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Pile foundations of Taiwan High Speed Rail

Fondations par pieux de la ligne ferroviaire à grande vitesse de Taiwan

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ABSTRACT

The 345 km guideway of the Taiwan High Speed Rail Project runs through the populated west coast of Taiwan Island, linking Taipei to southern city of Kaohsiung. The geological conditions along the route vary substantially, having mountainous terrain in the north to thick sedimentary deposits in the south. As a result, the northern section is constructed mostly by cut-and-fill, with bridges and tunnels, while the southern half is mostly elevated supported by large bored piles. The contracts were awarded as design-and-build basis under relatively tight schedule, therefore significant efforts had been placed on optimization of design and construction. In design stage, the focus was on establishing effective soil investigation programs, verification of pile design formulae through extensive pile load tests. In construction stage, attention had been concentrated on construction of pile foundations, pile quality control and remedial methods etc. Discussed herein are some relevant geotechnical information gathered which may be useful to the engineers.

RÉSUMÉ

Les 345 km du projet de ligne ferroviaire à grande vitesse de Taiwan (« Taiwan High Speed Rail ») traverse la côte ouest de l'île de Taiwan à forte densité de population, reliant Taipeh à la ville de Kaohsiung au Sud. Le profil géologique le long de l'alignement varie de manière significative, avec des terrains montagneux au Nord et d'épaisses couches sédimentaires au Sud. En conséquence, la partie Nord est construite principalement en déblai/remblai, avec des ponts et tunnels, tandis que la moitié Sud est principalement en ligne aérienne fondée sur pieux forés de grand diamètre. Les contrats ont été attribués sur la base d'une conception/réalisation suivant un planning relativement tendu, par conséquent, des efforts importants ont été consentis pour optimiser les études et la construction. Pendant la phase étude, l'objectif était de définir une campagne d'essais géotechnique efficace, de vérifier les formules de dimensionnement des pieux au travers de nombreux essais de pieux. Pendant la phase de construction, l'attention s'est concentrée sur la construction des pieux de fondation, le contrôle qualité des pieux et les méthodes de réparation, etc. Les informations géotechniques pertinentes, qui pourraient être utiles aux ingénieurs, sont rassemblées et examinées dans le présent document.

1 INTRODUCTION

The Taiwan High Speed Rail Project (THSR) runs through the highly populated western coastal plains of Taiwan island as shown in Fig. 1, linking the major cities from north to south. Because of the magnitude of this project, the works were divided into several contract lots. The design and construction of the system started in Year 2000 and the operation was scheduled to be at the end of 2005.

Taiwan is located at the Circum-Pacific earthquake belt, which was created by the subduction of the Philippines Plate underneath the Eurasian Plate. The geological condition along the rail route alignment varies tremendously from the northern mountainous zone to sedimentary deposits in the south, crossing three (3) active earthquake faults. The sedimentary deposits in the south are highly susceptible to liquefaction because of loose nature and thick deposits. Approximately three-quarters of the route were carried by viaducts and bridges with 14% in tunnels and 9% on embankments. The foundations supporting the superstructures of the rail vary from place to place along the route. In the northern section, accounting for one-fifth of the route, the rail line was mostly constructed by cut-and-fill with bridges across rivers and tunnels through mountainous terrain. The rest of the route runs through the coastal plain with mostly elevated viaducts founded on piles. Because of the variation in ground conditions and different methods of construction, geotechnical issues to be considered are also different in various locations. For the northern section, the major considerations are slope stability and prevention of geo-hazards, and for the rest of the route, economical design of piles is of primary importance. Discussion in this paper highlights on the geotechnical issues related to the pile foundations only.

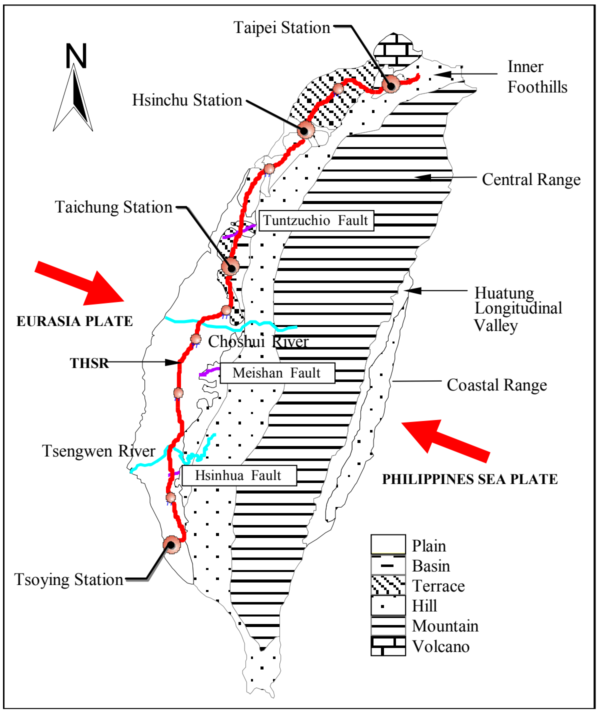

Figure 1. Geology of Taiwan and route of High Speed Rail.

2 SOIL INVESTIGATION PROGRAMS

As part of the design requirements, the subsoil condition at each foundation pier had to be determined through soil investigation. Most contracts adopted soil boring method with SPT tests and sampling. Because of the design specifications for foundation works were primarily based on SPT N value, hence parameters such as skin friction, end bearing, liquefaction potential and definition of particular sites, have to be expressed as function of N value. To accelerate the soil investigation and to enhance the soil profiling, the cone penetration tests were also adopted in some contracts, and a conversion procedure from the CPT data into equivalent SPT values has been established through correlating the CPT test results with measured SPT N values at eight (8) test locations as shown in Fig. 2.

Since CPT test data do not provide any physical properties of the soil, it is necessary to determine a method of classifying the soil type in a CPT test. The soils classified through actual laboratory tests on soil samples taken from the soil borings were used as the basis of establishing the relationship. The soils are only classified as granular soil (mainly sand) and cohesive soil (predominantly clay), a "criterion line" is defined to distinguish these two soil types. The criterion line separating sand and clay zones was determined through an optimisation procedure. Since each data point contains soil type from actual physical property tests (SPT samples), q_c and FR values from CPT tests, then the results can be plotted on the q_c-FR plot proposed by Olsen and Farr (1986) as illustrated in Fig. 3. The criterion line takes the following form:

$$\text{Cone Resistance, } q_c = 13\ e^{(\text{Friction ratio, FR})} \qquad (1)$$

where e is the exponent, cone resistance is in *kg/cm²* and friction ratio in *percentage*.

The soil profiles obtained from soil boring and CPT tests have been compared as shown in Fig. 4, indicating relatively good match.

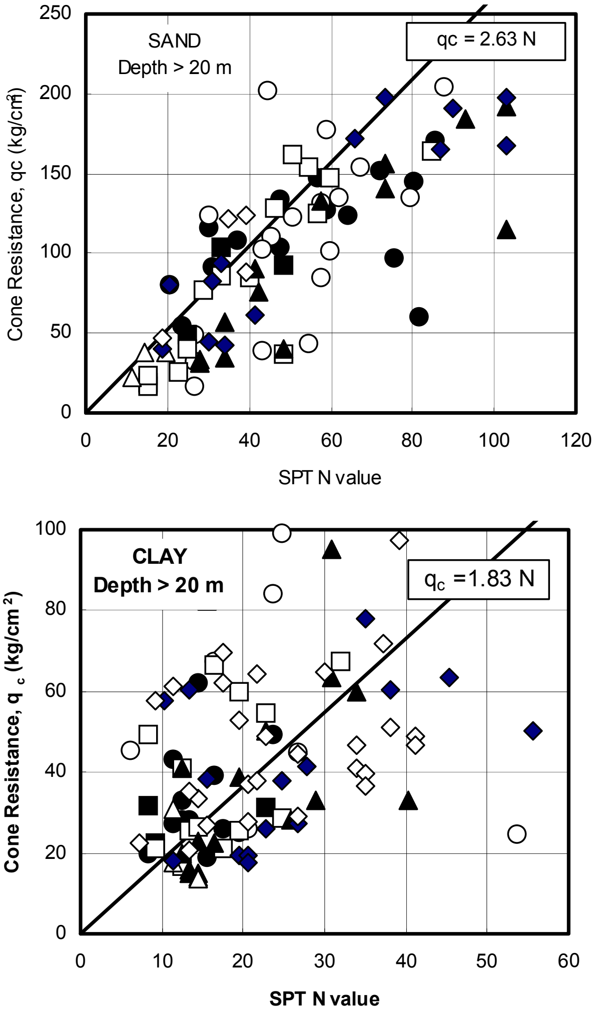

Figure 2. Correlation between q_c and SPT N value.

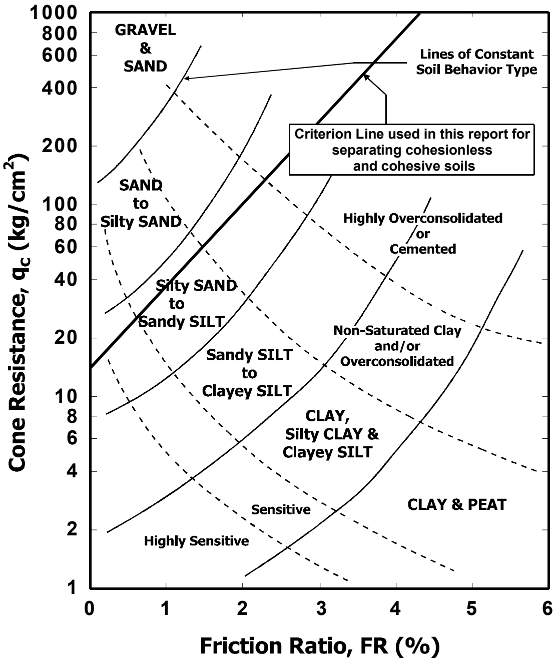

Figure 3. Soil Classification for Electric Cone (from Olsen and Farr, 1986).

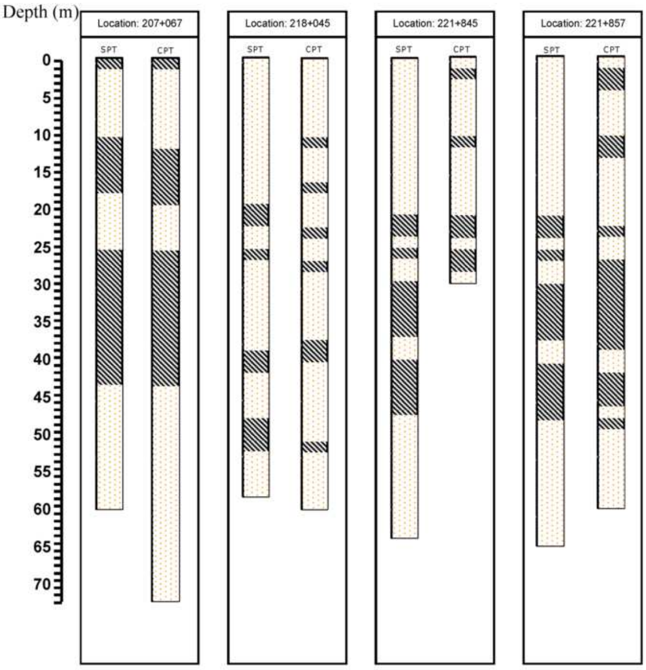

Figure 4. Soil Profiles from Soil Borings and CPT Tests.

3 BORED PILE DESIGN AND CONSTRUCTION

Due to significant variations in ground conditions along the THSR route, different construction methods are adopted for the installation of piles. In the north segment of the viaduct section, the route runs along foothills on mostly terrace deposits with layer of gravel close to the surface underlain by layers of sandstone or mudstone. Under these conditions, the bored holes would have to be protected by casing and excavated by hammer grab (within gravel layer) or drilling bucket (within rock). The excavated holes were either fully or partially cased depending on the stability of the holes and the seepage condition. For the southern half with a route length of about 155 km, over 20,000 piles have been installed for supporting the viaducts, having diameters of 1.5 to 2 m and lengths of 35 to 72m. In this region, the major soil compositions are interbedded sand and clay. Piles were mostly installed by reverse-circulation method due to its popularity, efficiency and availability in Taiwan. Rotary bucket type of drilling was also used in one of the contract sections for pile installation, but this method was primarily used for pile length not exceeding 60 m in sedimentary deposits. Higher skin resistance has been achieved through the use of this method.

The preliminary pile test results of several contracts have led to the following design correlations for bored piles installed by the reversed circulation (RC) method:

Unit skin friction:

- Granular soils (refer to Fig. 5):

$$f_s = 0.33N \;\; (\text{ton/m}^2) \text{ with limit of } 16.5 \text{ ton/m}^2 \text{ or } N \leq 50 \qquad (2)$$

- Cohesive soils (refer to Fig. 5):

$$f_s = 0.27N+2.6 \;\; (\text{ton/m}^2) \text{ for } N \geq 5 \text{ with limit of } 15 \text{ ton/m}^2 \qquad (3)$$

Unit end bearing:

- Both cohesive and granular soils:

$$q_b = 5.3\ N \;\; (\text{ton/m}^2) \text{ with limit of } 250 \text{ ton/m}^2 \qquad (4)$$

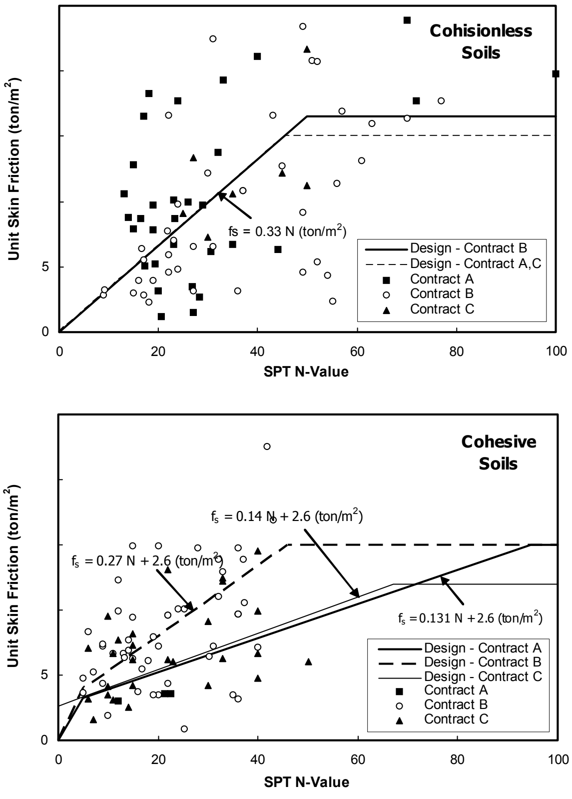

Figure 5. Correlation between Unit Skin Friction and SPT N values.

The problem of soft toe caused by sedimentation of soil at the bottom of excavated holes was minimized via injecting cement grout at high pressure in stages to strengthen the weak zone surrounding the pile toe. With pressure grouting at toe, it was found that the end bearing capacities of piles were greatly improved with less settlement.

4 QUALITY CONTROL AND TESTING OF PILES

Each stage of the bored pile installation was checked by following methods:

- Stabilization of hole: Most of the contractors had used polymer as stability fluid with excavated ponds as settling ponds, only a small number had adopted settling steel tanks. Nevertheless, the quality of the stabilizing fluid had been checked throughout the drilling process in most contracts.
- Verticality and dimensions of bored hole: Once the hole had drilled to required depth, echo sounding or drilling monitoring was performed to check the verticality and dimensions of the hole.
- Toe cleanliness: To ensure minimum sediment in the bored hole, airlifting was conducted to remove the loose sediment at the bottom of the hole. Special sampling of base sediment had also been used by some contractors for checking the cleanliness of the base before concreting.
- Uniformity of concreting: Honeycombing, segregation and discontinuity of concreting are common problems in bored piling. For this project, over 20 % of the piles were subjected to non-destructive integrity tests. In addition, piles suspected to be defective as indicated by piling records were also subjected to tests. If test results indicated that the pile might be defective, remedial measures would be taken accordingly. In some cases, continuous coring had been performed to check the quality of the suspected piles.

Method of repairing the problem piles varies from contract to contract, and it also depends on extent of the problem. For example, if the problem is severe due to the collapse of hole at deep depth during drilling or poor concreting, the problem pile may be replaced by additional piles with some modification to the pile cap layout. In less severe situation, grouting around the piles was adopted to improve the pile capacity.

4.1 *Pile Load Tests*

Extensive pile load tests were conducted in the design phase to verify design assumptions and to optimize the pile design. The pile load test programs generally included various types of testing methods, including static compression, static tension, static lateral load, dynamic pile load, Osterberg cell and Statnamic tests. Since this project was divided into twelve (12) contract sections under different designers, therefore different testing methods were adopted. For example, some designers conducted static tests together with dynamic tests; others had adopted Osterberg cells in conjunction with static tests. The merits and limitations of different types of pile load tests, including instrumented static pile load, dynamic pile load and Osterberg cell, are summarized in Table 1. Conventional load tests were normally carried out to loads of over 4,000 tons.

The conventional static pile load test with instruments had been used by most of the contractors because of simple data interpretation with adequate local experience and equipment availability.

Table 1: Types of Pile Load Tests performed

Type	General Comments
Conventional Static Load	• Max. load tested: 4,400t • Correlation established through instrumentation for pile design • Most widely used
Dynamic	• Hammer used: 40t • Max. Drop: 2-3m • Max. load mobilized: 3,000t • Used on testing of working piles
Statnamic	• Max. load mobilized: 3,000t • Limited success
Osterberg Cell	• Two level O-Cell adopted • Correlation established through instrumentation for pile design

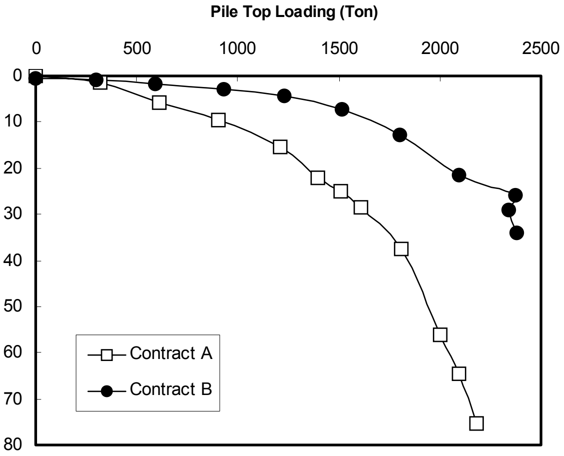

Figure 6. Load Movement Curves of Pullout Tests.

The Osterberg cells were used in two (2) contracts as standard tests with significant success, providing an alternative to conventional static pile load tests. But the Osterberg cells would only produce meaningful results if the entire pile has been moved; otherwise extrapolation of data would be needed.

Significant attention had been placed in conducting pullout tests due to option given in the design specifications, which stated a limit of 40% (ratio of compression to tension skin friction). Several contractors had concentrated on the pullout tests (refer to Fig. 6) to raise this limit since in several cases that the tension capacity was a governing factor in design of piles under seismic condition. Based on some of the available results, the ratio of ultimate tension capacities to compression capacities (without end bearing) ranges from 62 to 105%, with a mean of 81±16 %.

Lateral pile load tests were conducted at locations with different soil conditions for determining horizontal modulus of subsoil reaction and to verify the design parameters. Test results revealed that the responses of test piles are quite similar to those predicted by the "p-y" curve method (Duann, et al., 2004); hence this method was adopted by some of the designers for predicting response of piles in design.

4.2 *Testing of Working Piles*

For ensuring the quality of construction and for confirming that the settlements of working piles are within required design limits, approximately 0.5% of working piles were tested. Conventional static tests were carried out up to loads of 2,200 tons (1.5-2 times of the working loads). Some of the contractors adopted dynamic load tests instead of conventional load tests and performed comparative studies beforehand to establish correlations between the results obtained by using different methods. Under this range of load, the pile would behave elastically and no plastic strain would be expected, and there would be minimum induced stress within the working pile. The measured load-settlement curve was compared with the predicted curve from load transfer method proposed by Coyle and Reese (1966). It is assumed that if the stiffness response of the working pile is close to that of the predicted curve, then the ultimate resistance of the working should be close to design value, validating the performance of the working pile. Fig. 7 shows the results of the comparison with reasonable agreement.

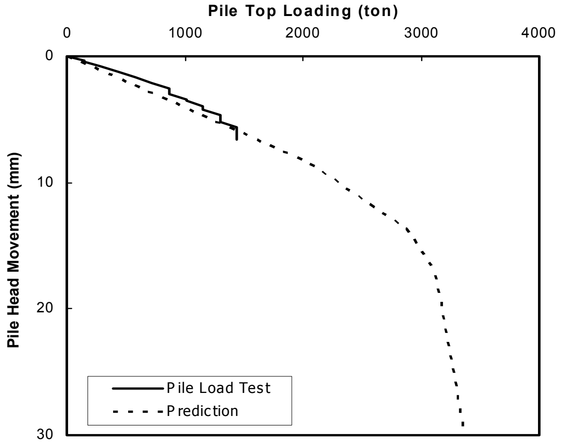

Figure 7. Load Settlement Curve of Working Pile.

5.CONCLUSIONS

The THSR project provides vast amount of geotechnical information, resulting in better database for local practice. Useful correlation has been established in soil testing as well as bored pile design. The preliminary pile load tests performed during the design stage had optimized the construction cost and reduced the uncertainty associated with bored pile design.

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