Defect And Length Predictions By NDT Methods For Nine Bored Piles

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Abstract

Nine bored piles were built at the National Geotechnical Experimentation Sites at Texas A&M University: five at the sand site and four at the clay site. The piles had a nominal diameter of 0.915 m and varied in length from 10.7 m to 24.1 m. Various defects were intentionally placed in the piles including necking, bulging, soft bottom, tremie displacement, mud cake, and inclusion. Five companies were invited to make class A predictions of the length of the piles and of the defects size and location. They used small strain dynamic methods including sonic echo, impulse response, impedance logging, and sonic logging. The results are an indication of how reliable these methods are for predicting length and defects.

Introduction

Bored piles are a very popular and cost effective type of foundation. The major objective of this project was to evaluate the ability of small strain dynamic testing methods to detect construction defects in bored piles, and to determine pile length. This objective was achieved by constructing 5 bored piles in sand and 4 bored piles in clay at the National Geotechnical Experimentation Sites at Texas A&M University, inviting various companies to perform small strain dynamic testing and make class A predictions of the defects size and location as well as predict the pile lengths. Another part of the project addressed the issue of static capacity of drilled shafts obtained by dynamic testing (Briaud et al., 2000).

Sites And Soil Description

The sites were the two National Geotechnical Experimentation Sites at Texas A&M University: Sand and Clay. The top layers, 12.5 m at the sand site and 6.5 m at the clay site, are 100,000 year-old river deposits while the hard clay underlying both sites is 45 million years old and was deposited by a series of transgression and regression of the Gulf of Mexico. The sand is a medium dense silty sand with the properties shown in Fig. 1a. The clay is a very stiff plastic clay with the properties shown in Fig. 1b. Details on the soil properties are in Briaud (1997) and Simon and Briaud (1996).

Bored Piles Construction

A total of 9 bored piles were constructed: 1 through 5 at the sand site and 6 through 9 at the clay site. All piles were 0.915 m in diameter and varied in length between 10.7 m and 24.1 m. At the clay site the piles were drilled dry, while at the sand site they were drilled dry to start with and then under slurry. Details are in Ballouz et al. (1991).

All piles were constructed by following good drilling and construction practices including desanding of the drilling mud and minimizing slurry stagnation between the end of drilling and the beginning of concreting. Pile 2 was an exception as described later.

The length of the reinforcement cages was equal to the length of the piles except for pile no. 9 for which the cage was only 3 m long. In addition, piles 1, 3, 5, 6 and 8 had eight dywidag bars because they would serve as reaction piles for the load tests and be loaded in tension. Also tied to the reinforcement cage were 4 PVC access tubes equal in length to the reinforcement cage and placed at the ends of two perpendicular diameters.

During the concreting operation, the volume of concrete filling the open hole was recorded as a function of depth. This was done by counting the number of pump strokes on the concrete truck and recording the level of the mud-concrete interface with a plumb line; this information was used to generate the shape of the bored piles as constructed (Figs. 2 and 3). The shapes helped to confirm the planned defects and indicated the existence of unplanned defects.

Planned And Unplanned Defects At The Sand Site

Table 1 gives a summary of the defects type and location for all piles at the sand site. Pile 1 (Fig. 2) at the sand site had a nominal cross-section area A_n of 0.66 m^2 . An unplanned bulging defect developed between 2 m and 4 m below the top of the finished pile due to collapse of the walls during drilling. The bulge resulted in a 20% increase in area (A = 0.79 m^2). A planned necking defect exists 5.6 m below the top of the pile; it was created by attaching sand filled plastic bags to the reinforcement cage and led to a 70% reduction in area (A = 0.2 m^2).

Pile 2 (Fig. 2) at the sand site had a nominal cross-section area A_n of 0.66 m^2. The planned defects included a mud cake on the walls of the hole, a soft bottom, and concrete contamination 5.3 m below the top of the pile. The mud cake was approximately 15 mm thick and was created by leaving the bentonite drilling mud in the open hole for 60 hours. The soft bottom was created when the sand mixed with the drilling slurry settled to the bottom of the shaft during the 60 hours and formed a 300 mm thick layer of loose sand. Concrete contamination at 5.3 m occurred when the concrete tremie was purposely pulled above the concrete-mud interface during the concreting process. An unplanned defect occurred 5.0 m below the top of the pile during this operation and resulted in a 45% necking or reduction in area (A = 0.36 m^2).

Pile 3 (Fig. 2) at the sand site had a nominal cross-section area A_n of 0.66 m^2. The planned defects were a bulb created by an underream and a soft bottom. The underream was 5.6 m below the top of the pile and generated a 450% increase in cross-section (A = 3.6 m^2). During the construction of the underream, an unplanned bulging defect occurred when partial collapse of the borehole walls took place. The unplanned bulging resulted in a 100% increase in cross-section (A = 1.3 m^2) between 3 m and 8 m below the top of the pile. The soft bottom was generated by attaching saw dust filled plastic bags under a disc of plywood tied to the bottom of the reinforcing steel.

Pile 4 (Fig. 2) at the sand site had a nominal cross-section area A_n of 0.66 m^2. It was intended to be a perfect pile however caving of the side walls created an unplanned bulging defect resulting in a 30% increase in cross-section (A= 0.86 m^2) between 1.2 m and 7.5 m below the top of the pile.

Pile 5 (Fig. 2) at the sand site had a nominal cross-section area A_n of 0.66 m^2. The planned defects were a necking and a soft bottom. The necking at 8.7 m below the top of the pile was created by attaching sand filled plastic bags to the reinforcement cage. It led to a 63% reduction in area (A = 0.24 m^2). The soft bottom was generated by not cleaning the bottom of the hole and letting the natural cuttings settle. An unplanned bulging defect formed from 3 m to 8 m below the top of the pile when the borehole walls caved in; the bulging resulted in a 20% increase in cross-section (A = 0.79 m^2). A similar unplanned bulging defect occurred from 11.5 m to 14 m below the top of the pile.

Planned And Unplanned Defects At The Clay Site

Table 1 gives a summary of the defects type and location fo all piles at the clay site. Pile 6 (Fig. 3) at the clay site had a nominal cross-section area A_n of 0.66 m^2. The planned defect was a necking at a depth of 18 m; it was created by attaching sand filled plastic bags to the reinforcement cage. It led to a 43% reduction in area (A = 0.37 m^2). The soft bottom occurred because a very soft and very wet layer of soil was encountered at the final depth of drilling.

Pile 7 (Fig. 3) at the clay site had a nominal cross-section area A_n of 0.66 m^2. This pile was planned and executed as a pile without defects. Pile 8 (Fig. 3) at the clay site has a nominal cross-section area A_n of 0.66 m^2. The first planned defect was a simulated cave-in defect 6.5 m below the top of the pile; it was created by attaching sand filled plastic bags to the reinforcement cage. It led to a 12% reduction in area (A = 0.58 m^2). The second planned defect was a soft bottom which was created by placing a 0.3 m thick layer of natural cuttings and debris at the bottom of the hole. The third defect or deviation from a straight pile was a 45 degree bell with a 2.15 m maximum diameter constructed at the bottom of the pile.

Pile 9 (Fig. 3) at the clay site had a nominal cross-section area A_n of 0.66 m^2. Only one planned defect was installed 2 m below the top of the pile: a cave-in which reduced the area by 50% (A = 0.33 m^2). It was created by attaching sand filled plastic bags to the reinforcing cage. Table 1 gives a summary of the defects type and location for all nine piles.

Defect Detection Methods Used

The defect detection methods are also called integrity testing methods or nondestructive testing or evaluation methods (NDT or NDE) or small strain (say $\varepsilon < 10^{-3}$) dynamic methods. These methods consist of generating a small strain impact on or in the bored pile, recording the response, and analyzing the data to infer the location and size of a defect. The methods which were performed in this study were the Sonic Echo method (SE), the Impulse Response method (IR), also called the Transient Dynamic Response method, the Impedance Logging method (IL), and the Sonic Logging method (SL).

The theories for these methods were developed gradually several decades ago but it is the progress in micro computers, data acquisition systems and instrumentation in the mid eighties which made these methods much more attractive. It is difficult to attribute precise credit for the development of those methods as well as references to describe the details of each method. The propagation of a stress wave in an elastic rod which is the basis for most methods can be found in classical textbooks on soil dynamics such as Richart et al. (1970). One of the original papers seems to be the work of Paquet (1968). The following names and references appear to be particularly relevant: Briard (1970), Davis and Dunn (1974), Koten and Middendorp (1981), Hearne et al. (1981), Olson and Thompson (1985), Rausche et al. (1988), Paquet (1991), Hertlein (1992), Baker et al. (1993), Davis (1995), Samman and O'Neill (1997), Finno and Gassman (1998). One can also get much information from the proceedings of the five international conferences on the application of stress wave theory to piles held in Stockholm (1980, 1984), Ottawa (1988), The Hague (1992), and Orlando (1996).

The Sonic Echo method (SE), also called seismic method consists of striking the top of the pile with a small hammer thereby sending a compression wave down the pile to the bottom or to any anomaly where it is reflected back to the surface. The travel time of the wave is recorded through geophones or accelerometers placed at the top of the pile. The analysis is done in the time domain and is used to infer the length of the pile, the location of anomalies and to some extent the size of anomalies.

The Impulse Response method (IR), also called Transient Dynamic Response, consists of striking the top of the pile with a small hammer. This hammer is instrumented with a dynamic load cell located at the hammer tip to obtain the force-time signal during the impact. The response is recorded through geophones or accelerometers placed at the top of the pile. The analysis is done in the frequency domain and is used to infer the length of the shaft, the location and size of anomalies, and the stiffness of the soil-pile system.

The Impedance Logging method (IL) is a special analysis of the IR data (Paquet, 1991). It leads to a complete image of the pile as it exists in the ground.

The Sonic Logging method (SL) consists of lowering a transmitter and a receiver probe in two preplaced access tubes in the pile, inducing a low strain impact with the transmitter and recording the time that it takes for the wave to travel horizontally from the transmitter to the receiver. The transmitter and the receiver are kept at the same elevation and the logging takes place continuously as the probes are pulled up from the bottom to the top of the pile.

Predictions By Defect Detection Methods

Five companies from France, the Netherlands and the United States were invited to test the 9 bored piles, and give their predictions of the type, location and size of the defects as well as the pile lengths. These companies were ESSI-Testconsults (1991), GRL and Associates Inc. (1991), Olson Engineering Inc. (1991), STS Consultants Ltd. (1991), and TNO Building and Construction Research (1991). The defects and lengths were kept unknown to all the testing companies in an attempt to evaluate the reliability and limitations of each method. For calibration purposes, the five companies were told however that piles 4 and 7 were approximately 10 m long and had no planned defects. Even though the physical aspects of the detection methods may look alike, the analysis and interpretation of the data obtained differed from one company to another and so did the results obtained.

The predictions submitted by the testing companies included two stages: "on-site predictions" before lowering any tools in the PVC access pipes, and "final predictions" as presented in the final reports a few months later.

The results of the "on-site predictions" relied solely on the quick analysis of the Sonic Echo and Impulse Response methods. These predicted results were obtained at the site shortly after the tests. One page forms were distributed to all the participating companies for them to report the pile length and the existence of any defects. The results of the pile length predictions are presented in Table 2.

The results of the final predictions were gathered from the report submitted by each company at least one month after the site visit or after thorough analysis. The prediction results are summarized in Tables 3, 4, 5 and 6 for the Sonic Echo method, the Impulse Response method, the Sonic Logging method, and the Impedance Logging method. The results of the Impedance Logging method are also shown in Fig. 4.

Comparison Between Predictions And Actual Features

The first possible comparison is between the predicted length and the actual length of the pile. This comparison can be done for the predictions made on-site before accessing the PVC pipes, and for the final predictions by the Sonic Echo method, by the Impulse Response method and by the Impedance Logging method. The comparison is presented in Table 7. Note that piles 4 and 7 are removed from the evaluation since the companies knew their approximate length. If the length was predicted within ?5% a full dot is shown, if the length was not predicted within ?5% but within ?15% a half full dot is shown; open dots are for length predictions not within ?15% or no length predictions. The percent success P is the number of full dots (counting the half full dots as 0.5) divided by the total number of predictions expressed as a percentage.

The second comparison is between the predicted defects and the actual defects. This comparison is shown in Table 8 for the various methods. If the type of defect was well defined by the predictor and if the predicted location of the defect was within ?0.6 m of the actual defect a full dot was given. If the type of defect was ambiguously defined by the predictor and if the predicted location was within ?1.8 m of the actual defect, a half full dot was given. If the type and location were undetected an open dot was used. The percent success P was defined as the ratio of the number of full dots (counting the half full dots as 0.5) divided by the total number of predictions expressed as a percentage. Table 9 shows the percent success for the various methods, the various defect types, and the predictions of length.

Analysis Of The Length Prediction Results

Fig. 5 shows the percent success for the prediction of pile length as a function of the pile length over diameter ratio (L/D). Each point on the figure corresponds to one pile and the percent success is calculated as the average for all methods. An L/D ratio of 30 has often been quoted as the limit of detection and this seems to be consistent with the trend in Fig. 5. The length of Pile No. 5 was not well predicted mainly because of the combination of two defects, a significant bulging from 3 to 8 m followed by a significant necking at 8.7 m, which made it quite difficult to see a clear return signal coming back from the bottom of the pile at 16.8 m and led several companies to conclude that the pile length was at 8.7 m.

Although these companies did not predict the pile length accurately, concluding that Pile No. 5 with a 63% necking at 8.7 m is actually 8.7 m would be practically reasonable. Table 7 indicates that for predicting pile length the simpler Sonic Echo method (SE) is as good as the more complicated Impulse Response method (IR) and that the Impedance Logging method (IL) gives the best percent success rate. Table 7 also indicates that the percent success can vary by a factor of two from one company to another; the opinion of the authors is that the experience of the operator at the site and of the engineer analyzing the data has a significant influence on the percent success.

Analysis Of The Defect Detection Results

Some of the factors influencing the detection of defects in a pile include the experience of the engineer, the size of the defect, the stiffness of the soil surrounding the pile, the depth at which the defect is located, the type of defect, and the detection method used. The percent success is influenced by this combination of factors. Fig. 6 shows the percent success P obtained from the average of the final predictions based on the SE, IR, and IL methods as a function of the normalized depth of the defect. The trend is weak but indicates that the percent success decreases as the depth of the defect increases. Fig. 7 shows the percent success P obtained in the same way as a function of the normalized size of the defect. The trend is non existent; this shows that the defect size by itself is not a major factor. If it is intuitively assumed that the intensity of the signal disturbance due to a defect is linearly proportional to the size of the defect and decreases exponentially with the depth at which the defect is located, a signal intensity index (SII) can be defined:

$$SII = \frac{A_d / A_t}{e^{D_d / B_p}} \tag{1}$$

Where A_d and A_t are the cross section areas of the defect and of the pile respectively, D_d is the depth of the defect, B_p is the diameter of the pile and e is 2.718. Fig. 8 shows the relationship between the percent success P and the decimal logarithm of SII. The trend shows that the percent success increases with SII as could be expected.

Neckings can be significant defects while bulges are rarely of concern. The sonic logging method gave the highest percent success (75%) for the detection of necking (Table 9); if access tubes are not available the Impedance Logging method gave the highest percent success (67%) for the same detection. Neckings decrease the pile diameter and are particularly detrimental if they are shallow and if horizontal loading is involved; indeed the stiffness against lateral loading is influenced by the moment of inertia which is proportional to the fourth power of the diameter while the resistance to vertical loading only involves the second power of the diameter through the area. The IR test can be used to obtain the vertical stiffness of the pile-soil assembly while the LATWAK test (Briaud, Ballouz, 1996) can be used as a non destructive test to evaluate the lateral stiffness of the pile-soil assembly.

Soft bottom, tremie displacement, and mud cake were all poorly predicted. The mud cake was not detected by any method; yet this is a very important defect which decreased the vertical capacity of the shaft by a factor of 3 as measured in load tests (Ballouz et al., 1991). The soft bottoms were also poorly detected; the question remains to know whether the planned and unplanned soft bottoms were still soft by the time the bored pile was completed and the concrete had cured. Indeed the weight of the column of concrete can prestress the soft bottom to a load equal to the weight of the bored pile. On the other hand, the load applied at the pile point during the life of the structure could be higher than that.

False Negatives

In the predictive process, a number of defects were predicted to exist and did not according to the construction record; this is referred to as a false negative. Table 10 shows the false negatives. For example, Pile 3 had a bulging defect from 3 to 8 m with a bell at 5.6 m yet three companies predicted a necking between 6 and 7.3 m. It could be that the decrease in cross-section below the bell was interpreted as a necking; however Pile 3 did not have a necking at that depth in the sense that the cross-section was not less than the nominal value $A_n = 0.66$ m^2. Another example is Pile 6 when at a depth of between 2.7 m and 4.3 m, two companies predict a bulb and one company predicts a necking.

Conclusions

The following conclusions are based on the prediction of pile length and the detection of multiple defects by five companies for five bored piles constructed in a medium dense silty sand and four bored piles constructed in a stiff to very stiff clay. Similar results were obtained in another part of this study done in California (Baker et al., 1993) and in a recent study done at the University of Houston National Geotechnical Experimentation Site (Samman and O'Neill, 1997, Samman, 1997).

The length of a pile with a length to diameter (L/B) ratio less than 20 was predicted with at least an 80% success rate. When the L/B ratio increased from 20 to 30 the success rate decreased rapidly; for L/B larger than 30 it does not appear that the pile length can be predicted reliably. The presence of a bulge immediately followed by a necking can significantly decrease the success rate for a given L/B ratio.

The success rate for the prediction of defects was not as high as the success rate for the prediction of length. The most influential parameter seems to be the depth at which the defect is located (Fig. 6) while the size of the defect does not seem to be as critical (Fig. 7). The percent success in the detection of soft bottoms, tremie displacement, and mud cakes was very poor. Several defects were predicted which did not exist (false negative) according to construction records.

The Sonic Echo, Impulse Response, and Impedance Logging methods, all gave about the same percent success (~ 80%) of length predictions with a slight advantage to the Impedance Logging method. The Impedance Logging method gave the best percent success for predicting bulging (100%) and necking (67%) when access tubes were not used. When access tubes are available and if they are judiciously located, the Sonic Logging method gives the best percent success (75%) for the detection of neckings.

One should not get the impression from this article that bored piles always have defects. Bored piles are used extensively, economically, and successfully when properly constructed. The NDT methods discussed here do not appear to be 100% reliable. Further practice and research is quite likely to improve the reliability of these methods which are already an important tool in infrastructure evaluation.

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Table 1: Planned and unplanned defects in the piles.

Site (1)	Pile no. (2)	Total Length (m) (3)	Embed. Length (m) (4)	Defect P/U* (5)	Defect Type (6)	Depth from Top of Pile to Defect (m) (7)	Actual Concrete Area (m^2) (8)	** Increase (+) Decrease (-) (%) (9)
SAND	1	16.6	15.7	U	Bulging	2.0-4.0	0.79	+20
				P	Necking	5.6	0.20	-70
	2	11.6	10.9	P	Mud Cake	0-11.6	0.66	0
				P	Concr. Contamin.	5.3	0.66	0
				U	Necking	5.0	0.36	-45
				P	Soft Bottom	11.6	0.66	0
	3	16.5	15.6	P	Bulging (bell)	5.6	3.6	+450
				U	Bulging	3.0-8.0	1.3	+100
				P	Soft Bottom	16.5	0.66	0
	4	11.4	10.6	U	Bulging	1.2-7.5	0.86	+30
	5	16.8	15.9	P	Necking	8.7	0.24	-63
				U	Bulging	3.0-8.0	0.79	+20
				U	Bulging	11.5-14.0	0.79	+20
				P	Soft Bottom	16.8	0.66	0
CLAY	6	24.1	23.0	P	Necking	18.0	0.37	-43
				P	Soft Bottom	24.1	0.66	0
	7	10.7	9.6		No Defects	-	0.66	0
	8	12.2	11.1	P	Necking	6.5	0.58	-12
				P	Bulging (bell)	12.2	3.6	+450
				P	Soft Bottom	12.2	3.6	+450
	9	10.4	9.3	P	Necking	3.0	0.33	-50

* P = Planned, U = Unplanned
** Increase or decrease with respect to the nominal area ($A_N = 0.66m^2$)

Table 2: On site length predictions before access to the PVC pipes was allowed.

Site (1)	Pile No. (2)	Company A L (m) (3)	Company B L (m) (4)	Company C L (m) (5)	Company D L (m) (6)	Company E L (m) (7)
SAND	1	16.7	12.2	17.2	18.3	16.5
	2	11.2	12.2	11.4	11.0	11.3
	3	17.1	11.6	17.4	16.5	16.0
	4	10.2	10.7	10.6	10.7	10.5
	5	8.9	9.3 or > 13.7	10.0	10.4	8.5
CLAY	6	23.2	9.8 or >> ?	23.0	11.3	9.0
	7	10.0	10.7	10.1	11.4	9.9
	8	11.7	12.8	11.7	13.7	11.4
	9	9.9	10.4	9.6	11.3	9.5

Table 3: Final predictions based on the sonic echo method.

Site (1)	Pile No. (2)	Company C L (m) (3)	Company C Defect (4)	Company C at (m) (5)	Company D L (m) (6)	Company D Defect (7)	Company D at (m) (8)	Company E L (m) (9)	Company E Defect (10)	Company E at (m) (11)
	1	16.7	Bulb Bulb	2.7 6.6	16.2	Bulb Necking	2.3 to 3.7 5.8 to 6.4	16.0	Bulb	3.5
	2	11.8	Necking Soft Bottom	6.4 Bottom	11.0	Bulging Small necking	2.5 to 5.4 5.9	11.0	Section reduction	5.5
SAND	3	16.1	Bulb Bulb Necking?	2.6 4.3 12.6	16.5	Bulb Bulb Necking	2.2 to 3.6 5.1 7.3	16.0	Bulb	2.0 to 6.5
	4	11.2	Necking	5.4	11.3	Slight bulging	2.4 to 5.6	10.0	Section reduction	5.0
	5	16.8	Bulb Bulb	3.1 9.7	8.4	Slight bulging Necking?	2.5 to 4.4 1.6	8.0	Bulb	2.0 to 6.0
	6	21.8	Bulb Necking	3.2 17.3	?	Necking Small Bulb	10.4 2.5 to 4.0	?	Bulb Necking	2.6 9.0
CLAY	7	10.7	Soft Bottom	Bottom	10.4			9.5		
	8	12.8	Necking Soft bottom	6.4 Bottom	12.6	Bulging	2.5 to 3.4	12.0	Bell	Bottom
	9	9.2	Bulb	3.2	10.4	Cave-in Bulb	2.5 to 3.3 4.9	9.3	Necking (30%)	2.8

Table 4: Final predictions based on the impulse response method.

Site	Pile No.	Company A			Company B			Company C			Company D		
		L (m)	Defect	at (m)	L (m)	Defect	at (m)	L (m)	Defect	at (m)	L (m)	Defect	at (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
SAND	1	17	Necking Bulb	6.0 2.7	21.6	Bulb Necking Cave-in (50%)	2.3 to 5.0 14.0 17.4	17.3	Bulb Bulb	3.0 6.5	16.8	Necking	5.5
SAND	2	11.3	Anomaly Bad quality concrete	5.3 Top part	10.7	Bulb (30%) Necking (30%) Soft bottom	3 to 4 6 to 7.6 Base	11.9	Necking Soft bottom	5.9 Base	11.1	Small necking	5.8
SAND	3	15.8	Necking or bad quality concrete Bulb	 6.0 2.3	16.5	Cave-in Bulb Bell?	6-7.6 2.8 to 4.2 9.7	16.1	Bulb Bulb Necking?	2.6 4.4 12.6	16.7	Necking	7.3
SAND	4	10.3	Anomaly	5.2	10.7	Bulging	2.7 to 5.8	11.3	Necking	5.6	11.3	Small bulging	2.4 to 5.6
SAND	5	16.5	Necking or bad quality concrete Bulb	 9.0 2.3	18.6	Necking (65%) Bulging	11.0 13.0	?	Bulb Bulb	3.1 9.8	8.5	?	
CLAY	6	22.3	Necking	9.5	17.7 ?	Small bulb Defect or toe ?	9.1 17.7	22.0	Bulb Necking Soft Bottom	3.1 17.1 Base	?	Necking Small bulb	10.2 3.7
CLAY	7	10.0	Small bulb Soft bottom	2.3 Base	10.7	Perfect, but small bulb near top		10.7	Soft bottom	Base	11.0	?	
CLAY	8	11.6	Bulb	2.1	12.2	Bulb (400%)	10.0	12.4	Small necking	6.2	13.7	?	
CLAY	9	9.9	Cave-in Soft bottom	2.6 Base	10.9	Necking (20%) Necking ?	2.7 10.0	9.4	Bulb	2.6	10.7	Cave-in	2.6

Table 5: Final predictions based on the sonic logging method.

Site (1)	Pile No. (2)	Company A Defect (3)	Company A at (m) (4)	Company C Defect (5)	Company C at (m) (6)
SAND	1	Poor bonding Defect Smaller anomaly	Top 3.0 5.8-6.1 11.6	Poor bonding Necking or poor bonding	Top 6.1 5.6-6.1
	2	Poor bonding Variable concrete quality: North/East South/West North/South	Top 3.0 1.5 & 3.0 Top 3.7 Top 4.6	Debonding, East/West North/South	Top 7.0 Top 3.7
	3	Poor bonding Bad concrete Shallow peripheral reduction or neck	Top 8.0 6.1-7.3 11.9	Poor bonding Defect, or lower quality concrete	Top 7.3 12.5-14.6
	4	The test could not be performed because of lack of water and leaks from the tubes		Debonding Debonding Defect around West tube (Intrusion)	Top 1.8 4.3-4.9 6.1
	5	Poor bond and variable concrete quality Minor anomaly Layer of contaminated material	Top 6.1 6.1 8.5-9.1	Poor bonding Severe debonding	Top 9.8 8.5-9.8
CLAY	6	Minor anomaly Significant peripheral contamination or neck Severe Defect	5.8 & 11.9 9.8 & 17.7 22.9	Poor bonding Defect Bad concrete Soil and water intrusion	Top 1.8 to 2.4 17.4-18.0 19.8-21.9 21.9-23.2
	7	Poor bonding Concrete quality variable	Top 1.5 Top 2.4	Poor bonding	Top 1.5 to 2.4
	8	Defect Bad concrete quality Inclusion; South/East	0.9 Top 1.8 4.6-6.1	Poor bonding Minor defect between North and East tubes	Top 1.2 to 2.4 5.5-6.1
	9	Variable concrete quality and poor bond Inclusion adjacent to South tube	Top 3.0 2.4	Severe debonding	Top 3.0

Table 6: Final predictions based on the impedance logging method

Site (1)	Pile No. (2)	Company A L (m) (3)	Defect (4)	at (m) (5)
SAND	1	16.5	Bulging (160%) Necking	2.5 - 4.4 6.0
	2	11.5	Bulging Small Neck	5.3 7.0
	3	16.5	Bulb (455%) Bulging (105%)	5.0 2.5 - 7.5
	4	10.5	Increase in Diameter	3.0 - 7.0
	5	18.0	Necking (66%) Bulging (47%) Bulging (23%) Small Neck	9.1 3.0 - 8.0 11.5 - 13.0 14.0
CLAY	6	23.0	Necking (66%) Small Neck	10.0 18.0
	7	10.3	Small Bulb	at Top
	8	12.3	Small Bulb Bulb (360%)	3.0 11.5
	9	10.0	Cave-in (56%) Reduction in Section	3.0 3.5 - 6.0

Table 7: Evaluation of length predictions.

Site (1)	Pile Number (2)	Actual Length (m) (3)	ON SITE A (4)	ON SITE B (5)	ON SITE C (6)	ON SITE D (7)	ON SITE E (8)	SE C (9)	SE D (10)	SE E (11)	IR A (12)	IR B (13)	IR C (14)	IR D (15)	IL A (16)
SAND	1	16.6	●	○	●	◒	●	●	●	●	●	○	●	●	●
	2	11.6	●	●	●	●	●	●	◒	●	●	●	●	●	●
	3	16.5	●	○	◒	●	●	●	●	●	●	●	●	●	●
	4	11.4	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	16.8	○	○	○	○	○	●	○	○	●	◒	○	○	○
CLAY	6	24.1	●	○	●	○	○	◒	○	○	◒	○	◒	○	●
	7	10.7	-	-	-	-	-	-	-	-	-	-	-	-	-
	8	12.2	●	●	●	◒	◒	●	●	●	●	●	●	◒	●
	9	10.4	●	●	◒	◒	◒	◒	●	◒	●	●	◒	●	●
	Percent Success		86%	43%	71%	50%	57%	86%	64%	64%	93%	64%	71%	64%	86%
	Average		61%					71%			73%				86%

On Site - Predictions made on site, the day of the test, before access to the PVC pipes was allowed.
SE, IR, IL - Final predictions made by Sonic Echo (SE), Impulse Response (IR), Impedance Logging (IL)
A,B, C, D, E -Letters identifying the predicting company
● - Length predicted within ±5%
◒ - Length predicted not within ±5%, but within ±15%
○ - Length not predicted within ±15%

Table 8: Evaluation of defect predictions by the various NDT method.

Site (1)	Pile No. (2)	ACTUAL DEFECTS: Type and Size (as % of Area) (3)	ACTUAL DEFECTS: Location from top (m) (4)	SONIC ECHO: C (5)	SONIC ECHO: D (6)	SONIC ECHO: E (7)	IMPULSE RESPONSE: A (8)	IMPULSE RESPONSE: B (9)	IMPULSE RESPONSE: C (10)	IMPULSE RESPONSE: D (11)	SONIC LOGGING: A (12)	SONIC LOGGING: C (13)	IMPEDANCE LOGGING: A (14)
SAND	1	Bulging (+20%) (U)	2.0 - 4.0	●	●	●	●	●	●	○	◐	◐	●
		Necking (-70%)	5.6	○	●	○	●	○	○	●	●	●	●
	2	Mud Cake (15 mm)	0 - 11.6	○	○	○	○	○	○	○	○	○	○
		Tremie Displ. (100%)	5.3	○	○	○	●	○	○	○	●	○	●
		Necking (-45%) (U)	5.0	◐	◐	●	●	◐	◐	●	○	○	○
		Soft Bottom (100%)	11.6	●	○	○	○	●	●	○	○	○	○
	3	Underream (+450%)	5.6	●	●	●	○	○	○	○	○	○	●
		Side Failures (Bulging +100%) (U)	3.0 - 8.0	●	●	●	◐	●	●	○	○	○	●
		Soft Bottom (Sawdust 100%)	16.5	○	○	○	○	○	○	○	○	◐	○
	4	Bulging (+30%) (U)	1.2 - 7.5										
	5	Necking (-63%)	8.7	○	○	○	●	◐	○	○	●	◐	●
		Bulging (+20%) (U)	3.0 - 8.0	●	●	●	◐	○	●	○	○	○	●
		Bulging (+20%) (U)	11.5 - 14.0	◐	○	○	○	●	◐	○	○	○	●
		Soft Bottom (Cuttings 100%)	16.8	○	○	○	○	○	○	○	○	○	○
CLAY	6	Necking (-43%)	18.0	●	○	○	○	●	◐	○	●	●	●
		Soft Bottom (100%)	24.1	○	○	○	○	○	●	○	◐	●	○
	7	No Defect											
	8	Inclusion (-12%)	6.5	●	○	○	○	○	●	○	●	●	○
		Underream (+450%)	12.2	○	○	●	○	◐	○	○	○	○	●
		Soft Bottom	12.2	●	○	○	○	○	○	○	○	○	○
	9	Necking (-50%)	3.0	○	●	●	●	●	○	●	●	◐	●

● - Good Prediction: Type well defined and location within ±0.6 m
◐ - Fair Prediction: Type ambiguous and location within ±1.8 m
○ - Poor Prediction: Type and location undetected
(U) - Unplanned Defect
A, B, C, D, E - Letters identifying the predicting companies

Table 9: Percent success for predictions of defects and length.

Type of Defect (1)	Location from Top of Pile (m) (2)	PERCENT SUCCESS			
		SE[1] (3)	IR[2] (4)	SL[3] (5)	IL[4] (6)
Bulging/Underream	0 - 8	100	44		100
	8 - 14	25	25		100
	0 - 14	75	38		100
Necking	0 - 8	56	56	69	50
	8 - 14	17	38	92	100
	0 - 14	39	50	75	67
Soft Bottom	11.6 - 16.8	13	15	20	0
Mud Cake	0 - 11.6	0	0	0	0
Tremie Displacement	5.3	0	25	50	100
Length	0 - 15	83	92		100
	15 - 25	62	59		75
	0 - 25	71	73		86

1. SE = Sonic Echo
2. IR = Impulse Response
3. SL = Sonic Logging
4. IL = Impedance Logging

Table 10: False negatives.

Site (1)	Pile No. (2)	Company A (3)	Company B (4)	Company C (5)	Company D (6)	Company E (7)
SAND	1		Cave-in (17.4 m)			
	2					
	3	Necking (6.0 m)	Necking (6.1 m) Bell (9.7 m)	Necking (12. 6 m)	Necking (7.3 m)	
	4			Necking (5.4 m)		Necking (5 m)
	5			Necking (4.8 m)		
CLAY	6	Bulb (3.2 m) Necking (9.5 m)	Bulb (2.7 m) Necking (10.4 m)	Defect (10.4 m)	Necking (4.3 m) Necking (10.4 m)	
	7	Bulb (2.3 m) Soft bottom	Small bulb near top	Soft bottom		
	8	Bulb (2.1 m)		Defect (2.6 m)	Bulb (2.7 to 3.7 m)	
	9	Soft bottom	Bulb (4 m) Necking (10 m)	Bulb (3.2 m)	Bulb (5.5 m)	

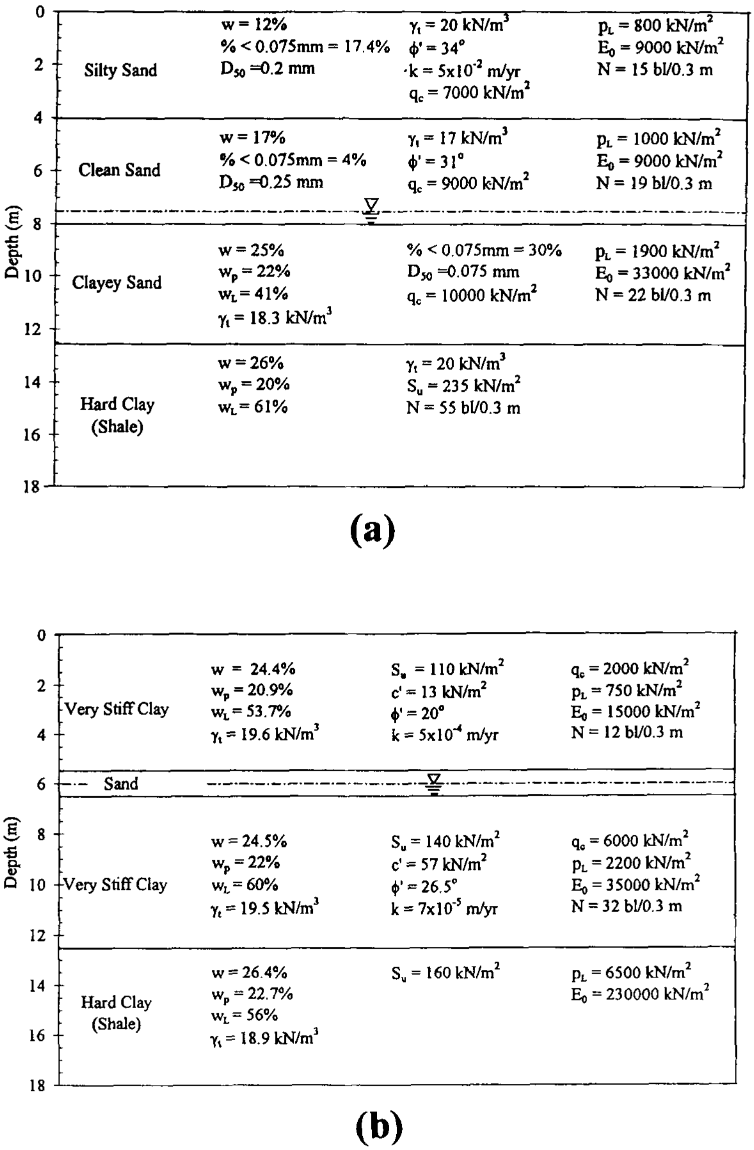

Figure 1: Summary of soil properties at the NGES-TAMU a/Sand Site, b/Clay Site.

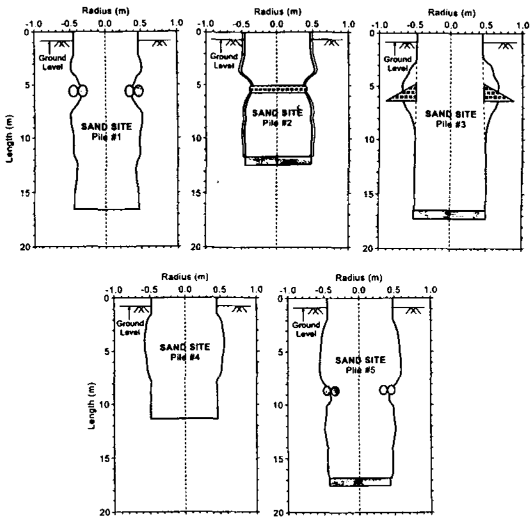

Figure 2: Bored piles at the NGES-TAMU Sand Site.

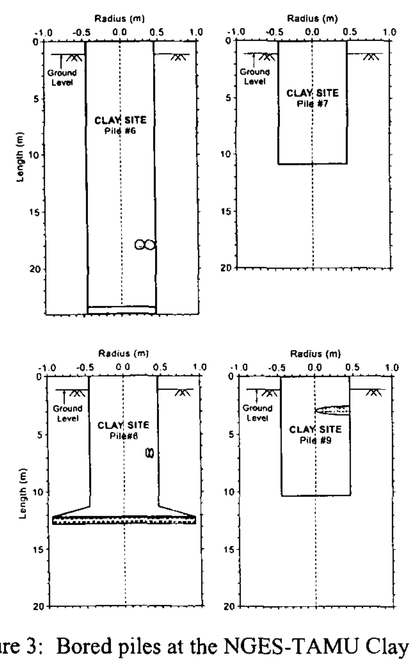

Figure 3: Bored piles at the NGES-TAMU Clay Site.

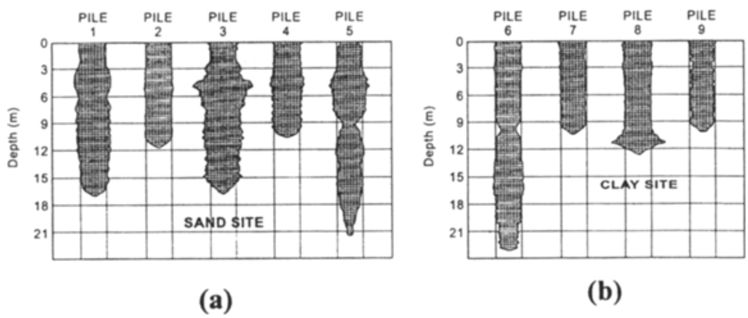

Figure 4: Results of the impedance logging method a/Sand Site, b/Clay Site.

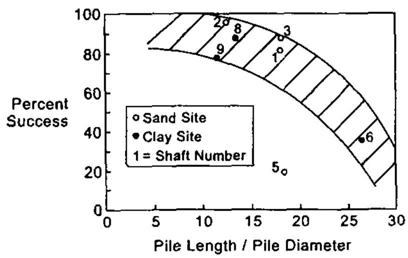

Figure 5: Percent success for pile length predictions.

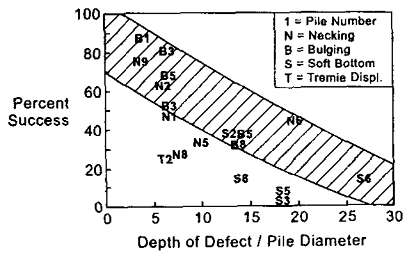

Figure 6: Percent success for defect predictions as a function of the depth of the defect.

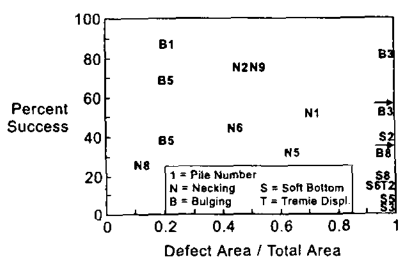

Figure 7: Percent success for defect predictions as a function of the size of the defect.

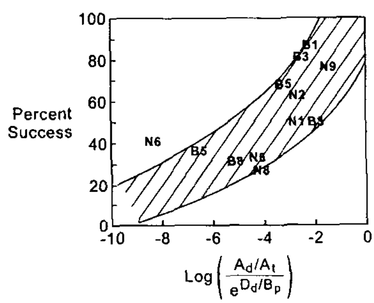

Figure 8: Percent success for defect predictions as a function of signal intensity index.