Pseudo-static slope stability analysis around the landslide at railway tunnel, South Sumatera, Indonesia

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Abstract. On January 23rd 2016 there was a landslide in the Lahat-Lubuk Linggau railway, right at the mouth of the railway tunnel in Lahat Regency. About 5 meters thick of soil covered the railway, causing the railway to be stopped for several days. Since the tunnel was built in 1928 until landslides occur in 2016 which means it has been 88 years. The landslide can be caused by several factors, these factors are slope geometry, physical and mechanical characteristics of rocks or soil, geological structure, hydrology and hydrogeology, and external forces such as ground vibration due to railway traffic and earthquake. The results of research on the main causes of landslides in the mouth of the railway tunnel include relatively steep morphological influences, degradation of rock strength due to weathering, dip rock structure in the direction of slope, and ground vibration due to earthquakes. Based on field observations, the slope next to the case study area of the landslide is also unstable. Therefore, it is necessary to analyze the slope stability in the area that has the potential to landslide, using a pseudo-static slope stability analysis on the consideration of the effect of ground vibration due to earthquakes is quite significant to slope stability. The results of the pseudo-static slope stability analysis is showing out that the factor of safety is around 1.22-1.16 with a seismic coefficient of 0.10-0.125 g. To anticipate future landslide we suggest to be conducted studies on slope stabilization methods including building retaining walls, drainage channels and shotcrete walls.

1. Introduction

The development of railway transportation in South Sumatra began in the Dutch colonial era which was built to support the plantation industry. The development of railway transportation was preceded by the construction of railways, where the slope of the railway was relatively flat, therefore, for the construction of hills / mountains, tunnels had to be made. Railway tunneling will change natural slopes to artificial slopes around the entrance of tunnel. There was a landslide at the mouth of the railway tunnel in Lahat Regency on January 23, 2016. Landslides covered the railway tracks with a thickness of almost 5 meters, so that the lines had to be closed for several days until the track was cleared. Factors that influence slope
stability are slope geometry which include slope height, slope angle, physical and mechanical characteristics of rock including rock or soil density, cohesion, and angle of friction, geological structure factors such as weak planes, orientation of the rock structure. Other factors are climate, hydrogeology or hydrogeology and external forces such as ground vibrations caused by railway traffic and earthquake. According to research conducted by Taufik Toha, et al. (2016)\textsuperscript{[1]}\textsuperscript{[2]}, the main cause of landslides around the mouth of the railway tunnel was due to weathering which resulted in degradation of rock strength. This weathering occurs due to the influence of ground vibration so that it changes the condition of the joint in the initially closed rock joint to open joint. After that the water to enter the opened joint rock structure so that there is weathering of rocks in physics and chemistry. Besides that, also the main factor causing landslides is morphology in the form of hills with relatively steep slopes and slope angles of rock structures is same with the direction of the slope. Based on observations in the research location in the area around the landslide case with morphological conditions, lithology and rock structure relatively similar, the area is potentially landslide in the future. Efforts to anticipate future landslides, it is necessary to analyze the slope stability with pseudo-static slope stability analysis.

2. Geological Condition
The South Sumatra Basin has an area of 117,000 square kilometers (De Coster, 1974)\textsuperscript{[3]}. Sedimentation that occurs in this basin lasts continuously during the Tertiary accompanied by a decrease in the basement of the basin.

Deposition that occurs in this basin occurs in two phases, first transgression phase, which consists of the Lahat Formation, Talang Akar Formation, Baturaja Formation and Gumai Formation. Second phase, consisting of Air Benakat Formation, Muara Enim Formation and Kasai Formation. During the transgression phase the basement decrease is faster than the speed of sediment supply, so the facies sequence starts from land deposits, transitions, shallow seas and finally deep seas. Based on the geological map compiled by S. Gafoer et al. (1986)\textsuperscript{[4]} and South Sumatra stratigraphy (Figure 1) the stratigraphic sequence of the South Sumatra Basin from old to young are: Basement rock, Lahat Formation, Talang Akar Formation, Baturaja Formation, Gumai Formation, Air Benakat Formation, Muara Enim Formation, Kasai Formation and Quaternary Sediments.

![Figure 1. Stratigraphy of South Sumatera Basin\textsuperscript{[4]}](image-url)
The research location included in the benakat water formation is composed of Shale Stone pasiran lithology and Shale Stone. The division of rock units based on unofficial Litostratigraphic units from old to young in the research location can be divided into: Alluvial Deposition Units, Airbenakat Sandy Shale Stone Units and airbenakat Shale Stone Units (Shale).

3. Research Method

Pseudo-static Slope Stability Analysis in the Mouth of the Railway Tunnel, Lahat Regency is carried out with the following stages of activities:

3.1. Data Collection

3.1.1. Primary data includes observations of geological, geotechnical, hydrological and hydrogeological parameters that can affect the slope stability at the mouth of the railway tunnel such as observation and measurement of rock layer structures, actual slope geometry measurements, soil / rock sampling with the help of hand drill, measurement topography of the land around the research location using the measuring instrument in the form of Theodolite.

3.1.2. Secondary data includes the results of previous studies related to landslides caused by ground vibrations both vibrations caused by earthquakes and vibrations generated from railway traffic\(^5\). Climate and rainfall data in poor districts, and theories about slope stabilization methods.

3.2. Data Processing and Analysis

Data that has been collected is further processed, such as data on soil / rock sampling obtained from the research location will be analyzed for physical and mechanical properties. Sample testing will be carried out in the rock mechanics laboratory at the Department of Mining Engineering at Sriwijaya University. Physical characteristics that will be observed are density, grain size distribution, moisture content, porosity, and so on. Besides physical characteristics, also carried out mechanical characteristics analysis which includes cohesion, angle of friction, strength of soil / rock. Both primary and secondary data that has been collected are processed and analyzed\(^6\)\(^7\). From the data, slope stability analysis will be carried out using the simplified bishop method with formula 1\(^6\):

\[
F = \frac{1}{\sum W \sin \alpha} \sum \left[ c' + (W - u_l) \tan \phi' \right] \frac{\sec \alpha}{\tan \alpha + \tan \phi'}
\]

After obtaining the slope stability value from the modeling cross section of the actual slope, then the slope stability analysis is performed using pseudo-static modeling by inputting the value of the ground vibrations produced either from earthquakes or passing trains. The ground vibration will affect the rock or slope constituent soil, rock or soil mass experience the addition of driving force and the reduction of normal force in the landslide field. Therefore it can be said that ground vibration causes a decrease in the stability of a slope. For this reason, the calculation of the pseudo-static slope stability with formula 2\(^6\):

\[
F = \frac{cA + (W(c \psi_p - k_H \sin \psi_p)) \tan \phi}{W(\sin \psi_p + k_H \cos \psi_p)}
\]

3.3. Conclusion and Recommendation

This study will produce actual slope strength from areas that are potentially landslide then slope strength by increasing the influence of vibration parameters generated by earthquakes or generated from rail traffic. From this strength it can be concluded whether the slope is stable or not. If the stability of the actual slope is close to critical then several slope stabilization methods will be recommended. Thus, it is expected that landslides can be minimized and train travel can take place smoothly and safely.
4. Results and Discussion

4.1. Parameters affecting slope stability

4.1.1. Geology Parameter

According to observations at the research location, lithology in the research location consisted of three types of material, which are top soil, soil (sandy clay), and shale rock.

![Figure 2. Lithology in Research Location](image)

The first material, top soil has a blackish brown color with clay grain size (1/256 mm), severe weathering level and has a layer thickness between 0.20 m to 0.30 m. The second material, soil in the form of sandy clay has a characteristic yellowish color with silt grain size (1/16 mm) up to clay (1/256 mm), severe weathering level and has a layer thickness between 0.40 m to 1.50 m. The last layer is shale layer (shale rock) has gray color with silt granular size (1/16 mm) up to clay (1/256 mm), weathering level is quite severe and has a layer thickness between 0.40 m to 1.40 m or more. Based on observations and measurements of rock structures through landslide walls and test pit in the research location, the orientation of the rock layer structure has a strike from West-East, N 100° E with dips ranging from 20° to 30°. The orientation of rock outcrops at the research location can be seen in Figure 3.

![Figure 3. Orientation of Structure Geology](image)

Orientation conditions of the rock layer structure that has a same direction with the slope (unfavorable slope) at the mouth of the eastern tunnel to the North exactly next to the landslide location, has a great potential for landslides (Figure 4).
4.1.2. Hydrology and Hydrogeology Parameter. Rain is one of the factors that determine often or not the landslides occur, because during the rainy season the soil becomes more crumbly and makes it easy to cause landslide. Based on monthly average rainfall data for 10 years, the highest rainfall in Lahat Regency was 389.67 mm which occurred throughout 2016 and the lowest was 150.92 mm which occurred in 2007\(^8\). Based on the type of climate, the research area located in Lahat Regency is included in the area with tropical rain climate (Koppen 1918), where it rains almost every month so the soil conditions are always moist and wet resulted in increasing the amount of soil mass and affect the shear stress of soil or rock so it can potentially causing landslides. The condition of ground water is only found in the layers of top soil and sandy clay. Whereas in the lower layer there is no water seepage, because there is a layer of marl (carbonate clay rock) which is impermeable. It is also seen from the lower slope wall that no groundwater seepage was found during the rainy season. Rainwater catchment area can be interpreted as a lower area to accumulate the flowing rainwater from a higher area. The calculation used in determining runoff water discharge is the Gumbel method for a 3-year rainy return period starting from 2015 - 2017. The research location is located in Catchment Area 1 with total water discharge 3,241 m\(^3\)/s (Figure 5).
4.1.3. Parameter of Physical and Mechanical of Slope Materials. Geotechnical investigations were carried out directly in the field from the observation of the location of the east of the tunnel, lithology in the east in the form of top soil with a thickness ranging from 0.20 m - 0.60 meters; soil 0.60 - 1.00 m, Shale Stone pasiran 1.00 m - 1.60 m and Shale Stone> 1.60 m (Figure 2). The results of testing the physical characteristics and mechanical characteristics of slope material in the laboratory, obtained the average value of the slope constituent material Table 1.

| Layer         | Water Content | Unit Weight | Specific Gravity | Cohesion | Internal Friction Angle |
|---------------|---------------|-------------|------------------|----------|-------------------------|
| Sandy Clay    | 33.86         | 17.36       | 2.51             | 22.55    | 14                      |
| Shale         | 4.00          | 23.34       | 3.01             | 25.82    | 18                      |

4.1.4. Morphological Parameters. In general, the research location included the category of undulating to hilly areas with the elevation of the study location at an altitude of 135 meters to 175 meters above sea level. The lowest elevation is on the Southeast side while the highest elevation is on the North West side. The slope of the slope at the study location was classified based on slope classification according to Van Zuidam (1985). Based on this classification, the slope of the slope at the study site varied from 8% to 20%. In the slope class with a value of 8% - 20%, the land is described as having steep slopes to steep slopes (14° - 55°), frequent erosion and ground movement at a slow pace[5]. The slope map of the research location can be seen in Figure 6. The slope measurement is also carried out in the field to determine the actual angle of the slope. Whereas based on the measurement results at the research location, the slope has a slope between 25° - 30°.

4.1.5. Ground Vibration Parameters. Ground vibrations that occur at the study site are sourced from earthquakes and rail traffic. The intensity of earthquakes, from 1917 to 2017, in the South Sumatra region tends to increase from year to year with earthquake occurrences more than 2000 times. The
strength of the earthquake centered on the Southwest region of Sumatra Island, South Bengkulu and West Sumatra with a fairly wide radius and high intensity where the average strength of the earthquake ranged from 3.5 to 6 mb and several epicenter with earthquake strength > 6.5 mb. Zoning Map of the Earthquake in 1917 - 2017 South Sumatra and Surrounding Areas (Figure 7).

![Seismic Zoning Map of Indonesia](image)

**Figure 7. Map of Earthquake Zonation[^8]**

Peak Ground Acceleration (PGA) due to earthquakes at the study site can be determined using the Indonesian earthquake zoning map in 2010 and the PGA peak acceleration map (Figure 8). The results of the interpretation of the earthquake zoning map, the study location has a range of PGA values between 0.20 to 0.25 g. The ground vibration can also be caused by railway traffic, this is because the research location is right next to the railway line on the Lahat - Lubuk Linggau line where the frequency of railway traffic in the location is quite high. Trains that pass in the location consist of two types of trains, namely oil-fuel transportation and passenger transport trains. Measurement results data at the research location, the average value of the acceleration of the ground vibration due to train traffic ranged from 0.026 g.

4.2. *Pseudo-static Slope Stability Analysis*

Slopes at the research location classified as artificial slopes. The strength of the slope composing material is Sandy clay and shale. Landslides that occur with the landslide field in the shale layer have experienced physical and chemical weathering which results in degradation of rock strength. The weathering process itself occurs due to rainwater acting with cracks in the shale layer. Flow chart of rock strength degradation in Figure 8. In addition, landslides occur supported by shale layer structures in the direction of slope and hilly morphology (Figure 3).
Analysis of slope stability at the research location was carried out with computer program called slide. In analyzing slope stability using the Slide program, it takes some input data such as slope geometry, physical and mechanical characteristics of the slope composing materials obtained from observations at the research location and some data for simulation purposes such as changes in groundwater conditions and earthquake coefficients. caused by external forces in the form of ground vibrations due to railway and earthquake traffic. The parameters used in the simulation of static and pseudo-static slopes can be seen in Table 1. Variations in groundwater conditions in the simulation were carried out with 2 conditions, starting from the condition of the ground water level only in the sandy clay layer and dry slope conditions. The purpose of applying variations in groundwater conditions is to find out the changes in the value of the security factor for each condition.

The results of the safety factor based on dry condition is 1.517 and on ground water table only on upper layer (saturated sandy clay) is 1.514. The differences between two condition above is not significant because sandy clay layer is relatively thin as can be seen in Figure 9. As a result of weathering that has caused the degradation of rock strength, there is a decrease in cohesion value from the material making up the slope which is shale rock, the prediction of cohesion value at the beginning of the slope made about 88 years ago is 0.86 kg / cm$^2$ with a safety factor 3. Then over time a decrease in the value of cohesion followed by a decrease in the value of slope safety factors. Furthermore, it is estimated that the value of cohesion will decrease to 0.06 kg / cm$^2$ with a safety factor of 1 (Figure 10).
Further analysis of the stability of the pseudo-static slope was carried out. In addition to soil parameters and slope geometry conditions, seismic coefficient data is needed to analyze the stability of the pseudo-static slope. The Slide Program uses a pseudo-static approach in calculating slope safety factors that are affected by ground vibration due to an earthquake. Therefore, a pseudo-static coefficient is needed or what is often called a seismic coefficient (Kh). This seismic coefficient controls the pseudo-static force acting on rock masses or soil on a slope. If the slope material is assumed to be rigid then the inertial force (pseudo-static force) will be equal to the horizontal acceleration of the earthquake. But in reality, the condition of the slope material is not rigid so that the value of the pseudo-static coefficient is smaller than the maximum horizontal acceleration / Peak Ground Acceleration (PGAmax). There are several assumptions of the seismic coefficient values proposed by experts, one of which is according to Hynes-Griffin and Franklin in 1984 where the seismic coefficient value is 0.5 from PGAmax\(^9\). Based on the interpretation of the earthquake zoning map for the study location, the PGA ranges between 0.20 to 0.25g, and the seismic coefficient value is 0.100 to 0.125 g. Whereas for the ground vibration due to railway traffic the average value produced is 0.025g to 0.026g, the seismic coefficient value is 0.013g.

Table 4 below is a change in the value of slope safety factors based on changes in groundwater conditions and earthquake loads.

### Table 2. Effect of Seismic Coefficients on Slope Safety Factors

| Condition                                      | Minimum SF |
|-----------------------------------------------|------------|
|                                               | \(K_h = 0.013\) g  | \(K_h = 0.100\) g  | \(K_h = 0.125\) g  |
| Dried Condition                               | 1,473      | 1,227      | 1,17         |
| Ground Water Table Only on Upper Layer (Saturated Sandy Clay) | 1,470  | 1,225  | 1,16        |

Table 4 show modeling with variations in groundwater levels and variations in earthquake loads in normal to critical conditions. By looking at these results it can be said that a rise in ground water level can affect the stability of a slope. This can be seen from the decrease in the value of slope safety factors on slope modeling with conditions of increasingly saturated groundwater. Although the condition of the ground water level can reduce the value of the slope safety factor, the decline is not significant. Whereas the effect of rising earthquake loads in various groundwater conditions shows a significant decrease in
slope safety factors. Based on the results of the stability analysis of static and pseudo-static slopes, it can be stated that under certain conditions the slopes that are the object of this study have the potential to landslide. To increase the slope safety factor, it is recommended to do a retaining wall construction with the existence of a reduced mass of material that has the potential to landslide. Next is the making of canals / canals on the slopes which serve as a reservoir for surface runoff to reduce run off so that the amount of water flowing into the slope and seep into the soil is relatively small. Then it is equipped with spraying the slope wall with cement (shotcrete) with the aim of covering the wall layer so as to prevent water from entering the soil layer and not weathering rock or soil caused by water\cite{10}\cite{11}.

5. Conclusions and Recommendations

The results of the pseudo-static slope stability analysis show that the slope conditions located next to the landslide location with a safety factor value of 1.5 and if coupled with the influence of ground vibration due to an earthquake the safety factor value decreases to 1.16 which means that the slope is in critical condition.

Factors that influence slope instability (unstability slope) are morphology, geological structure with a slope in the direction of the slope, degradation of rock strength due to weathering and ground vibration caused by earthquakes.

There are many ways to anticipate the potential landslide area next to the landslide site. The recommended efforts are studying the construction of retaining walls, open channel and shotcrete walls.

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