The Analysis of Liquefaction Potential Based on A Comparation of Various Cyclic Resistance Ratio

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Abstract- Prambanan Temple located in the Special Region of Yogyakarta is one of the most beautiful temples in the world. One of the potential geo hazards in the region of Prambanan is the earthquake. Geotechnically, the condition of the soil layer in Prambanan Temple consists of fine and uniform sand. Therefore, there is a possibility of liquefaction, if it receives the earthquake load. This study was aimed to investigate the condition of the subgrade of the Prambanan Temple foundation against the potential of liquefaction. Analysis of liquefaction potential in Regions Prambanan was conducted using semi-empirical method which were the *cyclic stress ratio* and *cyclic resistance ratio* with data from the field test results, *Standard Penetration Test.* The calculation of the value of *peak ground acceleration* was conducted using various empirical formula. The parameters of the liquefaction threat were based on *Liquefaction Potential Index, Liquefaction Risk Index* and *Liquefaction Severity Index.* The analysis showed that the *peak ground acceleration* value based on the 2006 Yogyakarta earthquake with a magnitude of 6.3 was 0,216g. Based on the condition of existing Prambanan temple with ground water level at -12 meters depth was safe against liquefaction threat. In case of an earthquake with greater strength than the 2006 Yogyakarta earthquake, with a PGA of 0.3 to 0.4g and shallow water level (-1 meters), then liquefaction might potentially occur.

Keywords: *Liquefaction, Cyclic Stress Ratio, Cyclic Resistance Ratio, Peak Ground Acceleration, Prambanan Temple*

1. Introduction

On Saturday 27th of May 2006, *Yogyakarta* and parts of Klaten region were shaken by tectonic earthquakes, with a magnitude of 6.3 SR. The earthquake that occurred not only destroyed the aspects of the life on Yogyakarta city, but also the buildings on the area, including the historical buildings, one of which was the Prambanan Temple because geologically Prambanan Temple is located the active fault that stretches from Prambanan, Piyungan, Pleret, Imogiri and Pundong. This fault is often called Opak fault. The faults are re-activated as triggered by the earthquake activity that occurs [1].

An earthquake is a natural disaster that can damage the structure of the land through which it passes. One of the damage to the earth structure caused by earthquakes is liquefaction. In general, the phenomenon of liquefaction occurs in a water-saturated granular soil layer, with the relatively low density and accepting cyclic loads caused by the earthquake. The vibration of the earthquake results in soil particles to contract and takes place so quickly in undrained conditions, it can trigger a rise in pore water pressure on the ground. When the pore water pressure value reaches as large as the total ground stress, the soil effective stress is zero and that is when the soil decreases the shear strength and collapses.

To know the condition of subgrade of Prambanan Temple foundation, it had to be tested for the liquefaction potential. The semi-empirical method was used to estimate liquefaction potential. Semi-empirical method is the ratio between the two variables namely seismic force in the soil layer called the *cyclic stress ratio* and capacity of the soil in resisting liquefaction called *the cyclic resistance ratio* [2]. Referring to the phenomenon of liquefaction, it is important to analyze the potential of liquefaction in Prambanan temple, whether the condition of the subgrade of Prambanan Temple foundation has the potential to experience liquefaction using semi empirical method. A study by Rahmi [3] carried out using *Cyclic Triaxial* argued that on the subgrade of Shiva temple, the land did not collapse due to liquefaction. For a_{max} = 0.2 g; the subgrade at Shiva temple showed a relatively small increase in deformation, whereas, the surface soil underwent great deformation due to its looser density.

The safety factor analysis of this liquefaction used a comparison of CSR and CRR values. According to Rauch [4], if the SF value > 1, then the area does not have a soil layer with potential liquefaction. On the other hand, if SF $\leq$ 1, then the area has liquefaction threats. Sonmez and Gokceoglu [5] argue that SF = 1.2 is the boundary between the liquefied and the non - liquefied zone. Condition of ground water level in Prambanan Temple area was at -12 m depth from ground level in Plataran Prambanan Temple.

2. Methodology

2.1 Liquefaction Analysis with Empirical Semi Method

Youd, et al. [2] along with researchers around the world developed a guide for determining liquefaction potential in an area using semi-empirical method. It is the result of a compilation of all recorded earthquake data worldwide causing liquefaction characterized by the breakdown of sand holes to the overturned buildings. The data from one of the following field test results: *Standard Penetration Test* (SPT), *Cone Penetration Test* (CPT) or *Vane Shear Test* (Vs) were used to conduct the analysis with semi-empirical method. The determination of liquefaction potential could be conducted using the graph of the relationship of one of the above field tests with the cyclical soil ratio.

2.2 Peak Ground Acceleration

The calculation of the acceleration of ground vibration value was achieved by using various empirical formulas (attenuation function) as follows.

a. Donovan [6]

$$a = 1080\frac{(e^{0,5M})}{(R+25)^{1,32}}$$

b. Mc. Guirre [6]

$$a = \frac{472,38 \cdot 10^{0,278M}}{(R+25)^{1,301}}$$

c. Esteva [6]

$$a = c_1 e^{c_2 M}(R + c_3)^{-c_4}$$

d. Kanai [6]

$$a = \frac{5}{\sqrt{T_0}} 10^{0{,}61M - \left(1{,}66 + \frac{3{,}6}{R}\right)\log R + \left(0{,}67 - \frac{1{,}83}{R}\right)}$$

e. Matuscha [7]

$$a = 119 \cdot e^{0{,}81M} \cdot (R + 25)^{-1{,}15}$$

2.3 Cyclic Stress Ratio Evaluation (CSR)

The calculation of Cyclic Stress Ration value was performed using various empirical formulas as follows.

a. *Simplified Procedure* [8]

$$CSR = 0{,}65 \left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_v}{\sigma'_v}\right) r_d$$

b. Tokimatsu & Yoshimi Method [9]

$$CSR = 0{,}1(M-1)\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_v}{\sigma'_v}\right)(1 - 0{,}015z)$$

c. Idriss & Boulanger's Method [10]

$$CSR_{7,5} = 0{,}65\left(\frac{\sigma_v \cdot a_{max}}{\sigma'_v}\right)\left(\frac{r_d}{MSF}\right)$$

2.4 Cyclic Resistance Ratio (CRR) Evaluation

The method used in the analysis of this research was as follows.

a. A. F. Rauch [4]

$$CRR_{7,5} = \frac{1}{34 - (N_1)_{60}} + \frac{(N_1)_{60}}{135} + \frac{50}{[10 \cdot (N_1)_{60} + 45]^2} - \frac{1}{200}$$

b. Tokimatsu and Yoshimi Method [9]

$$CRR = a \cdot C_r \left[\frac{16\sqrt{N_a}}{100} + \left(\frac{16\sqrt{N_a}}{C_a}\right)^n\right]$$

2.5 Safety Factors

The ratio of CRR and CSR values could be interpreted as a safety factor in areas with liquefaction threats.

$$FS = \frac{CRR}{CSR}$$

According to Rauch [4], if the SF value > 1, then the area does not have a soil layer with potential liquefaction. On the other hand, if FS ≤ 1, then the area has liquefaction threats. Sonmez and Gokceoglu [5] argue that SF = 1.2 is the boundary between the liquefied and the non - liquefied zone.

2.6 Liquefaction Potential

In this study, three methods, namely *Liquefaction Potential Index* (LPI), *Liquefaction Risk Index* (LRI) and *Liquefaction Severity Index* (LSI), were used to determine the occurrence of liquefaction potential

a. Methods of *Liquefaction Potential Index* (LPI)

$$LPI = \int_0^{20\,m} Fw(z)dz$$

b. Methods *Liquefaction Risk Index* (LRI)

$$LRI = \int_{0}^{20\ m} P_L W(z) dz$$

c. *Liquefaction* method *Severity Index* (LSI)

$$LSI = \int_{0}^{20\ m} P_L(z) W(z) dz$$

3. Discussion

3.1 Field Investigation

In this study, the soil investigation data were used for the analysis of liquefaction potential. The soil investigation resulted in soil conditions, ground water surface (MAT) and the *Standard Penetration Test* value (SPT). The results of geotechnical test (the result of drilling and *Standard Penetration Test* (SPT) were as follows.

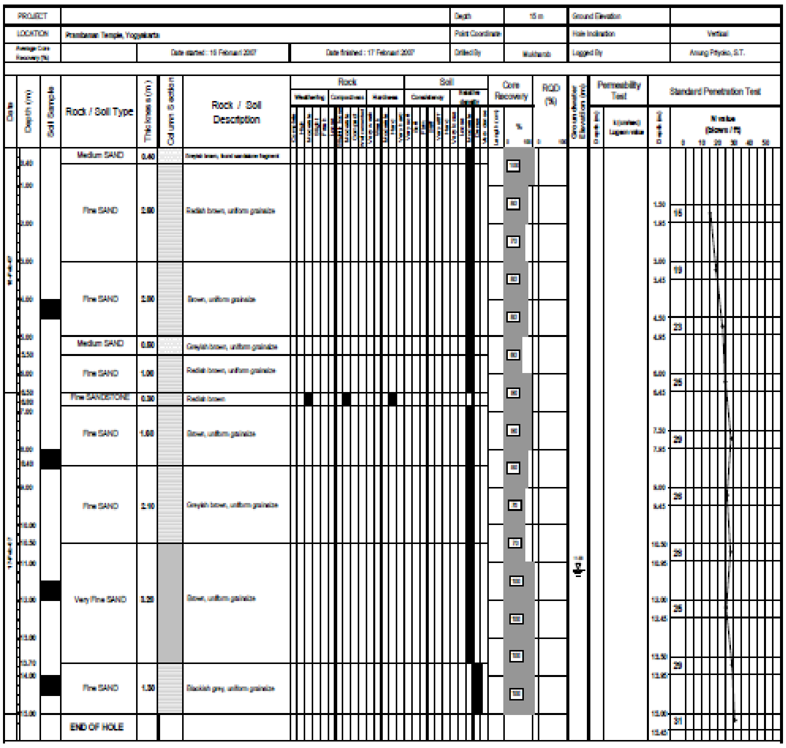


Figure 1 Drill Test Results [1]

Prambanan Temple building complex was located on a basin which then filled with earth. This result was supported by the drill and geo-electric test results. The location of the original ground surface varied. However, it can be concluded that the original ground surface was generally sloping from northwest to southeast. At the north-west, the depth of the original soil surface was -5.00 m, while at the southeast, the depth of the original soil was approximately -8.00 to -16.00 m, while at the location of Shiva temple, the depth of the original soil surface was at -14.00 m. The hard soil layer (rocks) was located deep enough, but with the same slope with the original soil surface. In the northwest part, the depth of the rock layer varied from -15.00 m to -33.00 m. In the southeast and east, the rock layer was at very deep or was not encountered. From Figure 2, the temple building was built on a basin area which was then filled with earth. This was supported by the gradation test and soil profile of the drill logs, showing that the soil layer of the Prambanan temple foundation was not a sedimentation layer. When this soil layer was the result of sedimentation, the soil layer consisted of large granule layer on the bottom side, While the small granules were on the upper side. This condition can be observed and was a layer of soil depicting that each layer was a season period. The soil at the location of the Shiva Temple was a compacted earth fill from a depth of -14.00 m. Below this layer was a layer of original soil surface with a higher density, as well as greater bearing capacity. Groundwater level was found at a depth of 11.20 m (from the geo - electrical interpretation across the complex, the surface of groundwater was at the -12.00 to -15.00 m (Figure 2)).

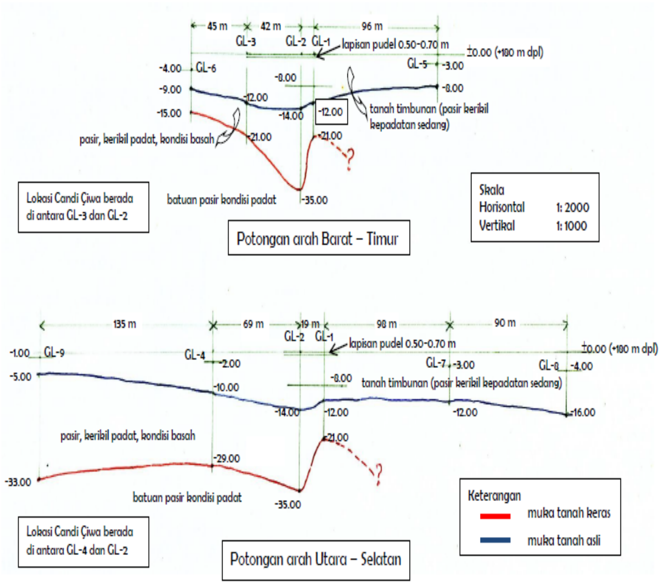


Figure 2. The Interpretation of subgrade condition at Prambanan Temple Foundation [1]

3.2 Peak Ground Acceleration

The calculation of *peak ground acceleration* was conducted using various empirical equations and earthquake data from BMKG, USGS and Elnashai version. The largest *peak ground acceleration* is presented in Table 1 as follows.

Table 1. The Largest Peak Ground Acceleration with various empirical formulas and versions of earthquake data

Eartquake Data	**FORMULA EMPIRIS (PGA analysis)**				
	Matsuchka	**Donovan**	**Mc. Guirre**	**Esteva**	**Kanai**
ELNASHAI	0,216 g	0,142 g	0,162 g	0,075 g	0,429 g
USGS	0,209 g	0,137 g	0,157 g	0,071 g	0,402 g
BMKG Yogyakarta	0,101 g	0,095 g	0,085 g	0,038 g	0,106 g

From the results of PGA calculations using various empirical formulas, the largest PGA value was obtained from the Matuschka empirical formula with Elnashai earthquake data during Yogyakarta earthquake, May 27, 2006 of 0.216 g (Magnitude = 6.3 SR and 10 km depth). These results were then used for the analysis of *Cyclic Stress Ratio* (CSR) and *Cyclic Resistance Ratio* (CRR). This result was in accordance with study of Djumarma, et al. [11] who conducted geo - seismic study using microtemor at Prambanan Temple with PGA 0.2 - 0.3g.

3.3 Comparison of Value of CSR and CRR

The calculation of CSR values was conducted using various methods and is presented in the graph below.

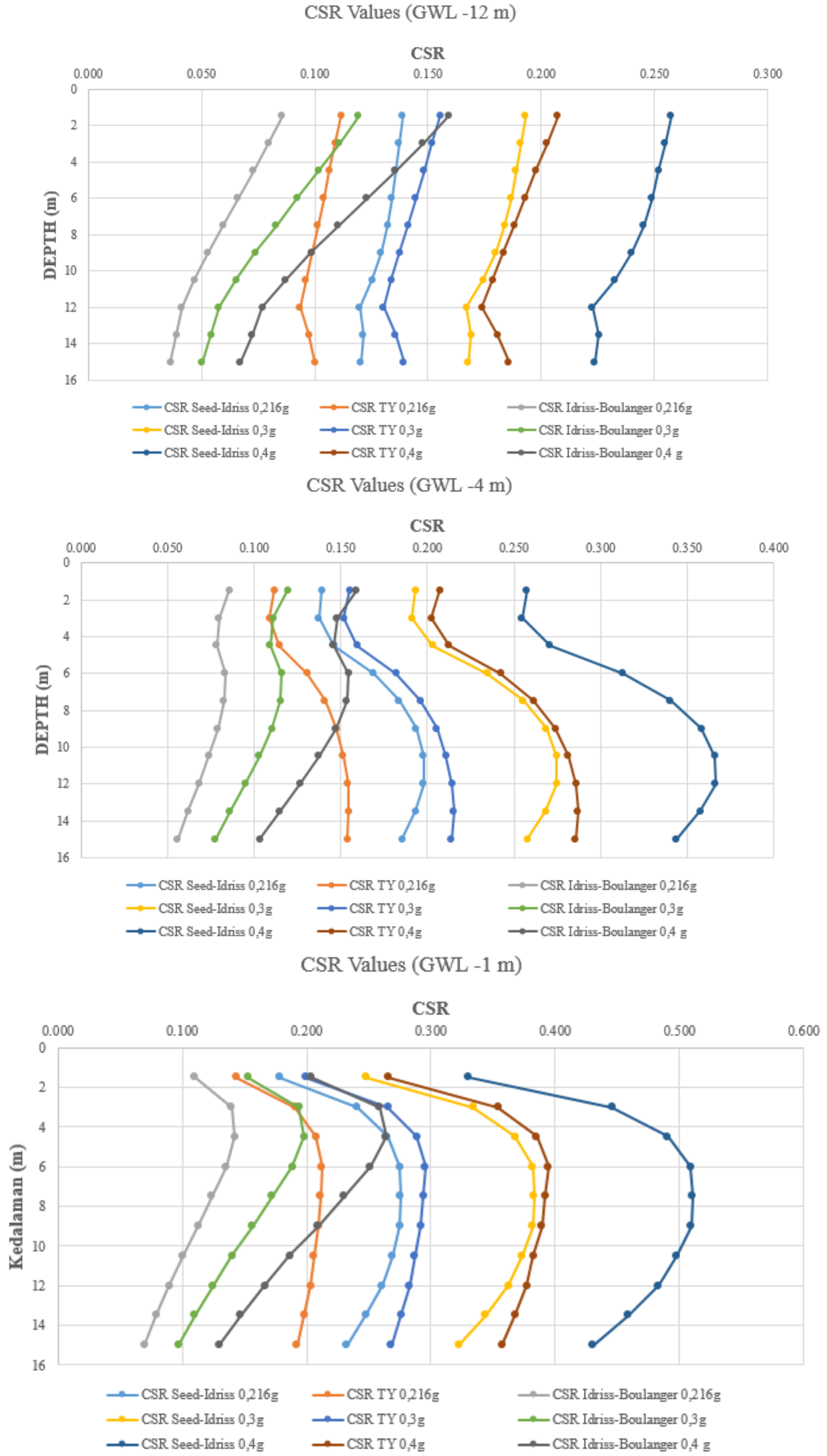


Figure 3. The Comparison Graphs of CSR values using various methods with variations in groundwater level and pga

The results of CRR values calculation using various methods are presented in the graph below.

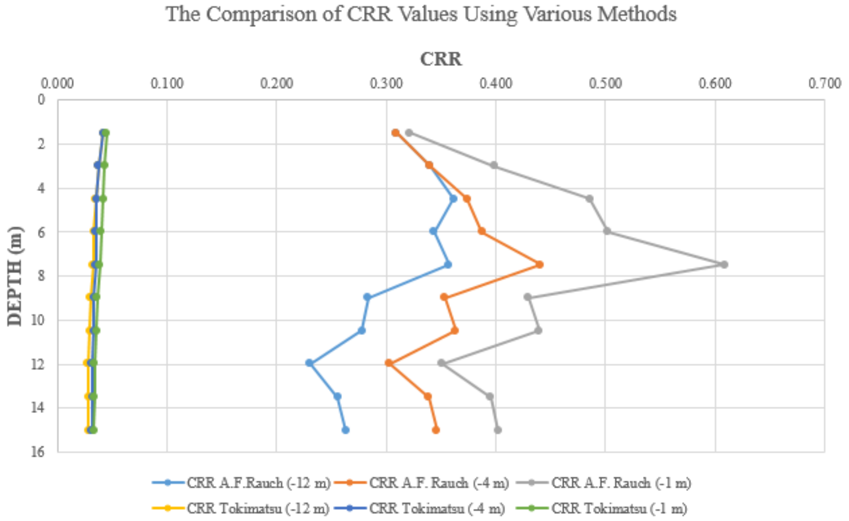


Figure 4. The Comparison of CRR values using various methods with groundwater variations

3.4 Safety Factor

The results of the safety factor range calculation from the various semi empirical methods are presented in Table 2 as follows.

Table 2. Value of CSR, CRR and FS *(Factor of Safety)* with a variety of semi-empirical method for the groundwater at a depth of 12 meters

CSR	CRR	FS
Seed & Idriss, 1971	Rauch, 1998	1,922 – 2,703
Seed & Idriss, 1971	Tokimatsu & Yoshimi, 1983	0,232 – 0,304
Tokimatsu & Yoshimi, 1983	Rauch, 1998	2,462 – 3,523
Tokimatsu & Yoshimi, 1983	Tokimatsu & Yoshimi, 1983	0,285 – 0,377
Idriss & Boulanger, 2006	Rauch, 1998	3,610 – 7,253
Idriss & Boulanger, 2006	Tokimatsu & Yoshimi, 1983	0,470 – 0,787

The table above shows the results of a safety factor (SF) for CSR using the methods of Seed & Idriss [8], Tokimatsu & Yoshimi [9] and Idriss & Boulanger [10] with CRR method from Rauch [4] which gives SF value> 1, this means an area is safe against liquefaction threat. However, for CRR based on the method of Tokimatsu & Yoshimi [9], SF value> 1 means an area is not safe against liquefaction events.

The suitable safety factor analysis against the occurrence of liquefaction in accordance with the soil conditions in the courtyard of Siwa Temple, Prambanan Temple Complex consisted of CSR method by Seed & Idriss [8], Tokimatsu & Yoshimi [9], and Idriss & Boulanger [10], with CRR method by Rauch [4].

The result of the analysis revealed that safety factor value at the depth of -1.5 meters to - 2.00 meters using CSR by Seed & Idriss [8] and CRR by Rauch [4] was high enough. At depth below -12.00 meters, the safety factor value was reduced because the soil was submerged by groundwater at a depth of -12.00 meters. Although the SF value at depths below -12.00 meters was decreased compared to the unsubmerged soil, the soil was safe against liquefaction incidence. The same results were also shown for CSR by Tokimatsu & Yoshimi [9] and CRR by Rauch [4]. Different results were shown for CSR by Idriss & Boulanger [10] and CRR by Rauch [4], the tendency of SF value from both methods proved a more comprehensive illustration, the SF value increased, although its value was fluctuating.

To determine the effect of groundwater level and *peak ground acceleration* to the safety factor of the soil to the occurrence of liquefaction, then the possibility of ground water level rise, from a depth of -12 meter, -4 meters and -1 meter was analyzed. *Peak ground acceleration* with the assumption of greater than 0,216 g to 0,3g and 0,4 g is presented in Figure 5-13.

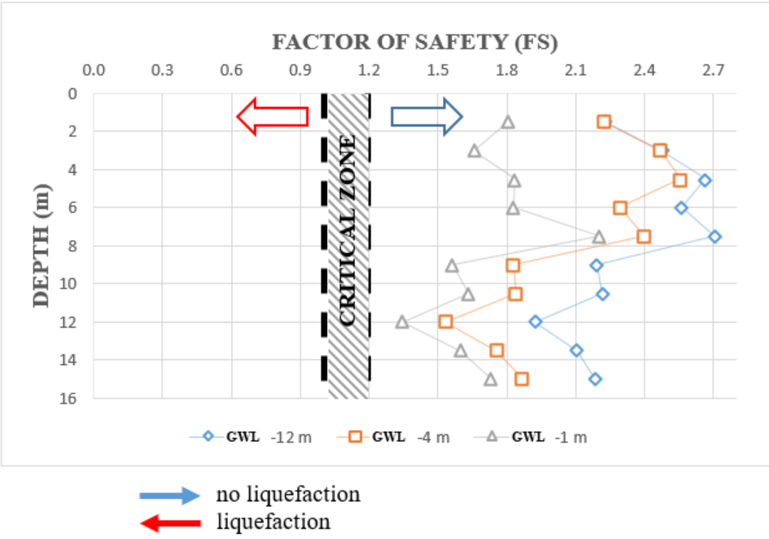


Figure 5. The Relationship between Factor of Safety (FS) and Depth based on CSR value by Seed & Idriss [8] and CRR by Rauch [4] with groundwater depth variation and PGA value of 0.216g.

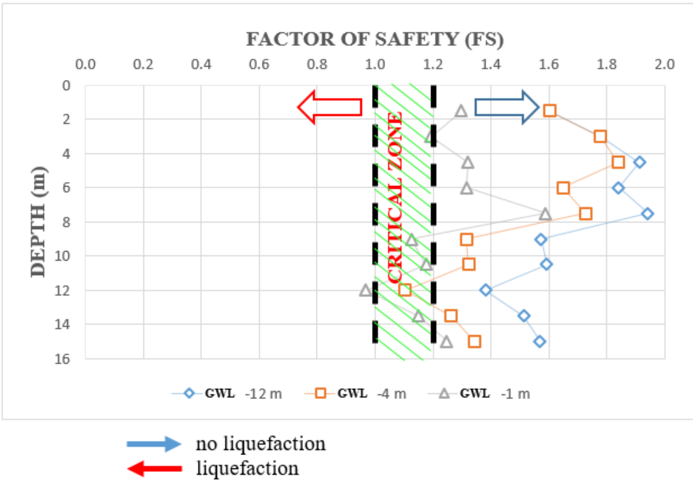


Figure 6. The Relationship between Factor of Safety (FS) and Depth based on CSR value by Seed & Idriss [8] and CRR by Rauch, [4] with groundwater depth variation and PGA value 0.3g.

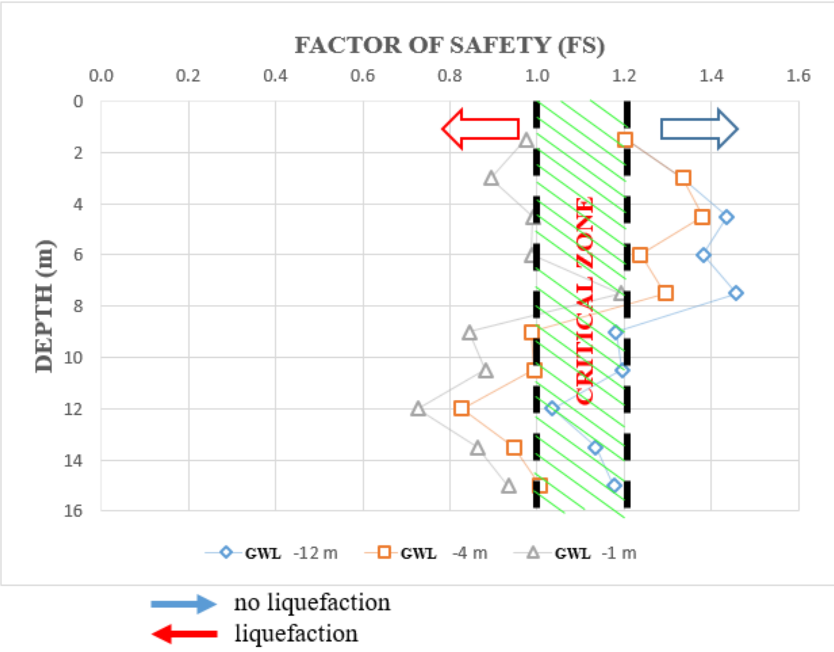


Figure 7. The Relationship between Safety Factor (FS) and Depth based on CSR value (Seed & Idriss, [8]) and CRR (Rauch, [4]) with groundwater depth variation and PGA value 0.4g.

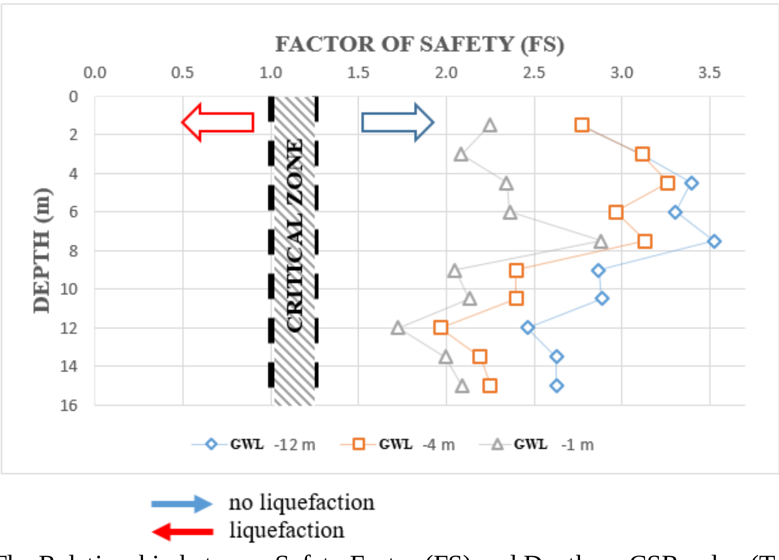
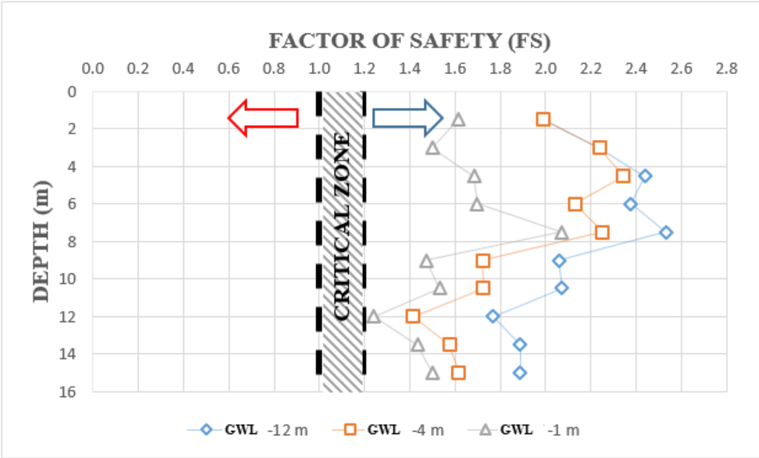
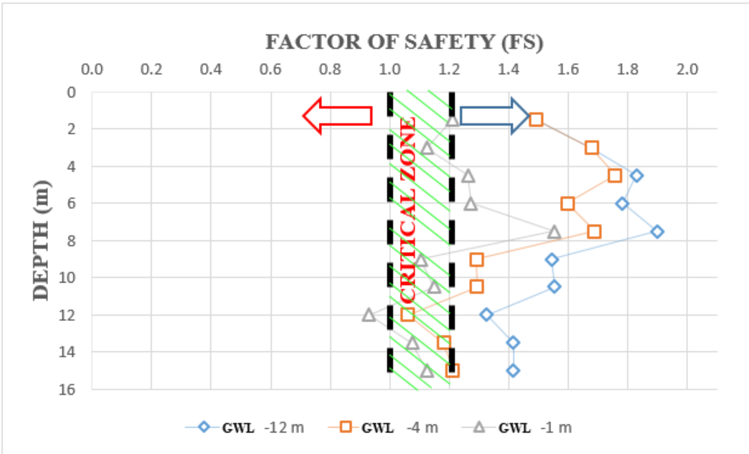


Figure 8. The Relationship between Safety Factor (FS) and Depth on CSR value (Tokimatsu & Yoshimi, [9]) and CRR (Rauch, [4]) with groundwater depth variation and PGA value 0.216 g.



no liquefaction
liquefaction

Figure 9. The Relationship between Safety Factor (FS) and Depth Based on CSR (Tokimatsu & Yoshimi, [9]) and CRR (Rauch, [4]) with groundwater depth variation and PGA value 0.3g.



no liquefaction
liquefaction

Figure 10. The Relationship between Safety Factor (FS) and Depth based on CSR value (Tokimatsu & Yoshimi, [9]) and CRR (Rauch, [4]) with groundwater depth variation and PGA value 0.4 g

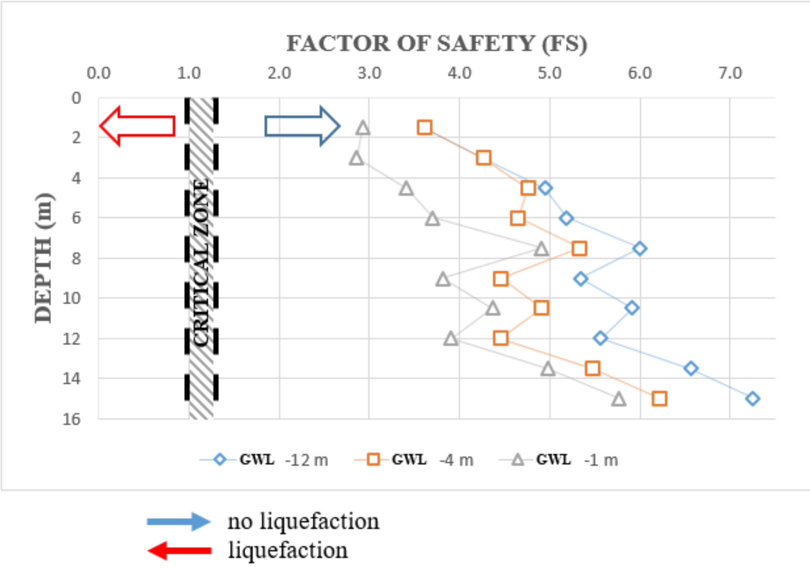


Figure 11. The Relationship between Safety Factor (FS) and Depth based on CSR value (Idriss & Boulanger [10]) and CRR (Rauch, [4]) with groundwater depth variation and PGA value 0.216 g

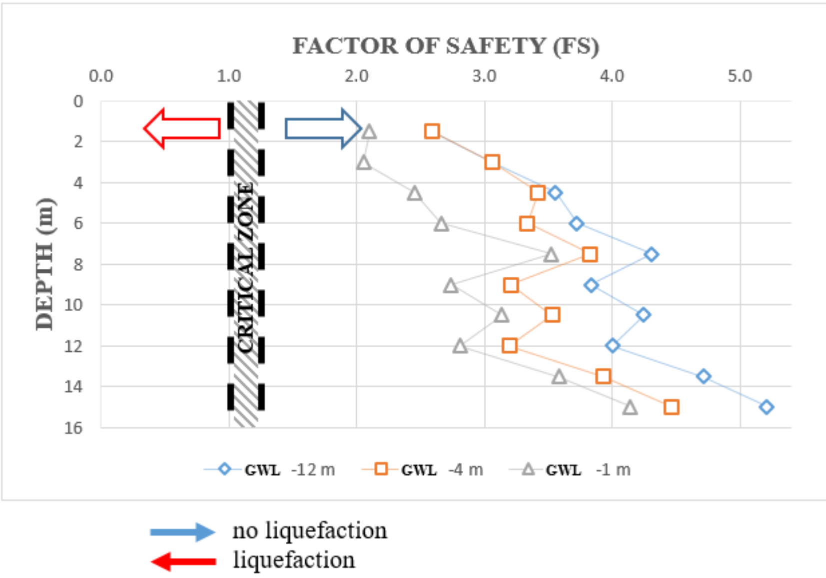


Figure 12. The Relationship between Safety Factor (FS) and Depth based on CSR value (Idriss & Boulanger, [10]) and CRR (Rauch, [4]) with groundwater depth variation and PGA value 0.3g.

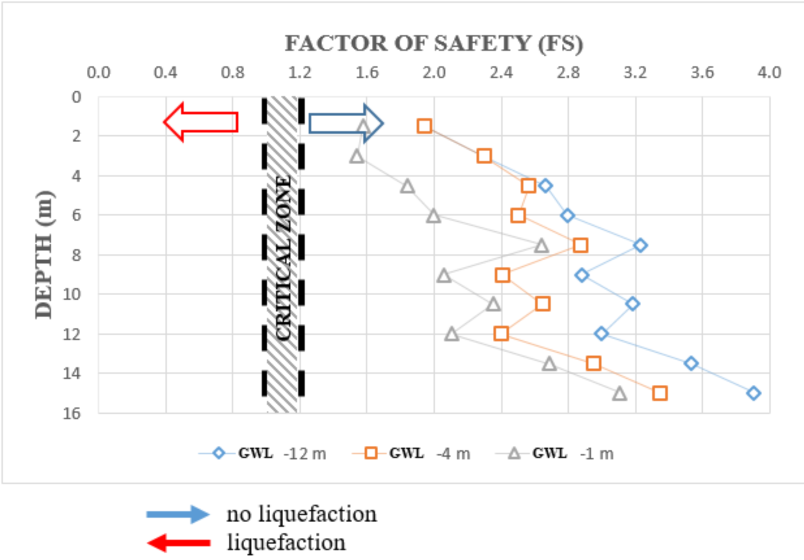


Figure 13. The Relationship between Safety Factor (FS) and Depth based on CSR value (Idriss & Boulanger [10]) and CRR (Rauch, [4]) with groundwater depth variation and PGA value 0.4g

3.5 Potential of Liquifaction Incidence

The analysis of the liquefaction potential rate was based on the FS value of each soil layer, as discussed in the theoretical base chapter. Based on *Liquefaction Potential Index* (LPI), *Liquefaction Severity Index* (LSI) and *Liquefaction Risk Index* (LRI) in the estimation of the incidence of soil liquefaction on a subgrade foundation around Shiva temple is presented in Table 3-5 as follows.

Table 3. Potential of Liquefaction Incidence with LPI Method and CRR value (Rauch, [4]) and CSR value (Seed & Idriss [8])

Depth	FS	LPI	Information
1,5	2,231	0,000	The potential for liquefaction incidence is very low
3	2,476	0,000	The potential for liquefaction incidence is very low
4,5	2,663	0,000	The potential for liquefaction incidence is very low
6	2,562	0,000	The potential for liquefaction incidence is very low
7,5	2,703	0,000	The potential for liquefaction incidence is very low
9	2,191	0,000	The potential for liquefaction incidence is very low
10,5	2,216	0,000	The potential for liquefaction incidence is very low
12	1,922	0,000	The potential for liquefaction incidence is very low
13,5	2,106	0,000	The potential for liquefaction incidence is very low
15	2,183	0,000	The potential for liquefaction incidence is very low

Table 4. The Risk of incidence with LRI Method and CRR value (Rauch, [4]) and CSR value (Seed & Idriss [8])

Depth	FS	LRI	Information
1,5	2,231	0,153	The low risk of liquefaction incidence
3	2,476	0,109	The low risk of liquefaction incidence
4,5	2,663	0,082	The low risk of liquefaction incidence
6	2,562	0,082	The low risk of liquefaction incidence
7,5	2,703	0,064	The low risk of liquefaction incidence
9	2,191	0,095	The low risk of liquefaction incidence
10,5	2,216	0,080	The low risk of liquefaction incidence
12	1,922	0,094	The low risk of liquefaction incidence

Depth	FS	LRI	Information
13,5	2,106	0,062	The low risk of liquefaction incidence
15	2,183	0,043	The low risk of liquefaction incidence

Table 5. The Weight of liquefaction incidence by LSI method and CRR value (Rauch, [4]) and CSR value (Seed & Idriss, [8])

Depth	FS	LRI	Information
1,5	2,231	0,042	The weight of the liquefaction incidence is very low
3	2,476	0,027	The weight of the liquefaction incidence is very low
4,5	2,663	0,020	The weight of the liquefaction incidence is very low
6	2,562	0,020	The weight of the liquefaction incidence is very low
7,5	2,703	0,015	The weight of the liquefaction incidence is very low
9	2,191	0,026	The weight of the liquefaction incidence is very low
10,5	2,216	0,022	The weight of the liquefaction incidence is very low
12	1,922	0,028	The weight of the liquefaction incidence is very low
13,5	2,106	0,017	The weight of the liquefaction incidence is very low
15	2,183	0,012	The weight of the liquefaction incidence is very low

The analysis of liquefaction potential incidence which employed three methods: *Liquefaction Potential Index* (LPI), *Liquefaction Risk Index* (LRI) and *Liquefaction Severity Index* (LSI) showed that at the court of Shiva temple as a whole, the possibility of liquefaction potential was very low.

Conclusion

The conclusions that can be drawn from this research were:

a. The analysis of *Peak Ground Acceleration* (PGA) using some empirical formula revealed that the Matuschka empirical formula [11] resulted in the largest PGA that was 0.216 g,
b. The earthquake that produced the largest PGA was the Yogyakarta earthquake, May 27, 2006 with magnitude 6.3 Richter Scale and a depth of 10 km based on the earthquake data from Elnashai version, 2006
c. The analysis of Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR) was conducted using several methods, they showed that the CSR method by Seed and Idriss [8], Tokimatsu & Yoshimi [9], and Idriss and Boulanger [10] with the CRR methods Rauch [4] were suitable for liquefaction analysis in the courtyard of Shiva Temple,
d. The method of CSR by Seed & Idriss [8] and CRR by Rauch [4 for PGA = 0.216 g with groundwater variations seemed quite safe against liquefaction potential (FS> 1). However, for PGA = 0, 3 g with a groundwater level at -1 meters depth, liquefaction tended to occur (FS <1), as well as for PGA 0.4 g with groundwater level of -4 meters,
e. changes in shallower ground water level and greater peak ground acceleration decreased the value of safety factor value to the incidence of liquefaction,
f. The analysis of liquefaction incidence by using three methods: Liquefaction Potential Index (LPI), Liquefaction Risk Index (LRI) and Liquefaction Severity Index (LSI) showed that the incidence of liquefaction at the courtyard of Shiva temple was the low and very low.

References

Tim Penyusunan Detail Engineering Design (DED). 2012. Kegiatan Studi Teknis Pelestarian Candi Siwa, Kompleks Candi Prambanan. BPCB Yogyakarta.

Yould, T.L, and Idriss, I.M. 2001. Liquefaction Resistance of Soil : Summary report from 1996 NCEER and 1998 NCEER Workshop on Evaluatin of Liquefaction Resistance of Soil Journal of Geotechincal and Geoenviromental Engineering.

Rahmi, Noor., 2011, Perilaku Regangan – Siklis Pembebanan Tanah Pasir Prambanan Dengan Uji Triaksial Siklis, Tesis, Jurusan Teknik Sipil (Geoteknik) dan Lingkungan, Universitas Gadjah Mada.

Rauch, A.F., 1997, EPOLLS : An Empirical for Predicting Surface Displacements Due to Liquefaction – Induced Lateral Spreading in Earthquakes, Dissertation, Faculty of the Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Sonmez, H and Gokceoglu, C., 2005. A liquefaction severity index suggested for engineering practice, Environmental Geology, 48, pp. 81-91.

Douglas, J. (2001), Ground Motion Estimation Equation 1962-2003. Imperial College of Science, Technology and Medicine Civil Engineering Department, London, United Kingdom.

Matuschka, T. 1980. *Assessment of seismic hazards in New Zealand*. Tech. rept. 222. Department of Civil Engineering, School of Engineering, University of Auckland. Reported in Stafford (2006).

Seed, H.B., and Idriss, I.M. 1971. Simplified Procedure for Evaluation Soil Liquefaction Potential. Journal of Soil Mechanics and Foundation, Division, ASCE, vol. 97, No.9, pp 1249-1273.

Tokimatsu, K., and Yoshimi, Y., 1983, Empirical Correlation of Soil Liquefaction Based on SPT-N Values and Fines Content. Soils Found. JSSMFE.23(4),56-74.

Idriss, I.M., Boulanger, R.W., 2006, Semi-empirical Procedures for Evaluating Liquefaction Potential during Earthquakes.Soil Dyna.and Earth. Eng.26, 115-130.

Djumarma, A., Soehaimi, A., and Marjiyono, 2010, Geoseismic Research Concerning The Safeguard From The Earthquake Hazards To The World Heritage Of Prambanan Temple, Bulletin Vulkanologi dan Bencana Geologi, Volume 5 Nomor 2.