The Failure of Road Embankment Along the Canal during Driven Piles Construction in Thickness of Soft Sensitive Clay

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ABSTRACT: The pile-retaining wall at Nonthaburi rural road no. 5036 was constructed using reinforced concrete piles or driven piles combined with a concrete retaining wall. The purpose of this structure was to enhance the slope stability of the canal-side road (road embankment along the canal). The damage to the driven piles occurred during the pile construction at 18 m depth below the ground surface. The resistivity survey and screw driving sounding test were employed to investigate the thickness of soft clay layers and unexpected stiff soil layers at the failure area. The field vane shear test was employed to investigate the sensitivity of the soft clay layer. Furthermore, the finite element model was analyzed to verify the failure behaviour of the road embankment during the driven pile's construction. Consequently, the investigation revealed that the subsoil in the failure area exhibited sensitivity values. The subsoil consisted of a layer of soft clay to medium stiff clay, ranging from 2-10 m below the ground surface, while the subsoil consisted of stiff clay below a depth of 10 m. The installation of the 18-m driven pile caused a disturbance in the soft sensitive clay layer above the stiff soil layer, resulting in a reduction in the strength of the soft clay and affecting the displacement of the driven pile during construction. Furthermore, the occurrence of rapid drawdown causes water seepage to continue to flow toward the canal side. This phenomenon produces active forces on the slope of the road embankment along the canal. As a result, the road embankment along the canal side can collapse due to a disturbance in the sensitive clay layer with rapid drawdown. The result was agreed with the study findings obtained by the finite element model.

KEYWORDS: Clay Thickness, Driven Pile, Sensitive Clay, Soft Clay, and Pile Damage.

1. INTRODUCTION

The soft Bangkok clay is located in the southern area of the Chao Phraya plain, which is covered by a thick series of alluvial and marine soil deposits. The soft Bangkok clay area is more than 14,000 km^2, covering approximately 350 km between the north and south (Ayutthaya province to the Gulf of Thailand) and 150 km between the east and west (Chonburi province to the Ratchaburi province) (Phienwej, 2009). Soft Bangkok clay has low strength, low bearing capacity, high settlement, and unstable slopes as geological issues (Ratananikom et al., 2015).

A retaining wall is a construction designed to resist the lateral force of the soil and enhance the stability of a slope. Retaining walls are generally divided into five categories: pile-retaining walls, anchored retaining walls, diaphragm walls, gravity-retaining walls, and cantilever-retaining walls. A selection of retaining wall type for construction is dependent on the material types, the construction area, the geological parameters, etc. Typically composed of steel or reinforced concrete piles are utilized in the construction of pile-retaining walls. The piles are fastened to a tie or horizontal beam. Pile-retaining walls are often used in areas where the soil or rock is not stable enough to support a traditional retaining wall, or where the wall needs to be built to a great height.

Piles can be installed using in-situ methods (bored piles), driving methods, or a combination of in-situ and driving methods. Driving methods, the driven pile is the process of pile installation into subsoil without ground excavation. The piles are typically driven by impacting the piles into the subsoil using a pile driver, which is a machine that delivers a blow on the top of the pile to drive it into the subsoil. When the pile has been driven to the desired depth, it is typically cut off based on the required level. The driven pile is constructed to carry and transmit the load (structure load, traffic load, construction load, etc.) to the soil foundation. Sometimes, driven piles serve only for ground improvement, such as to improve the bearing capacity, increase the density, and enhance the stiffness of the surrounding soil.

One problem of driven pile construction is related to the unexpected stiff soil layer, which can lead to soil-surrounding disturbance, pile damage, and other issues (Chaiyaput et al., 2023). Previously, there are many researchers studied the impact of driven piles (Hwang et al., 2001; Massarsch et al., 2008) and the effects of pile construction near other structures (D'Appolonia, 1971). When a machine delivers a blow on the top of the pile, the energy is transferred as P-wave and S-wave in the surrounding soil. The occurrence of ground vibrations from pile driving depends on the subsoil conditions and the distance between the machine delivery and the structure (Deckner, 2013).

Driven piles were normally designed by using total stress analysis. Therefore, the undrained shear strength of subsoil at the construction site is normally measured by using the standard penetration test (SPT) and field vane tests. Soil sensitivity is an important parameter that indicates the loss of soil strength under the effect of static or seismic loading (Rosenqvist, 1953). The soil sensitive has more porosity, a lower dry bulk quantity, and a higher moisture content. Sensitivity is defined as the ratio between undisturbed undrained shear strength and the remoulded undrained shear strength of the soil. Skempton et al. (1952) mentioned that most clays (except heavily over-consolidated and boulder clays) lose the shear strength during remoulding state. Moreover, the sensitivity was classified by Skempton et al. (1952) as the following: sensitivity of ~ 1 is insensitive clays; 1-2 is low sensitivity clays, 2-4 is medium sensitivity clays; 4-8 is sensitive clays; > 8 is extra-sensitive clays; and > 16 is quick clays. On the other hand, Bowles (1996) mentioned that a sensitivity of ≤ 4 is insensitive clays; 4-8 is sensitive clay; > 8 is extra-sensitive clays.

This research primarily focuses on a case study that examines the failure of a road embankment during driven piles construction in a soft sensitive clay layer along a canal in Nonthaburi province, Thailand. The resistivity survey and screw driving sounding test were employed to identify and confirm the thickness of soft clay layers and unexpected stiff soil layers, whereas the field vane shear test was utilized to determine the sensitivity of the soft clay layer.

2. CONSTRUCTION SITE AND SOIL INVESTIGATION

The construction site was located in Nonthaburi province, in the central region of Thailand. The Nonthaburi rural road no. 5036 (NB.

5036) is a two-lane road with each lane about 3 m wide. One lane is for traffic driving in one direction, and the other lane is for traffic driving in the other direction. The road is located between the Khunsri canal and a paddy field. The NB. 5036 is constructed to connect the intersection of Nonthaburi rural road no. 3004 to Lat Bua Luang, Sai Noi, Nonthaburi, as illustrated in Figure 1.

According to the soil investigation, the boring log provides details of the soil type, recovery blow counts, undrained shear strength, Atterberg limit (natural water content, plastic limit, and liquid limit), and total unit weight as shown in Figure 2. The soil layer was divided into 4 layers, which were clayey sand with trace gravel (SC) from 0.00-3.00 m depth below the ground surface, silty clay with low plasticity (CL) from 3.00-4.50 m depth below the ground surface, silty clay with high plasticity (CH) from 4.50-15.00 m depth below the ground surface, and silty clay with low plasticity (CL) from 15.00-19.95 m depth below the ground surface, respectively.

In the standard penetration test, the blows of 12 inches penetration resistance of subsoil are recorded as blows/unit penetration, which is called N value (SPT-N) with a unit of blows/ft. SPT-N of subsoil was 13 blows/ft for SC at 1 m depth below the ground surface, 19-30 blows/ft for CH at 10.50-15.00 m depth below the ground surface, and 65-70 blows/ft for CL at 16.00-19.95 m depth below the ground surface.

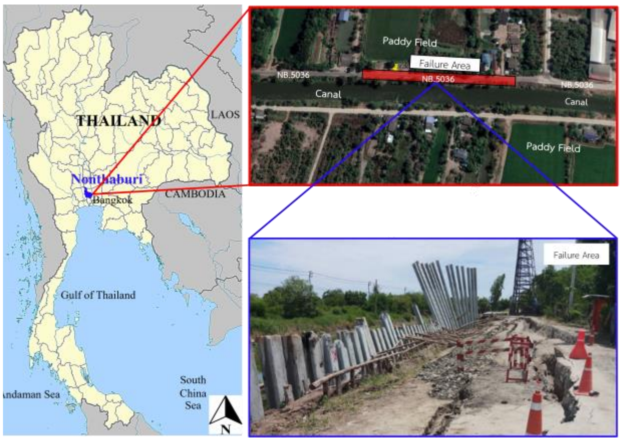

Figure 1 Location of NB. 5036 (modified from Suksawat et al., 2023)

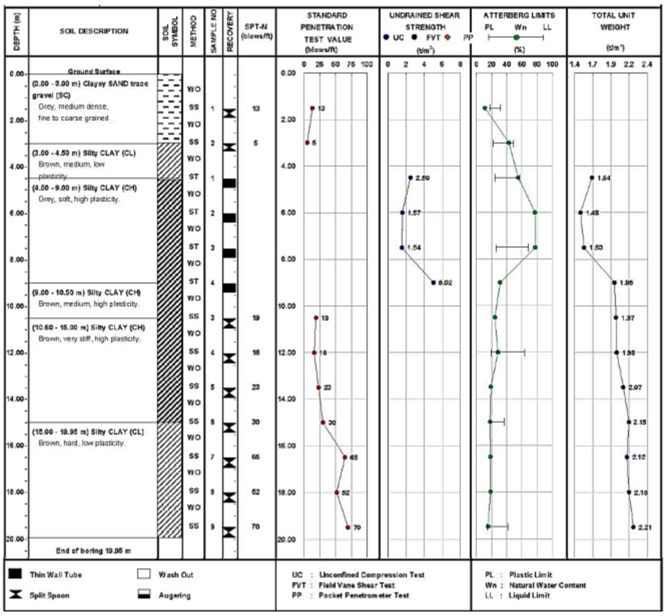

Figure 2 Boring log of NB. 5036 (Suksawat et al., 2023)

The undrained shear strength of CH at 4.50-9.00 m depth below the ground surface was about 25-50 kPa. The natural water content (W_n) continuously increased from 20% to 80% at 1-8 m depth below the ground surface. On the other hand, W_n continuously decreased to 20% and was constant from 10.50 m depth below the ground surface. The total unit weight was about 16 to 22 kN/m^3, and 21 to 22 kN/m^3 for CH and CL, respectively.

3. FAILURE OF ROAD EMBANKMENT DURING DRIVEN PILES CONSTRUCTION

The retaining wall, which was reinforced concrete piles combined with concrete retaining wall, was designed, and constructed to increase the stability of the road embankment along the canal. The size of the reinforced concrete pile was 0.40×0.40×18.00 m. The size of the concrete retaining wall was 0.83×1.00×0.08 m with a 3 m depth, as shown in Figure 3.

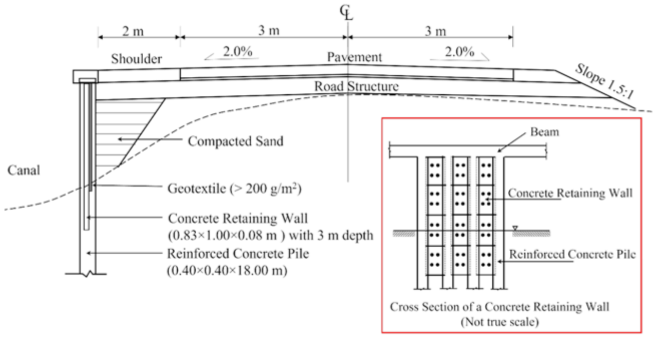

Figure 3 Cross section of a reinforced concrete pile (Suksawat et al., 2023)

(a)

(b)

Figure 4 Driven piles construction (a) non-failure area (b) failure area (Suksawat et al., 2023)

(a)

(b)

Figure 5 Failure area (Suksawat et al., 2023)

The reinforced concrete piles were constructed by using the driven method, called the driven concrete piles or driven piles. The driven piles were installed along the road embankment for 3.20 km (KM. 11+900 to 15+100), as shown in Figures 4(a) and 4(b). The driven piles were driven into the subsoil by delivering a blow from the pile driver machine to the top of the pile into the tip of the pile at the subsoil.

In the failure area, the top of the driven piles was damaged during the driven pile's installation along the road embankment because the unexpected stiff soil layer was located at the tip of the piles. This is related to the appearance of cracks on the ground surface can be observed in Figure 4(b). After the occurrence of the rapid drawdown occurred, the failure of the road embankment occurred in the same area of the driven pile's damage, as shown in Figure 5.

4. SITE INVESTIGATION AT FAILURE AREA

The failure area was investigated by using a resistivity survey, standard penetration test, and screw-driving sounding test to confirm the thickness of soft clay layers and unexpected stiff soil layers. Furthermore, the field vane shear test was used to investigate and confirm the sensitivity of the soft clay layer. The process of the resistivity survey, screw driving sounding, and field vane shear test were explained in the previous work (Chaiyaput et al., 2021; 2022a).

The resistivity survey was utilized and covered to investigate the properties of subsoil at the non-failure area (KM. 14+900 to 15+100) and failure area (KM. 11+900 to 12+600) as shown in Figure 6. The difference colour of resistivity ranges means the characteristic of different soil type. At the top layer from the ground surface to 4.00 m depth, the inverted electrical resistivity (ρ) was higher than 7.5 Ωm, which indicated the pavement surface. The lower of ρ, which was lower than 4.00 Ωm, was found at the failure area. This lower of ρ can be referred to present a clay layer with high water content. While the higher of ρ, which was between 4.00-15.00 Ωm, was found at the non-failure area.

Additionally, the soil layer in the failure area was harder than that in the non-failure area at a depth of more than 10 m below the ground surface. This higher of ρ can be referred to as the decrease in the water content and increase in the SPT value. The ρ result from the resistivity survey can confirm the unexpected stiff soil layer at the failure area.

Moreover, standard penetration testing (SPT) was used to classify the type of soil with the different depths based on its strength and density at the failure area (KM. 12+050), as shown in Table 1. The SPT-N of 2.00-15.00 m was 0-4 blows/ft, which was classified as very soft to soft clay. In addition, the SPT-N of 15.00-18.00 m was > 50 blows/ft, which was classified as very dense yellow sand with clay. The investigation results show the relative between the SPT-N results and ρ. The thickness of clay was found at the failure area. On the other hand, the very dense sand with clay was found at 15.00-18.00 m depth below the ground surface, which is related to the top of the pile damage.

The screw driving sounding (SDS), which is an in-situ method from Japan, is applied to confirm the depth of soft clay at the failure area (KM. 12+050) on NB. 5036 based on the undrained shear strength (S_u) at various depths. Figure 7 shows the relationship between the S_u from SDS tests and the depths of the failure area.

The S_u of subsoil at the failure area was divided into 5 layers, which were identified by the different S_u. The 1st layer, which was from the ground surface to 2 m depth below the ground surface, was a road structure. The S_u of this layer fluctuated from 7.5 kPa to 30 kPa, due to the strength of the road-structure material. The 2nd layer (from 2 m depth to 5 m depth below the ground surface) exhibited the S_u distribution in the range of 10 kPa to 25 kPa. The 3rd layer (from 5 m to 8 m depth below the ground surface) exhibited the S_u distribution in the range of 17 kPa to 25 kPa.

The 4th layer (from 8 m to 10 m depth below the ground surface) exhibited the S_u distribution in the range of 25 kPa to 70 kPa. The 5th layer (from 10 m depth below the ground surface) exhibited a high S_u distribution in the range of > 60 kPa. The S_u at the 2nd, 3rd, 4th, and 5th subsoil layers at the failure area were in good agreement with S_u of very soft clay, soft clay, medium stiff clay, and stiff clay, respectively (Figure 7).

The sensitivity of soil or sensitivity, which is the ratio of the undrained shear strength of undisturbed soil to the undrained shear strength of disturbed soil, is a reduction in the shear strength of soil under the effect of disturbance or remoulding as shown in Equation 1.

$$\text{Sensitivity} = S_u \text{ of undisturbed soil} / S_u \text{ of disturbed soil} \quad (1)$$

The effect of a blow from the pile driver machine led to the loss of soil strength, therefore the sensitivity of soil is concerned. However, the strength of disturbed soil in some clays is quite low, which cannot be tested by an unconfined compression test in the laboratory. Therefore, the vane shear test is often used to measure the undrained shear strength of subsoil in the construction site (Abuhajar et al., 2010).

In this research, soil sensitivity was evaluated using the field vane shear test (FVT), according to ASTM D-2573. The field vane shear test (FVT) is a common in-situ method to evaluate the undrained shear strength (S_u) of subsoil on the construction site. FVT is rotating a vane, which is typically 2 heights: 1 width, into the subsoil and measuring the soil resistance to shear at varying depths. The FVT at the NB. 5036 was tested by the Department of Rural Road, Thailand before the construction was begun.

Table 1 SPT-N results at KM. 12+050 (Suksawat et al., 2023)

Depth (m)	Soil Consistency	SPT-N, blow/ft
0.00 - 2.00	Topsoil	-
2.00 - 15.00	Very soft to soft clay	0 - 4
15.00 - 18.00	Very dense sand with clay	> 50

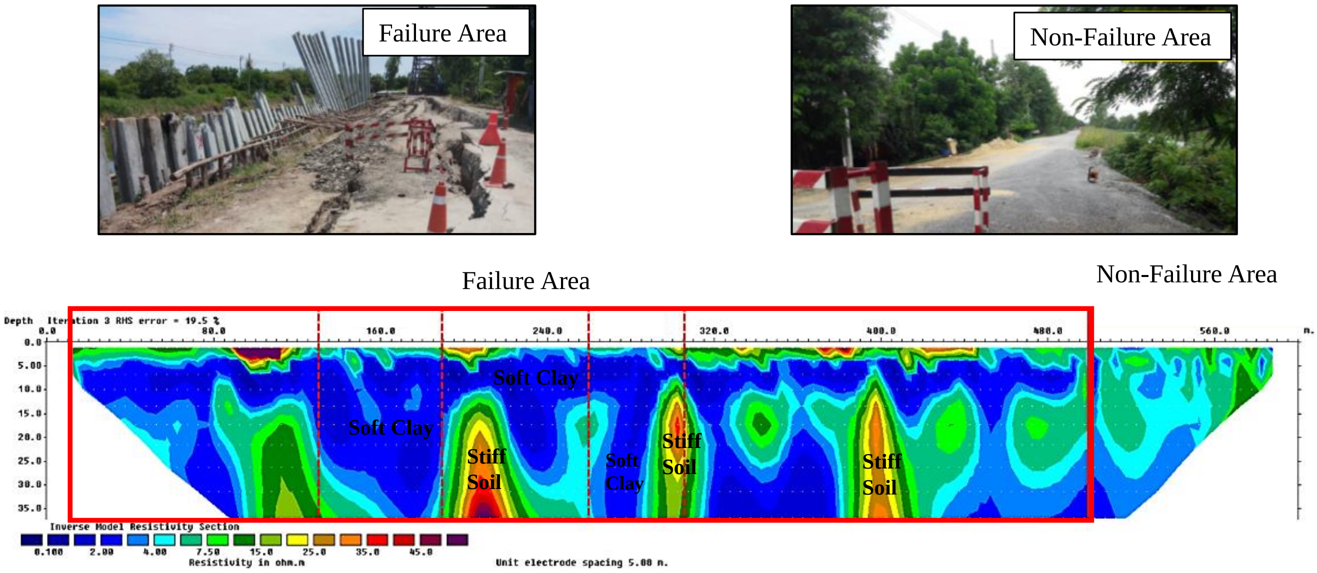

Figure 6 Resistivity survey (modified from Suksawat et al., 2023)

The driven pile was constructed in the soft clay area, therefore, the reduction in shear strength of soil under disturbance was evaluated based on the sensitivity values. The sensitivity values from FVT were found between 2.5-5 (Figure 8), which was moderately sensitive and sensitive (Skempton et al., 1952; Rosenquist, 1953). Therefore, the driven pile was 18.00 m in length, but a very soft to soft clay layer was found until 10-15 m depth below the ground surface. This means that the tip of the driven pile was installed in the very dense sand with a clay layer, which affected the disturbing of the above soft sensitive clay layer to reduce its strength.

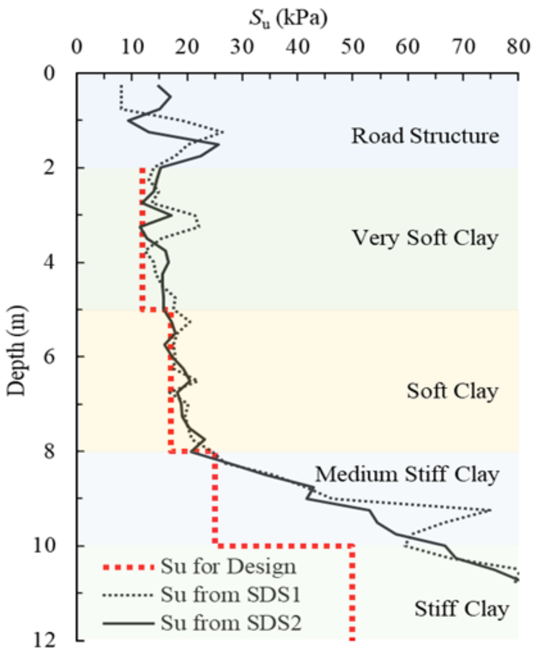

Figure 7 SDS at failure area (Suksawat et al., 2023)

5. FINITE ELEMENT ANALYSIS

5.1 Finite Element Model and Analysis Conditions

The finite element model (FEM) was utilized to validate the effect of the soft sensitive clay layer on the failure of road embankment during the driven piles construction. The 2D-PLAXIS software, which is a 2-dimensional analysis, was applied to simulate the installation process of driven piles on NB. 5036 at the failure area. The boundary condition for a 25×100 m area was assigned as depicted in Figure 9. The boundary conditions for the FEM model were assigned as follows: a fixed boundary condition was assigned to the bottom of FEM model, a free boundary condition was assigned to the surface of FEM model, and roller boundaries were assigned to the sides of FEM model.

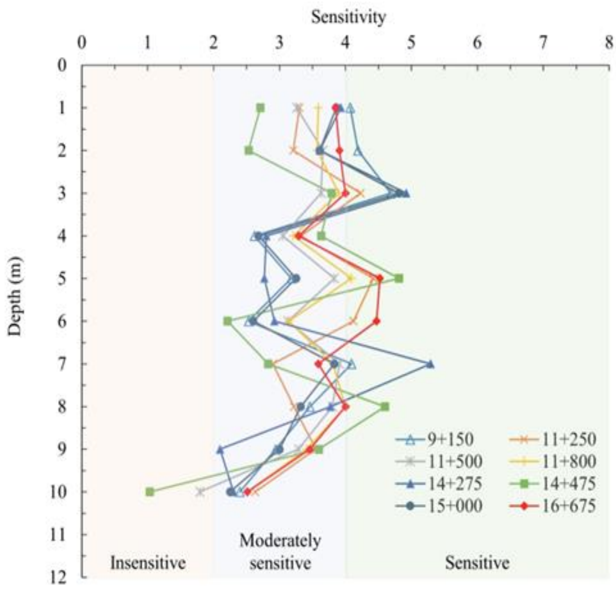

Figure 8 Sensitivity results (Suksawat et al., 2023)

Table 2 The properties of subsoil and pile in the FEM model (Suksawat et al., 2023)

Materials	Thickness (m)	Model	Material behavior	γ_{sat} (kN/m³)	γ_{unsat} (kN/m³)	$k_x = k_y$ (m/day)	E' (kPa)	ν'	c' (kPa)	S_u (kPa)	$\varnothing'$ (deg)	R_{in}
Subsoil Properties												
Road structure	2	MCM	Undrained	20	17	0.800E-3	6000	0.30		30		0.80
Very soft clay	3	MCM	Undrained	18	16	0.800E-3	1950	0.35		13		0.80
Very soft clay (Disturbed)	3	MCM	Undrained	18	16	0.800E-3	1560	0.35		10.40		0.80
Soft clay	3	MCM	Undrained	18	16	0.800E-3	2550	0.33		17		0.80
Soft clay (Disturbed)	3	MCM	Undrained	18	16	0.800E-3	2040	0.33		13.60		0.80
Medium stiff clay	2	MCM	Undrained	18	16	0.800E-3	5000	0.30		25		0.80
Stiff clay	2	MCM	Undrained	18	16	0.800E-3	10000	0.30		50		0.80
Sand	13	MCM	Drained	16	16	0.5000	25000	0.25	10		35	0.80
	Length (m)	**Material type**	**EA (kN/m)**	**EI (kNm²/m)**								
Piles												
Concrete Pile	18	Elastroplastic	4.552E6	60.71E3								
Prestressed Concrete Pile	10	Elastroplastic	1.377E6	5.50E3								

MCM: Morh-Coulomb Model

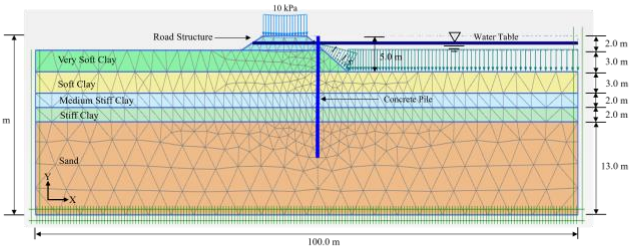

Figure 9 Model of NB. 5036 at the failure area (Suksawat et al., 2023)

The height of the road structure was about 2 m from the ground surface, and the depth of the canal was about 5 m from the surface of the road structure. The side slope of the NB. 5036 road was 1V : 1.5H. The reinforced concrete pile of 0.40 x 0.40 m was used to support the side slope of the road embankment along the canal with an 18 m length.

The subsoil layer and design parameters in the FEM software were simulated to generate the failure of road embankment during the driven pile construction based on the resistivity survey and the SDS test (Chaiyaput et al., 2021). Therefore, the data from field investigation at the construction site were used to create the geometrical model of the road embankment along the canal at the failure location. The subsoil layers were divided into 5 layers, which were a 3 m-thick very soft clay with S_u of 13 kPa, a 3 m-thick soft clay with S_u of 17 kPa, a 2 m-thick medium stiff clay S_u of 25 kPa, a 2 m-thick stiff clay with S_u of 50 kPa, and a 13 m-thick sand.

Due to the sensitivity values from FVT, the sensitivity of the clay layer was found between 2.5-5.0 as shown in Figure 8. The disturbing soft sensitive clay layer, which was disturbed during driven pile construction, affected to reduce the strength of the clay layer, therefore the strength of clay layer was reducing of 20%. S_u of clay layers was assigned to 10.40 kPa and 13.60 kPa for very soft clay and soft clay, respectively. Moreover, the elasticity (E') was 1950 kPa for the undisturbed very soft clay layer and 1560 kPa for the disturbed very soft clay layer. E' was 2550 kPa for the undisturbed soft clay layer and 2040 kPa for the disturbed soft clay layer.

The properties of subsoil and pile in the FEM model (Table 2), Mohr-Coulomb model, and elastoplastic model were assigned as the properties of subsoil and piles, respectively. The Mohr-Coulomb model has been employed to generate soil models, which are commonly used approaches for analyzing soil behaviour under various stress conditions (Chaiyaput et al., 2021; 2022a; 2022b). A Mohr-Coulomb failure criterion under undrained condition has been considered in all clay layers, while those under drained condition has been considered in the sand layer. Poisson's ratio (ν') was assigned to 0.30, and 0.25 for the clay layer and sand layer, respectively.

The stability of the road embankment and a driven pile can primarily be assessed by the factor of safety (FS) based on the phi-c reduction method as described in the previous work (Artidteang et al., 2013; Chaiyaput et al., 2012; 2014; 2021). FS is a very useful index to identify how close or far from a failure. The road embankment is considered as stable when the FS is more than 1. This means that the resisting shear strength is greater than the driving shear stress.

For the analysis conditions, 2D-FEM was utilized to confirm the effect of the soft sensitive clay layer along the canal on the stability of the road embankment and the driven piles. Moreover, the water level in the canal was assigned as full and 3.5 m depth below the ground surface as analysis conditions to confirm the effect of rapid drawdown with a soft sensitive clay layer.

The 2D-FEM was analysed by 3 main models. The first model was modelled as an undisturbed very soft clay layer (non-sensitive very soft clay layer) and soft clay layer (non-sensitive soft clay layer), under the condition of full water level in the canal and the water level in the canal at 3.5 m depth below the ground surface, as shown in Figures 10(a) and 10(b), respectively. The second model was modelled as disturbed very soft clay and disturbed soft clay layer, which represented a decrease of 20% of those S_u and E'. The water level in the canal of the second model was full and at 3.5 m depth below the ground surface, as shown in Figures 10(c) and 10(d), respectively.

To solve the problem of road embankment failure during driven piles construction in the soft sensitive clay layer, the stability of the road embankment was improved by incorporating prestressed concrete piles. Therefore, the road structure was reinforced by using 4-row piles made of prestressed concrete. These piles had dimensions of 0.22 x 0.22 m and a length of 10 m. Figures 10(e) and 10(f) represent the simulation of a road embankment (second model) reinforced by 4-row piles under the water level at full capacity, and the water level 5 m below the ground surface, respectively.

Under the feature of staged construction, the modelling steps started at the in-situ stresses for subsoil simulation (before the construction begins), which was generated by the K_0 procedure. The subsoil was divided into 5 layers, with 1 layer for road structure. The second step was the installation of concrete piles and prestressed concrete piles. The third step was assigning the 10 kPa of load spreading to generate traffic load and construction load. The last step was to simulate the water level under the conditions of full water level, a water level of 3.5 m depth below the ground surface, and a water level of 5 m depth below the ground surface, respectively.

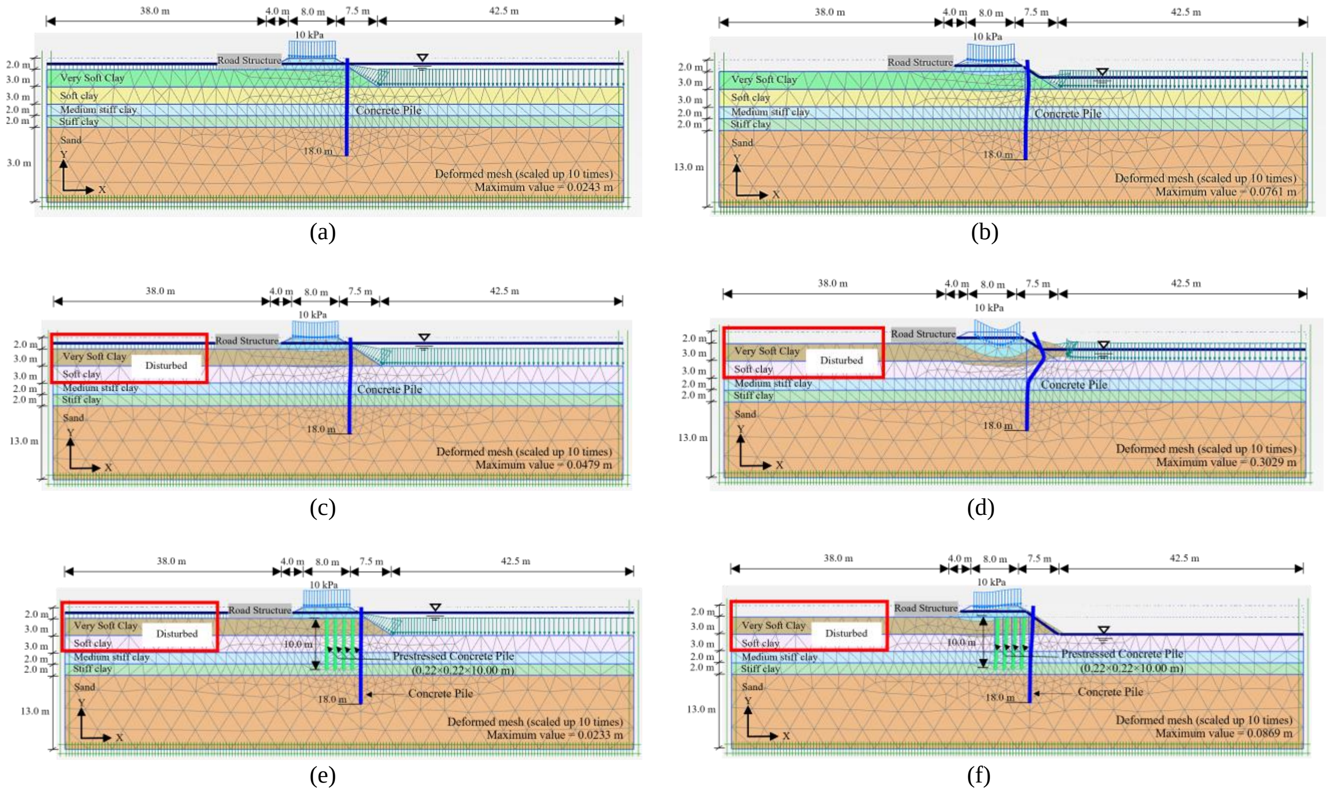

Figure 10 Model of a driven pile at failure area on (a) the soft clay layer under full water level (b) the soft clay layer under the water level of 3.5 m depth below the ground surface (modified from Suksawat et al., 2023) (c) the soft sensitive clay layer under full water level (d) the soft sensitive clay layer under the water level of 3.5 m depth below the ground surface (modified from Suksawat et al., 2023) (e) the reinforced by 4-row piles under full water level (f) the reinforced by 4-row piles under the water level of 5 m depth below the ground surface (modified from Suksawat et al., 2023)

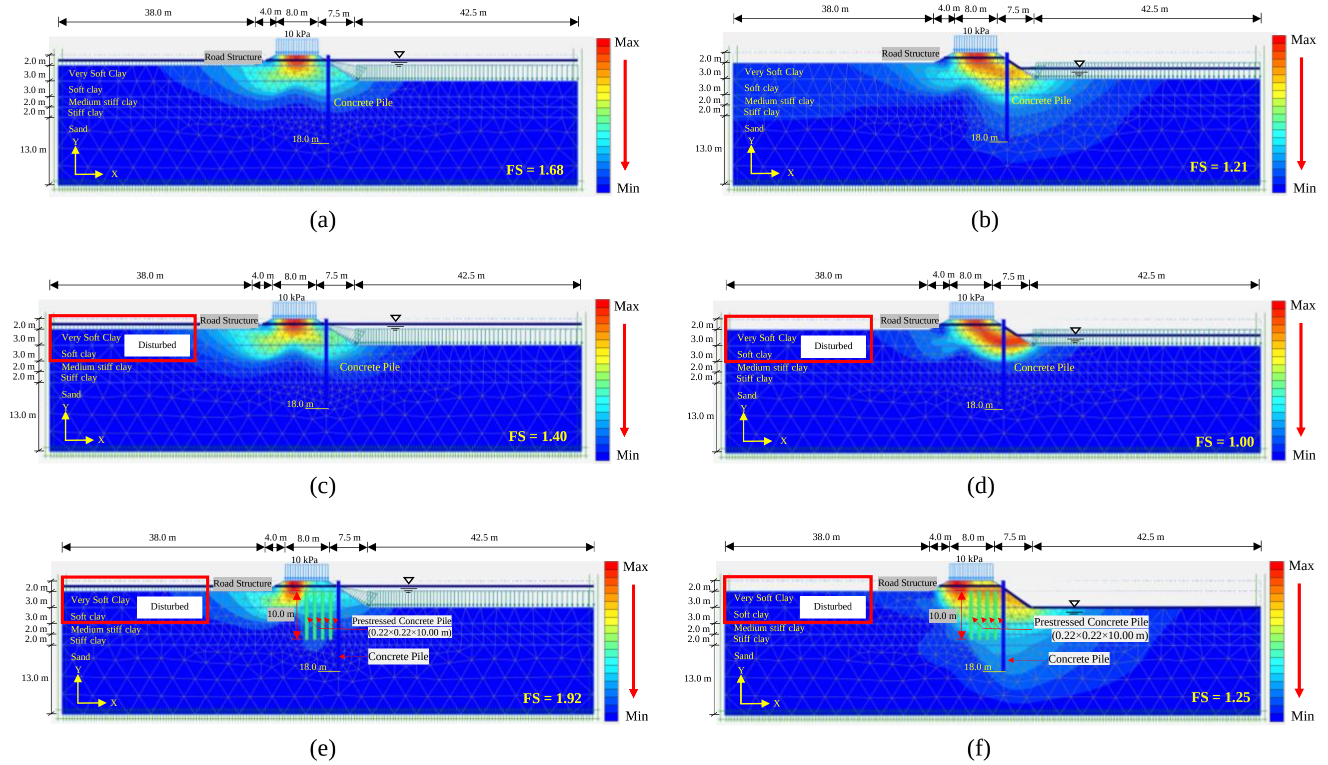

Figure 11 Displacement contour (a) the soft clay layer under full water level (b) the soft clay layer under the water level of 3.5 m depth below the ground surface (c) the soft sensitive clay layer under full water level (d) the soft sensitive clay layer under the water level of 3.5 m depth below the ground surface (e) the reinforced by 4-row piles under full water level (f) the reinforced by 4-row piles under the water level of 5 m depth below the ground surface

5.2 Results and Discussions

In case the driven pile of 18 m was constructed in the non-sensitive soft clay layer, FS was 1.68 under full water level in the canal, and 1.21 under rapid drawdown conditions (Table 3). The simulation results presented that the FS of the road embankment along the canal was significantly affected by the water level in the canal. The FS of the road embankment along the canal decreased with a decrease in the water level in the canal. Moreover, it was confirmed that the failure of the road embankment and driven pile did not appear when the driven pile was constructed on a non-sensitive soft clay layer as shown in Figures 10(a), 10(b), 11(a), and 11(b).

Considering the model of a disturbed very soft clay and disturbed soft clay layer, the 18 m driven pile was constructed to pass through the clay layer, while the tip was placed on a stiff soil layer. The distribution load from the construction was transferred to the very soft clay and soft clay layers, which were sensitive. This means that the very soft clay and soft clay layers were disturbed, and the strength of the clay was decreased during pile installation (Abuhajar et al., 2010; Lee et al., 2019).

Moreover, the clay layer was not provided with sufficient friction for the driven pile, resulting in lateral movement or sliding. This led to the road embankment and driven piles failure as shown in Figures 10(c), 10(d), 11(c), and 11(d). From Table 3, FS was 1.40 under full water level in the canal, and 1.00 under rapid drawdown conditions (the water level at 3.5 m depth below the ground surface).

Generally, the global FS for the natural slope is considered between 1.2 and 1.4. The water level in the canal of the existing road decreased rapidly to 3.5 m depth below the ground surface (under rapid drawdown condition), and the FS was going to be close to 1 (Figures 10(d) and 11(d)).

The displacement contour, which was coloured, can be used to indicate the area of shear strength reduction and stability reduction. Moreover, those can be utilized to indicate a potential failure area. The decrease in shear strength is directly correlated with an increase in driving stress, which causes the movement of the road embankment along the canal.

The contour of displacement in Figure 11(d) indicated that the failure surface occurred with a circular shape, which was located and extended to a certain depth within the disturbed very soft clay and disturbed soft clay layer. Moreover, the result of the 18 m driven pile movement was found in the FEM. This means that the decrease in the FS in the FEM simulation was directly correlated with the disturbed very soft clay and disturbed soft clay layer. This simulation result was consistent with the situation of water level in the canal, which was similar to the actual situation in the failure area at NB. 5036.

To increase the number of piles for the load spreading was simulated to solve the above problem. The 4-row piles (Figures 10(e) and 10(f)), which were prestressed concrete piles 0.22 x 0.22 m with 10 m length, were used to support the road structure because the piles have been used successfully in slope stabilization to act as resisting structure for increasing the bearing capacity and decreasing lateral movement (Collin, 2007; Satibi et al., 2007; Smethurst and Powrie, 2007).

Analysis conditions, the 4-row piles with a square arrangement and spacing of 1.00 x 1.50 m, which were supported at the side slope of the road embankment along the canal, were calculated and compared to determine the appropriate design pattern based on the FS. The water level in the canal was assigned from full water level to 5 m depth below the ground surface to simulate the rapid drawdown condition.

From the numerical results (Figures 11(e) and 11(f)), the FS of 4-row piles supported the road embankment along the canal under the condition of full water level in the canal, and rapid drawdown conditions were 1.92 and 1.25, respectively, which were stable (FS = 1.2-1.4). These results can be concluded that the piles can support and increase the stability of the road embankment along the canal during driven piles construction on a soft sensitive clay layer with rapid drawdown.

Table 3 FS of analysis conditions

Analysis Conditions	FS	
	Full water level	**3.5 m (Rapid drawdown)**
Driven piles at an undisturbed soft clay layer	1.68	1.21
Driven piles at a soft sensitive clay layer	1.40	1.00
	Full water level	**5 m (Rapid drawdown)**
A road structure reinforced by 4-row piles	1.92	1.25

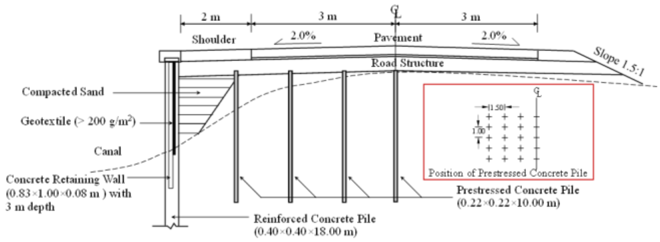

Figure 12 Cross section of a road structure reinforced by 4-row piles

FS of 4-row piles supporting the side slope of the road embankment along the canal represented the low chance of road embankment failure, even though the water level in the canal had almost dried up as shown in Figure 12.

6. CONCLUSIONS

The construction of the road embankment along the canal at Nonthaburi rural road no. 5036 had a failure during the 18-m driven piles construction. The cause of driven pile failure was evaluated using field investigation tests, including resistivity survey, screw driving sounding test, and field vane shear test. Moreover, the finite element model (FEM) was utilized to confirm the behaviour of driven pile failure. From the results, the following conclusions and recommendations can be made:

1. The S_u of soft Bangkok clay exhibited an upward trend as the depth of the subsoil layer increased.
2. The energy generated by an impact or vibratory hammer from driving a pile during construction can cause disturbance and displacement of the surrounding soil, especially in soft and sensitive clay. This leads to a reduction in the strength of the soil.
3. During driven pile installations, the tip of the driven pile was located on a stiff soil layer, which was directly affected to damage the pile and disturbed the soft sensitive clay layer. This led to a reduction in the strength of the soft clay layer and affected the displacement of the driven pile during construction, especially under rapid drawdown condition.
4. The row piles supported the road embankment along the canal were proposed to prevent the road embankment and driven piles failure during the construction on the thickness of the soft sensitive clay layer as a suitable design approach for reparation and stabilization based on the reinforcement efficiency.

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