Potential study of the liquefaction hazard at the reclamation development site of I Gusti Ngurah Rai airport, Nusa Dua region, province of Bali

Heri Suprijanto¹, Andre Primantyo Hendrawan¹, Antonius Wayan Bayu Nugraha²

¹ Water Resources Engineering Department, Faculty of Engineering, Universitas Brawijaya, Malang 65145, Indonesia
² Graduate of Water Resources Engineering, Universitas Brawijaya, Malang 65145, Indonesia

E-mail: heri_swt_25659@yahoo.co.id

Abstract. I Gusti Ngurah Rai Airport is an international airport in the Province of Bali with high traffic. The government of the province encouraged the airport services company to increase the airport’s capacity by expanding the aircraft apron. To initiate this project, land reclamation had been carried out on the west side of the existing apron. However, a sea wall was used for protecting the reclamation area from attack by waves. This case study of the reclamation area is intended to investigate its geotechnical aspect, in which the potential of liquefaction is necessary to be evaluated. The liquefaction is quantified by referring to CPT (cone penetration test) and SPT (standard penetration test) data. Analysis results of the reclamation area at location 1 (CPT testing) and location 2 (SPT testing) showed occurrences of the liquefaction hazard, where the FS (safety factor) was found to be less than 1. This means that soil improvements, such as utilizing a vibro-compaction method, are required. The steps of the vibration method are considered as the simplest method, particularly for compaction of sand material in the reclamation area. The criteria evaluation standard for the compaction is Dₛ (relative density) of greater than or equal to 70%.

Keywords: liquefaction, CPT, SPT, relative density

1. Introduction

Bali had been claimed as one of the top tourist destinations in the world by the Trip Advisor Travellers’ Choice Awards in 2017. This will certainly affect tourist growth, both local and international. As well, in October 2018, Bali had been selected as the host for the 2018 International Monetary Fund (IMF)-World Bank Annual Meeting. Thus, the flight traffic at I Gusti Ngurah Rai airport was estimated to significantly increase within the year. To anticipate crowds at the airport, an expansion of the west side apron as well as the airside area (land services) was conducted by performing coastal land reclamation.

According to Indonesian law, Law No. 27 of Year 2007, coastal reclamation is an activity in coastal areas that is performed by people in charge to exploit land resources for environmental, social, and economic purposes by carrying out area embankment or land drainage. In this case, the reclamation was carried out with area embankment by performing sand nourishment.
For the activities carried out on a land area of 48 Ha, coastal construction is required to protect land reclamation. The land has dimensions of 900 m x 525 m. A seawall construction has been planned as a divider between land and ocean; a breakwater holds back wave overflow towards the land behind the seawall and maintains aesthetics.

In addition, a potential geotechnical problem was detected, in that soil liquefaction may occur on the reclaimed land; soil improvements need to be implemented to prevent soil liquefaction when an earthquake occurs. The analysis is based on in-situ testing using CPT and SPT resistance for the evaluation of liquefaction potential [1].

2. Material And Methods

2.1. Study Location

The reclamation area in I Gusti Ngurah Rai airport development for this case study is depicted below:

![Site Plan of Reclamation Area 48 Ha](image)

**Figure 1.** Site area study

The main point of discussion in this paper focuses on the liquefaction hazard potential and solutions for soil improvement. During preliminary planning, the seawall structure design for protection of the reclamation area used and referenced the shore protection manual (see Figure 2).
2.2 Liquefaction Process
When earthquakes occur, the shaking in the ground may cause a loss of strength or stiffness that would result in the settlement of buildings, landslides, failure of earth dams or reclamation area embankments, or other hazards. The process that leads to such loss of strength or stiffness is called soil liquefaction. Earthquake conditions cause liquefaction, especially on saturated sandy soil layers. Then, the ultimate bearing capacity must be corrected. Commonly, the following conditions are applied:
- Soil layer depth < 20 m soil surface
- Groundwater surface depth < 10 m
- Soil gradation D$_{50}$ range value 0.02 mm – 2.0 mm

2.3 Liquefaction Potential Analysis
Based on investigation data of soil mechanics, analysis of the reclamation area in I Gusti Ngurah Rai airport development comprised grain size distribution analysis, cone penetration test, and standard penetration test. The liquefication hazard potential calculation was based on the three following methods:

a. Grain Size Gradation Method
Results of grain size distribution analysis were used to identify the uniformity of the material. The liquefaction hazard was analysed based on uniformity coefficient Cu < 3.5 or Cu > 3.5, with saturated material and earthquake condition. The simple method to estimate liquefaction is by using a grain size gradation graph and the uniformity coefficient.

b. Cone Penetration Test (CPT)-Based Liquefaction Triggering
The stress-based approach for evaluating the potential for liquefaction triggering, initiated by Seed and Idriss (1967), compares the earthquake-induced cyclic stress ratio (CSR) with the cyclic resistance ratio (CRR) of the soil [2]. The CRR of the soil is usually correlated to an in-situ parameter such as CPT penetration resistance.

\[
CSR = 0.65 \frac{\sigma_v}{\sigma'_v} \cdot \frac{a_{\text{max}}}{g} \cdot r_d
\]

Where:
- $\sigma_v$ = vertical total stress at depth Z
- $\sigma'_v$ = vertical effective stress at depth Z
- $a_{\text{max}}/g$ = maximum horizontal acceleration (as a fraction of gravity) at the ground surface
- $r_d$ = shear stress reduction factor

CPT penetration resistance is corrected for overburden stress effects by:

\[
q_{c1} = C_N \cdot q_c = C_N \cdot q_c
\]

Where:
- $q_{c1}$ = corrected penetration resistance (kg/cm$^2$)
- $q_c$ = penetration resistance (kg/cm$^2$)
- $C_N$ = overburden correction factor (Figure 4)
For $\text{Cu} < 3.5$

(b) For $\text{Cu} > 3.5$

Figure 3. Soil grain size distribution curve for liquefaction susceptibility

Figure 4. Graph of soil effective stress in relation to $C_N$
Robertson and Wride (1998) suggested the following:

- For $q_{c1} < 50$, then $CRR_{7.5} = 0.833 \frac{q_{c1}}{1000} + 0.05$
- For $q_{c1} > 50$, then $CRR_{7.5} = 93 \left(\frac{q_{c1}}{1000}\right)^3 + 0.08$

Figure 5. Relationship of $q_c$ and CSR for liquefaction potential

Figure 6. Relationship of $q_c$ and depth for liquefaction potential

Safety factor (FSL) for the liquefaction hazard in relation to CSR and CRR is shown below:

$$FSL = \frac{CSR}{CRR} \cdot MFS$$  \hfill (3)

Where:
- FSL = safety factor of liquefaction
CSR = cyclic stress ratios
CRR = cyclic resistance ratios
MFS = magnitude scaling factor, $M_w = 7.5$

$$MSF = \left(\frac{M_w}{7.5}\right)^{-2.56} \quad (4)$$

Liquefaction potential, when $FSL \leq 1$

### a. Standard Penetration Test (SPT)-Based Liquefaction Triggering

The analysis of potential liquefaction for a sandy soil layer, using equations related to the number of blows with the standard penetration test, is detailed below:

$$F_p = \frac{R_p}{L} \quad (6)$$

$$R_f = 0.0882 \left(\frac{N_{SPT}}{\sigma_v + 0.7}\right)^{0.5} \quad (7)$$

$$R_p = R_f + 0.19; \quad 0.02 \text{ mm} < D_{50} < 0.05 \text{ mm} \quad (8)$$

$$R_p = R_f + 0.225 \log_{10} \left(\frac{0.35}{D_{50}}\right); \quad 0.05 \text{ mm} < D_{50} < 0.60 \text{ mm} \quad (9)$$

$$R_p = R_f - 0.05; \quad 0.60 \text{ mm} < d_{50} < 2.00 \text{ mm} \quad (10)$$

$$L = r_d \cdot K_h \left(\frac{\sigma'_v}{\sigma_v}\right) \quad (11)$$

$$r_d = 1.0 - 0.015 Z \quad (12)$$

Where:

- $F_p$ = safety factor for the liquefaction hazard; when $F_p < 1$, liquefaction process will occur
- $R_p$ = dynamic load, retained soil strength element
- $L$ = dynamic load, earthquake impact
- $Z$ = depth of soil layer from original soil surface (m)
- $K_h$ = earthquake coefficient
- $\sigma'_v$ = undrained vertical stress (kg/cm²)
- $\sigma_v$ = effective vertical stress (kg/cm²)
- $N_{SPT}$ = number of blows of the standard penetration test

### 2.4 Soil Improvement Method

An effort to avoid a potential liquefaction hazard in a reclamation area is the implementation of soil improvements. This can be achieved by performing the following activities [3]:

1. Increasing bearing capacity and shear strength
2. Increasing soil modulus
3. Decreasing compressibility and soil settlement
4. Decreasing soil swelling potential
5. Decreasing liquefaction hazard susceptibility

The following are various methods for soil improvement:

1. Chemical methods, such as usage of cement, carbonate, and so on
2. Physical methods such as compaction, consolidation, dewatering, replacement, and so on
Technical Vibro-Compaction (Vibroflotation) is one of the soil improvement methods that uses compaction and is suitable for granular soil with coarse-grained classification such as sand (fine content < 20%) and silt < 3% [4]. The compactability limit criteria of soil are illustrated in Figure 7.

![Figure 7. Compactability limits](image)

3. Results And Discussion

3.1. Gradation analysis

The results of grain size gradation testing of existing soil in the reclamation area site plan are shown below:

Particle size percent fineness:
- $D_{60} = 0.70 \text{ mm}$ and $D_{10} = 0.27 \text{ mm}$, then $C_u = 0.70/0.27 = 2.59$
- $D_{50} = 0.60 \text{ mm}$

The above results of the particle sizes and uniformity coefficient was plotted on the grain size gradation graph. This then indicated a liquefiable zone.

3.2. Calculation of Liquefaction Potential

Based on CPT and SPT data, a liquefaction potential was identified. The calculation results were used to find the liquefaction potential for the reclamation area (as detailed in Table 1, Table 2, and Figure 8).

![Table 1. Liquefaction analysis results for the CPT-S12 location (100-year return period)](image)

Note: L = Liquefiable; N = No Liquefaction
### Table 2. Liquefaction analysis results for the BH-06 location (100-year return period)

| Depth (m) | Soil Type | Nppt | $\gamma$ | $\alpha$ | $\frac{\phi_{2}}{\gamma}$ | $\frac{\phi_{3}}{\gamma}$ | D50 | N1 | R1 | Rp | Kh | L | Fp | Remark |
|-----------|-----------|------|-----------|---------|----------------|----------------|------|----|----|----|----|---|----|--------|
| 1         | Sand      | 12   | 1.682     | 0.316   | 0.985         | 1.682         | 0.682 | 0.6 | 13.5 | 0.276 | 0.226 | 0.316 | 0.126 | 1.788 | N   |
| 2         | Sand      | 10   | 1.682     | 0.316   | 0.97         | 3.364         | 1.364 | 0.6 | 12.5 | 0.217 | 0.167 | 0.316 | 0.124 | 1.344 | N   |
| 3         | Sand      | 13   | 1.682     | 0.316   | 0.955         | 5.046         | 2.046 | 0.6 | 14   | 0.199 | 0.149 | 0.316 | 0.122 | 1.219 | N   |
| 4         | Sand      | 8    | 1.631     | 0.316   | 0.94         | 6.524         | 2.524 | 0.6 | 11.5 | 0.167 | 0.117 | 0.316 | 0.115 | 1.014 | N   |
| 5         | Sand      | 8    | 1.631     | 0.316   | 0.925         | 8.155         | 3.155 | 0.6 | 11.5 | 0.152 | 0.102 | 0.316 | 0.113 | 0.905 | L    |
| 6         | Sand      | 6    | 1.631     | 0.316   | 0.91         | 9.786         | 3.786 | 0.6 | 10.5 | 0.135 | 0.085 | 0.316 | 0.111 | 0.763 | L    |
| 7         | Sand      | 18   | 1.733     | 0.316   | 0.895        | 12.130        | 5.130 | 0.6 | 16.5 | 0.148 | 0.098 | 0.316 | 0.120 | 0.822 | L    |
| 8         | Sand      | 20   | 1.784     | 0.316   | 0.88         | 14.271        | 6.271 | 0.6 | 17.5 | 0.160 | 0.090 | 0.316 | 0.122 | 0.734 | L    |
| 9         | Sand      | 3    | 1.631     | 0.316   | 0.865        | 14.679        | 5.679 | 0.6 | 9    | 0.105 | 0.055 | 0.316 | 0.106 | 0.518 | L    |
| 10        | Sand      | 4    | 1.631     | 0.316   | 0.85         | 16.310        | 6.310 | 0.6 | 9.5  | 0.103 | 0.053 | 0.316 | 0.104 | 0.507 | L    |
| 11        | Sand      | 4    | 1.631     | 0.316   | 0.835        | 17.941        | 6.941 | 0.6 | 9.5  | 0.098 | 0.048 | 0.316 | 0.102 | 0.474 | L    |
| 12        | Sand      | 28   | 1.784     | 0.316   | 0.82         | 21.407        | 9.407 | 0.6 | 21.5 | 0.129 | 0.079 | 0.316 | 0.114 | 0.691 | L    |
| 13        | Sand      | 28   | 1.784     | 0.316   | 0.805        | 23.191        | 10.191 | 0.6 | 21.5 | 0.124 | 0.074 | 0.316 | 0.112 | 0.661 | L    |
| 14        | Sand      | 13   | 1.682     | 0.316   | 0.79         | 23.547        | 9.547 | 0.6 | 14   | 0.103 | 0.053 | 0.316 | 0.101 | 0.525 | L    |
| 15        | Sand      | 13   | 1.682     | 0.316   | 0.775        | 25.229        | 10.229 | 0.6 | 14   | 0.100 | 0.050 | 0.316 | 0.099 | 0.502 | L    |
| 16        | Sand      | 13   | 1.682     | 0.316   | 0.76         | 26.911        | 10.911 | 0.6 | 14   | 0.097 | 0.047 | 0.316 | 0.097 | 0.481 | L    |
| 17        | Sand      | 13   | 1.682     | 0.316   | 0.745        | 28.593        | 11.593 | 0.6 | 14   | 0.094 | 0.044 | 0.316 | 0.095 | 0.462 | L    |
| 18        | Sand      | 13   | 1.682     | 0.316   | 0.73         | 30.275        | 12.275 | 0.6 | 14   | 0.092 | 0.042 | 0.316 | 0.094 | 0.445 | L    |
| 19        | Sand      | 13   | 1.682     | 0.316   | 0.715        | 31.957        | 12.957 | 0.6 | 14   | 0.089 | 0.039 | 0.316 | 0.092 | 0.429 | L    |
| 20        | Sand      | 13   | 1.682     | 0.316   | 0.70         | 33.639        | 13.639 | 0.6 | 14   | 0.087 | 0.037 | 0.316 | 0.090 | 0.414 | L    |

Note: L = Liquefaction; N = No Liquefaction

#### 3.3 Soil Improvement Recommendations

According to the finding during liquefaction analysis, soil improvement is suggested to use the vibro-compaction or vibroflotation method. Vibro-compaction for soil improvement has the aim of increasing compaction and soil strength. A simple technical solution is by providing probe equipment for compacting and filling material embankments without using another source.
The final recommendation of soil improvement is to achieve the post-compaction soil parameter target. The major parameter reference is relative density ($D_r > 70\%$) (unliquefiable). The post-compaction soil parameter target can be seen in the following table:

Table 3. Post-compaction target

| Depth (m) | $D_r$  | $N_{SPT}$ | $q_c$ (kg/cm²) |
|-----------|--------|-----------|----------------|
| 2         | >70 %  | 20        | 70             |
| 4         | >70 %  | 23        | 100            |
| 6         | >70 %  | 26        | 130            |
| 8         | >70 %  | 29        | 150            |
| 10        | >70 %  | 31        | 160            |

4. Conclusion
1. The first construction of seawall structure for protection of the reclamation area consists of three designed height dimensions of 7.25, 7.50, and 7.75 m.
2. Based on the results of the drilling cone penetration test and standard penetration test, the analysis of the liquefaction hazard for an earthquake with a 100-year return period and a magnitude of 7.5 shows that the reclamation area is susceptible to a liquefaction hazard. The liquefaction potential is up to 10.00 m – 20.00 m in depth.
3. The vibroflotation method for compaction must be tested in the field to achieve a compaction desirable target $D_r > 70\%$ in order to reduce the liquefaction hazard potential. As well, after compaction, the CPT and SPT should be repeated afterwards to find whether or not the target has been met.

Acknowledgments
Special thanks are given to PT. Pembangunan Perumahan in Bali for the help in collecting data and thus completing this article.
References

[1] Robertson PK, Woeller DJ And Finn WDL, (2016), Seismic Cone Penetration Testing for Evaluating Liquefaction Potential, Canadian Geotechnical Journal.

[2] Idriss, M dan Boulanger. (2008). Soil Liquefaction During Earthquakes. USA: EERI.

[3] Darwis (2017). Basic Technical of Soil Improvement. Yogyakarta: Imprint Penerbit YLJK2 Indonesia.

[4] Jie Han, (2015), Principles and Practice of Ground Improvement, John Wiley & Sons, Inc., Hoboken, New Jersey.