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Causes of Landslides in Road Embankment with Retaining Wall and Pile Foundation: A Case Study of National Road Project in Porong-Sidoarjo, Indonesia

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***Abstract*— This study was conducted to determine the cause of landslides in the toll road embankment of the national road project in the Porong-Sidoarjo area. The landslide was observed only on the north side of the embankment, with a maximum height of 7.8 meters from the subgrade despite the reinforcement with a retaining wall and pile foundation. The land shift and subsidence on the Northside led to a decline in the embankment elevation and the displacement to a maximum depth of 3.50 m. Back analysis through the limit equilibrium method was used to determine the strength of the existing reinforcement against the landslide. The results showed that the heavy rain was indeed one of the causes of landslides in the location, while the main cause was the depth of soft soil, much deeper than those in the surrounding locations. This is why a severe landslide was recorded on one side of the embankment. Moreover, the existing anti-slide pile reinforcement was discovered not to be sufficient due to its shallower length compared to the area of the landslide, and this was associated with the absence of overall stability analysis in this design. The findings showed that it is necessary to conduct a comparative study between the overall stability and the active and passive forces analyses for the soil to produce the safest design required to avoid landslides.**

***Keywords*— Case study; landslide; slope stability; anti-slide pile; back analysis.**

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I. INTRODUCTION

Landslides are a disaster that is primarily due to natural factors such as an earthquake and extreme rainfall, as well as sudden downward soil slopes under various conditions and geomorphic features [1]–[6]. However, this phenomenon is limited to natural embankments and artificial construction [7], [8]. Several previous studies [9]–[13] have been conducted on landslides associated with embankments in different countries to determine causes to provide long-term solutions.

The findings showed the reasons for landslide occurrence are generally not similar due to several factors such as subgrade conditions, embankment dimensions, existing reinforcement, and climate factors [14]–[16]. Moreover, several predictions on the landslide in the embankment area showed a critical safety factor below one (SF<1). Still, there was no certainty in the locations discovered to have initially experienced the disaster [17], [18].

Landslides have also been recorded at a high elevation of road embankments during highway construction in Porong Sidoarjo, East Java, Indonesia, despite reinforcements implemented using retaining walls and pile groups foundations. Sliding was discovered to have occurred before the final grade elevation was achieved, and the subgrade settled due to the embankment load. Furthermore, backfill was conducted through the stage construction method to avoid future occurrences. The embankment was also expected to be adequately safer against landslides due to the increase in the underlying subgrade parameters through embankment stage construction combined with PVD [18]–[20]. However, landslides were occurring continuously, adversely affecting human lives and properties. The failures materialize on one side while the other only experiences a horizontal shift. It is also important to note that the dimensions and retaining wall reinforcement on both sides of the embankment appear similar.

A landslide was reported to have occurred on Tuesday, March 18, 2014, in the embankment of Porong-Gempol toll road at Sta 43 + 340 to 43 + 456.8. The impact was mainly on the north segment of the route to Gempol, located behind the bridge abutment. The land shift and subsidence led to a decline in the embankment elevation and the displacement of the retaining wall to a maximum depth of 3.50 m, as shown in Figure 1. Meanwhile, the embankment in the south zone was impact-free even though the retaining walls generally experienced horizontal movements between 10 and 20 cm.

Fig. 1 Landslides reduced the embankment elevation to 3.5 meters and damaged the existing retaining wall due to landslides.

The toll road section was constructed on a soft subgrade with low bearing capacity, but the soil subgrade had already been improved using vertical and horizontal drained systems combined with the embankments and stage construction. It is important to note that the embankment constructed at the location has a maximum final grade elevation of 7.8 m while the maximum initial height (H initial) is 11.1 m, as observed behind the bridge abutment, but the elevation decreases towards the east. The embankment consists of 9.8 m of borrowed material and 1.3 m of surcharges. Moreover, the settlement of the soil subgrade was predicted at 2 m, while the embankment was dredged for elevation adjustment at a 1.3-m-thick surcharge to ensure it reached the final grade elevation of 7.8 m after the completion of the subgrade settlement. The 1.3-meter landfill surcharge represents the equivalent masses of the concrete pavement layer and the traffic load.

The embankment construction was compacted layer by layer thickness of 20-30 cm. The landfill was made between July 2013 and March 2014, but cracks were reported in several residences around the south segment on January 30, 2014. Moreover, another crack was recorded in the housing area around the north section, the route to Gempol, on March 4, 2014. The houses with heavy faults were found to be 15 m from the embankment toe, with most of them seriously damaged, as indicated in Figure 2. These defects continued to increase with landslides and cracks discovered behind the north side of the retaining wall. Therefore, there is a need for long-term reinforcement to prevent further damage or subsequent landslides.

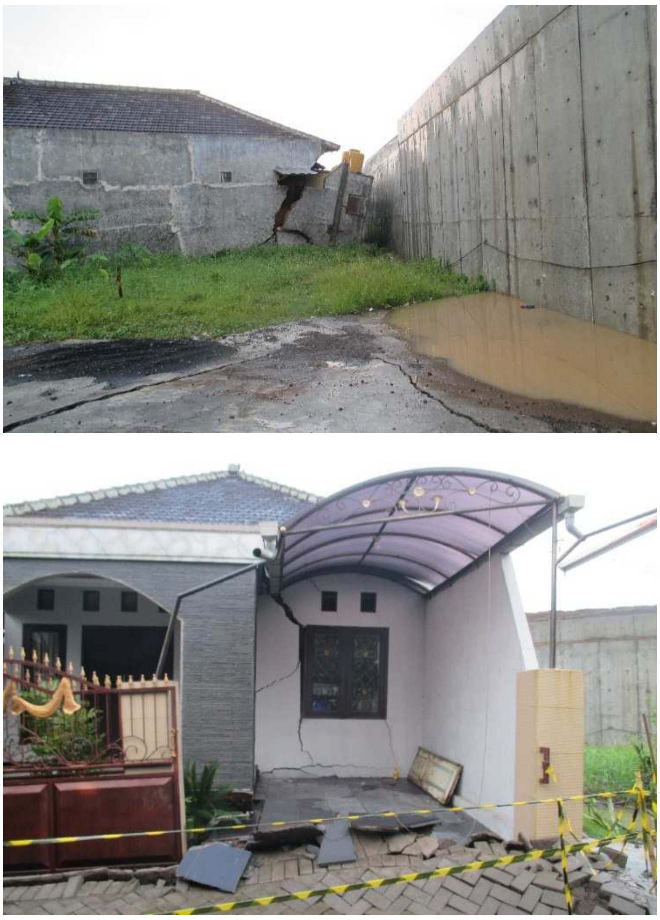

Fig. 2 The damage caused to the house close to the embankment landslide

The background information provided led to the study of the landslides caused by adopting a back analysis approach to observe the existing field reinforcement and ascertain the source of the failure. The findings are expected to be used as a reference to prevent similar landslides in other locations.

II. MATERIALS AND METHOD

A back analysis was conducted on the field conditions to determine the cause of the landslide. The stability of the road embankment was evaluated using the limit equilibrium method, while back analysis was used to determine the effectiveness of the existing strength through manual calculations of the retaining wall strength against shearing, overturning, and subsidence. Moreover, the strength of the pile foundation under the retaining wall was also analyzed using the anti-slide pile method. These are indicated in the flow chart presented in Figure 3. It is important to note that the analysis was conducted using soil data obtained from the field before the landslide and used in planning the existing design and those recorded after the landslide specifically to handle the disaster.

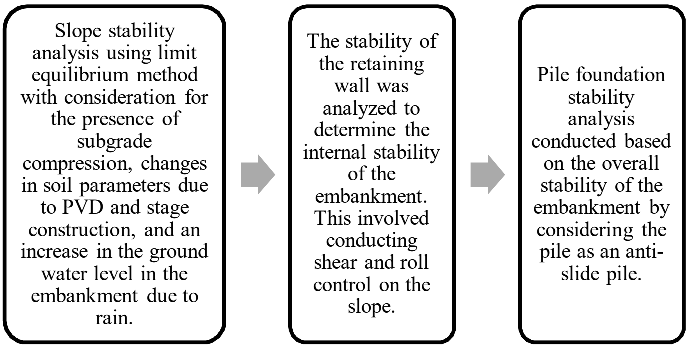

Fig. 3 Research Methodology

Landslide occurrences in selected locations were analyzed using two soil data groups: the existing soil data under initial conditions before the landslide and the additional soil data after the landslide. Moreover, four preliminary soil data were obtained from the center or middle of the embankment road. At the same time, twelve were retrieved from different sites after the landslide, as indicated in Figures 4 and 5.

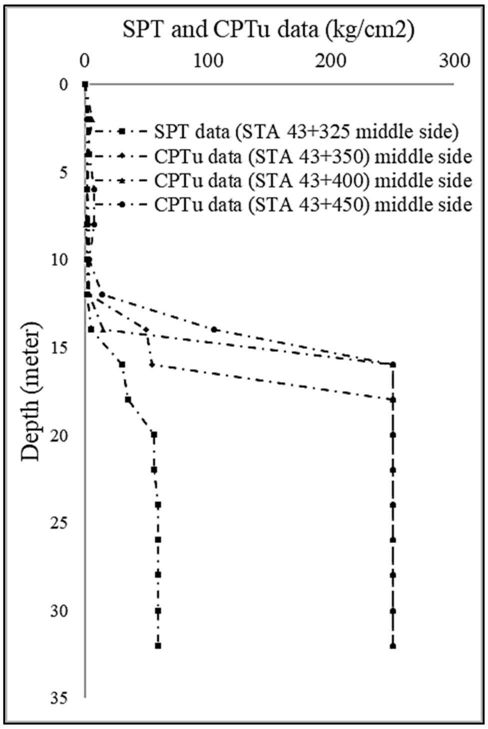

Fig. 4 Summary of soil data obtained before the landslide

The difference in the elevation of the soft soil depth was also observed from the data obtained before and after the landslide. A striking difference was discovered at shallow elevations due to the impact of landslides, while the deeper elevations were found to be normal. This means the depth of hard soil in the center of the embankment tends to be shallower when compared to the north side. The existing reinforcement was planned using the soil data from the middle of the embankment, and this can cause differences in the reinforcement needed and the dimensions of the foundation required. Therefore, this study compared several existing data to determine the most accurate for planning purposes.

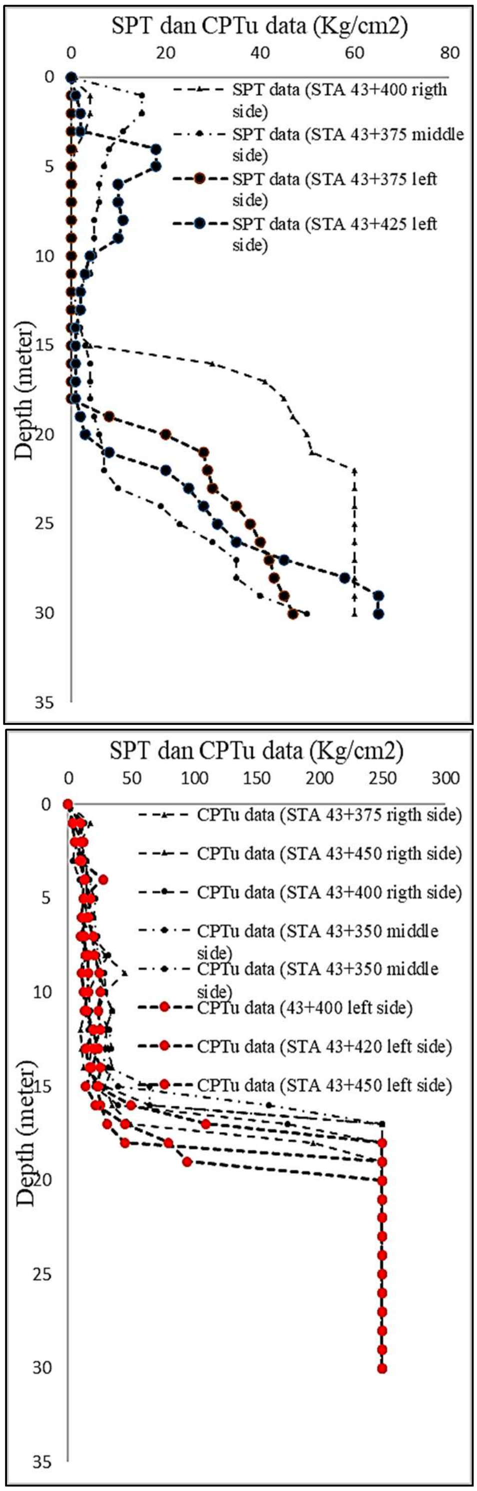

Fig. 5 Summary of soil data obtained after the landslide. (top) summary of SPT data; (bottom) summary of CPTu data.

The parameters of the soft clay, such as the undrained shear strength (Cu) and angle of friction (ϕ°), were determined using the empirical formula developed by Ardana and Mochtar [21], while the consistency was determined in the field based on experience. These data were later used for the road embankment stability analysis to determine the effectiveness of the existing reinforcement, calculate the ones needed, and find a long-term solution to the problem.

The analyses conducted showed that the following conditions are suspected to be the causes of the landslides in the field.

- The difference in the subgrade conditions at each location led to variations in the parameters, such as the compressible soil depths. This, therefore, can cause errors in the planning process.
- The embankment filling was not implemented according to the planned stages, leading to the soil subgrade's inability to carry the designed embankment load.
- The abutment foundation pile, an anti-slide pile for embankment stability, has a length that does not reach the stable soil layer.
- The anti-slide pile assumed and calculated in the existing design is not in line with the real conditions in the field.

These four suspicions were analyzed, and the results are presented in the next chapter.

III. RESULTS AND DISCUSSION

The settlement plate measurements are made in several places around the landslide location. The result from the measurement showed that the average settlement of soil subgrade was at ±1.0 m. At the same time, the consolidated settlement of ±2.0 m is expected under this circumstance due to the ±10 meter maximum elevation of the embankment from the ground level. Therefore, the total settlement was estimated at ~50% of the total compression prediction. However, there is a need to employ several assumptions on embankment elevation to determine the cause of the landslide, and these include: 1) An embankment elevation H = 10.0 meter (the soft subgrade has been compressed with a degree of consolidation U of 60%); 2) An embankment elevation H = 8 meter (the soft subgrade has been compressed with a degree of consolidation U of 60%); 3) An embankment elevation H = 6 meter (the soft subgrade has been compressed with a degree of consolidation U of 60%). The 6-meter and 8-meter elevations were due to the reduction of the embankment height towards the east with a road slope of ±3%.

It is also important to note that H = 8 m represents the elevation in the eastern region that experienced the landslides around Sta. 43 + 420 while H = 6m indicates the embankment height external to the area at Sta. 43 + 600. Moreover, as previously stated, the assumption of the 60% degree of consolidation (U) for points a, b and c was based on the total average subsidence of the subgrade at 50%. The parameter also experienced a degree of consolidation >50% while the subsoil had <50%. This means a 60% degree of consolidation of 60% led to an increase in the average shear strength of the soil subgrade in the surface layer, which was observed to have suffered soil movements and landslides.

The embankment landslides experienced on the soft subgrade were the reason for more decisive conditions observed for the soil stability, such as the reinforcement through soil retaining walls and pile foundations based on overall stability. This was established by considering the pile foundation of the retaining wall as an anti-slide pile that has the capacity to withstand collapse. Moreover, the retaining wall design was calculated in the construction plan based on the active and passive horizontal soil pressure and the assumption that the retaining wall showed no sliding, horizontal movement, or subsidence. This condition generally appears to be less dangerous when compared to the landslides influenced by the overall embankment stability. Therefore, it is important to calculate the pile stability based on rotational sliding or overall stability using the stage method of constructing an embankment as an anti-slide pile.

Soil stability analysis performed to determine the cause of landslides adopt the assumption of overall stability, not horizontal ground force calculations. Meanwhile, two separate soil data were used for evaluation, and these include the SPT data at STA 43 + 325 obtained from the middle of the embankment before the landslide and SPT data at STA 43 + 375 obtained after the event. It is also important to note that the effect of rainfall was not considered. The SPT data in STA 43+325 was found to have a safety factor value between 1.146 and 1.514 for H = 10 m embankment and 60% degree of soil consolidation without any rainfall, while the value when the rainfall was considered was within 0.725 and 0.826 (Figure 6).

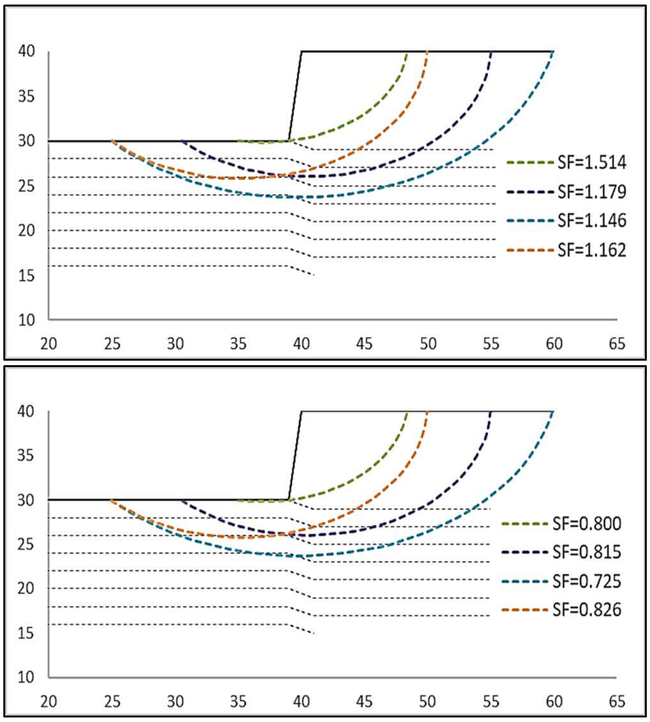

Fig. 6 Analysis of the overall stability of the embankment without considering the existing reinforcement. (top) low water table; (bottom) high groundwater level

The results showed a lower value during precipitation or shortly after the downpour. This condition causes an increase in groundwater level and soil saturation, thereby reducing the stability of the embankment [22]–[24]. This is more dangerous for the embankment stability when compared to the situation when there is no rainwater. This means there is a possibility of landslides in conditions with heavy rainfall. Therefore, a 50 cm diameter pile was installed in reality to serve as anti-slide support under the soil retaining wall. The number of existing mounted poles was three rows at a 1.5 m distance or the equivalent of two piles with a 1 m spacing, but the landslides still occurred continuously. Therefore, the back analysis is required to determine the capacity of the existing piles to withstand the landslides.

The back analysis used for the anti-slide pile was in line with Rusdiansyah, Mochtar, and Mochtar [25]. The results showed that support was not required in conditions without precipitations, but 2.4 piles per m were needed for those with rainfall (Figure 7). The amount of pile reinforcement used is the largest number of predictive landslides, namely SF = 0.725.

The analysis conducted using the SPT data at STA 43 + 325 showed that the embankment stability generally matched the requirements for a ±10 m height and a subgrade extending to 60% degree of consolidation (U) for both conditions - with and without rainfall. However, 2.41 pieces per m were required in the retaining wall length, but the existing piles were 2 pieces per m. Subject to rainfall, it is important to note that insufficient piles do not necessarily instigate landslides because it normally occurs in three-dimensional mode. At the same time, the calculations were made based on a two-dimensional (2D) sliding assumption. The 2D slide generates a lower SF than 3D, which requires lesser piles [26], [27]. This means the number of pile foundations for the retaining wall barely matched the requirements for the overall stability of a 10 m pile. A similar trend was observed for the heights of other embankments at 8.0 and 6.0 m which are believed to be safe.

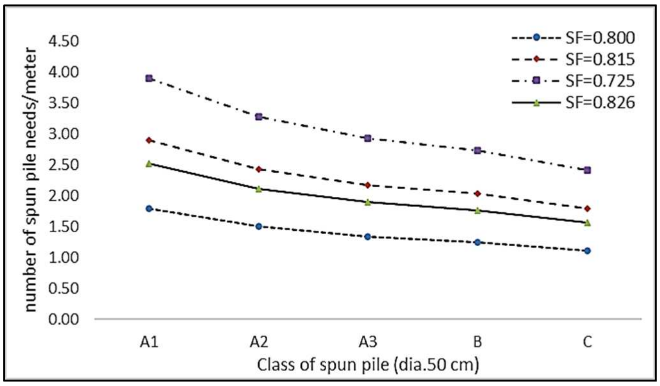

Fig. 7 The amount of reinforcement needed for piles to withstand landslides during rainfall

The embankment and existing pile stabilities were analyzed using soil data at STA 43 + 375 with H = 8 and 6 m and U= 60%. The results of this analysis are the safety factor of the 8-meter embankment is from 0.7 to 1.0 and from 0.58 to 0.68 in the absence and presence of rainfall conditions, respectively. Meanwhile, in the H = 6 m ridge, the safety factors ranged from 0.8 to 1.1 and from 0.52 to 0.76 without and with rain considerations, respectively. The required piles were estimated at 2.71 and 0.89 without rain consideration in 8 meters and 6-meter embankment heights, respectively. At the same time, the piles required 3.17 and 1.44 in the presence of rainfall conditions for 8 and 6 meters, respectively. (Figure 8). The conclusions of this stability analysis results and the need for anti-slide pile reinforcement can be seen in Table 1.

TABLE I
THE CONCLUSIONS OF THIS STABILITY ANALYSIS RESULTS AND THE NEED FOR ANTI-SLIDE PILE REINFORCEMENT

Embankment height (m)	**Conclusions for reinforcement**
6	• An embankment with a 6 m was assumed to be safe against landslide threats, either during extreme rainfall or with traffic loads. • The number of piles needed as a shear barrier was 1.44 pieces per m, and it was confirmed to be relatively safe.
8	• The embankment with 8 m height did not fulfill the stability requirements, making it vulnerable to landslide hazards, particularly during rainfall. • The number of piles needed as a shear barrier was estimated at 3.17 pieces per m length of the retaining wall, while only 2 per m were installed. • The analysis also ascertained the possibility of overall embankments with H > 8 m experiencing landslides, specifically during heavy rainfall. • Landslides were predicted to occur for every 8 m or above embankment height, with the most critical cases discovered during intense rainfall.

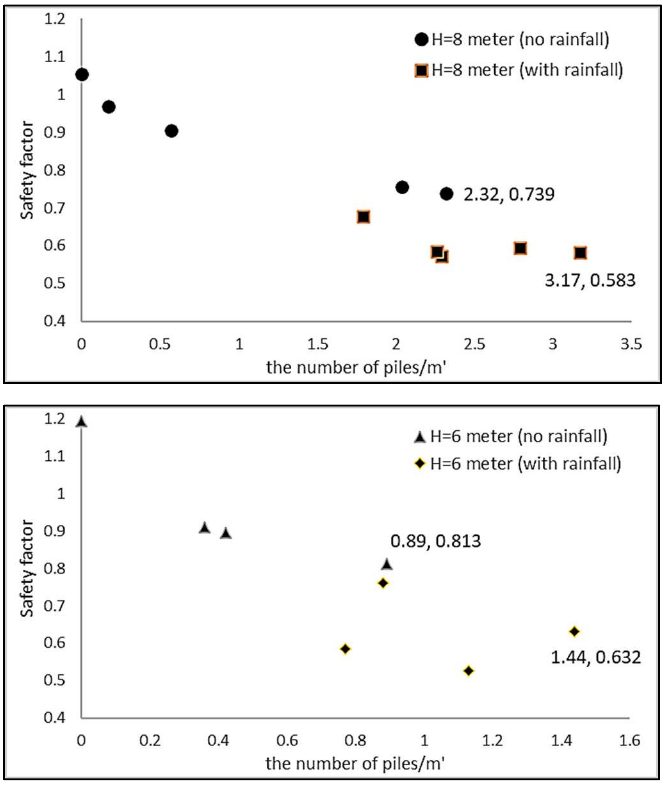

Fig. 8 Summary of the safety factor results and the need for the number of piles at H=8 meters (tom) and H=6 meters (bottom).

The overall analysis showed that the causes of land shifting and landslides are that the soil data and parameters significantly varied from relatively very soft to stiff. This led to landslides, possibly due to the wrong assumption of data. Moreover, the field data taken after the landslide incidence showed a very soft soil layer from a depth of 0 to -18 m.

Subsequently, samples at a depth of -20 to -26 m in stiff clay and hard soil layers were uncovered at a depth of >26 m. These conditions were, however, not detected in the previous soil data.

Furthermore, based on many recent studies, the presence or absence of rainfall significantly influenced the embankment stability. Moreover, the embankment is not equipped with a horizontal drain which is proven to be effective in reducing the impact of rain on the stability of the embankment [28], [29]. Heavy rain hit the field just before the landslide and continued to rain for several days. Therefore, the practical geotechnical planning method used for existing designs never involves special factors during heavy rainfall. Several global studies have also reported rainwater as the primary cause of landslides. It is also important to note that precipitation does not necessarily increase the groundwater table elevation in the embankment. Still, the initial crack (longitudinal direction) in the landfills allows rainwater penetration, thereby completely saturating the available spaces [30], [31]. The presence of cracks will also affect the stability of the slope, especially when it rains [32], [33]. These, therefore, consequently instigate a maximum horizontal soil pressure similar to the groundwater level conditions, which affects the overall stability of embankments with high elevation.

IV. CONCLUSION

This case study found that the landslide was caused by several factors, including highly varied subgrade conditions, climatic conditions that caused heavy rain before the landslide incident, and the failure to conduct the overall stability analysis in the plan for the embankment. Meanwhile, overall stability analysis is more important in abutment design and ensuring bridge stability, but most designers are more concerned with active and passive stress analysis. Moreover, the effect of heavy rains on extreme climatic conditions was also an important thing to consider in the design of roads with high embankments. Therefore, this study's novelty is in conducting an overall embankment stability analysis in designing bridge abutments with anti-slide-pile. Comparing the stability analysis results with the active force of the sand and the overall stability analysis is considered important to obtain the most suitable design for the extreme conditions in the field. This study is expected to be a reference for designers in road and bridge design planning to avoid the occurrence of similar landslides in the future.

NOMENCLATURE

PVD	Prefabricated Vertical drain	
PHD	Prefabricated Horizontal drain	
SPT	Standard penetration test	
N	Standard penetration test result	
H	Embankment height	m
Cu	undrained shear strength	Kpa
U	Degree of consolidation	%

Greek letters

ϕ	angle of friction	°

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