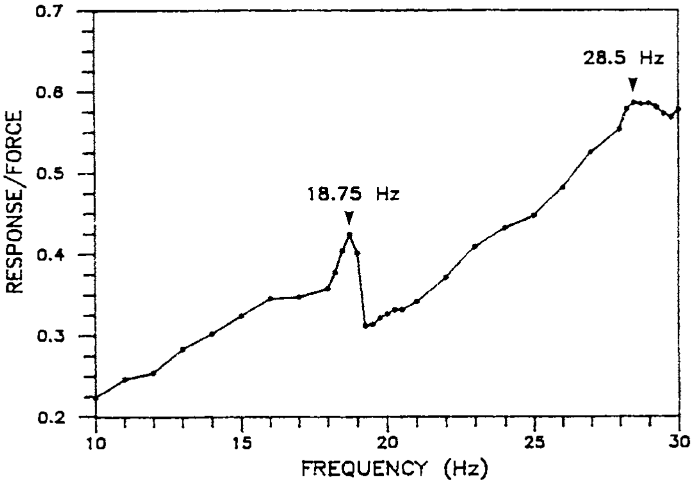


Figure 4 Measured Frequency Response Function - Case History No.1

Case History No. 2

As part of the modernization of an existing newspaper machine in Vancouver Island, British Columbia, Canada, a new high speed gap former was to be installed to replace an existing former. Dynamic analysis of the new machine section on the existing foundation was required to ensure that the stringent performance criteria specified by the machine vendor can be met. Available records indicated that the existing foundation was supported on two large pile groups consisting of 100 and 130 closely spaced timber piles. The piles had been driven through soft silts and clays to end bearing in very dense glacial soils. The pile lengths varied considerably but averaged only about 2.4 to 3.0 m.

Access to the foundation soils for dynamic in-situ testing was impractical during the design stage because it would require prolong shutdown of the machine operation. Instead, a forced vibration testing program was conducted at the operating floor of the former section in the existing machine room during a brief machine stoppage. An electromagnetic shaker was again used to generate vertical sinusoidal excitations at selected locations adjacent to the existing machine, and frequency response functions using the swept sine procedure were obtained at several locations. Figure 5 shows a typical frequency response curve and an identifiable resonant frequency at 18.25 Hz corresponding to a combined vertical and rocking mode of vibration. A two-dimensional machine-foundation-soil computer model (Figure 6) was then "calibrated" by adjusting the soil parameters until the computed modal frequencies and mode shapes matched the

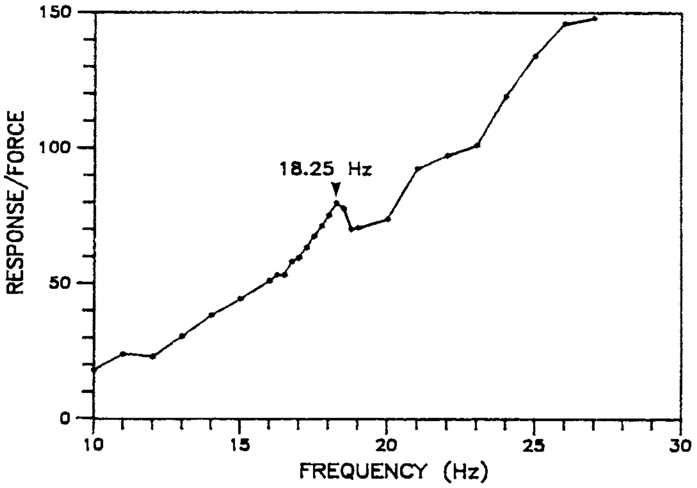


Figure 5 Measured Frequency Response Function - Case History No.2

observed values. Figure 7 shows the first two significant computed natural frequencies and mode shapes. The calibrated computer model was then used to more confidently analyze the response of the new replacement machine.

CONCLUSIONS

Current trends in the design and analysis of paper machine foundations have been presented. Because of the stringent alignment and deflection tolerances that must be met for successful operation of modern high speed paper machines, dynamic analysis is required for all sections of the paper machine. Current finite element analysis considers the complete machine-foundation-soil system as one model in which the soil is represented by equivalent springs. Soil and structural damping is also included in the response calculation.

Impedance functions for shallow and pile foundations are available from analytical and numerical solutions in simple equations, tables and charts which can readily be used in practice. These impedance functions are for idealized conditions and should be corrected for other factors as necessary. It is recommended that several of the available methods or solutions be used, as well as a range of soil properties, to estimate the stiffness and damping of the foundations. This will allow the engineer to appreciate the confidence limits on his/her best estimates and the effects of the limits on the computed response.

For very sensitive machines, it is recommended that full scale vibration tests be conducted to confirm the design assumptions or to calibrate the computer model used in the dynamic analysis.

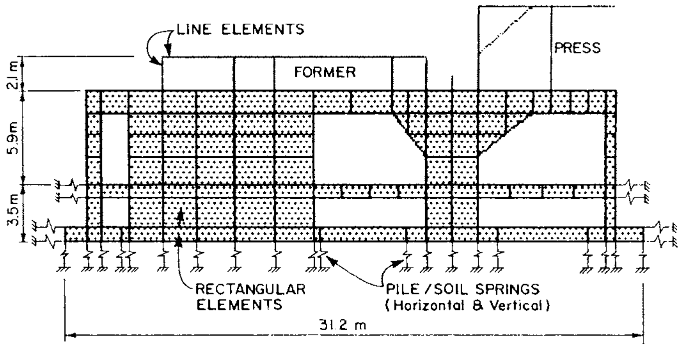
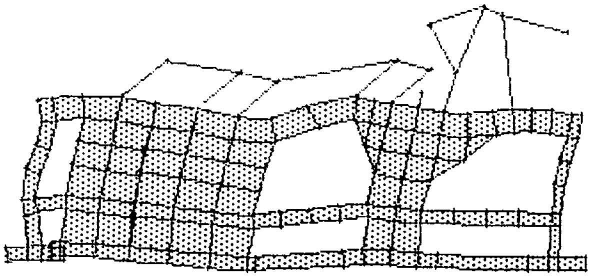
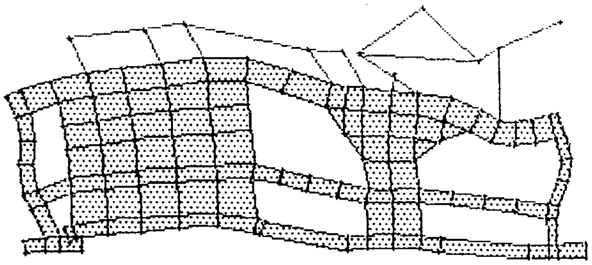


Figure 6 Computer Model of Former Foundation - Case History No.2



CALCULATED FREQUENCY = 17.2 Hz , ROCKING



CALCULATED FREQUENCY = 18.9 Hz , VERTICAL WITH SOME MINOR ROCKING

Figure 7 Computed Mode Shapes and Frequencies - Case History No.2

REFERENCES

Dobry, R. and Gazetas, G. (1988), "Simple Method for Dynamic Stiffness and Damping of Floating Pile Groups", Geotechnique, Vol. 8, No. 4, pp. 557-574.

Dobry, R. and Gazetas, G. (1986), "Dynamic Response of Arbitrarily Shaped Foundations", J. Geotech. Eng., ASCE, Vol. 112, No.2, pp. 109-135.

El Sharnouby, B. and Novak, M. (1986), "Flexibility Coefficients and Interaction Factors for Pile Group Analysis", Can. Geotech. J., 23, pp. 441-450.

Gazetas, G. (1983), "Analysis of Machine Foundation Vibrations: State of the Art", Journal of Soil Dynamics and Earthquake Engineering, Vol. 2, No. 1, pp. 2-42.

Kaynia, A.M. and Kausel, E. (1982), "Dynamic Behaviour of Pile Groups", Proc. of Conf. on Numerical Methods in Offshore Piling, Univ. of Texas, Austin, Texas, pp. 509-532.

Novak. M. (1974a), "Dynamic Stiffness and Damping of Piles", Canadian Geotechnical Journal, Vol. II, pp. 574-598.

Novak, M. (1974b), "Effect of Soil on Structural Response to Wind and Earthquake", Earthquake Eng. & Struct. Dyn., Vol. 3, pp.79-96.

Novak, M. and El Sharnouby, B. (1983), "Stiffness Constants of Single Piles", J. Geotech. Eng., ASCE, Vol. 109, No. 7, July, pp. 961-974.

Poulos, H.G. (1968), "Analysis of the Settlement of Pile Groups", Geotechnique, Vol. 18, No. 4, pp. 449-471.

Poulos, H.G. and Davies, E.H. (1980), Pile Foundation Analysis and Design, John Wiley & Sons.

Werkle, H. and Waas, G. (1986), "Dynamic Stiffness of Foundations on Inhomogeneous Soils", Proc. 8th European Conf. on Earthquake Eng., Lisbon, Vol. 2, pp. 5.6/17-23.