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Sheet Pile Failure Caused by Scouring and Sand Mining at Padang River Bank

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ABSTRACT Ground movement occurred on the banks of the river in Padang which has been protected by steel sheetpile which borders the Factory property. Indications of ground movement are detected through visual observations. It was also reported that the day before the incident there had been continuous rain until the next day. Based on the results of the technical drilling, it appears that the soil density becomes lower after 10m depth. There is a layer of sandy silt with a soft to medium consistency at a depth of about 18m to 26m. With soil conditions that are dominated by sandy soil, the risk of scouring due to river flow is one of the things that needs to be considered. Landslides occur gradually because changes in river flow patterns gradually changed due to internal and external factors. Internal factors are caused by the flow and behavior of the river itself, while external factors are the activity of mining of sand material around the riverbanks. Along with the swift river flow, especially during flood water conditions, the layers of soil material move and are washed away by the flow of water so that there is a gap between the sheetpile and the original soil. These conditions cause the passive resistance of the sheet pile to gradually decrease and to experience deformation due to the pushing of the soil material that has experienced a movement. Important findings in the investigation is that the very soft clay layer underneath the sandy layers was not detected prior to the investigation.

KEYWORDS Failure; Sheet Pile; River Banks; Scouring; Flow Pattern; Degradation; Gradual

1 INTRODUCTION

Ground movement occurred on the banks of the river in Padang, West Sumatra. The study area is a Factory area that has been protected using steel sheet pile. Indications of the ground movement were detected through visual observations supported by CCTV footage on September 30, 2021. As a result of this incident, the sheet pile was damaged along 85.5m. The location is shown on Figure 1 below.

Figure 1. Situation of the project site

Figure 2. Soil movement documentation (September 30th, 2021)

Figure 2 shows the condition of the sheet pile that has experienced deformation and the condition of the factory area which has decreased due to soil movement.

Slope instability is one of the major problems in geotechnical engineering where loss of life and property can and do occur (Vanmarcke, 1977). Slope riverbank failure is a natural event occurring globally on riverbanks worldwide. Slope riverbank failure is a common result due to slope instability. Various factors cause slope instability, such as rainfall, a rise in the groundwater table, seepage, rapid drawdown, or a shift in stress conditions (Nazaruddin et al, 2002).

2 CHRONOLOGY OF EVENTS

The following is a chronology of landslide events at the study site. The Factory Manager informed that previously there had been a landslide in 2012. Regarding that event, steel sheet piles were installed along the river banks. In 2014, another landslide occurred at the same location where the subsidence was getting wider. Based on the Site Engineer information, it can be seen that the moving material was embankment material. Table 1 lists the landslides that have occurred several times.

Table 1. Landslide chronology

Date of Event	Events
2012	Landslide at near Boiler Area Soil Investigation (3 points of CPT) Steel Sheet Pile Installation
2014	Landslide at river banks
2016	Landslide at near Boiler Area. Soil Investigation (2 points of CPT)
September 2021	The river overflows cause by heavy rainfall Landslide at river banks
2022	Additional Soil Investigation (2-points of boreholes + 5 points of CPTu) Bathymetry Survey

Figure 3. Landslide chronology documentation

Figure 3 depicts the sheet pile piling work in 2012. It is noticeable that the piling was done near the river. In the documentation of ground movement from 2014, it was discovered that the penetration depths of the sheet piles were not uniform. Another land movement happened in another location in 2016.

3 GEOLOGICAL AND SOIL CONDITION

3.1 Geological Condition

The study location is generally located in surface sedimentary geological formations in the form of Alluvium (Qal), which consists of silt, sand, and gravel materials scattered on the coastal plains or river banks. The formation includes swamp deposits to the north of Tiku, to the southwest of Lubukalung, and the east of Padang. The following is the location of the project on the Geological Map of Lembar Padang, Sumatera by Kastowo, et al in 1996. Figure 4 shows the site location on geological map.

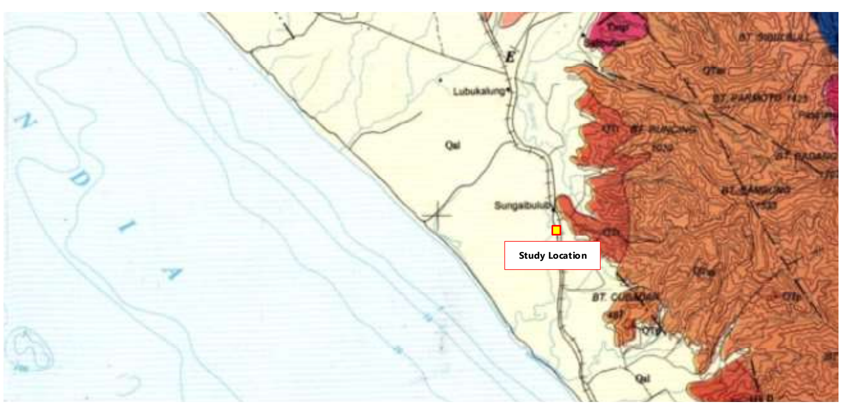

Figure 4. Geological conditions of study location (source: Geological Map of Lembar Padang, Sumatra by Kastowo, Gerhard W. Leo, S. Gafoer & T.C. Amin in 1996)

3.2 Previous Soil Investigation Data

Based on soil investigation data in 2012, it appears that local soil conditions are dominated by layers of sand with medium density, and at certain depths, there are indications of loose sand. CPT data is limited to reaching depths of 12–26 m due to increasingly denser soil conditions, as seen in the increasing value of the cone tip resistance. The position of the soil investigation is not indicated. Figure 5 shows the estimated soil stratification based on CPT data in 2012.

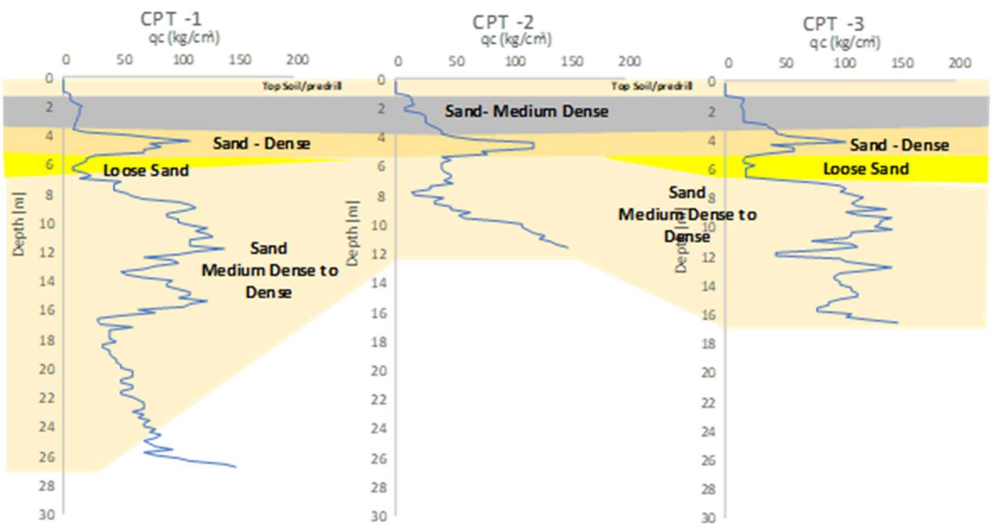

Figure 5. Preceding CPT Test in 2012

Based on CPT data in 2016, it can be seen that local soil conditions are dominated by layers of sand with medium density, and at certain depths there are indications of loose sand. CPT data is limited to a depth of 5-8m due to the increasingly compact soil conditions seen by the increasing value of the cone tip resistance. Figure 6 shows the estimated soil stratification based on CPT data in 2016.

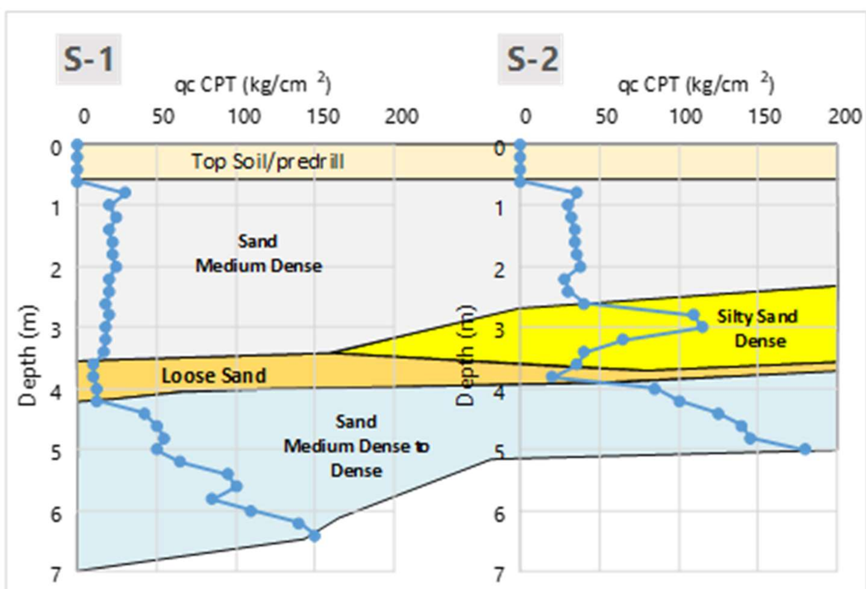

Figure 6. Previous CPT test in 2016

3.3 Latest Soil Investigation Data

The location of the soil investigation points in 2022 are focused on the area along the landslide or the movement of the steel sheet pile.

Figure 7. Latest soil investigation layout

The CPTu test is carried out to determine the characteristics of the soil based on the value of the cone resistance, skin friction, and pore pressure. The test is carried out electrically and the test results are displayed in a computer which automatically records when the test is carried out. Interpretation of the soil stratification profile was carried out based on Robertson, 1986 using data on the value of the cone resistance (qc) and the ratio of pore water pressure (Bq).

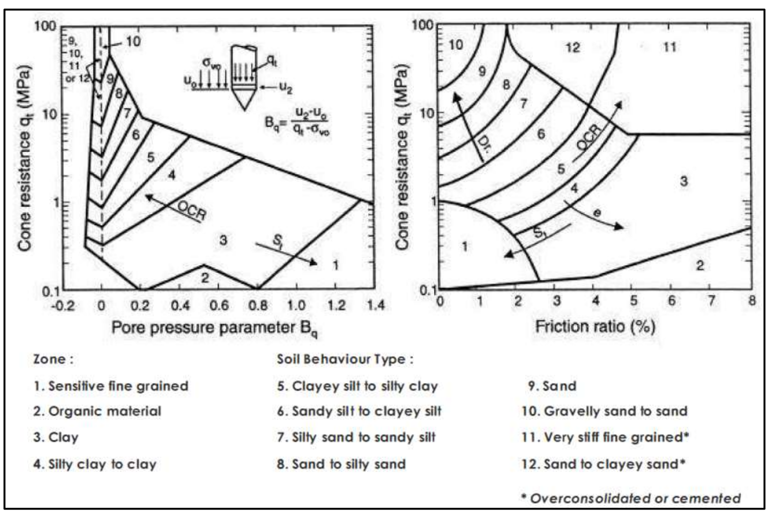

Figure 8. Determination of soil profile based on behavior during penetration (Robertson, 1986)

Soil conditions based on drill data and CPTu (Piezocone) are consistent, where the soil layer is dominated by soft clay on the surface with a thickness of 2m to 5m. The second layer is gravelly sandy soil with loose to moderate density to a depth of 15m. The third layer is very soft clay, which is uniformly found down to a depth of 25m. The CPTu test ended at this depth due to limited penetration and hard soil. The next layer is interpreted based on drill data, where the next layer is dense sandy soil to a depth of 35m. The next layer is silt clay of medium to stiff consistency, which was encountered until the end of the drilling at a depth of 50m. Figure 9 shows the estimated soil stratification based on piezocone data and technical drilling in 2022.

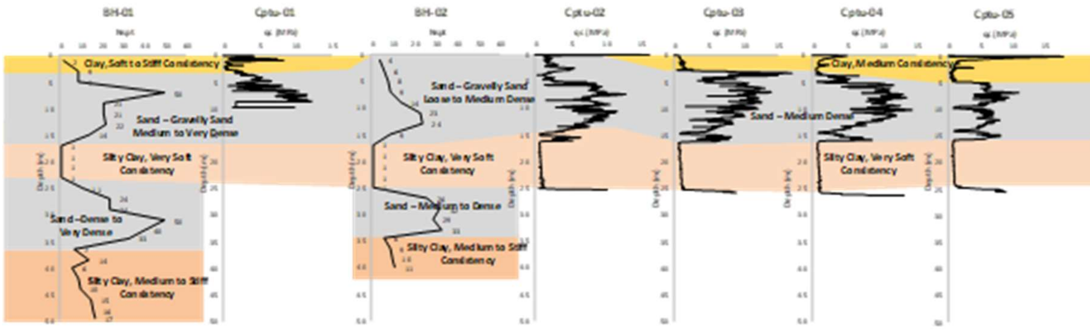

Figure 9. Soil Stratification Interpretation of Latest Soil Investigation

4 Identification of Problems and Possible Causes of Landslide

Bank erosion problems are rarely the result of a single process or mechanism, but rather are usually the result of complex interactions between a number of processes and mechanisms that may operate on the bank either simultaneously or sequentially (Thorne et al. 1996). Erosion processes transport particles, failure mechanisms that leads to movement, and weakening processes which increase its erodibility and reduce stability. As Jaksa, et al (2013) explained, categorizing failure processes is essential prior to landslide susceptibility assessment and hazard mapping.

Based on aerial photos taken during the site visit in 2022, there was a wide gap of 10-12 meter between the sheet pile and the Factory site. It was expected that the sheet piles condition are in critical condition because most of the sheet pile structures are no longer embedded below the ground. Figure 10 below shows the situation in the Factory area from an aerial view and the sheet pile conditions.

Figure 10. Sheet Piles Movement in 2022

Landslides can be caused by inadequate soil investigation data before the construction period, so that in planning there are several things that have not been considered related to field conditions and local soil conditions. Landslide can occur slowly or suddenly, with or without a clear trigger. Slope failure usually occurs gradually with reduced soil strength or with changes in geometric conditions such as steepness of a slope. Considering the actual site condition, it can be said that there are 2 sheet pile failure patterns as shown in the following Figure 11.

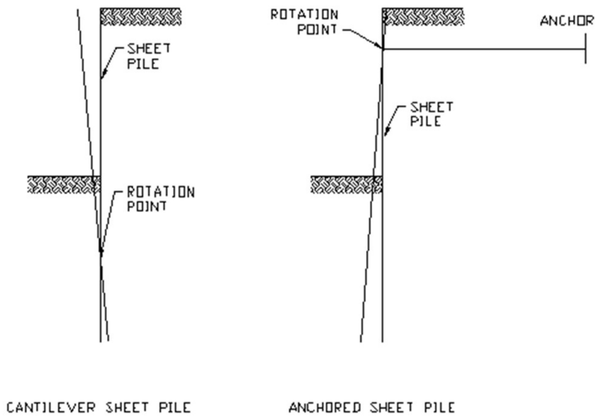

Figure 11. Commonly assumed failure mode of cantilever sheetpile

Based on site observation, the landslide mechanism that occurs is caused by the material behind the sheet pile being scoured so that the soil resistance is reduced. Referring to the technical drilling data that has been carried out, it can be seen that at the foot of the sheet pile, there is a layer of very soft soil, which can have an impact on the lack of resistance so that the sheet piles are unstable.

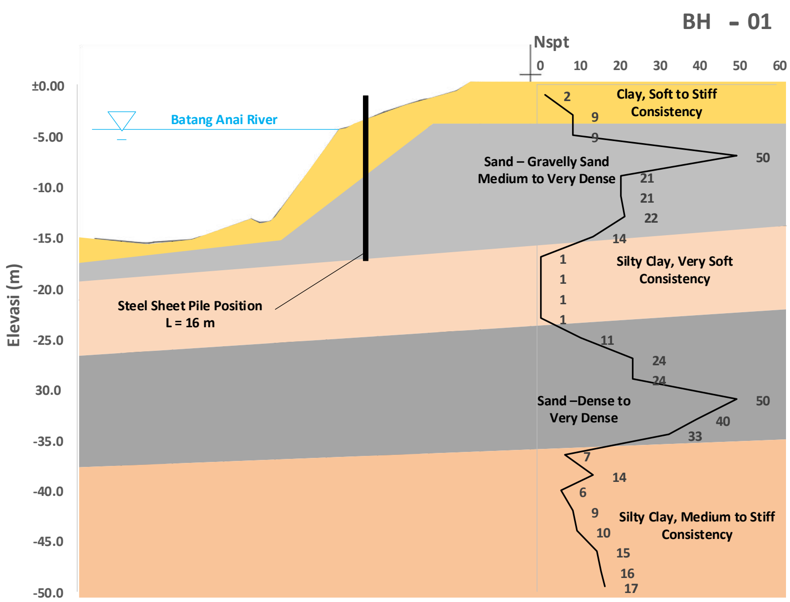

Figure 12. Sheet piles on soil stratification

To understand the history of land development from year to year, satellite imagery from Google Maps is used. Based on the image, the condition of land and riverbanks area along the steel sheet pile protection can be seen from 2005 to 2021.

Based on the Figure 13 below, it can be seen that part of the land area beside the Factory is suspected as embankment material. In 2021 it can be seen that Factory land is increasingly being eroded towards buildings. Briaud (2008) explained that the input to an erosion problem is always three fold: the soil or rock, the water, and the geometry of the obstacle that the water is encountering. Meanwhile, Duong and Do (2019) also found that Riverbank failure occurs by multiple factors, especially during a rainy season, such as the fluctuation of river water level, groundwater, pore water pressure, soil strength (soil suction and shear strength), and soil erosion.

Figure 13. Land development history (source: Google Earth image)

Based on images of the land development history as shown in Figure 14, the position of the BH-01 drill point which was conducted in 2022 was formerly part of the River area. The embankment material is suspected of experiencing scouring and landslides. It is suspected that the soil condition of the embankment has not been adequately compacted so that scouring occurs easily.

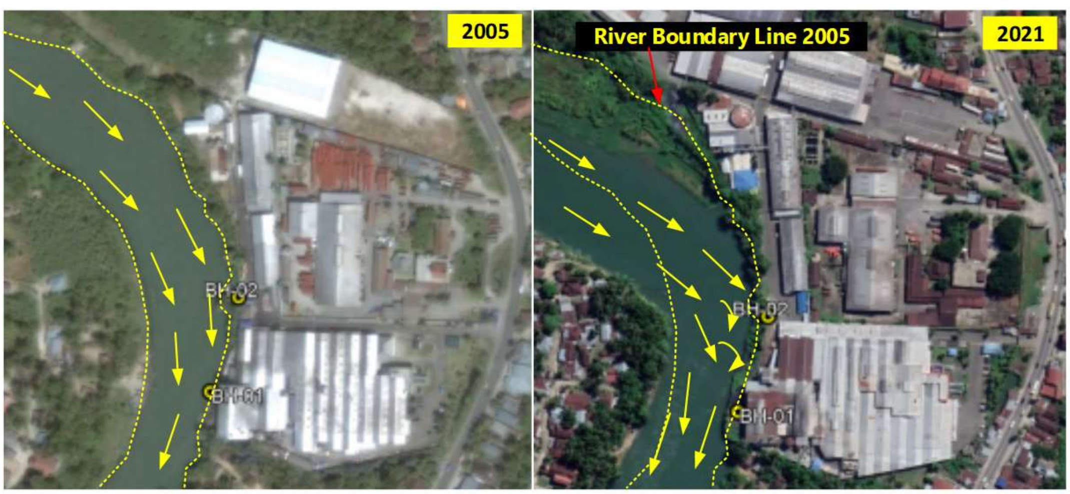

Figure 14. Changes in the flow pattern of the river

Based on the 2005 satellite imagery compared to the 2021 data, it can be seen that the appearance of the river has changed, which has caused the river to flow directly into the factory land area.

Figure 15. Sand mining around riverbanks

Land movements and landslides occur due to changes in the flow patterns of the River, which occur gradually due to two factors. The first factor is caused by the flow and behavior of the river itself, while the second factor is the mining of sand and soil materials around the riverbanks. Sand mining around riverbanks shown in Figure 15.

In the case of land movement that occurred on September 30 2021, there is data of rain conditions on September 29-30 2021 in the Batang Anai District area, Padang City obtained from the BMKG weather report. Based on MAX Weather Radar Imagery on September 29 2021, the maximum reflectivity value reaches 35 dBZ from noon to early morning (around 13.00 WIB to 04.00 WIB). Based on weather radar data for the CMAX product, cloud growth was observed to occur in water areas and move into the mainland of West Sumatra at 13.00 WIB with a reflectivity value of 30-40 dBz indicating moderate intensity rain. Furthermore, it was observed that cloud growth continued to cover the Padang Pariaman area with a reflectivity of 40 dBZ until 22.00 WIB.

Rainfall data collected from the local BMKG is radar image data. Meanwhile, based on the website bmkg.go.id, weather radar images depict potential rainfall intensity detected by weather radar. Measurement of rainfall intensity (precipitation) by weather radar is based on how much the radar energy beam is reflected back by water droplets in the clouds and is described by the product Reflectivity which has units of dBZ (decibels). The greater the reflected energy received by the radar, the greater the dBZ value, and the greater the dBZ reflectivity value indicates the greater the rain intensity that occurs.The dBZ scale in the legend ranges from 5 - 75 which is indicated by a sky blue to light purple gradation. If the color gradation is towards purple, the intensity of the rain will be higher. The range of rain intensity based on the color scale dBZ and mm/hour is presented in the following table:

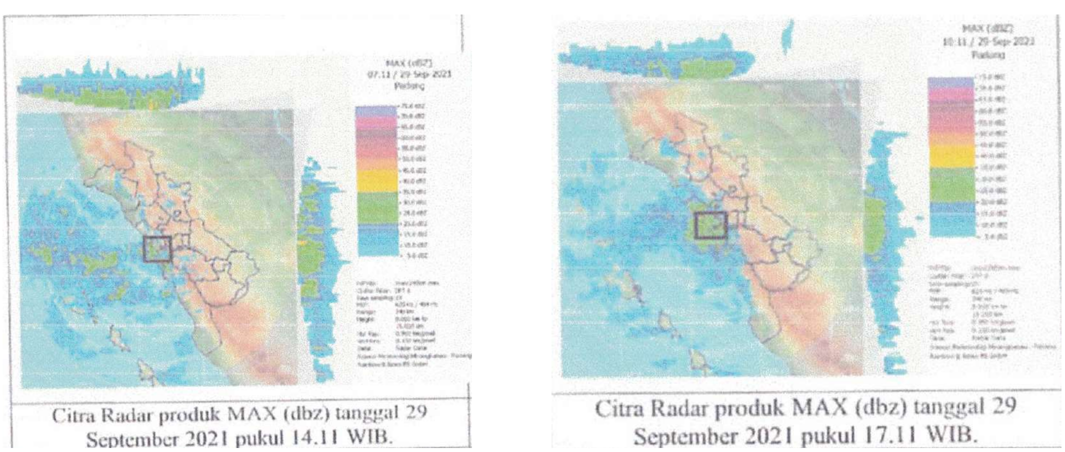

Figure 16. Rainfall Data BMKG

Table 2. Rain Intensity Category based on BMKG

Kategori Intensitas Hujan	Nilai dBz	mm/jam
Hujan ringan (light rain)	25 - 35	1 - 5
Hujan sedang (moderate rain)	35 - 45	5 - 10
Hujan lebat (heavy rain)	45 - 55	10 - 20
Hujan sangat lebat (very heavy rain)	> 55	> 20

Based on radar imagery the reflectivity value only shows indications of moderate intensity rain, but this condition occurs continuously from day to night which causes the cumulative rainfall value to reach the category of extreme rain (> 150 mm/day). The total accumulated daily rainfall intensity, based on the Padang Pariaman Minangkabau Starnet Station, reaches 250mm, which is included in the extreme rain category. This rainfall is a factor that greatly influences the condition of the flow pattern of the Batang Anai River which causes the river flow rate to become very heavy.

This change in flow patterns is confirmed by a comparison of the 2012 cross section drawing to the latest of 2022 cross sectional drawings. Based on those drawings, it is known that there is elevation difference between the deepest river bed and the river water level which deepens up to 3-4 meters over 10 years period. These are the two processes that most commonly cause bank instability The process of lateral erosion increases the bed width of the channel and results in steepening of the bank, which reduces its stability. Bed lowering increases the bank height, which also decreases stability (Osman and Thorne, 1998).

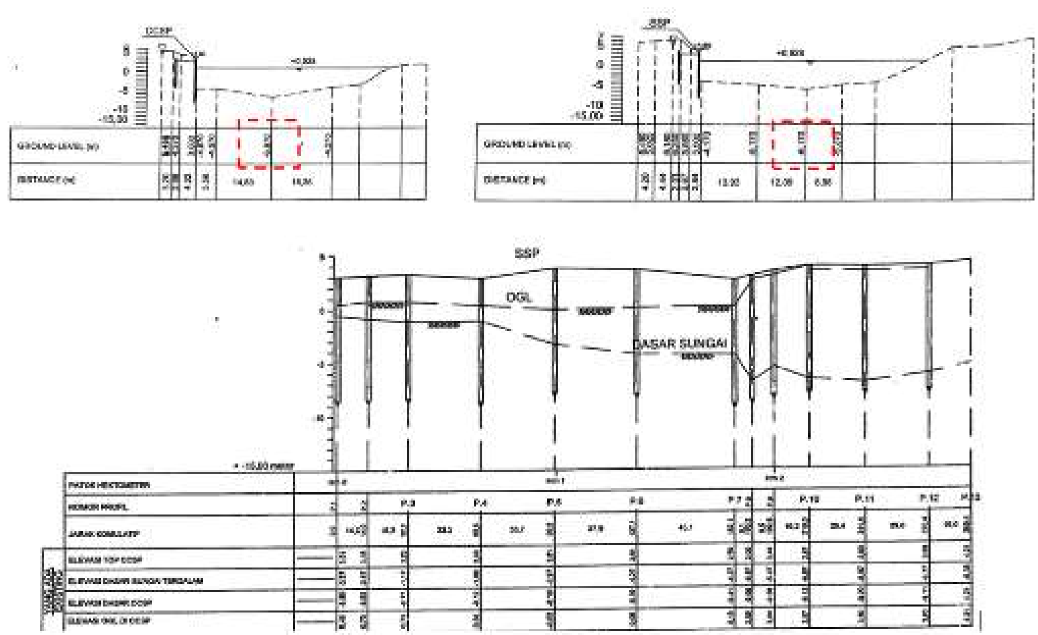

Figure 17. River bed elevation in 2012 (7.1 – 7.9 meter below river water level)

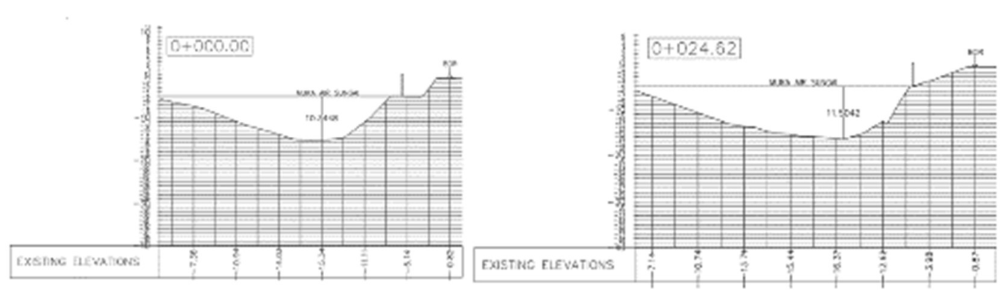

Figure 18. River bed elevation in 2022 (up to 11.5 meter below river water level)

5 DISCUSSION

It is advised that the reinforcement of the river slope should be in the area of original soil that has not moved, based on the mechanism of slope failure that shows in the field. Installing a river protection system in an area that has moved or on an existing sheet pile area that has moved is not a safe option regarding the risk of scouring and increased stress on the retaining wall.

Installing secant piles with a minimum diameter of D600 is one of the slope protection options that can be taken into consideration. The secant pile is a soil-retaining structure consisting of a series of primary piles (in the form of drilled holes filled with ready-mix concrete without reinforcement) and secondary piles (in the form of bored piles). Consideration of secant piles to anticipate scour issues that occur on the slopes.

In principle, a layer of soil that is unlikely to be scoured or that is a slipping plane must be reached by the length of the depth of the soldier pile or the retaining structure. The Figure 19 below presents the position of River slope reinforcement recommendation is located:

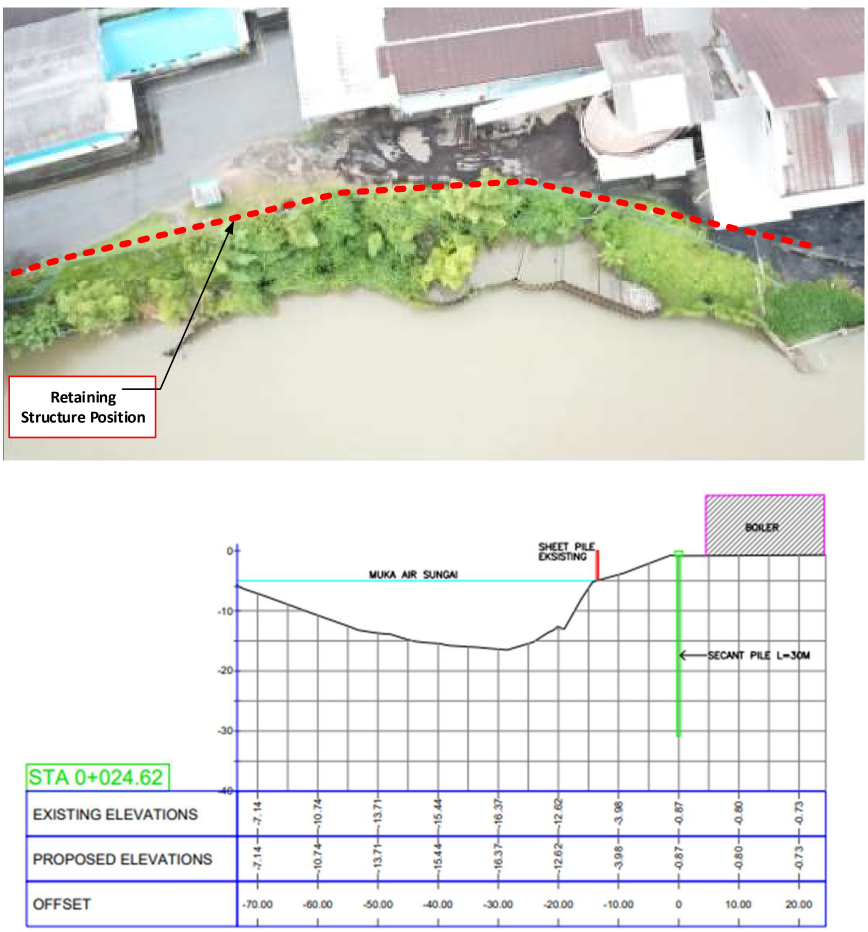

Figure 19. Secant pile position recommendation

Figure 20 shows a sketch of the position of the secant pile placement on the existing slope that is experiencing land movement. Placement of secant piles is estimated to at least reach a depth of 30 meters in order to anticipate the potential for future landslides due to soft soil layers at a depth of 20 - 25 m.

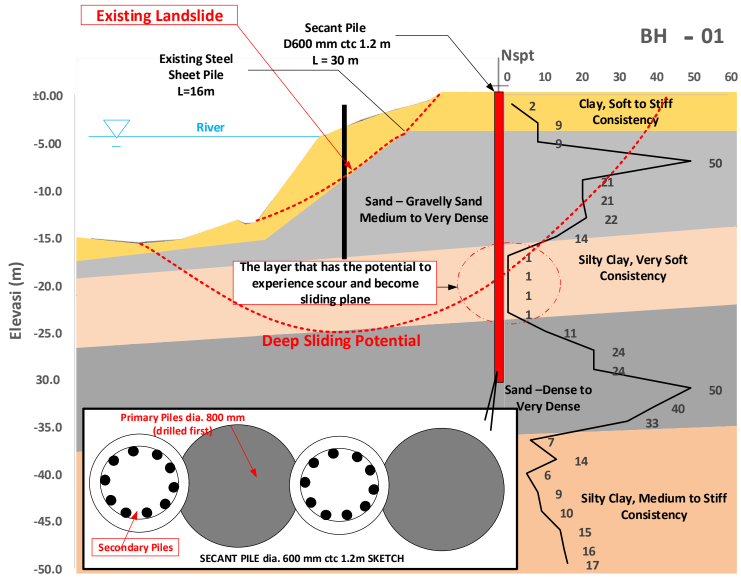

Figure 20. Secant pile illustration on slope

Based on the cross section and soil data obtained and by using the Plaxis 2D program, slope stability analysis is carried out with the following analysis stages: Existing conditions → Secant pile construction. 600 mm ctc 1.2 m Leff=30 meters → Analysis of the safety factor for slope stability (phi-c reduction). As the stability of slope is a function of the shear strength and the development of failure shear strain reflects the potential failures zone of slope, the shear strain developed in the slope increases with reducing the shear strength.

Oo, et al (2013) and Matsui & San (1992) explained that the Finite Element Method uses the strength reduction technique by factoring the model parameters c and phi. The strength reduction factor is gradually increased until failure of the slope occurs. Modeling and analysis by Plaxis 2D program was carried out at the area which represent sheet pile condition that was deformed due to the main landslide event. The analysis was carried out by modeling the soil layers based on the closest drilling data, namely BH-1. Soil stratification is modeled as 5 layers as shown in Figure 21 below.

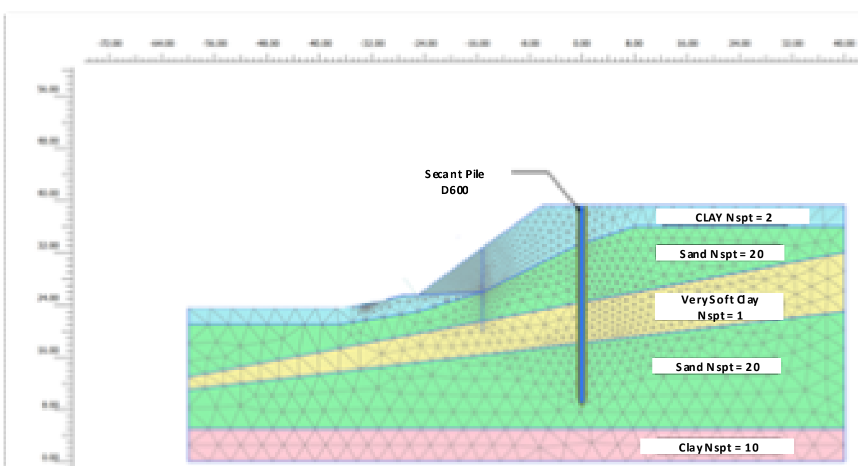

Figure 21. Soil model on Plaxis2D

The initial slope analysis was carried out by modelling the existing condition of the slope where the factor of safety condition is 1.0. Back analysis is based on the cross section and the nearest soil investigation data. The results of the actual condition slope analysis using the help of the Plaxis 2D finite element program are shown in Figure 22. The shear strength reduction technique has a number of advantages over the method of slices for slope stability analysis. Most importantly, the critical failure surface is found automatically (Dawson et al, 1999). The analysis results obtained that the factor of safety does not meet the allowable criteria, therefore reinforcement is needed.

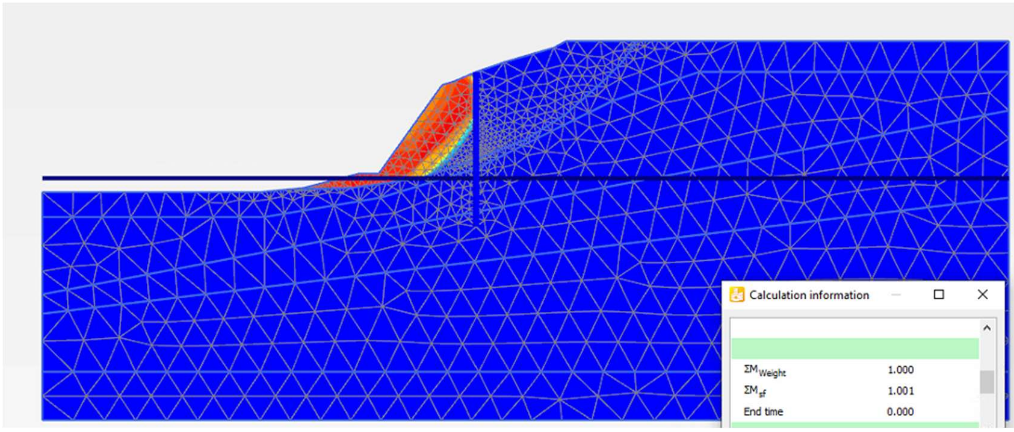

Figure 22. Back-analysis result

The soil parameters from the back-analysis can be obtained with a residual friction angle as ±20º. This value is used during the soil improvement process. The recommended reinforcement is to use secant pile D600 mm c.t.c 1.2 m. After installing the D600 mm ctc 1.2 m of Secant Pile, the slope stability safety factor is increased to more than 1.5 (Figure 23).

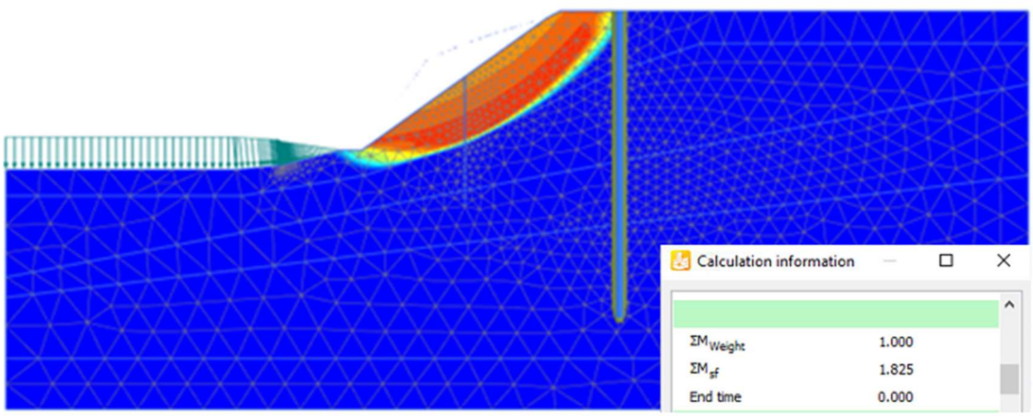

Figure 23. Slope stability analysis after reinforcement

6 CONCLUSION

The project location is principally located in a geological formation of surface deposits in the form of Alluvium (Q_{al}) consisting of silt, sand and gravel materials scattered on the coastal plains or river banks. The formation includes swamp deposits to the north of Tiku, to the southwest of Lubukalung and to the east of Padang. The consistency of soil materials in this formation tends to be soft and loose.

According to the information gathered, first landslide took place in 2012, around the time that steel sheet piles were put in along the river banks. Another landslide happened in 2014 at the same spot, where the slide was getting worse. It is thought that the moving materials is embankment material. In 2016, the land movement grew more severe, and then there is movement again in September 2021.

Landslides may take place due to the changes in river flow patterns that occur gradually due to two causes. First was the flow and behavior of the river itself, while the second was the mining of sand and soil material around the river banks.

Important findings in the investigation is that the very soft clay layer underneath the sandy layers was not detected prior to the investigation. Hence, scouring has caused lower stability of the river bank and gradually failed.

The scouring on the river bank across are thought to be repeated in the sheet pile area. This causes the soil behind the sheet pile to be washed and the sheet piles become free-standing resulting in a lack of passive resistance on the sheet pile due to scour along the sheet pile.

Installing retaining structures can be taken into account. In general, soil layers which unlikely to be scoured must be reached by the length of the penetration depth of the retaining structures.

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