Vibration Studies on Large Compressor Foundations Resting on Soils

by

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Introduction

DYNAMIC design of machine foundations (low speed and high speed) has been a subject of study for past two decades or so and several theories have been put forward to estimate the vibration characteristics of the foundations under actual dynamic loads. However, there has been paucity of actual prototype data to supplement theoretically obtained results. Further, these involved theories require precise knowledge of various physical parameters of the supporting soil as such it is rather difficult to use them readily for practical purposes. Central Water and Power Research Station, Poona, India, has been actively engaged for last more than a decade in collecting the prototype vibration data for various machine foundations such as compressors, thermal power statioens, hydroelectric power stations, *etc.*, with a view to streamline the roc dure for design of these foundations. The present paper deals with the comparative theoretical and experimental results for four compressor foundations resting on soils, *viz.*, Ammonia synthesis main gas compressor foundations, Bombay (A); Nitrogen high pressure compressor foundations, Bombay (B) ; Ammonia synthesis compressor foundations, Sindri (C) ; and Gas reforming plant foundations at Sindri (D) ; Fertilizer Corporation of India. A simplified approach to the problem, though qualitative in nature, has also been suggested.

Theoretical Studies

The basic concepts of the various theories so far advocated may be *summarised broadly as follows :*

(1) The machine-foundation-soil system is replaced by a spring-mass system having appropriate number of elements and known masses, spring characteristics and damping factors. The response of the system to the exciting force is then obtained from the usual theory of vibrations. The difficulties

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This paper was received on 9 February 1971. It is open for discussion up to December 1971.

lie in estimating the various constants and, in particular, the mass of the soil participating in the vibrations and its coupling to the surrounding soil (Barkan, 1962 ; Lorenz, 1953 ; Pauw, 1953 and others).

(2) The soil is considered here as a semi-infinite isotropic elastic medium subjected to a periodic load applied at the surface. The resulting equations of motion are solved for various surface loadings. This is the dynamic analogue of the "Boussinesq problem" (Reissner, 1936 , Richart, 1960 ; Toriumi, 1956 and others).

The vibration characteristics, *viz.*, natural frequencies and amplitudes of vibrations in various modes have been computed following mainly, *Barkan (1962), Pauw (1953), Richart (1960), and Ford and* Haddow (1960), for the four foundations (A, B, C and D) and computed results thus obtained are given in Tables I and II. These computations have been made for two sets of values of soil parameters* as the precise values of these parameters were not known, and also to bring out their predominant influence on the foundation vibrations. Foundations A and B at Bombay are underlain by lean concrete of about 170 cm thickness resting on soil while foundations C and D at Sindri rest directly on soil (mostly dense sand). Figure 1 shows plan and section of foundation A.

It is seen from Tables I and II that theoretically computed values of natural frequencies in various modes for foundations A, B and D are much different from operating frequencies (4·5, 4·5 and 2·8 cycles/sec respectively) of the compressors and, therefore, the amplitudes of vibrations are comparatively small. On the other hand, the computed natural frequencies, in case of foundations C are very close to the operating frequency (5·0 cycles/sec) of compressors or its nearest harmonic. This closeness of natural frequencies of foundations and the operating frequency, in the later case, possibly has resulted in its large amplitude of vibrations. It may also be due to the fact that soil below foundations A and B has a much smaller predominant period (about 0·03 sec as estimated by impact studies) as compared to the predominant period of soil at Sindri (where the foundation directly rests on soil) which is expected to be large and closer to the operating frequency of the compressors. It is interesting to note that the natural frequencies and amplitudes of vibrations computed by the four methods are more or less of the same order. Also, these values are largely dependent on the 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. More detailed discussions on this aspect will follow later.

Experimental Studies

Extensive experimental set-ups such as Philips electro-dynamic pick-ups with pre-amplifiers, calibrators and recording oscillograph, having frequency range up to several hundred cycles per second, three component Sprengnether seismographs ($\times$ 50 and $\times$ 500) having frequency range up to

* These are the probable limiting values of Soil Constants for the supporting soil under study as could be expected from field tests such as estimation of elastic constants by seismic velocity measurements, *etc.*

TABLE I

Theoretically computed natural frequencies of vibrations in various modes.

Soil data		After	Vertical (cps)	Sliding (cps)	Rocking (cps)	Fundamental Higher (cps)	Fundamental Lower (cps)
Set—I							
Compressional wave velocity (cm/sec)	A* 1·2×10^5	Barkan	A 31·6	26·5	48·8	54·9	25·7
	B 1·2×10^5		B 30·0	25·8	43·8	50·4	24·7
	C 1·0×10^5		C 15·0	12·1	10·5	22·5	8·5
	D 1·6×10^5		D 23·3	18·8	23·1	33·0	16·2
Density (gm/cc)	A 2·2	Pauw	A 18·9	11·5	20·3	20·3	11·5
	B 2·2		B 18·3	9·9	15·1	15·1	9·9
	C 1·8		C 8·4	4·9	12·3	12·6	4·8
	D 1·8		D 11·3	6·7	13·4	13·7	6·5
Poisson's Ratio	A 0·35	Richart	A 13·1	17·1	28·4	29·6	16·4
	B 0·35		B 40·9	18·7	26·2	28·2	17·3
	C 0·45		C 10·7	11·0	9·3	15·2	6·3
	D 0·45		D 12·2	19·6	13·2	23·6	10·6
		Ford and Haddow	A 22·0	13·3	sand	—	—
			B 20·9	12·7		—	—
			C 16·5	9·7		—	—
			D 20·6	12·1		—	—
		—do—	A 17·2	10·3	clay	—	—
			B 16·2	9·8		—	—
			C 13·6	8·0		—	—
			D 16·7	9·8		—	—
Set—II							
Compressional wave velocity (cm/sec)	A 4·6×10^4	Barkan	A 10·7	9·1	16·8	18·9	8·8
	B 4·6×10^4		B 10·4	8·9	15·0	17·3	8·5
	C 7·5×10^4		C 11·2	9·1	7·9	17·0	6·3
	D 1·0×10^5		D 14·7	11·8	14·5	22·7	11·6
Density (gm/cc)	A 2·0	Pauw	A 6·6	4·0	6·7	6·7	3·4
	B 2·0		B 6·4	3·4	5·4	5·4	3·4
	C 1·8		C 6·6	3·9	9·4	9·7	3·8
	D 1·8		D 7·1	4·7	8·4	8·6	4·1
Poisson's Ratio	A 0·37	Richart	A 4·7	6·1	10·1	10·1	6·1
	B 0·37		B 13·7	6·7	9·3	10·1	6·2
	C 0·45		C 7·8	9·4	6·9	12·6	5·2
	D 0·45		D 7·7	12·3	8·0	14·9	6·7

* Values of natural frequencies corresponding to A, B, C and D correspond to Ammonia compressor foundations at Bombay, Nitrogen compressor foundations at Bombay, Ammonia compressor foundations at Sindri and G.R.P. compressor foundations at Sindri, respectively.

TABLE I (*Contd.*)

Ford and Haddow	A	7·6	6·7	sand	—	—
	B	7·4	6·4		—	—
	C	12·4	7 3		—	—
	D	12·9	7·6		—	—
—do—	A	5 9	5·2	clay	—	—
	B	5·8	4·9		—	—
	C	10·2	6·0		—	—
	D	10·6	6·2		—	—

about 100 cps, vibration meter and vibration analyser (General Radio Cambridge, Mass) with crystal pick-ups, *etc.* were used to measure the vibrations at the compressor foundations. Very thorough vibration survey was made and the measured amplitudes of displacements at some of the positions of observations are shown in Figures 2 to 6.

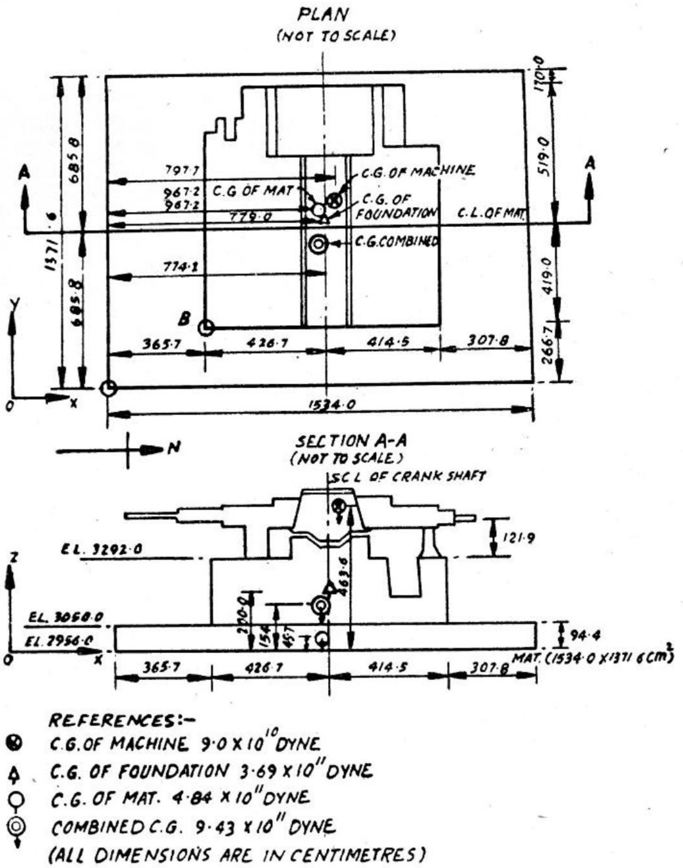


Figure 1 :- Plan and section of ammonia synthesis main gas compressor foundation, Fertilizer Corporation of India Ltd., Bombay (India)

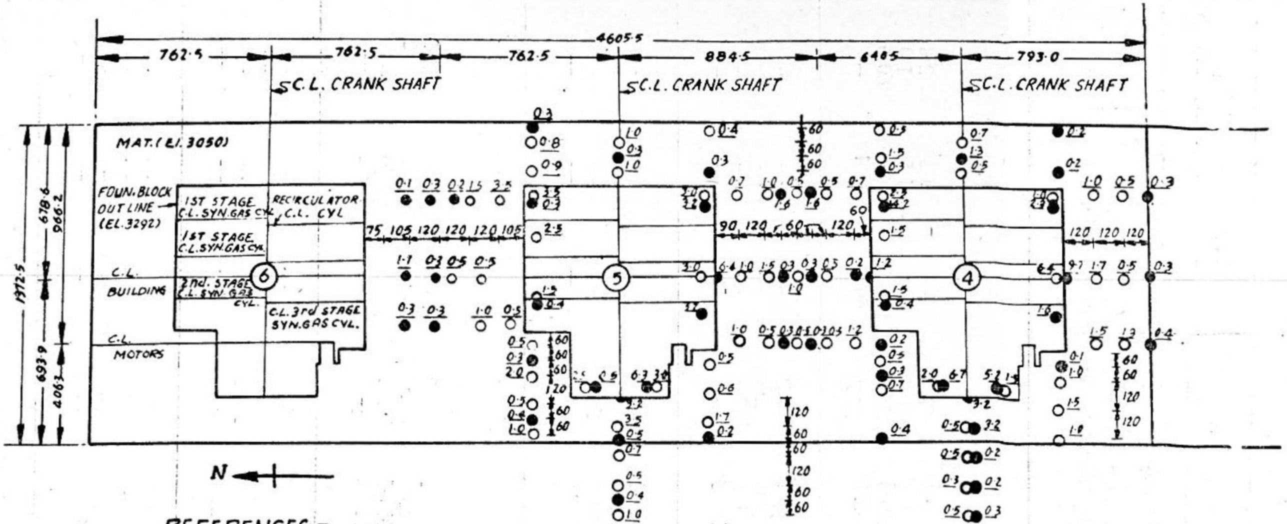
FIGURE 1

TABLE II

Theoretically computed amplitudes of vibrations in various modes.

After	Vertical		Sliding + Rocking (Separate)			Simultaneous sliding and Rocking (combined)	
			At top of foundation (microns)	At C.G. of machine (microns)	At upper edge of mat (microns)	At top of foundation (microns)	At C.G. of machine (microns)	At upper edge of mat (microns)
Set—I								
Barkan	—	A*	3·5	3·8	2·9	3·1	3·2	2·8
	—	B	1·3	1·5	1·0	3·1	4·5	1·0
	14·2	C	163·8	177·1	55·6	143·7	154·0	60·6
	—	D	44·4	46·9	—	44·9	47·4	—
Pauw	—	A	7·8	8·1	7·2	—	—	—
	—	B	3·0	3·0	2·8	—	—	—
	10·0	C	210 1	211·7	197·3	—	—	—
	—	D	114·7	118·5	—	—	—	—
Richart	—	A	7·6	9·4	4·0	—	—	—
	—	B	2·8	3·6	1·3	—	—	—
	15·7	C	147·0	159·4	54·3	—	—	—
	—	D	237·5	257·8	—	—	—	—
Set—II								
Barkan	—	A	37·2	40·1	31·7	34·7	36·4	31·6
	—	B	14·1	15·6	11·4	16·2	18·3	12·2
	28·1	C	372·7	403·6	122·0	441·9	473·0	187·1
	—	D	114·4	120·8	—	99·5	106·1	—
Pauw	—	A	105·9	109·6	98·9	—	—	—
	—	B	25·3	26·5	22·7	—	—	—
	19 2	C	194·3	197·5	169·2	—	—	—
	—	D	313·0	323·0	—	—	—	—
Richart	—	A	60·0	76·3	28·6	—	—	—
	—	B	24·0	30·8	10·9	—	—	—
	27·7	C	262·0	282·4	84·1	—	—	—
	—	D	599·5	650·0	—	—	—	—

* Values of amplitudes of vibrations corresponding to A, B, C and D correspond to Ammonia compressor foundations at Bombay, Nitrogen compressor foundations at Bombay, Ammonia compressor foundations at Sindri and G.R.P. compressor foundations at Sindri, respectively.



REFERENCES:-

I ○ POSITIONS OF OBSERVATIONS OF SPRENGNETHER SEISMOGRAPH (X500)

II ● POSITIONS OF OBSERVATIONS OF PHILIPS ELECTRO-DYNAMIC PICK-UPS.

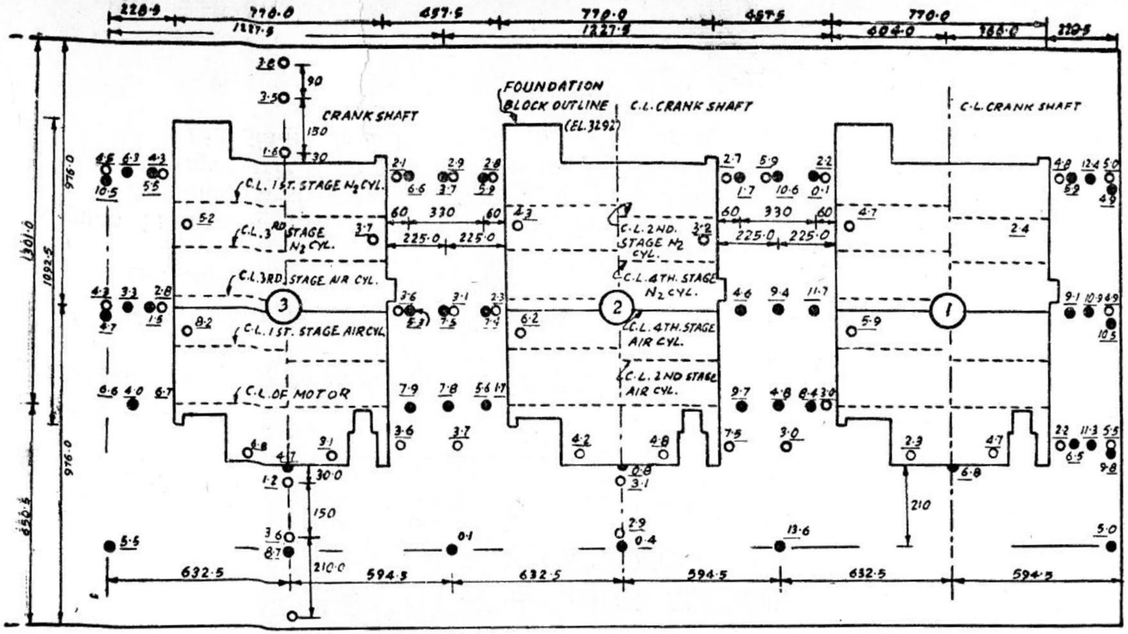
III UNDERLINED NUMBERS ARE MEASURED AMPLITUDES (SINGLE) OF DISPLACEMENTS IN MICRONS

IV ALL DIMENSIONS ARE IN CENTIMETRES.

(NOT TO SCALE)

Figure 2:- Positions of observations of Sprengnether seismograph (x500) and electro-dynamic pick-ups on basement floor and on top of foundation blocks of ammonia synthesis main gas compressors, Fertilizer Corporation of India Ltd., Bombay (India)

FIGURE 2.



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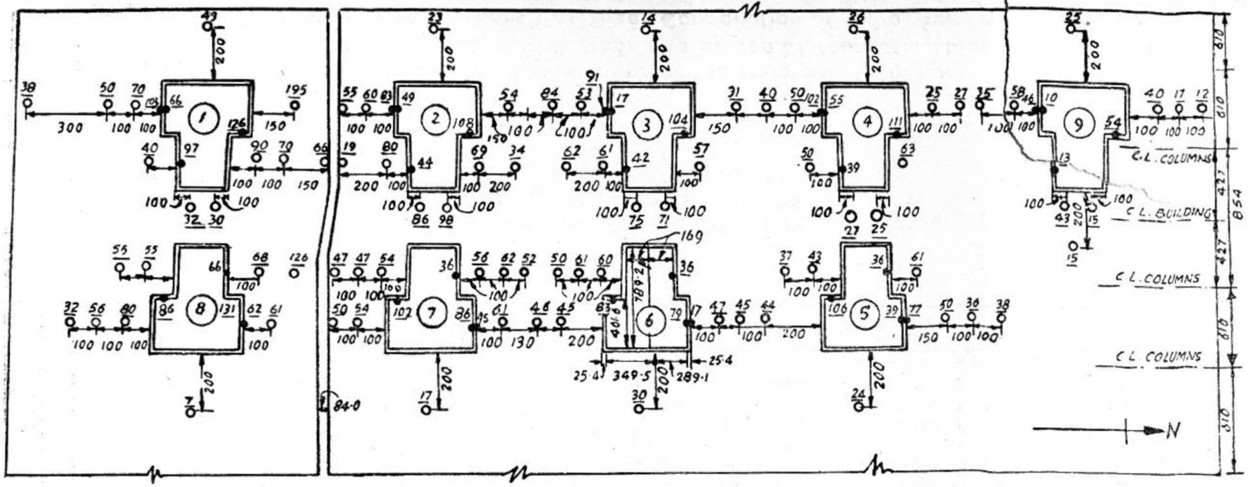
IV ALL DIMENSIONS ARE IN CENTIMETRES (NOT TO SCALE)

Figure 3 :- Positions of observations of Sprengnether seismograph (X500) and Phillps electro-dynamic pick-ups on basement floor and on top of foundation blocks of nitrogen nigh pressure compressors, Fertilizer Corporation of India, Bombay (India)

FIGURE 3.



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I ○ POSITIONS OF OBSERVATIONS OF SPRENGNETHER SEISMOGRAPH (X50)

II ● " " " " PHILIPS ELECTRO-DYNAMIC PICK-UPS.

III UNDERLINED NUMBERS ARE MEASURED AMPLITUDES (SINGLE) OF DISPLACEMENTS IN MICRONS

IV ALL DIMENSIONS ARE IN CENTIMETRES

(NOT TO SCALE)

Figure 4:—Positions of observations of Sprengnether seismograph (x50) and Philips electro-dynamic pick-ups on basement floor and vertical faces of ammonia synthesis main gas compressor foundations, Fertilizer Corporation of India Ltd, Sindri (India)

FIGURE 4.

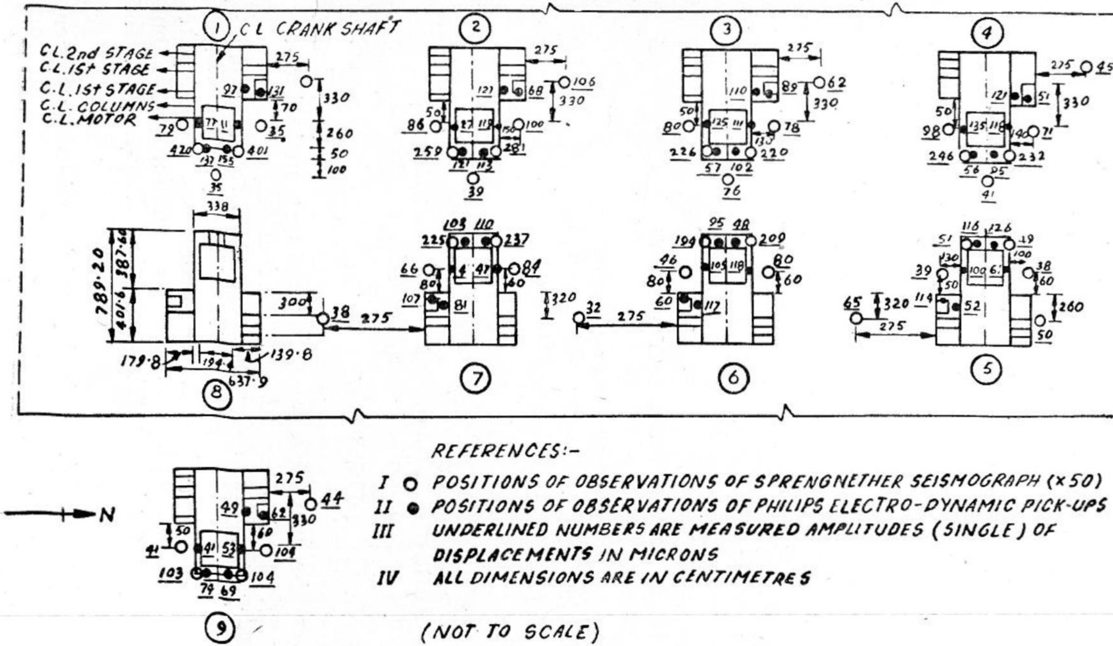
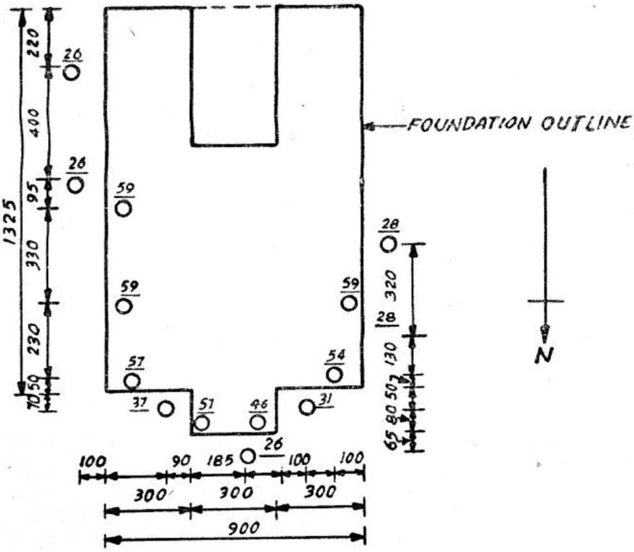


Figure 5:—Positions of observations of Sprengnether seismograph (x 50) and Philips electro-dynamic pick-ups on top of ammonia synthesis compressor foundations and on operating floor, Fertilizer Corporation of India Ltd., Sindri (India)

FIGURE 5



REFERENCES:—

I POSITIONS OF OBSERVATIONS OF SPRENGNETHER SEISMOGRAPH (X 500)

II UNDERLINED NUMBERS ARE MEASURED AMPLITUDES (SINGLE) OF DISPLACEMENTS IN MICRONS

III ALL DIMENSIONS ARE IN CENTIMETRES (NOT TO SCALE)

Figure 6:—Positions of observations of Sprengnether seismograph (x500) on top of gas reforming plant foundation and basement floor, Fertilizer Corporation of India, Ltd., Sindri (India)

FIGURE 6.

Table III gives the maximum amplitudes of measured vibrations and associated average frequencies for all the four foundations under study. The measured amplitudes of vibrations are closer to the computed from Barkan's method (*vide* Table II). The measured frequencies in case of foundations A, B and D are almost equal to the operating frequencies of the compressors as expected, while the same for foundations C are equal to the nearest harmonic of the operating frequency of the compressors.

Figures 7, 8 & 9 show typical records obtained from three component Sprengnether seismographs ($\times 500$ and $\times 50$) for compressor foundations at Bombay and Sindri. Figure 10 shows a typical displacement record obtained using Philips electro-dynamic pick-ups for foundations *C*. It is curiously obsereved from Figures 7 to 10 that there are higher frequencies also in the records in addition to low frequencies (almost equal to the operating frequencies of the compressors). This may indicate that the recorded foundation vibrations are not purely due to the primary force of the compressors. However, the exact source of these high frequency vibrations has not been investigated in detail.

TABLE III

Experimentally obtained values of amplitudes and frequencies af vibrations.

Sl. No.	Foundation	Maximum amplitude of vibrations at		Associated average frequency (cps)	Operating frequency of compressors (cps)	Type of supporting soil
		Top of foundation (microns)	Basement floor (microns)			
1	Ammonia synthesis main gas compressors at Bombay (A)	14·2 T	1·5 T	4—5	4·5	Lean concrete resting on hard strata of safe bearing capacity of $3{\cdot}8 \times 10^6$ dyne/cm^2 under saturated conditions.
2	Nitrogen high pressure compressors at Bombay(B)	8·2 T	7·5 T	4—5	4·5	—do—
3	Ammonia gas compressors at Sindri (C)	420·0 T	195·0 V	10	5·0	Mostly dense sand of safe bearing capacity of $1{\cdot}6 \times 10^6$ dyne/cm^2.
4	Gas reforming plant at Sindri (D)	59·5 T	37·0 V	2·7	2·8	Soil of medium strength (silty with some sand) of safe bearing capacity of $2{\cdot}5 \times 10^6$ dyne/cm^2.

T=Horizontal component of vibration perpendicular to the crank shaft.
V=Vertical component of vibration.
L=Horizontal component of vibration parallel to the crank shaft.

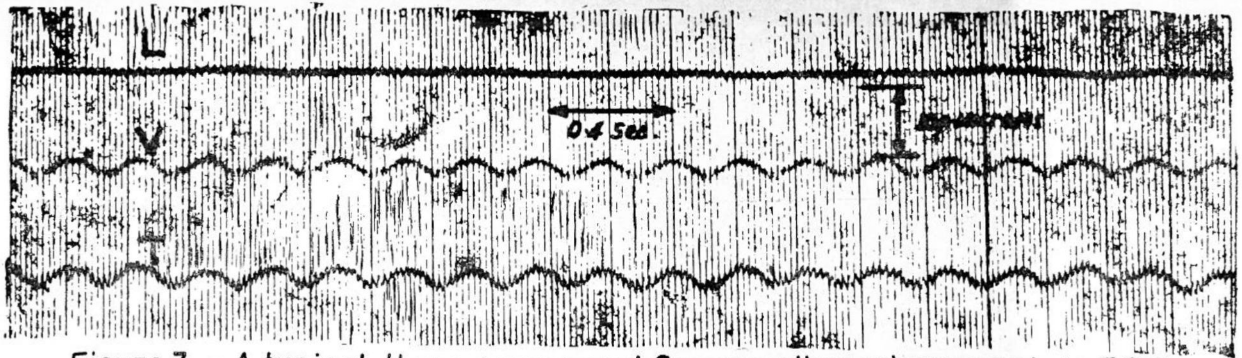


Figure 7 – A typical three component Sprengnether seismograph (x 500) record on the top of ammonia synthesis main gas compressor foundation, Fertilizer Corporation of India Ltd., Bombay (India)

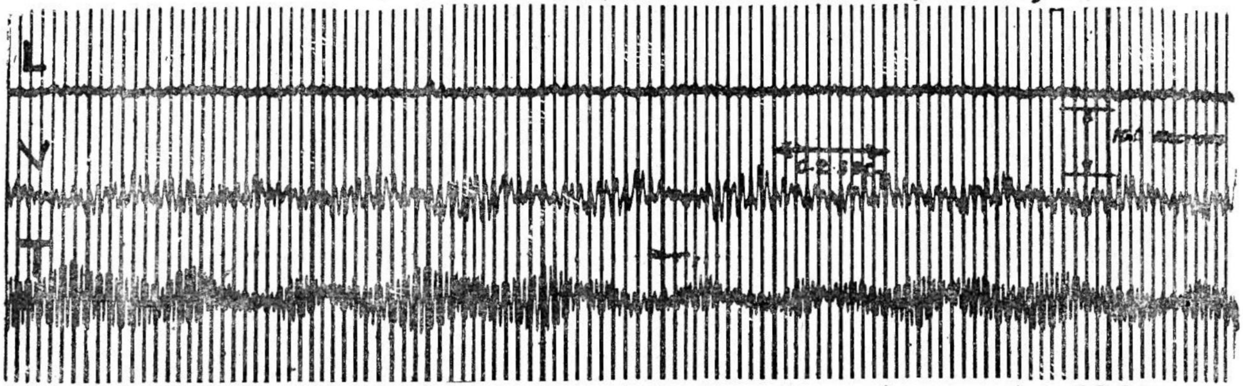


Figure 8 – A typical three component Sprengnether seismograph (x500) record on the basement floor of nitrogen high pressure compressor foundation, Fertilizer Corporation of India Ltd, Bombay (India).

FIGURES 7 and 8.

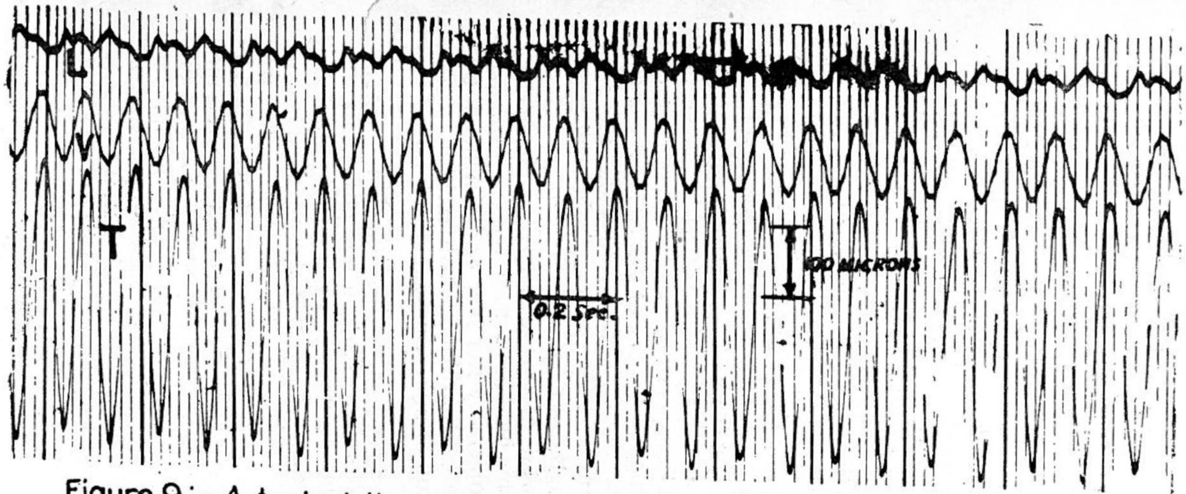


Figure 9 :- A typical three component Sprengnether seismograph (x 50) record on top of ammonia synthesis compressor foundation, Fertilizer Corporation of India Ltd., Sindri (India).

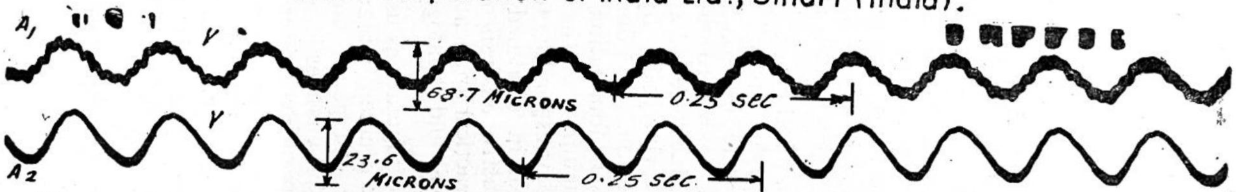


Figure 10 :- A typical philips electro-dynamic pick-up record showing vertical component of vibrations (displacement) at top of ammonia synthesis compressor foundation, Fertilizer Corporation of India Ltd., Sindri (India).

FIGURES 9 and 10.

Discussions and Conclusions

The results of prototype vibration studies justify broadly the validity of various theories, particularly Barkan's method, though these are based on somewhat different concepts. The theoretical computations (*vide* Tables I and II) and the experimental results (*vide* Table III) show that the measured frequencies of vibrations in all cases except for foundations C, are far away from the computed natural frequencies of their foundations and hence the associated amplitudes of vibrations are small. In case of foundations C, the computed natural frequencies of the foundations are almost the same as observed and equal to the nearest harmonic of the operating frequency of the compressors. This closeness of the frequencies might have resulted in excessive amplitudes of vibrations of about 420 microns. The design criterion generally followed namely, that the natural frequencies of the foundation should be $\pm$ 25 per cent away from the operating frequency of the machine or its harmonic, is not satisfied in case of foundations C. The excessive amplitude of vibrations can perhaps be conveniently reduced, under the present conditions, by increasing the elasticity of the supporting soil through chemical grouting techniques (Tschebotarioff, 1964).

The dynamical process involved in forced vibrations of foundations on semi-infinite half-space is not fully accounted for by the statical analogue in pressure bulb concept of soil mass. The limited body of soil mass is also unable to take into account the dissipation of the elastic energy in soil due to foundation vibrations as dissipation of elastic energy is governed, principally, by damping coefficient of soil (K) and not by static deformation. The dominant parameter is the effective wave-length in soil due to the foundation vibrations. The response of the soil-mass will be maximum, when the wave-length of the superimposed vibrations equal to that corresponding to the lowest group velocity through surface wave dispersion in stratified soil. This has been achieved in principle through exhaustive analysis of the problem by Reissner and extended by Barkan for practical applications, though they have dealt exclusively the case of isotropic and homogeneous soil of non-dispersive character.

Simple computations using any of the theories like that of Barkan, show that the resultant vibration amplitude is overwhelmingly influenced by moderate change in the physical properties of the supporting soil, while significant changes in area and mass of a normal size foundation produce comparatively lesser impact on vibration amplitudes *i.e.*, resultant response. The response of low frequency machine foundation is accentuated on deep and soft supporting soil having high predominant period while the same for high frequency machine attains large response only on compact soil or shallow soil underlain immediately by rock having low predominant period—a fact which distinctly shows the influence of the supporting soil in foundation vibrations. Kanai (1957, 1961) had made detailed theoretical and observational investigations on structural damage during earthquakes in Japan and had concluded that the predominant period of the site as suggested from microtremor studies plays a very important role in vibrations and consequently in the damage of the structures. This predominant period of the site (T_o) according to Kanai can be obtained by treating the problem as propagation of progressive waves in the layered earth. Perhaps, the predominant period could also be obtained theoretically through surface wave dispersion analysis corresponding to the layered earth and would correspond to the lowest value of the group velocity. In case of simple stratification, *i.e.*, soft layer underlain by highly elastic layer, the predominant period is approximately given by $4H/V_s$ where H=thickness of the soft layer and V_s=velocity of shear waves in it. Extensive measurements of microtremors confirm the validity of this simple relationship. The response of the soil layer during forced vibration to approximately proportional to

$$\left[\left\{1-\left(\frac{T}{T_o}\right)^2\right\}^2+\left\{K\frac{T}{T_o}\right\}^2\right]^{-\frac{1}{2}}$$

where T is the period of vibration.

From the above studies and analysis of other similar data collected by this Research Station during the last decade, it is inferred that though theoretical analysis of Reissner and Barkan is reasonable for the design of machine foundations ; yet a more simplified and physical approach to the problem could be well anticipated by combining the results on predominant period of the site (microtremor) as developed by Kanai and others with the dynamics of the rigid body vibrating with the frequency of the machine. The response of the foundation will be maximum when the predominant period of the site (T_o) equals to the operating frequency of the machine. Thus prior knowledge of the predominant period of the site, the operating frequency of the machine and the damping coefficient of soil would determine, qualitatively for all practical purposes, the relative response of the machine foundation. on soil. For normal damping of soil of about 15 per cent or so (Newcomb, 1951), the operating frequency should be ± 25 per cent away from the predominant frequency of soil for safe foundation design. Alternatively, a second maximum of lower magnitude of the foundation vibrations can be anticipated when the half wave length in vibrating soil equals the effective linear dimension of the foundation. The efficacy of the present approach lies in its simplicity and ready application in anticipating the response of the machine foundation. The physical principle involved in the complex mathematical treatment of Reissner and Barkan has actually been expounded in this simplified approach suggested here for design of machine foundations.

Acknowledgement

The authors record with great appreciation the encouragement received from the Director and the Joint Director, Central Water and Power Research Station, Poona, India.

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