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Dynamic Soil - Pile Parameters

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SYNOPSIS: Results of lateral dynamic load tests conducted on precast driven concrete piles at two Project sites, one in South India (two individual piles) and another in Western India (one individual pile and two numbers of two-pile groups) are reported in the Paper. Shear wave velocities were determined from Cross Hole tests at the pile cut-off level at the test pile locations at the two sites. These values are compared with those reported in literature for two similar types of soils, namely, alluvial clay and alluvial sand. The subsoil conditions including Standard Penetration Test data and Static Cone Penetration Test data and also the pile driving record are presented along with the results of soil-pile stiffness.

INTRODUCTION

Design of pile foundations subjected to dynamic loads, and in earthquake zones, requires the determination of response of soil-pile system under horizontal dynamic loads. The method of analysis requires the use of natural frequencies of soil-pile system under different modes of vibrations, damping coefficient, and also overall soil-pile stiffness coefficients under dynamic loads. The in-situ test on piles subjected to lateral vibrations is the most reliable method to obtain the above mentioned data.

The response of the piles subjected to dynamic loads, however, depends not only on the subsoil conditions but also on the restraints offered by the superstructure at the pile top, the sustained load carried by the pile and the nature of ground motion.

Lateral dynamic load tests were conducted on precast driven concrete piles at the following sites:

(a) A Fertilizer Project in South India

Tests were conducted on two individual piles.

(b) A Petrochemical Project in Western India

Tests were conducted on one individual pile and two numbers of two-pile groups.

Pile details and information on pile driving and pile cap dimensions are given in Table-1.

SUBSOIL CONDITIONS

The subsoil conditions obtained from the nearest bore hole(s) are given in Figs.1 (a) to (e). The energy for driving the pile for every 1m depth, the recorded Standard Penetration Test (SPT) values, the ground water table at the time of boring and the results of Static Cone Penetration Tests, wherever available, are also presented in Figs.1 (a) to (e).

The subsoil at the South India site consists of a layer of sand in the top 6.8 to 7.6 m depth, followed by thick layers of soft clay and stiff clay. Ground water table, at the time of boring was at a depth of 1.8 to 2.5m.

The subsoil at the Western India site consists of a thin layer of sand in the top 1.8 m followed by medium stiff clay upto a depth varying from 4.2 to 8.1 m, followed by a thick layer of silty sand.

TEST PROCEDURE AND RESULTS

Lateral Dynamic Load Tests on Piles

The test procedure is in accordance with Indian Standard 9716 - 1981, "Guidelines for Lateral Dynamic Load Tests on Piles". The procedure is briefly described below:

A Mechanical Oscillator was mounted on the pile cap in a position which would cause forced horizontal vibrations on the pile. The vibration response was recorded using Accelerometers (inductive system with differential choke; Specifications are given in Appendix-1), fixed on a vertical face of the pile cap. The response was found to be very small for frequencies less than about 800 rpm. Accelerations were therefore recorded for frequencies in the range of 800 to 3400 rpm, the maximum running speed of the Mechanical Oscillator being 3600 rpm. The accelerations were recorded for different settings of the eccentric mass.

Amplitudes of vibration (A_x) were computed from the recorded accelerations using the following relationship:

$$A_x = \frac{a_x}{4\pi^2 f^2}$$

where

a_x = horizontal acceleration of vibration (expressed in the same units as A_x), at frequency f (cycles/sec).

The damping coefficient (ξ) was determined using the following expression (Indian Standard 5249 - 1977), Method for Test for determination of Dynamic Properties of Soil).

$$\xi = \frac{f_2 - f_1}{2 f_n}$$

where

f_2, f_1 = frequencies at which the amplitude is $= \frac{A_m}{\sqrt{2}}$

A_m = maximum amplitude, and

f_n = frequency at which the amplitude is maximum (resonant frequency)

Typical results obtained from the forced horizontal vibration tests are presented in Fig.2.

The dynamic force (F_o) was then computed for each eccentric setting of the mass for different frequencies of vibration.

Typical relationships obtained between the dynamic force and the amplitude of vibration are presented in Fig.3.

The static amplitude (δ_{st}) was then computed using the following relationship, for each setting of the eccentric mass.

$$\delta_{st} = \frac{A_x}{\mu}$$

where

A_x = dynamic amplitude of vibration and

μ = magnification ratio, given by:

$$\mu = \frac{1}{\sqrt{\left[\left\{1-\left(\frac{w}{w_n}\right)^2\right\}^2 + \left(2\xi\frac{w}{w_n}\right)^2\right]}}$$

in which

ξ = damping coefficient obtained from free vibration records

w = forcing frequency and

w_n = resonant frequency

A typical relationship obtained between dynamic force and static amplitude is presented in Fig. 4. The tangent modulus of the dynamic force-static amplitude relationship gives the soil-pile stiffness (k_{hp}) under dynamic loading condition.

The above interpretation is based on the assumption that, for all practical purposes, there is a unique variation between δ_{st} and F_o irrespective of variation in forcing frequency (w) and resonant frequency (w_n) as these are taken corresponding to larger amplitudes.

A summary of results of forced lateral dynamic load tests on piles is given in Table 2. A comparison of the soil-pile stiffness obtained for the various piles tested at the two project sites is made inTable 3.

Cross Hole Tests

These tests were conducted as described by Stokoe and Woods (1972).

The procedure adopted in the present investigation is briefly described below:
Three bore holes were made at a distance of approximately 20 m from each other to form a triangle with the pile at its centre. The bottom of each bore hole corresponds to the pile cut-off level. Galvanized iron casing pipes of 150 mm internal diameter were left in place to retain the bore holes.

An impulse was given at the bottom of the bore hole through a hammer blow using a steel rod, with a plate welded to it at the bottom. The shear waves were received at the next bore hole into which an accelerometer was lowered. The accelerometer was encased in a stainless steel casing to prevent contact with water.

The tests were repeated with the transmitter in another bore hole. The distance between the bore holes divided by the time taken for arrival of the shear waves gives the shear wave velocity.

SOIL-PILE STIFFNESS

It may be observed from Table-3 that substantial variations in the soil-pile stiffness have been found for piles even within a particular Plant area. The subsoil immediately below the pile cut-off level (for a thickness of about a metre) is denser at the Urea Plant than at the Ammonia Plant (recorded SPT values of 41 and 18 respectively) at the South India site. The stiffness of the two individual piles is the same. These results, therefore, suggest that the compactness of the sand immediately below the pile cut-off level for a thickness of a few pile diameters (pile widths in this case) plays a very important role on the soil-pile stiffness.

At the test pile locations in Western India, the subsoil below the pile cut-off level (2m below GL) is essentially medium stiff clay for a thickness corresponding to atleast about 3 pile diameters. Further, at the location of the Gas Turbines (East and West), the two-pile groups with individual piles of 300 mm x 300 mm cross-section and at Ethylene Tank, a single pile of 400 mm x 400 mm cross-section give a soil-pile stiffness of more or less the same order (200 to 300 kN/mm). However, this order of pile stiffness is lower than those obtained for medium dense and dense states of sand occurring for a depth of a few pile diameters immediately below the cut-off level at the South India site.

SHEAR WAVE VELOCITIES AT PILE CUT-OFF LEVEL

The results of shear wave velocities presented in Table 2 suggest the following general obser-

TABLE - 1 DETAILS OF PILES TESTED

Type of pile (all piles tested): Precast driven concrete piles

Sl. No.	Description	South India		Western India		
		Ammonia Plant	Urea Plant	Gas Turbine (E)	Gas Turbine (W)	Ethylene Tank
1.	Single pile or pile group	Single pile	Single pile	Group of two piles (A&B)	Group of two piles (C&D)	Single pile
2.	Cross section of individual pile (mm x mm)	400 x 400	400 x 400	300 x 300	300 x 300	400 x 400
3.	Driven length (m)	22.7	22.7	12.3 (A) 14.5 (B)	13.9 (C) 13.3 (D)	17.55
4.	Concrete mix	M 25	M 25	M 35	M 35	M 35
5.	Total energy used in driving the pile (MN.m)	59.6	56.4	20.5 (A) 27.2 (B)	22.8 (C) 20.6 (D)	60.9
6.	Weight of hammer (kN)	43	43	40	40	50
7.	Height of fall of the hammer(m)	1.2	1.2	1.0	1.0	1.0
8.	Time interval between date of driving the pile and date of test (days)	72	74	39 & 38	41 & 41	69
9.	Pile cap dimensions	(E)	(E)	(F)	(F)	(E)
10.	Coated length of upper portion of pile (m)	12.0	12.0	6.1 & 7.0	6.9 & 6.3	7.0

Size (E) = 1250 mm x 1250 mm x 600 mm thick   Size (F) = 2400 mm x 800 mm x 1000 mm thick

TABLE - 2 SUMMARY OF RESULTS OF FORCED LATERAL DYNAMIC LOAD TESTS

Sl. No.	Description	South India		Western India		
		Ammonia Plant	Urea Plant	Gas Turbine (E)	Gas Turbine (W)	Ethylene Tank
1.	Natural frequency from Free horizontal vibration tests (rpm)	1500	2200	6000	2000	6660
2.	Damping coefficient from Free horizontal vibration tests	0.16	0.16	0.14	0.17	0.08
3.	Natural frequency from Forced horizontal vibration tests (rpm)	1140 (48°) 1230 (64°) 1170 (80°)	1770 (48°) 1670 (64°)	1740 (32°) 1740 (64°)	1610 (32°) 1380 (64°)	1800 (32°) 1600 (64°)
4.	Damping coefficient from Forced horizontal vibration tests	0.145 (48°) 0.122 (64°) 0.103 (80°)	0.065 (48°) 0.048 (64°)	0.046 (32°) 0.023 (64°)	0.084 (32°) 0.065 (64°)	0.053 (32°) 0.078 (64°)
5.	Shear wave velocity at pile cut-off level (m/s)	170 - 185 at 2.0 m depth	220 - 265 at 2.0 m depth	135 at 2.0 m depth	145 at 2.0 m depth	125 at 2.0 m depth
6.	Depth of ground water table at the time of test (m)	1.0	0.45	1.2	1.2	1.6

Values in parantheses refer to eccentricity of mass

TABLE-3 SOIL-PILE STIFFNESS OBTAINED FOR PILES TESTED

Sl. No.	Site location	Plant designation	Dynamic force range (kN)	Soil-pile stiffness (kN/mm)	Nature of soil*
1.	South India	Ammonia Plant	0 - 8.2	800	Medium dense sand
2.	South India	Urea Plant	0 - 8.0	3330	Dense sand
3.	Western India	Gas Turbine (E)	0 - 5.0	370	Medium stiff clay
4.	Western India	Gas Turbine (W)	0 - 8.0	190	"
5.	Western India	Ethylene Tank	0 - 3.0	310	"

* for a depth of a few pile diameters, below the pile cut-off level

vations depending on the nature of the soil.

Nature of Soil	Average Shear Wave Velocity
Medium stiff clay below ground water table (Gas Turbines East and West; and Ethylene Tank at Western India Project site)	135 m/s
Medium dense sand below ground water table (Ammonia Plant at South India Project site)	175 m/s
Dense sand below ground water table (Urea Plant at South India Project site)	250 m/s

The shear wave velocities obtained in the present investigation are compared with those reported in the literature in Fig.5 wherein the shear wave velocity is correlated with the SPT values for alluvial clays and also (seperately) for alluvial sands. Eventhough the scatter is large (considering that the shear wave velocity is presented in a logarithmic scale), the results obtained by the authors confirm the trend in the relationship between the shear wave velocity and SPT values reported by Imai (1977) for clays and sands.

The shear wave velocity for commonly occurring deposits of sands and clays is in the range of 100 to 300 m/s, as against values of the order of 700 to 800 m/s for weathered rock obtained by the authors at some other sites in Western India as well as for clayey sand stone and very hard clay reported by Rodrigues (1981).

CONCLUSIONS

The following conclusions are drawn from an analysis of the results obtained in the present investigation as well as from a comparison of the shear wave velocity with those reported in the literature.

(i) The compactness of sand or stiffness of clay immediately below the pile cut-off level for a depth of a few pile diameters plays a very important role on the soil-pile stiffness.

(ii) The soil-pile stiffness in medium stiff clays for precast driven single concrete piles of 400 mm x 400 mm cross section and for two-pile groups of 300 mm x 300 mm each pile, is more or less the same. It is of the order of 200 to 300 kN/mm.

(iii) The soil-pile stiffness for a pile cross section of 400 mm x 400 mm in medium dense sand in the top few diameters below the pile cut-off level is of the order of 800 kN/mm.

(iv) The soil-pile stiffness for a pile cross section of 400 mm x 400 mm in dense sand for a depth of a few pile diameters below the pile cut-off level is of the order of 3000 kN/mm.

(v) The shear wave velocity for medium stiff clay below ground water table is about 135m/sec whereas it is of the order of 175 m/sec and 250 m/sec for medium dense and dense sands (respectively), below ground water table.

(vi) An approximate estimate of the shear wave velocity for clays and sands can be obtained from an empirical relationship suggested by Imai (1977) which is presented in Fig.5. Results obtained by the authors further confirm the validity of the above mentioned empirical relationship.

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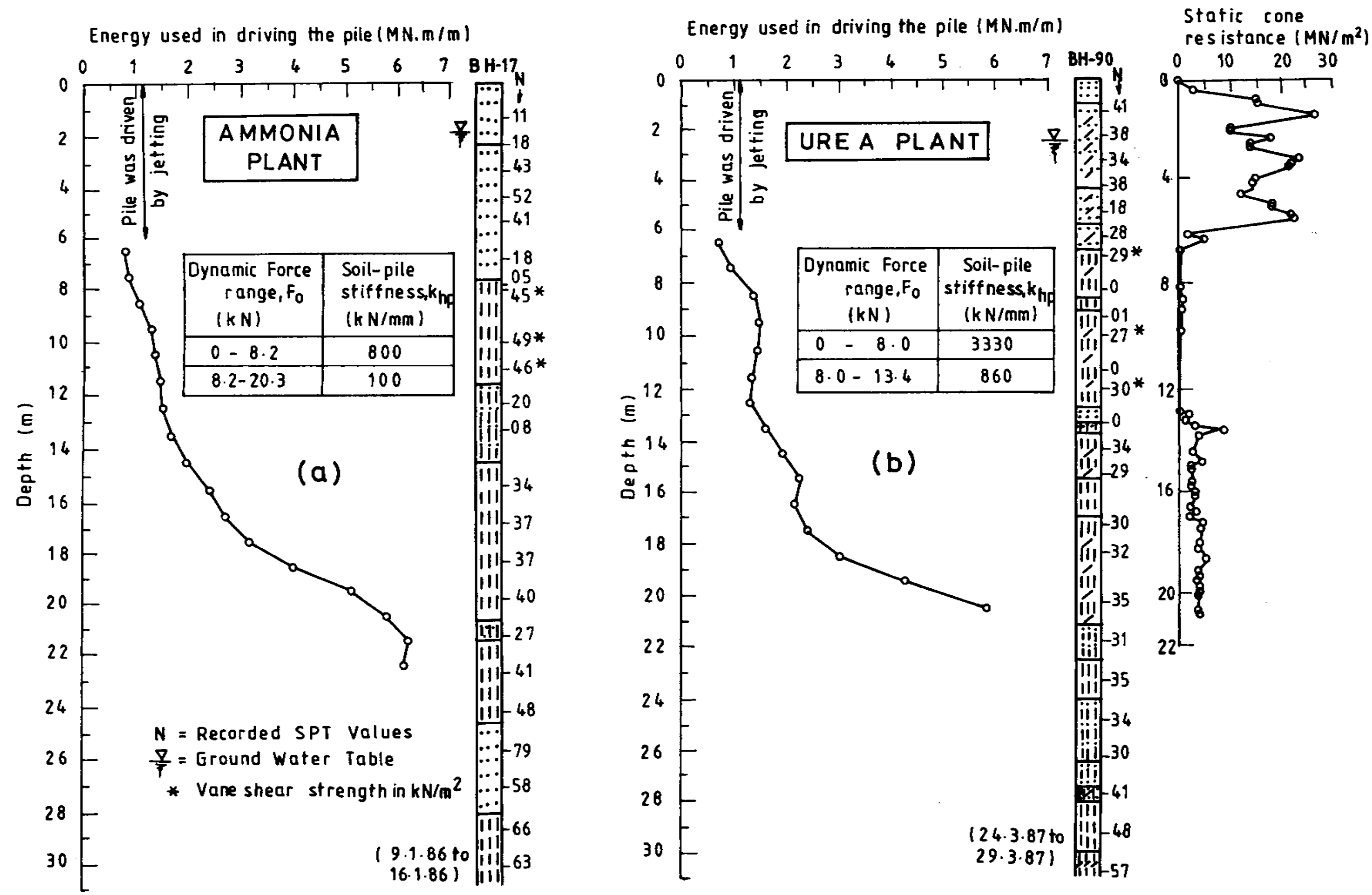
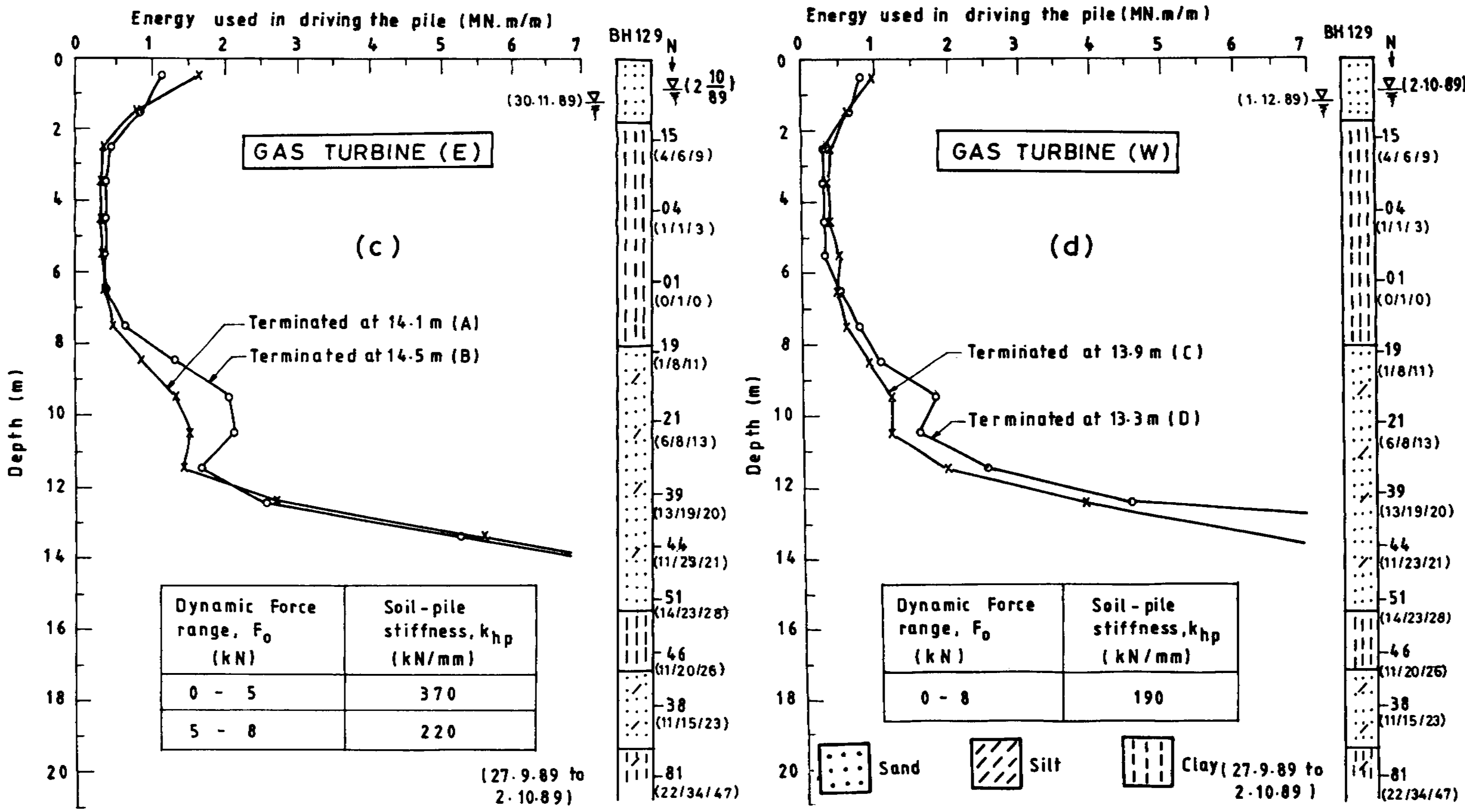


FIG.1. SUBSOIL CONDITIONS NEAR THE TEST PILE LOCATIONS AND PILE DRIVING DATA



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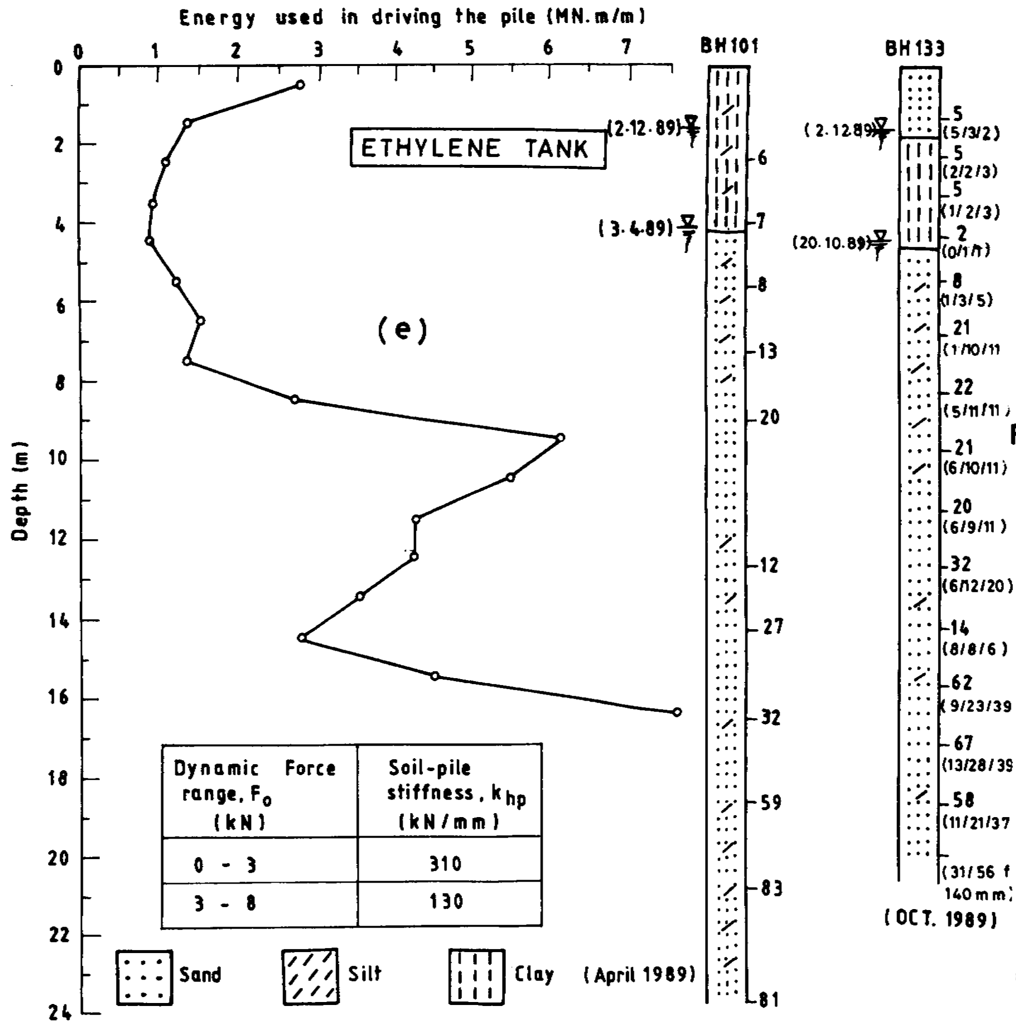

Dynamic Force range, F_o (kN)	Soil-pile stiffness, k_{hp} (kN/mm)
0 - 3	310
3 - 8	130

FIG. 1. SUBSOIL CONDITIONS NEAR THE TEST PILE LOCATIONS AND PILE DRIVING DATA

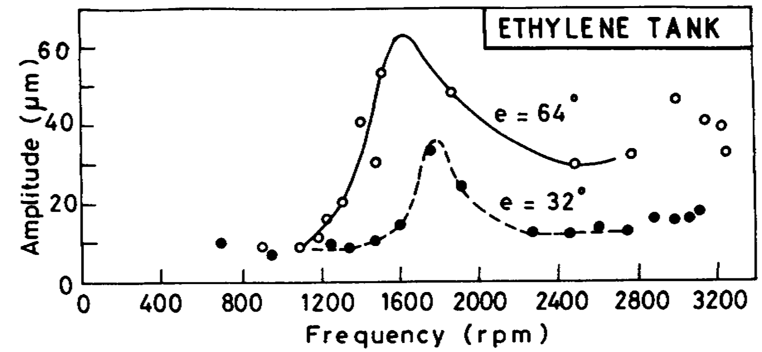

FIG. 2. A TYPICAL RELATIONSHIP BETWEEN FORCING FREQUENCY AND AMPLITUDE OF VIBRATION

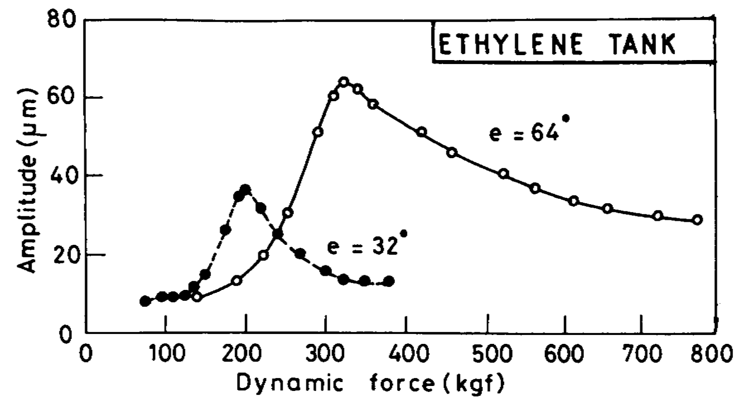

FIG. 3. A TYPICAL RELATIONSHIP BETWEEN DYNAMIC FORCE AND AMPLITUDE OF VIBRATION

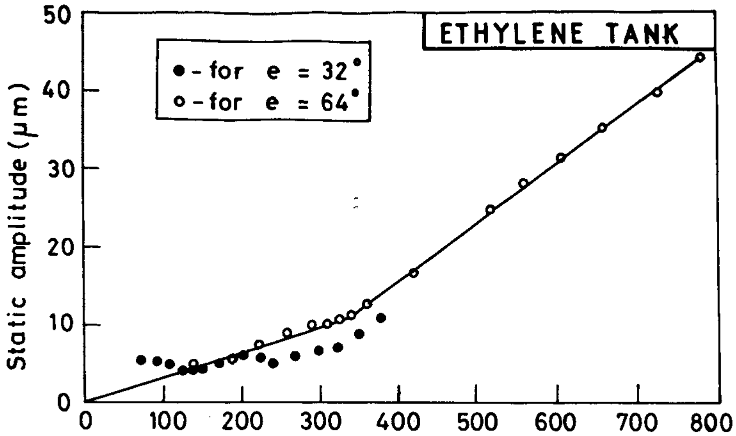

FIG. 4. A TYPICAL RELATIONSHIP BETWEEN DYNAMIC FORCE AND STATIC AMPLITUDE

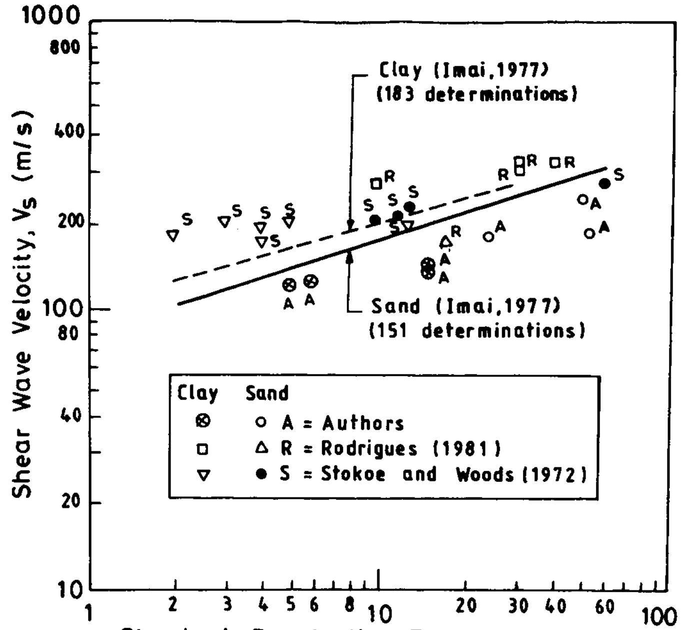

FIG. 5. RELATIONSHIP BETWEEN V_S AND SPT

APPENDIX-1

SPECIFICATIONS OF ACCELERATION TRANSDUCER

Make	: Hottinger Baldwin Messtechnik, GERMANY
Measurement principle	: High tuned spring-mass vibrator
Natural frequency	: 200 Hz
Measuring frequency range	: 0 - 100 Hz
Damping D at reference temperature	: 0.6 ± 0.1
Nominal acceleration	: ± 200 m/s^2
Temperature error of the output signal per 10 K related to the actual output signal in the nominal temperature range, typical	: ∠ ± 0.2 %
Temperature error of the zero point per 10 K related to the nominal output signal in the nominal temperature range, typical	: ∠ ± 0.25 %
Linearity error including hysteresis related to nominal output signal span	: ∠ ± 2 %
Transverse sensitivity (directional factor)	: ∠ ± 3 %
Relative side load limit related to the nominal acceleration	: 100 %
Electrical measurement principle	: Inductive system with differential choke
Reference temperature	: 23° C
Nominal temperature range	: - 10 .. + 60° C
Service temperature range	: - 10 .. + 60° C