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Behavior of Dune Sands of the Thar Desert Under Dynamic Loading

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ABSTRACT

Forced vibration test were conducted on concrete blocks for a power project in north-western Rajasthan (India). The site is in the Thar desert and has meta-stable aeolian sand deposits. At shallow depth, the amplitude versus frequency curves shows two peaks, suggesting that the soil structure was probably collapsing and settling under the dynamic load. Tests conducted on the deeper, relatively more stable soils confirm a good response to dynamic loads. The instability under static loading conditions is also highlighted and correlated to the dune morphology.

INTRODUCTION

For the design of dynamically loaded turbo-generators of a major thermal power plant in the dune sands of the Thar Desert in the state of Rajasthan (India), block vibration tests were conducted. The results have been analyzed and correlated with the site conditions and borehole data so as to evaluate the dynamic characteristics of aeolian sands.

The site is located in the north-western part of the state of Rajasthan, about 15 km from Suratgarh town. A map of India showing the site location is presented on Fig.1.

Fig.1 : Vicinity Map

GEOLOGY

A large tract of western and south-western Rajasthan and Sindh, 640 km long and 160 km wide, constitutes the "Thar Desert" (Krishnan, 1982). The aeolian accumulations of the Thar is a wide expanse of wind blown sand and bare rock stretching from the west of the Aravalis to the basin of the Indus and from the southern confines of Punjab to the basin of the Sutlej.

The sands cover an irregular rocky floor, but occasionally local prominences and ridges rise above the level of the sand. Over the greater part of the area, the sands are piled up into dunes.

The desert condition seems to have grown gradually only during the last 3000 to 4000 years. The origin of the Thar Desert is attributed to a long, continued and extreme degree of aridity of the region combined with the sand drifting action of the south-west monsoon winds which sweep through Rajasthan for several months of the year without precipitating any part of their contained moisture.

SITE STRATIGRAPHY

At the project site, the aeolian sands occur to about 10 to 12 m depth below the ground surface and are underlain by a deposit of cemented sand that probably forms the floor of the underlying older formation.

This underlying formation consists of cemented calcareous sand with an irregular surface. The overburden of the aeolian sand is also calcareous and the topography at ground surface roughly follows the same pattern as the profile of the irregular base of the cemented sand. The stratigraphy as disclosed by three boreholes in the vicinity of the block vibration test reported in this paper is presented on Fig. 2.

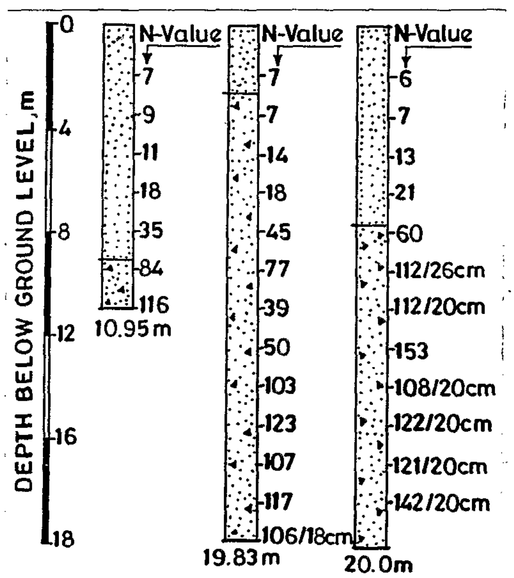

Fig. 2 : Site Stratigraphy

The surficial soils are loose with N-values less than 10 to about 3 to 4 m depth below the ground surface. This is underlain by medium dense soils with N-values of 10 to 30 to about 6 to 8 m depth. Below this depth SPT values increase rapidly with depth, exceeding 100 below about 9 to 10 m depth. The sands below 8 to 12 m depth exhibit weak carbonate cementation and consequently the SPT values are high.

STABILITY OF DUNE SAND

The dune sands of the Thar desert have hydro-consolidation potential due to cementation of fine sand particles with calcium carbonate (Haq and Kibria, 1994).

Alam Singh et al (1985) classify dune sand as a meta-stable or collapsible soil that goes through radical re-arrangement of particles and loss in volume upon wetting with or without load application. The SPT values and relative density of the soil are a function of the overburden. Thus, higher the overburden pressure, the lower is the relative density for the same SPT value. Table 1 presents SPT values for stable and unstable dunes.

Table 1 : **SPT N-Values for Stable and Unstable Dunes (Source : Alam Singh et al, 1985)**

Depth (m)	Condition	N-Value	
		Stable Dune	Unstable Dune
1.0	Dry	8 – 12	5 – 7
2.0	Dry	10- 17	7 – 13
3.0	Dry	12 – 25	9 – 15
4.0	Dry	16 – 35	14 - 15
1.0	Submerged	-	1 – 2
2.0	Submerged	-	3 - 4

The behaviour of dune sand is not governed by the normal laws of soil-water relationship. In the loose desert sands of Rajasthan, the increase in total settlement under static loading due to rise in water table (or saturation of the sands) is much larger than twice the initial settlement (i.e. the settlement under dry condition). The conventional practice of doubling the initial settlement (use of water table reduction factor, R_w, of 0.5) grossly under-estimates the settlement of desert sands.

To study the behaviour of the dune sands, static tests as well as dynamic testing were done. The static behaviour was evaluated from plate load tests. The dynamic behaviour was studied by conducting forced vibration tests on concrete blocks.

PLATE LOAD TESTS

To assess the behaviour of the dune sand on saturation, two plate load tests were conducted at about 6.9 m depth at the TG location. These tests were conducted on a 600 mm x 600 mm size test plate. The purpose was to assess the additional settlement that would occur on saturation. The additional settlement is a pre-cursor to identifying instability.

The first test was conducted by the standard procedure (maintained load method) on the natural soils in the in-situ condition, applying each load increment till the settlement stabilizes.

A second test was conducted about 2 m away from the location of this test under saturated condition. The test was initially started in the natural (dry) state and a bearing pressure of 2 kg/cm^2 was applied on the plate. The load was then held constant and the sands were saturated by flooding. About 2 to 3 cm of standing water was ensured above the plate level during the entire period of the test. After the settlement under 2 kg/cm^2 pressure stabilized after saturation, the test was carried out further. Test results are plotted on Fig.3.

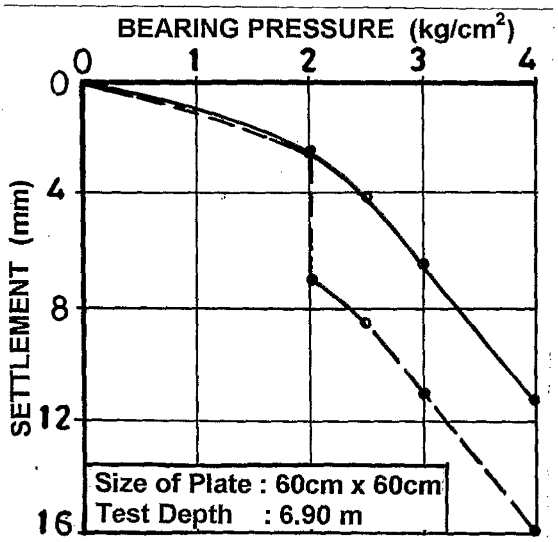

Fig. 3 : Plate Load Test Results

It can be seen from the test results that the increase in settlement on saturation is about 2.8 times the settlement under dry condition at 2.0 kg/cm^2 bearing pressure. The saturation/water table reduction factor, R_w, thus works out as 0.36. R_w factors of as low as 0.3 has been reported in literature from dune sands of Rajasthan.

BLOCK VIBRATION TESTS

The tests were conducted on plain concrete blocks of dimensions 1.5 m by 0.75 m by 0.70 m. Foundation bolts for setting the frame on which the test equipment were to be installed were fixed at the time of casting these blocks. The blocks were cured for at least 15 days prior to conducting the test.

Initially, the tests were conducted at 3.0 m depth. After review of the results of the test at 3 m depth, and the results of the plate load test at 6.9 m, it was decided to construct the TG foundations at 8 m depth. Therefore, a second test was conducted at 8.0 m depth to test the deeper soils. The results of tests at 3.0 and 8.0 m depth at the location where the TG foundation was planned are presented here.

A mechanical oscillator with a DC motor were fixed on the top of the concrete block. A speed control unit and a display device were connected to the oscillator through a 220 volt power supply. Geophones used were calibrated prior to start of the test. Fig. 4 presents the test set-up.

Forced vibration tests were conducted in both the vertical and horizontal modes. For conducting the vertical vibration test, the oscillator was mounted so as to generate vertical sinusoidal vibrations with the line of action of the vibration coinciding with the center of gravity of the block. For conducting the horizontal vibration test, the horizontal sinusoidal vibrations were generated in the direction of the longitudinal axis of the concrete block.

The dynamic force generated was varied by changing the angle of eccentricity of the rotating masses. The test procedure was in general accordance with Indian Standard Code of Practice IS 5249 - 1977.

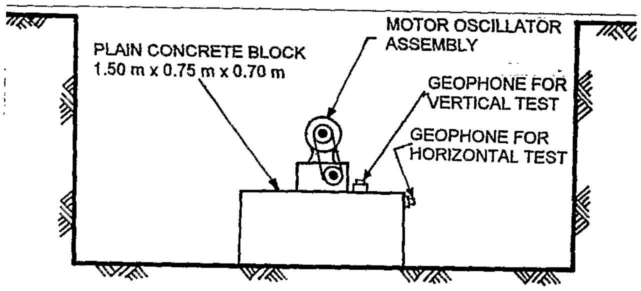

Fig. 4 : Schematic of Test Set up

PRESENTATION OF RESULTS

The field results are presented as amplitude versus frequency curves on Fig 4 and 5. The peak on these curves represents the resonant frequency.

The coefficient of elastic uniform compression, C_u and coefficient of elastic uniform shear C_τ have been computed using the values of resonant frequency mass of

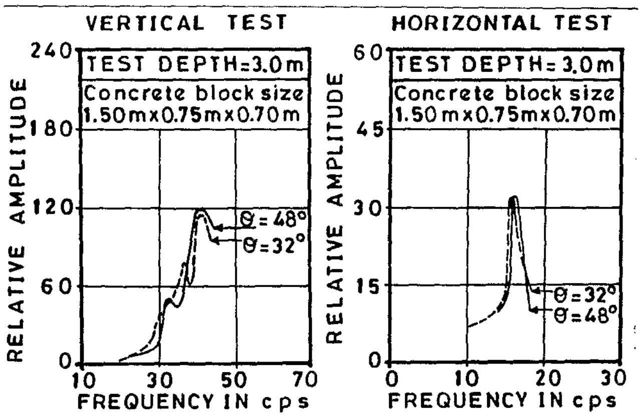

Fig. 5 : Results of Forced Vibration Tests at 3.0 m depth

Table No.2 : **Summary of Block Vibration Test Results**

Test Depth m	Angle of Eccentricity Degrees	VERTICAL FORCED VIBRATION TEST					HORIZONTAL FORCED VIBRATION TEST			
		f_{ny}, cycles per second	Dynamic Force at Resonance, kg	C_u, kg/cm^3		Dynamic Young's Modulus kg/cm^2	f_{nx}, cycles per second	Dynamic Force at Resonance, kg	C_τ, kg/cm^3	
				For Test Block	For 10m^2 Area				For Test Block	For 10 m^2 Area
3.0	32	35.8	227.1	8.67	2.91	72	15.3	32.7	1.86	0.62
3.0	48	30.2	318.7	6.14	2.06	51	15.0	46.7	1.80	0.60
8.0	40	49.3	349.6	16.44	5.72	137	28.0	112.6	6.27	2.18
8.0	52	47.7	418.3	15.35	5.34	128	27.5	139.2	6.05	2.10
8.0	64	47.1	495.1	15.03	5.23	126	27.2	164.3	5.90	2.05

f_{ny} : Resonant frequency
f_{nx} : Resonant frequency in horizontal mode of vibration
C_u : coefficient of elastic uniform compression
C_τ : Coefficient of elastic uniform shear

the concrete block plus oscillator assembly, and the base contact area (1.5 m x 0.75 m).

The parameters C_u and C_τ change in inverse proportion of the square root of the base area (Barkan, 1962) for areas of upto 10 m^2. For larger areas, the C_u and C_τ values for 10m^2 area may be used. The resonant frequency and dynamic force at resonance are presented together with C_u and C_τ and dynamic Young's modulus, E, on Table. 2.

DISCUSSION OF RESULTS

Dynamic Behaviour at 3.0 m Depth

The test location is near the dune crest. Therefore, the sands at this location are loose and unstable. The field SPT values are in the range of 7-12 and indicate that the top 3-4 m are loose and in the unstable part of the dune.

In the vertical mode of vibration, the test results show two peaks in the amplitude versus frequency curve (See Fig.4). This suggests that the soil structure was probably collapsing and the sand was re-arranging into a more compact state. Initially, the resonant frequency was very low but as the sand compacted, the resonant frequency increased somewhat. This resulted in two peaks being observed in the amplitude versus frequency curve. Visual observation also confirmed that the block had settled by more than 50 to 60 mm during the test.

The parameters given on Table 2 for the vertical vibration test is based on the first peak. The second peak is obtained at a frequency of 39-40 cycles per second. But using either of the two peaks for the analysis is fraught with uncertainty since the soil structure is probably collapsing. The resonant frequency in the horizontal mode of vibration is also fairly low.

The C_u and C_τ values at 3 m depth are very low and it was unpractical to design the foundation for such low parameters. Further, there is a risk of the foundation system undergoing excessive settlement due to the vibratory loads. Therefore, the soils at 3 m depth are considered unsuitable for supporting dynamically loaded foundations.

Dynamic Behaviour at 8.0 m Depth

The results of the block vibration tests at 8 m depth (See Fig.5) indicate a substantial improvement in soil properties. The resonant frequencies also increase substantially. The test confirmed that the sand at this level is dense and compact, and therefore suitable to support the dynamic loads. Thus, the testing was used effectively to design the TG foundations.

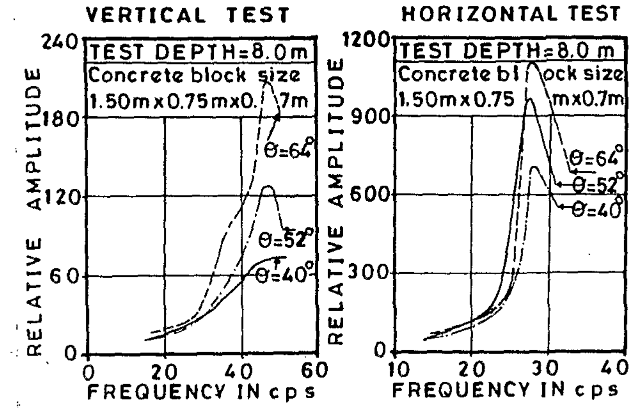

Fig. 6 : Results of Forced Vibration Tests at 8.0 m depth

Behaviour under Static Loading

Even under static loading, the meta-stable character of the dune sand is evident. At a depth of 6.9 m, the influence of saturation is to increase the settlement substantially. A water table reduction factor, as interpreted from the plate load test, of 0.36, suggests that the soils structure is like a card-house, which collapses on saturation.

Therefore, the collapse of the soil structure under dynamic loading is only to be expected. The block vibration test may be considered as a model test. The results at 3.0 m depth confirm the collapsible nature of the strata. These sands are likely to experience excessive settlement under dynamic loading and during earthquakes.

CORRELATION WITH DUNE MORPHOLOGY

Aeolian transportation sorts the sands in a near-uniform gradation. The continuous aeolian transportation of the sands results in a dynamic equilibrium between erosion and deposition. Changes in wind regime and climate will influence the dune form.

Dune crests are better sorted than the lower parts of the dune flanks. The deposition is in the loosest form with relative density of less than 20 percent near the crest. At the deeper levels, the sand has compacted under the overburden pressure, and therefore is relatively more stable. Further carbonate cementation is evident in the deeper sands.

The internal structure of the dune as explained by Thomas, 1989 (based on observations by Tsoar, 1982) is illustrated on Fig.7.

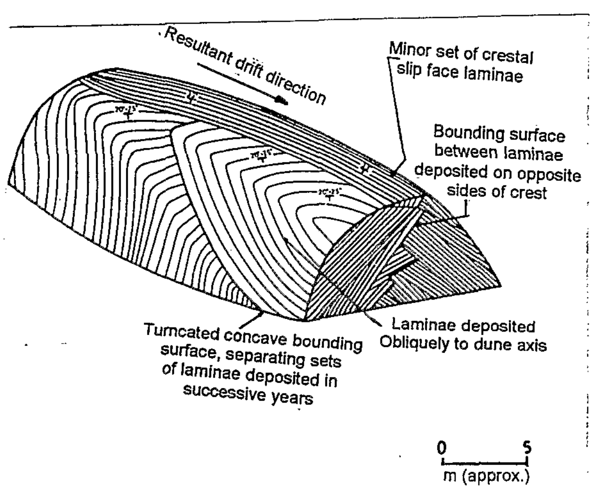

Fig. 7 : Internal Structure of Sand Dune observed by Tsoar Source : Arid Zone Morphology by D.S.G. Thomas (1989)

When the wind direction is acute to the crest, the zones of erosion on the lee-side will probably have a rippled surface. Accretion in the lee-side deposition zones occurs through grain-fall and grain flow, giving rise to sets of steeply dipping laminae. As dunes of erosion and deposition advance down the dune, deposition occurs on the former eroded zones, starting at angles of 10 to 20°, steepening as deposition progresses through the season, giving rise to an increase in grain flow structures. As the dune crest is sinuous, the boundary between the sets of laminae is curved. Deposition on the plinth is almost always in the form of low angle laminae.

CONCLUDING REMARKS

Dune sands of the Thar Desert are vulnerable to disturbance. These aeolian sands, particularly at shallow depths, are susceptible to excessive settlement due to collapse of the soil structure.

Dune sands have low bearing capacity under static loading conditions. The traditional and standard methods of computation of soil bearing capacity and settlement tend to over-predict the allowable bearing pressure. Under dynamic loading, the behaviour is even more complex and the currently used design methodologies may not predict the performance of dune sands realistically.

The reason for this meta-stable nature lies in the mode of deposition. The behaviour of these sands under earthquakes is a matter of serious concern.

Careful planning and thorough testing is required to ensure stability of dynamically loaded foundations on aeolian sands. Foundation embedment depths should be decided based on the nature of the dune and its stability. Further research and field testing is required to understand the complex nature of this class of arid soils.

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