Dynamic Response of Unbalanced Machine Foundation on Piles

Réponse Dynamique d'un Fondation Non-Equilibre sur Pieux

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SYNOPSIS Prediction of dynamic response of a highly unbalanced 3-cylinder compressor foundation supported on cast-in-situ bored piles has been dealt with. The soil-pile stiffness parameter needed for prediction of dynamic response was calculated theoretically first and design was checked subsequently with the soil-pile stiffness parameter evaluated from in-situ dynamic tests on piles. The evaluated soil-pile stiffness was reported as a function of amplitude of vibration and the value corresponding to the permissible amplitude of vibration was used for predicting the response. The vibration measurements were made on the foundation after the plant was commissioned to evaluate the observed response. A comparison between observed and predicted response of this foundation has been made and a rational approach to predict the dynamic response of pile-supported foundation subject to dynamic loads with reasonable accuracy has been suggested.

INTRODUCTION

Effective and economic design of pile foundations subjected to dynamic loads need a prediction of dynamic response close to the one expected to be observed under such foundations. The complexity of soil-pile interaction often makes such prediction very difficult. Thus, a simple rational approach for the design of such foundations is still not available to the practising engineers. Author, therefore, intends to share his experience in this field by presenting an actual case history together with the actual observations made on the foundation following the commissioning of the plant.

Foundation for the highly unbalanced three-cylinder 2200KW reciprocating compressor foundation was required to be designed for a plant in northern India. The maximum amplitude of vibration for this foundation was restricted to 25 microns. Restricted space available made it difficult to design a suitable open foundation resting on soil directly for this machine to restrict the amplitude of vibration to 25 microns. It was, therefore, decided to support this foundation on pile though piling was not required for any other foundation of this project. Since piling under this foundation constituted the total piling requirement of the project, 40cm dia., 10m long, 50te cast-in-situ bored piles were adopted for this foundation after making a techno-economic study. This paper outlines the approach followed to predict the dynamic response of the foundation. Actual measurements taken on the foundation after the plant was put into operation enabled a comparison between the predicted and observed response of the foundation. Useful conclusion from the study has been reported.

EVALUATION OF SOIL-PILE STIFFNESS OF SINGLE PILE

Typical Soil Profile of the Site is given in Figure-1.

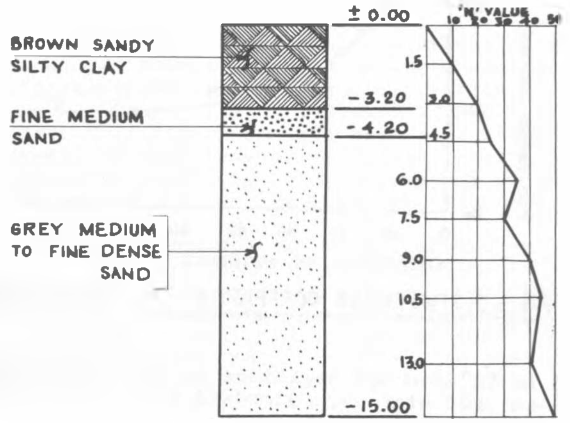

FIG.-1. SOIL PROFILE

Soil-pile stiffness was evaluated by conducting in-situ dynamic tests on single pile in both vertical and horizontal modes of vibration. Since the amplitude of vibration of the foundation was to be restricted to a very small value, the tests were conducted at various excitation levels and it was decided to evaluate both vertical stiffness (K_V) and horizontal stiffness (K_H) of soil-pile system as a function of amplitude. Fig.2 and Fig.3 show the variation of 'K_V' and 'K_H' with amplitude of vibration.

It was seen from the results that 'K_V' was more or less constant in the range of observed amplitudes of vibration whereas 'K_H' depended on the amplitude of vibration. 'K_H' and 'K_V' evaluated from single pile worked out as follows:

$$K_V = 1000 \pm \text{SD te/cm} \qquad (1)$$

$$K_H = 12.83\ A^{-0.155} \pm \text{SD te/cm} \qquad (2)$$

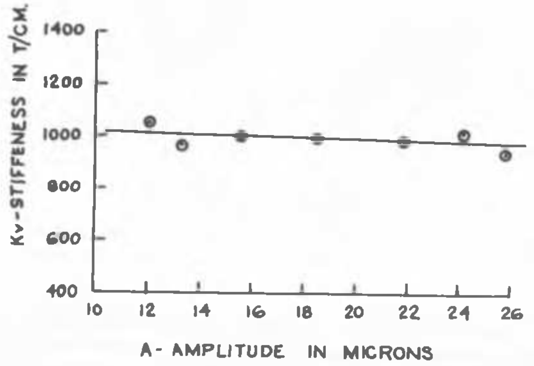

FIG.-2. STIFFENESS COEFFICIENT Kv Vs AMPLITUDE

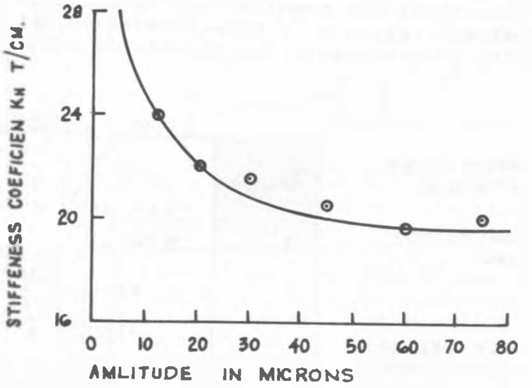

FIG.-3. STIFFENESS COEFFICIENT 'KH' Vs. AMPLITUDE

A in (2) denotes amplitude of vibration between 5 and 120 microns. Standard deviation (SD) was found out by equation

$$SD = \sqrt{\frac{(K_{c_i} - K_{o_i})^2}{n}} \qquad (3)$$

K_{c_i} = Computed value of 'K' at an amplitude A

K_{o_i} = Observed value of 'K' at an amplitude A

SOIL-PILE STIFFNESS FOR PILE GROUPS

The values of 'KV' and 'K_H' evaluated from in-situ tests were for single free head piles. But in actual practice piles are embedded in pile caps which would restrain pile heads against rotation. For the vertical mode, the group action will increase the settlement and thus decrease effective stiffness of piles (specially, if piles are friction piles). Therefore, from evaluated vertical stiffness of single pile K_V, vertical stiffness of pile group can be taken as $K_{Vg} = n \times K_V \times R$ where n is number of piles in group. R is a reduction factor depending upon the pile spacing. In case of end bearing pile 'R' can be taken as unity.

The effect of fixity due to pile cap in the horizontal mode will be to decrease deflection for a given load and that of group action will be to increase deflections. The overall effects of these two factors on 'K_H' were estimated by computing deflections at ground level for the case of free head as for a group of piles. Assuming a condition intermediate between full fixity and full pinning, overall increase in stiffness of pile groups was taken as:

K_{3d} - 1.10 for piles spaced at 3d.
K_{4d} - 1.25 for piles spaced at 4d.
K_{5d} - 1.41 for piles spaced at 5d.

Depth of fixity worked out to be 2.4m to 2.7m.

MACHINE DATA

Machine data for the design of foundation is given in table I.

TABLE - I.

Weight of motor	- 25.00 te
Weight of compressor	- 39.00 te
Operating speed	- 333 rpm
Primary horizontal inertial forces	- 0.2 te
Secondary horizontal inertial forces	- 2.6 te
Primary vertical inertial forces	- 7.5 te
Primary horizontal inertial couple	- 8.0 tem
Secondary horizontal inertial couple	- 5.0 tem
Primary vertical inertial couple	- 7.5 tem

PREDICTION OF DYNAMIC RESPONSE

The design of pile foundations subjected to dynamic loads requires the selection of a possible foundation configuration and the prediction of its dynamic response to the anticipated loading. As could be seen from table I, this machine had its secondary horizontal inertia force thirteen times more than the primary horizontal inertia force. This added to the difficulty of tuning of the foundation, since secondary mode of vibration also contributed substantially to the amplitude of vibration of foundation. Since resultant amplitude of vibration had to be restricted to 25 microns only, the restricted space available made a suitable configuration of foundation very difficult. For the prediction of dynamic response following two assumptions were made for the design of the foundation -

(a) Pile was assumed as end bearing since 73% of the designed capacity of the pile was carried by end bearing.

(b) A condition intermediate between full fixity and full pinning was assumed to affect on the top of the pile.

As has been stated earlier, the piling of this foundation constituted the entire piling requirement of the project, therefore, it was not possible to get the results of in-situ dynamic test of piles in the initial stages of design when number of piles had to be assessed. The soil-pile stiffness which is an important parameter in predicting the dynamic response of the foundation was evaluated theoretically based on the above assumptions. Pre-piling design charts (Irish and Walker, 1969) was very helpful in evaluating the frequencies of vibration in various modes. Depth of fixity was assumed as 2.4m (6 x pile diameter) in theoretical evaluation of soil-pile stiffness. Frequencies of vibrations were computed for vertical, horizontal, rocking, torsional modes of vibration and also for combined rocking and sliding modes of vibration. For the given unbalanced forces and couples, amplitude of vibration was computed in all the modes. Resultant amplitude of vibration was kept at 25 microns. After a number of trials, the possible configuration of foundation shown in Fig.4 was selected. Forty-two piles were required to support the foundation. The piles were spaced at 4 x diameter of piles.

Subsequently, when the results of in-situ pile tests were available, the soil-pile stiffness values corresponding to 25 microns were chosen and used for prediction of dynamic response of the foundation. Again, asbefore, the frequencies and amplitudes of vibration were computed in various modes of vibration. The difference between two sets of calculation was marginal. Though the configuration of the foundation could be slightly altered and three or four piles could be reduced, same was not done at this project.

The predicted response computed by both the above methods appear in table II.

VIBRATION MEASUREMENTS ON THE FOUNDATION

In order to assess the accuracy of predicted response, it was decided to evaluate the performance of this foundation after the plant was commissioned. When vibration measurement programme was drawn up, it was intended to obtain the measurements at different frequencies. Measurements were only possible only when the machine was operating under 80% and 100% load. Both the amplitude of vibration and frequencies were noted at different points on the foundation both at pile cap level as well as on the top of the foundations. Fig.4 shows the various points at which vibration measurements were taken. Table II gives a comparison between the predicted response and observed response at 100% load.

DISCUSSION ON PREDICTED AND OBSERVED RESPONSE

While measuring the response on the foundation during the operation of the machine, it has been assumed that forcing functions given by machine manufacturer and listed in Table-I are correct. This assumption has been made after the machine manufacturer had reconfirmed the data after testing the machine in shop before its despatch. The comparison of observed response with the predicted one will be meaningful only if forcing functions are correctly evaluated.

From table II, it can be clearly seen that observed response did not vary very much from the predicted one. This validates the two assumptions made during the prediction of the dynamic response of this foundation. The effective length assumed for the evaluation of soil-pile stiffness theoretically also was in more or less agreement with the evaluated depth of fixity. This perhaps is one of the reasons why the predicted response by two sets of calculations were not very much different. The comparison of predicted amplitude of vibration with the measured vibration for unbalanced compressors foundations on piles reported earlier (JogeshwarP.Singh et al 1977) also showed that assuming full fixity on pile head will result in predicted amplitude of vibration lower than the measured amplitude. The assumption of full fixity, therefore, is likely to be incorrect.

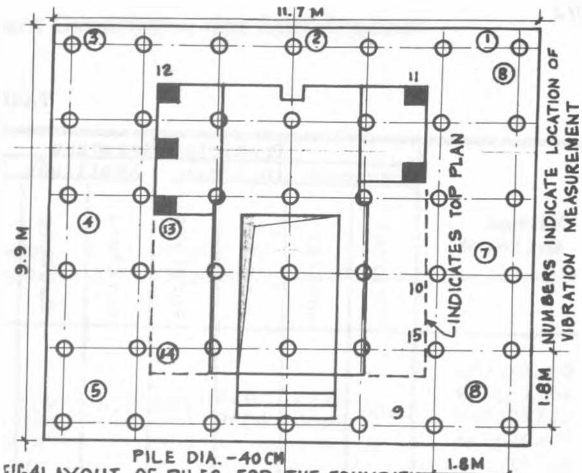

FIG.4 LAYOUT OF PILES FOR THE FOUNDATION

Further, it is noted that pre-piling design charts (Irish and Walker, 1969) can also be effectively used in working out the predicted response and piling requirement. However, in using this chart suitable assumption should be made for effective length of pile. In practice this varies between 1.5m to 3.5m (according to author's experience). But since the frequencies in horizontal and torsional modes varies as

$$\frac{1}{\sqrt{(\text{effective length})^3}}$$

improper assumption of effective pile length may make wide difference in thepredicted response which may ultimately result not only in over-design, but also in improper tuning of the foundation. Therefore, even in the absence of dynamic test on piles in-situ, the depth of fixity should be evaluated from horizontal load test on pile.

It is felt from author's experience that soil-pile stiffness parameters from in-situ dynamic test on piles should be evaluated as function of strain level (amplitudes of vibration). This would enable designer to use a soil-pile stiffness parameter corresponding to permissible amplitude of vibration of foundation in the design of pile supported foundations. Thus, the predicted response would also be very close to the observed one. Author has used the same approach for the design of the foundation for the same machine at a different project site. At that site, the foundation was supported on cast-in-situ driven piles. The performance of that foundation has also been very satisfactory

TABLE - II

Method followed	Predicted Response								Observed Response							
	Frequency in c/min.				Amplitude (microns)				Frequency in c/min.				Amplitude (Microns)			
	Vertical	Rocking	Pitching	Torsional	Vertical	Rocking	Pitching	Resultant	Vertical	Rocking	Torsional	Pitching	Vertical	Rocking	Pitching	Resultant
Computing soil-pile stiffness theoretically	2400	440 3400	420 4350	740	5.0	23	8	24.8	2530	485 3620	810	469 4660	3	21	6	22.1
Using Evaluated soil-pile stiffness	2380	498 3530	446 4500	825	4.5	22	7	23.8								

and the predicted response there also was in fair agreement with the observed response. Lack of space prohibited the presentation of these data here. Since then, author has used the same approach for the design of unbalanced machine foundations on piles at three different sites. The performance of all these foundations has been very satisfactory.

One more important observation made at this project was that the response of the bored piles has not been very much different from that of driven piles. This has been confirmed from the observed response of driven piles at a location close to this site having similar soil condition.

CONCLUSION

One of the most important factor affecting the accuracy of the predicted dynamic response is the soil-pile stiffness factor. Author's experience has been that the soil-pile stiffness should be evaluated from insitu dynamic test on piles as a function of amplitude of vibration. Using from the results of dynamic tests, stiffness factors corresponding to the permissible amplitude of vibration of the foundation will enable the prediction of dynamic response with an accuracy of ± 10%. In the absence of dynamic tests, the design charts (Irish and Walker, 1969) could be used to predict the dynamic response of the foundation with an accuracy of ±20% provided that effective length of pile is either correctly assumed or evaluated from horizontal load test on pile.

Since the behaviour of soil-pile interaction is very intricate, it is hoped that relatively simple method of analysis outlined in this paper may be a useful tool for all practising engineers in designing a pile-supported foundation subjected to dynamic loads.

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