Identification of Test Pile Defects in a Super-tall Building Foundation

Identification des anomalies dans les essais de chargement de pieu pour les fondations d’une tour de très grande hauteur

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ABSTRACT: As part of the foundation design verification process for a super-tall tower in South Korea, a program of pile load testing was initiated. The test program involved vertical load tests on four piles and a lateral load test on two piles, jacked against each other. The vertical load tests used the Osterberg cell method, with two sets of Osterberg cells installed in each pile, one near the pile base, and the other about 6m above the base. In addition to the vertical load tests, sonic tubes were installed in the test piles to examine the integrity of the constructed pile. The sonic tube testing revealed defects in one of the test piles, and the behaviour of this pile under load was found to have a number of anomalies. This paper sets out the process by which the defects were identified, and approach used to interpret the sonic logging data to produce tomographic images of the pile along its length. The consequences of the defects and the irregularities in pile diameter on the inferred distribution of load along the pile are also described.

RÉSUMÉ : Dans le cadre du processus de vérification de la conception des fondations d’une tour de très grande hauteur en Corée du Sud, un programme d’essais de de chargement de pieux a été entrepris. Le programme d’essais implique des essais de chargement vertical sur quatre pieux et des essais de chargement latéral sur deux pieux, vérinés l’un à l'autre. Les essais de chargement vertical utilisent la méthode d’Osterberg, avec deux jeux de cellules d’Osterberg installés dans chaque pieu, un près de la base et l'autre environ 6 m au-dessus de la base. En plus des essais de chargement vertical, des tubes acoustiques ont été installés dans les pieux pour examiner leur intégrité. Les essais acoustiques ont révélé des défauts dans l'un des pieux testé, et le comportement de ce pieu sous charge présentait un certain nombre d'anomalies. Cet article décrit le processus par lequel les défauts ont été identifiés, et l’approche utilisée pour interpréter les données d'enregistrement acoustique pour produire des images tomographiques du pieu sur toute sa longueur. On décrit aussi les conséquences des défauts et des irrégularités du diamètre du pieu sur la distribution présumée de charge le long du pieu.

KEYWORDS: analysis ; defects; foundations ; integrity testing ; piles ; tall buildings.

1. INTRODUCTION

Figure 1 illustrates the proposed 151 storey Incheon Tower, which is located in district 8 of the Songdo Incheon Free Economic Zone in South Korea. The site lies entirely within an area of reclamation underlain by up to 20m of soft to firm marine silty clay, which in turn overlies residual soil and a profile of weathered rock, which is underlain by a better quality rock referred to as “soft rock”. The tower is composed of approximately 30 storeys of office floors, 8 storeys of hotel and other supporting facilities, 100 storeys of residential floors, and several levels of mechanical plant. The base of the tower consists of retail, a future subway station, and several levels of parking. It is anticipated that the total area of the tower and the base for Phase 1 construction will be approximately 412,000 m^2. The structural system of the tower in the east-west direction consists of a reinforced concrete core wall system linked to the exterior mega columns with reinforced concrete or composite shear panels. The tower superstructure is founded on a pile supported raft foundation. The 5.5 m thick reinforced concrete raft is supported on a total of 172 bored piles, 2.5 m in diameter, with variable lengths, extending 5 m into the soft rock for added stiffness and axial load capacity. Details of the geotechnical conditions and the foundation design are given by Abdelrazaq et al (2011).

2. PILE LOAD TESTING

Introduction

As part of the final design process, five pile load tests were undertaken, four on vertically loaded piles via the Osterberg cell (O-cell) procedure, and one on a laterally loaded pile jacked against one of the vertically loaded test piles. For the vertical pile tests, two levels of O-cells were installed in each pile, one at the pile tip and another at a level between the weathered rock layer and the soft rock layer.

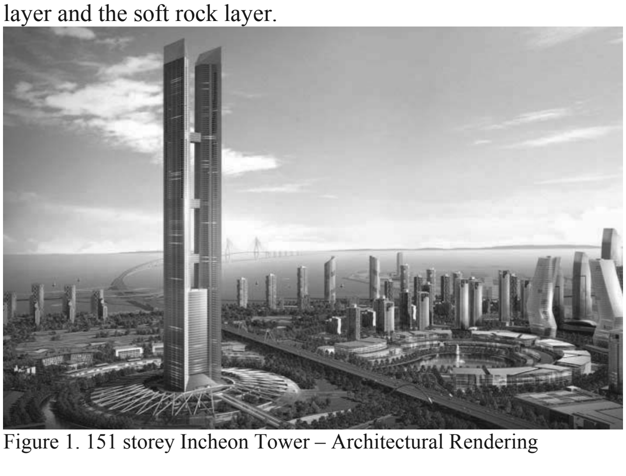

Figure 1. 151 storey Incheon Tower – Architectural Rendering

The results of three of the axial tests are summarized by Abdelrazaq et al (2011). However, the as-built records for one of the nominal 2.5 m diameter test piles, TP-03, indicated a variation in verticality, concrete quality and pile shape. The as-built records for TP-03 were reviewed ahead of the pile test, and assessment was made of the the likely performance of the as-built pile under the proposed pile test load sequence. The as-built assessment was based on construction records for excavation and concreting and the results of non-destructive testing (Koden and sonic logging). These records facilitated an assessment of the pile shape, verticality and concrete quality. These characteristics were then used to assess the way in which load is shed along the test pile.

Excavation of the pile hole to a depth of 34 m (within the weathered soil) was carried out by reverse circulation drilling (RCD) between 10 and 11 May 2010. Further advance of the pile hole to the final depth of 47 m was carried out by RCD after a 3 day interval between 15 and 18 May 2010.

2.2 *Koden Survey and Pile Verticality*

A Koden survey of the pile profile was carried out one day after excavation of the pile hole had been completed by RCD. The Koden results showed the following:

- pile casing installed vertically with casing shoe located at a depth of approximately 33 m (i.e. 14 m above the pile toe).
- pile diameter variation in the range of 2.5 m to 3.2 m within the weathered soil, weathered rock and soft rock.
- pile profile inflection at an average depth of 37 m from near vertical to 1(H):10(V).
- socket profile over-break with short and long wavelength variation of 0.4 m over approximately 4 m lengths and superimposed shorter wavelength variation of 0.1 m to 0.2 m over 1 m lengths, respectively.

2.3 *Pile Concreting Summary*

Pile concreting was carried out on 22 May 2010 over a period of approximately 12 hours (4 days after pile hole excavation had been completed). A total of 282 m^3 of concrete was used to fill the pile hole to a depth of 4 m from the surface.

The theoretical concrete volume for a pile of 2.35 m net diameter and 47 m in length is 204 m^3. It was therefore assessed that an additional approximately 38% concrete volume was used for pile TP-03. The pile temporary casing was lowered to the pile toe and then raised in 7 stages of 5 m and 6 m lengths depending on casing section length, with measurements of the concrete level taken prior to and after extraction of each section of casing. Small changes in concrete level were noted during extraction of the first two lengths of casing, indicating a difference between theoretical and measured concrete volume of approximately 3 to 6 m^3. This reflected a deficit of about 10-20% as compared with the Koden over-break measurements and it was considered that water entrapment may have occurred as the casing was lowered to the base of the pile at the start of concreting; therefore the pile socket bond could have been affected.

A large drop in concrete level (approximately 6.5 m) was measured as a result of extracting the third length of casing. This represented a significant over-break within the depth range 31.5 m to 36.5 m. The summary chart of concreting works indicated that the tip of the tremie tube was located 2 m below the "fallen" concrete level. Further drops in concrete level in the range of 1.5 m to 3 m were measured for the extraction of the remaining four sections of casing.

The measured differences in concrete level for each casing extracted are summarized in Table 1. These measurements indicated a variation in the diameter of the pile with depth.

2.4 *Sonic Logging Survey*

A sonic logging survey was carried out for TP-03 on 28 May 2010, 6 days after concreting of the pile was completed. An assessment of the survey results could not be carried out using the standard sonic report sheets as poor correlation was observed with apparent changes in wave velocity ("artefacts") associated with subsequent observations of irregular pipe spacing, poor pipe verticality and possible de-bonding. The summary wave trace files were therefore obtained from the testing sub-contractor and are summarized in Figure 2, which indicates the large range in wave speed measured and variation thereof over short and long depth intervals.

An iterative process was adopted to exclude the artefact effects mentioned above from the measured wave velocities, and the results were resolved to provide sonic tomography representations of the concrete quality along the piles length in two sections at right angles to one another. The adjusted sonic tomography plots showing variation along the pile length are shown in Figure 3.

Table 1. Summary of as-built concreting records

Casing Depth Range (m)		*Casing Length (m)*	*Concrete Level Drop (m)*
9	14	5	2.0
14	19	5	3.0
19	24	5	2.0
24	29	5	2.0
29	35	6	6.5
35	41	6	1.0
41	47	6	0.5

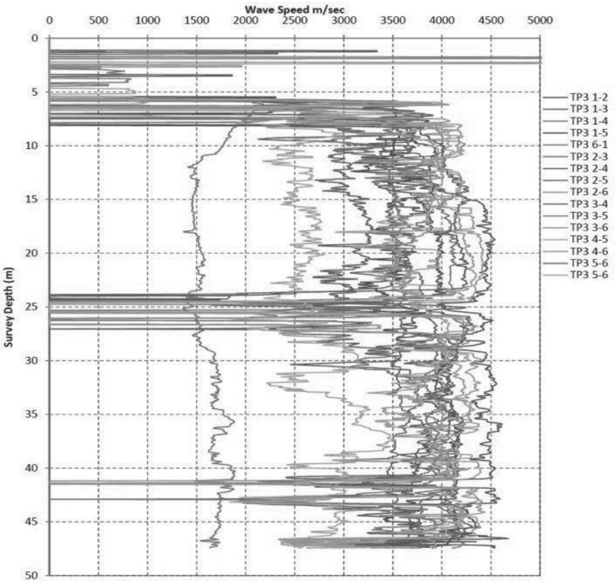

Figure 2 Measured wave speed versus depth along pile

Figure 3 indicates that poor concrete quality (shown as the darker zones) is restricted to discrete levels with abrupt and pervasive boundaries. The concrete quality was also found to vary across the pile cross section. The information so derived was processed to estimate the percentage of good quality concrete within various depth ranges, as summarized in Table 2 below.

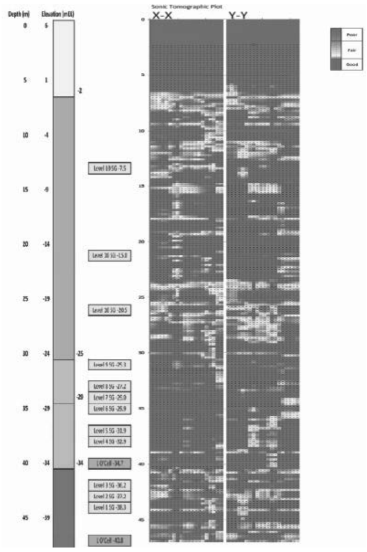

Figure 3 Tomographic image of pile

3. ANTICIPATED EFFECTS OF NON HOMOGENEITY

The effect that variation in the pile profile (i.e. over-break and necking) and concrete quality could have on strain measurements obtained during the pile load testing was estimated based on the measurements during construction described above. The effect of the pile shape and concrete quality was assessed using the finite element analysis program PLAXIS.

3.1 Pile Shape Effect on Strain Measurements

The strain measurements recorded during the pile load test were resolved to assess stress at levels within the pile based on the cross sectional area of the pile and the concrete modulus. A uniform cylindrical pile shape was assumed but it was recognised that, where large over-breaks occurred, the stress within the pile at these locations could be underestimated, as the pile stiffness is proportional to the square of the pile radius.

The measurements taken during the pile concreting were limited to measurements every 5 m or 6 m and therefore did not enable the pile profile to be accurately assessed. Table 3 gives an indication of the effect of pile over-break on pile stiffness, for various length intervals, based on some of the diameters that may be possible on the basis of the concreting records. If the pile diameter is not considered when the pile load results are analysed, capacities will be underestimated at over-break levels and overestimated where necking occurs. This phenomenon may then appear as an apparent stress reversal within the pile.

3.2 Concrete Quality Effect on Strain Measurements

In interpreting pile load test data, the pile concrete quality is generally assumed to be homogeneous throughout the pile and results are resolved from a single modulus value for the pile.

The sonic logging results for TP-03 derived from the sonic tomography showed that marked variation in the pile concrete quality occurs at specific locations across the full cross section of the pile, and also occurs non-uniformly along the pile. Variable strains are therefore likely to develop within the pile during testing, with measured differences in excess of 50% anticipated. The sonic logging tomography assessment facilitates reconciliation of the measured results with the concrete quality and allows attribution of apparent "bending" to concrete quality variation, rather than to changes in pile verticality or shape. In general, the stress at a particular level is assessed based on an average of 2 or 4 strain gauge measurements and results will need to be reviewed individually to avoid the pile stress being miscalculated.

Table 2. Summary of Assessed Concrete Quality

Depth Range m		*Assessed % good quality concrete*
4.5	7.5	10
11.5	13.5	70
23.5	27.0	0 to 30
27.0	29.0	30 to 70
41.0	47.0	60

Table 3. Pile stiffness variation due to pile overbreak

	% change in pile stiffness due to overbreak		
Depth range m	*Interval length of pile section considered m*		
	1	2	3
9-14	300	150	122
14-19	400	275	133
19-24	300	150	122
24-29	300	150	122
29-35	750	263	172
35-41	200	125	111
41-47	150	113	105

3.3 Finite Element Analysis: Pile Shape and Load Distribution

Finite element analyses were carried out for TP-03, using the computer program PLAXIS, to assess the impact of over-break on the load distribution along the length of the pile.

An axi-symmetric model using 15-node elements was developed to model a uniform cylindrical pile, as well as models representing piles with varying overbreak diameters over varying sections of the pile. A summary of the cases analysed is presented in Table 4. Ground elevation was at +6.0mEL.

Table 4. Summary of Finite Element Analysis Cases

Case	*Pile Diameter (m)*	*Overbreak Diameter (m)*	*Elevation of Overbreak Section (m EL)*
1	2.4	N/A	N/A
2	2.4	6.6	-30.2 to -31.2
3	2.4	4.3	-28.2 to -31.2
4	2.4	3.5	-25.2 to -31.2

The geotechnical parameters used in the analysis are summarised in Table 5. The pile load test was simulated by the application of a traction load of 7500kPa at depths of EL-34.4 m and EL-34.8 m, which are similar to the elevation of the upper O-cell and below the modelled pile over-break zones. The pile was modelled using linear elastic elements with appropriate concrete stiffness parameters ascribed. A plate element with negligible axial stiffness was also modelled within the concrete to allow assessment of the normal force developed within the pile due to the applied loading.

The results of the PLAXIS analysis are summarised in Figures 4 and 5. Figure 4 shows the assessed load distribution along the pile length resulting from the applied load. Figure 5 shows the calculated difference in pile stress at locations along the pile as compared to the expected distribution for a pile of uniform cross-section. It can be seen from Figure 5 that the presence of irregularities in the pile cross section results in unusually high stresses being calculated within the pile section immediately below the pile over-break zones.

Table 5. Summary of key geotechnical parameters

Layer	*Thickness (m)*	*Young's modulus MPa*	*Shear strength*
Marine 1	3.5	4.6	18.5 kPa
Marine 2	2	30	35°
W. soil	3.5	60	200 kPa
W. rock	5	2000	700 kPa
Soft rock	11.5	3000	1000 kPa

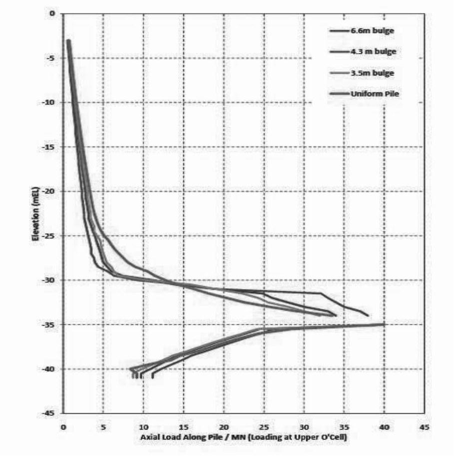

Figure 4 Computed axial load distributions

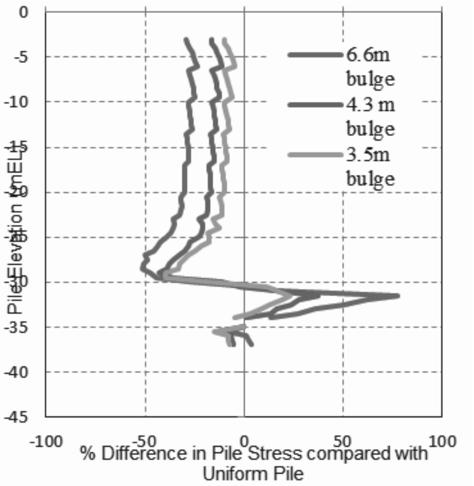

Figure 5 Effect of pile non-uniformity on pile stress

4. CONCLUSIONS

The available as-built records for test pile TP-03 indicated the presence of a number of anomalies associated with the construction of the pile which were likely to affect the results of the pile load test. It is possible that these anomalies were due to the entrapment of water during pile construction. The anomalies included an irregular pile shape due to zones of over-break, the largest of which was assessed to be present at a depth of about 35 m, and possible necking of the pile at a depth of about 25 m. Based on the results of the Koden tests, it was assessed that the pile profile changed in verticality from near vertical to about 1(H):10(V) at a depth of about 37 m. It would appear that this anomaly was removed by further pile excavation, as the concreting records show that the casing was lowered to the pile toe.

The sonic tomography plots indicated that the concrete quality along 70% of the pile length was reasonable. The concrete quality in the section of the pile within the soft rock varied and it was considered that water entrapment may have occurred as a result of the casing being lowered to the base of the pile at the start of concreting. The measured drop in the concrete level resulting from the extraction the first section of casing was less than that expected to account for the over-break in the socket. It was therefore considered that the bond at the soft rock-concrete interface may be affected. The assessed 4 m long section of poor quality concrete at a depth of about 25 m was attributed to the large concrete level drop recorded during construction of the pile and possible contamination of the concrete by spoil at the top of the concrete column. This feature may also indicate necking of the pile via a reduced pile diameter.

The results of the finite element modelling indicated that the presence of irregularities in the pile cross section results in unusually high stresses being generated within the pile section immediately below the pile over-break zones. Proper interpretation of load test data requires consideration of possible non-uniformity of pile section and concrete quality.

REFERENCE

Abdelrazaq, A., Badelow, F., Sung-Ho Kim and Poulos, H.G. (2011). Foundation design for the 151 storey Incheon tower in a reclamation area. *Geotechnical Engineering, Jnl. SEAGS, AGSEA,* Vol. 42, No.2, 85-93.