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Assessment of Shape and Quality of Bored Concrete Piles by Integrity Testing

by

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Introduction

Bored cast-in-situ concrete piles are in frequent use to support structures of varied description on difficult soils. In case of bored underreamed piles it is important to know whether the underreamed bulb is properly formed or not. Low strain integrity testing technique based on one dimentional stress wave approach is becoming an accepted reliable practice for assessing quality of concrete piles in various parts of the world (Middendorp and Van Brederode 1983, Seitz 1986, Rausche et al 1988). In India, the integrity testing has been started recently by the Foundation Pile Diagnostic System (FPDS) which makes use of digital data processing technique for monitoring of velocity traces (Reiding et al 1984 and 1988, Bhandari et al 1989, Prakash et al 1990). The realiability of assessment of integrity of piles depends mainly upon quality of measured velocity traces/signals and accuracy of their interpretation. Though the monitored signals by the FPDS are of good quality, there is a lack of published data providing correlation between the monitored signals and the actual built-in-shape of piles, which is needed for proper inter-pretation. It is all the more true for the underreamed piles. Therefore, in order to establish the accuracy and to generate data base for precise interpretation of integrity test results as well as to quantify the variations in pile cross-section and defects, a study was carried out on (*i*) specially cast straight shaft and underreamed piles, (*ii*) exhumed underreamed piles and (*iii*) production underreamed piles, designad and constructed for the purpose at one site.

Integrity Testing

Principle

The principle of low strain or sonic integrity testing method is the time domain reflectometry of stress wave propagation through the pile shaft

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acting as the one dimensional medium. A compression wave, generated by a short hammer blow on pile head, travels down the pile length in axial direction. The particle velocity, V at any level is dependent on force, F and impedance of pile, Z at that level.

$$V = F/Z \tag{1}$$

and

$$Z = EA/C = A\sqrt{E\rho} \tag{2}$$

where A = Area of cross section of pile,

E = Young's modulus of pile material,

ρ = Density of pile material, and

C = Stress wave velocity.

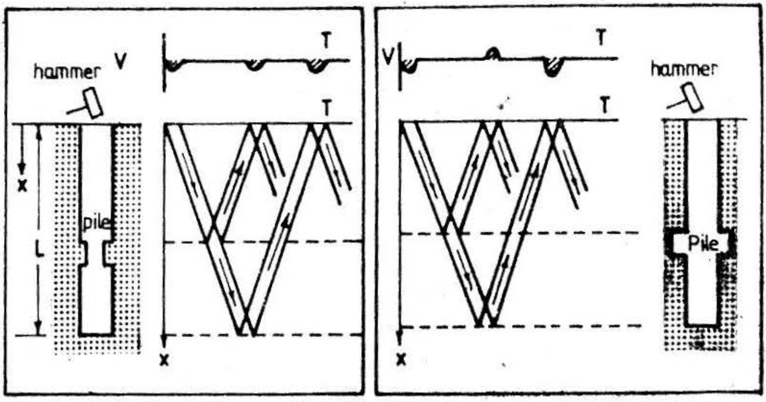
It is clear from Equations (1) and (2) that if there is no change in pile impedance throughout its length, the wave will reflect from pile toe. Changes in cross-sectional area, inclusions, cracks and concrete quality represent different magnitudes of shaft impedance thus causing variation in the particle velocity. At the levels of variation in pile impedance, a part of the wave is reflected and the remainder transmitted (Fig. 1). If there is total discontinuity in the pile shaft at any level, the complete wave is reflected from that level. The magnitude and type of reflections depend on size and type of variation in pile cross-section or defect, each type producing its own unique type of reflected wave. Monitoring and analysis of these reflections form the basis of integrity testing.

Method of Testing

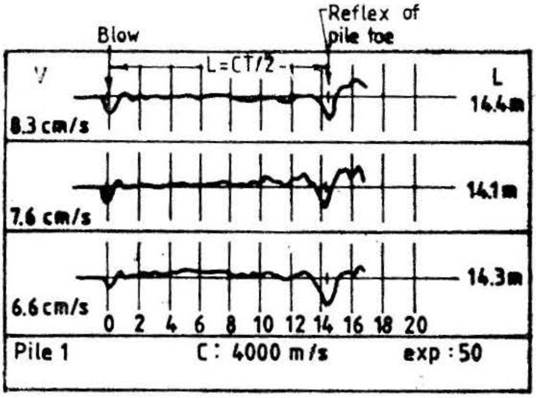
The test is conducted by striking the pile head using a small hand held hammer, in such a way that a blow with a short rise time is achieved (Fig. 1). The reflections are picked up by an accelerometer, pressed on pile top close to the location of hammer blow. The signal is amplified, converted into velocity, digitised and finally after processing, displayed on the computer screen providing information about variations in cross-section or defects, if any and approximate pile length. The results are also stored on the hard disk of FPDS computer for subsequent analysis. A typical record for a structurally sound bored pile is given in Fig. 1. The generated compression wave experiences damping effect due to soil friction acting along the pile shaft. However, increase in gain with time compensates for signal loss due to soil friction and to obtain a clear toe reflex, signal can be amplified upto desired level by selecting suitable gain value.

Quantitative Estimate of Sectional Variations/Defects

For a quantitative assessment of sectional variations/defects, integrity



Stress wave pattern of reflections



V = Particle velocity
L = Length of pile
C = Stress wave velocity
T = Time

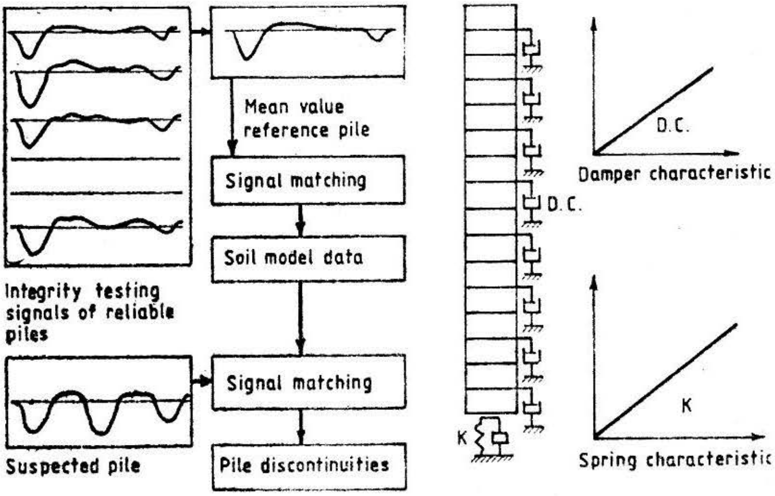
Reflections of a structurally sound bored pile

FIGURE 1 Concept of Integrity Testing System testing signal matching technique using the program TNOWAVE (Middendorp and Reiding, 1988) is used. The program is based on the 'method of characteristics applied to a mathematical model representing one dimensional stress wave propagation through the pile.

The first step in signal matching involves the derivation of soil model by matching the average integrity test signal, selected for a structurally good pile typical for a particular site, by using iteration method, Fig. 2(*a*). The first part of the measured velocity signal i.e. impact blow, is used as an input to the pile head. The first estimate of soil model is taken on the basis of soil investigation results. Since the movement of the pile caused by a small hand held hammer is very small ($<<$ 0.1 mm), the shaft resistance is schematized by a combination of linear spring and a linear damper Fig. 2(*b*). The derived soil model is taken to represent a particular area and is used for signal matching of suspected piles. The model, if required, can be adjusted to incorporate any local change in soil stratigraphy, density or hardness for any other pile location in the area. For signal matching of suspected piles also, the first part of the measured velocity signal i.e. impact blow is taken as input to the pile head of computer model. A best fit match is then obtained between calculated and measured velocity signals by varying cross-section of computer model pile at location of variations/defects, obtained from field curve, through a number of iterative steps. The cross-sectional variations in the computer model are then considered to represent the impedance changes of the suspected pile.

Casting of Piles

The integrity tests were conducted *n* 300 mm diameter and about 4 m



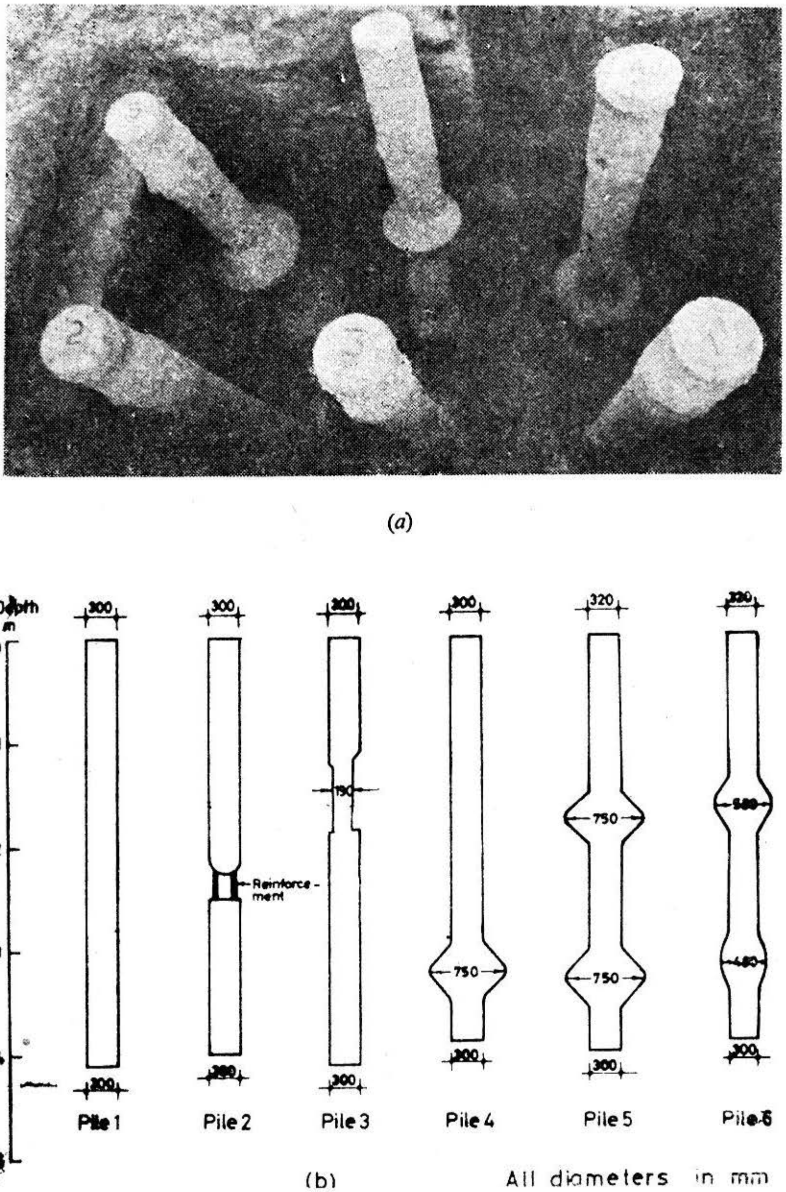
(a) Sequence (b) Soil model

FIGURE 2 Signal Matching Procedure and Soil Model deep, specially cast six piles in silty-sand (SM) deposit at the Central Building Research Institute (CBRI) premises. The tests were conducted at different time intervals to study the variation in stress wave with the setting time of concrete in piles. After field tests, the signal matching was done to predict the shape of piles. Subsequently, the piles were exhumed for verifying the shapes. The integrity tests were performed on exhumed piles also and the signal matching done to estimate the effect of soil inter-action with piles. A photograph of exhumed piles in the pit is given in Fig. 3(*a*) and the sketched shaped of piles is shown in Fig. 3(*b*).

The straight shaft and underreamed piles were constructed following the conventional practice using spiral auger and underreamer. For creating the complete discontinuity in pile 2, the concrete was intially poured upto about 1.5 m and then it was left for 24 hours. Next, a calculated amount of loose earth was poured into the borehole to fill about 300 mm height of borehole above the already poured concrete. Rest of the borehole was filled with concrete in the usual way. For constructing pile 3, the concrete was first poured upto about 2.25 m. After about 24 hours, a steel pipe of 120 mm internal diameter was placed above the already poured concrete. The portion of borehole outside the pipe was then filled with loose earth for about 600 mm height and concrete was poured inside the pipe upto a height such that after lifting the pipe from the borehole, the concrete spilled over the soil. The rest of the borehole was then filled with concrete in the usual way. In all the piles, the nominal reinforcement, 4 Nos. of 10 mm diameter high strength steel deformed bars and M15 grade concrete were used.

Field Test Results

The results of tests conducted on the six piles prior to exhuming have been discussed here as no difference has been observed in the velocity reflectogram obtained during different tests and these results can be directly compared with the results of tests, conducted on piles after exhuming. The velocity-reflectogram of pile 1 is like a free end pile as expected in such soil deposits. The signal is repeated four times, each time the dip (toe reflex) is reduced due to dissipation of energy with time. The upward rise in the reflectogram at about 1.5 m is probably due to local increase in soil stiffness at this level. The reflectogram of pile 2 shows a sharp reflection of reduction in pile impedance at about 2.1 m, similar to pile toe reflex. The strong repetition of signal indicates that there is complete break in pile shaft at this level and the pile is of only 2.1 m length, thus confirming the discontinuity created. In the reflectogram of pile 3, a reduction in pile impedance at about 1.1 m followed by increase in impedance can be seen. Since there is no repetition of the signal subsequenly, it leads to the interpretation that there is a reduction in cross-section at this level but the continuity in the concrete of pile stem is not lost. The toe reflection is not so clear. Also the equivalent built-in length of pile corresponds to a reduced



(a)

(b)

FIGURE 3 Details of Especially Cast Piles

wave velocity of 3100 m/s in comparison to pile 1 and 2. This may be probably due to improper bond between the concrete at the bottom level of cross-sectional reduction as there was a time gap between the concrete poured upto that level and that poured through the pipe without taking any measure to establish the proper bond between the two. The observed reflectogram thus appears to be in accordance with the defects created in the pile shaft at this level.

The velocity-reflectogram of pile 4 shows a sharp increase in impedance at about 3.2 m, indicating the increase in cross-section, confirming provision of bulb at this level. In the velocity-reflectogram of pile 5, a sharp increase in impedance at about 1.7 m, followed by little decrease in impedance and then again increase in impedance at about 3.3m, indicate the enlargements in cross-section at these levels, confirming the presence of bulbs at these locations. The built-in length of the pile in this case corresponds to the stress wave velocity 3300 m/s probably due to concrete of slightly reduced strength in this pile. Since the concrete poured in piles was mixed by hand, the difference in concrete strength is quite possible. The velocity-reflectogram of pile 6 is very similar to that of pile 5. However, the increase in impedance in this case is less than that observed in the reflectogram of pile 5. Also there is difference in the location of second increase, slightly above than that in case of pile 5. These observations clearly confirm the increased cross-sections created in the pile.

The Fig. 5 shows the velocity-reflectograms of the integrity tests conducted on exhumed piles. The pattern of these reflectograms is almost same to that obtained for the piles in ground. The reflections for increases and decreases in cross-sections are slightly more sharp in these traces. Further there is almost no variation in pile impedances in the straight portion of shafts. Also clear toe reflections are observed corresponding to exponential gain, 1 against the exponential gain, 50 used for the piles in ground. These observations clearly indicate that even though the soil-interaction with pile affect the reflectogram, the salient features of piles in the ground are clearly projected by the integrity tests. Further, it is observed that soil-interaction has no effect on stress wave velocity as in the two cases the built-in lengths correspond to the same stress wave velocities.

Variations in Stress Wave Velocity with Time

Table 1 shows the variations in stress wave velocity for piles 1,2,4,5 and 6. The values for pile 3 have not been included as the stress wave velocity was affected due to the bond between two concretes at the bottom of reduced cross-section level. These stress wave velocities correspond to the actual built-in lengths of the pile. It can be seen that the stress wave velocity corresponding to 7 days is about 90 per cent of that for 28 days and there is very little difference between the values corresponding to 21 and 28 days. An increase of about 10 per cent in the stress wave velocity has been observed in about 5 months time over the values corresponding to 28 days time. Beyond 5 months period, the stress wave velocities remain unchanged.

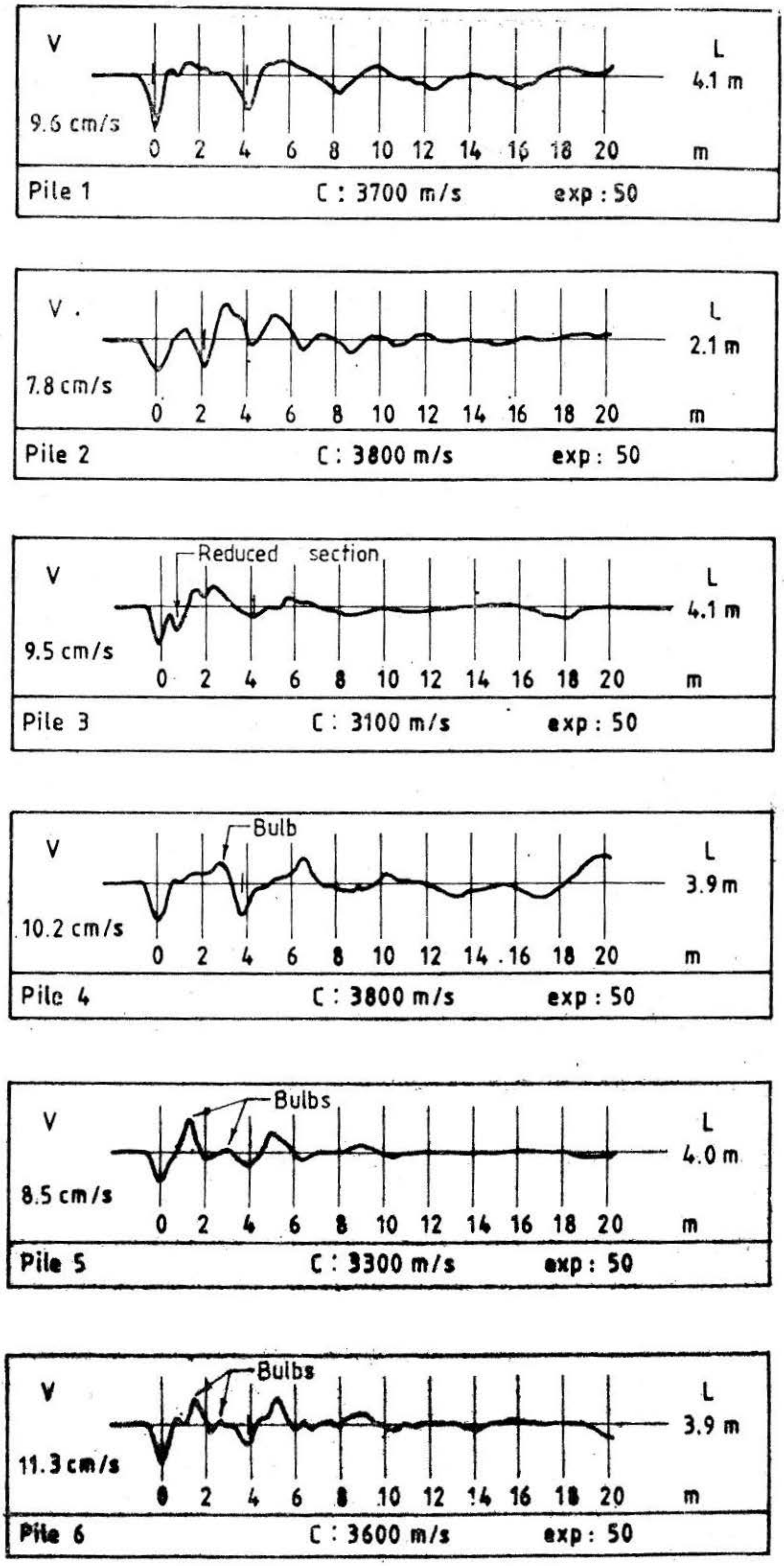


FIGURE 4 Integrity Test Results of Especially Cast Piles in Ground

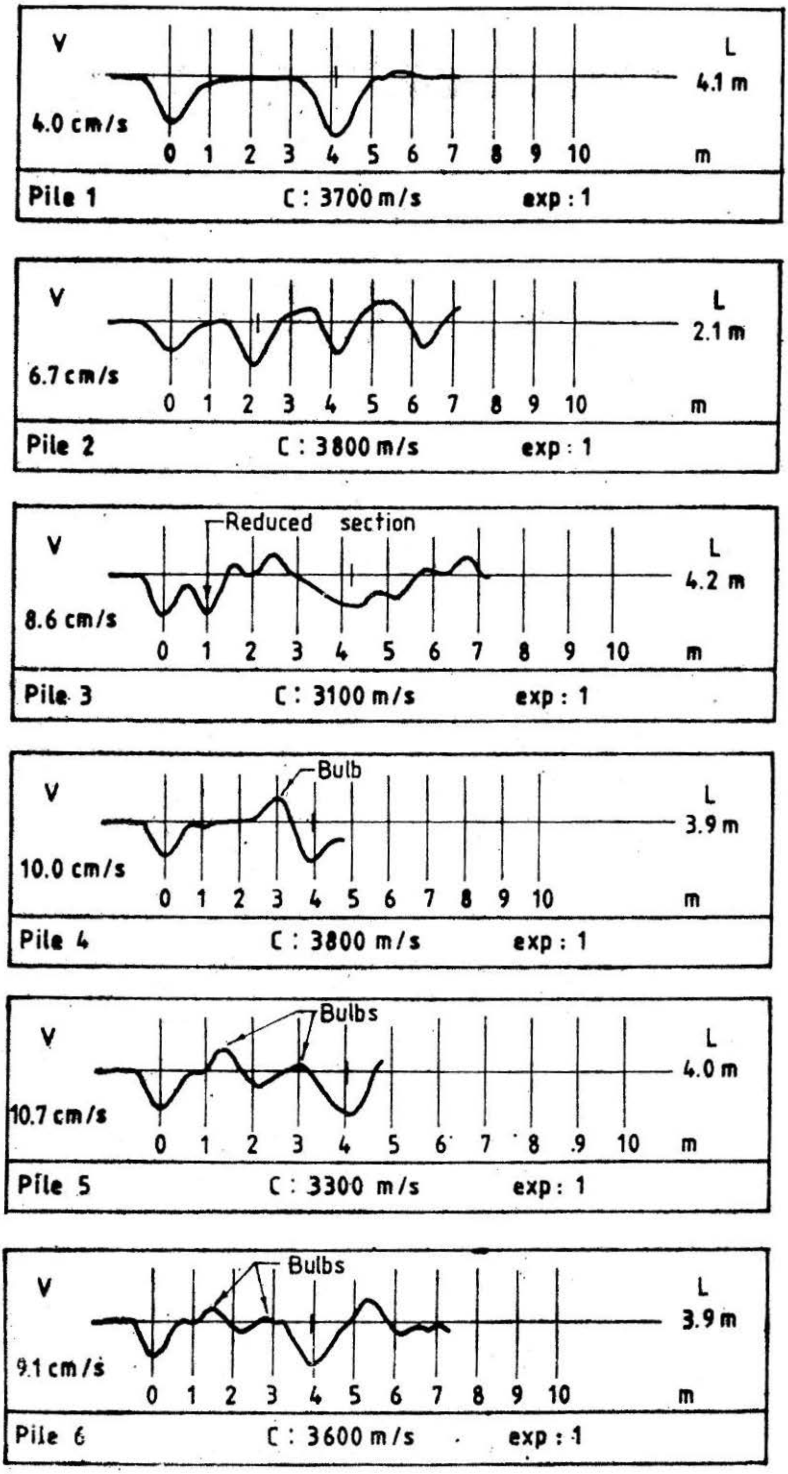


FIGURE 5 Integrity Test Results of Exhumed Especially Cast Piles

TABLE 1

Variation in stress wave velocity with Aging of concrete

Sl. No.	Time (Days)	Stress Wave Velocity (m/s)				
		Pile 1	Pile 2	Pile 4	Pile 5	Pile 6
1.	7	3100	3100	3000	2750	2900
2.	21	3400	3300	3200	3000	3000
3.	28	3400	3400	3300	3000	3150
4.	35	3450	3400	3450	3100	3200
5.	49	3450	3500	3500	3200	3400
6.	153	3700	3700	3800	3300	3600
7.	245	3700	3800	3800	3300	3600
8.	365	3700	3800	3800	3300	3600

Predicted Shapes by Signal Matching

For deriving soil model, the pile 1 has been taken to be a 300 mm diameter truly straight shaft of 4.1 m length. The derived soil model, obtained through matching integrity test signal of pile 1, is depicted in Fig. 6 along with sub-soil investigation results. The best fit signal matches for the six piles are shown in Fig. 7 and the modelled shape of piles obtained through these matches is shown in Fig. 8.

The signal matching for pile 2 indicates that this is a pile of 2.1 m length. In case of pile 3, the model shows a compatible cross-section with the built-in shape of pile though the exact shape and lateral dimensions are slightly different. These two cases clearly show that the signal matching technique predicts reasonably well the discontinuities in the pile shaft.

The model of pile 4 shows the bulb at 3.2 m, same as in case of built-in pile (Fig. 3) with diameter 470 mm, about 63 per cent of 750 mm, actually built. The shape of bulb obtained through the model is also slightly different from the actual built-in shape which is obvious. For pile 5, the model shows the first bulb at 1.7 m against 1.75 m in the built-in pile with a bulb diameter of 520 mm, about 70 per cent of 750 mm, actually built. The second bulb has been reflected at 3.3m, same as in case of built-in pile with diameter 460 mm, close to that in case of pile 4. For pile 6, the model shows the bulbs at the same locations as in case of built-in pile with diameter about 72 per cent and 77 per cent for top and bottom bulbs respectively with shapes

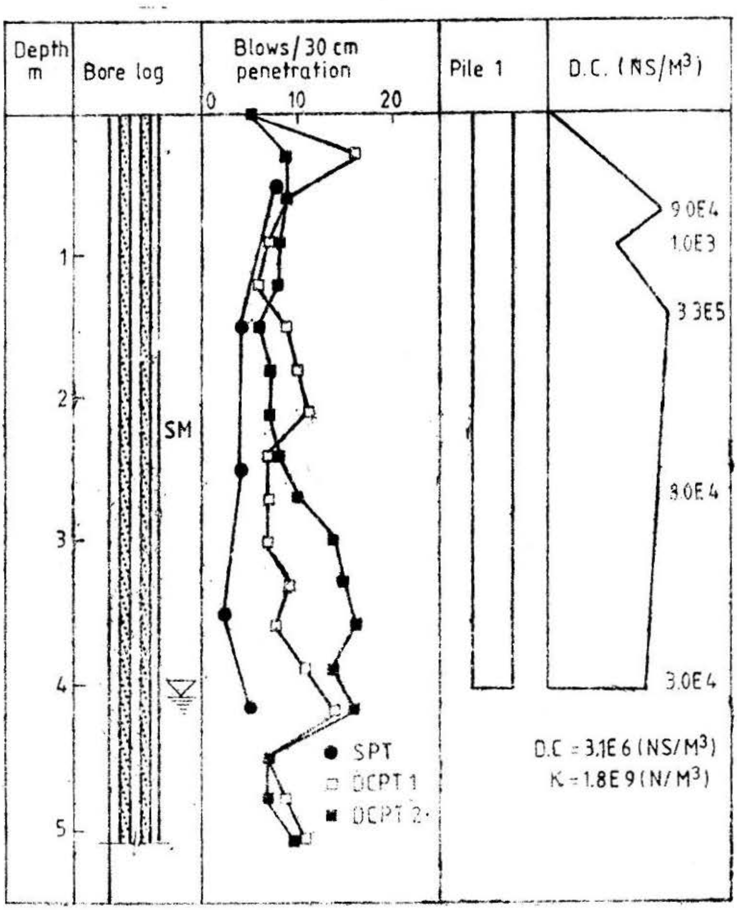


FIGURE 6 Sub-soil Data and Derived Soil Model (CBRI Site)

similar to those revealed in case of piles 4 and 5. Thus it can be construed that the signal matching technique provides the estimate of bulbs almost at the same location with diameter 60 to 75 per cent of the actually built. The overall predicted shapes are very similar to the built-in piles with slight difference in lateral dimensions.

A similar exercise of signal matching has been done for the results obtained for these piles after exhuming. No difference has been revealed by these matches in the predicted shapes of piles 1, 2 and 3 in two cases. In case of underreamed piles, the location of bulbs is also same in two cases. However, the bulb diameters are 65 per cent to 80 per cent in this case, following the pattern similar to that exhibited by the signal matching of piles in the ground. This also confirms the finding revealed by field tests in the two cases that though there is effect of soil interaction, even then the salient

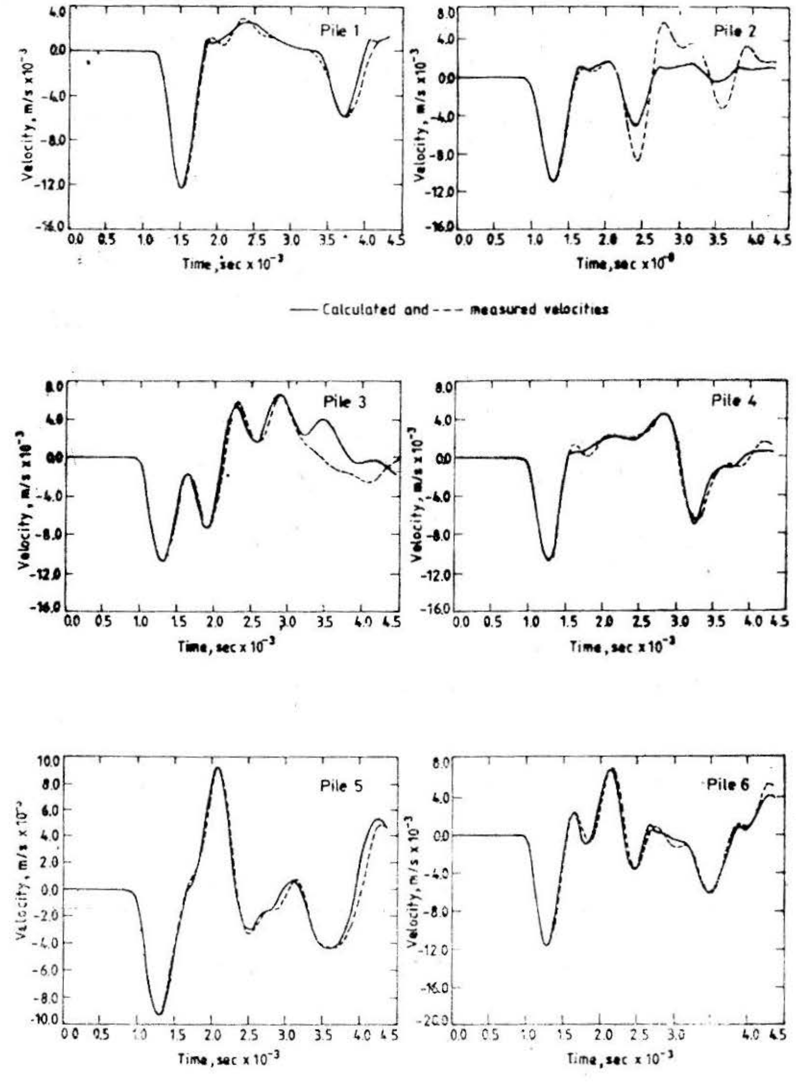


FIGURE 7 Best Fit Signal Matches for Especially Cast Piles

features for the piles in the soil are reflected in the same way as for the piles without soil.

Exhumed Underreamed Piles

In order to verify the outcome of specially cast exhumed underreamed piles, the integrity tests were carried out on the already exhumed piles from other sites, kept in CBRI for demonstration purpose. The actual built-in shape of piles alongwith the shapes predicted by best fit signal matches of integrity test reflectograms is shown in Fig. 9. Among these, pile 4 is a

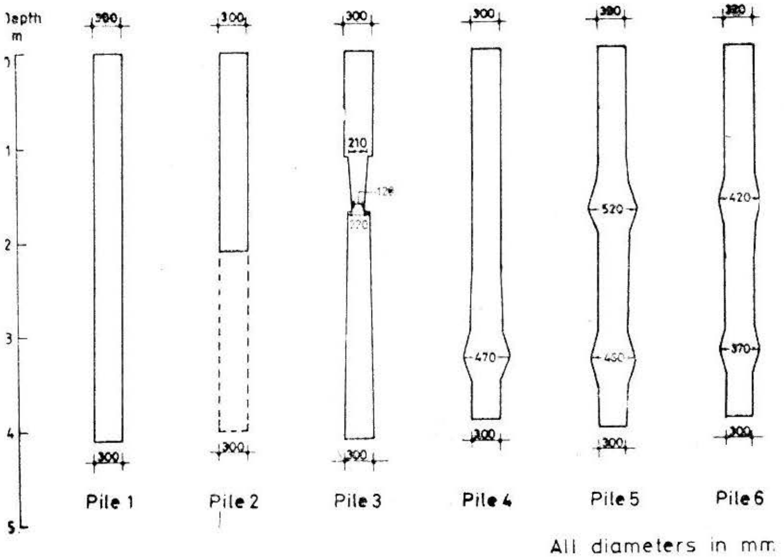


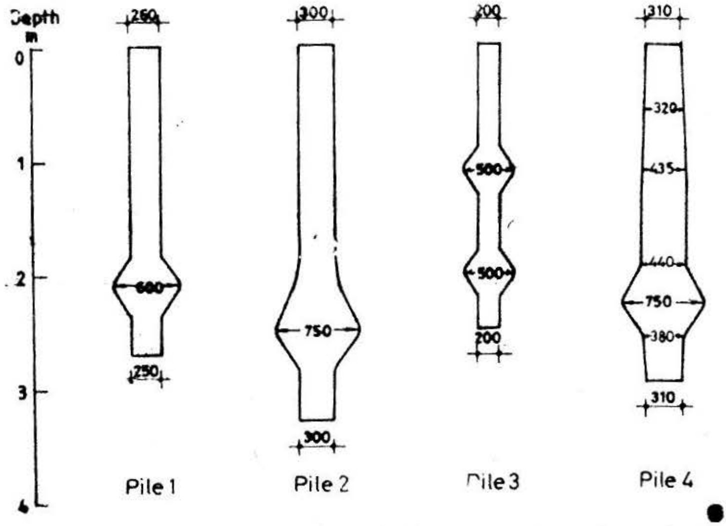
FIGURE 8 Shape of Especially Cast Piles Obtained Through Signal Matching

bored compaction underreamed pile. The field test results on these piles are given in Fig. 10.

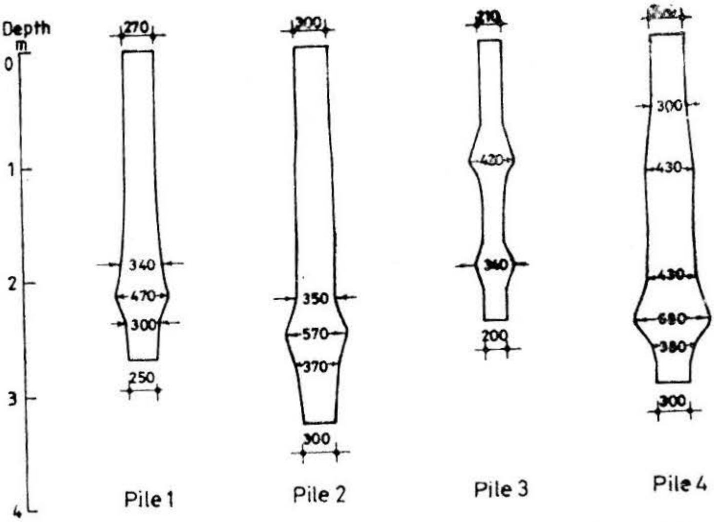
The velocity-reflectograms obtained through field tests clearly show the reflections for bulbs in this case also (Fig. 10). For pile 4, it can be seen that the increase in diameter in pile shaft has been reflected by increase in impedance at about one metre. The pattern of predicted shapes by signal matches is the same as that obtained in case of specially cast piles, discussed earlier. For the two single underreamed piles (pile 1, and 2), the predicted diameter of bulbs are about 77 per cent. In case of pile 3, the predicted diameter of top bulb is about 84 per cent while it is about 68 per cent for bottom bulb. The predicted shape and diameters of shaft and bulb are very close in case of bored compaction underreamed pile (pile 4), bulb diameter about 90 per cent. The predicted diameter of bulbs for pile 4 in this set and for pile 6 in the earlier set suggests that the predictions of bulb diameter are dependent on bulb-to-shaft diameter ratio. If this ratio is less, the difference between the predicted diameters and actual built-in diameters will be less. There is only a marginal difference in the predicted and actual location of bulbs in this case also.

Production Underreamed Piles

For collecting data on different types of underreamed piles with a view to its application in the actual case, the tests were carried out on production underreamed piles. The piles were designed and constructed in accor-



(a) All diameters in mm



(b) All diameters in mi

FIGURE 9 Built-in (a) and Predicted (b) Shape of Exhumed Underreamed Piles

dance with the guidelines given in IS : 2911 (part III)-1980 and the Handbook (1978) on the subject to support Deaf and Dumb school Building in a sandy soil deposit at the campus of University of Roorkee. The details of different type of piles used are depicted in Fig. 11. The pile 1 (type I) which is a straight shaft pile, was constructed to compare the results of underreamed piles and to derive soil model for signal matching. The piles were

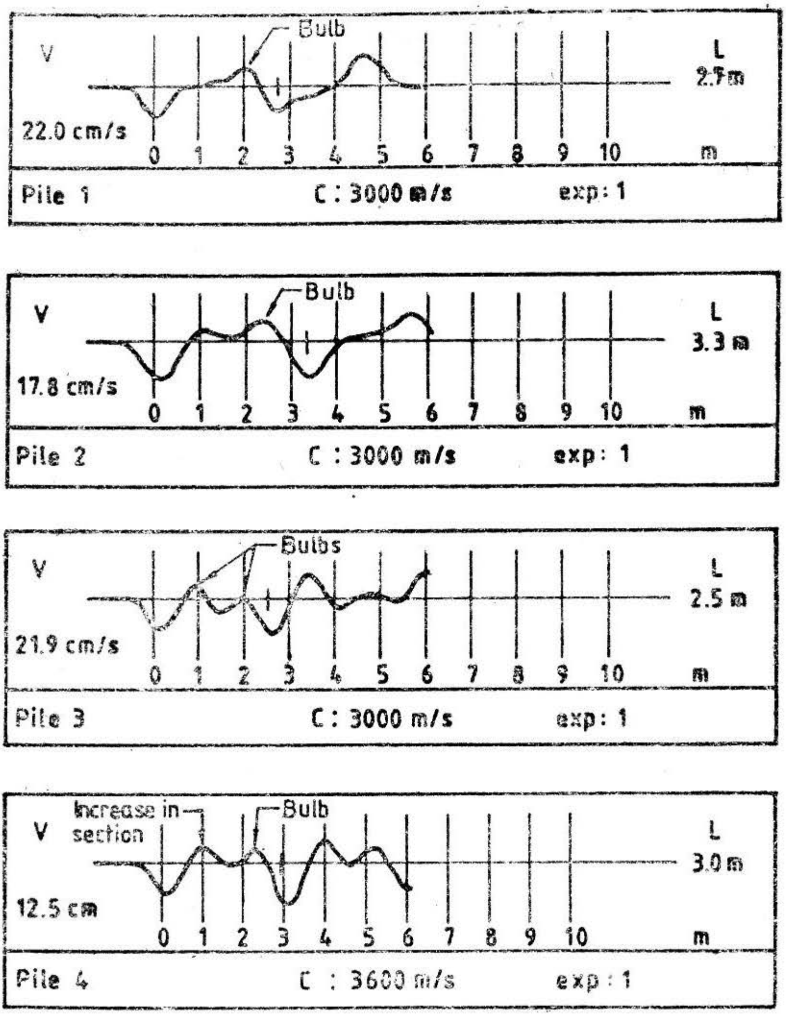


FIGURE 10 Integrity Test Results of Exhumed Underreamed Piles

constructed in the usual way using spiral auger and underreamer for boring and underreaming. The reinforcement used was nominal, 4 bars of 10 mm diameter in 250 mm stem diameter piles and 4 bars of 12 mm diameter in 300 mm stem diameter piles. The concrete was poured in the dry boreholes upto cut-off level. For investigating the variation in the stress wave velocity for the different grades of concrete, the concrete used in six piles was of M 20 grade and in six other piles it was of M25 grade. Rest of the piles were constructed with M15 grade concrete. The field tests were conducted on all the piles after about 15 days of their construction. Subsequent to the field tests, the shapes of different type of piles were predicted by signal matching.

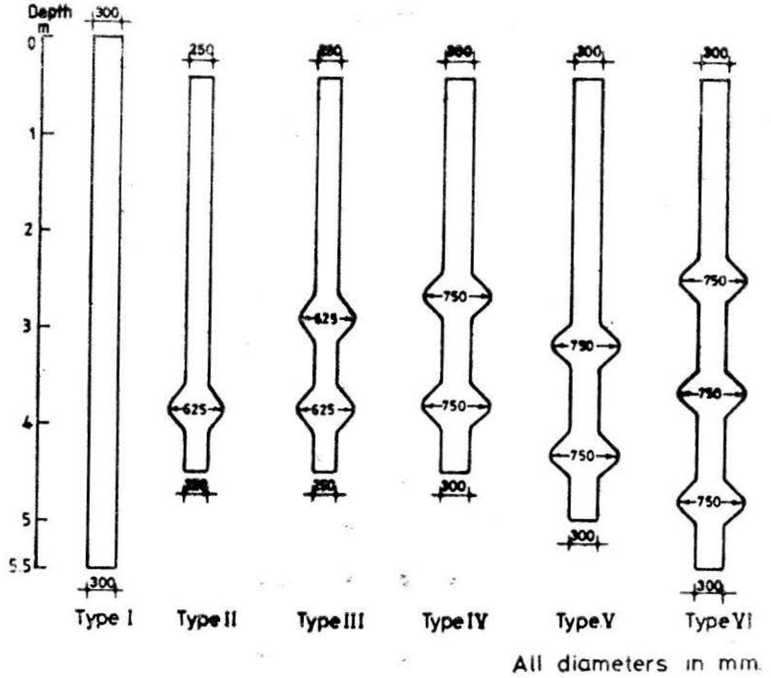


FIGURE 11 Details of Different Type of Piles at Deaf and Dumb School Site

Field Test Results

The field integrity test results on 6 types of piles having the same grade of concrete except for pile 31 (Fig. 11) are given in Fig. 12. For all the piles, the representative velocity-reflectograms correspond to the stress wave velocity ranging between 3200 to 3500 m/s and exponential gain 5 to 20 indicating that some variations in stress wave velocity at the actual site may be observed. Also, depending on local variations in soil strata, different exponential gain values may have to be used for obtaining clear toe reflections. The observed lengths of all the piles are almost equal to the built-in lengths. Further, the velocity-reflectograms clearly show the reflections of bulbs almost at the intended built-in locations. The results of pile 31 have been included to demonstrate that the presence of some increase in cross-section in the upper portion may not affect much the reflections of bulbs at lower levels. The increases are due to the removal of brick bats encountered during construction of this pile. The reflections for bulbs are quite clear even in case of three bulb pile (pile 42).

Variations in Stress Wave Velocity with Grade of Concrete

The stress wave velocity for two types of piles (type IV and V) having different grades of concrete, M15, M20, and M25 are compared in Table 2.

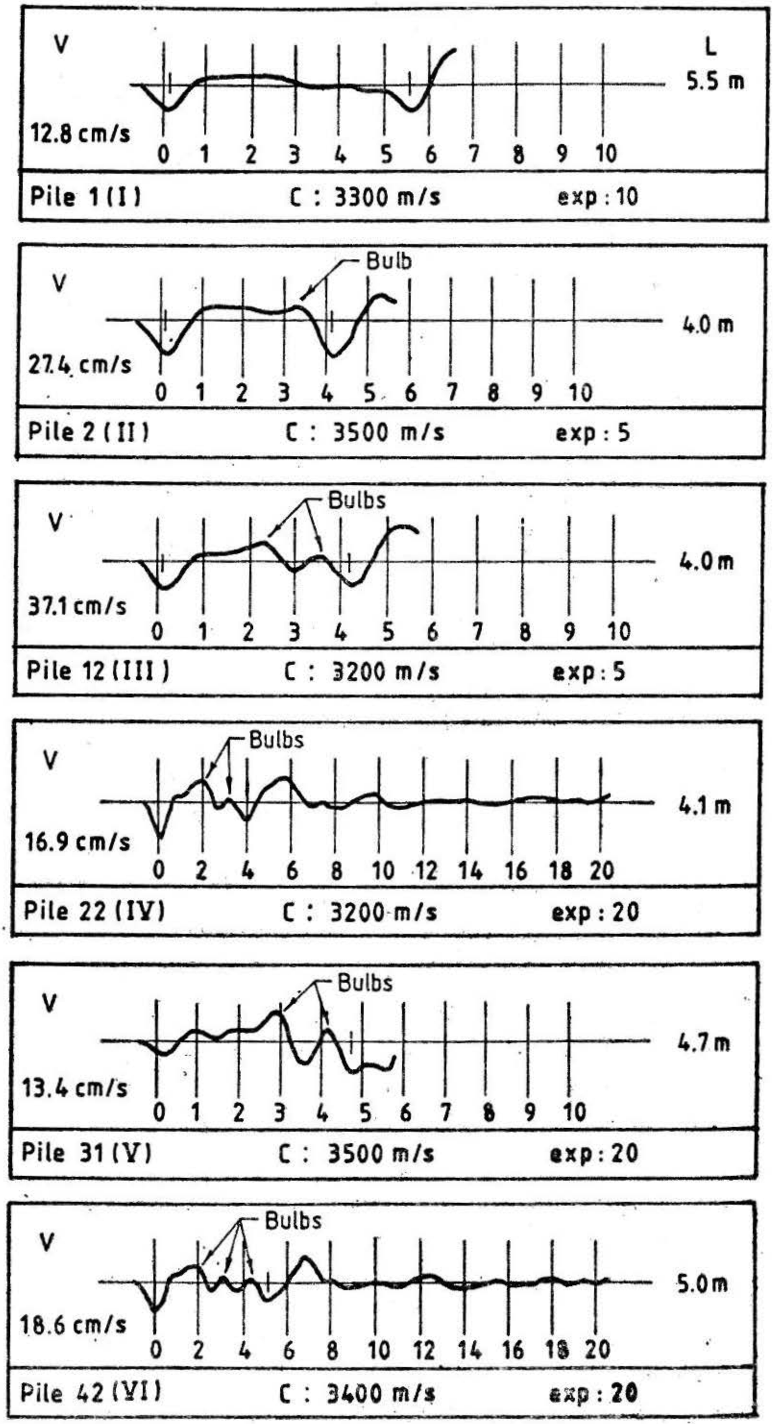


FIGURE 12 Integrity Test Results of Piles at Deaf and Dumb School Site

TABLE 2

Variation in Stress Wave Velocity with Concrete Grade

Sl. No.	Pile Type	Stress Wave Velocity (m/s)		
		M 15	M 20	M 25
1.	IV	3000	3500	3700
2.	IV	3200	3400	3400
3.	V	3300	3500	3500
4.	V	3200	3400	3600
5.	V	3300	3600	3600
6.	V	3200	3300	3600

These stress wave velocities correspond to the length of piles measured prior to concreting of the borehole in these cases. An increasing trend in the stress wave velocity with the increase in grade of concrete as expected is clear even though there are variations in the stress wave velocities for piles with one particular type of concrete. For the three grades of concrete the range is 3000 m/s to 3300 m/s for M15 grade, 3300 m/s to 3600 m/s for M20 grade and 3400 m/s to 3700 m/s for M25 grade. The average values may be taken as 3200 m/s, 3400 m/s and 3600 m/s respectively for the three grades.

Predicted Shapes by Signal Matching

For carrying out signal matching of the production underreamed piles, the soil model has been derived by matching of signal for pile 1 by considering it as a 300 mm diameter truly straight shaft of 5.5 m length. The derived soil model is shown in Fig. 13 along with the sub-soil investigation results. The best fit signal match is given in Fig. 14 alongwith the signal matches for other piles. The predicted shapes of the piles by signal matching are shown in Fig. 15. For pile 31, the best fit signal match has been obtained by neglecting increases in top portion of shaft.

The overall predicted shapes are very similar to those obtained in the case of specially cast piles, compatible with the intended built-in shape of piles. The length of piles as predicted is either the same or 5 to 10 cm more than that obtained by field integrity tests, for a 4.0 m long pile giving variation of 2.5 per cent. Similarly, the predicted locations of bulbs are also exactly the same or within 2.5 per cent variation of the intended built-in locations. The predicted diameter of bulbs ranges between 50 to 76 per cent, the minimum being for bottom bulb of triple underreamed pile (pile 42). For 250 mm

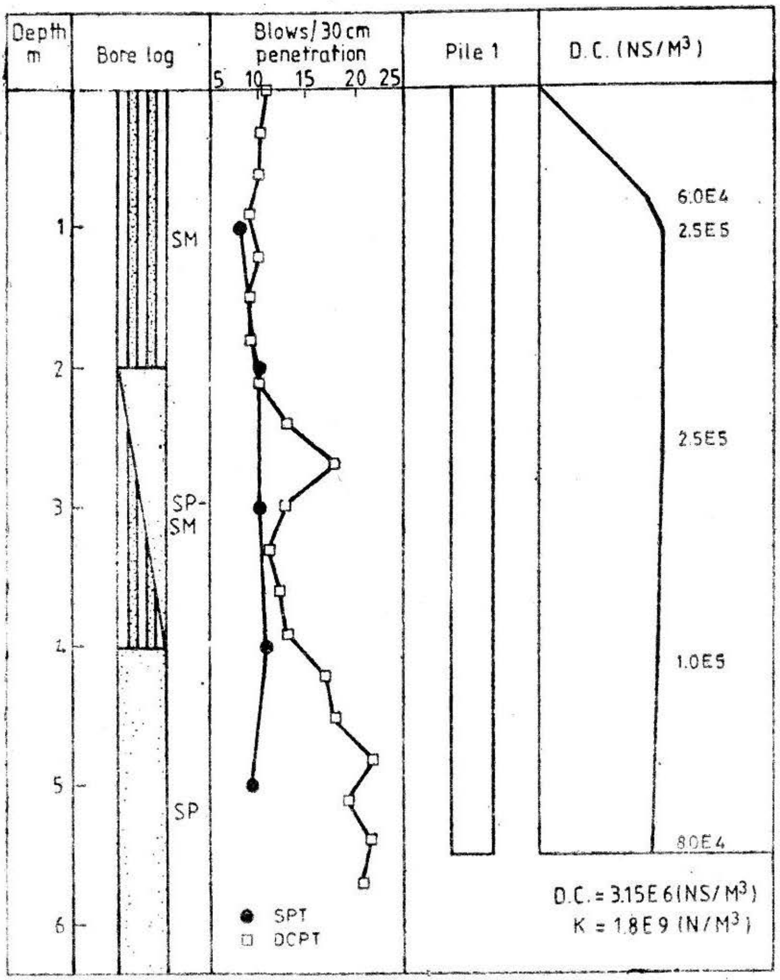


FIGURE 13 Sub-soil Data and Derived Soil Model (Deaf and Dumb School Site)

diameter piles, the predicted diameters are 63 to 76 per cent of the actual diameter. In case of 300 mm double underreamed piles, this range is 57 to 65 per cent. The predictions for top two bulbs of the triple underreamed pile also fall within this range. The predicted diameters for bottom bulbs in all the piles are less than the predicted diameters for upper bulbs. This happens probably due to the loss in travelling wave on account of the reflection at upper bulbs. Based on the predicted shapes in this case alongwith the predictions in other two sets reported earlier, it can be construed that the signal matching technique provided a very reasonable quantitative estimate of pile shapes, bulbs almost at the same built-in locations with diameters 50 to 75 per cent of the actually built-in depending on their location and the ratio of bulb diameter to shaft diameter.

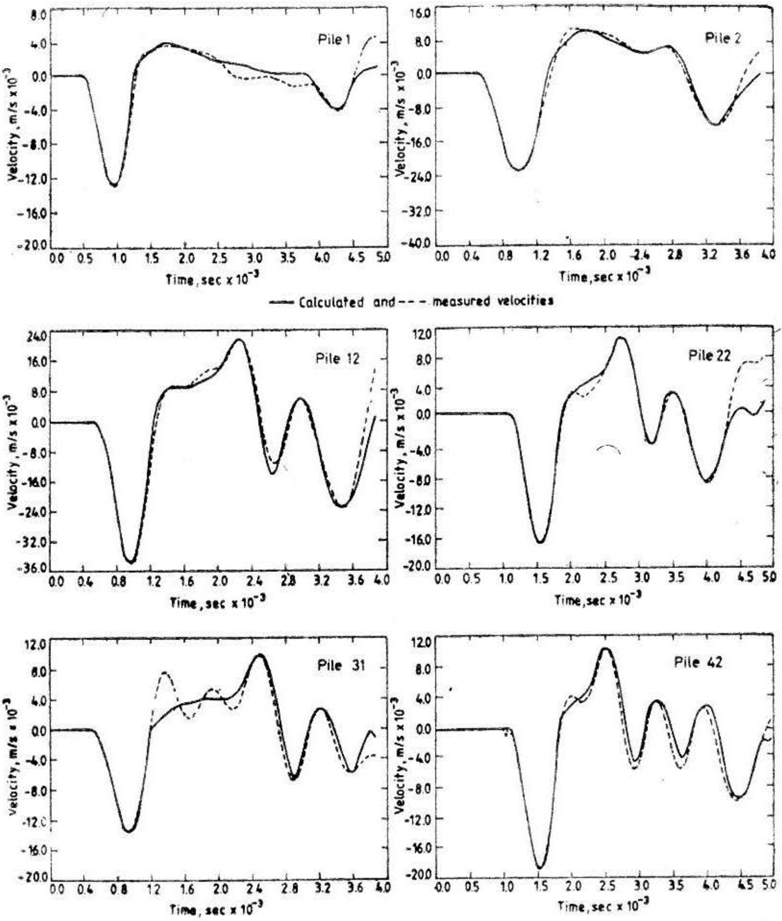


FIGURE 14 Best Fit Signal Matches for Piles at Deaf and Dumb School Site

Conclusions

Based on the work reported herein the following conclusions can be drawn:

1. The low strain integrity testing technique based on one dimensional stress wave approach as employed by the FPDS is an efficient technique for diagnosis of bored cast-in-situ concrete piles in detecting defects, continuity and variation in the cross-section of piles as also the presence of bulbs in case of underreamed piles. The pile length can also be determined to a fairly reasonable degree of accuracy.

2. The soil-interaction with pile though does affect the integrity test velocity-reflectogram, the salient features present on the pile shaft in

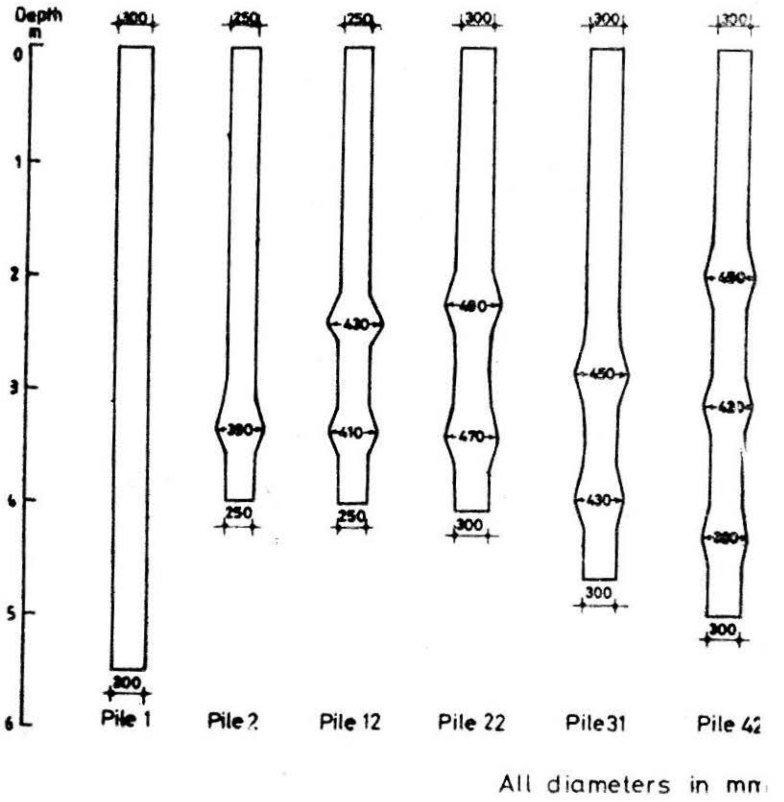


FIGURE 15 Shape of Piles Obtained Through Signal Matching (Deaf and Dumb School Site).

the form of defects or variation in cross-section are very well reflected for the piles in the ground.

3. The technique is simple, quick and requires minimal interference with site activity and can be employed to check structural integrity of production cast-in-situ piles even after 10 to 15 days of their construction. Since each defect/variation in cross-section of pile produces its own unique reflection in velocity-reflectogram, an idea about their type and location can be had directly from the field curves at the site itself.

4. The signal matching technique provides a resonable quantitative estimate of defects in the bored cast-in-situ concrete piles. In case of underreamed piles, it provides an estimate of bulbs location very close to the actual built-in locations and their diameters 50 to 75 per cent of the actual depending on their location, number of bulbs in the pile and the ratio of bulb diameter to shaft diameter.

5. The stress wave velocity, similar to strength of concrete, depends on both grade and aging of concrete. However, the change in stress wave velocity on account of aging or grade of concrete does not affect the reflections of salient features in the pile. In the field, due to variations in the strength of concrete of cast-in-situ piles, there will be variations in the stress wave velocity and this fact should be kept in mind during integrity testing.

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