International Journal of Engineering & Technology, 7 (3.18) (2018) 21-25

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Technical paper

Review on Lateral Stability of Piled Riverine Structures in the Estuaries of Sarawak

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Abstract

Soft soil conditions with very soft and deep silty clay have constantly endangered the stability of the riverine and estuarine structures in Sarawak. There have been many failures of jetties, wharves and bridges in Sarawak. In many cases of failures, the piles were not designed to resist the lateral movement, unless they were included to stabilize unstable slopes or potential landslides. This practice may be due to reasons such as erroneously judging the river bank as stable in slope stability analysis or simply due to the inexperience of designers. Also, when the river bank approaches the limiting stability in its natural state any construction activity on the river bank could result in lateral soil movement. This paper highlights this important geotechnical problem in Sarawak. Then it presents the details of a few failures of estuarine structures. A review of situations causing lateral loading of piles is then presented. The results of the in-soil and in-pile displacement measurements are shown in this paper and it is found that the computation made to compare between field and 3D modeling is agreeable.

Keywords: *Bridges; Foundation; Lateral stability; Modelling; Soft soils.*

1. Introduction

River banks located in the southern region's coastal area of Sarawak are mostly underlain with very soft and deep sedimentary soil (SPT-N value less than 2). The soft soil conditions at the banks and beds of rivers and estuaries have constantly endangered the stability of the riverine and estuarine structures such as wharves, jetties, ferry ramps, and bridges in Sarawak. These structures are invariably supported on long piles. Many cases of estuarine structures which experienced distress due to soil movement have been reported in Sarawak. Some of them even collapsed when lateral forces induced by the soil movement were greater than lateral load capacity of the pile [1]. Most of the investigations carried out in the past to determine the reasons of failure showed that the failure was due to the pile foundation being not able to resist the lateral load induced by the riverbank soil movement.

Generally, the piles of the estuarine structures are designed to support only the vertical load. This practice is perhaps due to reasons such as judging the river bank erroneously as stable in the slope stability analysis or simply due to the inexperience of designers. Also, when the river bank approaches the limiting stability in its natural state, any construction activity on the river bank could result in lateral soil movement. Other reasons for lateral soil movement are, scouring of soil in front of the riverine structure, dredging of river bed and the effects due to tidal fluctuation in the water level. Followings are some examples of failures in wharves, jetties and bridges.

The remains of the collapsed reinforced concrete wharves at Sg. Saribas (Pusa) and Batang Lupar (Lingga) are shown in Figs. 1 and 2, respectively. The distress on the piles due to large fluctuations in the river water level and river bank erosion resulted in the collapse of the two wharves. A jetty at Kpg. Hulu Sebuyau suffered creep movement towards the river causing structural distress to the main deck and it had to be demolished (Fig. 3). A bridge at Sg. Palasan collapsed just before it was opened for public use (Fig. 4). The failure of the bridge pier was due to lateral soil movement caused by a layer of silt deposited at the bottom of the pier. The piles were also not designed to resist the lateral movement of the river bank. A bridge in Sg. Menyan located at Kanowit collapsed 10 years after construction (Fig. 5). The collapse was initiated by the toppling of one of the piers, which caused the progressive collapse of the spans. The reasons of the failure of pier were, first there was local scour at the base of the pier and second the pile was not designed to resist lateral movement.

Fig. 1: Remains of collapsed wharf at Sg. Saribas

Fig. 1: Remains of a collapsed wharf at Batang Lupar

Fig. 3: Failure of a jetty at Kpg. Hulu, Samarahan Division

Fig. 4: Collapsed Sg. Palasan Bridge in Betong Division

Fig. 5: Failure of Sg. Menyan Bridge

Despite numerous cases of failures of riverine structures in the coastal region of Sarawak, to date, research studies to formulate appropriate design guidelines are scarce. Therefore, a study has been undertaken with the aim to develop a better understanding of the soil-pile interaction at the river banks influenced by high tidal fluctuation and to formulate procedures for the construction of the estuarine structures in a more stable manner. The failures of two estuarine structures in Sarawak are first presented in this paper to highlight the importance of this geotechnical problem. A critical review of literature relevant to this topic is then presented. The salient features of the proposed study are explained briefly.

2. Case Histories in Sarawak

2.1. Wharf at Sg. Saribas

A wharf located at Sarawak was reported to experience structural distress in early 1990s [1]. A comprehensive monitoring of the wharf was carried out to study the behavior of the wharf. The monitoring work included measurement of expansion gap between the wharf and the access bridge. The measurement was carried out by measuring the movement of a point in the access bridge with respect to another fixed point at the wharf using a measuring tape. Besides that, precise level survey, water level survey, inclinometer observations, and lateral load measurements were also carried out.

The tidal fluctuation from low water level (LWL) to highest water level (HWL) was 6.8 m. The subsurface condition consisted of about 53 m deep soft alluvial deposit, underlain by sand bearing stratum. The undisturbed undrained strength (Su) was 20 kPa at the top 10 m and from 11 to 53 m Su increased to 106 kPa. Limit equilibrium slope stability analysis showed that the undrained factor of safety varied widely between 0.77 and 1.35 as the water level varied from LWL to HWL.

The study showed that the wharf structure moved laterally towards the riverside during the low tide and during high tide the structure moved back, but the wharf did not move back to its original position and there was a residual lateral movement. A total movement of 1.1 m was recorded over 3 years and the average rate of movement was about 0.94 mm per day. To observe the lateral movement of soil, two inclinometer casings were installed into the ground. The inclinometer readings showed that the movement of the ground was concentrated within the top 12 m. The behavior of the wharf was also analyzed by finite element method (FEM) and the results were consistent with the inclinometer readings. The lateral force induced by the soil movement was measured by installing steel plates between the main wharf structure and the access bridge at the deck level and strain gauges were affixed on the steel plate. The strain gauge readings showed changes in the lateral load with fluctuation of the river water level. The maximum load recorded was 1465 kN. The results of analysis using theoretical methods by [2-5] were in agreement with the loads recorded in the field. The important conclusions from the study were: 1) The stability of the river channel was significantly affected by the fluctuation of water level, ranging from stable state at HWL to unstable state at LWL; 2) The wharf moved laterally at an average rate of 0.94 mm per day; 3) The wharf movement was a result of the fluctuation of the river water level, and it was the aggregate of the permanent residual movement during each cycle of high and low water levels; and 4) The lateral load induced in each pile can be estimated by any one of the methods mentioned before.

2.2. Bridge at Sg. Menyan

A 3 span bridge (Fig. 6) of total length 60 m located in Sibu Division, and constructed in July 1997 collapsed in September 2005. The collapse of the bridge was investigated in March 2006 [6] and it was found that the collapse was initiated by the toppling of Pier 2. Pier 2 was fully submerged in the water and only the pier head was visible. A survey carried out after the failure showed that there was a 2 m deep scour hole at Pier 2. Pier 2 was supported on fourteen 254 x 254 mm, 85 kg/m, H-piles. These piles were adequate to carry axial compression loads but not lateral loads. However, to examine the capacity of the piles to resist the lateral movement, analysis was carried by comparing the ultimate lateral capacity of the pile with possible lateral forces. The possible types of lateral forces which will be transmitted to the foundation are; 1) loading from the structure itself; 2) consolidation settlement of the soil at the approach embankment due to self-weight of embankment; 3) change of water level in the river; and 4) scouring in front of the piles. The bridge foundation was analyzed using FEM, Plaxis 2D. Plane strain was assumed in modeling the pile-soil system (Fig. 7). The top soil layer at Pier 2 consisted of 10 to 16 m thick soft clay, the standard penetration test (SPT) resistance N-value was < 3. The underlying layer was 4.5 to 5.5 m thick stiff to hard clay (10 < N < 50). The results of the FEM analysis showed that; 1) high bending moment occurred at the top of the pile in all conditions; 2) consolidation settlement increased the bending moment of the piles; 3) rapid draw down of the water level contributed additional bending moment to the piles.

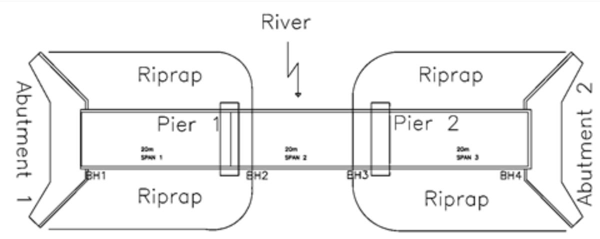

Fig. 6: Layout of bridge at Sg. Menyan

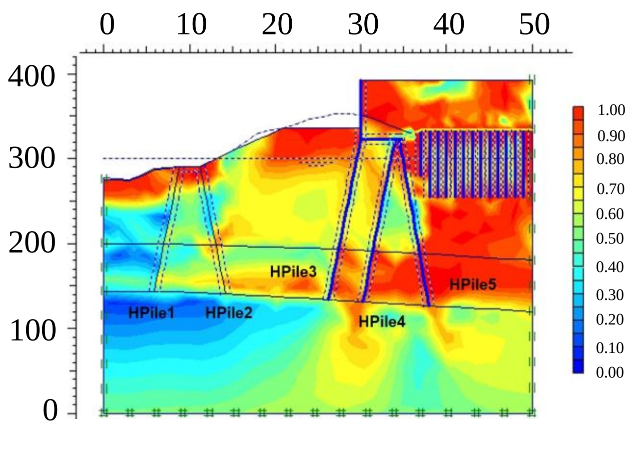

Fig. 7: Typical section of bridge at Sg. Menyan for FEM analysis

3. Situation Causing Lateral Loading of Piles and Their Analysis

In general, a laterally loaded pile is designed either as an active pile or passive pile with regard to the load transfer between the pile and the surrounding soil [7]. An active pile is a pile designed to support a superstructure which applies lateral load at its top and transmits the lateral load to the soil. Passive piles are piles designed to resist the unstable soil layer along the length of pile due to soil movement or to resist earth pressure. Many methods have been developed to analyze and design the piles subjected to lateral forces. The available methods range from relatively simplistic approaches to estimate the ultimate lateral capacity to relatively complicated numerical analysis to estimate the pile soil interaction.

3.1. Piles Subjected to Lateral Soil Movement

[8] developed a theoretical equation to estimate the lateral pressure on passive pile in clay and sandy soils. They carried out laboratory tests to validate the theoretical equation. [9] adopted the classical plasticity theory to derive exact solution for the limiting lateral resistance of a circular pile subjected to purely horizontal movement in cohesive soil. [10] carried out a detail study of the ultimate lateral resistance of the soil for passive piles. [11] proposed a simple method to predict the lateral resistance of piles in cohesionless soil and compared the values with the centrifugal test results. [12] used finite element simulation to study the behavior of the passive loading and compared the results with the experimental work.

3.2. Piles Adjacent to Embankment

[13] studied the passive lateral loading from soil movement due to adjacent surcharge loading. He also constructed p-y curves to study the behavior of pile-soil interaction. [14] described a simplified numerical procedure based on FEM for analyzing the response of single piles to lateral soil movement induced by filled embankment. [15] carried out a series of centrifuge model to study the lateral earth pressure induced by the adjacent embankment on soft ground. [16] developed a new method to estimate the lateral movement of pile adjacent to the embankments on soft ground. An instrumented test embankment was constructed in order to develop soil stiffness degradation curves. With the soil stiffness degradation curves the soil-pile interaction mechanism can be solved. He also created the computer modeling using 3-D FEM to validate the new method. The new method showed a good agreement with the results from computer modeling.

3.3. Effect of Scouring on Piles

[17] developed a laboratory model to simulate the behavior of the pile subjected to scour. Tests on model piles of PVC and aluminum embedded in soft marine clay bed formed at different consistency indices and load eccentricity ratios were conducted with and without scour. The pile materials were chosen to represent a good variation in the rigidity of the piles. From the model tests, it was noticed that scour resulted in the reduction in the lateral load capacity and increase in bending moments. The lateral load capacity was reduced by 18% for the flexible pile and by 15% for the rigid pile. Bending moment in the pile increased by 17%.

[18] investigated the effect of local and global scour on the behavior of laterally loaded piles using a finite element model and a Winkler model in PLAXIS and LPILE computer software, respectively. According to Mostafa, scour had relatively more significant effect on piles in sand than in clay. Scour generally increased lateral displacement of piles and bending moment in the pile; it decreased the lateral load capacity. The pile head displacement increased by 20% in soft clay and 36% in stiff clay when compared to the no scouring case.

3.4. Effect of Fluctuation in Water Level on Slopes

According to [19], the fluctuation in water level would influence the factor of safety of a slope. He also demonstrated that when the water level went down rapidly and the pore water pressure was maintained (undrained case) in the slope, the factor of safety decreased. In the case of water level rising very fast, the factor of safety increased.

4. Research on Estuarine Structures in Sarawak

The review of past studies shows that there are different situations which can affect the lateral stability of piles. However, very little research had been carried out to study the behavior of soils and piles in estuarine conditions where there is a combination of deep soft soil deposits and high tidal fluctuation. Therefore, a research study has been initiated in Universiti Malaysia Sarawak in collaboration with Department of Works (JKR), Sarawak, with the overall aim of contributing to the proper understanding of the complex riverine and estuarine structure-pile foundation-soft soil interaction problem and to formulate means for construction of riverine and estuarine structures in a more stable manner. Thus, inclinometer casings and vibrating wire piezometers have been installed at 2 project sites (a bridge at Sg. Rimbas and a jetty at Sg. Seduku) by JKR, Sarawak, to study the behavior of the river bank. The inclinometer survey is carried out by recording the inclination of the casing at every 0.5 m interval which starts from the toe of the inclinometer casing to the top of the casing. The cumulative horizontal displacement can be obtained by summing up all the L Sin θ which can be derived from the computation of the interval of the readings (refer to Fig. 8).

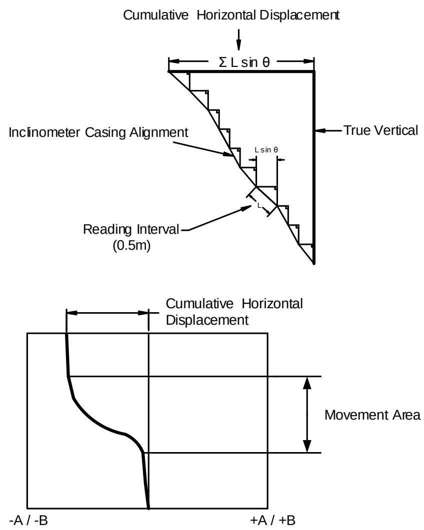

Fig. 8: Inclinometer survey description

4.1. A bridge at Sg. Rimbas in Pusa and a jetty in Seduku

A bridge is proposed to be constructed across Sg Rimbas at Pusa in the Betong Division of Sarawak. The subsoil at the banks is soft to a large depth. The river bank at town side, the standard penetration test value (N) is 0 to a depth of about 50 m which increases to 50 at about 88 m depth. Two piezometers (one at 5 m and another at 10 m below ground level) and 1 ABS inclinometer casing (55 m deep) have been installed in the river bank (in-soil inclinometer).

A jetty is proposed to be constructed at Seduku. The soil conditions at this site are similar to those at Pusa. The N-value is 0 to a depth of about 50 m below the ground level. The maximum tidal fluctuation is 6.5 m. The instrumentation at this site consists of one 90 m long inclinometer casing in the soil at the river bank slope, one 45 m long inclinometer casing in a 350 mm diameter spun pile in the river bank slope (in-pile inclinometer).

4.2. Three Dimensional Finite Element Modeling

[20-21] have validated that the Plaxis 3D is able to simulate the passive pile on slope. In this research the author utilises the Plaxis 3D to create the computer model.

The author has discussed the field instrumentation and results of the inclinometer and piezometer in the previous papers [22-23]. In summary, the results show that the river bank is moving toward the river during low tide and resume to its original position at high tide. Therefore, the 3D model is developed using Plaxis 3D (shown in Fig. 9 and Fig. 10) and will be benchmarked against the field data. Due to the complexity of the boundary condition for the soft river bank which is subjected to tidal fluctuation, the 3D models are created based on only 1 cycle of tidal fluctuation. The material properties for the soil and pile model are shown in Table 1. The calculation method is based on the elastoplastic undrained analysis. The next section will discuss on the comparison between 3D model with the field data results.

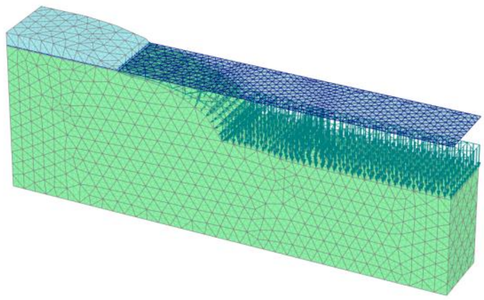

Fig. 9: Model view for Pusa site

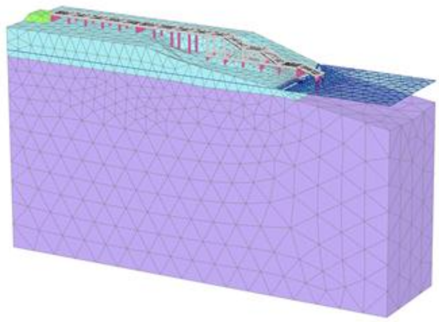

Fig. 10: Model view for Seduku site

5. Results and Discussion

Fig. 11 shows the comparison of the results between the inclinometer and the Plaxis 3D results for in-soil inclinometer at Pusa site. The readings taken at 1 cycle tidal fluctuation (from low tide to high tide) on 2 different days. Fig. 11 (a) and (b) show survey data from inclinometer measurement and simulated displacement from Plaxis for lateral displacements on 14/11/2012 (PINC1-8) and 15/11/2012 (PINC1-12). The 3D model shows about 7 percent overestimated lateral movement compared with the field inclinometer reading. The comparison of the in-pile inclinometer and 3D model at Seduku Jetty side is shown in Fig. 12. The readings were taken on 7/11/2013 (SINC14) and 4/12/2013 (SINC24) and are shown in Fig. 12 (a) and (b). Top 10 m shows about 12 percent overestimated lateral displacement compared with the in-pile inclinometer readings but below 10 m the error increases to 50 percent maximum.

Table 1: Material properties for the soil and embedded pile model

Parameter			Value	
	Soil model		**Seduku**	**Pusa**
	Material model		Mohr Coulomb	Mohr Coulomb
General	Drainage type		Undrained	Undrained
	Unit weight (kN/m^3)	γ_{sat}	16	16
Strength parameters	Deformation modulus (kN/m^2)	E_u	$600S_u$	$550S_u$
	Poisson's ratio	ν_u	0.495	0.495
	Undrained soil strength (kN/m^2)	S_u	$S_u = -1.56z + 17.57$, $0 \text{ m} \leq z \leq 6 \text{ m}$; $S_u = 1.86z - 2.04$, $z > 6 \text{ m}$	$S_u = -4.46z + 32.58$,0 m $\leq z \leq 4$ m; $S_u = 5.07z - 8.43$, $z > 4$ m
	Internal friction angle	φ_u	0	0
	Dilantancy angle	ψ	0	0
	Interface	R_{inter}	0.667	0.667
Embedded pile model			**Seduku**	
	Deformation modulus (kN/m^2)	E	36 x 106	-
Strength parameters	Unit weight (kN/m^3)	γ	26	-
	Predefined pile type		Circular tube	-
	Pile diameter (m)	d	0.35	-
	Thickness (mm)	t	80	-
	Maximum traction allowed at the pile top (kN/m)	$T_{top,max}$	12	-
Skin resistance	Maximum traction allowed at the pile bottom (kN/m)	$T_{bot,max}$	86	-
	Base resistance (kN)	F_{max}	68	-

In general, it can be observed that the top soil and top pile lateral movement from the 3D modellings are very similar with the in-soil and in-pile inclinometer readings and the soil model results are considered agreeable to the site river bank behavior. From these early findings, it is proven that a certain degree of lateral movement could be observed and with agreeable data found between field and model, further parametric study is planned.

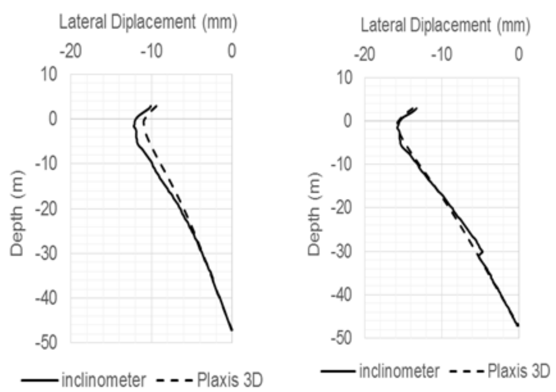

Fig. 11: Comparison between Pusa inclinometer reading with Plaxis 3D

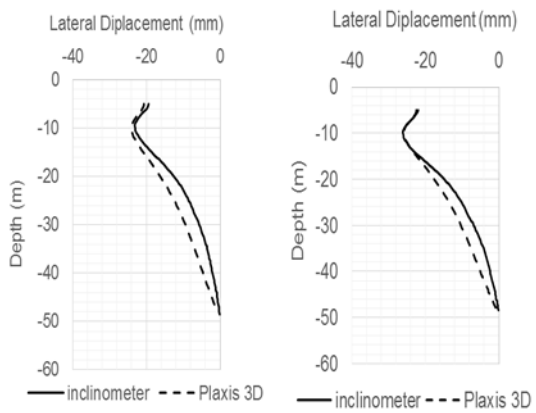

Fig. 12: Comparison between Seduku in-pile inclinometer reading with Plaxis 3D

6. Conclusions

The major conclusions from the study of the case histories, unpublished reports on failure of riverine structures, and literature on analysis of situations causing lateral loading of piles are summarised below.

a. The lateral soil movement will reduce the lateral load capacity of pile and increase the bending moment in the pile.
b. Anthropogenic activities such as dredging of the sea or river bed, deep excavation, and construction of high embankment fills will trigger soil movement and affect the lateral stability of adjacent piles. Natural phenomena such as scour and seismic activity too can induce lateral movement of soil and thus affect their stability.
c. In estuarine conditions of deep soft soil deposits, high tidal fluctuation could lead to lateral soil movement. However, very little research had been carried out to study the behavior of soils and piles in the estuarine conditions.
d. In the current study for cases in Pusa and Seduku, Sarawak, the 3D finite element modeling which is developed based on the site boundary conditions are showing agreeable results with the site inclinometer data. Hence, further parametric study could be performed in order to investigate the impact of selected parameters/conditions to the lateral instability of riverbank piles.

Acknowledgement

The authors acknowledge the support of Public Works Department (PWD) Sarawak, for installation of instrumentation at project sites. The first author thanks PWD Sarawak, for providing him with study leave and financial support. The authors thank the Research and Innovation Management Centre of Universiti Malaysia Sarawak for the Principal Investigator Grant (02(DPI19)955/2013(02)) that supports this research.

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