JOS - MRK *Volume 6, Nomor 1, Maret 2025, Page 223-231*

Journal homepage: http://jurnal.polinema.ac.id/ **ISSN: 2722-9203 (media online/daring)**

ANALYSIS OF MUD VULCANO (LUSI) EMBANKMENT DAMS STABILITY WITH SHEET PILE AND PVD USING FINITE ELEMENT METHOD (FEM)

Ach. Bustomi Zuhri[1], Moch. Sholeh[2], Mohamad Zenurianto[3].

Mahasiswa Manajemen Rekayasa Konstruksi, Jurusan Teknik Sipil, Politeknik Negeri Malang[1].
Dosen Manajemen Rekayasa Konstruksi, Jurusan Teknik Sipil, Politeknik Negeri Malang[2]. Dosen Manajemen Rekayasa Konstruksi, Jurusan Teknik Sipil, Politeknik Negeri Malang[3].
achbustomizuhri@gmail.com[1]. moch.sholeh@polinema.ac.id[2]. mzen@polinema.ac.id[3].

ABSTRACT

The Lumpur Sidoarjo air shelter at point 68 in the Kedungbendo area had a loosening on April 10, 2018. It is frequently employed to analyse the use of finite elements in an effort to find the slope's security factor. Through software modelling, the researchers attempted to evaluate the parameters that affected the lapindo mud slopes' stability. The Mohr-Coulomb method and 2D Plaxis V20 are used in conjunction with the finite element method. Furthermore, a comparison is performed using the Geo5 2024 Trial Version application. We can ascertain the influence of the seismic-free slope security factor and its impact according to SNI using this geotechnical assistance programme. The Geotechnical Aid Program's security factor values are nearly same, and the Geo5 2024 Trial. The difference is caused by the addition of the modulus unloading and reloading parameter in version. Additionally, the study assessed the efficiency of prefabricated vertical drains (PVD) and sheet piles for slope reinforcement. In the absence of PVD, the 90% consolidation time equals 868.3 days, so the safety factor is 1.59. With PVD, the 90% integration time is only 258 days, and the safety factor is 1.60. PVD has been shown to be an effective instrument for accelerating the soil consolidation process without compromising the structure's stability.

Keywords *: Lapindo Mud Slope, Finite Element Analysis, SNI, Plaxis 2D V20, Geo5 Trial Version.*

1. INTRODUCTION

According to (Braja et al., 1995), the process of occurrence of a slide is the sudden or slow descent of mass of soil, rocks, or other material from a slope or hill. On April 10, 2018, the air shelter of Lumpur Sidoarjo at point 68 in the area of Kedungbendo underwent a loosening. (Mazzini et al., 2022). Geohazard of BPLS stated that the landslide was due to over-topping in landslides to about 5 meters. Effective repair strategies are needed to counteract slope loosening using sheet pile and PVD. Both techniques aim to improve the safety factor (FS) of slopes and improve soil characteristics associated with critical groundwater conditions. As to the masks and purposes of this research as follows:

1. Knowing the soil behavior conditions of the slope existing as a result of the earthquake load.
2. Find out the Safety Factor value after reinforcement using the Sheet Pile, by applying the earthquake load factor from the results of the analysis.
3. Know the Safety Factor value and the time it takes to reach a 90% consolidation degree, without PVD and PVD combination.
4. Drafting methods for efficient implementation of repairs for the strengthening of the Sidoarjo Lumbers at point 68.

Slope Stability

The force of sliding rocks or dirt that is greater than the sliding voltage of gravity or other loads is what causes variations in topographic shapes on the surface of the earth. Soil slide strength, according to is the soil's capacity to tolerate internal shifts or collapses along the sliding field. A type of difficulty that soil particles exhibit to pressure or attraction is known as soil sliding strength. Critical conditions of both sliding voltage and normal voltage combine to cause a field to collapse. (Labuz & Zang, 2012). The security factor value represents the level of security on a slope. Table 1 presents the security elements needed to analyse the slope's stability in accordance with SNI 8460:2017. Its foundation is the evaluation of the cost and ramifications of slope failure in relation to the degree of analysis conditions' uncertainty.

Table 1. The Required Safety Factors for Slope Stability Analysis

Costs and Consequences of Slope Failure	Level of Uncertainty in Analysis Conditions	
	Low^{a}	$High^{b}$
The cost of repairs is proportional to the cost of additional design for a more conservative slope.	1,25	1,5
The cost of repairs exceeds the cost of additional design for a more conservative slope.	1,5	2,0 more than

[a] The level of uncertainty in the analysis conditions is categorized as low if the geological conditions are well understood, soil conditions are uniform, and soil investigations are consistent, complete, and logical with field conditions.

[b] The level of uncertainty in the analysis conditions is categorized as high if the geological conditions are highly complex, soil conditions are variable, and soil investigations are inconsistent and unreliable.

Source: SNI 8460:2017, 2017

Plaxis 2D V20

The Plaxis 2D V20 application is a geotechnical aid programme used to analyse soil behaviour and structures numerically in two-dimensional conditions with up-element models. In this application, there are 4 sub-programmes: input, calculation, and output (laporan hasil analisis). Using the Plaxis 2D V20, users can model case situations both in plane strain and axis. This allows precise modelling to understand soil behaviour and make predictions of potential collapse or structural deformation in the soil.

Geo5 2024 Trial Version

The Geo5 2024 Trial Version application is a geotechnical utility used for the analysis and design of geotechnical structures. Geo5 covers a variety of modules, including Geo FEM, which enables modelling and analysis of geotechnical problems such as landfall and slope stability. In this application, there are 3 sub-programmes: input data topology, calculation construction stages, and output (laporan hasil analisis).

Planning of Sheet Pile

A sheet pile is a structure designed to withstand the lateral (horizontal) pressure of the soil. The soil lateral pressure behind the grip wall is determined by the angle of the soil slide and the cohesion between soil particles. This side pressure applies from the top to the bottom of the gripwall. Planning a sheet pile with an anchor involves steps that should be taken into account in the calculation of fertility:

1. Draw the distribution of active and passive soil pressure

   To draw the distribution of active and passive soil pressure in this calculation, use the following equation:

   $$\sigma_{h\,aktif} = \sigma_v Ka - 2c\sqrt{Ka} \quad (\mathbf{1})$$

   $$\sigma_{h\,pasif} = \sigma_v Kp + 2c\sqrt{K} \quad (2)$$

   Where:

   $$Ka = tan^2(45 + \frac{\theta}{2}) \quad (\mathbf{3})$$

   $$Kp = tan^2(45 + \frac{\theta}{2}) \quad (\mathbf{4})$$

2. Searching Inside Sheet Pile

   To find the depth of the Sheet Pile, the moment balance at point A, that is, at the installation of the anchor, uses the equation. $\sum M_a = f(d)_A = 0$. The Sheet Pile depth is then multiplied by a security factor between 1.5 and 2.0.

3. Specify Sheet Pile Profile

   To draw the distribution of active and passive soil pressure in this calculation, use the following equation: The Sheet Pile profile is determined on the basis of the maximum moment experienced by the sheet pile. The maximum moment is calculated from the derivative of the moment equation, and the value obtained is then compared to the Moment crack on the Sheet Stack according to SNI 8460:2017 $\mathrm{M_{max}} < \mathrm{M_{crack}}$.

PVD Planning

Based on the understanding (SNI 8460:2017) of the Geotechnical Design Requirements, prevabricated vertical drain is defined as a compound geosynthetic material that can be used in low-permeability, high-compressibility soft soil repair design, combined with pre-loading of cluster soil. One method widely used to speed up the soil consolidation process is the installation of a prefabricated vertical drain.

The geotechnical aspects considered under (SNI 8460:2017) of the Geotechnical Planning Requirements are:

1. The minimum safety factor for ground support is 1.5.
2. The reduction limits of the aggregate (consolidation) are at least 90% of the consolidation degree.
3. The depth of PVD is mounted until hard soil or solid slate soil no longer causes a drop that cannot be tolerated by the structure.

According to (S. Hansbo, 1979), there are two theories about the patterns of the vertical drain installation. The pattern of the installation is a four-square pattern, as seen in **Figure 1,** and a triangular pattern, as seen in **Figure 2.**

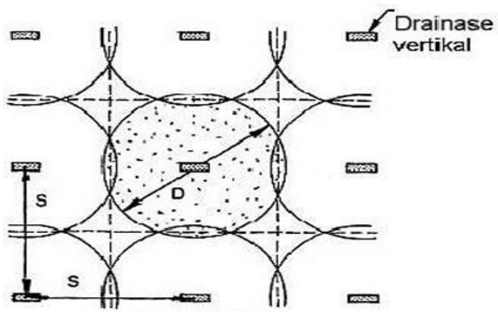

Figure 1. Installation PVD Pattern Four Square
Source: SNI 7833:2012

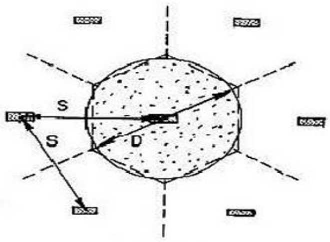

Figure 2. PVD Triangle Pattern Installation
Source: SNI 7833:2012

2. METHOD

The completion of the final task entitled "Analysis of Mud Volcano (Lusi) Embankment Dams Stability with Sheet Pile and PVD Using Finite Element Method (FEM)" is carried out in several stages, namely:

Data collection

This research data collection uses secondary data analysis from the P.T. Teknindo Geosystem Unggul, which is located at point 68 tanggul Lumpur Sidoarjo, Ngembul Kidul Village, Gempolsari, Tanggulangin Prefecture, Sidoorjo District, East Java. The secondary data used included the topography of the slope, pictures of slope pieces with specific coordinates, N-SPT test data in the field, as well as laboratory test data for the physical and mechanical parameters of the soil.

Data Analysis and Parameter Correlation

Analysis of soil data includes physical and mechanical parameters obtained from the Standard Penetration Test (SPT) as well as the results of laboratory tests. These parameters include:

1. Soil Test (Wc, γt, Gs, γd, n, dan e)
2. Grain Size
3. Liquid and Plastic Limit Test
4. Direct shear test (c dan φ)
5. Modulus young (E)
6. Poisson rasio (v')

Simulation of existing conditional stability slope modeling with geotechnical help program

Simulation of stability modelling of existing slope conditions with a geotechnical aid programme aims to evaluate the security factors of slopes that have been reinforced with gabions. The analysis is carried out under the influence of the earthquake load and the impact assessment of the earthquake load. The calculation is done using the Plaxis 2D V20 programme to ensure accurate results, which are then compared with the Geo5 application. The results of this analysis will be used to conclude the cause of the leakage on the shell.

Simulation of stability modeling of reinforced slopes using sheet piles

Analisis ini mencakup pemeriksaan terhadap kompresibilitas dan kapasitas dukung tanah dasar terhadap beban dari timbunan dan Sheet Pile. Jika faktor keamanan Sheet Pile memenuhi standar SNI 8460:2017 dengan nilai Safety Factor > 1,5, maka perkuatan tersebut dapat diterapkan pada lereng tanggul Lumpur Sidoarjo. Namun, jika faktor keamanannya tidak memenuhi syarat, maka perlu dilakukan analisis kembali dengan mempertimbangkan sistem kombinasi PVD. Adapu Aspek-aspek perencanaan geoteknis meliputi: perencanaan timbunan, perbaikan tanah, perkuatan dengan menggunakan Sheet Pile (termasuk kedalaman dan profilnya),

Simulation of stability modeling of reinforcement using pile sheet PVD combination

This simulation of slope stabilisation modelling using sheet pile reinforcements includes testing of the compressibility and capacity of the base ground support against the load of the cluster and sheet pile. This analysis determines that if the Sheet Pile safety factor meets SNI standard 8460:2017 with a Safety Factor value > 1.5, then such reinforcement can be applied to the slope of the Sidoarjo slope. However, if the safety factor is not eligible, then additional analysis is required, taking into account the PVD combination system. The geotechnical planning aspects covered include landfill planning, soil repairs, and reinforcement using sheet piles (termasuk kedalaman dan profilnya).

Planning Implementation Methods

Planning implementation methods are crucial in the construction project, including resource allocation and risk assessment that may arise during the project execution.

Conclusions

Upon completion of the planning calculations, conclusions can be drawn to evaluate the effectiveness of soil repair with PVD and preloading systems in accelerating consolidation as well as improving ground support capacity.

3. RESULTS AND DISCUSSION

The soil data used in this study consists of the results of the Standard Penetration Test (SPT) and laboratory data from the soil investigation in the Sidoarjo Lumpur Tanggul Improvement project. There are two drilling points used: the DB-1 is located above the roof with a ground water level (GWL) of ±3,00 m and a depth of 50,00 m, while the DB-2 is located below the rooftop with a GWL of ±0,50 m and a depth of 50.00 m. The layout of the drilling point pickup can be seen in **Figure 4.**

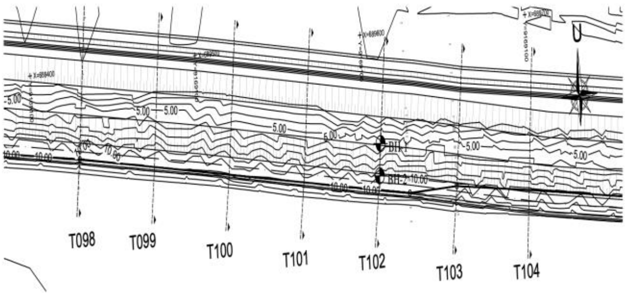

Figure 3. Layout of the Boring Point Location
Source: PT. Teknindo Geosistem Unggul

With a summary of the results of the SPT tests and laboratory tests at the planning site presented in **Table 2** and **Table 3.**

Table 2. DB-1 Physical and Mechanical Parameters Data
Source: PT. Teknindo Geosistem Unggul

Depth (m)	SPT	γ g/cm3		Strength	
		Wet	Dry	c Kg/cm2	ϕ (°)
3-3,5	10	1,85	1,35	0,50	13
9-9,5	10	1,88	1,40	0,10	35
15-15,5	9	1,70	1,16	0,18	29
19,5- 20	1	1,49	0,79	0,08	0
23-23,5	1	1,47	0,76	0,09	0
29-29,5	5	1,52	0,84	0,23	5
40- 40,5	34	1,74	1,20	0,66	3

Table 3. DB-2 Physical and Mechanical Parameters Data

Depth (m)	SPT	γ g/cm3		Strength	
		Wet	Dry	c Kg/cm2	ϕ (°)
3-3,5	2	1,42	0,72	0,08	0
6-6,5	1	1,64	1,06	0,05	20
9-9,5	1	1,45	0,74	0,10	0
15-15,5	1	1,47	0,76	0,11	0
19,5-20	1	1,48	0,77	0,09	0
29-29,5	4	1,50	0,82	0,17	0
40-40,5	48	1,78	1,27	0,10	39

Source: PT. Teknindo Geosistem Unggul

In **Figure 4.3**, there is a graph showing the consistency of the N-SPT values of the two test points, indicating the homogeneity of the data. Therefore, in this study, we combined data from the BH-1 and BH-2. DB-1 represents the cluster soil up to the elevation of the rocky foot, whereas DB-2 represents the native soil of the location. A summary of the combined data can be seen in **Table 4.**

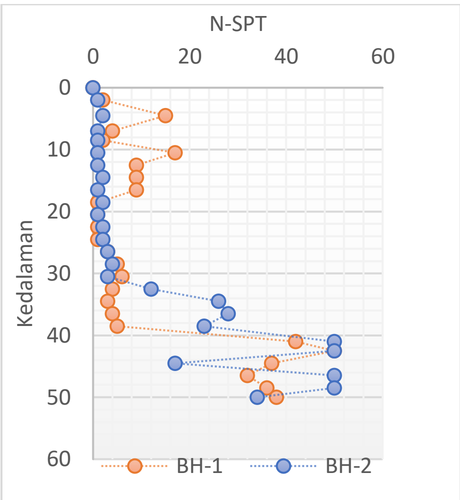

Figure 4. N-SPT value relationship and depth

Table 4. Combined ground parameters between DB-1 and DB-2 for application program input

No.	Depth	γ (kN/m^3)		Strength		E	v'	k
		Unsat	sat	c (kN/m^2)	ϕ (°)	(kN/m^2)		m/day
1	+04,00 s/d +09,00	12,00	21,80	12,00	25,000	9414,38	0,3	5,46E-03
2	+02,00 s/d +04,00	18,14	23,04	49,03	13,00	76936,31	0,3	5,46E-03
3	00,00 s/d +02.00	18,44	23,53	9,81	35,00	15387,26	0,3	8,64E-02
4	00,00 s/d -03,50	13,93	16,86	7,84	5,00	6272,00	0,3	2,42E-03
5	-03,50 s/d -06,50	16,08	20,20	30,00	20,00	20590,56	0,3	7,74E+01
6	-06,50 s/d -09,50	14,22	17,06	9,81	5,00	6864,66	0,3	1,39E-03
7	-09,50 s/d -15-50	14,42	17,25	10,79	5,00	7551,12	0,3	7,02E-04
8	-15-50 s/d -20-00	14,51	17,35	8,83	5,00	6178,19	0,3	1,43E-03
9	-20,00 s/d -29,50	14,71	17,84	16,67	5,00	16671,31	0,3	5,14E-04
10	-29,50 s/d -40,50	17,46	22,25	9,81	5,00	44314,29	0,3	7,73E-02

Simulation of existing conditional stability slope

The stability analysis of existing slopes is performed using the 2D Plaxis V20 and Geo5. The focus of this analysis is the security evaluation of the slope that has been reinforced with gabions. The modelling involves the geometry of the slope as high as 9 metres from the surface of the legs, as seen in Figure 7. The method used is the finite element method (FEM) to ensure accurate analysis results. The modelling process covers the entire slope from top to bottom, based on the results of the Standard Penetration Test. (SPT). This analysis also considers two conditions: no earthquake load and the addition of a pseudo-static seismic load to evaluate its impact on the security factor of the slope.

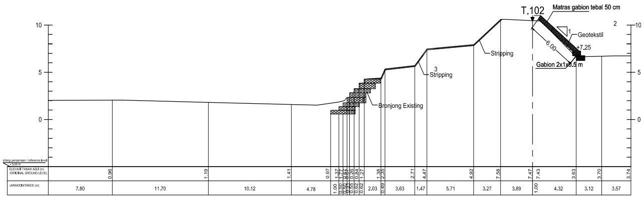

Figure 5. Slope Geometry in Existing Condition
Source: PT. Teknindo Geosistem Unggul

As for the results of the analysis as follows:

1) Results of analysis without impact of earthquake load

An analysis of the stability of the slope without the influence of the earthquake load in the Plaxis 2D V20 application shows that the most critical sliding field is located at the foot of the pendulum slope in the left direction. The safety factor value obtained was 0.9756, with a total displacement of 0.9833 meters. Similar results were obtained from the Geo5 application, with the safety factor = 0.90 and the z shift = 0.455 metres. Both of these safety factor values do not qualify for the safety stability of slopes under SNI 8560-2017, which requires a safety factor > 1.5.

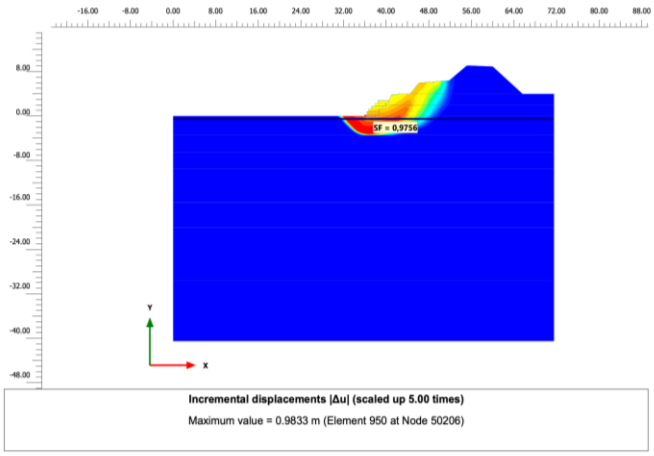

Figure 6. Plaxis 2D V20 Application Analysis Results Without Earthquake Load

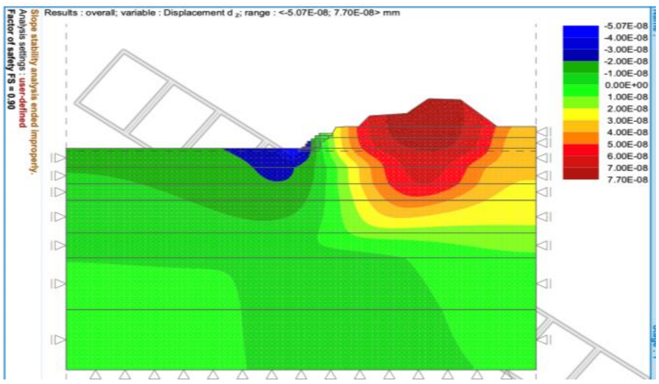

Figure 7. Geo5 Application Analysis Results Without Earthquake Load

2) Results of Earthquake Load Impact Analysis

In an earthquake with a PGA of 0.3389 Gal, the results of the Plaxis 2D V20 application showed that the slope was unstable with a low Safety Factor, i.e. SafetyFactor = 0.3326.

The total ground movement caused by the earth's load was 5.241 meters. Similar results were obtained from the Geo5 application, with a Safetyfactor condition = 0.35 and a z-directional ground movement of 0.409 meters. Both analyses showed that the slope did not meet the required security stability.

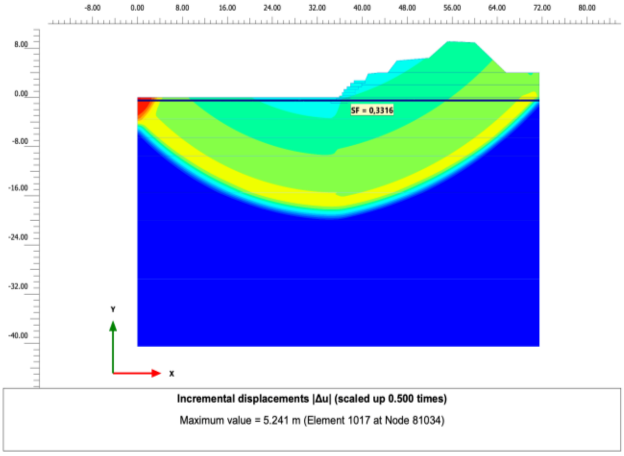

Figure 8. Plaxis 2D V20 Application Analysis Results Affected by Earthquake Load

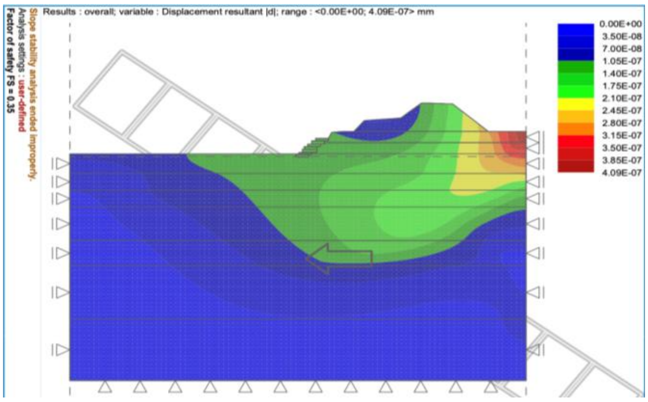

Figure 9. Results of Geo5 Application Analysis affected by earthquake load

Simulation of reinforced slopes using sheet piles

Slope stability analysis using sheet piles reinforced with ground anchors is an early stage of alternative reinforcement analysis. Planned geotechnical aspects include the use of sheet piles based on maximum moment analysis results. The pile sheet used is type W-600, with a total length of 27 meters. Ground anchor is installed with a length of 10 metres according to SNI regulation 8460:2017, with a horizontal space of 1.5 metres and an angle of inclination of 30°. The assembly is carried out in two stages: 5 metres in the first stage and 2 metres in the second stage. Alternative slope reinforcement geometry using pile sheets can be seen in **Figure 12.**

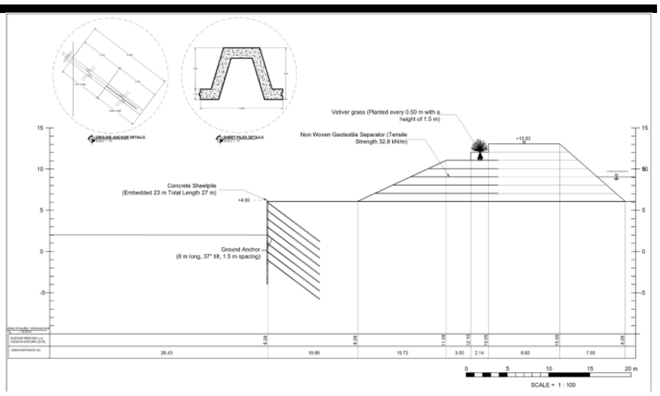

Figure 10. Geometry of alternative slope reinforcement using Sheet Pile

As for the results of the analysis as follows:

1) Results of analysis without impact of earthquake load

Analysis results using the Plaxis 2D V20 app showed a safety factor value of Safety Factor = 1.20 before the earthquake burden was added. Meanwhile, analysis results from the Geo5 app revealed a security factor value of Safety Faktor = 1.14. Both safety factor values did not meet the recommended standard, safety factor > 1.5.

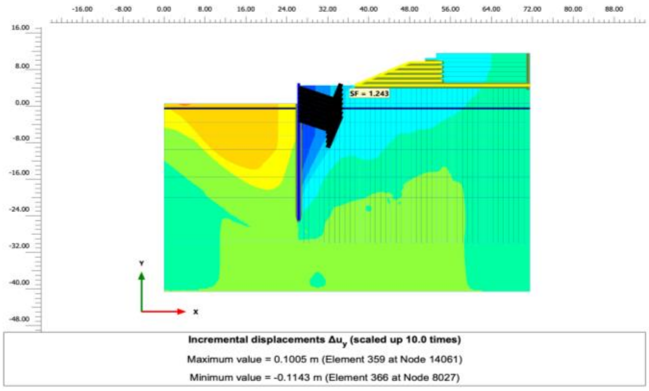

Figure 11. Results of Plaxis 2D V20 Analysis for Sheet Pile Reinforcement Without Earthquake Load

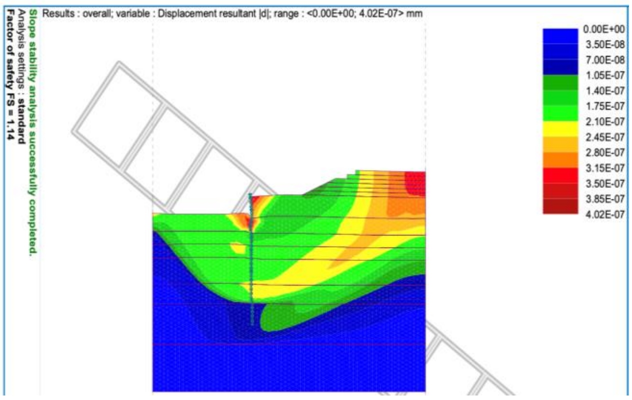

Figure 12. Results of Geo5 Analysis for Sheet Pile Reinforcement Without Earthquake Load

2) Earthquake Load Impact Analysis

Results Analysis results using the Plaxis 2D V20 application showed a safety factor value of 0.52 after an earthquake load was added.

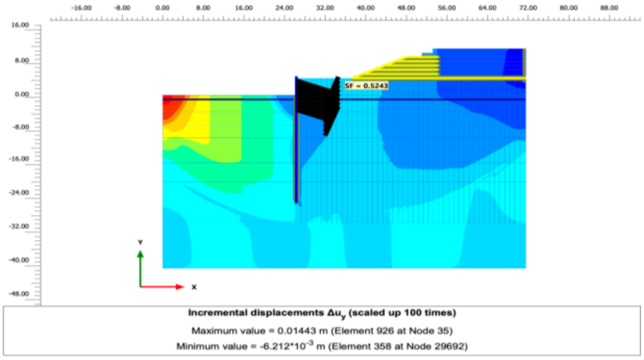

Figure 13. Results of Plaxis 2D V20 Analysis for Sheet Pile Reinforcement Affected by Earthquake

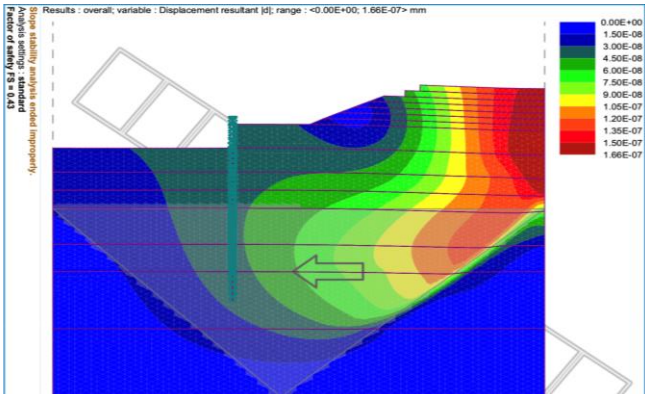

Figure 14. Results of Geo5 Analysis for Sheet Pile Reinforcement Affected by Earthquake

Stability modeling of reinforcement using pile sheet PVD combination

At the stage of slope stability analysis with reinforcement using sheet pile combined with PVD, only the Plaxis 2D V20 application can be used due to license limitations for comparing analysis results with Geo5. Planned geotechnical aspects include the depth, patterns, and distance of installation of PVD in accordance with SNI 8460:2017. The accumulation process is carried out gradually, with each stage having a height of 1 metre and using geotextiles as separators. This analysis also includes a preloading system to evaluate the influence of PVD on land consolidation time. A picture of the slope geometry plan can be seen in the picture below.

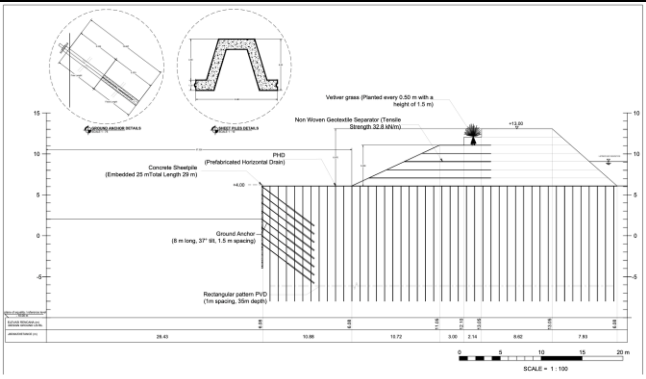

Figure 15. Geometry of alternative slope reinforcement using Sheet Pile combined with PVD

As for the results of the analysis as follows:

1) Results Analysis Without PVD

The results of the analysis showed that the value of the safety factor for land consolidation without the use of PVD was 1.59, as shown in Figure 4.24. The graph shows that the time required for consolidation was 90% longer, that is, 868.3 days, with a total land decrease of 0.4320 metres.

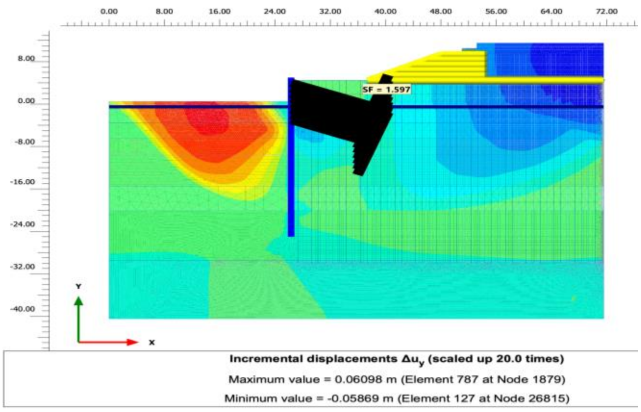

Figure 16. Safety Factor Value Without PVD

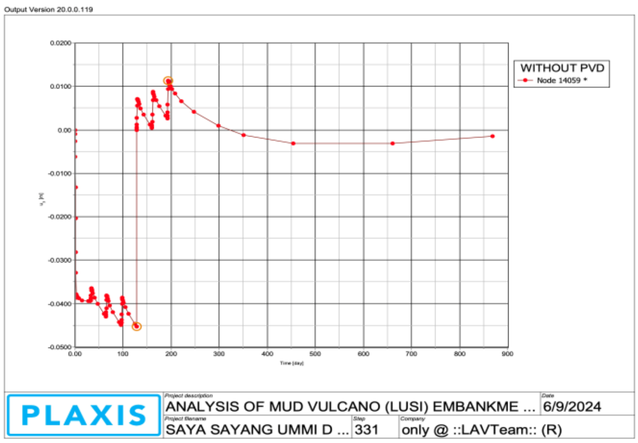

Figure 17. Settlement and Time Graph to Achieve U90% Without PVD

2) Results of analysis using PVD

The safety factor value using PVD from the Plaxis 2D V20 application is 1.60, with the time it takes to a 90% consolidation being 259 days. Using PVD allows the soil to consolidate faster, reducing the risk of structural failure or deformation due to unequal decline. A graph of the relationship between the decrease and the 90% consolidation time without and with the use of PVD can be seen in **Figure 29.**

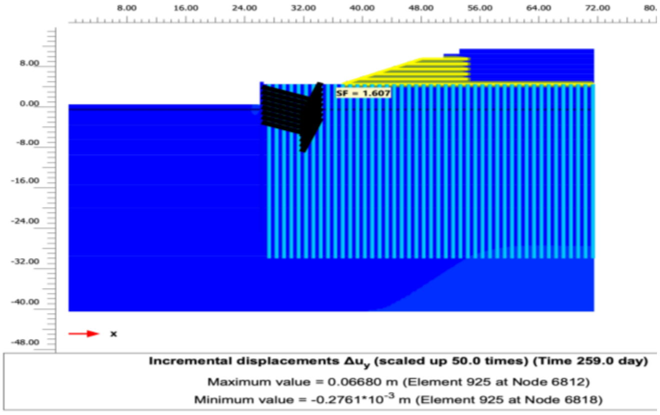

Figure 18. Safety Factor Value with the Use of PVD

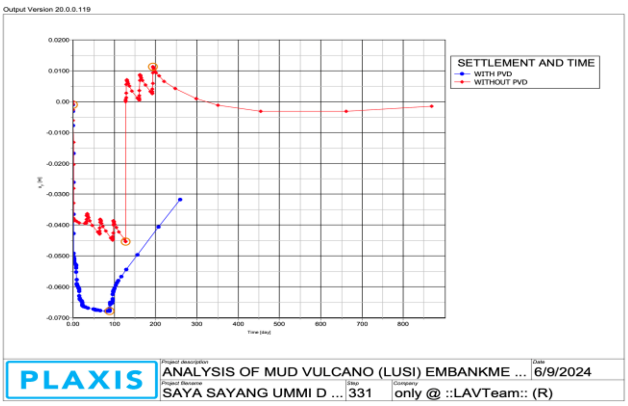

Figure 19. Graph of Settlement and Time to Achieve 90% Consolidation Without PVD and with PVD

4. CONCLUSIONS

The conclusions of the analysis obtained from the two geotechnical assistance programmes are as follows:

1.) Analysis showed that the slopes of the Sidoarjo Lamp, point 68, Kedungbendo Village, had a safety factor of 0.9 without earthquake load, with a landfall of 0.98 meters. When the earthquake load was applied, the safety factor decreased to 0.3, and the landfall increased to 5.241 metres. It can be concluded that the impact of the earthquake load on the stability of the slope is one of the causes of leakage on the slopes. According to Geohazard's information from BPLS, the leakages are due to a landfall of 5 metres.

2.) The analysis of the use of sheet piles for the strengthening of the slopes indicates that initially, without earthquake loads, the safety factors calculated using Plaxis 2D and Geo5 are Safety Factor = 1.24 and Safety Factor = 1.14. However, after considering the impact of earthquake loads, this safety factor decreases to safety factor = 0.52 and safety factor = 0.43. These results indicate that the planned safety factor, in accordance with SNI standard 8460:2017 (safety factor > 1.5), has not been achieved. Therefore, it was concluded that additional reinforcement using PVD was necessary.

3.) The conclusion of the analysis using the application of Plaxis 2D on the combination of sheet pile with PVD reinforcement is as follows:
- Without PVD, the safety factor achieved is SF = 1,59, which meets the planned safety standard (SF > 1.5). However, the consolidation process to reach 90% took a long time, about 868.3 days. This prolonged land degradation process has potential safety implications for the sheet pile structure.
- With PVD, the safety factor increased to SF = 1.60 compared to conditions without PVD. Moreover, the time required to achieve 90% consolidation is significantly reduced to about 258 days. Thus, the use of PVD effectively accelerates soil consolidation without sacrificing the safety of the structure of the sheet pile.

4.) The stability of the slope has the potential to cause economic losses, damage the environment, and even be life-threatening. Therefore, the methods of implementation of stability improvements on the slope must be carried out with care to ensure the safety and sustainability of the project, as well as comply with the established standards. To see a 3D visualisation of the method of execution in this study, please visit the following video link: bit.ly/ThesisBustomizuhri

BIBLIOGRAPHY

Braja, J. 1, Bahasa, A., & Noor, L. (1995). *Principles of Geotechnical Engineering*. https://drive.google.com/file/d/0B_7VxNCK5BXnTU5IQVRIaWlkdFE/view?resourcekey=0-216EFBjxXiTZ0L93JzUPOg

Braja M. Das. (2017). *Braja M. Das - Principles_of oundation Engineering, SI Edition, 9th*. www.cengage.com/highered

Das, B. M., Khaled, |, Das, S., Sobhan, _, & Sobhan, K. (2018). *Principles of Geotechnical Engineering*. www.cengagebrain.com.

Labuz, J. F., & Zang, A. (2012). Mohr-Coulomb failure criterion. *Rock Mechanics and Rock Engineering*, *45*(6), 975–979. https://doi.org/10.1007/s00603-012-0281-7

Mazzini, S. A. A., Etiope, G., Sadavarte, P., Houweling, S., Pandey, S., & Husein, A. (2022). Relevant methane emission to the atmosphere from the geological gas manifestation of the LUSI eruption study case, Indonesia. *Researchgate*. https://doi.org/10.46427/gold2022.12025

Nasional, B. S. (2012). *Badan Standardisasi Nasional SNI 7833:2012*. www.bsn.go.id

S. Hansbo. (1979). *INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING*. INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING. https://www.issmge.org/publications/online-library

SNI 8460:2017. (2017). www.bsn.go.id