Evaluation of Probabilistic Slope Stability Due to Updating of Indonesia Seismic Hazard Maps

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Abstract. This paper presents an evaluation of probabilistic slope stability due to updating of Indonesia seismic hazard maps from 2010 to 2017 edition. The evaluation is conducted by presenting case study to compare the probability of failure of slope which subjected to seismic load determined from those seismic hazard maps. At first, simple slope models are built and the horizontal seismic coefficients are selected. Then, the probabilistic slope stability analysis is conducted using Monte Carlo simulation in LEM-based software so called Rocscience Slide 6.0. The simulation results indicate that the revision of Indonesia seismic hazard maps causes increasing of probability of failure of slope in the study area. These results show that the slope models become more prone to failure subjected to seismic load obtained from the seismic hazard maps.

Keywords: Evaluation, slope stability, seismic, hazard

1. Introduction

Indonesia appears to be one of the most seismically active region in the world since it is situated between two continental plates: the Eurasian Plate and Australian Plate; and between two oceanic plates: the Philippine Sea Plate and Pacific Plate. Anually, up to ten damaging earthquake events have been occurred causing dramatic human and infrastructure losses associated with structural failures of buildings, landslides, and related ground failure. Therefore, the research about earthquake engineering has become an interesting topic in recent years. Seismic hazard map is an essential instrument used in seismic design of structural and non-structural components. In 2017, the Indonesia seismic hazard maps have been updated. These new edition were made based on probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA) concepts using the current information, data and methods for Indonesia region. One of those current informations is the finding of several new active faults such as Kendeng fault which crosses some areas in East Java such as Bojonegoro regency. The updating of seismic hazard maps causes several construction designs need to be evaluated to ensure that the designs are still safe.

Furthermore, some areas of Indonesia are composed with hillslope. Therefore, the construction designs should be ensured to be safe against landslide. Commonly, the slope stability analysis is done by using deterministic limit equilibrium method. However, the deterministic limit equilibrium analyses have limitation that it only considers the average value of geomechanical parameters. Even though, spatial variability of soil properties might cause nominal similar slopes have the same factor of safety but different probabilities of failure. Therefore, probability analysis is necessary to be conducted. In this study, the effect of updating of Indonesia seismic hazard maps to probabilistic slope stability is evaluated by presenting case study. At first, slope models are built and the seismic load are...
chosen based on Indonesia seismic hazard maps 2010 and 2017. Then, the probability of failure (Pf) obtained from simulation are compared.

2. Case Study

2.1. Slope Modeling

The geometry of slope models used in this study is shown in Figure 1. The slope models are 5 m high. To investigate the effect of slope angle ($\alpha$) to the probability of failure (Pf), the slope angle is varied i.e 30°, 40°, 50°, 60° and 70°. To simplify the number of samples, the mean unit weight ($\mu_{\gamma}$), mean cohesion ($\mu_c$) and mean friction angle ($\mu_\phi$) for each slope model were set into the same values of $\mu_{\gamma} = 17$ kN/m$^3$, $\mu_c = 7.2$ kPa and $\mu_\phi = 30^\circ$.

![Figure 1. Geometry of slope model](image)

2.2. Selection of Horizontal Seismic Coefficient

Pseudo-static analysis is one of the most simplest methods to analyze the seismic slope stability problems using limit equilibrium methods in which the inertia forces due to earthquake shaking are represented by a constant horizontal force (equal to the weight of the potential sliding mass multiplied by a coefficient. The inertial effect is specified as kh (horizontal seismic coefficient) and kv (vertical seismic coefficient). These coefficients can be considered as a percentage of g. For example, a kh coefficient of 0.4 means the horizontal pseudo-static acceleration is 0.4 g. The use of vertical seismic coefficient (kv) often has little impact on the factor of safety. Therefore, in this study, the kv is neglected.

The horizontal seismic coefficient (kh) was determined based on criteria in Indonesian national standard (abbreviated SNI) about requirement of geotechnical design (SNI 8460:2017). It was mentioned that kh should be taken as 0.5 of peak ground acceleration which have been adjusted with site class coefficient (PGA$_M$). The PGA$_M$ is determined based on SNI 1726:2012 about the procedures for seismic design of building and non-building structures, which can be calculated as follows:

$$PGA_M = F_{PGA} \times PGA$$  
(1)
which $F_{PGA}$ is site class coefficient and PGA is peak ground acceleration. The site class coefficients for different PGA values are shown in Table 1. In this study, the soil property of slope models were assumed to be SD (intermediate soils).

**Table 1. Comparison of horizontal seismic coefficient**

| Site Class | PGA ≤ 0.1 | PGA = 0.2 | PGA = 0.3 | PGA = 0.4 | PGA ≥ 0.5 |
|------------|------------|------------|------------|------------|------------|
| SA         | 0.8        | 0.8        | 0.8        | 0.8        | 0.8        |
| SB         | 1.0        | 1.0        | 1.0        | 1.0        | 1.0        |
| SC         | 1.2        | 1.2        | 1.1        | 1.0        | 1.0        |
| SD         | 1.6        | 1.4        | 1.2        | 1.1        | 1.0        |
| SE         | 2.5        | 1.7        | 1.2        | 0.9        | 0.9        |
| SF         | See section 6.9 in SNI 1726:2012 |

The PGA was determined using peak ground acceleration map in bedrock (SB) for probability exceeded 2% in 50 years from Indonesia seismic hazard maps. In this study, the slope models were assumed to located at Bojonegoro regency. The comparison of PGA values from Indonesia seismic hazard maps 2010 and 2017 for Bojonegoro regency is shown in Figure 3. It is clearly shown that the PGA values for this area have been increased from 0.3-0.4 g to 0.4-0.5 g. To consider the worst case, the highest values of PGA were chosen. Then the calculated horizontal seismic coefficients are presented in Table 2.

![Figure 2. Comparison of PGA from Indonesia seismic hazard maps 2010 and 2017](image-url)
Table 2. Comparison of horizontal seismic coefficient

| Indonesia Seismic Hazard Maps | PGA   | F<sub>PGA</sub> | PGA<sub>M</sub> | kh  |
|-------------------------------|-------|----------------|--------------|-----|
| 2010                          | 0.4 g | 1.1            | 0.44 g       | 0.22|
| 2017                          | 0.5 g | 1.0            | 0.5 g        | 0.25|

2.3. Probabilistic Slope Stability Analysis Method

In this study, the geotechnical engineering software so called Rocsience Slide 6.0 was utilized to perform probabilistic slope stability analysis. The analysis begins by enabling probability analysis mode and to input the number of samples for the Monte Carlo simulation of 4500. The mean factor of safety (FS<sub>mean</sub>) was determined using the simplified Bishop method. Furthermore, the geometry of the slope model was made and the soil properties of the mean unit weight (μ<sub>γ</sub>), mean cohesion (μ<sub>c</sub>) and mean friction angle (μ<sub>φ</sub>) were assigned. Moreover, the statistical parameters for cohesion and friction angle were inputted in the form of the mean and standard deviation values so the desired coefficient of variation (COV) values would be obtained. Both parameters were modeled with a log-normal distribution. For relative minimum and maximum values were adjusted to the determined COV so that the analysis results would be at the same level of confidence of 90%. The search method chosen for this analysis was auto refine search. Subsequently, the slope model could be analyzed to determine the probability of failure (Pf) for COV<sub>c</sub> = COV<sub>φ</sub> = 0.1 and the probability of failure (Pf) for COV<sub>c</sub> = 0.5, COV<sub>φ</sub> = 0.2. Those COV values were chosen based on the suggestion of Javankhoshdel dan Bathurst.

3. Results and Discussion

The result of probabilistic slope stability analysis for slope model with α = 50°, COV<sub>c</sub> = 0.5, COV<sub>φ</sub> = 0.2 and kh = 0.22 is shown in Figure 3. The probability of failure (Pf) for this slope model is obtained as 59.489% with mean factor of safety (FS<sub>mean</sub>) equals to 0.967.

![Figure 3](image-url)
Figure 4 shows the result of probabilistic slope stability analysis for slope model with $\alpha = 50^\circ$, $\text{COV}_c = 0.5$, $\text{COV}_\phi = 0.2$ and $kh = 0.25$. It is clearly presented that the probability of failure ($P_f$) for this slope model is obtained as 66.156% with mean factor of safety ($FS_{\text{mean}}$) equals to 0.930. The value of probability of failure ($P_f$) increases up to 6.667% compared with the same case which analyzed using horizontal seismic coefficient ($kh$) obtained from Indonesia seismic hazard maps 2010 ($kh = 0.22$) as shown in Figure 3. This result indicates that the slope model becomes more prone to failure.

Figure 4. Result of probability slope stability analysis for slope model with $\alpha = 50^\circ$, $\text{COV}_c = 0.5$, $\text{COV}_\phi = 0.2$ and $kh = 0.25$

Figure 5 and Figure 6 present the comparison of probability of failure ($P_f$) for all slope models with $\text{COV}_c = \text{COV}_\phi = 0.1$ and $\text{COV}_c = 0.5$, $\text{COV}_\phi = 0.2$, respectively. In general, probability of failure ($P_f$) increases as the increasing of slope angle ($\alpha$). The increasing of the value of horizontal seismic coefficient ($kh$) from $kh = 0.22$ to 0.25 due to updating of Indonesia seismic hazard maps causing varied increasing of probability of failure ($P_f$) for all slope models. The most significant increasing of $P_f$ is shown in slope model with $\alpha = 50^\circ$, $\text{COV}_c = \text{COV}_\phi = 0.1$ which increases up to 21.422%.

Figure 5. Probability of failure ($P_f$) for $\text{COV}_c = \text{COV}_\phi = 0.1$
Figure 6. Probability of failure (Pf) for $COV_c = 0.5$, $COV_\phi = 0.2$

4. Conclusion

In this study, the effect of updating of Indonesia seismic hazard maps to the probabilistic slope stability is assessed by comparing the probability of failure (Pf) of slope models using LEM based software so called Rocscience Slide 6.0. In general, the results of simulation indicate that the updating of Indonesia seismic hazard maps causing increasing of probability of failure (Pf) for all slope models which exhibits that the slope models become more prone to failure. To overcome this problem, the use of slope reinforcement is suggested so that it becomes more stable.

5. References

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