Forensic on Construction Induced Failure of Pipe Pile Foundations

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6th International Conference on
Case Histories in Geotechnical Engineering, Arlington, VA, August 11-16, 2008

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ABSTRACT

This paper introduces a case where pipe piles failed during construction. The accident happened when constructing the Jiaoxi Pumping Station project in the southern China. The site consists of very soft sludge and silt deposits. Pipe piles were used as foundation under the station structure. The installed pipe piles were observed to show significant inclination during the construction. A forensic investigation was performed. The driving forces for pipe pile failure were attributed to the lateral load induced by the excavation activities. Small strain integrity test and inclination measurement were taken to determine the location of breakage and the extent of inclination. The test results combined with theoretical analysis were able to determine the cause of pipe pile failure. Remediation measures were designed and implemented based on the results of forensic analyses. Recommendations were proposed to guide construction activities on soft soil deposit. The results of implementing these guidelines during remediation construction were satisfactory.

INTRODUCTION

The pre-stressed concrete pipe pile features many advantages including possessing a variety of selections, fastening the construction speed, shortening the construction time, allowing for a reliable QA/QC program, resulting in low unit construction cost etc. It has becomes a favorite type of pile selection in Southern China, both among designer and builders. Pipe piles have been widely utilized in many projects in Guangdong province of Southern China in the recent years. Attentions, however, need to be paid on pipe pile construction during the site investigation, design and construction stages. Ignorance of the details during any of these stages could lead to catastrophic failures. This paper presents a case history on the failure of pipe pile during construction. It demonstrates the necessity of embracing a comprehensive view on the design and construction issues related to pipe piles to ensure the quality of construction.

DESCRIPTION OF CASE HISTORY

Jiaoxi pumping station is located in the Nansha District of Guangzhou city in the southern province of Guangdong, China. It belongs to part of a comprehensive hydraulic project for JiaoMen Canal. A schematic of the pumping station design is shown in Fig. 1. It includes wing-wall, house of pump station, and transition inducts, and sluice etc. Deep foundation was selected due to the thick soft soil layer, which involved the use of pre-stressed concrete pipe piles to reduce structure settlement. Prior to installing the pipe piles, the ground under pumping station was treated by cement deep mixing. The diameter of these cement deep mixing columns is 0.5m with distance between columns of 1.1 to 1.15m. Pipe piles were installed to a depth of around 35m below the ground. Each pipe pile is spliced from sections of around 12m.

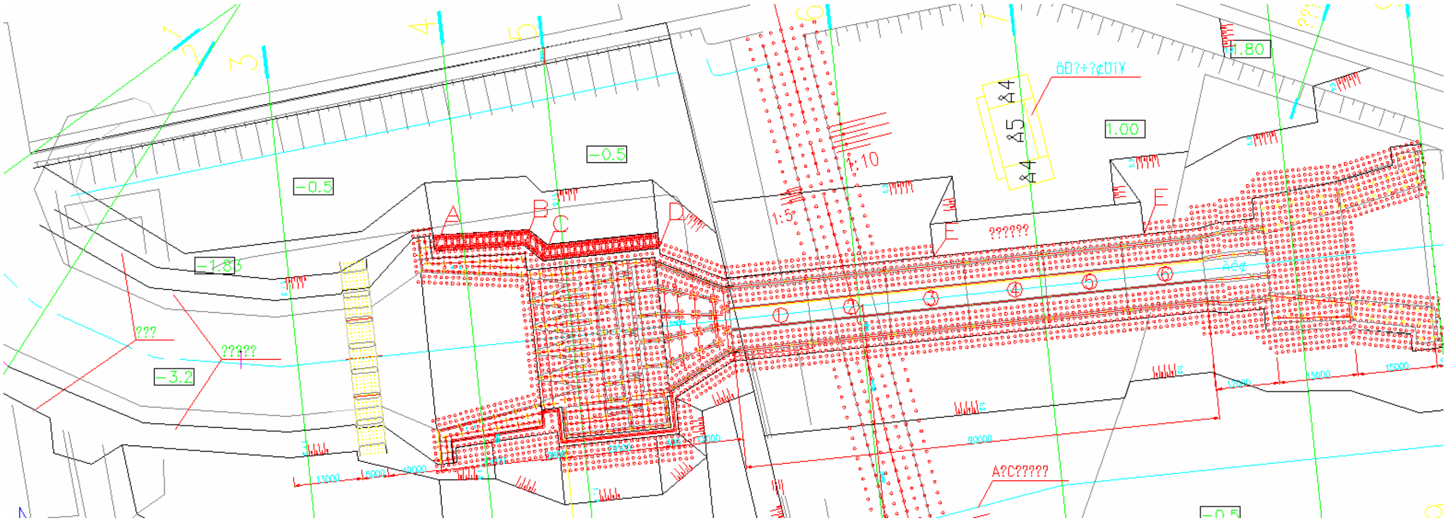

Fig. 1 Schematic design of Jiaoxi pump station

Upon the accomplishment of foundation installation, construction activities proceeded which included excavation for ground grading with backhoes (Fig. 2a). Severe inclination of pipe piles, however, were observed at a number of locations during the excavation process. The construction activities were halted after observing these excessive inclinations. The inclination of pipe piles continue to increase slightly until it reaches a stable condition. Figure 2b gives an example photo showing the inclination of individual pipe pile. Result of post-accidental survey indicated that the maximal lateral displacement at the top of pile reached as large as 2.6m. A statistics of the magnitude of pipe pile inclinations is listed in Table 1.

(a) (b)

Fig. 2 Severe inclination observed during excavation a) photo during construction; b)illustration of pipe pile inclination

Table 1 Statistics of pipe piles based on amount of inclination

Amount of Inclination	>2.0m	>1.5m	>1.0m	>0.5m
Percentage	11%	30%	55%	88%

FORENSIC INVESTIGATION

A forensic investigation was conducted at the site immediately after the accident was observed. This involved a complete review of the design and construction documents. The goal was set to identify the major cause of this accident and propose remediation actions that can be taken to ensure the safety of sluice structure.

Based on the results of subsurface investigation, analyses of initial design, and referring to construction experience under similar geological conditions, it was suggested that the disturbance of thick sludge layer is the major cause of pipe pile failure. The information from site investigation indicates there exists a thick layer of soft sludge at this site, which is typical of thick soft sludge deposit. Table 2 lists the geological and geotechnical parameters of major geological layers. A thick soft sludge layer of high water content exists at this site. It is characterized by the high water content and low penetration resistance. The tip of pipe pile was placed into a fine sand layer to offer the bearing capacity.

Table 2. Summary of geological and geotechnical features

Notation of soil layer	(2)-1	(3)-1	(3)-3	(4)-1	(4)-3	(4)-4
Soil description	sludge	Sand embedded with sludge	Fine sand	Silty clay	Sand	Gravel
Thickness (m)	17.3-25.6	2.5-10.30	1.7-5.3	0.7-18.30	1.2-13.2	1.5-9.5
Side friction (kPa)	12	22	42	50	80	116
Tip resistance (kPa)	/	/	/	/	7000	7000
Notation	w = 65%	N = 3	Moderate to high density	Hard plastic	Moderate to high density	dense

Ground vibration due to motion of construction equipment caused the sludge layer into a semi-liquified condition. Figure 3 shows a photo of the status of sludge to indicate effects of construction vibration on the sludge behaviors. As can be seen from the left hand side of this photo, the construction vibration caused the sludge to behave like a liquid.

Fig. 3 Effects of construction vibration on sludge

In conjunction with this effect, the differences in elevation due to excavation caused sludge to flow gradually under gravity. These subsequently applied a significant amount of unbalanced lateral force on pipe piles. As the consequent, the soil layer offered insignificant amount of lateral resistance. This unbalanced lateral force together with the lack of lateral support caused large bending moment action on the pipe piles, which was sufficiently large to cause the failure of spices in many cases. Among the factors led to the accident, the internal factor is the thick soft sludge layer with high moisture content; the triggering factor is the difference of elevation due to excavation activities.

As part of the forensic study, both Pile Integrity Tests (PIT) and inclination measurement were performed on the failed pipe piles. 164 such tests were conducted altogether. Example of measured results is shown in Fig. 4. Both the PIT signal and inclination data imply that the pipe pile fails at around 11m, which is close to the location of the last splicing. Similar failure pattern was observed on other pipe piles.

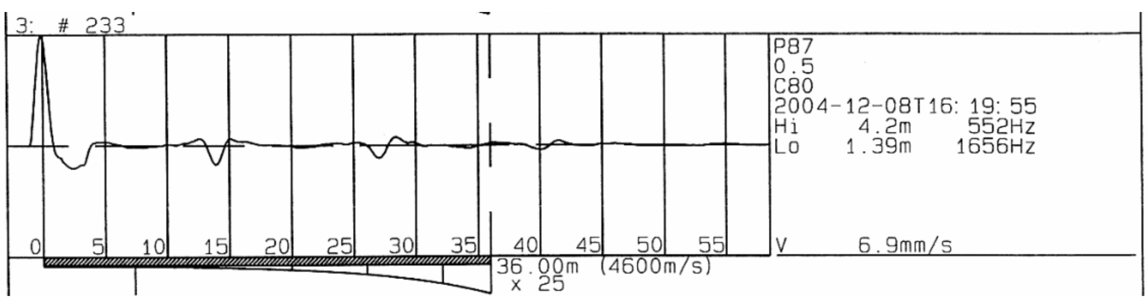

Fig. 4 Example of PIT and inclination measurement on pipe pile

Based on assessment of the load bearing conditions of the failed pipe piles, it was determined that most of the failed pipe piles could not be utilized for foundation support. Foundation at the location of failure was redesigned with new large diameter piles to ensure the bearing capacity and settlement criteria. The economic loss caused by the foundation failure was estimated to be around 20M Yuan.

ANALYSES OF PIPE PILE BREAKAGE MECHANISM

The flow of soft sludge around the pipe piles generate a drag force. The magnitude can be estimated from various theories, including for example, the drag force concept from aerodynamics, theory for turbulence induced vibrations, and other theoretical analyses results using flow field principle.

Referring to turbulence induced vibrations, the drop of pressure for flow across a pipe of diameter d and length l is calculated as (Sevik 1983):
where Δp is the drop of pressure, ρ is the density of flow, u is the velocity of flow, λ is the coefficient.

$$\Delta p = \frac{\rho u^2}{2} \lambda \frac{l}{d}$$

The equation indicates the existence of an unbalanced pressure for flow across a static pipe.

$$F_d = \frac{\rho u^2}{2} C_d A$$

The drag force can also be estimated by referring to the drag force concept, whose magnitude is estimated to be (Au-Yang 2003).
where Cd is the drag coefficient that is related to the Renold number and surface smoothness, A is the cross section area.

For a complete stagnant condition, the drag force can be estimated from Bernoulli's equation (which

$$p_{stagnant} = \frac{1}{2} \rho u^2 + p_{static}$$

is to the conservative side).
All these theories predict an unbalanced lateral pressure acting on the pipe piles when sludge flows around them. The magnitude of such force is proportional to the velocity of flow, or the gradient of ground elevation during the excavation process. The unbalanced force can be controlled through two aspects. The first, to reduce the tendency of flow (or to prevent the sludge from entering the semi-liquid status) , which can be achieved by proper control of construction vibration. Secondly, to reduce the velocity of flow, which can be achieved by proper construction control to reduce the differences in the ground elevation during the excavation process.

IMPLICATION FOR SIMILAR PROJECT

Based on the forensic study, the following recommendations were made to prevent construction vibration and excavation induced pipe pile failure at similar sites, i.e., 1) to reduce the difference in excavation elevations. Properly deploy the construction equipment to avoid the formation of steep slope during excavation; 2) to reduce the effects of construction vibration on soils by placing pad under the construction equipment; 3) to apply field monitoring program to provide warning on potential triggering factors. These recommendations were followed during the rehabilitation construction as well as during other similar projects. No failure was observed during these projects. An example of field photo taken during the construction at a similar site is shown in Fig. 5. The field monitoring data indicate the amount of inclination of these pipe piles are all controlled within the allowable limits. The successful experience validated the results and recommendations of the forensic study.

Fig. 5 Photo of construction activities following the recommendations

CONCLUSIONS AND DISCUSSIONS

Construction on thick soft soils such as sludge present unique challenges for the design and construction. A case history is presented on the failure of pipe piles during the construction of a sluice. Construction induced vibration together with inappropriate excavation control are identified to be the major causes of this failure. The forensic analyses and experience with construction on similar projects highlight the following recommendations for the design and construction on soft ground conditions. 1) Be aware of special geological conditions and the potential effects of construction disturbance on soil mechanical properties. This is especially critical for soils with high moisture content and high structural sensitivity. 2) Maintain proper construction control to avoid the adverse effects. These include proper layout design for deployment of the construction equipment, proper operation procedures, temporary drainage system installation, etc. 3) Implement a field monitoring program, which can be a most cost effective way to identify potential triggering factors of failure and ensure preventative measures can be taken in time to prevent catastrophic failure.

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