Slope Stability Modeling in Jalur Jalan Lintas Selatan (JJLS) Planjan-Baron Section Using Limit Equilibrium Methods

Ceri Eliesa Suhartini*, I Gde Budi Indrawan, Nugroho Imam Setiawan

Department of Geological Engineering, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia
**Corresponding author. Email: cerieliesa@mail.ugm.ac.id*

ABSTRACT

The construction of Jalur Jalan Lintas Selatan (JJLS) infrastructure is implied to facilitate access and increase the potential for agriculture and tourism in the South Coast Region of Java. Slope stability evaluation should be done in this development infrastructure area to build sustainable and resilient infrastructure. However, no studies have been conducted about the slope condition in one of the road sections, Planjan-Baron, which is situated in the Gunungkidul Region. Hence, slope stability models in Planjan-Baron Section are presented in this paper. This research aims to analyze the slope condition in Planjan-Baron Section by using the Limit Equilibrium (LE) methods, i.e. Bishop Simplified, Janbu Simplified, and Morgenstern-Price. The research started with literature studies and continued with field investigation and laboratory testing. The analysis step began with slope modeling from its original condition using Slide software to determine the Factor of Safety (FS). The result showed that FS obtained on the slope reviewed at STA 3+800 was less than 1.2. This result indicated that the condition of the slope was unstable. Furthermore, this paper also showed the comparison of LE methods in the case of this study. FS results of the LE methods used showed that Bishop Simplified and Morgenstern-Price obtained almost similar results while Janbu Simplified dan Morgenstern-Price got significantly different results. Various kinds of mitigation were suggested for the slope stability of the Planjan-Baron Section to minimize the risk of landslide potential.

Keywords: *Agriculture and tourism, Planjan-Baron Section, Slope stability, Limit equilibrium method, Factor of safety.*

1. INTRODUCTION

Jalur Jalan Lintas Selatan (JJLS) is a connecting road between regions on the southern coast of Java Island. Planjan-Baron Section is one part of JJLS that pass Gunungkidul Regency, Yogyakarta Special Region. It has a panoramic view of rice fields, plantations, and karst hills and is closed to favorite tourist objects, such as Baron, Ngrawe, Kukup, Sepanjang, Drini, Ngrumput, Krakal, and Slili Beach. This construction development will undoubtedly be able to positively impact the ease of community access to agriculture and tourism in that location, which can improve the local economy.

The area has a steep karst hills morphology [1], weathered slope outcrops [2], and an earthquake hazard potential [3]. These cannot guarantee stable slope conditions along with the infrastructure. As a result, road access can be cut off and hinder the mobility of goods and services or even cause loss of life. This research was carried out to evaluate the slope stability of the Planjan- Baron Section to minimize the risks that may arise and ensure the sustainability of the road in the future.

Limit Equilibrium (LE) method is considered one of the appropriate approaches to analyzing slope stability problems [4]. This study used different LE methods, i.e. Bishop Simplified, Janbu Simplified, and Morgenstern-Price methods. Although simplified methods such as Bishop and Janbu Simplified are not always wrong in calculating safe slopes, they sometimes can be miscalculated on unsafe slopes because they neglect all equilibrium conditions, so the Morgenstern-Price method, which considers all interslice forces and equilibrium conditions, is slightly more accurate than simplified method [5]. Besides that, some assumptions

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of several LE methods are needed in considering the slope safety factor because there is no universal method, and there are many uncertainties in investigating slope stability, such as slope geometry, properties of the slope, slope parameters, groundwater condition, and soon [6]. Therefore, it is necessary to determine the comparison of the results obtained from these methods in the case of this study.

Furthermore, there has been no research regarding slope stability analysis in the study area. A previous study by the National Road Planning and Supervision Work Unit of Yogyakarta Special Region [7] was just about design review, including a geological survey conducted for foundation planning and detailed engineering design. Slope construction in the study area was based only on the design plan and did not carry out further slope stability analysis. Overall, this study might be helpful for a better understanding of slope conditions in the area that may affect the construction.

1.1. Study Area and Geological Condition

This study is focused on the section of Planjan-Baron. It is located at Kemadang and Banjarejo Village, Tanjungsari District, Gunungkidul Regency, Yogyakarta Special Region (Figure 1). Physiographically, the area is included in the Gunungsewu Subzone, part of the Southern Mountain Zone [8]. The morphology of this area is a karst landform [9]. It is dominated by conical karst hills [10]. Its development is related to fractures (including faults) where dissolution occurs more quickly through those and then produces the remains of the platform in the form of carbonate hills [11]. The study area has a topography with a slope angle of 5°-20° and an elevation between 75-400 masl [12]. That topographic range is classified as slightly steep to steep based on the classification of van Zuidam [13], where the potential for mass movement such as landslide can occur in this condition.

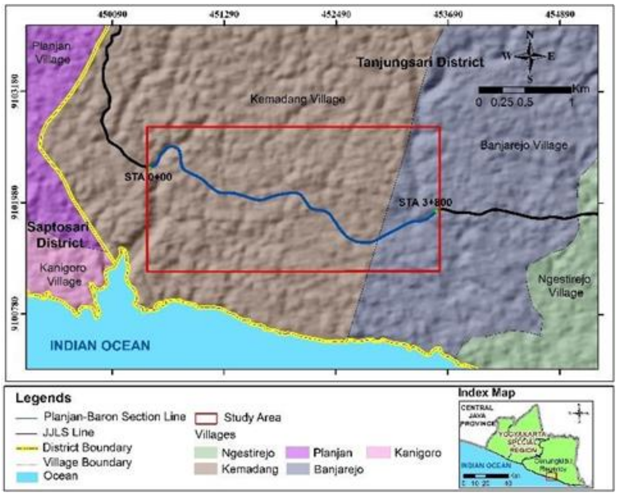


Figure 1 Study Area

By referring to Surono et al. [14], the stratigraphy of the Southern Mountain, from the oldest to the youngest, is composed of Kebo-Butak Formation, Semilir Formation, Nglanggran Formation, Sambipitu Formation, Oyo Formation, Wonosari-Punung Formation, Kepek Formation, and Alluvial deposit. The Wonosari-Punung Formation is exposed in the study area. The age of this formation is Neogene (Middle Miocene to Earliest Pliocene). Its thickness is estimated at 300-800 meters. Lithologically, the study area consists mainly of reef limestones [8, 14–16]. The groundwater level in the reef limestone can reach up to 150 m depth or even more [17].

The geological structure in the study area and its surrounding is generally controlled by fault patterns trending northeast-southwest (Meratus Pattern) and northwest-southeast (Java Pattern) [18]. During the Neogene, the structures began to form, reactivating preformed structures and contributing to the creation of new structures in the area.

Based on the earthquake hazard-prone map of D.I. Yogyakarta, scale 1:200,000 by Robiana and Indra [3], the study area is in the moderate earthquake hazard zone. In addition, Peak Ground Acceleration (PGA) ranges from 0.3g to 0.4g. This shows that the study area has a high risk of earthquakes and other possible hazards, which can be resulted, i.e. landslides.

1.2. Limit Equilibrium (LE) Methods

LE method is a commonly used approach for slope stability analysis due to its simplicity and accuracy of the Factor of Safety (FS) obtained [19–21]. Several methods of LE have been developed to analyze slope stability. Generally, LE methods consider moment and interslice forces equilibrium (interslice normal and shear forces). Simplified methods neglect both or one of them, i.e. Fellenius method neglects both interslice forces equilibrium, Bishop Simplified method neglects the interslice shear force, Janbu Simplified method neglects moment equilibrium and the interslice shear force, Corps of Engineering and Lowe-Karfiath methods neglect moment equilibrium. Nevertheless, advanced methods consider all equilibrium conditions, i.e. Spencer, Sarma, and Morgenstern-Price [22, 23].

According to Duncan et al. [24], Bishop Simplified is suitable for circular slip surface, Janbu Simplified applies to non-circular slip surface, and Morgenstern-Price is an accurate procedure applicable to virtually all slope geometries and soil profiles. This study compared the outcome of each simplified and advanced LE method. The FS of the methods to analyze slope stability can be expressed using Equations 1 to 5.

The calculation of the FS in the Bishop Simplified method based on Bishop [25] is to use Equation (1).

$$FS = \frac{1}{\sum W \sin\alpha} \sum \left[\frac{c'l + W \tan\phi' - \frac{c'l}{FS} \sin\alpha \tan\phi'}{m_\alpha} \right] \tag{1}$$

In Equation (1), m_α can be determined by Equation (2).

$$m_\alpha = \cos\alpha + \frac{\sin\alpha \tan\phi}{FS} \tag{2}$$

where FS is the factor of safety, W is the weight of sliding mass (kN/m), l is slice base length (m), α is the inclination of slip surface at the middle of the slice (°), c' and ϕ' are the cohesion and friction angle respectively in effective stress terms (°).

Based on Equation (1), FS appears on both sides of the equation, so an iterative procedure is required in this method to calculate FS. The initial value of FS is used to calculate m_α, and then a new value of FS is obtained. Then, a new value of FS is used to calculate m_α, and another new value of FS is obtained. This procedure is continued until the last obtained FS converges to the previous FS.

Janbu Simplified method proposed by Janbu [26] computed the FS using Equation (3) as:

$$FS = \frac{\sum (c'l + (N - ul) \tan\phi') \sec\alpha}{\sum W \tan\alpha + \sum (E_2 - E_1)} \tag{3}$$

where N is the effective base normal force acting on slip surface (kN/m), u is the pore water pressure (kN/m^2), and E is the interslice normal force (kN/m).

Morgenstern-Price [27] calculated the interslice forces to obtain FS by an iterative procedure until F_f in Equation (4) is equal to F_m in Equation (5).

$$F_f = \frac{\sum [\{c'l + (N - ul) \tan\phi'\} \sec\alpha]}{\sum \{W - (T_2 - T_1)\} \tan\alpha + \sum (E_2 - E_1)} \tag{4}$$

$$F_m = \frac{\sum (c'l + (N - ul) \tan\phi')}{\sum W \sin\alpha} \tag{5}$$

where T is the interslice shear force (kN/m).

Referring to Priest and Brown [28], the FS value indicated the condition of the slope. The slope was stable when FS ≥ 1.2, critical when 1 ≤ FS < 1.2, and unstable when FS < 1.

1.3. Failure Criterions

There are two kinds of failure depending on the material type used in this study.

1.3.1. Mohr-Coulomb Criterion

Mohr-Coulomb criterion is usually used to model soil strength [29]. This criterion describes the linear relationship between major and minor principal stresses of the material [30]. According to Edelbro [31], the Mohr-Coulomb criterion is expressed by Equation 6.

$$\frac{\sigma_1}{\sigma_2} = \frac{2c \cos\phi}{\sigma_3 (1 - \sin\phi)} + \frac{1 + \sin\phi}{1 - \sin\phi)} \tag{6}$$

where σ_1 and σ_3 are the major and minor principal stresses (kN/m^2), ϕ is internal friction angle (°), and c is cohesion (kN/m^2).

1.3.2. Generalized Hoek-Brown Criterion

Hoek and Brown [32] presented the non-linear relationship between major and minor principal stresses at failure, successfully estimating rock mass strength. The Generalized Hoek-Brown (GHB) criterion by Hoek et al. [33] can be written as Equation (7).

$$\sigma_1 = \sigma_3 + \sigma_{ci} \left(m_b \frac{\sigma_3}{\sigma_{ci}} + S \right)^a \tag{7}$$

where m_b, s, and a are estimated from GSI for the rock mass as follows:

$$m_b = m_i exp \left(\frac{GSI - 100}{28 - 14D} \right) \tag{8}$$

$$s = exp \left(\frac{GSI - 100}{9 - 3D} \right) \tag{9}$$

$$a = \frac{1}{2} + \frac{1}{6} \left(e^{-GSI/15} - e^{-20/3} \right) \tag{10}$$

where σ_{ci} is the uniaxial compressive strength, m_i is the Hoek-Brown constant for intact rock mass, and D is the disturbance factor.

1.4. Seismic Load

Slope stability analysis in this study considered a seismic load. According to the National Standardization Agency of Indonesia [34], the effect of seismic load needs to be calculated on the slope of the road to ensure transportation routes are not interrupted after an earthquake occurs. Due to earthquakes, PGA can cause significant inertial forces on the slope, resulting in instability or permanent deformation. This study analyzes slope performance against seismic load using a pseudo-static model approach by changing the force that arises due to dynamic earthquake loads into static by applying a lateral force that works through the center of mass, acting towards the outside of the slope. This method ignores the cyclical nature of the earthquake and applies additional static forces to the slope. The horizontal seismic coefficient (k_h) is determined as follows:

$$K_h = 0.5 \times PGA \times F_{PGA} \tag{11}$$

where PGA is peak ground acceleration at the bedrock with a return period and F_{PGA} is site coefficients.

2. METHOD OF RESEARCH

The study was begun by studying the geological conditions in the research area. Then continued collecting the primary and secondary data. Primary data was collected in the field, including rock samplings (for thin section, physical and mechanical testing), slope geometry, and Geological Strength Index (GSI). The work was followed by laboratory analyses: thin section analyses were carried out to determine the lithology of the study area, whiles physical and mechanical testing of rock using Uniaxial Compression Strength (UCS) test and soil using direct shear test were done to obtain the basic parameters for design analysis in this study. Furthermore, secondary data was collected, i.e. seismic loading data obtained from the Indonesian Spectra Design website which collects seismic data in various regions in Indonesia. It was done by entering location input data, i.e. latitude and longitude coordinates or the city's name. Then, the spectral design curve include PGA appeared for various soil types at the construction site. Referring to Equation (11), k_h is calculated to be 0.5 of the horizontal peak acceleration by determining the site class and amplification factor.

Then, slope stability conditions were modeled in the 2D LE methods using Bishop Simplified, Janbu Simplified, and Morgenstern-Price methods. The boundary conditions used in the model such as Bishop simplified satisfies moment equilibrium and interslice normal force, Janbu Simplified satisfies only interslice normal force, and Morgenstern-Price satisfies overall moment and interslice forces equilibrium.

Soil strength was modeled by Mohr-Coulomb, and rock strength was modeled by the GHB criterion. In the Mohr-Coulomb criterion is required the data input, i.e. unit weight, cohesion and internal friction angle, while in the GHB criterion, i.e. unit weight, UCS and GSI to determine m_b, s, and a.

FS was calculated using Slide software by entering the required input parameters corresponding to each method's equations. The stability level of each slope in the study area was determined from the obtained FS and classified as stable, critical, or unstable using the classification of Priest and Brown [28]. The FS results of each LE method were also compared in this study.

3. RESULTS AND DISCUSSION

In this study, the actual slope conditions were analyzed in the construction of the Planjan-Baron Section. Slope stability analysis using LE methods (Bishop Simplified, Janbu Simplified, and Morgenstern-Price methods) was carried out at two locations of the section, i.e. STA 3+00 and STA 3+800 (Figures 2 and 3). The two locations were selected because they represent the lithology that composes the Planjan-Baron Section, have poor rock mass quality and steep slope geometry. Hence, they need to be analyzed further. Parameters for slope stability analysis were obtained from field observations and laboratory testing. The analytical parameters for slope stability at each layer (from bottom to top) are shown in Tables 1 and 2.

Figure 2 Slope outcrop on Planjan-Baron Section STA 3+00

Figure 3 Slope outcrop on Planjan-Baron Section STA 3+800

Table 1. Parameters for slope stability analysis at STA 3+00

Layer	Lithology	Parameters	Value
1	Floatstone (Slightly weathered)	Unit weight (kN/m^3)	19.71
		UCS (kPA)	29400
		GSI	40
		Constant m_b	1.1732
		Constant s	0.001273
		Constant a	0.5114
2	Floatstone (Moderately weathered)	Unit weight (kN/m$^{3)}$	22.85
		UCS (kPA)	17040
		GSI	15
		Constant m_b	0.4804
		Constant s	0.000079
		Constant a	0.5611

Table 2. Parameters for slope stability analysis at STA 3+800

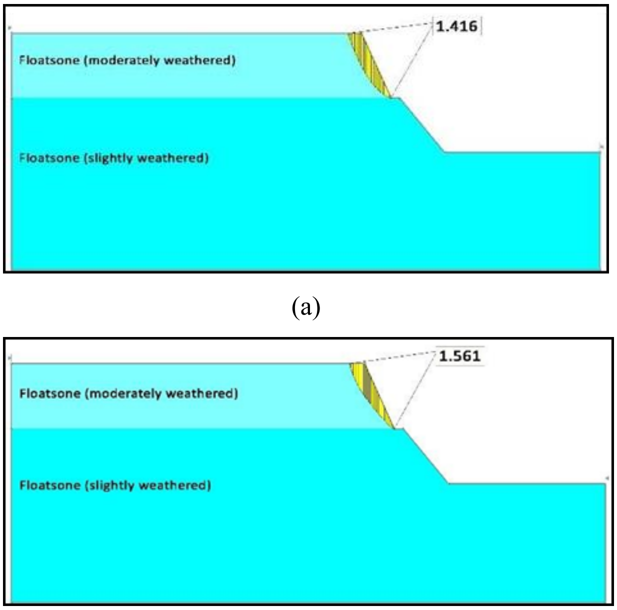
Layer	Lithology	Parameters	Value
1	Rudstone	Unit weight (kN/m^3)	21.28
		UCS (kPA)	14530
		GSI	25
		Constant m_b	0.6866
		Constant s	0.00024
		Constant a	0.5313
2	Residual Soil	Unit weight (kN/m$^{3)}$	14.94
		Cohesion (kPa)	0.22
		Friction Angle (°)	43.92

The parameters in Tables 1 and 2 were used as the input in the simulation of slope stability analysis. The seismic load was also considered for the slope stability analysis, where the PGA value is obtained from the Indonesian Spectra Design website, and k_h is determined using Equation (11), so the input of seismic load in the slope stability model is 0.27.

The slope condition at STA 3+00 (see Figure 2) shows the possibility of a wedge failure, so the selected LE methods were Janbu Simplified and Morgenstern-Price method. Meanwhile, Bishop Simplified and Morgenstern Price were used in slope stability analysis at STA 3+800 because of the possibility of circular failure, as shown in Figure 3. In this study, the Factor of Safety (FS) results from the simplified methods were compared with the advanced method. The results of the investigation are as follows.

3.1. Slope Stability Analysis Results at STA 3+00

Based on the simulation result of slope stability analysis, the FS obtained from Janbu Simplified and Morgenstern Price were 1.416 and 1.561, respectively, as indicated in Figure 4. The FS obtained from the Janbu Simplified method is smaller than the FS from the Morgenstern-Price method. Significant differences in the results between the two approaches can be caused by the Janbu Simplified method that neglect moment and interslice shear forces equilibrium in determining FS, in contrast to the Morgenstern-Price method which considers the moment and interslice forces equilibrium. However, the overall FS values for both Janbu Simplified and Morgenstern-Price methods indicate that the slope condition at STA 3+00 is stable.



(a)

(b)

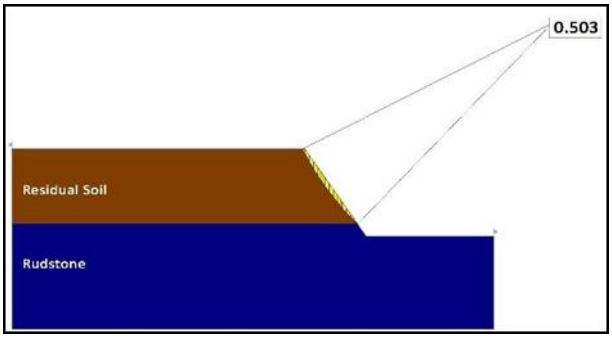
Figure 4 Slope stability analysis results at STA 3+00 using LE methods (a) Janbu Simplified method result (b) Morgenstern Price method result

3.2. Slope Stability Analysis Results at STA 3+800

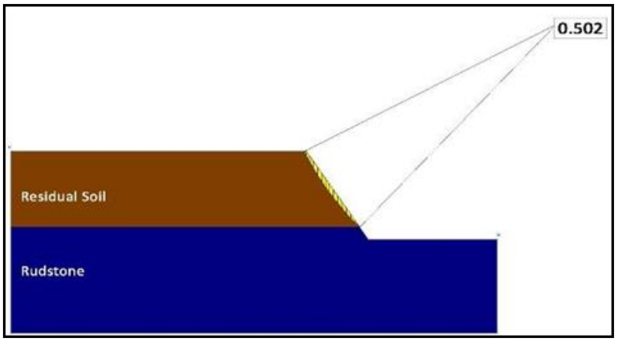
The FS results obtained from Bishop Simplified and Morgenstern Price were 0.503 and 0.502, respectively (as shown in Figure 5). In general, the results from both approaches gave roughly similar results. This occurred because both Bishop and Morgenstern-Price methods consider the equilibrium of moment and interslice normal force. However, there is a slight difference in the results due to the Bishop Simplified method neglecting interslice shear forces. The FS, based on the results of the two approaches, shows that the slope at STA 3+800 is unstable.

Slope instability at STA 3+800 can occur due to the character of the lithology that composes the slopes, consisting of residual soil with high plasticity and very soft so that it has swelling properties when exposed to wet. In addition, this condition is exacerbated by the steep slope geometry.

Figure 5 shows the potential for slope failure along the plane on the residual soil material. The properties of the residual soil have easily passed water. As a result, the shear strength of the soil decreases and the pore water pressure increases significantly during the rainy season, and the surface of the residual soil becomes slippery. Therefore, this slope becomes unstable and has the potential for landslides to occur.



(a)



(b)

Figure 5 Slope stability analysis results at STA 3+800 using LE methods (a) Bishop Simplified method result (b) Morgenstern Price method result

The existence of an unstable slope at STA 3+800 of the Planjan-Baron Section is necessary to provide slope reinforcement to mitigate landslide potential. The recommendation for slope reinforcement is to install the following constructions: anchor, soil nailing, shotcrete, catch wall, retaining walls, or pile work.

4. CONCLUSIONS

The results of this study show that the slope at STA 3+800 is unstable, and various reinforcements need to be installed to minimize the risk of landslide potential, i.e. anchor, soil nailing, shotcrete, catch wall, retaining wall, or pile work. In the comparison results of LE methods used in this study, it is known that the FS obtained based on the circular slip surface assumption of Bishop Simplified and Morgenstern-Price methods have almost similar results. However, FS based on the assumption of non-circular slip surface using Janbu Simplified and Morgenstern-Price methods obtained significantly different results because of the many different assumptions considered.

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