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A Research for Deviation Estimation Analysis for Driven Piles Foundation: A Case of Penang Second Marine Bridge

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Abstract. The aim of this preliminary research is to study the accept tolerance of driven piles with position's deviation. More than five thousand driven piles were installed in the approach bridge, which adopted two classes, i.e.Φ1.6m steel pipe pile and Φ1.0m spun pile. The original position acceptance criteria was deviation tolerance less than 75mm. This was not reasonable enough to take into account the marine construction conditions. According to a detailed comparison of the existed different standards and simplified calculation with representativeness, The recommended acceptance criteria could be adjusted to 150mm. This study makes up for the lack of Malaysia pile foundation technical specification especially for large diameter driven piles and it will effectively promote the practical application of ones in Southeast Asia infrastructure works.

1 Introduction

The Penang Second marine bridge located at Penang island channel is approximately 22km in length with a total of 16.5km of bridgeworks of which around 15km is over water. It is the largest bridgework in the southeast Asia. The bridge is made up of multiple approach span viaducts from both sides with a signature structure featuring longer spans and a higher clearance envelope over the southern navigation channel. The general view of the bridge is shown in *Figure 1*.

The Malaysian Public Works Department (Malay: Jabatan Kerja Raya Malaysia), abbreviated JKR, is responsible for construction of public infrastructure in West Malaysia. The foundation of approach bridge mostly consisted of driven piles, i.e.Φ1.6m steel pipe pile and Φ1.0m spun pile. The number of 5168 spun piles and 396 steel pipe piles were installed in whole project. The proportion with deviation exceed original acceptance criteria, i.e. 75mm ruled by JKR specification, reached around 85 percent. Acceptance piling work faced specific challenges. In order to avoid delaying the time limit for the project, Appropriate revision of existing control standards would be essential.

2 Specifications used in different countries

2.1 Malaysia JKR standard specifications for roadworks

The Employer Requirement of this case was followed by Malaysia JKR Standard[1]. The Clause 10.2.2 of Section 10 Piling Works stipulate as follows:“For a pile cut off at or above ground level the maximum permitted deviation of the pile center points shown on the Drawings shall not exceed 75mm in any direction.”This specification did not specify the difference of pile deviation between land piles and marine piles, therefore the tolerance was generally 75mm.

2.2 Hong Kong general specification

In the Hong Kong General Specification[2], both the installation tolerances for marine and land bored piles are given. The tolerances are 150mm and 75mm for marine and land piles respectively.

Figure1. General view of Penang Second Marine Bridge.

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2.3 British standard BS 8400 and BS6349

BS8400[3]: Clause 7.4.1.3.1 General of Section 7 Pile Foundations stipulate as follows:"When driven, piles should not deviate more than 75 mm from their designed positions; a greater tolerance may be permitted for piles driven over water."

BS8400: Clause 7.4.2.5.4 Position and Alignment Tolerances of Section 7 Pile Foundations stipulate as follows:"Piles should not deviate more than 75 mm from their designed positions at the working level of the piling rig. Greater tolerance may be prescribed for piles driven over water and for raking piles." & "Any pile deviating beyond these limits and to such an extent that the resulting eccentricity cannot be taken care of by a redesign of the pile cap or pile ties should, at the discretion of the engineer, be replaced or supplemented by one or more additional piles."

BS6349[4]:Part 2: Clause 6.13.1 Pile Head "The centre of piles at the junction with the superstructure should be within 75 mm of the specified position for structures built on land or in sheltered waters. For piles driven through rubble slopes this tolerance may be increased to 100 mm. For access trestles and jetty heads a tolerance of 75 mm to 150 mm should be adopted, depending on the exposure of the site. The design of piles and deck members should take into account the specified tolerances."

Both standards specify the deviation of land piles is 75mm, and allow appropriate greater tolerance of deviation for marine piles. In BS6349, it is specified a tolerance 150mm for piles in jetty or access trestles.

2.4 Habour engineering standard of China

Clause 8.5.2.1 of the Specification of Pile Foundations for Port Engineering (JTJ-254-98) [5] is stipulated as follows in *table 1*:

This specification clearly specifies the different pile deviations at different regions, based on different operating conditions of marine piling works. Currently similar projects in China strictly follow the requirements of condition "Coastal Water without Cover" in *Table 1* to control the pile deviation. In addition, the condition "Coastal Water without Cover" is more in line with the sea conditions of this project and can be reference of this project.

3 Factors affecting pile deviations

Considering the actual situation of this project and summaries of similar projects[6], the major reasons for the deviations of driven pile using the current piling workmanship are listed in *Table 2*.

According to the servey of pile deviations' statistics, vertical piles have smaller deviations which basically can satisfy the requirement of 75mm. The deviations for raking pile are larger and are difficult to comply with the requirement of 75mm. The pile deviation for raking pile are within 150mm generally and individual pile exceeds 200mm.

Combining the pile arrangements of the bridgework and the data of completed piles, the following preliminary conclusions can be drawn for the influence to pile foundations due to pile deviations:

- As the spatial piles are adopted generally, it is possible to have deviations in the twist angle, rake and plan coordinate of single pile. In addition, the probability of having deviations in plan coordinates is the largest and the magnitude is the largest. It is the major factor that results in the force-taking of pile foundations different from the design value.
- Table 2 reveal that, the non human manageable factors that resulting plan coordinate deviations are more. It leads to large discreteness of deviated pile quantity, direction and deviation amount within a single pilecap. This shows that, by estimation to determine the maximum allowable tolerance for pile, it is difficult to cover different situations of actual piling works.
- With the provision of the discreteness of pile deviation, if a individual pilecap has more supporting pile and basically symmetrical pile arrangement, the actual pile group capacity after driving will have less difference against design value.
- From the pile material point of view, steel pile is obviously better than spun pile[7]. The former has better adaptability after the occurrence of pile deviation. However, the water for steel pipe pile zone is deeper and the steel pile body is longer. It makes the deviation control for steel pile is much difficult than that for spun pile. It is estimated that the deviation tolerance for steel pile can be larger than that of spun pile.

Table 1. Requirements for Pile Foundations Deviation Unit: mm

Pile Type	Spun Pile		Steel Pile	
	Vertical	Rake	Vertical	Rake
River and Coastal Water with Cover	150	200	100	150
Coastal Water without Cover	200	250	150	200
Offshore Water without Cover	250	300	250	300
Coastal water means distance to coast < 500m; offshore water means distance to coast ≧ 500m				

Table 2. Reasons for Deviations of Pile

Item	Reasons for Deviations
1	Accuracy of GPS measurement

2	Piling barges uses anchor and cable for positioning. Certain degree of waving and even shifting will be resulted under the effect of wind, wave and water flow.
3	Accuracy of setting-out before driving and errors

4 Analysis

4.1 Selection of Critical Pier Type

As this project has many type of pile arrangements, representative pier types with consideration of number of piles, scour depth and type of arrangement (see *Table 3*) are selected to perform estimation.

According to the comparison result in Table 3, Type 3 of steel pile and Type 4 and 6 of spun pile is selected as control pier type to carry out calculation.

4.2 Assumed Load Case

Considering the results from detailed design, distance that much possible appeared in pile deviation and the worst favorable deviation direction are selected to perform calculation. The determination of formation of pile deviation is listed in *Table 4*.

The influential factors considered in calculation and calculation procedure are as follows:

Step A. Select appropriate estimated deviation amount (Factor 1, Symbol A shown in *table 4*)

Step B. Select unfavorable pile deviation direction (Factor 2, Symbol B shown in *table 5*)

Step C. Select external control load case (Factor 3, shown in *table 6*) → *Perform Assessment to Analysis Result*

These 3 factors do not have relationship with each other, accurate calculation should take into account the envelop value from different combination of these 3 factors. However, with the limitation of huge amount of actual combinations and calculation results may not show any regular pattern, it can only consider the adverse conditions in 3 factors separately together with actual conditions in the analysis.

Table 3. Control Pier Type Comparison

Pile Type	Pier Type	Control Pier Type	Among same Pilecap type		
			Min. No. of Pile	Max. Scour Depth	Non-symmetrical Pile Arrangement
Steel Pile	Type 1/2/3	Type 3	√	√	√
Spun Pile	Type 4/5/6	Type 4	√	√	√
		Type 6	-	√	√

Table 4. Selection of Appropriate Estimated Deviation Amount (Symbol A) Unit: mm

Deviation Amount	A1 < 75mm	A2 < 150mm	A3 < 250mm	Remark
Relevant Standards	JKR-	Hong Kong General Spec. & JTJ-254-98	JTJ-254-98	-
Occurrence % in Actual Piling	10 %	80 %	10 %	Currently the quantity of completed steel pile is small, lack of actual deviation data
Appropriate Pile Type	Spun Pile	Spun Pile	Steel Pile	
Amount A selected in analysis	√	√	√	

Table 5. Selection of Unfavorable Pile Deviation Direction (Symbor B)

Deviation Direction	B1a(b) – All Longitudinal (Transverse) Deviation	B2 – All Radial Deviation

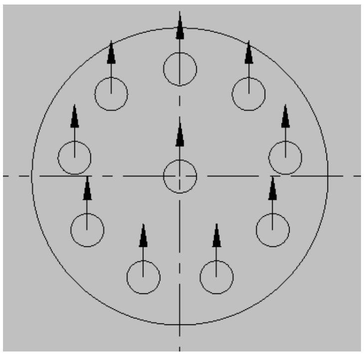
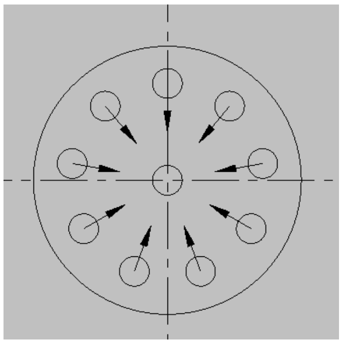
Diagram		
Description	Longitudinal and transverse deviation, separate analysis	All radial deviation (towards centre), individual analysis

Table 6. Selection of External Control Load Case

Pile Type	Spun Pile			Steel Pile	
Check Items	Single Pile Capacity	Stress Check under SLS	Strength Check under ULS	Single Pile Capacity	Pile Body Strength Check
Analysis Load Case	Operation Stage / Construction Stage	Operation Stage (wind + wave)	Operation Stage (seismic)	Operation Stage / Construction Stage	Operation Stage (seismic)

4.3 Summary of Analysis Result

Considering the deviation amount, deviation direction and different combinations of control load cases, the analysis combinations and corresponding results are tabulated as follows:

Considering spun pile, The above summary tables show that the deep water region like Type 5 and 6, due to longer pile free length, the control item after pile deviation is pile body stress under SLS conditions which is closed to the limit of pile. For most of pile in Type 4, the single pile working load is closed to the limit of 3800kN under certain load cases. Based on the presumed deviation, the working loads of pile in above combinations are closed to presumed design capacity and the pile group is still found to be structurally acceptable under the assumed pile deviation. Analysis Results of spun pile types are listed in *table7* and *table8*.

Considering steel pile, The above reason shows that the steel pile zone in deep water region, when large pile deviation happens, the single pile working load becomes large while the pile body strength still have certain amount of capacity. Based on 200mm assumed deviation for analysis, the working loads of pile in above combinations are comparatively large. However, if it is calculated based on 150mm deviation, the pile load will be well within the 7300kN capacity. Analysis Results of steel pile type is listed in *table9*.

Table 7. Analysis Results for Type 4 Pile Deviation Unit: kN,m MPa

Analysis Description	Single Pile Working Load	SLS Stress Check	ULS Strength Check		Conclusion
Analysis Combinations		Max. Tensile Stress	Relevant Axial Force	Moment	
A1&B1a	3527/4234	8.7	5354	1455	Single pile working load is closed to max. 3800kN in some combinations
A1&B1b	3547/4332	9.1	5337	1425	
A1&B2	3627/4361	8.4	5267	1410	
A2&B1a	3446/4134	9.2	5463	1498	
A2&B1b	3513/4375	8.6	5403	1454	
A2&B2	3712/4388	8.9	5274	1411	

Table 8. Analysis Results for Type 6 Pile Deviation Unit: kN,m MPa

Analysis Description	Single Pile Working Load	SLS Stress Check	ULS Strength Check		Conclusion
Analysis Combinations		Max. Tensile Stress	Relevant Axial Force	Moment	
A1&B1a	3425/3628	11.1	5421	1588	Tensile stress is

A1&B1b	3324/3533	8.4	5562	1605	close to max. 11.9MPa under in SLS conditions
A1&B2	3507/3713	10.9	5493	1551	
A2&B1a	3358/3566	11.2	5493	1625	
A2&B1b	3274/3575	8.6	5546	1648	
A2&B2	3523/3737	10.8	5494	1549	

Table 9. Analysis Results for Type 3 Pile Deviation Unit: kN,m MPa

Analysis Description	Single Pile Working Load	ULS Strength Check		Conclusion
Analysis Combinations		Relevant Axial Force	Moment	
A3&B1a	7527	11074	3231	Single pile working load slightly exceeds 7300kN in some combinations, about 3%
A3&B1b	7488	11264	2709	
A3&B2	7139	11043	2834	

5 Conclusions

The conclusions of this research could be listed as followed:

- The analysis results are based on simplified assumed conditions. The deviations in actual piling process are randomized. The abovementioned extreme cases should not exist.
- The deviations for spun pile affect single pile axial force and pile body tensile stress. Based on the estimation from current combinations, *the maximum deviation for spun pile is limited within 150mm should be practical.*
- The main effect due to the deviations for steel pile is increase of pile body axial force. Based on 200mm assumed deviation for analysis, the basic results in some combinations slightly exceed 3% of limitation value. However, considering the deviations in actual piling process are randomized and the presumed deviation should not exist, *the maximum deviation for steel pile is limited within 150mm should be acceptable.*
- It is recommended for any pile group with piles deviated not more than 150mm, additional calculation will not be conducted for demonstration of acceptability. However, *for pile group with pile deviation greater than 150mm, Reviewing calculation shall be carried out to justify the structural acceptance.*
- As this project adopts precast R.C. shell to be the external formwork for pilecap construction, the extended length of the R.C. shell below the bottom of pilecap is comparatively long. *Over-deviated pile foundations will result to difficulty of R.C. shell installation. Therefore the Contractor shall strictly control the deviation direction and amount.* Every endeavour shall be tried to comply with 75mm of deviation requirements which is stipulated in JKR Standard Specifications for Road works.

This study is providing an approaching to solve the problem of driven pile foundation acceptance criteria and promoting the updating of local bridgework technical specification. The recommendation could be adopted for the similar huge marine bridgeworks which installed large diameter driven piles and will effectively promote the practical application of ones in Southeast Asia infrastructure works.

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