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Vibration Studies of Block Type Machine Foundations

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SYNOPSIS Detailed vibration measurements were undertaken at eight block type machine foundations with different supporting soil conditions. These extensive measurements were supplemented by theoretical vibration calculations using principlly Barkan's method but, at times, using methods of Reissner, Pauw, Richart and Ford and Haddow. The results of prototype experiments and theoretical studies on various compressor foundations described above as also on similar foundations in the country justify broadly the validity of various theories, particularly Barkan's method, though these are based on somewhat different concepts. Design criteria for foundations are generally described in terms of limiting values of amplitudes of displacement at the operating conditions. In general, the permissible amplitude of vibration decreases as the frequency increases. Thus, the allowable vibration amplitude has to be considered along with the operating frequency of machine.

INTRODUCTION

In this review various methods which are in vogue presently for analysing the vibrations of block type machine foundations are presented. Emphases have been given on the methods which are currently in practice and are also under development. In order to compare the efficacy of various methods, a number of Indian case histories with prototype results have been presented. Such comparative studies are expected to be helpful in justifying the various assumptions involved in the theoretical dynamic analysis.

REVIEW OF CURRENT PRACTICE

Several theories have been put forward to estimate vibration characteristics of machine foundations under their actual dynamic loads. The problem of foundation vibrations was considered as single vibrating mass supported by weightless spring and subjected to viscous damping. Extensive series of tests conducted by DEGEBO (Deutschen Forschungsgesellschaft fur Bodenmechanik) showed that such simple damped mass-spring theory was not adequate to explain the test results obtained from vertical motion of an oscillator resting on soil. It was necessary to consider an 'in-phase' mass of soil oscillating together with the machine and its foundation. Inspite of several methods involving pilot tests, this procedure has been rather limited in its application since Lorenz (1934) and others found that the computed in-phase soil was not a constant quantity but varied appreciably with different surface loadings. This method of analysis has been used by Pauw (1953), Slade (1953), Barkan (1962), Major (1962), Newcomb (1951), Tschebotarioff (1953), Eastwood (1953) and others.

In order to solve this problem, analytical means were resorted to for the studies of propagation of elastic waves in solid bodies. Reissner (1936) following Rayleigh and Lamb presented an analytical solution to the problem of vertical motion of an oscillator resting on elastic half-space. His solution included the dynamic behaviour of elastic half-space and represented the oscillator by a pulsating pressure uniformly distributed over a circular contact area. More recently, both Sung (1953) and Quinlan (1953) have extended Reissner's treatment to cover different contact pressure distributions between the oscillator and elastic body. Arnold et al. (1955), Toriumi (1955) and Hsieh (1962) have considered various modes of vibrations. In a procedure proposed by Crockett and Hammond (1948), the in-phase soil mass is determined from the volume contained in an envelope of the pressure bulb for some selected pressure intensity. It was possible to calculate a steady-state response of a rigid foundation - soil system in the low frequency range. Fortunately, this range includes the operating frequencies of the most of the machines and above solutions are, therefore, useful for practical purposes. This was demonstrated by Richart, Jr. (1960) who also considered rocking and sliding modes of vibration.

Since dimensions of the soil system representing the elastic half-space are infinite, energy applied to the foundation and transmitted into the elastic half-space is not reflected or received back to the foundation. This gives rise to a system which is damped even though the medium is perfectly elastic. Hall and Richart (1963) have shown that for the amplitudes of vibrations involved in a foundation system, the energy loss attributed to material damping should be insignificant as compared to the energy transmitted into the half-space except possibly for some conditions of rocking motion. Experimental evidence tends to support these theoretical assumptions adequately when one considers the accuracy with which the soil properties can be estimated (Fry, 1963, Drnevich et al 1965). Lysmer and Richart (1966) have further shown how an analogue can be derived for the vertical motion of a rigid foundation which approximates exact solutions well within the accuracy required for engineering purposes. Hall, Jr. (1967) extended the work of Lysmer and Richart to include analogues which are applicable to the coupled rocking and sliding vibrations of rigid circular foundations resting on the surface of elastic half-space and compared the theoretical solutions with the published field test results of Fry (1963) on full size foundations.

The above theory of elastic half-space is derived on the basis of circular contact base of foundation and hence the effect of foundation shape is ignored. Kobori (1962) considered a rectangular shape foundation and formulated a mathematical procedure to evaluate vibration amplitudes in the vertical, horizontal and rocking modes of vibrations. Chae (1969) suggested use of an equivalent radius based on perimeter characteristics to estimate dynamic response of rectangular foundation.

Most of the above theoretical solutions treat the foundation as a rigid body resting on free surface of elastic half-space. However, actual foundations are partially or completely embedded in elastic half-space and experiments indicate that embedment can considerably affect dynamic response of foundation. The most promising way of approaching this problem seems to be the finite element analysis used by Lysmer and Kuhlemeyer (1969) and by Kaldjian (1969) for static stiffness. An approximate analytical approach was formulated by Baranov (1967) whose solutions were found to yield reasonable result in any vibrational mode. Novak and Beredugo (1972) used Baranov's solution and compared the same with the finite element solutions and also with the experimental results in order to verify its applicability. Special attention was devoted to the vertical mode of vibrations. A brief consideration of all vibration modes is given by Novak and Beredugo (1971). Coupled horizontal and rocking vibrations are analysed by Beredugo and Novak (1972), and Srinivasan et al. (1972) have also dealt with the problem of embedded foundations.

Barkan (1962) has dealt with the dynamic behaviour of block type foundations subjected to impact loads.

Some of the abovementioned theoretical methods which yield useful results for practical application and which have been widely accepted as standard practice for predicting the dynamic behaviour of machine foundations under superimposed vibratory loads have been used for computations of vibrations.

CASE HISTORIES

As mentioned earlier, some of the Indian case histories with both theoretical, prototype experimental results are described. The vibration characteristics, viz., natural frequencies and vibration amplitudes in various modes have been computed following, mainly, Reissner (1936), Barkan (1962), Richart (1960), Pauw (1953), and Ford and Haddow (1960) for the following compressor and forge hammer foundations :

1. Ammonia Synthesis Main Gas Compressor Foundations, Fertilizer Corporation of India (F.C.I.), Trombay Unit, Bombay (Maharashtra) No. of Units : 3
2. Nitrogen High Pressure Compressor Foundations, Fertilizer Corporation of India (F.C.I.), Trombay Unit, Bombay (Maharashtra) No. of Units : 3
3. Ammonia Synthesis Compressor Foundations, Fertilizer Corporation of India (F.C.I.), Sindri Unit, Sindri (Bihar). No. of Units : 9
4. Gas Reforming Plant (G.R.P.) Foundations, Fertilizer Corporation of India (F.C.I.), Sindri Unit, Sindri (Bihar). No. of Units : 1
5. Construction Power House (C.P.H.) Compressor Foundations, Koyna Hydroelectric Project (Maharashtra). No. of Units : 3
6. Catalytic Reforming Unit (C.R.U.) Foundation, Gujrat Oil Refinery Indian Oil Corporation, Baroda. No. of Units : 4 (Only experimental)
7. Synthesis Gas Compressor Foundations, Rourkela Fertilizer Plant, Hindustan Steel Ltd., Orissa (Only experimental)
8. Forge Hammer Foundations, Bharat Forge Co. Ltd., Poona (Maharashtra). No. of Hammers: 8

Various parameters required for the dynamic computations for all above compressor and forge hammer foundations are obtained from design data. The computed results for each compressor foundation are given in Tables I and II. Table III shows the same for Forge Hammer Foundations of different capacities. The computations have been made for two sets of values of soil parameters as precise values of the same were not known and also to bring out their predominant influence on the vibration characteristics. The values of soil parameters in these two sets are the probable limiting values of soil constants for the supporting soil as could be expected from the field experiments such as seismic velocity measurements etc..

Extensive experimental set-up such as Philips electro-dynamic pick-ups with preamplifiers, calibrators and recording oscillographs having frequency range upto several hundred Hz, three component Sprengnether Engineering Seismographs (x50, x500, VS-1100 and VS-1200) having frequency range of about 100 Hz, vibration meters, Askania Hand Vibrograph, Elcomatic

TABLE I. Theoretical Results of Nitrogen Compressor Foundation, F.C.I., Bombay (Maharashtra)

Natural frequencies of foundation, Hz						Vertical	Amplitudes of vibrations, micron			
							Separate mode		Combined mode	
After	f_{nz}	f_{nx}	$f_{n\phi}$	f_{n1}	f_{n2}	A_z	$A = A_1 + A_2$		$A' = A_1' + A_2'$	
Set-I : V_c = 1.20 km/sec, d = 2.2 gm/cc p = 0.35							At top of foundation	At upper edge of	At top of foundation	At upper edge of mat
Barkan	30.1	25.8	43.8	50.4	24.7	-	1.3	1.0	3.1	1.0
Richart	40.9	18.7	26.2	-	-	-	2.8	1.3	-	-
Pauw	18.3	9.9	15.1	15.1	9.9	-	3.0	2.8	-	-
Ford and	20.9	12.7	Sand	-	-	-	-	-	-	-
Haddow	16.2	9.8	Clay	-	-	-	-	-	-	-
Set-II: V_c = 0.46 km/sec; d = 2.0 x gm/cc; p = 0.37										
Barkan	10.4	8.9	15.0	17.3	8.5	-	14.1	11.4	16.2	12.2
Richart	13.7	6.7	9.3	-	-	-	24.0	10.9	-	-
Pauw	6.4	3.4	5.4	5.4	3.4	-	25.3	22.7	-	-
Ford and	7.4	6.4	Sand	-	-	-	-	-	-	-
Haddow	5.8	4.9	Clay	-	-	-	-	-	-	-

f_{nz} = Natural frequency of vertical vibrations, Hz
f_{nx} = Natural frequency of sliding (horizontal) vibrations, Hz
$f_{n\phi}$ = Natural frequency of rocking vibrations, Hz
f_{n1}, f_{n2} = Fundamental higher and lower natural frequencies of foundation-soil system respectively OR hammer-foundation-soil system, Hz
A_z = Amplitude of vertical vibrations due to exciting force (P_z), micron
A = Total amplitude of horizontal (due to sliding or shear) and rocking vibrations (separate modes) due to primary and secondary exciting forces and moments, micron
A_1 = Total amplitude of horizontal and rocking vibrations (separate mode) due to primary exciting force and moment, micron
A_2 = Total amplitude of horizontal and rocking vibrations (separate mode) due to secondary exciting force and moment, micron
A' = Total amplitude of horizontal and rocking vibration (combined mode) due to primary and secondary forces and moments, micron
A_1' = Total amplitude of horizontal and rocking vibration (combined mode) due to primary exciting force and moment, micron
A_2' = Total amplitude of horizontal and rocking vibration (combined mode) due to secondary force and moment, micron
V_c = Velocity of elastic compressional waves in soil, km/sec
d = Mass density of soil, gm/cm^3
p = Poisson's ratio of soil

amplifiers and recorders was used to measure vibrations at the compressor and forge hammer foundations. Very thorough vibration survey was made. Table IV gives maximum amplitudes of measured vibrations and associated average frequencies for all the five compressor foundations under study and Table V shows the same for forge hammer foundations.

RESULTS AND DISCUSSIONS

It can be seen from the Tables I and II that the theoretically computed values of natural frequencies in various modes for compressor foundations at Bombay, Koyna (CPH) and Sindri (GRP) are much different from operating frequencies of the compressors and, therefore, the amplitudes of vibrations are comparatively small and are within the prescribed permissible safe limit of 200 microns as suggested by Barkan (1962) for such types of machine foundation. On the other hand, the computed natural frequencies in case of Ammonia compressor foundation at Sindri are very close to the operating frequency (5.0 Hz) of compressor or its nearest harmonic. This closeness of computed natural frequencies of the foundation and the operating frequency, in the latter case, possibly has resulted in its large amplitude of vibrations of about 420 microns (vide Tables II and IV). The design criteria generally followed viz., that the natural frequencies of foundation should be at least ± 25% away from the operating frequency of the machine or its nearest harmonic is not satisfied in case of this Ammonia Compressor Foundation at Sindri. Also, it may be due to the fact that soil below the foundations at Bombay and Koyna has much smaller predominant period (about 0.03 sec estimated by impact studies) as compared to the predominant period of site at Sindri where

TABLE II Theoretical Results of Ammonia Compressor Foundation, F.C.I. Sindri (Bihar)

Natural frequencies of foundation, Hz						Vertical, A_z	Amplitudes of vibrations, micron			
							Separate mode $A = A_1 + A_2$		Combined mode $A' = A_1' + A_2'$	
After	f_{nz}	f_{nx}	$f_{n\phi}$	f_{n1}	f_{n2}		At top of foundation	At upper edge of mat	At top of foundation	At upper edge of mat
Set - I : V_c = 1.0 km/sec; d = 1.8 gm/cc p= 0.45										
Reissner	-	-	-	-	-	10.7	-	-	-	-
Barkan	15.0	12.1	10.5	22.5	8.5	14.2	163.8	55.6	143.7	60.6
Richart	10.7	11.0	9.3	-	-	15.7	147.0	54.3	-	-
Pauw	8.4	4.9	12.3	12.6	4.8	10.0	210.1	197.3	-	-
Ford and	16.5	9.7	Sand	-	-	-	-	-	-	-
Haddow	13.6	8.0	Clay	-	-	-	-	-	-	-
Set - II : V_c = 0.75 km/sec; d = 1.8 gm/cc; p = 0.45										
Reissner	-	-	-	-	-	17.7	-	-	-	-
Barkan	11.2	9.1	7.9	17.0	6.3	28.1	372.7	122.0	441.9	187.0
Richart	7.8	9.4	6.9	-	-	27.7	262.0	84.1	-	-
Pauw	6.6	3.9	9.4	9.7	3.8	19.2	188.3	161.1	-	-
Ford and	12.4	7.3	Sand	-	-	-	-	-	-	-
Haddow	10.2	6.0	Clay	-	-	-	-	-	-	-

TABLE III Theoretical Results of Forge Hammer Foundations, Bharat Forge Co. Ltd. Poona (Maharashtra)

Sr. No.	Forge hammer (Capacity, lbs)	W_o, Ton	Natural frequencies, Hz				Amplitude of Vibrations, mm		Stresses in Korfund pad, dyne
			f_{na}	f_1	f_{n1}	f_{n2}	A_F	A_A	$\times 10^{-6}$
1.	Set-I 2000	1.48	28.2	178.0	204.0	27.5	0.130	2.9	9.6
2.	3000	2.83	28.8	135.0	148.0	29.0	0.011	3.8	12.9
3.	4000	3.20	25.5	128.0	143.0	25.6	0.420	3.7	13.8
4.	6000	4.43	24.5	116.0	131.0	24.2	0.100	3.5	11.6
5.	12000	7.49	18.9	105.0	121.0	18.8	0.030	4.2	13.2
6.	16000	10.40	18.3	97.6	113.0	18.1	0.100	4.3	13.2
7.	20000	11.26	16.7	98.4	115.0	16.7	0.390	4.3	12.2
8.	25000	14.50	14.1	92.6	106.0	14.2	0.140	5.6	17.7
9.	Set-II 2000	1.48	28.2	103.0	119.0	28.0	0.036	2.8	9.6
10.	3000	2.83	28.8	77.9	86.3	28.5	0.130	3.8	12.7
11.	4000	3.20	25.5	73.7	83.0	25.2	0.100	3.8	12.6
12.	6000	4.43	24.5	66.6	76.6	24.2	0.100	3.5	11.6
13.	12000	7.49	18.9	62.4	70.5	18.8	0.030	4.2	13.0
14.	16000	10.40	18.3	56.2	66.1	15.9	1.200	4.8	11.3
15.	20000	11.26	16.7	56.7	66.6	16.7	0.039	4.3	13.5
16.	25000	14.50	14.1	53.3	61.3	14.2	0.140	5.6	18.3

W_o = Combined weight of foundation and machine, dyne

f_{na} = Limiting frequency of natural vibrations of the anvil on korfund pad, Hz

A_A = Amplitude of displacement of anvil vibrations, mm

f_1 = Limiting frequency of natural vibration of the anvil-hammer foundation-soil system, Hz

A_F = Amplitude of displacement of hammer-foundation vibrations, mm

TABLE IV Experimentally Observed Amplitudes and Frequencies of Vibrations at Compressor Foundations

Sr. No.	Compressor foundation	Component of vibration	Maximum amplitude of vibration at, micron		Associated average frequency, Hz	Operating frequency, Hz	Type of supporting soil
			Top of foundation	Basement floor (mat)			
1.	Ammonia Synthesis main gas compressors, FCI, Bombay	L	1.4	1.2	4 - 5	4.55	Lean concrete resting on hard strata of safe bearing capacity of 3.8 x 10^6 dyne/cm^2 under saturated condition
		V	19.7	6.3	"	"	
		T	15.3	7.8	"	"	
2.	Nitrogen high pressure compressors, FCI, Bombay	L	1.4	0.8	4 - 5	4.55	
		V	6.8	5.0	"	"	
		T	8.2	11.2	"	"	
3.	Ammonia gas compressors, FCI, Sindri	L	60.2	25.0	10.0	5.0	Mostly dense sand of safe bearing capacity of 1.6 x 10^6 dyne/cm^2
		V	101.0	195.0	"	"	
		T	450.0	98.0	"	"	
4.	Gas reforming plant, FCI, Sindri	L	13.0	7.0	2.7-2.8	2.8	Soil of medium strength (silty with some sand) of safe bearing capacity of 2.5 x 10^6 dyne/cm^2
		V	40.0	37.0	"	"	
		T	59.5	28.0	"	"	
5.	Compressor foundation of construction Power House, Koyna H.E. Project	L	17.0	10.6	30 - 100	7.13	Hard murrum
		V	14.0	11.5	70 - 80	"	
		T	4.4	2.9	7.3-7.5	"	
6.	Catalytic Reforming Unit (C.R.U.), Gujrat Oil Refinery, Baroda	L	21.3	-	2.8	2.8	Thick alluvium underlain by harder strata
		V	8.5	-	"	"	
		T	3.7	-	"	"	
7.	Synthesis gas compressors foundations, HSL, Rourkela	L	17.1	-	5.0	5.0	Thick alluvium underlain by harder strata
		V	73.0	-	5.0	5.0	
		T	61.2	-	5.0	5.0	

Note : L = Longitudinal component of vibration parallel to direction of crank shaft
V = Vertical component of vibration
T = Transverse component of vibrations perpendicular to the direction of crank shaft

the foundation directly rests on soil. The predominant period of the latter is expected to be larger and closer to the period of operating frequency of the compressor. It is interesting to note that the natural frequencies and vibration amplitudes computed by using five methods, as mentioned in the case histories are more or less of the same order. Also, their values are largely dependent on elastic properties of the supporting soil (alternatively, predominant period of the site) as can be seen from sets-I and-II in Tables I and II.

Experimentally measured vibration amplitudes (vide Table IV) are closer to those computed by Barkan's method. The measured frequencies in case of foundations at Bombay and Sindri (GRP) are almost equal to the operating frequency of the respective compressors as expected, while the same for ammonia foundation at Sindri are equal to the nearest harmonic (10.0 Hz) of the operating frequency of the compressor (5.0 Hz). It can be observed from records that there are higher frequencies also in the vibration records in addition to the low frequencies (almost equal to the operating frequency). This may indicate that the recorded foundation vibrations are not purely due to primary exciting forces of the compressors. Recorded frequencies in case of foundations at Koyna (CPH) are much larger than the operating frequency (vide Table-IV). However, exact source of these high frequency vibrations has not been fully investigated.

In case of forge hammer foundations, it is observed from Tables III and V that the computed and measured amplitudes of anvil vibrations (A_A) are generally corroborated and are within

TABLE V Experimentally Observed Amplitudes and Frequencies of Vibrations at Forge Hammer Foundations, Bharat Forge Co. Ltd., Poona (Maharashtra)

Sr. No.	Forge hammer (Capacity, lbs)	Component of Vibration	Anvil		Foundation		Anvil		Foundation		Type of supporting soil
			V_A	f_A	V_F	f_F	V_A	f_A	A_F	f_F	
1	2000	Vertical	157.4	-	-	-	1.8	14.0	-	-	Soft and hard weathered basalt upto a depth of about 3 meters underlain by compact basalt
2	2000*	"	265.3	-	62.0	-	3.2	13.3	0.75	13.3	
3	4000	"	285.9	-	120.6	16.0	3.5	13.0	1.20	-	
4	12000	"	244.3	-	-	-	3.5	11.1	-	-	
5	25000	"	220.0	-	119.3	50.0	2.7	13.0	-	-	
6	6000	"	181.3	-	147.9	11.4	2.4	12.2	2.10	-	
7	6000*	"	136.0	-	118.6	-	1.9	11.4	1.65	11.4	

* Measured by Askania hand vibrograph both on anvil and foundation

V_A = Amplitude of particle velocity of anvil vibrations, mm/sec

f_A = Associated average frequency of anvil vibrations, Hz

V_F = Amplitude of particle velocity of hammer foundation vibrations, mm/sec

f_F = Associated average frequency of hammer foundation vibrations, Hz

A_F = Amplitude of displacement of hammer-foundation vibrations, mm

the prescribed permissible limit of 3 to 4 mm for low capacity hammers (upto 6000 lbs) and upto 5.0 mm for high capacity hammers (above 6000 lbs). Similarly, though the measured and computed displacement amplitudes of foundation vibrations (A_F) differ considerably the same are within the prescribed permissible safe limit of 1.0 to 1.2 mm (Barkan, 1962) except for foundation of 6000 lbs capacity hammer in which case measured amplitudes of vibrations vary from 1.65 to 2.10 mm and the same was also incidentally malfunctioning at the time of experiments. It is further observed that the computed as well as the measured vibration frequencies of both anvils and foundations are quite away from the natural frequency of the supporting soil i.e. 30 to 35 Hz as estimated from the explosions studies (Wedpathak et al. 1974) indicating no possibility of resonance. This can be verified from the small amplitudes of anvil and foundation vibrations obtained both by measurements and computations except for 6000 lbs hammer. The computed dynamic stresses in the korfund pads are also within the prescribed permissible safe limit of 3.0×10^7 dyne/cm^2 (vide Table III) as suggested by Barkan (1962). Thus, it can be said that the foundation bearing areas and other related parameters have been properly selected and satisfy the conditions required for dynamic stability of foundations under impact loads (Barkan, 1962; Gupta et al. 1967; Prakash et al. 1968). The moderate changes in the elasticity of supporting soil (using dynamic and static values of elasticity, vide Table III) has produced considerable change in the computed natural frequencies (f_1 and f_{n1}) and displacement amplitudes (A_F) as is evident from the theoretical analysis of rigid body resting on elastic half-space.

CONCLUSIONS

Various theoretical methods which are in vogue for estimating dynamic characteristics of block type machine foundations subjected to sinusoidal and impact loads are briefly mentioned though extensive use has been made of the methods of Reissner (1936), Barkan (1962), Pauw (1953), Richart (1960), and Ford and Haddow (1960) for the purpose. The results of prototype experiments and theoretical studies on various compressor foundations described in case histories in Tables I to V as also on similar foundations in the country justify broadly the validity of various theories, particularly Barkan's method, though these are based on somewhat different concepts.

Design criteria for foundations are generally described in terms of limiting values of amplitudes of displacement at the operating conditions. The amplitude of vibrations should be such that its magnitude is within tolerance limit at the operating frequency of the machine. In general, the permissible amplitude of vibrations decreases as the frequency increases. Thus, the allowable vibration amplitude has to be considered alongwith the operating frequency of machine. Information given by Richart (1960) can be used as a guide line for permissible amplitude of vibrations of foundations.

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