CURRENT DEEP FOUNDATION PRACTICE IN TAIWAN AND SOUTHEAST ASIA

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Current Deep Foundation Practice in Taiwan and Southeast Asia

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Abstract:

The current practice of constructing deep foundations, including driven piles, drilled shafts, large diameter drilled caissons, barrette foundations and minipiles, in Southeast Asia is reviewed. Research studies which have been conducted in this region on aspects of negative skin friction, pile group effects, pressure grouting at pile toes and the use of backbone t-z curves and their mutants for unloading and reloading for evaluating the performance of piles are briefly discussed.

Introduction

This paper summarizes current practice of constructing deep foundations in Taiwan, Hong Kong, Thailand, Malaysia and Singapore, covering a total land areas of about 1 million square kilometers. With a population of more than 100 millions, this region has in the past two decades become the most rapidly developing region in the world. Accompanying the remarkable economic growth, numerous prestigious buildings were constructed and many large scale infrastructures were completed. Many of these major projects, which rank among the world records, involved significant piling works.

Due to the geographic nature, all these countries have long coastal lines and most economic developments spread along the coasts. Therefore the most important landform in the region is the low flat deltaic plains which count for an appreciable portion of the usable land. Soft soils of sedimentary origin become one of the most commonly encountered ground conditions in constructions. However, as plains become too congested, hilly lands become people's choices. With the convenience of modern transportation, developments even stretch into mountainous area where people can stay away from noise and enjoy their lives. The ground conditions in

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mountainous areas are quite different from the ground conditions in plains and are frequently unsuitable for piling works. Special techniques have been developed to suit local environments, for example, large diameter hand-dug caissons are widely used to deal with the unique geological conditions in Hong Kong. Malaysia is very notable for karstic limestone formations in which large cavities are present (Ting, et al, 1993). Underpinning of bored piles offers a unique and innovative solution.

Types of Deep Foundations Commonly Used

The types of deep foundations commonly adopted in this region are not different from those adopted elsewhere. They include driven piles, drilled shafts, drilled caissons, barrettes, minipiles, etc.

Driven Piles

Steel pipe pile, steel H-pile and prestressed concrete pile are the three types of deep foundations most commonly used in this region. They all are competitive with preference different from place to place because of local environments, availability and costs.

In Taiwan, driven piles are seldom used in urban areas because of the concerns on noise and vibration. They are used primarily for highways and industrial facilities in rural areas, coastal and reclaimed sites. One of the most notable recent piling projects is the construction of Taichung Steam Power Plant where the site was reclaimed by hydraulic sandfill about 6m in thickness. Closed-ended steel pipe piles of 0.8m in diameter were driven to a maximum depth of 58m 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 closed-ended piles. Therefore, recently prestressed concrete piles (typically 600mm in diameter) are more 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).

In Hong Kong, steel H-piles and spun concrete piles are usually adopted for foundations on land while steel pipe piles are often used for marine structures such as wharves and jetties. Piles are commonly driven by diesel hammers, which are becoming less and less popular for environmental reasons. The use of hydraulic hammers is being promoted by the Hong Kong Government. For H-piles, the most popular size is Grade 55, 180 kg/m piles with an allowable axial load of about 30 MN. Steel pipe piles are generally driven open-ended, although sometimes closed-ended piles are adopted to suit special occasions. To reduce long term maintenance problems in a marine environment, piles are frequently infilled with concrete to the seabed level. Spun piles are cast in factories where concrete is compacted by spinning and autoclave curing is carried out to produce a characteristics strength of 78.5 MPa. Tendons are pretensioned so the shell is prestressed and is able to resist hard driving. The most popular size is 500mm O.D piles with an allowable load of 2.3 MN.

Steel H-piles, square concrete piles and spun concrete piles are the three most commonly used types of piles in Thailand. The maximum penetration is approximately 26m for H-piles and square concrete piles (maximum size: 400 x 400mm). In Bangkok, spun piles (maximum diameter: 1m) can be driven through the First Sand Layer by hydraulic hammers to reach a depth of about 30m.

In Malaysia, prestressed cylindrical concrete piles dominate the scene because of their cost advantages. The common sizes are 300mm to 600mm. Steel pipe piles and H-piles are seldom used because of the relatively high cost of steel. Prestressed spun hollow concrete piles of 350mm diameter are also popular. The Penang Bridge, connecting Penang Island with the mainland of Peninsular Malaysia, is supported on 500mm and 1,000mm diameter spun piles with depths of embedment up to 60m (Chin, 1986). The Bridge, opened to traffic in 1985, is one of the world's longest bridges. The total length of the linkage is 13.5 km of which 8.4 km is over a water channel. The main span of the bridge is a cable-stayed concrete girder bridge.

Prestressed concrete pile is the most commonly used type of pile in Singapore. To a lesser extent, steel H-piles and spun concrete piles are also popular. One of the major piling projects is the Marina Centre Development in Singapore, a total of 9,349 Raymond piles were installed to support three hotels varying from 22 to 37 stories in height (Moh and Woo, 1984).

Drilled Shafts (Bored Piles)

Drilled shafts are almost always referred to as bored piles in this region and are commonly used to support heavy loads from tall buildings, bridge piers, towers, etc. They 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.

In Taiwan, modern tall buildings in cities are almost exclusively supported on bored piles which are mostly bored by using the reverse circulation method, followed by the auger-and-bucket method in popularity. 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 2.4m (for China Trust Financial Building). Piles with diameters in the range between 1.6 m and 2.0 m are most frequently used. In order to gain more bearing from underlying gravels and boulders, bored piles of 2m diameter used to support the 50-story Shin-Kwang Building, the tallest building in Taipei, were underreamed to a maximum diameter of 3.3m. Chung-Yang Bridge, a cable-stayed bridge, is supported on 2m diameter bored piles, installed to a maximum depth of 94m which probably is the record length in Taiwan. Sometimes, instead casting the piles in-situ, precast concrete piles can be lowered into pre-drilled holes infilled with soil-cement mixture. This eliminates the vibration and noise associated with driven piles and, meanwhile, avoid the many problems associated with installation of conventional bored piles, such as "soft toe", necking, etc. A total of 309 prestressed concrete piles, with a diameter of 450mm and a length of 15m, 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, 2m diameter casings were driven 9 to 24m through the Chingmei Gravels, in which boulders as large as 800mm in diameter are present, and penetrated into the bedrock by 6 to 14m (Wang, 1992). For the Widening of Chungshan Freeway Project and the Second Freeway Project, hydraulic oscillators and rotators are being extensively used and the maximum casing length of 70m is probably a record in Taiwan. The use of full-length casings is found necessary for maintaining the stability of the bores where soft/loose deposits extend to a great thickness and/or gravels are present. Test results indicate that even in residual soils the use of casings is cost effective because of the much greater shaft frictions of piles obtained in comparison with those installed by using the reverse circulation method.

In Hong Kong, bored piles commonly range from 1m to 2.5m in diameter, although in special circumstances piles up to 3.2 meter in diameter have been constructed. For the construction of Western Harbor Crossing - Sai Ying Pun Interchange, 2.5m diameter bored piles were sunk to a depth of 80m, which is the record depth in Hong Kong. The method of excavation depends on the ground conditions and availability of plant. Typically, a pile will be excavated through soil under water using a grab with temporary steel casing to support the open bore. Obstructions such as boulders are penetrated either by heavy chisel or by using a reverse circulation drill. The temporary steel casings are installed and removed either by vibrator or oscillator. An alternative to the temporary casing is to excavate the pile under bentonite if the ground is sufficiently competent.

In Thailand, bored piles are the most popular for highrise buildings. In the recent piling practice in Bangkok, almost all the bored piles are drilled by using "the auger and bucket method". The upper portion of the bore in soft clay is protected by using casing, while the lower portion is stabilized by bentonite slurry. Piles usually range from 0.5 to 1.5m in diameter with the pile tips embedded in the Second-Sand

Layer at depths of 50 to 60m. The design load can be as much as 10 MN. A maximum total load of 25 MN has been reported (Balasubramanium, 1994). The world's longest cable-stayed bridge at the Chao Phraya River Crossing in Bangkok is supported on 2m diameter bored piles extending to depths varying from 30 to 70m below the sea level. The bridge has a total length of 782m composed of a 450m main span and two 166m back spans.

In Malaysia, bored piles, ranging from 450mm to 1,200mm in diameter, are often employed in city areas where noise control is implemented. The largest bored pile, up to 1.83m in diameter was used in the Core Project (Government Office Complex) in Shah Alam, near Kuala Lumpur. The deepest bored piles, up to 50m, were used in the Hotel Istana and the Mall, in Kuala Lumpur. Malaysia is notable for the presence of huge cavities in the limestone formation. Small cavities are usually grouted. In some cases, bored piles are underpinned by micropiles spanning over cavities. For example, the 30-storey Pan Pacific Hotel in Kuala Lumpur is partly supported on barrettes and partly on bored piles. Eleven out of the 73 bored piles, 1.2m in diameter, were underpinned. They were terminated at a short distance into the limestone formation, or even above the limestone formation. The toe of each pile were underpinned by four micropiles with a 156mm internal diameter. Permanent casings of 4.5mm in wall thickness were are cased 3m above and 3m below any cavities (Mitchell, 1985).

Bored piles compete closely with prestressed concrete piles in Singapore. A total of 2,599 piles, up to 1.6m in diameter, were installed in 10 months in one of the largest commercial development projects, Suntec City Project (Chan and Lee, 1990). The site conditions were not favorable for any type of foundation. It is a reclaimed land with very soft marine clay varying considerably in thickness. The piles are embedded in the underlying Old Alluvium and the depth of piling varies from 19m to 61.9m below ground surface.

Drilled Caissons

They are usually excavated in the dry by digging circular holes and casting concrete lining in approximately 1 meter intervals in depth. Smaller caissons (as small as 0.6m in diameter) are excavated by hand while small excavators may be used at the bottom of larger caissons. Careful consideration must be given to groundwater control during caisson construction. This type of caisson can also be used as a retaining structure (e.g. Moh, Chiang and Ou, 1979).

In Taiwan, large drilled caissons have not been used. Small diameter (less than 1.5m in diameter) hand-dug caissons were used in developments on slopes as retaining structures.

In Hong Kong, hand-dug caissons, upto 70m in length, are very popular. The 78-storey Central Plaza Building, the tallest in Asia, the fourth tallest in the world and the world's tallest concrete structure, is founded on 28 hand-dug caissons, which vary from 5 to 7.5m in diameter and are embedded in unweathered granite by 30m (Construction & Contract News, 1990, 1991). Reinforced concrete liners were cast as excavation proceeded. The 70-storey Bank of China Building, the fifth tallest building in the world, is supported on only four hang-dug caissons of which the largest is 9m in diameter belled out to 10.5m (Barcham & Gillespie, 1988). These caissons are 30m in length. The design load is 380 MN increasing to 510 MN under windload. Diaphragm walls of 1m in thickness were installed prior to excavation to form liners and to control the ground water during excavation. The foundations for the 66-storey Gilman Plaza, now under construction, employ hand-dug caissons 26m in diameter and 40m in depth with diaphragm walling as the liner.

The 50-storey DBS Building is probably the first application of large diameter caissons in Singapore. It was the tallest building in Singapore upon its completion in the mid-70's, and once held the world record of the largest caissons (6.8m in diameter) in the Guinness Book (Stephens, 1976). The tower is supported on 4 caissons, carrying a load of 183 MN each. The deepest one is 64m in depth (Ramaswamy, 1979). The 62-storey OUB Centre, the current tallest building in Singapore and the tenth tallest building in the world, is 280m in height and is supported on 7 caissons founded on bedrock at a depth of about 100m below the ground level (Kurzeme & Rush, 1985). The caissons have shaft diameters of 5 and 6m, belled out to 6 to 9m, respectively. They were designed as end-bearing piles founded on sandstone bedrock in the Jurong formation underlying the Boulder Clay. Just a block away, the 280m tall tower block for the United Overseas Building Plaza is supported on 12 caissons with diameters of 4.7m, 6.2m and 6.8m, and a maximum length of 60m (Broms and Han, 1991). They are designed as friction piles and gain their resistance from the Boulder Clay. The maximum depth of the caissons in the Boulder Clay is 43m. The excavation for the caissons in the soft marine clay was supported by 0.8m thick diaphragm walls which extended about 2m into the underlying stiff residual soils. Circular reinforced concrete segments of 1.5 to 2m in depth were used as liners in Boulder Clay. For confirming the adhesion between these segments and the Boulder clay, 15 jacking tests were carried out in the bores by jacking against neighboring segments. The largest caissons are 8m in diameter and were sunk to a depth of 50m for supporting the Treasury Building. They are embedded in sandstone/mudstone of the Jurong formation.

Hand-dug caissons were recently used for multi-storey buildings in very steep mountain terrain in Penang and Genting Highland of Malaysia. In places where transportation is difficult and labors are inexpensive, the use of hand-dug caissons appears to be an obvious option.

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 using 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 to be built on MRT station and entrances. The barrettes, 1.2m wide, 5.4m (Contract CC277) or 6.6m (Contract CC278) long and upto 78m deep, penetrated into the bearing stratum by 6m. The bases of these barrettes were pressure-grouted for ensure a solid contact between the underlying gravels and the toes. The construction of Shin-Kwang Tienmu Building is another example in which barrettes of 1.2m x 7.4m with a design load of 19 MN were used. They are 23.5m in length. In constructing Far East Plaza Building, barrettes of 1.2m x 3m were connected to diaphragm walls to a depth of 33m to form buttresses for reducing the wall movements, thus ground settlements as a precautionary measures to protect adjacent building.

In Malaysia, the 30-storey Kuala Lumpur Pan Pacific Hotel, is partly supported on rectangular barrettes, 0.6 x 2.7m in size and up to 86m in depth (Mitchell, 1985). It was necessary to perform contact grouting and cavity grouting underneath these barrettes because of the presence of limestone cavities. Barrettes are also used to support the 88-storey Petronas Twin Towers, now under construction, in the Kuala Lumpur City Centre Project. It is claimed that these Twin Towers with a height of 450m will be the tallest buildings in the world, surpassing the Sears Towers, the current record holder, by 7m.

In Hong Kong, the most common sizes of barrette are 2.8m long by 1.0 or 1.2m wide. They are excavated under bentonite using a clamshell and obstructions are broken up using heavy chisels. They have proved to be particularly cost-effective as foundations for highway structures.

Minipiles

Minipiles are not capable of supporting heavy loads. They are often used for sites with limited headroom or difficult access. The are also highly suitable where there are numerous obstructions such as boulders or concrete in the ground. They generally have diameters of between 100mm and 250mm and load carrying capacities up to 1,400 kN. In Singapore, minipiles were used to underpin the Convent of Holy Infant Jesus as a precautionary protection measures before the passing of the twin tunnels of the Mass Transit System (Todo, Hwang and Hulme, 1992). In Penang, Malaysia, City Bank Building was underpinned by minipiles to arrest uneven settlements.

In Malaysia, minipiles in shallow karst limestone formations has gained widespread acceptance. The piles range in diameter from 250mm to 300mm with working loads upto 1.5 MN.

Tests on Piles

Loading tests are routinely carried out for confirming the design capacities of piles. For large projects, tests are carried out on 1, 2, or 3 the most, piles to a maximum load of 2.5 times to 3 times of working loads. Ultimate load tests to failure, however, are relatively infrequent. Test are usually carried out in a constant-load mode (stage loading), rather than the constant-rate mode. Loading tests are also routinely carried out on 10 to 50% of working piles. Furthermore, in some projects, particularly those for public works, non-destructive testing (sonic, seismic and vibration) is conducted on all the piles to check their integrity. If defects are detected, coring is then carried out for confirmation.

Up to the present, the maximum test load is 24 MN in Taiwan (on a 1.2m x 6.6m barrette of Contract CC278 of TRTS). In Hong Kong, a maximum load of 25 MN was tested on a 0.6m x 2.8m barrette. In Malaysia, a 1.2m diameter bored pile of Kuala Lumpur City Centre Project was tested to 30 MN and test on a barrette is planned to go up to about 32 MN. In Singapore, the maximum test load is 23 MN on a 1.5m diameter bored pile for a highway interchange project.

Recently, a number of tests have been carried out using the "Osterberg Cell" (Osterberg, 1989) in Hong Kong. The use of such cells has not been reported elsewhere in the region.

Test results are judged on a pass-or-no-pass basis. Extrapolation of results for the ultimate capacity is seldom performed as the piling contract has been let, the tests are performed by the awarded piling contractor and the only thing he is interested is to confirm the adequacy of the design load.

Extrapolation of test results for estimating the ultimate capacities of piles is usually done by using the Davisson's (Davisson, 1972), Van Der Veen's (Van Der Veen, 1953), Mazurkiewicz's (Mazurkiewicz, 1972), Butler and Hoy's (Butler and Hoy, 1977), Fuller & Hoy's (Fuller and Hoy, 1970), and Chin's methods (Chin, 1970). While the Chin's method appear to be the most popular in Malaysia, Davisson's method appears to be most widely used elsewhere. Basically, all these methods are more appropriate for friction piles than end-bearing piles. Therefore, the degree of success really depend on the sharing of loads between shaft friction and end bearing which sometimes totally out of phase. If end bearing comes into play only at the last stage when the full shaft friction has nearly mobilized, there is no possibility for any of these method to work.

The use of t-z curves for back analyses of ultimate bearing capacities of piles (Coyle and Reese, 1966) so far is still quite limited. This is by far a superior method because it takes friction and end-bearing separately into consideration. However, unless instruments are installed and strains and/or displacements are measured at, say, 3 to 4 levels, t-z curves can not be uniquely determined from back analyses.

The use of pile-driving-analyzer (PDA), in lieu of static loading tests, is not popular in this region yet although the use is increasing. Dynamic testing has been conducted on several large scale piling works. For example, tests were carried out on 80 bored piles in the Suntec City Project using a hammer weighing 250 kN.

The use of dynamic formulas for estimating bearing capacities is fading away and is discouraged by codes in many countries. Where it is used, the Hiley' formula is probably the one most commonly followed.

Codes of Practice

In Taiwan, design of pile foundation follows "Foundation Design Code" which is based on Building Regulations issued by the Ministry of Interior. There are no national standards nor code of practice specifically on piling works. Government agencies responsible for major public works have their own design manuals and standard technical specifications.

In Thailand, design and production of precast piles are governed by "Thai Industrial Standards". However, no standards are available for the design and production of bored piles. Only in Bangkok, allowable settlements of test piles and factor of safety are mentioned in Regulations on Construction.

In Malaysia, a national standard exists but practice is largely based on British Code of Practice (BS8004: Foundations). Construction works are regulated by the Engineers Act, Uniform Building Bye-Laws, Factories and Machinery Act and the Environmental Act. There are no specific laws for foundations. Singapore has its own code, CP4, which is under revision and the new version is expected to be issued by the end of 1995.

In Hong Kong, private sector projects are controlled by laws of Hong Kong entitled "The Building (Construction) Regulations (BCR)" which are administrated by the Buildings Department of the Hong Kong Government. All deep foundation designs are submitted to the Buildings Department who check that they comply with the relevant laws, regulations, codes and practice notes, all of which are available to local practitioners. Construction is not permitted to commence till consent to do so is granted by the Buildings Department. Public sector projects fall outside the Building Regulations. They are controlled by the individual government departments which are responsible for the works. The revised BCR published in 1990 permits, for the first time, the use of rational design methods (rather than conservative "rules") for foundations. A Geoguide on Pile Design & Construction is under preparation by the Geotechnical Engineering Office aiming at guiding the profession to good practice.

Environmental Regulations

Environmental concerns have become a major issue in piling practice in this region. Considering the noise and vibration caused by pile driving, the use of driven piles is discouraged, or even prohibited, in cities. Another problem associated with diesel hammers is the air pollution. Currently, where the use of driven piles is not banned, the use of hydraulic hammers is being promoted.

The major environmental problem of bored pile construction is the disposal of slurry. Almost all governments in this region have laws and regulations on the control of disposal of waste slurry. But the enforcement of these regulations varies significantly from place to place. Construction safety is another concern. Recently, the Hong Kong Government has started discouraging the use of hand dug caissons on the grounds of health and safety to workers. This could in the future lead to a ban on this type of construction except in special circumstances where there are no practical alternatives.

Design Practice

The conventional designs still base on the principle of applying partial factors of safety on ultimate shaft and tip resistances which are computed from soil strengths. Allowable loads so determined are not coupled to the permissible settlements which rely on pile loading tests for confirmation. With sufficient data obtained from tests on instrumented piles, it is now possible to establish load transfer curves for various ground conditions and settlements of piles can be estimated with reasonable confidence. This rational approach has been incorporated in AASHTO (1992) and will be the future trend of design. However, the design codes require updating which is overdue.

This is particularly true for bored piles. The phenomenon of "soft toe" has recently been observed in many tests on instrumented piles. The end bearing of bored piles, following the conventional design procedures, has been grossly over-estimated. Fortunately, skin friction which was back analyzed from the results of load tests on un-instrumented piles by arbitrary assumptions on the sharing of loads between shaft friction and end bearing, was grossly under-estimated. Therefore, most of the designs are "adequate" because of the mutually compensating errors. This discrepancy has been recognized and corrected in a Japanese design manual by increasing the partial factor of safety to 10 for end bearing (Japanese Association of Construction, 1988).

In design of foundations for supporting structures, the effects of several natural hazards have to be considered in addition to the normal loading conditions. In Taiwan, effects of seismic activities and typhoons have to be incorporated in the design. In

Hong Kong, for most of structures only wind loads (typhoons) have to be considered. However, for road bridges seismic effects have to be incorporated in the designs. The other three countries, i.e. Malaysia, Singapore and Thailand are fortunately free from these problems.

In Taipei, old buildings are normally less than 10 storeys in height and are mostly supported on footings and compensating foundations. Negative skin friction was not a serious concern. Restriction on building heights was lifted in the early eighties and the number of tall buildings erected increased sharply. Fortunately, ground subsidence has stopped as groundwater table recovered as a result of the banning of withdrawal of ground water. Therefore, the problem with negative skin friction has been eased. It remains to be a problem in newly reclaimed coastal areas in southern Taiwan where industrial parks are located.

Negative skin friction is a common problem in Hong Kong. A large amount of the colony's usable area is reclaimed and much of the reclamation has been carried out by placement of fill directly on top of soft marine or alluvial soils. It is normal for negative skin friction to be considered as an imposed load. For highway projects, it is not uncommon to design deep foundations for a combination of dead load, live load and negative skin friction, which is obviously conservative. The problem is sometimes dealt with by coating the piles using asphalt.

Negative friction is seldom a problem in Malaysia. Where this is encountered the design method is based on the total stress approach described in the Canadian Foundation Engineering Manual.

In Singapore, negative skin friction is a common problem in foundation involving deep layer of soft clay. A common practice is to limit the long-term working load to a value equal to the soil resistance of the pile below the neutral point divided by a safety factor, less the negative skin friction above the neutral point. The safety factors normally vary from 1.2 to 1.5.

Research Studies

A few research studies conducted in the past years in this region are quite interesting and are thus briefly introduced herein.

<u>Non-Friction Piles</u>

The effectiveness of non-friction piles (trade name NF pile) was studied by a full scale loading test (Moh, Ou and Woo, 1983) on a reclaimed land in Singapore. As depicted in Fig. 1, the sand fill of about 3.7m in thickness is underlain by soft deposits to a depth of 32m. The consolidation of marine clay layers as a result of surcharge load from the new fill may lead to ground settlements and hence negative skin friction on piles.

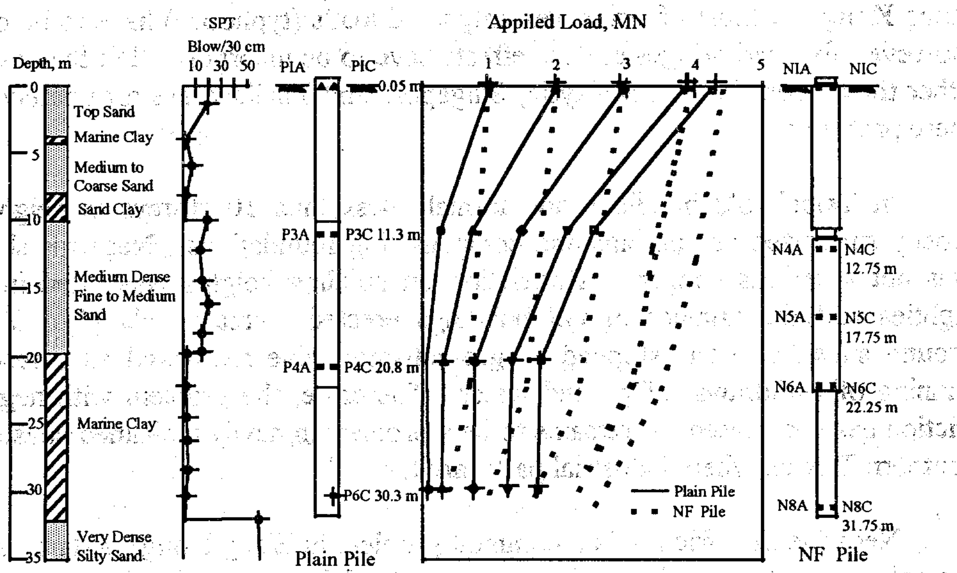

Fig. 1 Soil Profile and Axial Loads in Piles

Two piles, one plain and one coated, were tested to investigate the effectiveness of NF pile in reducing skin friction. They are steel pipe piles of 610mm in diameter with a wall thickness of 12.6mm. Each of them comprises three sections, with lengths of 12m (10.5m for the plain pile), 12m, and 9.5m. The NF pile has its top two sections surrounded by protective sliding sleeves, 11.5m in length and 3mm in thickness. Between the protective sleeve and the pile is an asphalt coating of 1.5mm in thickness.

For measuring load transfer in the piles, electrical resistant type strain gauges were mounted on the inside surface of the piles. The strain gauges were protected from possible damage due to driving by a steel channel welded on the inner surface of the piles. A total of 18 gauges were on the NF test pile at 5 levels and 12 gauges were mounted on the uncoated plain test pile at 4 levels. Settlements of the piles during loading tests were measured by means of displacement dial gauges at the tops.

The two test piles were loaded to 4.5 MN in 5 cycles for the plain pile and 6 cycles for the NF pile. The load-settlement curves for the two piles are compared in Fig. 2. At the maximum test load, the plain pile settled by 16mm while the NF pile settled by 72mm. The loads at different levels, computed from readings obtained by the strain gauges, for the two piles are compared in Fig. 1. The average shaft friction in the two coated sections was 21 kPa, while that for the corresponding plain sections was 51 kPa. The residual negative skin friction on NF pile estimated on the basis of visco-elastic theory is approximately equal to 4.5 kPa at a ground subsidence rate as much as 300 mm/year and the total negative friction will be 242 kN. For the plain pile, the total negative skin friction will be 2.4 MN. The effectiveness of NF pile in reducing negative skin friction is thus apparent.

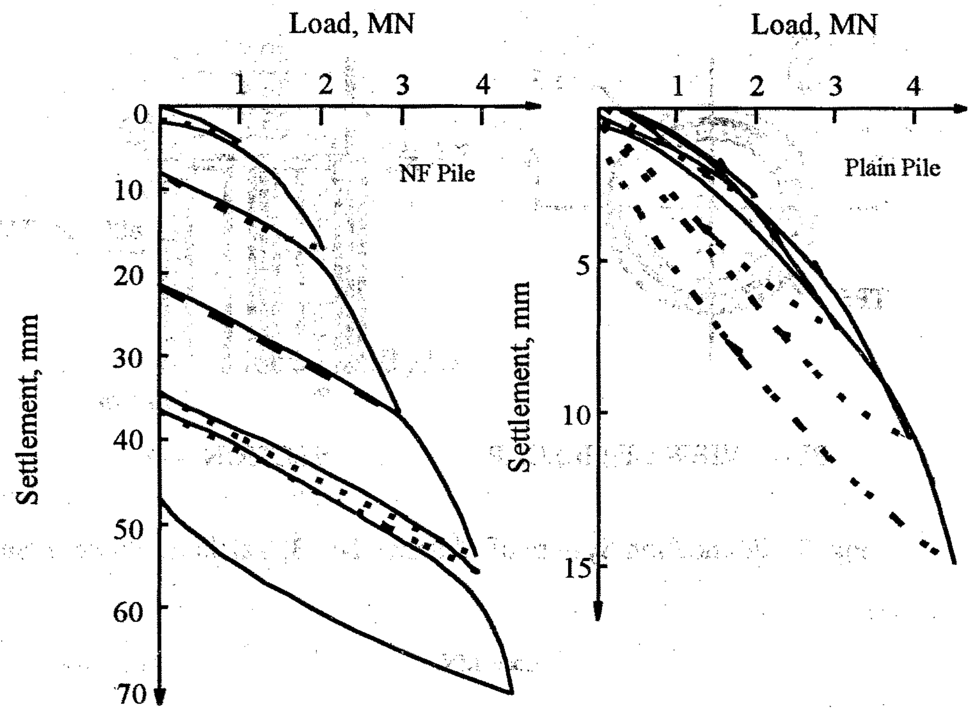

Fig. 2 Load-Settlement Curves

Group Effects

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 closed-ended steel pipe piles of 800mm in diameter. Preliminary loading tests were performed on 6 piles, 2 for each chimney. For simplicity, only details for Chimney No. 3 are presented herein.

The foundation system and the layout of piles of Chimney No. 3 are given in Fig. 3. Tests were carried out to a maximum load of 6,600 kN which is twice of the working load of 3,330 kN. Test results for TP5 and TP6 are shown in Fig. 4. As can be noted the full test loads were taken entirely by shaft friction. However, the long-term monitoring during the construction stage revealed that, as shown in Fig. 5, end bearing accounted 100% of the load applied on the top for the case of TP5 and 30% for the case of TP6. 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 loading tests on single piles.

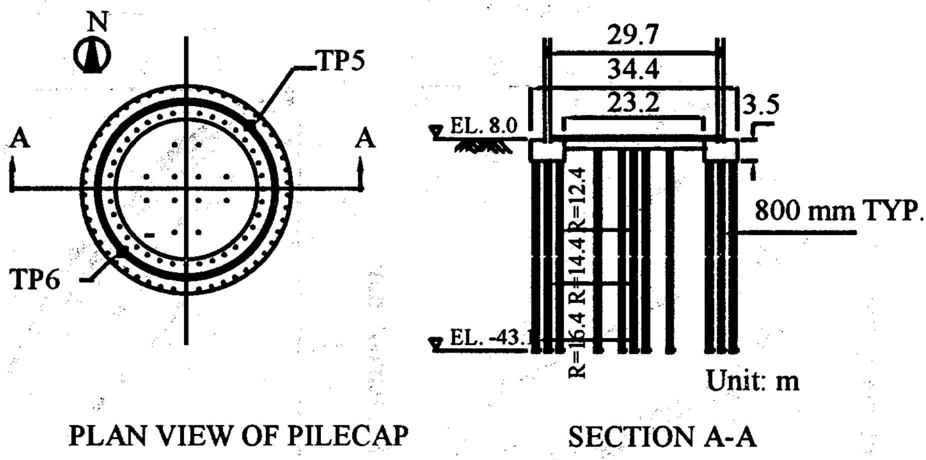

Fig. 3 Foundation System of Chimney No. 3, Taichung Power Plant

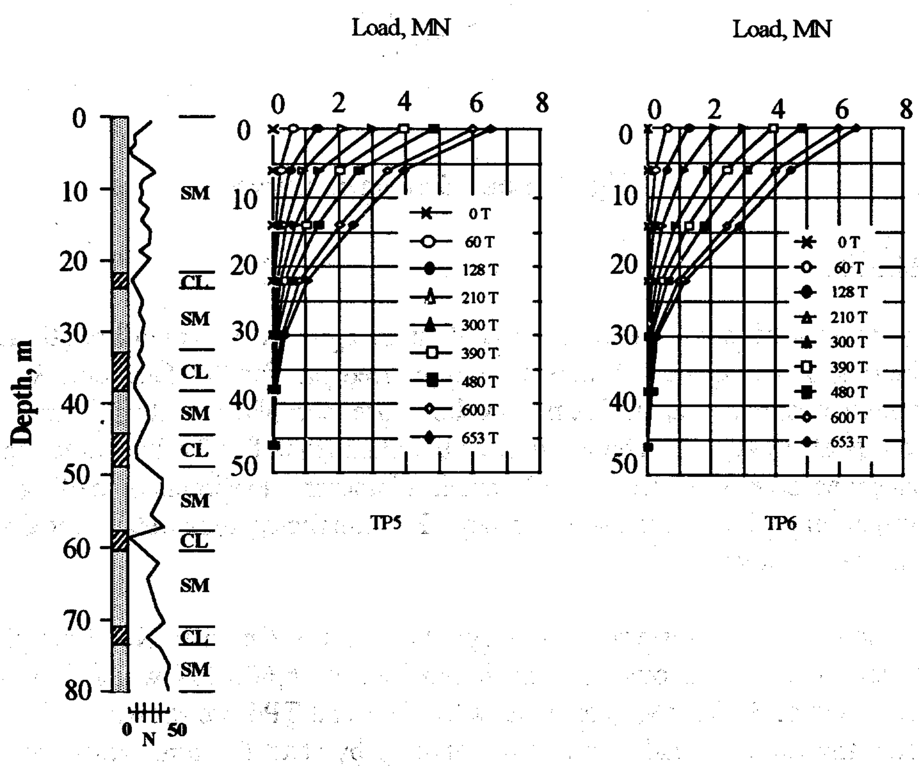

Fig. 4 Results of Preliminary Pile Loading Tests, Taichung Power Plant

It is a general practice to install piles at spacings equal to at least 2.5 times of pile diameter, therefore, bearing capacity is unlikely to become a problem. However, the shifting from shaft friction to end bearing would cause much greater settlements than what test results indicate. This is particularly true for bored piles which are very likely to have soft toes. Many bridge piers suffer from serious subsidences. The reason for buildings to be unaffected is that the contact pressures acting on the baseslabs are usually not taken into consideration and building foundations are thus much over-designed. In some cases, the uplift forces acting on the buildings are in fact greater than the building weights, yet piles are designed to support the full weights.

Pressure Grouting

Phenomenon of "soft toe" has been recognized and base grouting is receiving growing attention. It has 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. They are 62m and 70m long. Results indicate limited improvements of grouted piles over ungrouted piles. Presumably the piles are too long and loads are fully taken by shaft friction (Guo, 1993).

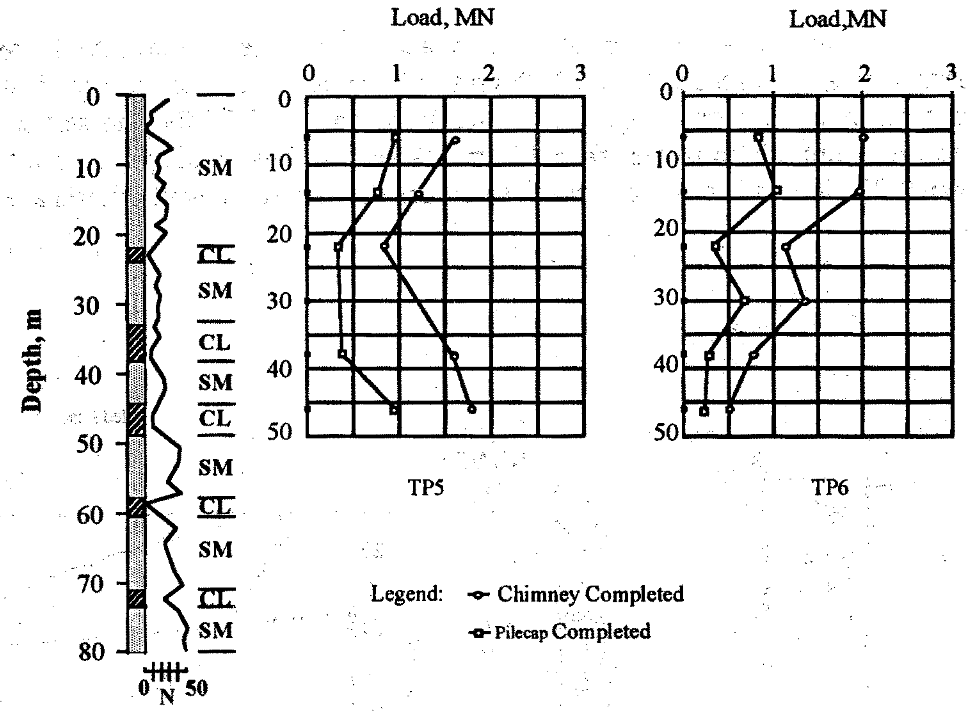

Fig. 5 Results of Long-term Monitoring during Construction, Taichung Power Plant

Pressure grouting technique has been used extensively in Bangkok. A summary is available in Wachiraprakarnpong (1993) in which the test results of 14 grouted piles are compared with the results of 34 ungrouted piles. For piles with their toes embedded in the First Sand Layer, which lies between depths of 32m to 38m below the surface, the improvements range from 26 to 66% for ultimate capacities, 24 to 66% for shaft friction, and 28 to 61% for end bearing . Improvements obviously decrease as the pile length increases. For piles with their toes embedded in the Second Sand Layer, which lies between depths of 45m to 55m below surface, the above values reduce to 12 to 24% for ultimate capacities, 9 to 27% for skin friction and 11 to 21% for end bearing.

In Malaysia, there is a recent case of the innovative use of post-grouted mini-piles for a 12-storey building (Lui, Cheung and Chan, 1993). In Singapore, it is reported that the capacity of a 1.5m diameter bored pile increased by 25 to 30 % while the cost of grout was about 10% of that of installation (Lee, 1994).

A recent study was conducted in the Nankang Depot of TRTS. Tests were performed at two locations and at each location two piles, one with its base grouted and one without, were tested. The test piles are 1.5m in diameter and 22m in length. Their toes are embedded in weakly cemented sandstone/shale by only 2m. 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. 6 and 7 for Site 1 and Site 2, respectively. Settlements were reduced from 160mm to 80mm 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 80mm to less than 10mm. Based on these findings, all the piles, more than 2,000 in number, were grouted to ensure that the settlement criteria are met.

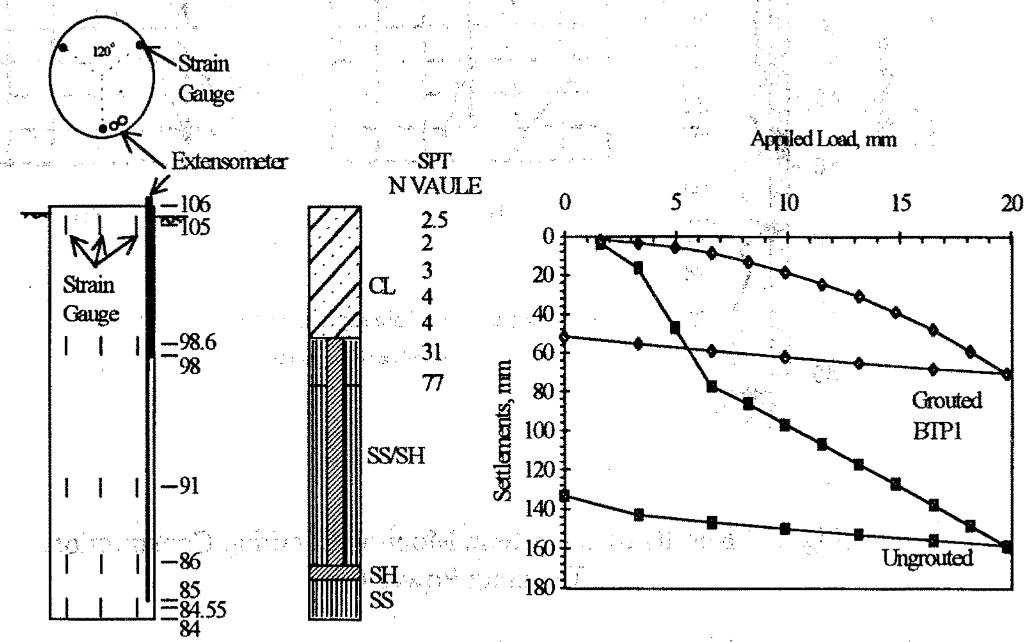

Fig. 6 Test Results at Site 1, TRTS Nankang Depot

Response to Load Reversals

A recent study successfully constructed the load-settlement curves for unloading and reloading cycles by using the concept of mutant curves (Moh, Chang and Hwang, 1995). To illustrate the idea, a typical backbone curve, representing the relationship between the soil resistance, q, and the relative displacement, δ, for a pile subjected to tension load and compressive load is shown in Fig. 8 and can be expressed as, in a normalized form:

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

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

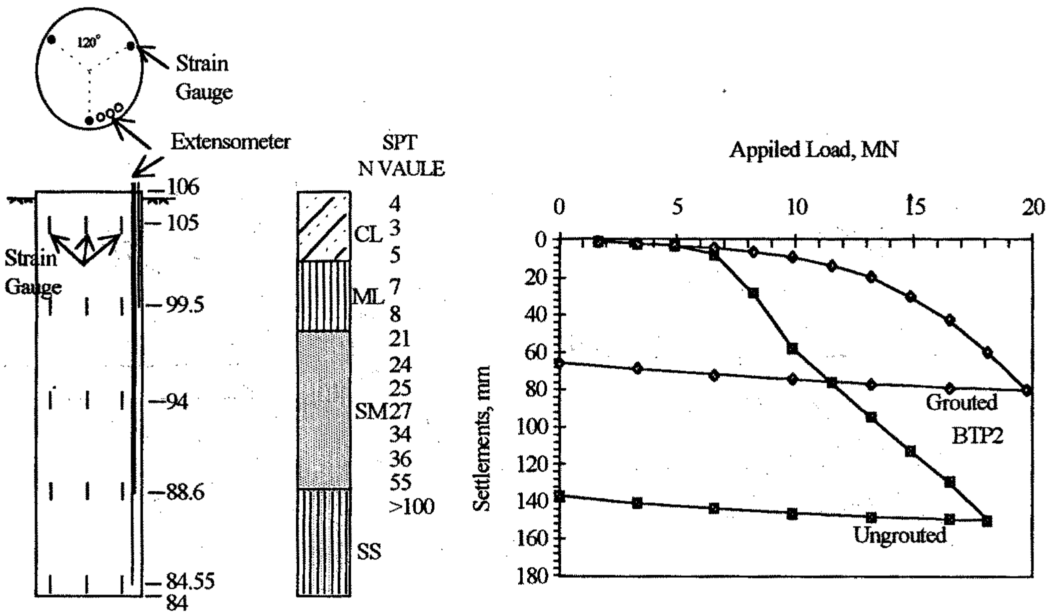

Fig. 7 Test Results at Site 2, TRTS Nankang Depot

Once the backbone is established, either by loading tests or by empirical formulations, the corresponding curves for unloading and reloading can be constructed by shifting the origin to a new position corresponding to the position before the load reversal, as illustrated in Fig. 9, for unloading and reloading, respectively. In other words, there is a nonlinear mapping the function from the q-δ system to q'-δ' system as follows:

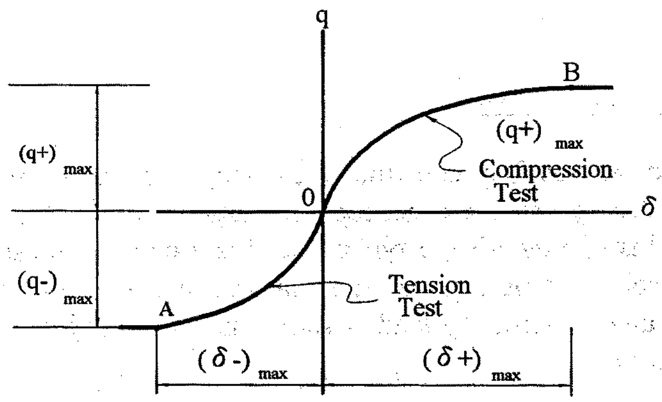

Fig. 8 Typical Backbone Curve

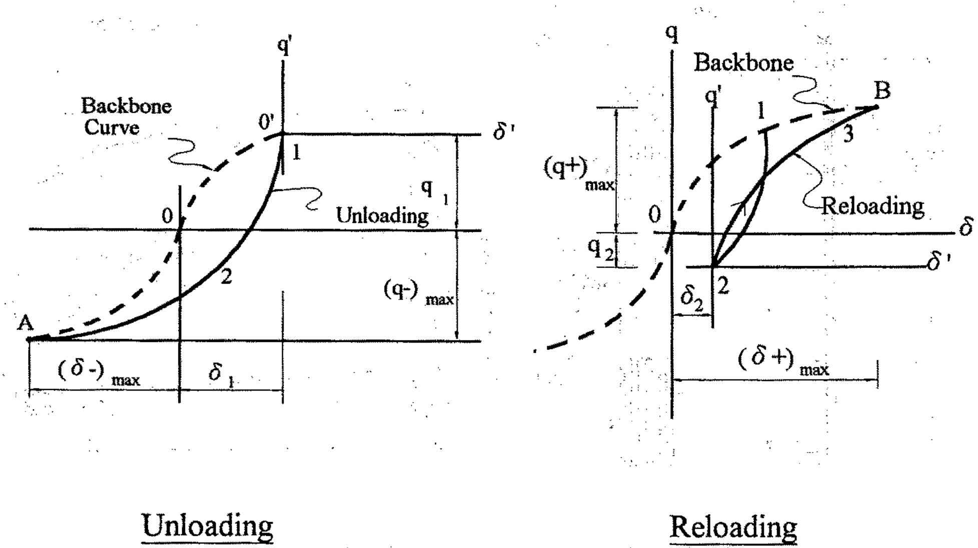

Fig. 9 Typical Mutant Curves

For Unloading

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

For Reloading

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

The results of a loading test, as shown in Fig. 10, were back analyzed using the backbone curves shown in Fig. 11. The test pile is a 1m diameter bored pile embedded in shale and sandstone by 3.3m. 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. 12. The agreement between the two sets of data is excellent in spite the simplicity of the procedure.

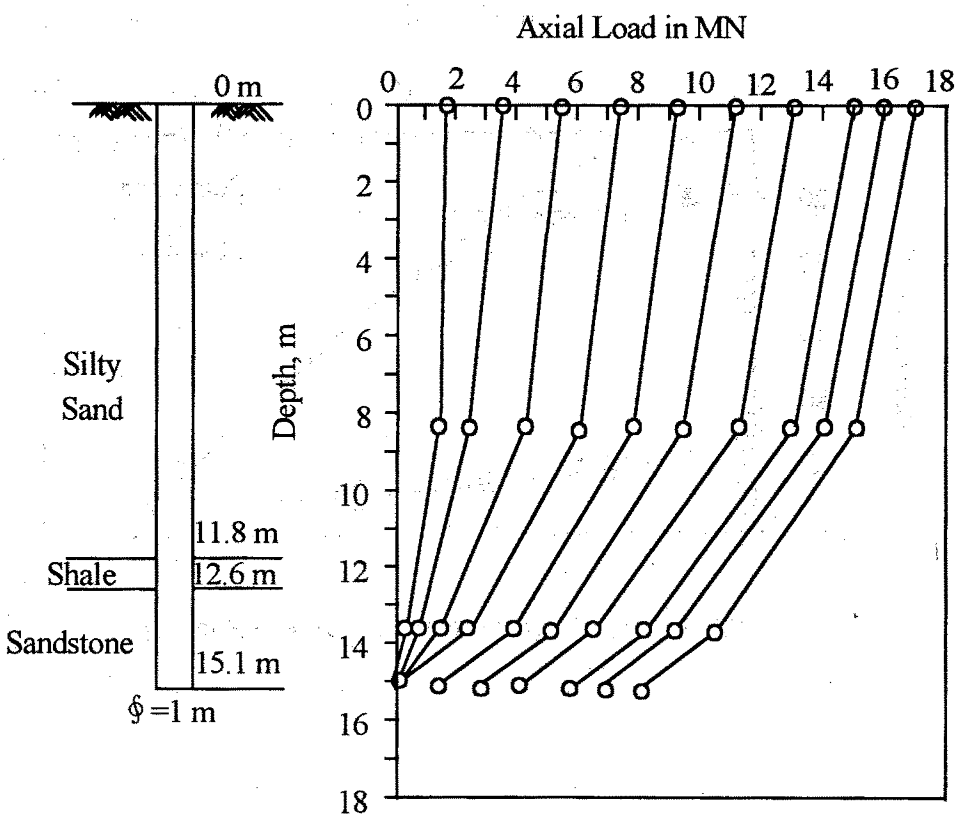

Fig. 10 Ground Conditions and Axial Loads in Test Pile TP3, TRTS Nankang Depot

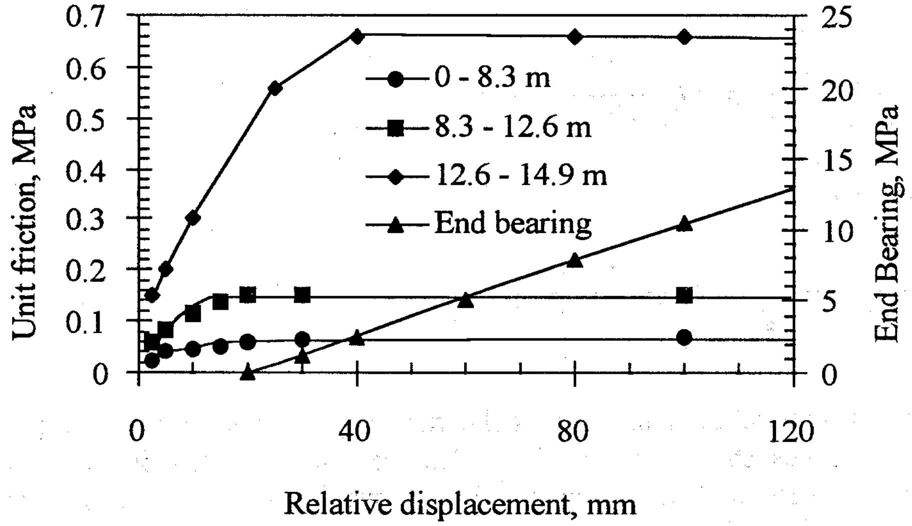

Fig. 11 The t-z Curves for TP3

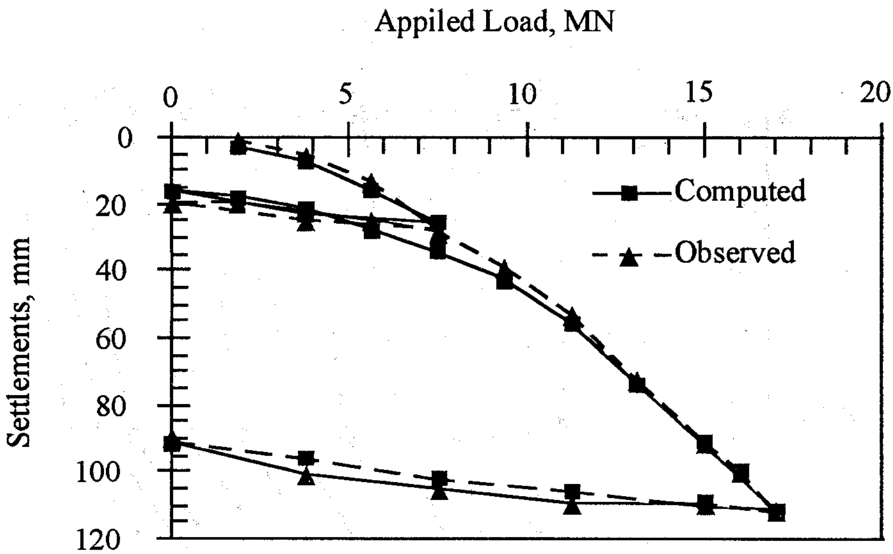

Fig. 12 The Load-Settlement Curve at Pile Top

Summary

The economy boom in the 80's and 90's has promoted numerous prestigious construction projects in Taiwan, Hong Kong, Thailand, Malaysia and Singapore. Many of these projects, in terms of size, rank pretty high in world records. The greater and greater structural loads call for high capacity piles, therefore there is a general trend of shifting from driven piles, to bored piles (drilled shafts), and to drilled caissons. The concerns on noise and vibration have practically eliminate the use of driven piles in populated cities.
Four research studies are discussed herein and the findings can be summarized as follows:

a. The use of non-friction piles effectively reduces negative skin friction as revealed in a full scale test.

b. Considerable amount of loads can be transferred to the toes as a result of group effects.

c. Base grouting is effective in reducing the settlements of short piles, but is ineffective for long piles.

d. The performance of piles in unloading and reloading can be evaluated by using the concept of mutant curves described herein.

Doubtlessly, there is much need for further researches. In addition to the four topics mentioned above, the areas of particular interest include the use of PDA and the use of Osterberg cells.

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