 Void ratio effect on dynamic shear modulus and shear wave velocity for soil stiffness in Banda Aceh and Aceh Besar

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Abstract. Aceh located in earthquake disaster-prone area because it is located between two tectonic plates and also surrounded by several active volcanos. When earthquakes shake, the building frequency (f) should not be equal to the natural soil frequency (f_n) as it may cause the collapse of buildings. The purpose of this study is to determine dynamic seismic parameters value on the surface layers for forthcoming disaster mitigation. The object study for this research were Rahmatullah Lampuuk Mosque, Sultan Iskandar Muda Airport, Lambaro Bridge in Aceh Besar, TDMRC building, and Taman Sari. Soil samplings from the locations and data obtained from the BMKG such as earthquake center map, coordinates, magnitude, and earthquake depths were used in the study. The result of this research was Gmax value based on Richart method. Kramer method was also used for computing the f_n parameters. Some static and dynamic calculation of design parameter result from Rahmatullah Lampuuk Mosque shows that with void ratio (e) = 0.92, the Gmax = 266 x 10^3 kg/m^2, Vs = 10.096 m/s and fn = 2.524 Hz. The comparison of f_n and f_structure = 2.50 Hz which not equal to zero make the building were safe from collapse during previous earthquakes in Aceh.

1. Introduction

Aceh-Indonesia, is one of the most active seismic activity in the world, particularly after several historical large earthquakes such as in the year of 2004 8.9Mw earthquake-tsunami. Latest Aceh large earthquake history was Pidie Jaya 6.4Mw earthquake on December 7th, 2016. The earthquake caused around 104 live loss and many construction failures and broken [1]. Natural disaster related to an earthquake is influenced by dynamic parameter change and soil bearing capacity. The effect of the earthquake, especially the earthquake wave, to the construction have to be measured for design purposes in order to avoid structural failure [2]. Earthquake damage can be caused by several factors [3] such as earthquake sources, in situ geotechnical characteristics, path characteristic, and also the construction structural design quality. The soil swelling behavior which should also be considered as explained by [4]. Additionally, soil layers stiffness are important parameters to be applied for dynamic soil-structure interaction analysis [5].

This article aim is to analyze several soil parameters effects to seismic-related soil parameter. In general, evaluation of soil response due to seismic and dynamic loads is related to dynamic shear modulus (Gmax) and shear wave velocity (Vs) as basic parameters [6]. The used of equations relation...
between $G_{\text{max}}$ values to fine content ($f_c$), void ratio ($e$) and plasticity index (PI) was based on equations from [7].

2. Literature Review

[8] describe guidelines and correlation between shear wave velocity ($V_s$) and some geotechnical engineering parameters for Norwegian Clays. The correlations are for soil index properties, cone penetration data, undrained shear strength, and 1D compression parameters. The result of this research explained that the empirical function of cone penetrometer data used was the best approximation of $V_s$ value if no existing in situ measurements unavailable.

The void ratio effect to $G_{\text{max}}$ value for coarse-grained soils was studied by [6]. Void ratio effect for $G_{\text{max}}$ value was confirmed by this research. However, several inconsistencies with the prediction value still presented. Thus, simple predictive equations used for practical geotechnical engineering design purposes can still be applied. Several related types of research regarding soil parameter correlation to a dynamic parameter of $G_{\text{max}}$ and $V_s$ were also conducted by [9], [10], [11], and [12]. In brief, dynamic soil parameters can be measured by both field and laboratory under real and engineering conditions.

[7], from series of resonant column experiments, found that the empirical relationship used for dynamic shear wave modulus ($G_{\text{max}}$) as site condition influence by natural site soil gradation which has $f_c$ (fine content). The equation for dynamic shear wave relationship to fine content ($f_c$), void ratio ($e$), plasticity index (PI), and soil gradation as equation (1) – (4).

1. Relationship between $G_{\text{max}}$ and fine content ($f_c$) can be presented in equation (1)

$$G_{\text{max}} = 0.0012f_c^3 - 0.1995f_c^2 + 8.4718f_c + 273.86 \quad (kPa)$$  

(1)

The equation (1) can be used for a vertical soil sample, or as vertical bedrock surface wave propagation through soil layers to surface.

2. Relationship between $G_{\text{max}}$ and void ratio ($e$) can be shown as equation (2) and (3)

$$G_{\text{max}} \text{ (vertical)} = 1067.3 \exp^{-1.51e} \quad (kPa)$$

(2)

$$G_{\text{max}} \text{ (horizontal)} = 811.9 \exp^{-1.11e} \quad (kPa)$$

(3)

3. Relationship between $G_{\text{max}}$ and plasticity index (PI) as in equation (4)

$$G_{\text{max}} = -0.04PI^2 + 2.7PI + 289.81 \quad (kPa)$$

(4)

Moreover, [13] present equations to examine natural soil vibration frequency ($f_n$) based on equation (5)-(7). Soil unit weight ($\rho$) is in kg/m$^3$, $\omega_0$ ($H_0$) as fundamental frequency, $V_s$ as shear wave velocity (m/s), and $H$ (m) is soil sample depth.

$$f_n = \frac{\omega_0}{2\pi}$$

(5)

$$\omega_0 = \frac{\pi NV_s}{2H}$$

(6)

$$V_s = \sqrt{\frac{G_{\text{max}}}{\rho}}$$

(7)

According to the Indonesia standard procedure of SNI 1726-2012 [14], structural vibration frequency ($f$) was calculated by equation (8) and (9). $T_s$ (s) is a fundamental period, and $N$ is a number of the multi-storey building for below 12 levels of the building. The value of $f_n$ should not similar to $f$ to avoid resonance that can cause construction failure. Resonance ratio of the building ($R$) which was used to identify construction resonance level then examined from equation (10) where $f_b$ ($H_b$) is building frequency and $f_t$ ($H_t$) is soil natural frequency.

$$f = \frac{\omega_0}{2\pi}$$

(8)

$$f = \frac{\pi NV_s}{2H}$$

(9)

$$R = \left(\frac{f_b}{f_t}\right)$$

(10)
\[
f = \frac{1}{t}
\]

(8)

\[
T_a = 0.1 \text{ N}
\]

(9)

\[
R = \frac{f_{b-a}}{f_t} \times 100\%
\]

(10)

3. Research Methodology

Several experimental works were performed in Soil Mechanic Laboratory of Syiah Kuala University, Banda Aceh - Indonesia. The soil samples study location for this article were Rahmatullah Mosque, Taman Sari, TDMRC Building, Lambaro Bridge, and Sultan Iskandar Muda Airport. Several disturbed and undisturbed soil samples and site coordinates were taken from the study area.

The laboratory test performed namely soil unit weight test, water content, Atterberg limit test, grain size analysis, and void ratio. All the test performed were according to American Standard Testing Method (ASTM). The result from the laboratory then analyzes for every parameter relationship based on equation (1) – (10).

4. Results and Discussion

Table 1 shows the soil parameter result for Banda Aceh and the surrounding area. As can be seen, several soil samples were collected from five research locations. The highest value of void ratio was from Sultan Iskandar Muda Airport which is 1.25. Moreover, the peak dynamic shear modulus and shear wave velocity were both from Rahmatullah Mosque.

| No | Location                        | e   | \(G_{\text{max}}\) (kg/m\(^2\)) | \(\rho\) (kg/m\(^3\)) | \(v_s\) (m/s) | \(f_{\text{th}}\) (Hz) | \(f_n\) (Hz) |
|----|---------------------------------|-----|---------------------------------|-----------------|-------------|----------------|-------------|
| 1  | Rahmatullah Mosque              | 0.92| 266,050.83                      | 2.610           | 10.096      | 15.851       | 2.524       |
| 2  | Taman Sari                      | 1.00| 235,777.22                      | 2.670           | 9.226       | 14.385       | 2.306       |
| 3  | TDMRC Building                  | 0.98| 243,006.30                      | 2.670           | 9.540       | 14.978       | 2.385       |
| 4  | Lambaro Bridge                  | 1.22| 169,133.34                      | 2.650           | 7.989       | 12.543       | 1.997       |
| 5  | Sultan Iskandar Muda Airport    | 1.25| 161,642.54                      | 2.590           | 7.900       | 12.403       | 1.975       |
|    | Average                         | 1.07| 215,122.00                      | 2.658           | 8.950       | 14.052       | 2.238       |

Table 1. Soil Parameters Results for Banda Aceh and Surrounded Area

![Figure 1. Dynamic shear modulus (G\(_{\text{max}}\)) and void ratio (e) relationship around Banda Aceh](image-url)
Void ratio of soil, in general, produces a strong influence to the dynamic shear modulus from the earthquake. The void ratio of soil is a comparison between saturated or unsaturated soil void volume and soil solid volume. Based on equation (2) and (3), the relationship between dynamic shear modulus ($G_{\text{max}}$) and void ratio ($e$) around Banda Aceh can be seen in figure 1.

![Figure 2. Shear wave velocity ($V_s$) and void ratio ($e$) relationship around Banda Aceh](image)

Furthermore, based on figure 2 of shear wave velocity ($V_s$) and void ratio ($e$) relationship around Banda Aceh, it can be concluded that higher value of void ratio can generate lower shear wave velocity of research location.

![Figure 3. Natural frequency ($f_n$) and void ratio ($e$) relationship around Banda Aceh](image)

In addition, based on figure 3, it can be explained that the relationship between lower natural frequency is may because of the higher void ratio of the site soil. Open space of soil void may reduce the vibration from the earthquake load, as a result, the natural frequency of soil may even be lost to zero.

5. **Conclusion**

The scope of this study was the calculation of earthquake geotechnical parameter such as vertical dynamic shear modulus ($G_{\text{max}}$). For the accuracy of this study, several recorded earthquake parameter and soil laboratory tests were conducted. Based on the soil sample taken and equation (1) to (10), larger void ratio parameter may reduce the value of dynamic shear modulus and shear wave velocity of soil. Moreover, the larger void within soil particle may also reduce the natural frequency of soil due to earthquake load.
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