Vibration tests for the analysis of machine foundations

Essais de vibration pour l'analyse des fondations de machines

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SYNOPSIS The paper presents the results of a set of vibration tests performed on a concrete block, resting on young residual soil, with the aid of a specially devised vibrator. The tests aimed at the evaluation of dynamic soil properties for the design of massive-type foundations for rotating machines. The vibrator and test procedures are presented in some detail. The vibrator can also be used to determine vibration modes and natural frequencies of already built bases.

INTRODUCTION

Up to the 1960's, most machine foundations were designed by nonrational rules-of-thumb or empirical rules, mainly due to lack of rational methods of analysis. Since then, a great deal of development in analysis models has been made, including numerical methods. An appropriate evaluation of parameters for these models, however, is not usually made.

Dynamic soil properties can be determined by laboratory or in-situ tests. The latter type should be preferred for a number of reasons, but mainly because they test undisturbed soil and are more representative of the whole mass. For machine foundations, the in-situ vibration test performed on a concrete block is clearly indicated.

With the aim of developing simple equipment and test procedures for in-situ evaluation of dynamic soil properties, the Federal University of Rio de Janeiro, with the cooperation of COBRAPI (Brazilian Company of Industrial Projects), a State owned company responsible for the design of steel works, initiated a research line from which the present paper has been extracted. It presents the vibrator and test procedures selected, together with the results of a set of vibration tests performed at the Volta Redonda Steel Works in the State of Rio de Janeiro.

VIBRATOR

For the in-situ vibration test, a vibrator was designed and built, both compact and capable of a high dynamic force output. The simplest scheme for producing a (sinusoidal) dynamic force is that of two rotating unbalanced masses shown in Figure 1. This scheme is used in most mechanical vibrators (Srinivasulu and Vaidyanathan, 1976).

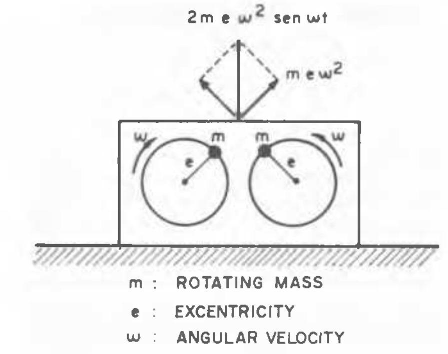

Fig.1 Principle of two rotating mass vibrator

The vibrator followed this scheme and the unbalanced masses were created by steel discs, each with one cylindrical hole; four different steel cylinders (same diameter as the hole but different heights) could be fixed at the holes to create four different unbalanced masses. A section of the vibrator along the two shafts is shown in Figure 2. In order to reduce the dimensions of the vibrator, one of the discs was splitted in two. A 5HP direct current electrical motor was used to turn the vibrator at different speeds (600 - 3000 rpm) with the aid of a speed control unit (by voltage variation).

The most relevant data of the vibrator are:

- dimensions: 42 x 26 x 25 cm
- weight (without motor): 1,5 kN
- dynamic force: 0 - 20 kN
- frequency range: 10 - 50 Hz

The vibrator can be placed in two positions in order to produce either a vertical or a horizontal dynamic force (Fig. 3).

TEST PROCEDURES

The following test procedures were adopted:

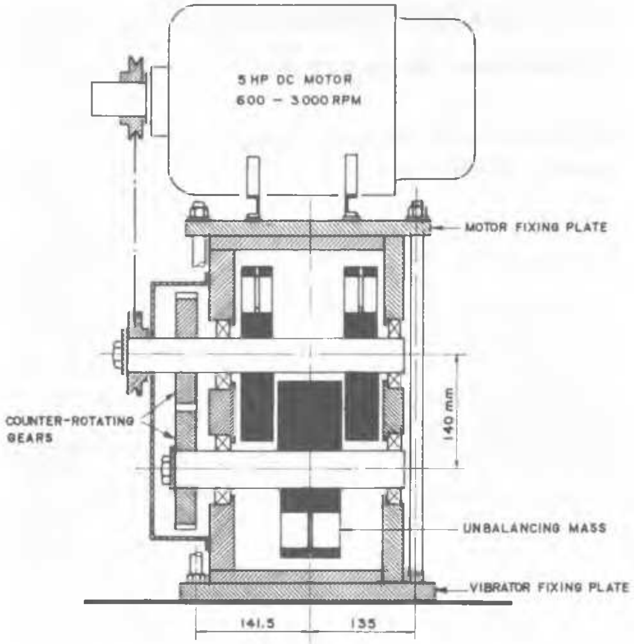

Fig.2 Simplified section of vibrator

(a) A pit is excavated to the level of the proposed foundation. Horizontal dimensions of the pit should be twice those of the test block.

(b) A test block is cast or, alternatively, is made of pre-cast concrete or steel plates held together by bolts (as suggested by Ivanoff, 1962). Dimensions of the block may vary with soil conditions and maximum dynamic force; a relation betwen (intended) maximum dynamic force and weight of the system (block plus vibrator and motor) of 0.5 is recommended.

(c) The vibrator and its motor are installed on the top of the block, first for vertical and second for horizontal excitation. Three unbalanced masses are used in each direction.

(d) Accelerations (or displacement amplitudes according to the measuring equipment) are measured at three points on the top of the block in the case of vertical excitation or at three points along a vertical line on the side of the block in the case of horizontal excitation.

(e) Measured accelerations (or displacement amplitudes) are plotted against frequency in the field in order to assure that resonance was passed through in every test.

TEST EXAMPLE

Test Site

The test procedures described in the previous item were applied at a site of the Volta Redonda Steel Works in order to evaluate local soil dynamic properties. Test lay-out is depicted in Figure 4 together with a neighbouring exploratory boring (with SPT). The exploration revealed a 80 cm thick fill, removed for the test, followed by a silty sand with little clay, of low plasticity, typical of young gneissic residual soil (in this region, the upper mature residual soil had been removed at the time of the earth works for the plant construction). Grain size distribution and index properties of a sample extracted just below the block base level can be seen in Figure 5. The water table was not found above 10 m.

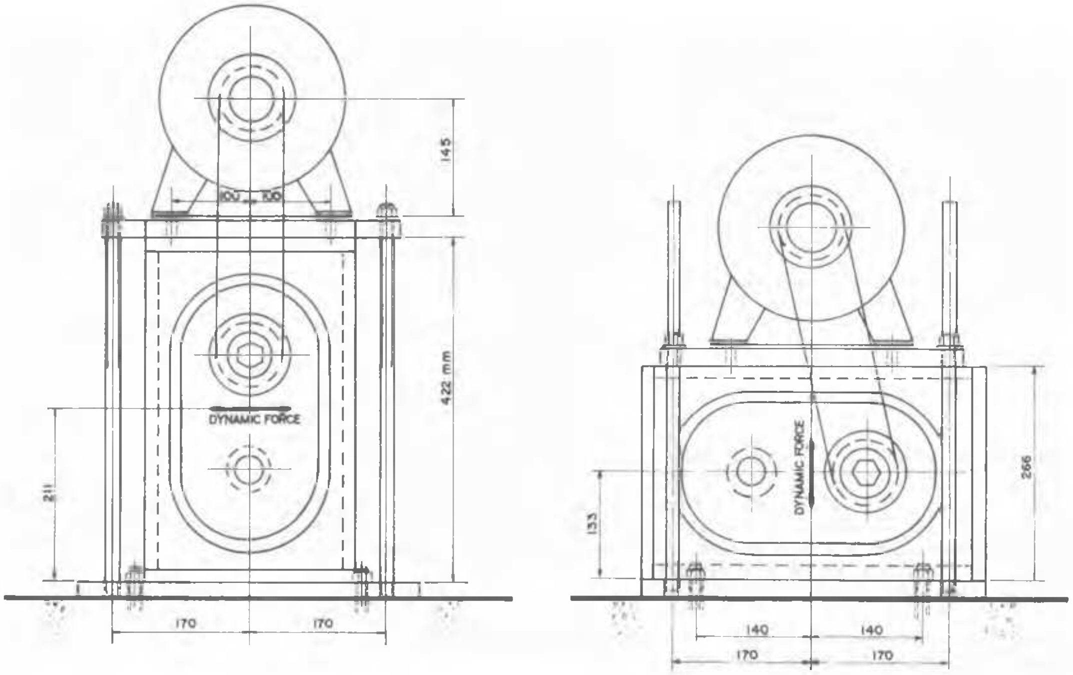

Fig.3 Vibrator set-up for horizontal and vertical excitation

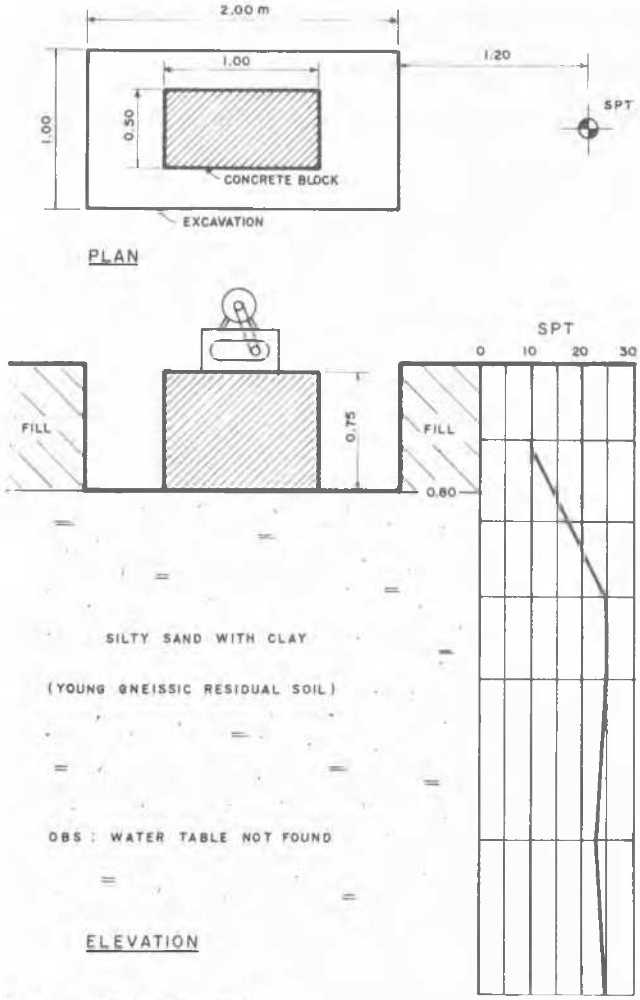

Fig.4 Test lay-out

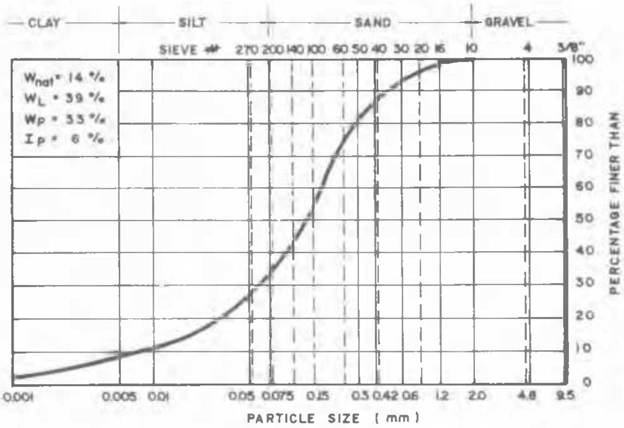

Fig.5 Grain size distribution and index properties

Test Results

The results of vertical and horizontal vibration tests are shown in Figure 6. It can be observed that an increase in the dynamic force causes a decrease in the natural frequency. This was explained by Novak (1960) as being due to the nonlinear stress-strain behaviour of soils (with an increase in stress level, there is a decrease in soil stiffness, which makes the system less rigid and therefore with a lower natural frequency).

Interpretation of Test Results

Test results can be interpreted to produce parameters for either a model which represents the soil as an isotropic elastic half-space or a model which represents the soil as a set of springs (better known after the work of Barkan, 1962). The latter model is more commonly used in massive-type foundation design practice and the interpretation herein presented will follow it. (Interpretation according to the elastic half-space does not present any additional difficulty.)

For the vertical excitation, the following expression can be used to determine the vertical spring stiffness (Barkan, 1962):

$$C_z = \frac{\omega_{nz}^2 \, m}{A} \qquad (1)$$

where ω_{nz} is the angular natural frequency (for vertical vibration),

m is the mass of the test block plus vibrator and motor and

A is the test block base area.

Since the horizontal dynamic force is not applied at the center of gravity of the block - vibrator system, it causes both sliding and rocking. Excited in this manner, the block may vibrate in two modes. A plot of displacement amplitudes measured at the 3 pick-up points will reveal whether the system is vibrating in the first mode (greater amplitude at the top) or in the second mode (greater amplitude at the base). According to Barkan (1962), the rotational spring stiffness C_ϕ is roughly 4 times the horizontal spring stiffness C_x. Assuming this relation between the two spring stiffnesses, the following expression can be used to evaluate C_x:

$$C_x = \frac{(A M_o + 4 m I)\,\omega_{nx}^2}{8 A I}\left[1 \pm \sqrt{1 - \frac{16 A I M m}{(A M_o + 4 m I)^2}}\right] \qquad (2)$$

The positive sign shall be taken when ω_{nx} is the first natural frequency and the negative sign when ω_{nx} is the second natural frequency. Other symbols in the equation have the following meanings:

M is the mass moment of inertia of system (block plus vibrator) about the horizontal axis passing through the centre of gravity of system and perpendicular to the direction of vibration;

M_o is the mass moment of inertia of system about the horizontal axis passing through the centre of gravity of base area of block perpendicular to the direction of vibration;

I is the moment of inertia of foundation base area about the horizontal axis passing through the centre of gravity of base area and perpendicular to the direction of vibration;

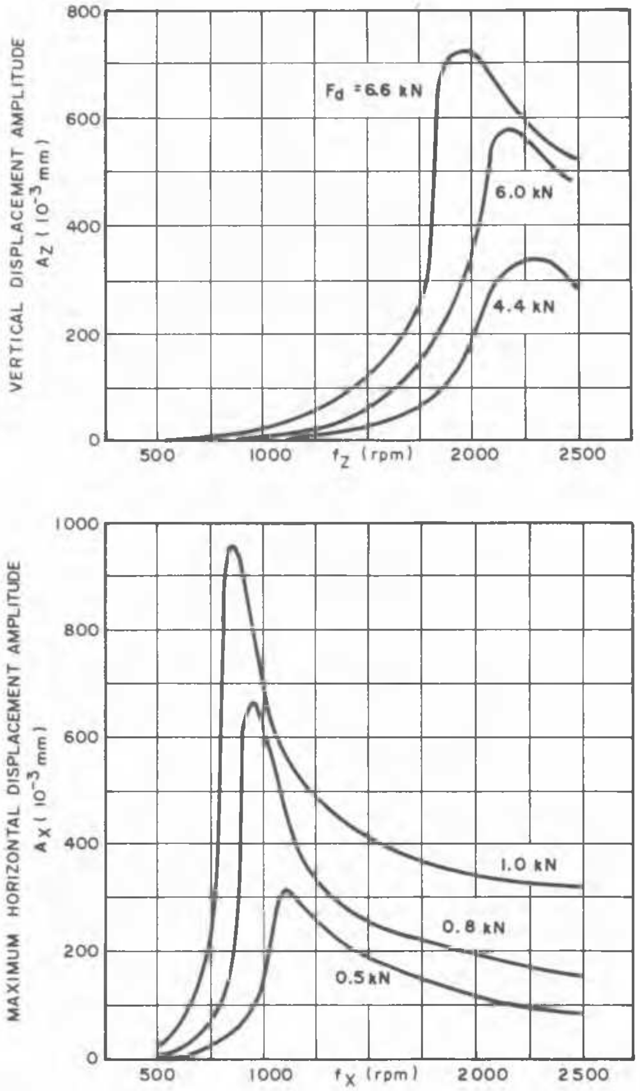

Fig.6 Response curves for vertical and horizontal vibration

A determination of C_x without an assumed relation between C_x and C_ϕ can be made with a somewhat more complex procedure (which requires more sophisticated equipment) as indicated by Yan (1981).

Since three somewhat different natural frequencies were obtained with the three dynamic forces, it is suggested that a plot of stiffness versus dynamic force - block weight ratio should be produced (Fig. 7). The appropriate design stiffness could be obtained entering the plot with the actual machine's dynamic force - block weight ratio.

The soil damping factor can also be evaluated in the test (by expression $\beta = \Delta f / 2 f_n$, where Δf is the frequency between two points on the response curve located $f_n/\sqrt{2}$ below the peak amplitude and f_n is the natural frequency). An average damping factor of 0.14 was obtained in the vertical direction.

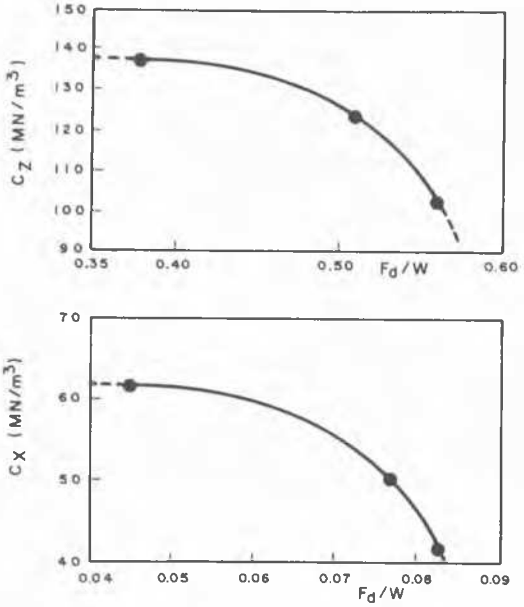

Fig.7 Dynamic force level *versus* soil response

CONCLUSIONS

The vibrator described, together with the proposed test procedures, proved to be adequate for a test which intended to be at the same time simple and capable of producing useful soil data. The vibrator can also be used to excite already built bases for an evaluation of their vibration modes and natural frequencies, also providing information on soil properties.

It would be desirable that this type of test were performed much more frequently, not only to provide parameters for an specific job but also to help gather data that would be useful to the geotechnical community. To homogeneize the gathered data, an international standard would be welcome.

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