Influence of Scouring Phenomenon on Slope Stability in Substructure Construction of Cipeles Bridge

Riskia Jordy[1], Dewi Amalia[1,*], Bambang Setio Budianto[1], Agastyasa Ghea Amarta[2]

[1]Department of Civil Engineering, Politeknik Negeri Bandung, Bandung 40559, Indonesia
[2]Department of Civil Engineering, Global University Jakarta, Depok 16412, Indonesia
**Corresponding author: jagoangeotek@gmail.com*

ABSTRACT

Slope stability represents a crucial aspect of terrain integrity, safeguarding against potential landslides and ensuring structural resilience. Instabilities arise primarily from diminished safety margins and landslide occurrences triggered by alterations in slope dimensions or geometry induced by river water scouring. Such scouring processes engender heightened slope steepness, exacerbating vulnerability to failure. Utilizing Finite Element Method (FEM) software, specifically Plaxis 2D Version 22, back calculation analysis, or reverse analysis, offers a robust approach to assess safety factors and collapse patterns resulting from scour-induced alterations. Our investigation reveals a pronounced expansion of slope failure zones attributable to scour phenomena, encompassing both primary and secondary scour instances. Concurrently, there is a discernible reduction in Safety Factor (SF) values and y-displacement magnitudes along the slope, with the most notable declines observed under condition 3 (displacement-y value reaches 79,53 mm). These alterations stem from geometric transformations within the slope, culminating in increased steepness and corresponding destabilization.

Keywords: Collapse, Displacement, River, Safety Factor, Scour, Slope.

1. INTRODUCTION

The escalating population growth in Indonesia over successive years necessitates commensurate advancements in transportation infrastructure. However, this burgeoning demand for transportation facilities contrasts starkly with the limited availability of road infrastructure provided by governmental authorities. Consequently, congestion frequently plagues numerous thoroughfares across the nation. In response to this pressing issue, the Ministry of Public Works endeavors to alleviate congestion by introducing alternative transportation routes, commonly called toll roads. The establishment of toll roads is envisaged as a strategic measure to ease traffic congestion and enhance travel efficiency. Through the provision of these alternative routes, the government aims to streamline transportation networks, fostering smoother traffic flow and facilitating more seamless commutes for the populace.

The Cileunyi-Sumedang-Dawuan (CISUMDAWU) toll road, situated in West Java, serves as a pivotal transportation artery linking the urban hubs of Bandung, Sumedang, and Majalengka. Spanning a length of 60.1 kilometers, the CISUMDAWU toll road plays a crucial role in facilitating swift connectivity between Bandung and remote locales such as Majalengka, Cirebon, and regions in Central Java. Noteworthy features of this toll road include its composite construction, comprising roadways, tunnels, and Bridges, each integral to ensuring efficient transit. Among the notable structures along the CISUMDAWU toll road is the Cipeles Bridge as seen on Figure 1.

Figure 1. Cipeles Bridge

Cipeles Bridge spans is 257 meters. Cipeles Bridge includes a reinforced concrete bridge structure. The engineering of bridge structures requires a comprehensive consideration of numerous factors, including the optimal placement of the bridge, the hydraulic characteristics inherent to the adjacent river, and the intricate flow patterns within the watercourse [1]. The construction of the Cipeles Bridge was conceived to surmount the natural impediments posed by the flowing waters of the Cipeles River. The perpetual discharge of water within rivers, coupled with fluctuating water levels, poses a significant erosive threat to the surrounding land within the river channel. This erosive process, known as scouring, is often instigated by morphological features of the river, including bends and channel constriction points. These natural variations in river morphology can intensify hydraulic forces, exacerbating erosion and altering the surrounding landscape.

Water discharge stands as a significant determinant in the initiation and progression of scour phenomena along riverbank slopes, profoundly impacting the integrity of surrounding construction services. This study investigates the relationship between water flow rates and scour magnitude, particularly examining their effects on abutments, pillars, and adjacent slopes. Prolonged scouring processes can lead to a reduction in slope safety factors, attributed to alterations in slope dimensions resulting in increased steepness. The assessment of safety factors and collapse patterns induced by scour employs the Finite Element Method (FEM) facilitated by Plaxis 2D Version 22 software [2], utilizing back calculation or reverse analysis techniques. The method used is to apply back calculation analysis often called reverse analysis. This analysis method is simply defined as a mathematical recalculation process to estimate the value of data using related parameters. In line with research that has been carried out [3], the aim of this research is to determine the influence of the pattern and magnitude of scour in the river on the condition of the slopes around the construction under the Cipeles Bridge which is indicated to affect the foundation under the Bridge.

2. CASE IDENTIFICATION

Based on the description described above, this study focuses on the scour phenomenon that occurs on the Cipeles River's slopes near the Cipeles Bridge. The scouring phenomenon is caused by numerous characteristics, one of which is the river's dimensions. Continuous scouring causes erosion of the close slopes. A slope study around the Cipeles Bridge's lower construction is required to examine the collapse pattern, safety factor (SF) value, and *y*-displacement value, as well as slope settlement due to scouring conditions.

3. LITERATURE REVIEW

3.1 Hydrological Analysis

Hydrology can be applied in a variety of industries, including civil engineering. References [1] show that hydrology can be utilized to construct and manage water infrastructure, control erosion and sedimentation, drainage, and furthermore. Rainwater hitting the slopes affects the hydrological conditions of the slopes, including changes in groundwater levels, saturation levels, and pore water pressure. Changes in these aspects require an impact on the slope's soil qualities [4]. This study examines the scouring behavior of the surrounding slope construction.

3.2 Scouring

Scour is an environmental phenomenon that continuously erodes a river bed, often known as an erosion event. The scour can be general, local, or localized. These three kinds can also be classified according to how the sediment transport occurs [5]. scouring is an erosion process that happens in river beds as a result of changes in flow patterns, particularly in alluvial rivers [3]. Changes in flow patterns can occur when the river flow encounters impediments or restrictions. In the current research, a condition that influences the slope's state is scouring, which occurs when the slope erodes or degrades.

3.3 Slope Stability

A slope is a surface that forms an angle and inclination to an unprotected horizontal level with stability being a crucial consideration [6]. Slope stability is a condition in which the slope's soil structure is stable and resistant to landslides. All sorts of prospective landslides on slopes or other structures must be studied to develop control plans or preventative strategies, before landslides occur and inflict additional losses [7].

3.4 Slope Collapse

Slope collapse was caused by several factors, including as a result of erosion which causes a reduction in the carrying capacity of the slope, natural and artificial movements occur on slopes and also by earthquake activity or other vibration activity occurs. Part of that, there is movement in the materials that make up the slope structure, in the base area of the slope, which is caused by scouring a river flows and seawater. Lateral earth pressure occurs due to cracks in the soils structure and there is a decrease in the value of soil shear strength due to condition of the constituent materials, climate changes, the influence of pore water pressure and changes in slope structure [2]. Those prevention of slope collapse can be improved by several ways there are make changes to slope geometry, control drainage and seepage, create additional structure for stabilization, carry out dismantling and moving and forms additional protection on the slope surface area [8].

3.5 Soil Parameter

The soil's characteristics as a component of slope structure have a significant impact on the slope's stability. Soil strength is affected by characteristics such as soil friction angle *(ϕ)* and soil cohesion value. The value of the soil friction angle will be smaller if the soil water content is high [9] [10]. This is directly proportional to the research conditions, where the slope surface is submerged by river water, indicating that the water content in the soil is probably high. Apart from the soil shear angle, high water content provides an impact on the cohesion value; the higher the water content, the lower the soil cohesion [11]. In other words, this situation causes a lack of density in the soil, which can decrease its bearing ability and soil [12].

3.6 Software Engineering Via Plaxis 2D v.22

Plaxis was utilized for mathematical modeling for assistance in slope stability performance analysis. The most significant achievement is security value. A slope's safety value ranges from >1.25 (very stable) to <1.07 (unstable) [13]. The improvement or increase of the value of cohesion and friction angle has the most influence on improving the value of the safety factor among the numerous variables utilized as input into this modeling [14] [15].

4. METHODHOLOGY

This research involves numerous steps, including:

1. Identify field-related difficulties.
2. Conduct literature studies on data analysis theories, problem-solving methods, and related research.
3. The data collection stage is carried out to obtain data related to the substance of the problem, such as land cover maps (data obtained from the website Tanahair.Indonesia.go.id with areas taken according to the review, namely Sumedang Regency), rainfall data (rainfall data rain taken from the last 10 years, starting from 2023 to the previous year and the data was obtained through a data request to the Citarum River Regional Office). This stage was then continued with taking soil samples around the research location and DEMNAS data obtained from the Geospatial Information Agency (BIG) website as supporting data.
4. Data processing provides drainage coefficient, rainfall intensity, river basin area (DAS), flow rate based on return duration, soil properties index, and soil mechanical properties.
5. Auxiliary software, HEC-RAS 6.0.0, was utilized to calculate scour using input data such as research location map, channel roughness coefficient, and water flow discharge during many return periods. After analyzing the data using HEC-RAS, the amount of scour was calculated based on the amount of water flow discharged over the return period. The research simulates two conditions. The simulation was implemented using rainfall return periods of two and ten years. The river's size and the return period utilized both influence the depth of the scour. The higher the return time, the more scour there will be.
6. After determining the scour magnitude, Plaxis 2D software was used for modeling slope conditions at the research location. The purpose of this analysis is to determine the safety factor for slope conditions before and after erosion.
7. The current research used Plaxis 2D V.22 software to simulate and analyze secondary and primary data. Primary data consists of data from direct soil testing conducted in the soil mechanics laboratory, specifically for soil sample depths ranging from +0.00 meters to -6.00 meters. For depths that range from -8.00 to -11.00, utilizing accessible secondary soil data.

The initial step was to analyze the amount of scour that occurred on the slope structure, and the results were used as a reference in modeling illustrations of slopes and scour using AutoCAD 2D software, therefore presenting the process of geometric depiction of slopes using Plaxis 2D software. The figure 2 illustrates the flow of the stability and safety factor analysis performed using Plaxis 2D software.

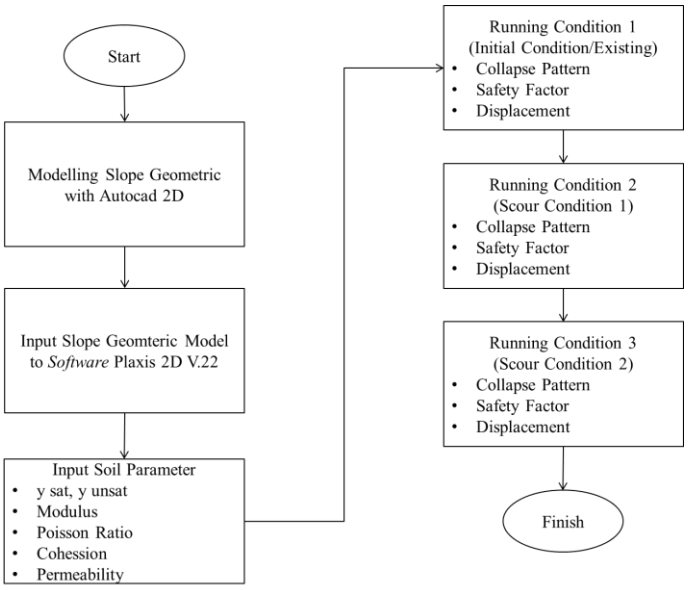

Figure 2. Flow Diagram Analysis with Software Plaxis 2D V.22

5. RESULT AND DISCUSSION

In the present research, slopes were geometrically modeled using AutoCAD 2D software. This is done to simplify the process and represent geometric situations that are similar to the genuine ones that occur. Slope condition modeling is performed with several conditions, including initial conditions, condition 1, and condition 2. These three conditions were determined through modeling with HEC-RAS 6.0.0. The beginning condition is the current condition of the slope. Condition 1 is acquired by modeling scour caused by a two-year rainfall return time, whereas condition 2 is obtained by modeling with a ten-year return period. As seen in the picture below, the first condition is a slope on its outer surface. Condition 1 is where the slope has been caused by 0.28 cm of scour, as seen in the scour area 1. In condition 2, the slope suffered by 0.42 cm of scour from the current slope. Scour area 1 and scour 2 are included in scour modeling under Condition 2. Figure 3 depicts a geometric representation of the slope structure.

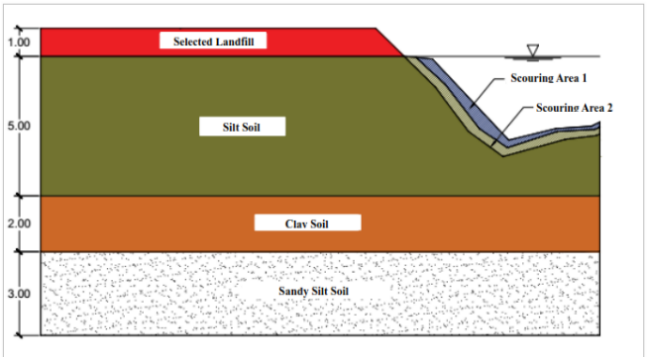

Figure 3. Geometric Illustration of Slope Structure

After generating the model with AutoCAD 2D software, the geometric depth is entered into Plaxis 2D software as stated in Figure 4, along with soil material data. Soil properties data are processed based on the results of primary data analyzed in the laboratory and secondary soil data received.

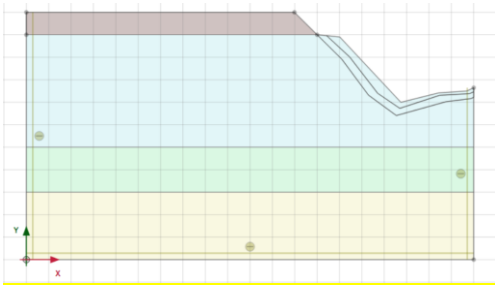

Figure 4. Geometric Slopes in Plaxis 2D V.22 Software

Table 1 displays the soil parameters used in this research. The soil conditions, soil density in saturated and unsaturated conditions, soil elastic modulus, Poisson ratio, cohesion, friction angle, and x and y coefficients represent the required characteristics.

Table 1. Geometric Slopes in Plaxis 2D V.22 Software

Soil	Model	Condition	γ_{unsat} kN/m^3	γ_{sat} kN/m^3	E kN/m^2	V	c_{ref} kN/m^2	φ ^{o}	k_x m/day	k_y m/day
Selected Landfill	Mohr - Columb	Undrained	19.00	21.00	8000.00	0.30	1.00	30.00	Default	Default
Silt Soil	Mohr - Columb	Drained	16.00	19.00	5000.00	0.40	8.00	25.00	Default	Default
Clay Soil	Mohr - Columb	Undrained	16.00	18.00	500.00	0.40	2.00	24.00	Default	Default
Sandy Silt Soil	Mohr - Columb	Drained	12.00	16.00	1000.00	0.30	5.00	16.00	Default	Default

Figure 4 demonstrate the results of the slope modeling analysis in Condition 1. Condition 1 is the existing condition where scouring does not occur in the river, resulting in a failure pattern displayed in Figure 5.

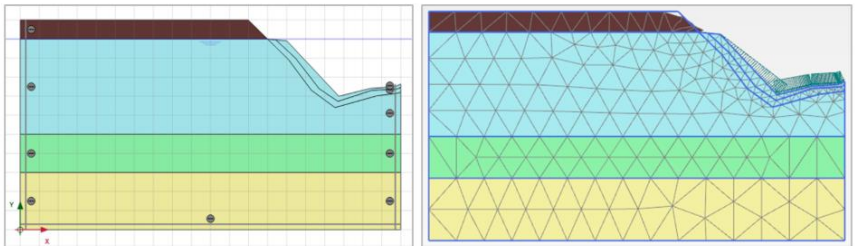

Figure 4. Slope Modelling Condition 1

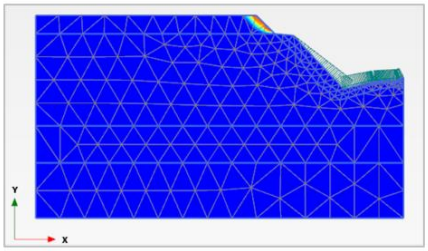

Figure 5. Collapse Pattern Condition 1

In condition 1, the soil structure displays stability, as indicated by a slight deformed mesh or network at the top, while the slope in direct contact with the water flow remains safe (colored blue). The safety factor (SF) value achieved in Condition 1 was 1.339, which results in a *y*-displacement of 37.80 mm.
Condition 2 is a model in which the initial scour occurred, resulting in the slope modelling analysis and failure pattern illustrated in the Figure 6 and 7 below

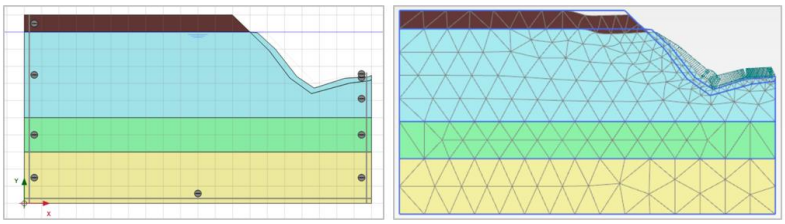

Figure 6. Slope Modelling Condition 2

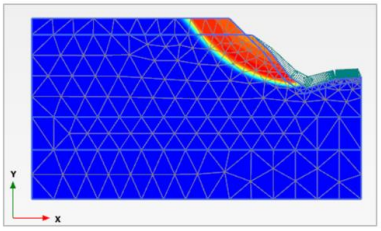

Figure 7. Collapse Pattern Condition 2

In Condition 2, the collapse section is larger, with the collapse pattern extending to the area in direct contact with the water flow over the slope. The Safety Factor (SF) and y-displacement values in this condition decrease to SF 1,240 and 56.25 mm. The red color in the present situation represents the stress and ground displacement that is occurring.

Condition 3, especially modeling, describes whenever the second scour occurs. Scour in condition 1 causes changes in condition 2, and condition 2 turns into condition 3. The scouring process triggers the slope configuration to become sharper than in conditions 1 and 2. Resulting in the slope modelling analysis and failure pattern in condition 3 displayed in Figure 8

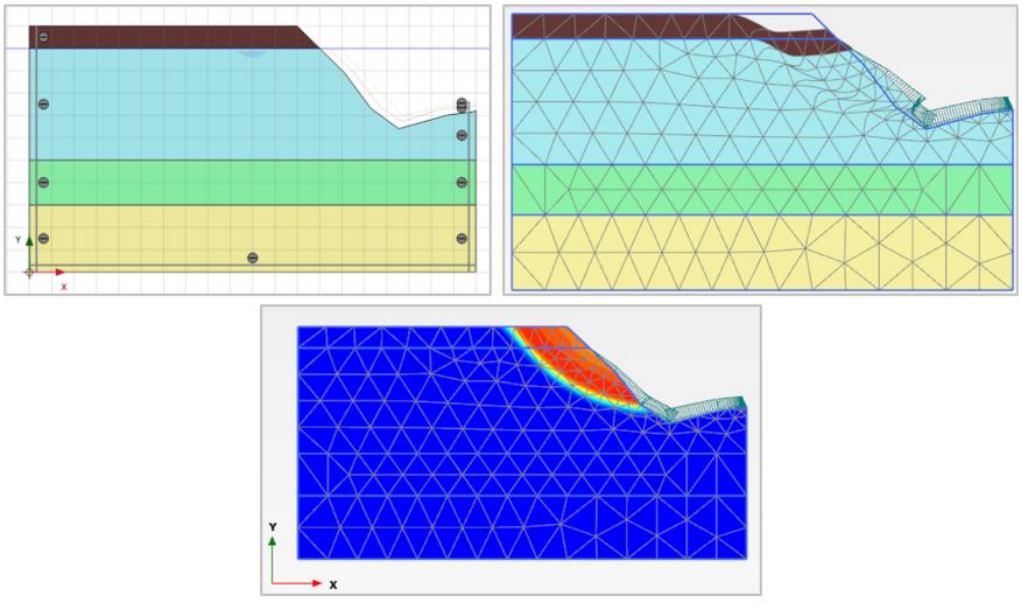

Figure 8. Collapse Pattern Condition 3

In terms of illustrations and collapse patterns, Condition 3 does not differ significantly from Condition 2, but the resulting numbers show a fall in the Safety Factor (SF) value to 1.122 and a y-displacement of 79.33 mm. Failure on slopes is generally expressed by the SF reaching a value of 1 by what was stated by references [13] regarding the correlation of the SF value and its stability characteristics, while the results of the research showed that the SF decreased and was close to 1. This condition is extremely unsafe and indicates an urgent issue or the potential of landslides. The results of the analysis are summarized in the tables and figures below for three situations: Condition 1 (beginning conditions), Condition 2 (conditions during scour), and Condition 3 (conditions after scour in condition 2 and modifications in slope geometry).

Table 2. Safety factor value that occurs due to scour

No.	Condition	Safety Factor Value (mm)
1.	Initial Condition	1.339
2.	Scouring Condition 1	1.240
3.	Scouring Condition 2	1.122

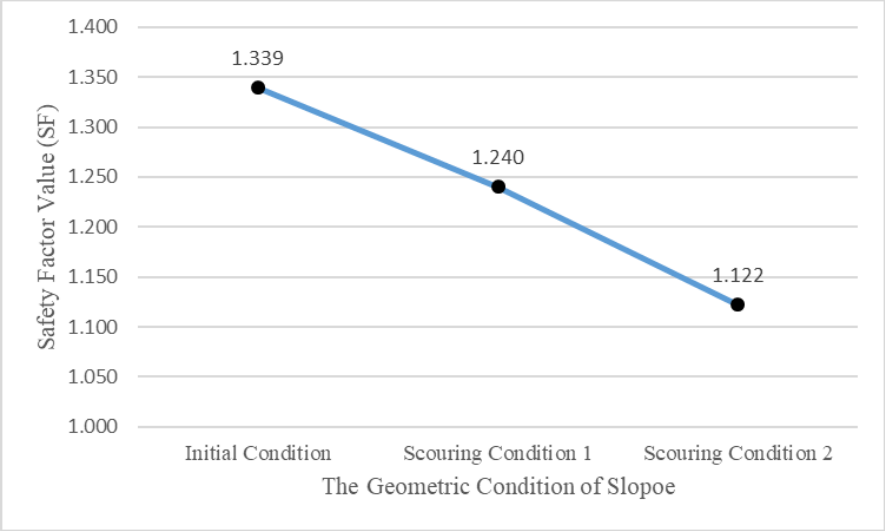

Figure 8. Graph of Safety Factor Values During Scour Occurrence

Table 3. Decreased value that occurs due to scour

No.	Condition	*y*-Displacement Value (mm)
1.	Initial Condition	37.80
2.	Scouring Condition 1	56.25
3.	Scouring Condition 2	79.53

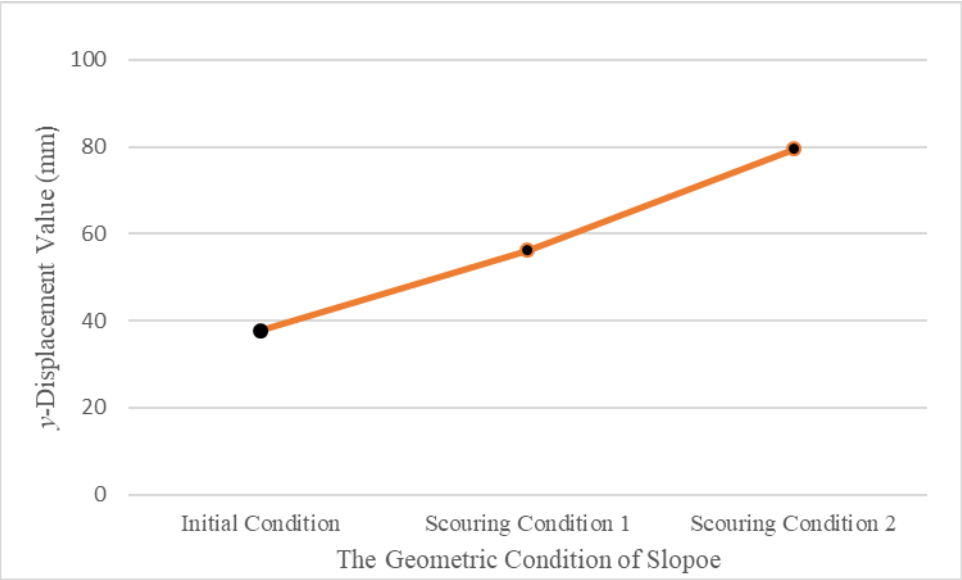

Figure 9. Graph of Decreased Value due to Scour

Figure 9 shows that the presence of scour indicates a decrease in SF under each circumstance. In addition to reducing SF, the value of soil deformation increased. These two factors represent the slope instability established by the Cipeles Bridge slope during various scenarios. Results of this study confirm the theory proposed by Triatmodjo and and S.R. Martini that hydrological conditions in the form of scour will have an impact on the condition of the soil covering the surrounding slopes, in this case, the soil in the Cipeles Bridge area.

6. CONCLUSION

Based on the results of the analysis applied with Plaxis 2D V.22 software, the following conclusions can be obtained:

1. The scour phenomena, including scour 1 and scour 2, cause a bigger slope failure pattern. This is indicated by the red color in the weakest region of the running results.
2. Scouring reduced the Safety Factor (SF) value on the slope, with condition 2 showing the greatest decrease. The Safety Factor (SF) value in condition 2 due to the impact of scouring reached 1.122 from the initial safety factor value in the initial condition of 1.339.
3. The *y*-displacement value reached 79.53 mm for the final condition (condition 3) from the initial condition which was originally valued at 37.80 mm.
4. Scouring forces dimensional or geometric changes in the slope, which result in a decrease in Safety Factor (SF) and y-displacement values as the slope becomes steeper. The steeper the geometry of the slope, the less resistance the particles that make up the slope have, which results in a weaker slope due to gravity and water exposure.
5. To prevent scouring, slope walls are required to be protected from direct exposure to water. soil.

BIBLIOGRAPHY

[1] B. Triatmodjo, *Hidrologi Terapan*, 6th ed. Yogyakarta: Beta Offset Yogyakarta, 2016.
[2] N. Afrianti, "Penggunaan Software Plaxis Dalam Menganalisis Stabilitas Lereng Dan Tinggi Kritis Timbunan Pada Perencanaan Escape Hill Dengan Pemodelan Material Set," *J. Civ. Eng. Student*, vol. 2, no. 1, pp. 15–21, 2020. (in Indonesian)
[3] Nenny and Hamzah Al Imran, "Pengaruh Kecepatan Aliran Terhadap Gerusan Lokal Disekitar Pilar Heksagonal," *J. Tek. Sipil*, vol. 7, no. 14, pp. 606–612, 2014. (in Indonesian)
[4] S. R. Martini, "Analisis Perubahan Hidrologi Lereng Akibat Hujan Terhadap Kestabilan Lereng Analysis Change of Slope

Hidrology Result of The Rainfall To The Slope Stability". (in Indonesian)

[5] I. Barokah and Didik Purwanto, "Pengaruh Variasi Debit Aliran Terhadap Gerusan Maksimal Di Bangunan Jembatan Dengan Menggunakan Program Hec-Ras," *Inersia*, vol. X, no. 2, pp. 175–184, 2014. DOI: https://doi.org/10.21831/inersia.v10i2.9965

[6] B. M. Das, "Mekanika Tanah (Prinsip-prinsip Rekayasa Geoteknik," *Penerbit Erlangga*, pp. 1–300, 1995. (in Indonesian)

[7] Q. Aini, R. Kopa, and R. Har, "Analysis of Slope Stability Case Study of Road Sicincin Malalak KM 27.6 Malalak District, Agam Regency," *J. Bina Tambang*, vol. 3, pp. 1–15, 2018, DOI: https://doi.org/10.24036/bt.v3i.10109

[8] A. Fauzi, S. Sukobar, D. I. Wahyudi, and R. A. T. Moeljono, "Analisa Stabilitas Lereng dan Alternatif Penanganannya Studi Kasus Proyek Pekerjaan Kanal Utama Row 80 Kawasan Industri JIIPE-Gresik," *J. Apl. Tek. Sipil*, vol. 17, no. 2, p. 59, 2019, DOI: https://dx.doi.org/10.12962/j2579-891X.v17i2.5447. (in Indonesian)

[9] G. S. Utami and J. Caroline, "Analisis Pengaruh Perubahan Kadar Air Terhadap Parameter Kuat Geser Tanah," *Pros. Semin. Nas. Sains dan Teknol. Terap.*, vol. 0, no. 0, p. 289, 2018. (in Indonesian)

[10] V. T. Haris, F. Lubis, and W. Winayati, "Nilai Kohesi Dan Sudut Geser Tanah Pada Akses Gerbang Selatan Universitas Lancang Kuning," *SIKLUS J. Tek. Sipil*, vol. 4, no. 2, pp. 123–130, 2018, DOI: 10.31849/siklus.v4i2.1143. (in Indonesian)

[11] S. Sugiarto, M. A. Maulana, and Y. T. Todingrara, "Analisis Penyebab dan Mekanisme Keruntuhan Lereng Sungai Konaweha, Studi Kasus Ruas Bts. Kab. Konawe Utara/Kab. Konawe – Pohara Km 29+750," *J. Manaj. Aset Infrastruktur Fasilitas*, vol. 6, no. 0, pp. 67–77, 2022, DOI: 10.12962/j26151847.v6i0.12080. (in Indonesian)

[12] Karno, "Analisis Jumlah Gilasan Uji Kompaksi Plat Getar Pada Tanah Urug," *J. Student Tek. Sipil*, vol. 2, no. 1, pp. 92–98, 2020. (in Indonesian)

[13] J. E. Bowles, "Analisis Dan Desain Pondasi Jilid 2 Edisi Keempat," *Jakarta: Erlangga*, vol. 2. p. 474, 1997, DOI : https://doi.org/10.24815/jarsp.v1i3.11768

[14] W. Wihardi, M. Munirwansyah, and S. M. Saleh, "Analisis Stabilitas Lereng Menggunakan Software Plaxis 8.6 Dengan Dinding Penahan Tanah (Retaining Wall) (Studi Kasus Ruas Jalan Nasional Banda Aceh-Medan Sta 83+135 Gunung Seulawah)," *J. Arsip Rekayasa Sipil dan Perenc.*, vol. 1, no. 3, pp. 76–82, 2018, doi: 10.24815/jarsp.v1i3.11768. (in Indonesian)

[15] A. Allowenda, E. Priadi, and Aprianto, "Analisa Modulus Elastisitas Dalam Memprediksi Besarnya Keruntuhan Lateral Dinding Penahan Tanah Pada Tanah Lunak," *Univ. Tanjungpura*, vol. 5, 2018, [Online]. Available: https://jurnal.untan.ac.id/index.php/JMHMS/article/view/26616. (in Indonesian)