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Case study on excessive pile deviation and lateral soil displacement due to massive pile installation in soft coastal alluvium in Northern Peninsular Malaysia

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ABSTRACT: This project involves constructing industrial plants with manufacturing facilities on 2m to 6m thick filled platform, over soft marine coastal deposits of 27m to 30m upper clayey alluvium and lower interbedded alluvium. Over 6,000 concrete piles were installed within three months immediately after the completion of building platform filling. The piled foundation was designed to support portal frame building columns on individual pile caps with pile-to-set piles and, also the flat slab floor with drop panel on fixed length single piles at grid pattern. Due to concurrent additional levelling earthwork and piling works, different levels of pile deviation at the group piles at pile caps and single piles for floor slab piles were observed during the as-bult survey taken at two separate stages, namely at piling platform and pile cut-off level. Both hammer driven rigs and jack-in piling rigs were deployed to install the 6,000 piles within the building footprint of about 25,000m^2 over very tight 3 months contract period. During the investigation, piling sequence and pile centre-to-centre spacing have significant influence on both pile deviating direction and magnitude in addition to the comparatively localised disturbance from the movement of heavy piling equipment and possible subsequent pile cap excavation instability. A number of pile tests ranging from pile integrity test (PIT), high strain dynamic pile test (HSDPT) and static maintained load test (SMLT) were conducted to verify the pile performance and also to detect any integrity problems that can potentially arise from the observed pile deviation. This paper discusses the probable mechanisms of the observed pattern and trend of pile deviation resulted from pile installation sequence for lesson learnt and experience sharing.

RÉSUMÉ :

KEYWORDS: Soft ground, earthworks, piling, soil displacement, pile deviation

1 INTRODUCTION

An electronic manufacturing industrial plant facility of approximately 25,000 m^2 over soft marine coastal deposits in northern Peninsular Malaysia was constructed with the foundation completed within a very tight contract period of 3 months. The foundation system comprises of over 6,000 pre-cast reinforced concrete square piles of 150mm to 350mm in sizes. The single floor slab piles that were hydraulically jacked to fixed length of 30m; while for group piles supporting columns that were hydraulically jacked to set with average piling length of about 55m. Other than the piling works, levelling earthworks also took place simultaneously at the project site up to platform levels.

In view of the urgency of the project, two rounds of piling as-built surveys were taken for the installed piles. The first as-built survey was taken progressively and mostly immediately after completion of the individual column group piles and single floor slab piles at piling platform level. Whereas the second as-built survey was taken as joint survey between Piling contractor and Main Building contractor for handover purpose at pile cut-off level. Disputes arose when there were inconsistent surveyed pile deviations between the first survey, which took place under on-going piling and earthwork construction, and the subsequent joint survey taken about 3 months later for project handover.

This paper presents the potential factors that led to the observed pattern of pile deviation mostly associated with the pile installation sequence adopted by the Piling contractor.

2 CHRONOLOGY OF EVENTS

As there were more than 6,000 piles installed within the 3 months, the piling contractor decided to carry out piling works and levelling earthworks simultaneously and splitting the site into several zoning namely Zones A, B, C, D and E for main building and Zones labelled as MCP, MSCP and TNB for other miscellaneous structures for all contracted works to complete in time. The construction sequence for different category of works within the contract period were illustrated in Figure 1.

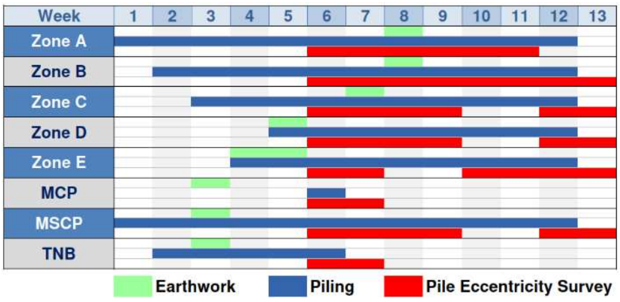

Figure 1. Gantt chart showing construction at different zones with additional levelling earthworks, piling and pile-eccentricity surveys.

3 GENERAL GEOLOGY

The project site is underlain by alluvium of Quaternary age according to the Geological Map of Pulau Pinang and Butterworth Area New Series L7011 Sheet 28, Pulau Pinang as published by the Director General, Minerals and Geoscience Department of Malaysia (2014). Alluvium is a common surficial deposit in Malaysia especially along the coastal areas. The alluvium generally consists of inter-layered sands, silts and clays from the fluviatile deposits in the main river valleys.

4 SUBSURFACE INVESTIGATION

4.1 *Subsoil condition*

Ten boreholes were carried out at the project site with locations as shown in Figure 2. The interpreted subsoil profile and SPT-N profile are presented in Figure 3. In general, the uppermost soils are 2m to 6m thick earth fill over the coastal surficial deposits consisting of upper alluvium of predominantly fine clayey soils (27m to 30m in thickness) and the lower alluvium of interlayered coarse-grained soils and fine clayey soils.

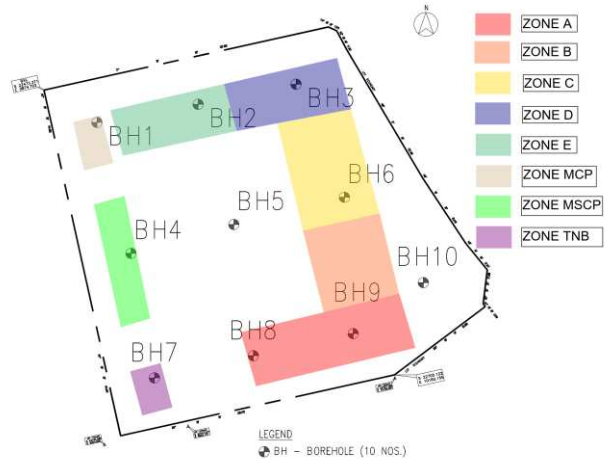

Figure 2. Borehole layout plan with different piling zones.

4.2 *Groundwater Level*

Groundwater level was measured in the boreholes over the course of the subsurface investigation, in which, the recorded groundwater levels were shallow and can be down to a depth of 0.90 m below filled platform level.

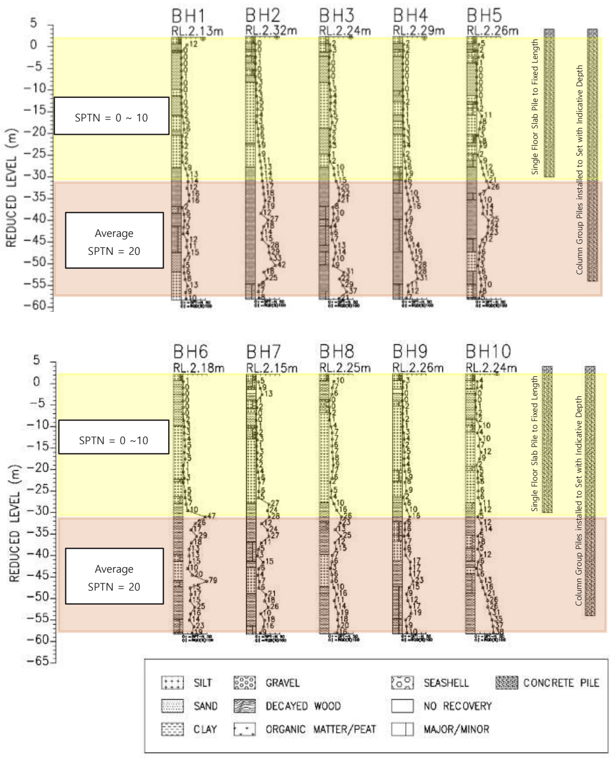

Figure 3. Borelog profiles with pile toe levels indicated to show that piles predominantly were terminated at about -30mRL (piled-to-length) and -54mRL (piled-to-set)

5 PILE ECCENTRICITY SURVEY

Two stages of pile eccentricity surveys were carried out for the installed piles at the proposed site, namely Piling Platform stage and Pile Cut-off stage. The pile eccentricity surveys for both stages in resultant directions for the group piles in Zone A to Zone E of Main Building are illustrated in Figures 4a and 4b.
The resultant pile deviations were classified into three categories, namely: (i) Deviation less than or equal to 200 mm (Blue to Magenta), (ii) Deviation more than 200 mm but less than or equal to 400 mm (Magenta to Orange), and (iii) Deviation more than 400mm (Orange to Yellow).

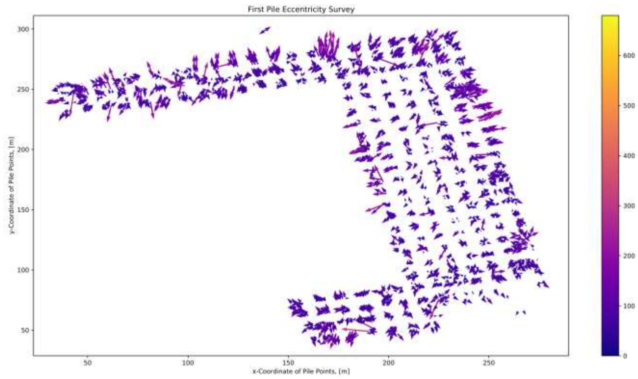

Figure 4a. Resultant Deviation of Group Piles – Piling Platform Stage

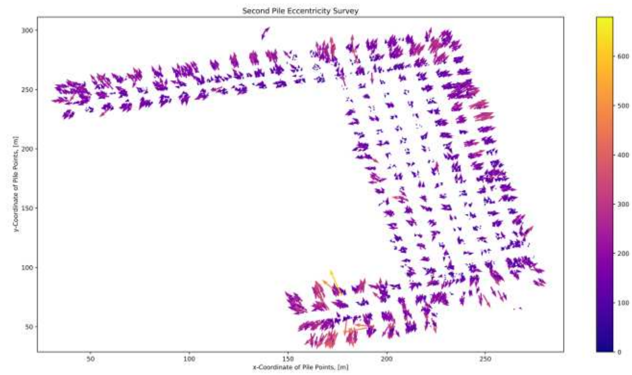

Figure 4b. Resultant Deviation of Group Piles – Pile Cut-off Stage

Severe pile deviations were observed on several column group piles along the external columns at the Pile Cut-off Stage survey in Figure 4b. However, much less severe pile deviations at external column group piles were observed at the Piling Platform Stage survey as shown in Figure 4a.

Observation can be made to both Figure 4a and Figure 4b. First, relatively significant net outward deviation within larger column group piles comparing to smaller column group piles (predominant phenomenon). Secondly, internal column group piles appear to have less net deviation in the Pile Cut-off stage survey, which can be attributed to the corrective push-back action from surrounding single floor slab piles. Lastly, external column group piles tend to have more net outward deviation.

6 PILE TESTS

6.1 *Pile Integrity Test (PIT)*

Pile integrity test (PIT) deployed is one of the popular pile structural integrity assessment methods in Malaysia piling industry. This test can detect pile damage with reference to the change of pile impedance from the test hammer impact.

A total of thirty (30) number of PITs were carried out on the installed piles. The test reports generally indicated that no observable pile impedance problem in all tested piles, thus implying no pile defect detected as concluded by the tester. However, authors have reserved their opinion that there is depth limit of pile integrity verification due to natural attenuation of the wave signal in a long friction pile. At best, the testing results shall be treated as no shallow defects detected within the effective depth of the detectable returning signal by the pickup sensor placed on the pile top.

6.2 *High Strain Dynamic Pile Test (HSDPT)*

High Strain Dynamic Pile Test (HSDPT) is another common pile testing method to verify the designed working capacity of pile foundation and integrity with longer verified pile length.

A total of three hundred and sixty-one (361) HSDPT were carried out on the installed piles. By observing the piling records, most of the large displacement piles were installed and terminated within the inter-layered alluvium with low permeable fine soils, which consequently causes the installed piles susceptible to the generated excess pore water pressure along the pile shaft. As such, the site has conducted HSDPT at least 7 days after the pile installation to allow beneficial strength gain in the subsoil for necessary dissipation of excess pore water pressure.

Generally, 94% of performed HSDPT were reported as intact piles without observable defects detected. The balance 6% test results identified defects that are either at pile joints with probable open gap at welded joints or pile body near to the pile joint due to accuracy of wave speed in determining the possible defect at the joint. Air gap at joint welding shall not be taken as defect affecting pile performance. Compensation piles were installed to replace the defective piles as identified by HSDPT and tie beams were proposed for column pilecaps that had excessive pile deviations by the design consultant. Thus, overall acceptable pile performance can be reasonably concluded based on these HSDPT results. A summary of the HSDPT results is presented in Figure 5.

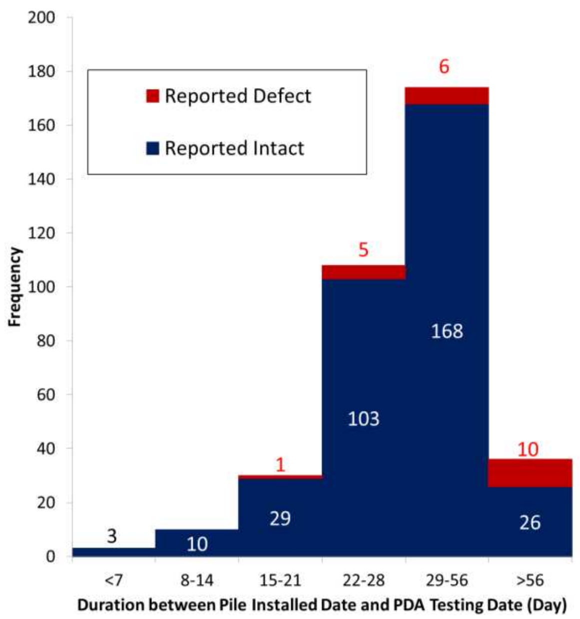

Figure 5. Histogram of the HSDPT test results indicating that majority of the piles are intact with no defects detected.

6.3 *Static Maintained Load Test (SMLT)*

Static Maintained Load Test (SMLT) is one of the most reliable pile assessment methods to determine the pile capacity and pile deformation performance under a designated test load.

A total of six (6) number of SMLTs were carried out on the installed piles and the results are tabulated in Table 1. Generally, the settlements of all tested piles are less than 12mm during the 1st cycle of the imposed load for most of the long friction piles at main building structure as shown in Table 1. Most test piles have also been proof loaded to load factor of 2.5.

Table 1. Tabulation of SMLT results indicating acceptable pile performance

Pile Ref.	Pile Length (m)	Pile Size (mm)	Settlement at 1xPWL (mm)	Settlement at 2xPWL (mm)
MLT 1	48.9	350X350	9.25	16.89
MLT 2	29.5	200x200	9.07	21.05
MLT 3	29.5	200x200	6.77	16.75
MLT 4	45.0	250x250	6.54	23.82
MLT 5	54.0	350x350	7.71	17.69
MLT 6	30.0	200x200	10.45	29.13

** PWL denotes as pile working load*

After collective review of all the pile test results, the pile performance shall be considered acceptable at the completion of the contract work and handover to building main contractor despite with the facts of observing pile deviation.

7 PROBABLE MECHANISMS OF SEVERE PILE DEVIATIONS

Based on the provided information and reviews on relevant test results, the probable mechanisms contributing to pile deviations can be as follows:

7.1 *Workmanship*

Two probable workmanship issues could have contributed to pile deviation as observed at the proposed site, namely error in pile setting-out survey and pile wandering movement deviated from initial setting out position during pile penetration.

Excessive pile deviation from its designated position can occur during the initial pile setting-out stage. This can be error in human surveying operation and equipment during the pile pegging process. However, since optical survey equipment and trained survey personnel were engaged to set out the pile position, this error shall be practically controlled within acceptable tolerance in piling works. It shall be logically and rationally the same standard of accuracy adopted in the pile as-built survey.

With ground variability, piles installed with compressive loading either by jacking pressure or hammer percussion impacts on pile head can deviate to the least resisting direction with comparatively weaker lateral constraints. Other than inclination control in the initial pile pitching related to workmanship problem, this type of installation deviation and wandering movement due to ground variability is difficult to avoid. Once deviation occurs during the course of pile penetration, corrective action to force verticality of pile is usually discouraged in practice as it may do more harm than good.

7.2 *Soil Movement Caused by Pile Installation*

The proposed site was located within the alluvium, which consists of thick layer soft compressible alluvial deposits exhibiting with the important behaviours as listed below:-

a. High degree of saturation
b. Highly impermeable with coefficient of permeability ranging from 10^{-7} to 10^{-9} m/s
c. Relatively incompressible soil matrix under rapid loading

d. Undrained behaviour where the subsoil deforms without volumetric change.

Installation of soil displacement pile will displace in-situ soil and subsequently push the preceding installed piles away from the installed position. Liew & Ho (2016) presented two modes of soil displacement with initial ground surface heaving in early stage of shallow pile penetration and, then predominantly radial displacement at deeper pile penetration after attaining sufficient vertical overburden pressure. Study conducted by Sagaseta & Whittle (2001) revealed the soil displacement due to pile installation could be severe if the preceding installed pile located near to subsequently installed pile. Figure 6 demonstrates the contour of radial soil displacement from a cylindrical pile of diameter 0.35m and 30m as suggested by Sagaseta & Whittle (2001).

The radial small-strain soil deformation from a cylindrical pile can be calculated with reference to Eq. 1.

$$\boldsymbol{\delta_{rSS}(r,0)} = \frac{\Omega}{2\pi}\frac{L}{r\sqrt{r^2+L^2}} \quad (1)$$

Where,

R denotes the radius of cylindrical pile
L denotes the driven length of cylindrical pile
r denotes the radial distance from the centroid of cylindrical pile
Ω denotes the cross-sectional area of pile

From Eq. 1a below, the radial small-strain soil deformation at three-pile diameter away from a cylindrical pile of radius 0.175m and 30m length can be calculated as below:

$$\boldsymbol{\delta_{rSS}(r,0)} = \frac{\pi\times 0.175^2}{2\pi}\frac{30\times 1000}{1.05\sqrt{1.05^2+30^2}} = \mathbf{15\ mm} \quad (1a)$$

A total of 6,248 piles from 150mm to 350mm in sizes were installed with majority piles located within the plant area of about 24,260m^2. For the top 30 m of subsoil, this number of pile points will have the total solid volumetric pile volume of 20,125 m^3. Considering soil displacement resulted from this volume of pile inclusion, the overall soil displacement ratio (ratio total volumetric soil displacement by piles to the total soil volume of prescribed geometry under consideration) is about 2.77%, which shall lead to a conservative average lateral outwards soil movement of about 364 mm around the main building perimeter.

If considering the largest column group piles of 16 numbers of 350 mm RC piles at centre-to-centre spacing of 3 times of pile size, the computed soil displacement ratio can be as high as about 16% which is again equivalent to an average lateral outwards soil movement of 135mm along the peripheral of the group piles.

In a more microscopic view of a single pile condition based on an earlier installed pile at centre-to-centre spacing of 3 times of pile size, the radial soil displacement movement of about 20 mm is expected at distance of 3 times of pile size for a penetrating 350 mm RC pile. However, the effect of soil displacement shall be a cumulative soil displacement by all later installed piles to the earlier installed piles. That is why larger outward soil movements occur in the scenarios of column group piles and, also entire main building as discussed above. It is worth to note that square pile of same width as diameter of circular pile will have larger cross-sectional area, thus larger soil displacement.

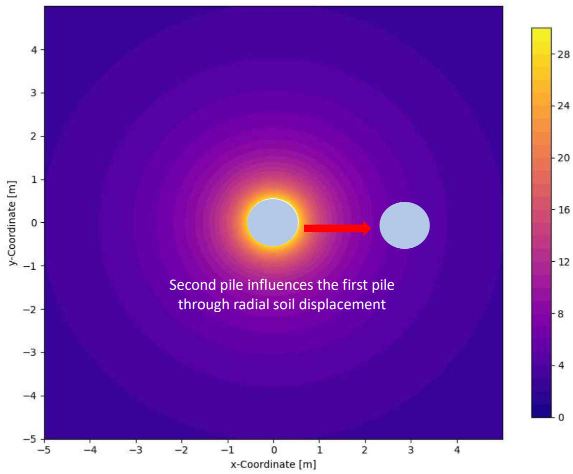

Figure 6. Contour of small-strain approximations of ground movements at point away from the pile based on Shallow Strain Path Method (Sagaseta & White, 2001)

The aforesaid phenomenon justifying the reason of column group piles located on the peripheral of the Main Building was observed with more net outwards deviations while pushing back the internal column group closer to their designated installed position.

Such soil displacement induced by massive piling works within short construction period is practically unavoidable. However, its severity can be substantially minimized with symmetrical piling pattern for balanced soil displacement for tank foundation as shown in Figure 7, in which a tank farm foundation with severe pile deviation was investigated and similar mitigating measures were suggested by Liew, et al. (2010).

Figure 7. Symmetrical piling pattern for tank foundation (Liew, et al., 2010).

7.3 *Numerical study on Soil Movement influenced by sequence of Pile Installation*

To investigate the influence of pile installation sequence on the pile deviation due to undrained soil displacement, Plaxis 3D finite element models with staged construction were set up to simulate two different installation sequences of group piles. A 9-

oordinates of Pile Points, m

pile configuration was adopted in the Plaxis 3D model to simulate two different piling sequences that are either in symmetrical or non-symmetrical pattern. The symmetrical and non-symmetrical piling configurations are illustrated in Figures 8a & 8b and Figures 9a & 9b respectively with labels from 1 to 8 indicating the sequence of pile installation for clarity.

Subsequently, pile head displacements of the pile of interest at the center or top right of the 9-pile configuration were then compared and recorded in Table 2. The square pile of interest was modelled using linear elastic concrete elements with dimension and length of 0.35 m and 30 m respectively.

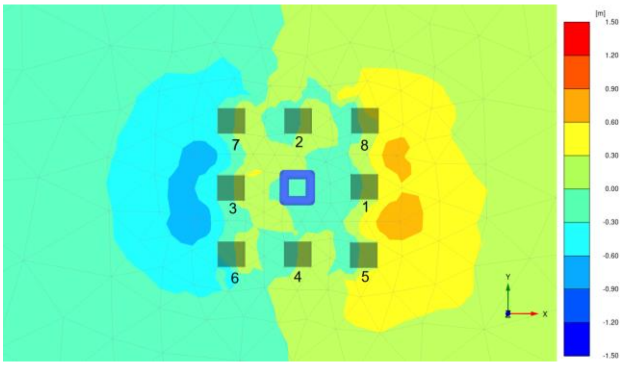

Figure 8a: Soil displacement in the direction of x, u_x due to symmetrical pile installation sequence.

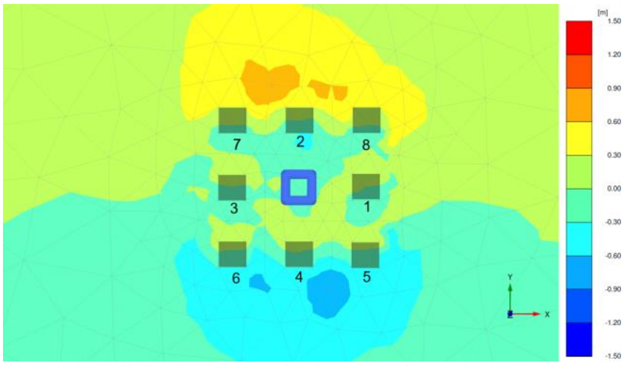

Figure 8b. Soil displacement in the direction of y, u_y due to symmetrical pile installation sequence.

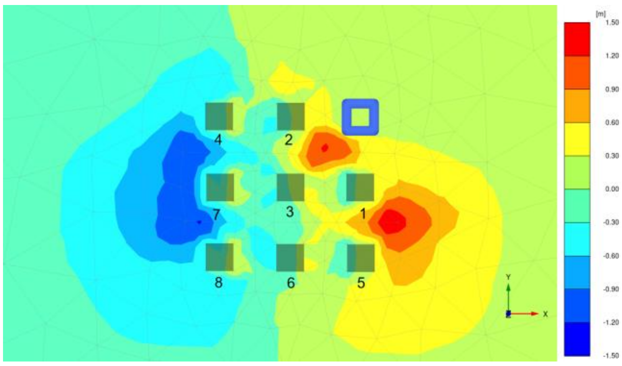

Figure 9a. Soil displacement in the direction of x, u_x due to non-symmetrical pile installation sequence.

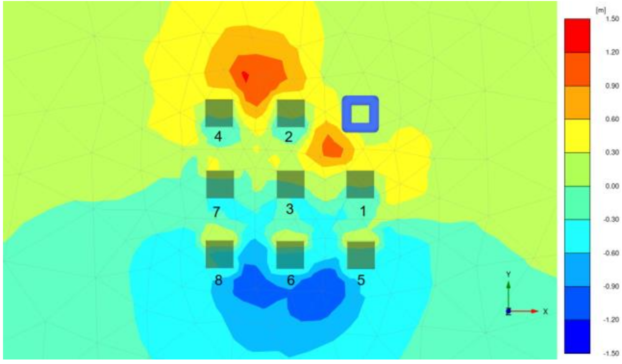

Figure 9b. Soil displacement in the direction of y, u_y due to non-symmetrical pile installation sequence

In the case for solid pile driven into undrained soil, soil can be displaced radially outwards or upwards as soil heaving. The volume of displaced soil is equal to the volume of the solid pile at undrained soil state. For depths greater than ten times the pile radius, Randolph et al. (1979) noted that the predominant soil displacement will be in the radial direction.

To simulate soil displacement in Plaxis 3D due to pile installation in undrained soil and to simplify the model, prescribed surface displacements over the entire length of installed pile were applied at locations labelled from 1 to 8 in running installation sequence, which are adjacent to the pile of interest enclosed with thick blue lines. Following the prescribed surface displacement of a particular pile, the pile material properties were assigned and activated to model the existence of the pile stiffness in the soil model for subsequent pile-soil interaction simulation. This will likely produce a conservative magnitude of soil movement profile with the radial distance from the installed piles as the soil displacement always happens beneath the pile toe of the installing pile as the pile penetrates.

With reference to Table 2, it is obvious that symmetrical pile installation sequence minimizes undesired pile deviation due to undrained soil displacement. For the case of symmetrical piling pattern, the pile head of interest remains undisturbed as pile head displacements in the x-direction and y-direction are marginal, with magnitudes of 45 mm and 78 mm respectively.

Table 2. Tabulation of maximum pile head displacements resulted from symmetrical and non-symmetrical piling configuration

Sequence of Piling	Pile Head Displacements	
	u_x (mm)	u_y (mm)
Case A: Symmetrical	-45	-78
Case B: Non-Symmetrical	+221	+221

As for the case of unsymmetrical piling pattern, pile deviation is more pronounced as evidenced by the larger pile head displacement in the x-direction and y-direction, with magnitudes of 221 mm for both directions.

7.4 *Disturbance by moving piling rigs and earthworks machineries*

As the site was located at the soft alluvium, it was probable that the high bearing pressure from the heavy self-weight of the jack-in pile machine including the kentledge counter-weight can cause some undrained soil deformation of the underlying weak alluvial soils and subsequently results in pile deviation.

The effect of pile deviation caused by the inadequate subsoil bearing capacity was believed to be relatively low compared with deviation caused by soil displacement by pile installation despite some bearing squeezing effect to the underlying subsoils can be expected. Otherwise, problem of piling machine sunk into the distressed piling platform shall have been reported.

7.5 *Timing Difference of As-built Surveys Taken*

As both as-built surveys were taken at different time with maximum time interval of about 2 to 3 months apart, difference of pile deviation also could possibly be caused by the construction disturbances, i.e. machineries movement, knocking of piles off position by construction equipment or disturbance during pile cap excavation. The effects of aforesaid construction disturbances are unable to be credibly quantified unless otherwise incident record was made right after any disturbance and as-built survey taken for the specific incident.

Hence, any inconsistent results of pile deviation due to construction disturbance is not unreasonable for the proposed site with 21 nos. of piling machines movement during the contract period and, also random pattern of earthwork construction.

8 CONCLUSIONS

From reviewing the problems in this case study, the following conclusions can be deduced and summarised for lesson learnt:

(i) More than 6,000 pile points ranging from 30m (pile-to-length) to 54m (pile-to-set) were installed on site for the proposed development. Earthwork and as-built surveys were carried out concurrently with piling works due to tight contract period of 3 months approximately.

(ii) Two stages of as-built survey were carried out on the installed piles with the following sequences:-

a. Piling Platform Stage –The survey was taken immediately after installation of column group piles, variance of pile deviation is relatively smaller implying the systematic soil displacement arising from pile installation to preceding installed piles.

b. Pile Cut-off Stage –The survey was taken only after all the piling works and earthwork had been completed by the Piling contractor. The variance of pile deviation is clearly larger implying more and random construction disturbance in addition to a sole soil displacement effect from pile penetration.

Reasons for the differences in observed pile deviation between the Piling Platform Stage and Pile Cut-off Stage are summarised as follows:-

a. Workmanship – error in pile setting-out survey shall be within the acceptable survey error in conventional optical survey and installation deviation (pile wandering) to the lateral direction of least resistance during pile penetration is something unavoidable due to ground variation, which is not within the purview of reasonable construction control in practice.

b. Soil movement caused by soil displacement pile installation – Due to soft compressible and low permeability nature of the alluvium, installation of soil displacement piles will cause soil displacement which will then push the preceding installed piles away from the initial installed position. Average volumetric soil displacement ratio of about 4% per installed pile at pile centre-to-centre spacing of 3 times of pile size could push the preceding installed pile away from the installed position as shown in the joint survey. The pile deviation is a cumulative effect of soil displacement from subsequently installed piles.

c. Disturbance by machineries – Jack-in pile machines were deployed for installation of 350mm RC piles. With machine self-weight and counter-weight, the existing ground may have the possibility of insufficient bearing capacity to sustain the load without squeezing of underlying soft subsoil and eventually causing lateral creeping soil movement pushing the piles. But pile deviation from such factor shall be less significant as no severe machine disturbance was reported.

d. Time difference of as-built survey taken - installation productivity of 69 piles per day was required to meet the 3 months contract period and 21 nos. of piling machines and many earthwork machineries were mobilised for the piling operations and earthworks respectively. As such, the installed piles are susceptible to accidental load from the machine which could possibly cause pile movement but not recorded in the incident report.

From the experience in this case study, some lessons learnt to reduce the risks of pile deviation in soft ground project sites are suggested below:

(i) To avoid massive piling with short construction period as undrained soil displacement can be reduced with longer duration for dissipating the induced excess pore pressure.

(ii) Where possible, smaller pile size shall be considered for friction pile design as it has larger pile surface area for pile capacity and lower volume of pile body for less soil displacement to provide a of unit pile carrying capacity.

(iii) Large pile size utilizing full structural capacity pile is preferred for end bearing pile design.

(iv) End bearing group piles with closer pile spacing supporting building columns, which have less tolerance of pile deviation shall be installed at later as compared to single fixed length floor slab piles at larger pile spacing.

(v) To plan the piling installation sequence for group piles to achieve symmetrical and counter acting soil displacement at opposite direction simultaneously, preferably from centre pile towards outer piles. This is to reduce the deviation of the group pile support centroid from the column.

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