Shear Strength Reduction of Expansive Soil and Its Impact on Sheet Pile Structure Stability
(Study at Cikarang District, Bekasi Regency, West Java)

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Abstract

Expansive clay soils are classified as a problematic soil type, which is very sensitive to changes in moisture content. This sensitivity causes volume fluctuations and a decrease in soil strength parameters over time. The phenomenon has implications for the degradation of soil shear strength, which is often overlooked in long-term stability analysis. A real case happened in Bekasi Regency, where a slope retaining sheet pile experiencing a slant that was not predicted in the initial design. At the design and construction stage, the structure did not experience movement. However, over the time the structure experienced a slow movement causing it to become lopsided and severely damaged, affecting the road below. This condition is suspected to be due to a decrease in soil strength over time. To investigate this issue, this study undertakes a numerical modeling approach with the Finite Element Method (PLAXIS 2D). It allows the simulation of gradual deterioration of soil parameters including cohesion (c), internal shear angle (ϕ) and modulus of elasticity (E) until results are obtained that match the current field conditions. The analysis revealed that the main cause of the sheet pile slope was a 35% decrease in soil shear strength after 13 years due to expansive soil characteristics. Accompanied by a bending moment generated of 88.6 tons.m so it is recommended to use corrugated concrete sheet pile (CCSP) type W600 Type B for this condition.

Keywords: expansive soil, slaking, sheet pile stability, shear strength degradation

1. Introduction

Expansive soils are a significant concern in geotechnical engineering due to their ability to undergo substantial volume changes with fluctuations in moisture content. These soils, primarily composed of clay minerals such as montmorillonite, swell when they absorb water and shrink when they dry, leading to severe structural damage. This behavior poses considerable risks to infrastructure, particularly sheet pile structures used for slope stabilization and earth retention. As soil parameters degrade over time, these structures may experience unexpected deformations, ultimately leading to failure.

One of the critical mechanisms contributing to the weakening of expansive soils is slaking, a process in which soil aggregates lose cohesion and disintegrate upon exposure to moisture. This phenomenon significantly reduces soil shear strength, affecting the long-term stability of retaining structures. Despite advancements in soil mechanics, conventional geotechnical design approaches often fail to fully account for the progressive deterioration of soil properties, leading to unforeseen structural issues.

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The area under analysis in this study is located in the Central Cikarang District, Bekasi Regency, West Java (Fig. 1). This study specifically focusing on a sheet pile structure located on the slope adjacent to the road. This sheet pile experiences a slope which is assumed to be due to a decrease in soil parameters.

Fig. 1 Study area

This study aims to examine the shear strength reduction in expansive soils and its impact on the stability of sheet pile structures. By employing numerical modeling using PLAXIS 2D, the research simulates soil behavior under cyclic wetting and drying conditions. Key soil parameters such as cohesion, internal friction angle, and elastic modulus are analyzed to determine their role in structural stability. The findings provide valuable insights into the interaction between soil degradation and structural performance, emphasizing the necessity of incorporating long-term soil behavior into geotechnical design frameworks.

2. Literature Study

Expansive soils exhibit distinctive properties that affect their engineering behavior. These soils contain minerals such as montmorillonite, illite, and kaolinite, which influence their swelling and shrinking characteristics [1]. Montmorillonite, in particular, has a high cation exchange capacity and a layered crystal structure that allows significant water absorption, leading to substantial volume changes [2]. Illite has a lower swelling potential but still contributes to soil instability in varying moisture conditions.

Slaking is a phenomenon in which expansive soils lose their structural strength when exposed to water. This phenomenon can cause particle disintegration, cracking and peeling of the rock surface layer over time. The slaking process is an exothermic reaction between calcium oxide (CaO) and water (H_2O) that produces calcium hydroxide $Ca(OH)_2$. The reaction that occurs is $CaO + H_2O \rightarrow Ca(OH)_2$.

The mechanical properties of expansive soils are crucial in evaluating their impact on infrastructure stability. The internal shear angle (ϕ) and cohesion (c) play a significant role in determining the soil's resistance to deformation. Research indicates that expansive soils experience a 70–90% reduction in shear strength when the moisture content exceeds 35% [3-4].

Soil classification techniques such as the Standard Penetration Test (SPT) and Cone Penetration Test (CPT) provide valuable data for assessing expansive soil properties. These tests help determine soil consistency, permeability, and strength, which are essential for designing safe and effective retaining structures [5]. Additionally, slope stability analysis methods are commonly used to evaluate the safety factor of slopes built on expansive soils [6]. The safety factor value in slope stability analysis is generally calculated using the following basic formula:

$$Safety\ Factor(SF) = \frac{Resisting\ Forces}{Driving\ Forces} \qquad (1)$$

According to SNI 8460:2017 [7], the explanation about slope stability safety factor, for any slope which has the possibility to create an ordinary failure, the minimum factor of safety is 1.5. Meanwhile, in more critical conditions or of lower risk, such as under a short-term condition or under temporary landfill conditions, a factor of safety of 1.25 can be used in slope design conditions as shown in Table 1.

Table 1 Soil slope safety factor

Cost and consequences of slope failure	The uncertainty level in the condition of analysis	
	Low	High
The repair costs are comparable to the additional costs of designing a conservative slope	1.25	1.5
The repair costs are comparable to the additional costs of designing a conservative slope	1.5	2.0 or more

Based on [6], the classification of Safety Factor values is categorized into two, one of which is the slope safety factor based on research. Slope safety factor is the ratio between the actual soil shear strength and the minimum shear strength required to prevent slope failure. This parameter is used in the initial design and analysis stage to ensure that the safety margin of the slope is sufficient to withstand potential failure. Table 2 shows recommended SF values based on research for planning future designs.

Table 2 Slope safety factor

Safety factor	Interpretation
1.5 – 1.75	Safe for slope reinforcement
1.3 – 1.4	Safe for excavation and slope filling
1.0 – 1.2	Doubtful slope safety
Less than 1.0	Not safe

The second classification, according to [6], is the safety factor in existing conditions. Safety factor in existing conditions works for assessing the safety of an existing slope or structure under current field conditions. In this case, the purpose will be to judge the existing conditions if they meet the required standard of safety without repairs or further changes. Table 3 depicts the values of SF in existing conditions that provide information on whether a current structure or slope is safe.

Table 3 Safety factors in existing condition

Safety factor	Interpretation
$SF \geq 1.25$	Stable
$1.07 \leq SF \leq 1.25$	Critical
$SF \leq 1.07$	Unstable

Based on [6] previous reference, a higher SF generally indicates better stability; with values of SF = 1.5 or higher, safety is considered, which can be proven from a study by [8]. In the present study, the stability analysis of the slope using the Spencer method showed that SF = 1.0 represents the balance point at which the slope is right at the balance between being stable and unstable. It represents a critical condition of limit equilibrium in which forces tending to promote slope collapse are balanced by forces resisting such a movement. This is what is called critical equilibrium, where the slope is going to fail but not collapse yet. The results in this study outline that for slope stability, the value of SF has to be always above 1.

3. Methodology

This study employs a numerical modeling approach using PLAXIS 2D to analyze the reduction in shear strength of expansive soils and its effect on sheet pile stability. The Finite Element Method (FEM) is used to simulate soil behavior under varying moisture conditions, replicating real-world deterioration over time. The overall steps of this study methodology (Fig. 2) are outlined in the following flowchart.

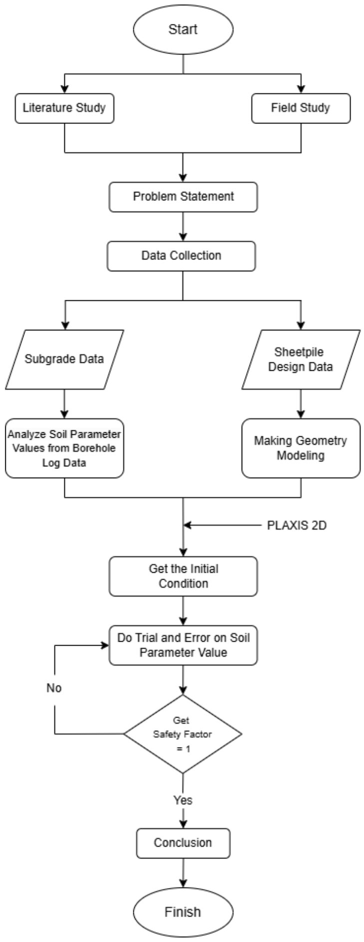

Fig. 2 Study methodology

The data adapted for use in the completion of this study are as follows:

1) Structural data (see Fig. 3)

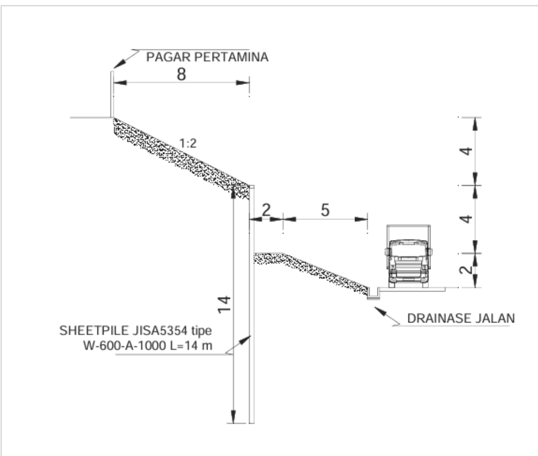

Fig. 3 Slope model and sheet pile structure

2) Geotechnical data

a) Soil layer (see Fig. 4 and Fig. 5)

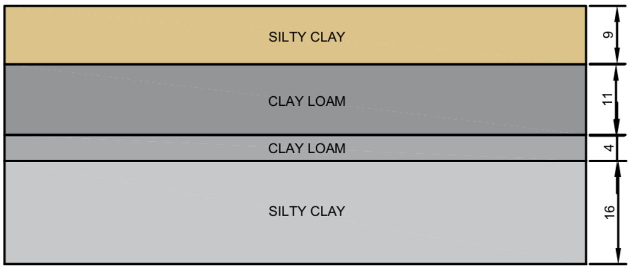

Fig. 4 Soil layer

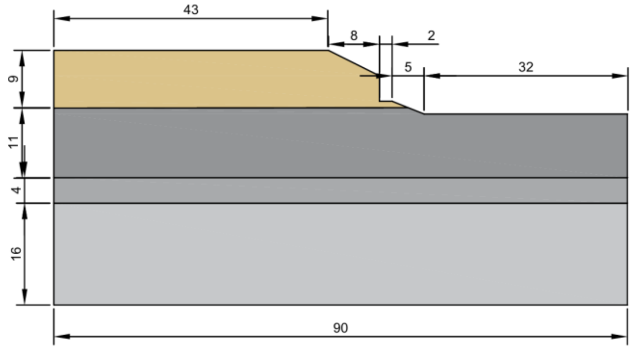

Fig. 5 Soil layer structure

b) Soil Parameters (see Table 4)

Table 4 Soil parameters

Layer no.	Soil type	Cohesion (kN/m^2)	Internal shear angle (◦)	Modulus of elasticity (kN/m^2)
1	Silty clay	13.04	4.235	2945.65
2	Clay loam	38.682	17.646	11105.71
3	Clay loam	55.814	19.553	16103.015
4	Silty loam	65.637	20.647	18968.575

The analysis was carried out using numerical modeling with PLAXIS 2D:

a. Model Development: The sheet pile structure and surrounding soil layers are modeled in PLAXIS 2D using borehole log data and soil classification parameters.

b. Soil Material Properties: The Mohr-Coulomb failure criterion is used to define soil behavior, incorporating factors such as cohesion, friction angle, and stiffness.

c. Boundary Conditions: The numerical model includes proper boundary constraints, groundwater table representation, and external loading conditions.

d. Mesh Generation: A structured finite element mesh is created with refinement in critical zones where high stress variations are expected.

e. Simulation of Shear Strength Reduction: A trial-and-error method is applied to systematically reduce soil parameters until the Safety Factor (SF) reaches 1.0, representing the critical stability condition.

f. Evaluation of Structural Response: Displacement, bending moments, and stress distributions are analyzed to determine the effect of soil degradation on sheet pile stability.

4. Results and Discussion

The factor of safety value coming from the computations was 1.579, which indeed means that both the structure and the soil at the location studied are safe (Fig. 6).

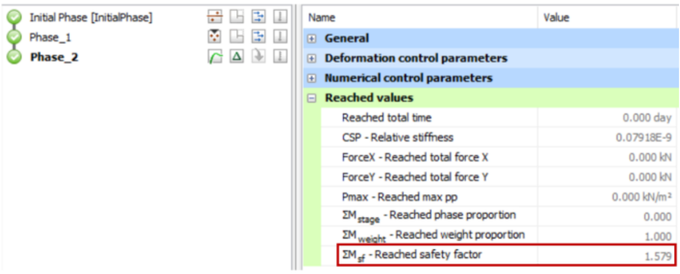

Fig. 6 Calculation result at initial

The deformation results can be viewed in Fig. 7. The biggest deformed area is around the sheet pile structure and upper slope, with a maximum deformation of 0.26m. As seen from Fig. 7 that presents the displacement distribution, the maximum displacement is obviously in the same area with a maximum value of 0.246 meters. The red color in the displacement image indicates large displacement, while the blue color signifies that very little or no displacement occurs in deeper soil layers and thus the soil layer is strong enough to bear the load without settlement.

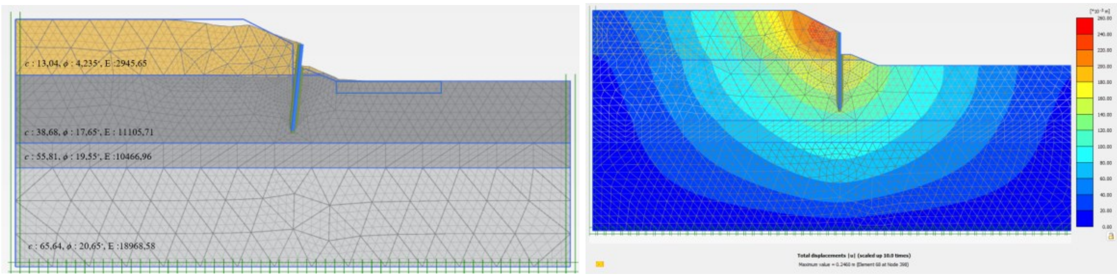

Fig 7. Deformation at initial

Then, a gradual trial-and-error process was carried out by reducing the soil parameters until the resulting output matches the actual condition (Table 5). The parameters include cohesion (c), angle of internal friction (ϕ), and modulus of elasticity (E). With a 35% reduction in parameters, resulting in a safety factor of 1.023 (see Fig. 8 and Fig. 9).

Table 5 Soil parameter after degradation

Parameter	Layer	Design	Actual condition (from trial and error)
Cohesion (kN/m^2)	1	13.04	8.48
	2	38.68	25.14
	3	55.81	36.28
	4	65.64	42.66
Internal shear angle (◦)	1	4.235	2.75
	2	17.65	11.47
	3	19.55	12.71
	4	20.65	13.42
Modulus of elasticity (kN/m^2)	1	2945.65	1914.67
	2	11105.71	7218.71
	3	16103.02	10466.96
	4	18968.58	12329.57

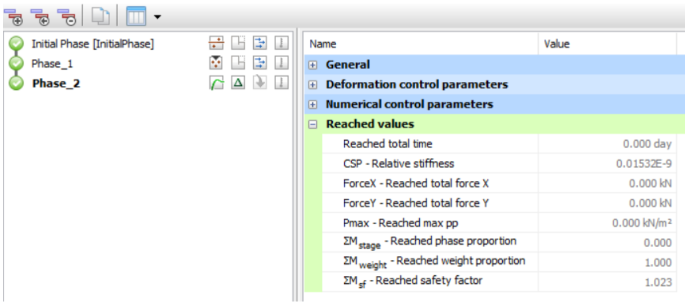

Fig. 8 Calculation results after 35% parameter reduction

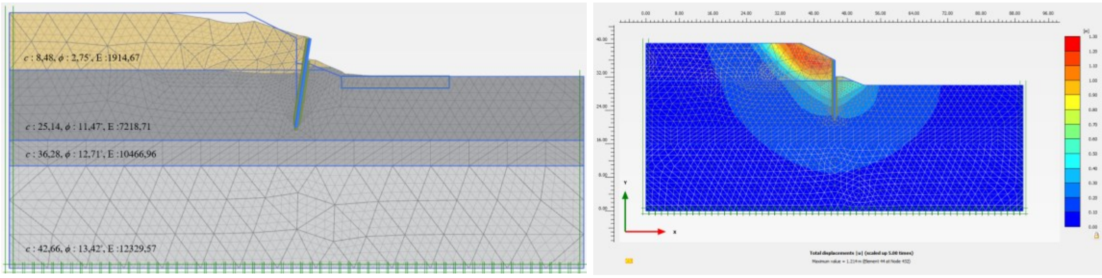

Fig. 9 Deformation after 35% parameter reduction

As obtained from the deformation results, the displacement of sheet pile by 2.025 meters (Fig. 10). To prove that the running result is similar to what happened at the study location, two segments of sheet pile damage from field measurements were taken. As a result, this condition is similar to the real situation in the study location where, in both sections, the sheet pile has shifted by 1.9 meters. Also, in the distance between the sheet pile and the crack boundary of the road damage: PLAXIS output given and actual in the field distances were similar. PLAXIS output gave the distance as 10.4 meters, while the actual distances in the field were 8.3 and 9.3 meters (Fig. 11).

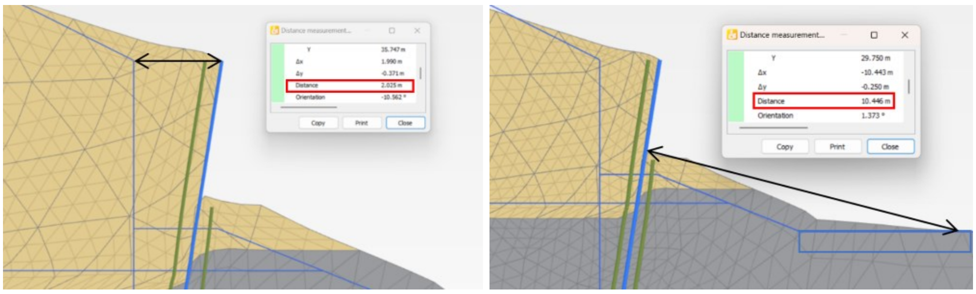

Fig. 10 Deformation after 35% parameter reduction

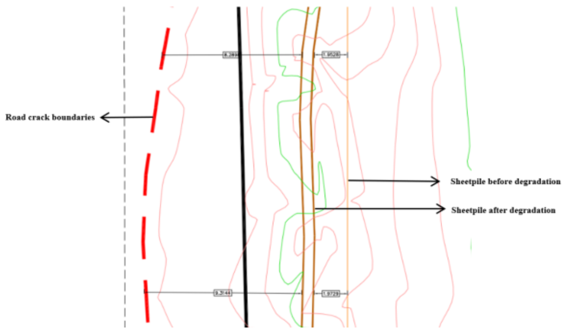

Fig. 11 Deformation after 35% parameter reduction

Other than that, based on the output results from PLAXIS, the damaged section of the road also showed an increase of 0.37 meters (Fig. 12 and Fig. 13). This condition is very similar to what happened in the field, where the difference in height between the road that is still in normal condition and the damaged road is 0.32 meters.

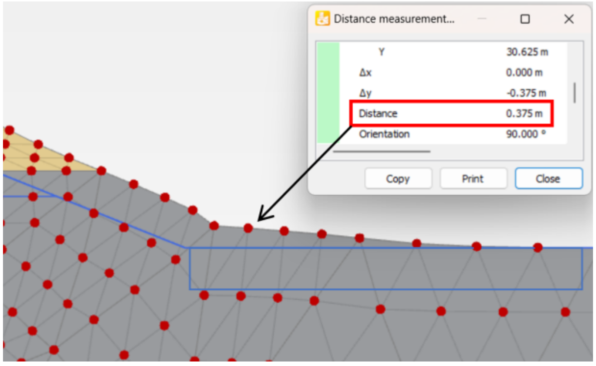

Fig. 12 Deformation after 35% parameter reduction

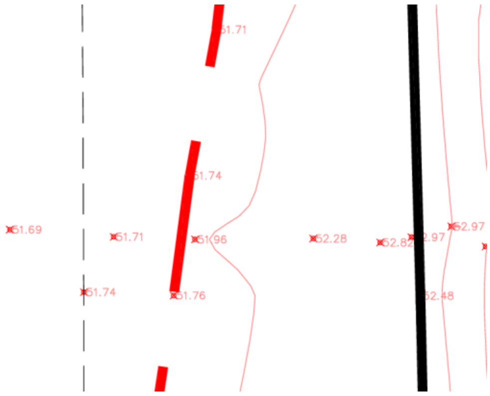

Fig. 13 Deformation after 35% parameter reduction

The field condition comparisons with the results of simulations using PLAXIS indicate that the ground movements developed in the PLAXIS model represent actual conditions in the study location. From the PLAXIS simulation, bending moment results were obtained based on previous calculations. The value of the bending moment is -886 kN.m/m or -88.6 tons.m/m (Fig. 14). This negative moment value represents the sheet pile is experiencing significant tensile forces in certain areas.

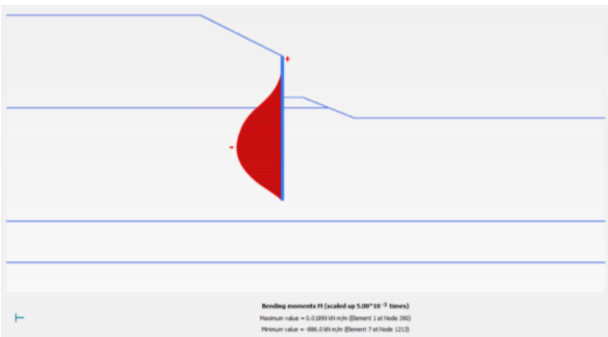

Fig. 14 Bending moment

To ensure that the sheet pile is able to withstand the moment resulting from the ground pressure, we need to compare the bending moment value with the sheet pile's capacity to withstand bending moment (Moment Break). In this case refer to the Corrugated Concrete Sheet Pile specification shown in Table 6.

Table 6 Corrugated concrete sheet pile specification

Type	Width (mm)	Cross Section (cm^2)	Section Inertia (cm^4)	Unit Weight (kg/m)	Class	Moment (ton.m)		Allow. Service Moment (ton.m)		Length* (m)
						Crack	Break	Temporary	Permanent	
W-325	996	1,315	134,264	329	A	11.40	22.80	10.07	6.74	8 - 15
					B	13.30	26.60	11.97	8.64	8 - 16
W-350	996	1,468	169,432	368	A	15.60	31.20	14.04	10.14	9 - 17
					B	17.00	34.00	15.44	11.54	10 - 18
W-400	996	1,598	248,691	400	A	20.10	40.20	18.10	13.08	10 - 18
					B	23.40	46.80	21.40	16.38	11 - 20
W-450	996	1,835	353,363	459	A	26.90	53.80	24.37	18.04	11 - 20
					B	30.70	61.40	28.17	21.84	12 - 21
W-500	996	1,818	462,373	455	A	35.20	70.40	32.22	24.76	12 - 22
					B	40.40	80.80	37.42	29.96	13 - 24
W-600	996	2,078	765,907	520	A	50.60	101.20	46.48	36.19	14 - 25
					B	59.60	119.20	55.48	45.19	15 - 27

According to the specification in Table 6, Moment Break capacity of sheet pile type W-600 Class B is 119.20 tons.m. This capacity is greater than the resulting bending moment (88.6 tons.m). Therefore, W-600 Class B is proper for use in this condition.

5. Conclusions

After carrying out a series of analyses, several conclusions can be drawn from this study as follows. The conditions of the soil in Bekasi Regency are expansive soils type that have reduced parameters over time. It is forecasted that this reduction will be about 35% of the initial value. Initially, sheet piles are constructed with soil parameters that are composed of: In the uppermost layer include cohesion = 13.04 kN/m^2, internal shear angle = 4.235° and elastic modulus = 2945.65 kN/m^2. Then in the second layer the parameters are cohesion = 38.68 kN/m^2, internal shear angle = 17.65° and elastic modulus = 11105.71 kN/m^2. In the third layer the parameters are cohesion = 55.81 kN/m^2, internal shear angle = 19.55° and elastic modulus = 16103.02 kN/m^2. In the fourth layer the parameters are cohesion = 65.64 kN/m^2, internal shear angle = 20.65° and elastic modulus = 18968.58 kN/m^2. With these parameters, the factor of safety reached a safe value of 1.579.

The soil at the study location is suspected to be degraded. To prove this assumption, numerical modeling using trial and error method was conducted on the soil parameters including cohesion (c), internal shear angle (ϕ) and modulus of elasticity (E) until the output was in accordance with the actual conditions in the field. The results of the numerical modeling showed an agreement with the field conditions, indicating that the soil was indeed degraded.

After several years, because of the reduction of the soil parameters, the factor of safety went down to 1. A reduced factor of safety means that the soil attained a balanced but critical condition, which is unstable yet does not collapse. In this condition the soil parameters change to in the uppermost layer become cohesion = 8.48 kN/m^2, internal shear angle = 2.75° and elastic modulus = 1914.67 kN/m^2. Then in the second layer the parameters are cohesion = 25.14 kN/m^2, internal shear angle = 11.47° and elastic modulus = 7218.71 kN/m^2. The cohesion is 36.28 kN/m^2, internal shear angle is 12.71° and elastic modulus is 10466.96 kN/m^2 for the third layer. Whereas in the fourth layer, cohesion is 42.66 kN/m^2 while the internal shear angle is 13.42° and elastic modulus is 12329.57 kN/m^2. The bending moment is 886 kN.m/m or 88.6 tons.m/m. Sheet pile type W-600 Class B is a suitable type of sheet pile used in this condition because it has a Moment Break capacity of 119.20 tons.m.

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