DEEP FOUNDATION PRACTICE IN TAIWAN

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Deep Foundation Practice in Taiwan

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Abstract

This paper presents a summary of the current deep foundation practice in Taiwan. Constructions of driven piles, drilled shafts, and barrette foundations are reviewed. This paper also presents major research results on piling in the past few years. Discussed research topics include the development of residual stress after pile driving, the long-term down drag force on pile, the load distribution of group piles, pressure grouting at pile toes, the application of CPT in pile design, and the use of backbone t-z curves for evaluating the performance of piles.

Introduction

The total area of the island of Taiwan is approximately 36,000 sq. km. Most of its 21 millions people live in the coastal plains and basins that covers only about one third of the entire area of Taiwan. These coastrel plains and basins are underlain by soft silty clays and loose to medium dense sands of recent deposits. In the past two decades, Taiwan has become one of the most rapidly developing regions in the world. Accompanying the remarkable economic growth, numerous high-rise buildings were constructed and many large scale infrastructures were completed. Many of these major projects involved significant piling works in soft ground and reclaimed land.

This paper has two major parts. The first part presents a brief summary of current practice of constructing deep foundations in Taiwan. The second part of this paper discusses the results of pile researches recently conducted in Taiwan.

Commonly Used Deep Foundations

In Taiwan, the predominantly used deep foundations are driven piles and drilled shafts. Barrette foundations have become more popular in recent years in the construction of high-rise buildings. Drilled caissons, which are not commonly used foundations in Taiwan, have been successfully used as retaining structure in the developments of slope lands (Moh et al.,1979). Minipiles have just been introduced to Taiwan. They have been reported to be widely adopted in various applications, mainly in the underpinning projects (Woo, 1993). Because this paper is focused on deep foundations, it will only review the use of driven piles, drilled shafts, and barrette foundations.

Driven Piles

Steel pipe piles and prestressed concrete piles are the most commonly used driven piles in Taiwan. Steel H-piles are seldom used as foundations, but are frequently used as the temporary retaininging structure during excavation.

Driven piles are seldom used in urban areas because of the noise and vibration concerns. They are mainly used for supporting bridges, highways, and industrial facilities in rural areas, coastal plains, and reclaimed sites. One of the most notable recent piling projects is the construction of the Taichung Steam Power Plant where the site was reclaimed by hydraulic sandfill about 6 m in thickness. Close-ended steel pipe piles of 0.8 m in diameter were driven to a maximum depth of 58 m to support three tall chimneys of 250m in height (Duann et al., 1994). Open-ended steel pipe piles were once popular for power generating facilities, for example, the Hsin-Ta Steam Power Plant, also on a reclaimed site, in southern Taiwan (Woo et al., 1990). Extensive studies have been carried out to study the plugging effects of open-ended pipe piles (Soo et al., 1980) and it was found that the loading capacities of open-ended piles, even with plugs effectively developed, were only 60% of those of close-ended piles. Therefore, recently prestressed concrete piles (typically 600 mm in diameter) are preferred. Raymond piles, with step-taper corrugated light-steel shells, were introduced to Taiwan in 1970's. For constructing the plant complex for China Steel Corporation, a total of 22,560 Raymond piles were driven in the first phase alone and many thousands more were installed in later stages (Moh, 1987).

Drilled Shafts (Bored Piles)

Drilled shafts are always referred to as bored piles in Taiwan. They are commonly used to support heavy loads from tall buildings, bridge piers, and so on. Bored piles are equally popular as, if not more popular than, driven piles. As noise becomes a major environmental issue, the use of bored piles is gaining additional momentum. Various techniques have been developed to improve their performance, such as, high pressure grouting, the use of full-length casings, etc. Special care is taken on the slurry disposal in order to minimize adverse environmental impacts.

In Taiwan, modern tall buildings in cities are almost exclusively supported on bored piles which are mostly bored by using the reverse circulation method. It is very common that a building column is supported by one large diameter bored pile instead of a group of smaller piles. The diameter of this type of pile can be as large as 2.4 m , as those used in the construction of the China Trust Financial Building. Piles with diameters in the range between 1.6 m and 2.0 m are the most frequently used. In order to gain more bearing from underlying gravels and boulders, bored piles of 2 m diameter used to support the 50-storey Shin-Kwang Building, the tallest building in Taipei, were underreamed to a maximum diameter of 3.3 m. Chung-Yang Bridge, a cable-stayed bridge, is supported on 2 m diameter bored piles, installed to a maximum depth of 94 m which probably is the record length in Taiwan (Wang, 1994).

Sometimes, instead of casting the piles at site, precast concrete piles can be lowered into pre-drilled holes infilled with soil-cement mixture. It can eliminate the vibration and noise associated with pile driving. Meanwhile, it also can avoid many problems associated with installation of conventional bored piles, such as "soft toe" and necking. A total of 309 prestressed concrete piles, with a diameter of 450 mm and a length of 15 m, were installed in such a manner for the construction of a sewer plant in Linyuan, Kaoshiung (Wang et al., 1991). Loading tests on such piles indicated slightly lower capacities in comparison with piles directly driven into the ground but higher capacities in comparison with the conventional bored piles.

The use of hydraulic oscillators to drive full-length temporary casings for installing bored piles is getting popular. For constructing the pier foundations of Bee Tan Bridge, 2 m diameter casings were driven 9 to 24 m through the Chingmei Gravel layer in which boulders are as large as 800 mm in diameter, and then further penetrated into the bedrock by 6 to 14 m (Wang, 1992). For the widening project of existing Chungshan Freeway and the construction projects of New Second Freeway, hydraulic oscillators and rotators are being extensively used and the maximum casing length of 70 m is probably the record length in Taiwan. The use of full-length casings is found necessary for maintaining the stability of the holes where soft/loose deposits extend to a great thickness to bearing stratum. Test results indicate that even in residual soils the use of casings is cost effective because that the developed shaft friction of piles is much greater than that installed without casings.

Barrette Foundations

Barrette foundations differ from other types of cast-in-situ reinforced concrete piles in that barrettes are rectangular in shape and are installed by diaphragm walling machines. Although they are far from being popular, barrette foundations have been used in quite a number of cases in recent years for the reasons that (1) they are able to carry huge loads, (2) they can be combined to form sections with different geometry, such as cruciform, T-shape and H-shape to provide better lateral resistance, and (3) they can be conveniently installed by using the diaphragm walling machine already mobilized to the site.

In Taiwan, rectangular barrettes are used in the Taipei Rapid Transit Systems (TRTS) to support multi-storey buildings which will be later constructed directly above MRT entrances and underground stations. The barrettes, 1.2 m wide, 5.4 m (Contract CC277) or 6.6 m (Contract CC278) long, and upto 78 m deep, penetrate 6 m into the bearing stratum. The bases of these barrettes were pressure-grouted to ensure a solid contact between their toes and underlying gravels (Hwang, 1994). The construction of Shin-Kwang Tienmu Building is another example in which barrettes of 1.2 m x 7.4 m with length of 23.5 m were used. The design load of each barrette is 19 MN. In constructing Far East Plaza Building, barrettes of 1.2 m x 3 m were connected to diaphragm walls to a depth of 33 m. The annexed barrettes act as buttress which greatly reduced the wall movements and its associated ground settlement. Barrettes in this case served not only as foundations but also as a precautionary measures to protect adjacent building (Wang, 1994).

Research Studies

In the past years, a few research studies on piling have been conducted in Taiwan. The application of these research results are believed to be very helpful to improve the current practice in Taiwan as well as in Southeast Asia.

Effect of Residual Stress on the Interpretation of Pile Load Tests

A research was carried out in Hsin-Ta Steam Power Plant to study the load distribution behavior of instrumented piles (Yen et al., 1989). Three test pile (TP4, TP5 and TP6) are all close-ended steel pipe piles and of the same size: 36 m in length, 609 mm in outside diameter, and 12 mm in wall thickness. All the test piles were driven with a diesel hammer. Strain gages and tell-tales were installed on each pile, as shown in Fig. 1.

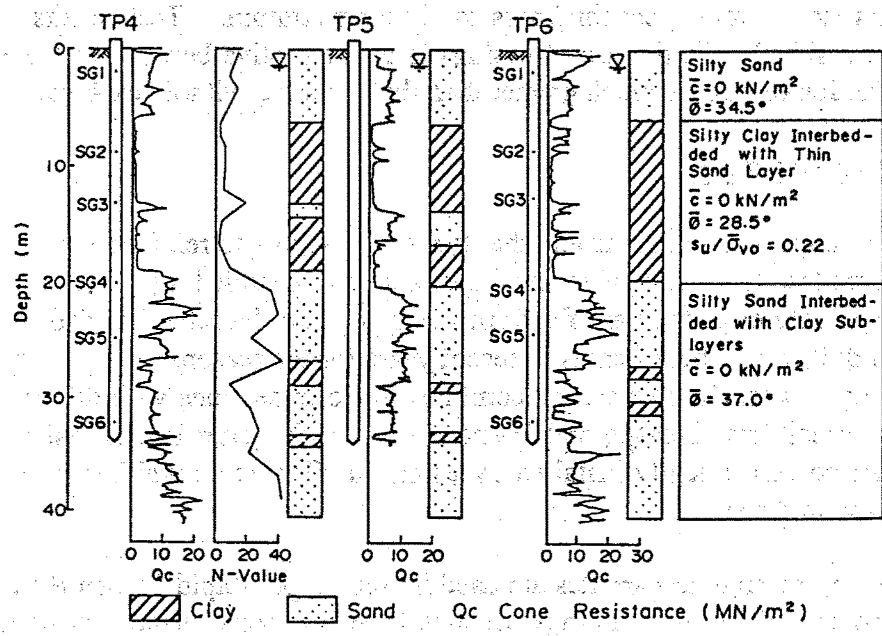

Fig. 1 Subsoil Conditions and Strain Gage Locations of Test Piles (After Yen et al., 1989)

The development of the residual stress after pile driving has long been recognized. The monitored pile forces at TP4 and TP6 immediately after pile driving are presented in Fig. 2. The monitoring results indicate that residual forces indeed locked in the driven piles due to pile driving. The extremely high forces of SG3, SG4, and SG5 at TP4, as well as SG2 and SG4 at TP6 were most likely due to the local buckling or neutral-axis shifting of the instrumented steel pipe piles caused by the severe driving impact.

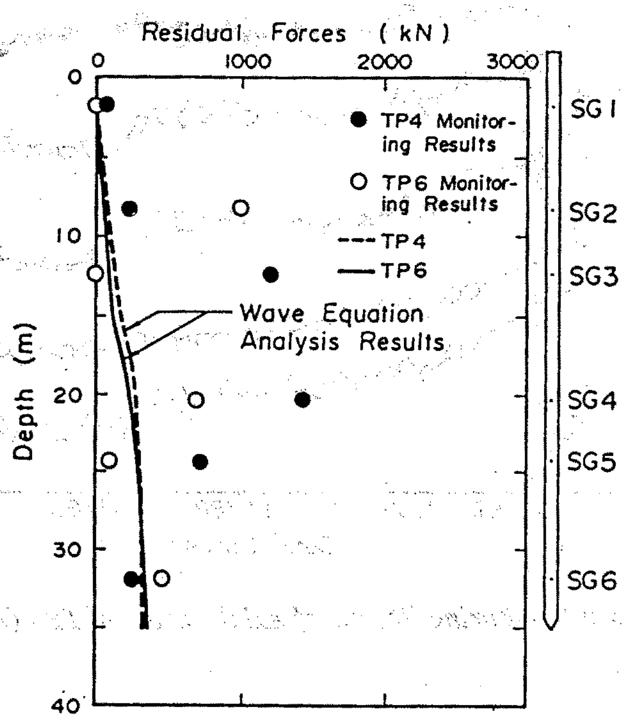

Fig. 2 Monitored and Estimated Residual Forces Due to Pile Driving (After Yen et al., 1987)

Fig. 3 presents the long-term monitoring results of the true axial forces of TP4. They indicate that the axial forces have increased significantly between the period of pile driving and pile load test which was conducted about 25 to 30 days after pile installation. In addition to the effect of the ground subsidence of the entire site, the increase of the axial force is most likely due mainly to the reconciliation of the clay soils, about 13 m thick, caused by pile driving. As indicated in Fig. 3, the maximum increment occurring at SG4 of TP4, located at about 20 m depth, is as high as about 1000 kN.

By referring to the strain gage data obtained prior to driving, the true axial forces of TP4 and TP6 as tested to the maximum load are presented in Fig. 4. However, conventionally used in the analysis is the apparent axial force calculated by considering the gage data prior to pile load test as reference reading. For comparison purposes, apparent axial forces are also shown in Fig. 4. The comparisons between true and apparent axial force show that the interpretation results of the apparent pile axial forces will lead to an apparent point resistance (150 kN) which is lower than the true point resistance (850 kN), and to an apparent skin friction (4000 kN) which is greater than the true skin friction (3300 kN). The lesson learned from this comparison is that the interpretation of pile load test results has to carefully take residual stress into account.

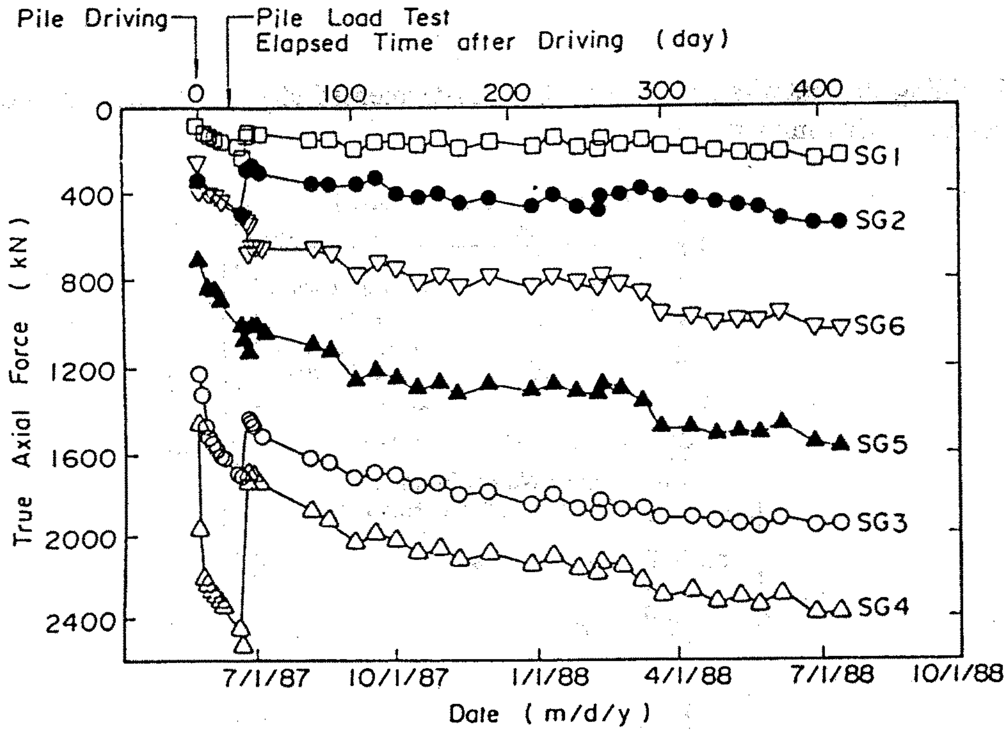

Fig. 3 Long-term Monitoring Results of Axial Forces of TP4 (After Yen et al., 1989)

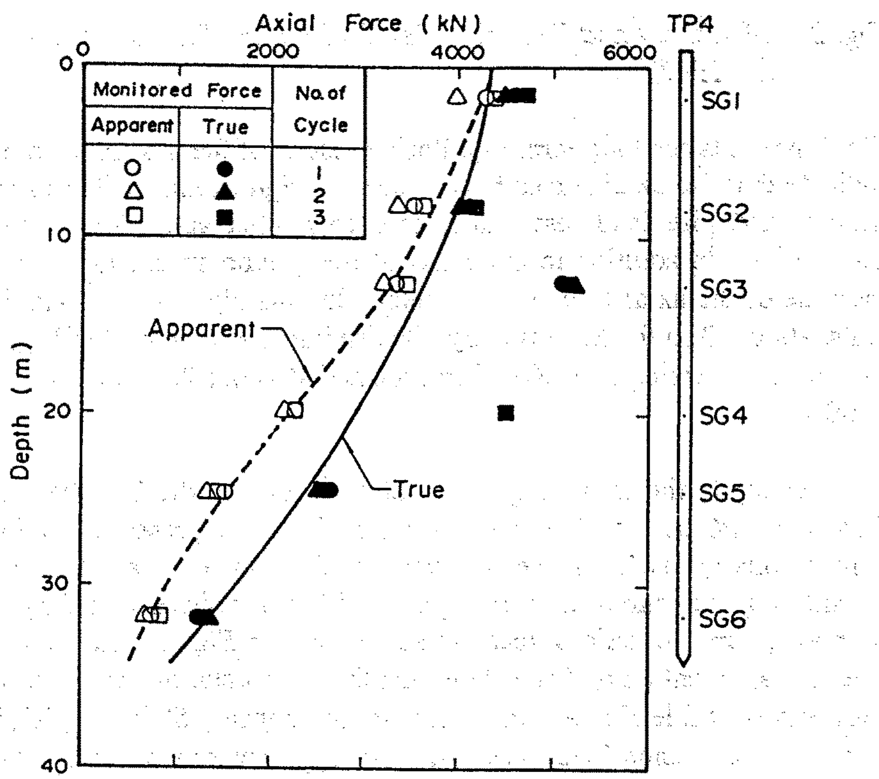

Fig. 4 Axial Forces along TP4 as Tested to Maximum Test Load (After Yen et al., 1989)

Long-term Down-drag Force of Pile in Reclaimed Land

This section follows the discussion of Test Pile TP4 in Hsin-Ta Steam Power Plant. The Plant is constructed on a piece of reclaimed land of 2,000 m by 7.50 m in 1978. All the major structures are supported on piles. Due to the presence of deep seated compressible soil strata, the entire site including the piled structures has been progressively settling. In 1982, the settlement rate has accelerated because of increase of pumping of ground water for fishery farms in areas adjacent to the Plant. Fig. 5 and 6 present the settlement contours of control piles in the period of July 1979 to May 1983 (Woo et al., 1990). Instrumented piles were installed in 1987, and long-term behaviors of these piles were monitored until 1987.

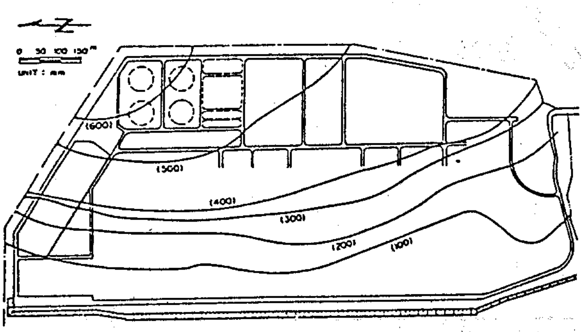

Fig. 5 Settlement contours of the 10 m piles, July 1979 to May 1983. (After Woo et al., 1990)

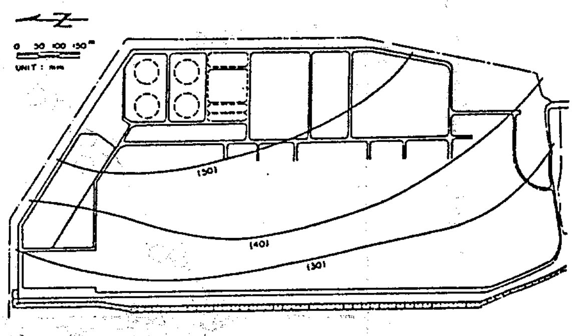

Fig. 6 Settlement contours of the 34 m piles, July 1980 to May 1983. (After Woo et al., 1990)

Fig. 7 presents the variation in axial force of TP4 after pile load test as well as long-term monitoring results of tell-tale and piezometer. Located adjacent to the instrumented pile, the piezometer was installed at a depth of about 25 m. These monitoring results indicate (Yen et al., 1989): (i) After the pile load test, the pile force has increased gradually. In other words, down-drag force on the test pile has developed. This phenomenon is consistent with the occurrence of ground subsidence in the study site at a rate of 1 to 4 mm per month. (ii) The variation in the axial force is closely related to the variation in the piezometric level caused by the groundwater pumping in adjacent areas. The force generally increased with the lowering of the piezometric level, which resulted in the increase of the effective stresses of the soils surrounding the test pile. On the other hand, the pile force decreased slightly, or even remained the same, with the rising of the piezometric level. The rapid response between the increasing axial forces and the lowering of piezometric level is most likely due to the increase in effective overburden pressure which caused the immediate settlement of the sandy soils above pile tip, and the increase of skin friction acting on the pile shaft. (iii) The monitored pile shaft deformation from the tell-tale increased with the rise in pile axial forces. This is consistent with the measurement results of the pile force from strain gages.

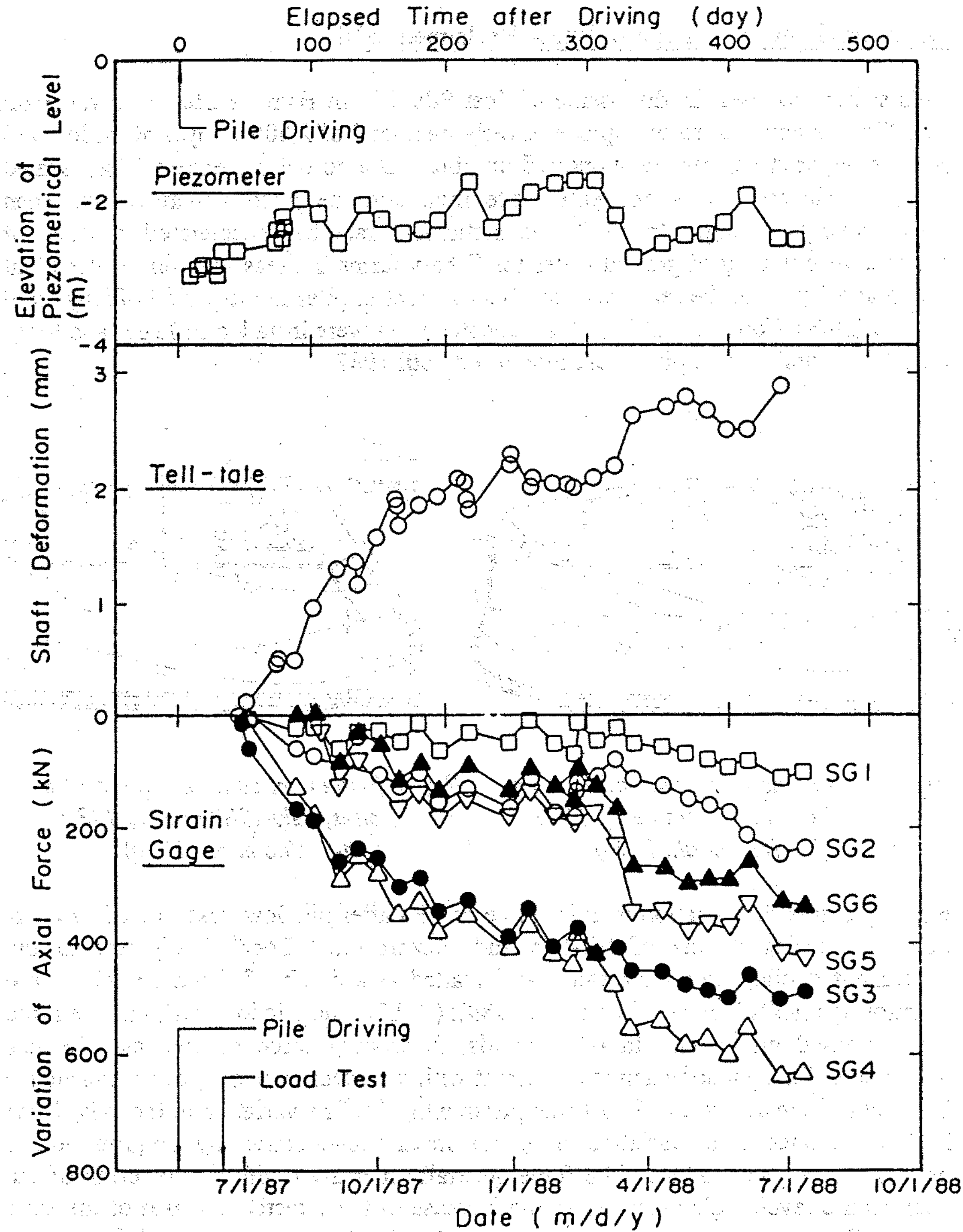

Fig. 7 Long-term Monitoring Results of Instruments at TP4 (After Yen et al., 1989)

The down-drag force occurring after pile load test in TP4 and TP6 are presented in Fig. 8. As indicated in this figure, the maximum down-drag force, approximately 700 kN, occurred at a depth of about 20 m which is approximately 17% of the ultimate compression capacity.

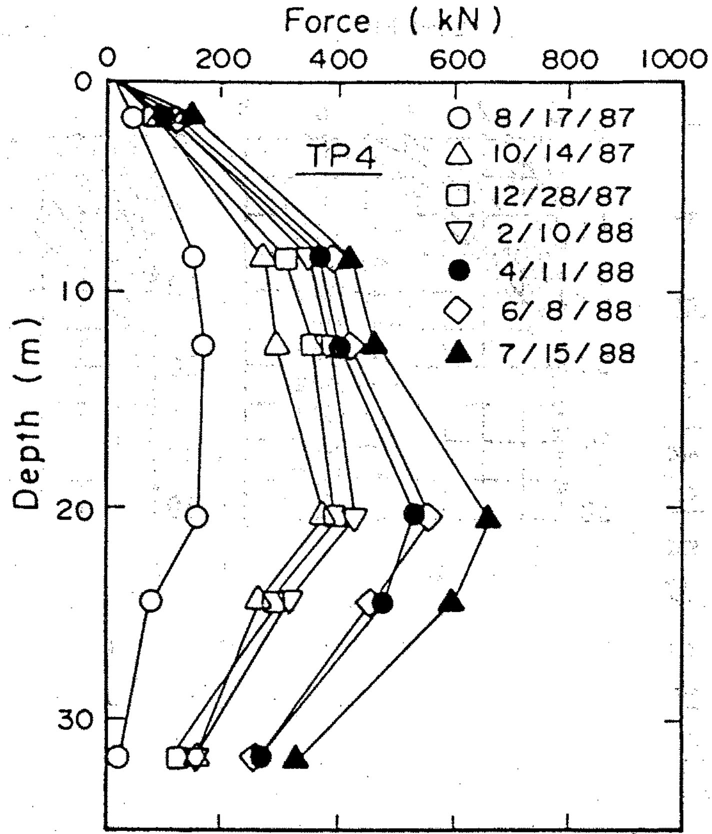

Fig. 8 Down-drag Force Occuring after Pile Load Test (After Yen et al., 1989)

Load Distribution of Group Piles

Group effects of piles are incorporated in designs mainly in a traditional way of considering block failure. A recent study carried out for the Taichung Steam Power Plant indicates that the problem may be more complicated than it appears to be (Duann, et al, 1994). There are three tall chimneys of 250m in height supported on close-ended steel pipe piles of 800 mm in diameter. Preliminary loading tests were performed on 6 piles, 2 for each chimney. For simplicity, only details of pile load tests for Chimney No. 3 TP5 and TP6, are presented herein.

Tests were carried out to a maximum load of 6,660 kN which is twice of the working load of 3,330 kN. Test results for TP5 and TP6 are shown in Fig. 9. It can be noted that the all test loads were entirely taken by shaft friction. However, the long-term monitoring data (Fig. 10) during the construction stage revealed that end bearing accounted 100% of the applied load for TP5 and 30% for TP6. Monitoring data of other test piles indicate similar phenomenon. The end bearing for other piles are 60% (TP1), 80% (TP2), 30% (TP3 and TP4) of the load. This gives rise to a serious concern on the meaningfulness of extrapolating loading tests on single piles to evaluate pile group performance.

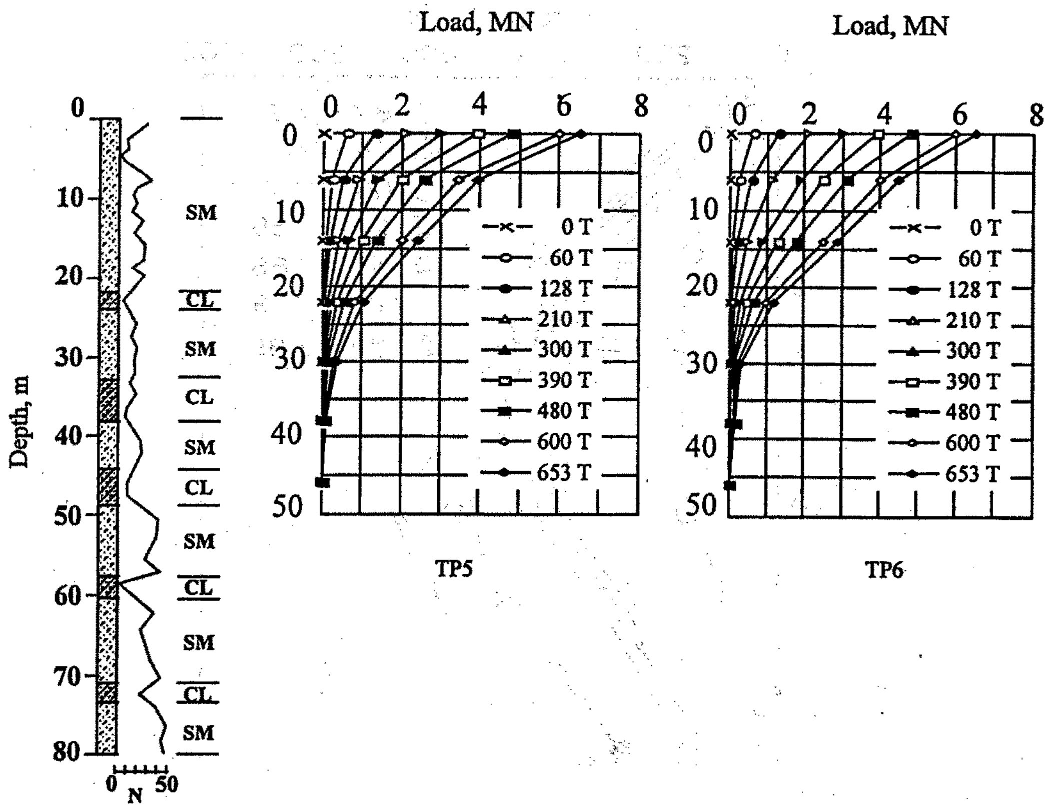

Fig. 9 Results of Preliminary Pile Loading Tests, Taichung Power Plant (After Duann et al., 1994)

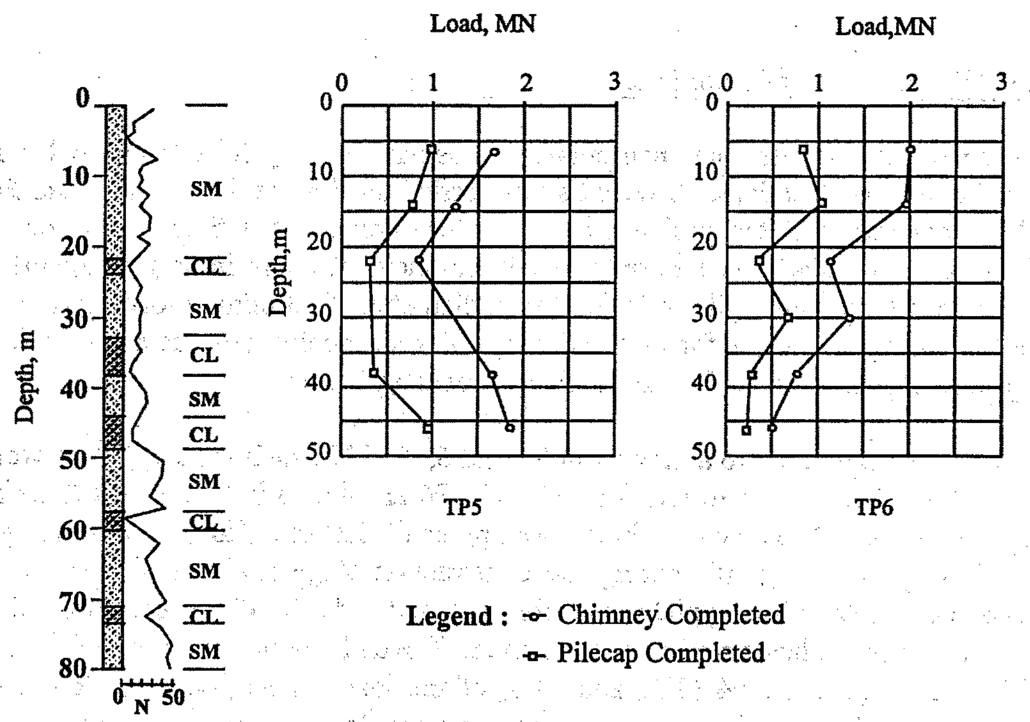

Fig. 10 Results of Long-term Monitoring during Construction, Taichung Power Plant (After Duann et al., 1994)

Effect of Pressure Grouting at Pile Toes

The phenomenon of soft toe of bored pile has been recognized. The use of high pressure base grouting has been generally accepted as an effective measure to improve the pile performance. Requirements for base grouting have been specified in a few public projects in Taiwan. Two pairs of piles were tested in Contract 17 of the Chungshan Freeway Widening Project for determining the effectiveness of grouting. Test piles are 62m and 70m long respectively. Results indicate the improvements of grouted piles is minor. The reason is that piles are too long, and loads are fully taken by shaft friction (Guo, 1993).

A recent study was conducted in the Nankang Depot of TRTS (Moh, 1994). Tests were performed at two locations and at each location two piles were tested. One test pile was base grouted, and the other was not. The test piles are 1.5 m in diameter and 22 m in length. Their toes are embedded in weakly cemented sandstone/shale by only 2 m. Grouting was carried out to a maximum grouting pressures of 22 kg/cm^2 and 30 kg/cm^2, at Site 1 and 2, respectively, and the intakes of grout were 380 liters and 500 liters.

The results are shown in Figs. 11 and 12 for Site 1 and Site 2, respectively. Settlements were reduced from 160 mm to 80 mm at a maximum test load of 19.8 MN as a result of base grouting. At the working load of 6.6 MN, the settlements were reduced from 80 mm to less than 10 mm. Based on these findings, all the piles, more than 2,000 in number, were grouted to ensure that the settlement criteria are met.

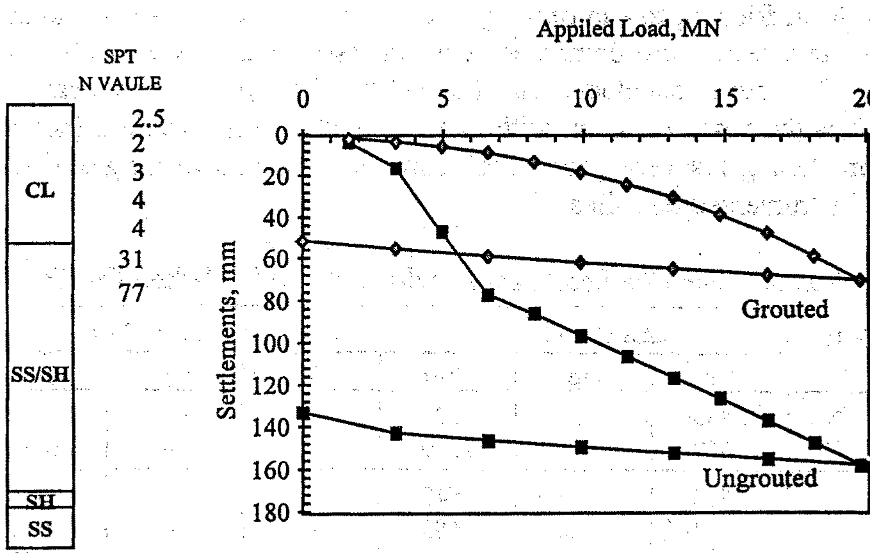

Fig. 11 Test Results at Site 1, TRTS Nankang Depot (After Moh, 1994)

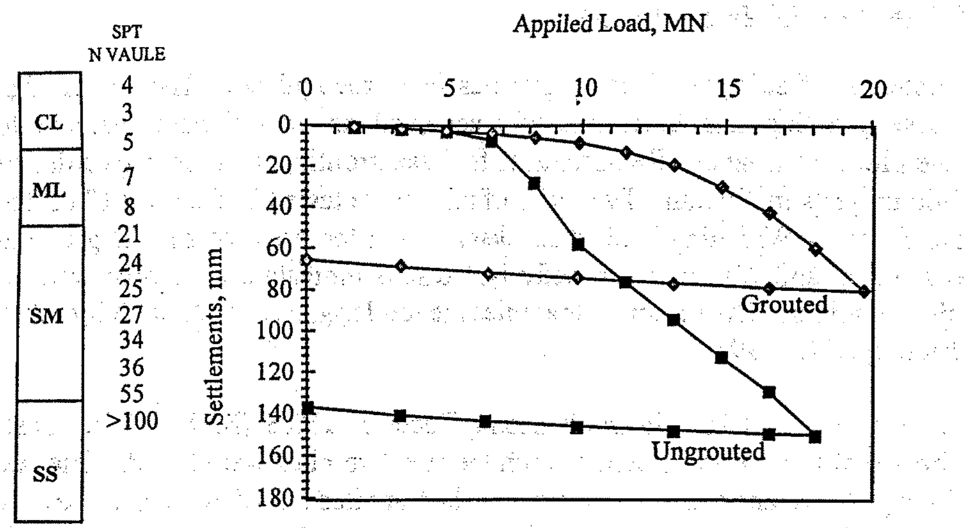

Fig. 12 Test Results at Site 2, TRTS Nankang Depot (After Moh, 1994)

Application of CPT in Pile Design

Cone Penetration Test (CPT) have been used during the site investigations of two coastal sites in southern and central Taiwan. Both sites are underlain by recent deposits of interbddded silty sand/sandy silt and silty clay/clayey silt layers. Figs. 13 and 14 shows typical CPT results of central site and southern site, respectively. The soil deposits are very heterogeneous and contain many thin lenses. As shown in Figs. 13 and 14, it is not easy to obtain a simplified profile and to assign reasonable soil parameters for each layer. Therefore the conventional methods cannot be easily used to estimate the pile capacity of these two sites. A study was conducted to evaluate various pile design methods which are directly relate the CPT measurements, i.e. tip resistance and/or local friction, to end bearing and shaft friction of piles (Duann et al., 1991). Pile load test results are compared with the estimated pile capacity of 14 design methods. The study concludes that the LCPC (Bastamante and Gianeselli, 1982) method gives the best agreement with pile load test results. Table 1 indicates that the LCPC method gives very good predictions on both end bearing and shaft resistance of the instrumented test piles.

Table 1 Comparison between Pile Load Test Results and LCPC Method Predictions

Site	Test Pile		LCPC Method			Pile Load Test		
			Qs	Qp	Qult	Qs	Qp	Qult
Central Site	PC3	*	865	120	985	—	—	1200
	SP2	**	857	252	1109	—	—	1040
South Site	TP1	*	502	37	540	—	—	514
	TP2	*	562	128	685	—	—	850
	TP3	*	495	94	589	—	—	563
	TP4	**	329	124	453	330	93	423
	TP6	**	371	146	517	330	203	533

* PC Pile ** Steel pipe pile

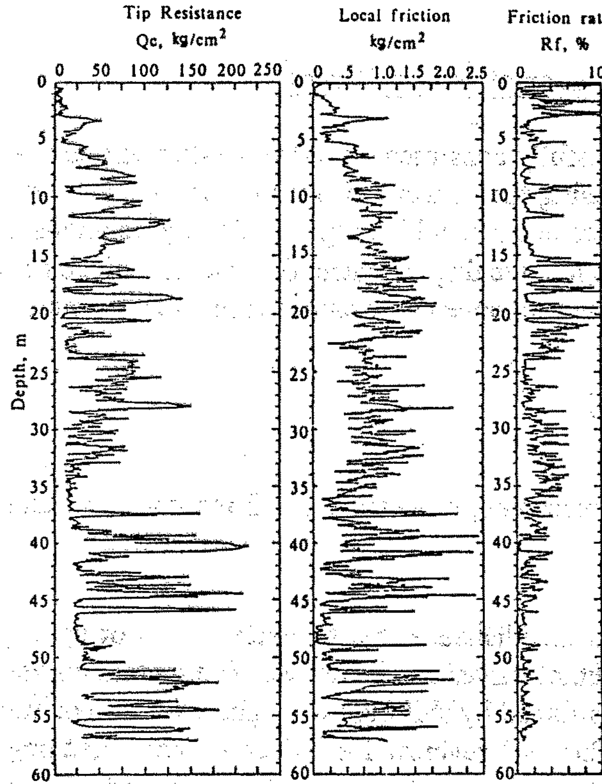

Fig. 13 Typical CPT Results at the Study Site in Central Taiwan (After Duann et al, 1991)

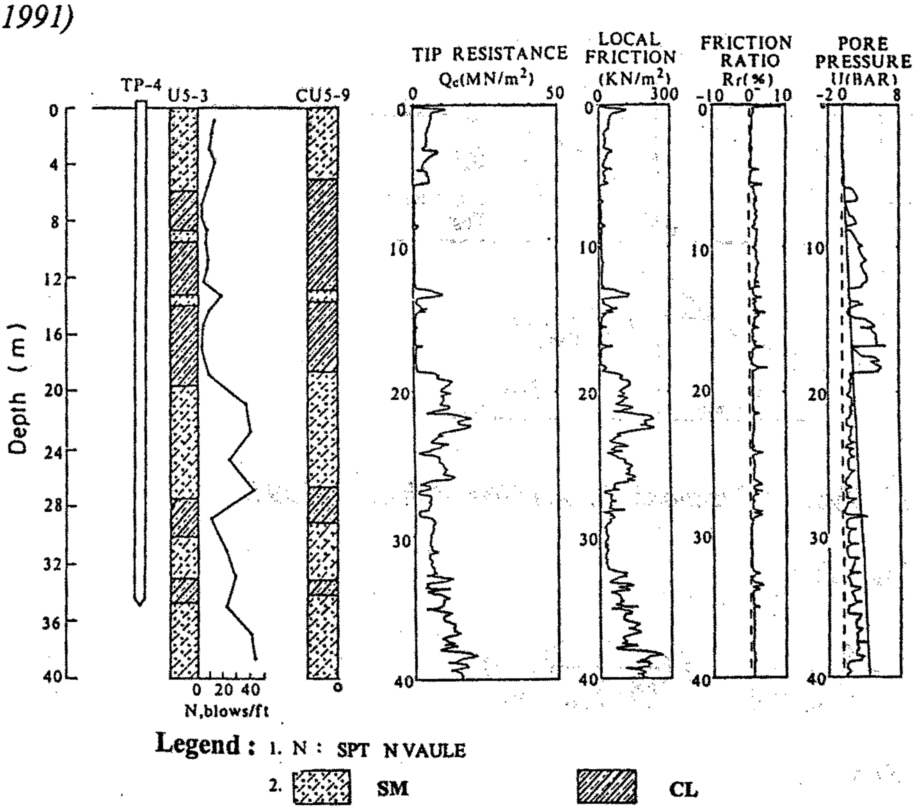

Fig. 14 Typical CPT Results at the Study Site in Southern Taiwan (After Duann et al., 1991)

Derivation and Application of Mutant Curves

A recent study successfully constructed the load-settlement curves for unloading and reloading cycles by using the concept of mutant curves (Moh, et al., 1995). Fig. 15 shows a typical backbone curve which representing the relationship between the soil resistance, q, and the relative displacement, δ, for a pile subjected to tension load and compressive load. The backbone curve can be expressed in a normalized form:

$$\frac{q}{q_{\max}} = f\left(\frac{\delta}{\delta_{\max}}\right) \tag{1}$$

where $\delta_{\max}$ is the displacement at which the soil resistance reaches its ultimate value of $q_{\max}$.

Once the backbone is established, either by loading tests or by empirical correlations, the corresponding mutant curves can be draws. The mutant curves for unloading and reloading can be constructed by shifting the origin to a new position corresponding to the position before the load reversal for unloading and reloading, respectively (Fig. 16). In other words, there is a nonlinear mapping the function from the q-δ system to q'-δ' system as follows:

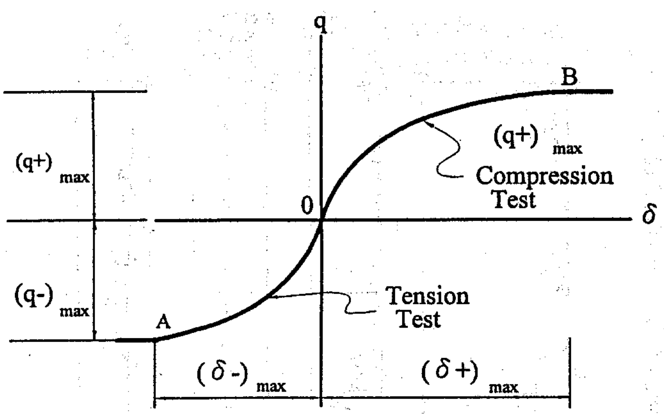

Fig. 15 Typical Backbone Curve (After Moh et al., 1995)

For Unloading:

$$\frac{q+q_1}{(q-)_{\max}+q_1} = f\left(\frac{\delta+\delta_1}{(\delta-)_{\max}+\delta_1}\right) \tag{2}$$

For Reloading:

$$\frac{q-q_2}{(q+)_{\max}-q_2} = f\left(\frac{\delta-\delta_2}{(\delta+)_{\max}-\delta_2}\right) \tag{3}$$

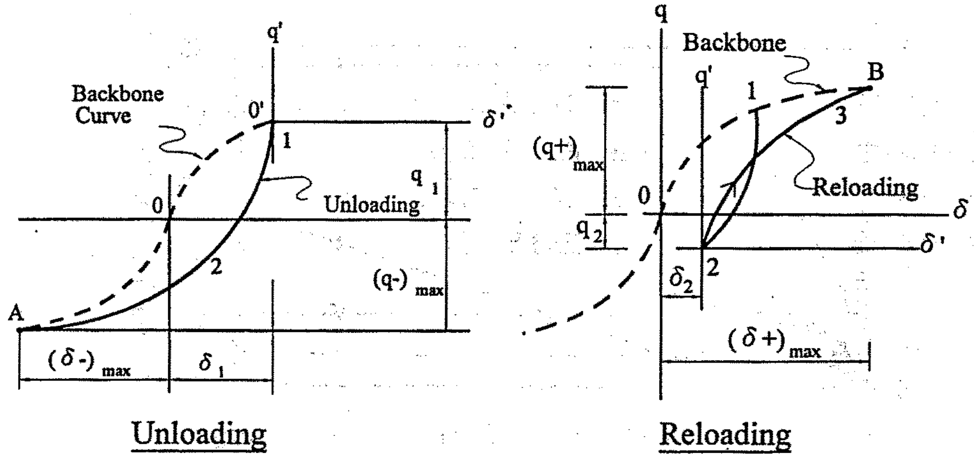

Fig. 16 Typical Mutant Curves (After Moh et al., 1995)

The results of a loading test shown in Fig. 17 were back analyzed using the backbone curves shown in Fig. 18. The test pile is a 1m diameter bored pile embedded in shale and sandstone by 3.3 m. It was loaded to a maximum load of 17 MN in 2 cycles. The computed load-settlement relationship at the pile top are compared with that obtained in the test in Fig. 19. The predictions are in excellent agreement with the measurements.

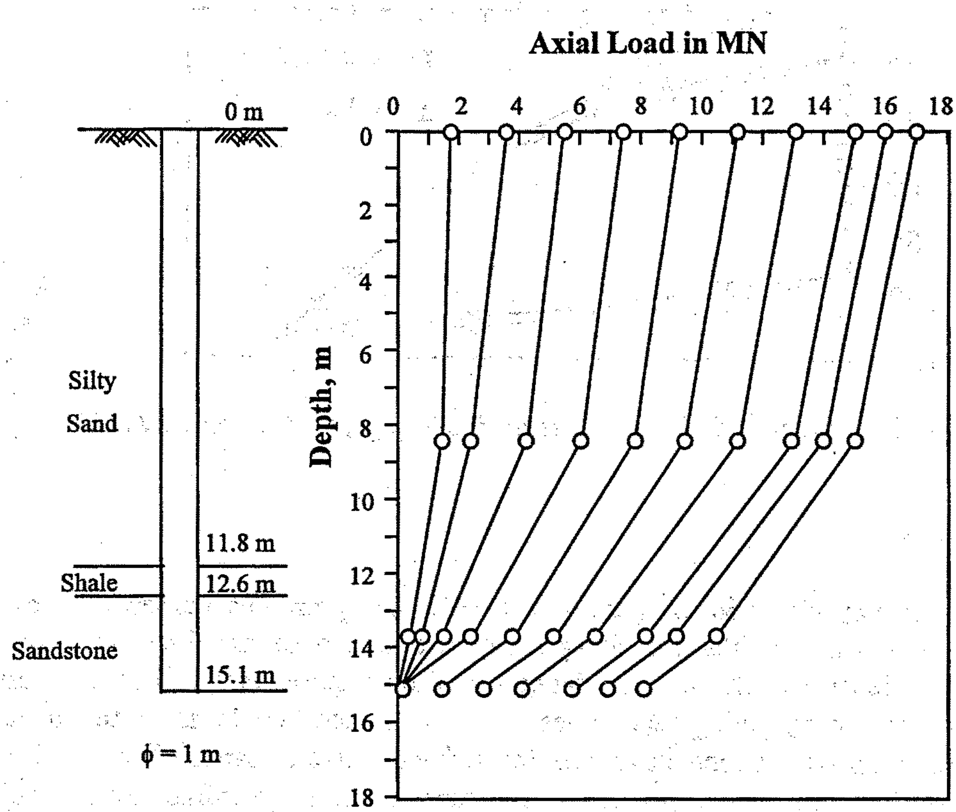

Fig. 17 Ground Conditions and Axial Loads in Test Pile TP3, TRTS Nankang Depot (After Moh et al., 1995)

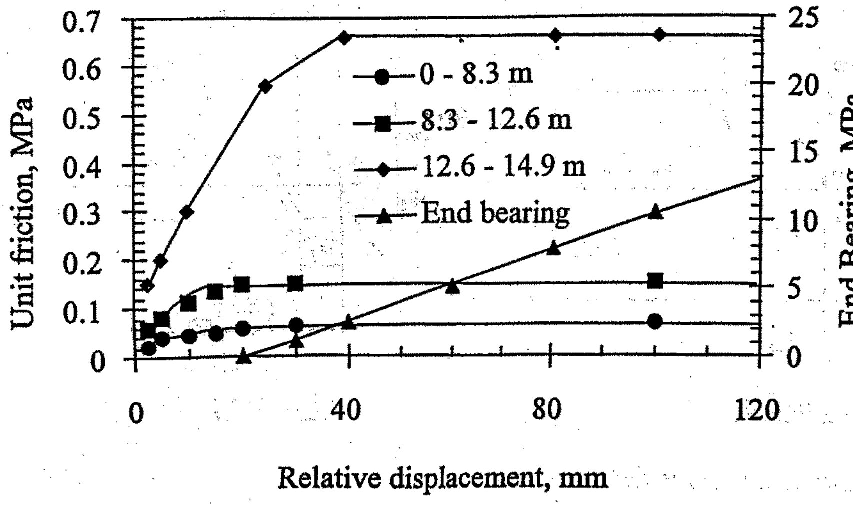

Fig. 18 The t-z Curves for TP3 (After Moh et al., 1995)

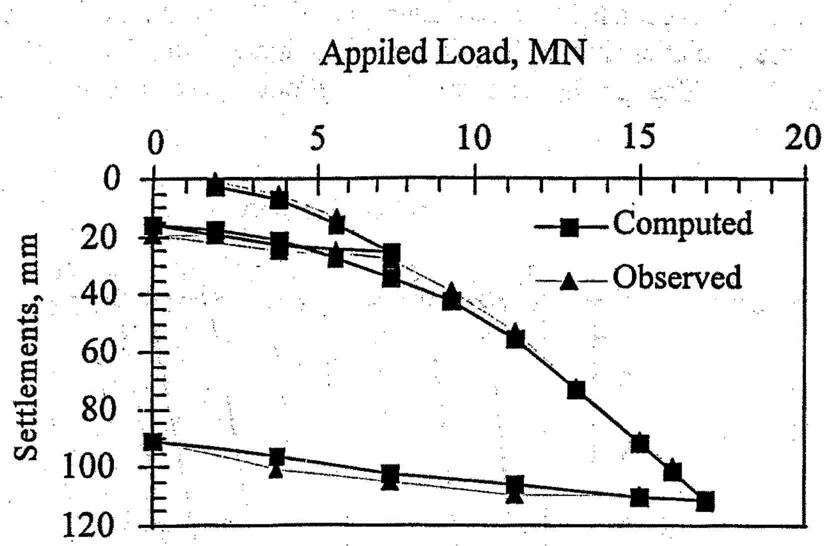

Fig. 19 The Load-Settlement Curves at Pile Top (After Moh et al., 1995)

Summary

The economy boom in the past two decades has promoted numerous construction projects in Taiwan. Various piling techniques have been introduced to Taiwan from abroad. Because of the very special construction requirements and ground conditions in Taiwan, many piling techniques have been modified to meet the local needs. Significant improvements have been through extensive research efforts, such as those discussed in this paper. In the future, more large scale infrastructure projects in Taiwan will demand more advanced piling technology. At the same time, environmental issues are expected to be another major concern for pile construction.

Acknowledgments

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