Liquefaction potentials analysis of sandy gravel on the sediment deposit of the Serpong formation

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Abstract. Experimental Power Reactor Design in Serpong has been completed consisting of 4 (four) buildings, namely reactor buildings, supporting reactors buildings, switchgear buildings, and turbine buildings which are the main building of RDE power plants. Soil testing series has been carried out and delivered a number of data on sediment deposit formation which in its surface area is a sandy gravel soil layer and has the potential for liquefaction. Several analyses were carried out to test the liquefaction potential including surface sediment vulnerability analysis, grain size distribution analysis, liquefaction safety factor analysis, and liquefaction index analysis. The results show the level of vulnerability of the Serpong formation liquefaction in the medium category and there is a zone that has a high potential for liquefaction at DH-16 and DH-17.

1. Introduction
A geotechnical investigation was done in order to attain the data needed to evaluate the site for Experimental Power Reactor (RDE) in Puspitek - Serpong, as such has been conditioned in the head of BAPETEN regulation No. 5 the year 2007 about the safety control of Nuclear Reactor Site Evaluation. One of the geotechnical disasters that are very hazardous in terms of infrastructure construction is the soil liquefaction, which is why geotechnical aspect and foundation site evaluation are highly required for the sufficiency analysis of the site that is based upon the geotechnical hazard potential. Liquefaction commonly occurs on sandy and water-saturated soil in event of an earthquake. The loss of shear strength due to the earthquake could cause a landslide, loss of bearing capacity on the foundation, and excessive foundation settlement. Liquefaction causes soil settlement that will damage the building that stands above it. In consideration of that event, investigation and analysis are needed in order to prevent the impacts that will be caused by the events as mentioned above. The test provides data collection, hazard factor identification, and also the sufficiency study of the site.

In the beginning, the study of liquefaction was based on cyclic loading tests of reconstituted samples. These tests were very useful for defining the mechanics of liquefaction and giving insight into potential consequences but it was quickly realized that such samples were not representative of field conditions and therefore could not be relied upon to assess the liquefaction potential in the field. Attention turned to the possibility of using in situ penetration tests to assess the density and hence the resistance of soils in situ to liquefaction. These studies have resulted in the development of Liquefaction Assessment Charts based on SPT-N, CPT-q and for soils that are difficult to penetrate, charts based on shear wave velocity, Vs. In the early days, site response analysis was not a viable option, so the study developed a simplified method for estimating the cycles of uniform stress.
representative of the actual shaking intensity of the earthquake [1]. This approach, despite advances in computational capacity, is still very widely used.

2. Methodology

The simplified procedure predicts what will happen to a soil element, the index \( I_L \) predicts the performance of the whole soil column and the consequence of liquefaction at the ground surface [2]. The following assumptions:

1) The severity of liquefaction is proportional to the thickness were made by the study in formulating index \( I \) of the liquefied layer [3],
2) The severity of liquefaction is proportional to the proximity of the liquefied layer to the ground surface, and
3) The severity of liquefaction is related to the factor of safety (FS) against the initiation of liquefaction but only the soils with FS < 1 contribute to the severity of liquefaction.

The first research developed the simplified liquefaction evaluation procedure to compute the factor of safety (FS) against liquefaction at a given depth in the soil profile [4]. Although the simplified procedure predicts triggering of liquefaction at a specific depth, it does not predict the severity of liquefaction manifestation at the ground surface, which more directly correlates to damage potential from liquefaction. To fill this gap is proposed the LPI to better characterize the damage potential of liquefaction, where LPI is computed as equation 1.

\[
\text{LPI} = \int_0^{20} F(z)w(z)dz
\]  

(1)

In equation 1, \( F = 1 - \text{FS} \) for \( \text{FS} \leq 1.0 \) and \( F = 0 \) for \( \text{FS} > 1.0 \) (where FS is obtained from a simplified liquefaction evaluation procedure); and \( w(z) = \text{depth-weighting function given by } w(z) = 10-0.5z \) for \( z < 20 \) m and \( w(z) = 0 \) for \( z > 20 \) m, where \( z \) = depth in meters below the ground surface. Thus, it is assumed that the severity of liquefaction manifestation is proportional to (1) the thickness of a liquefied layer; (2) the amount by which FS is less than 1.0; and (3) the proximity of the layer to the ground surface. It can be shown that the depth-weighting function allot maximum contributions to LPI from the first, second, third, and fourth 5-m depth increments of 43.75, 31.25, 18.75, and 6.25%, respectively.

Given this definition, LPI can range from 0 for a site with no liquefaction potential to a maximum of 100 for a site where FS 50 over the entire 20-m depth. Using standard penetration test (SPT) data from 45 liquefaction sites in Japan, the study found that 80% of the sites had LPI > 5, while 50% had LPI > 15. Based on this data, it was proposed that severe liquefaction should be expected for sites where LPI > 15 but should not be expected for sites where LPI > 5. This criterion for liquefaction manifestation, defined by two threshold values of LPI, is subsequently referred to herein as the Iwasaki criterion.

The factor of safety against the initiation of liquefaction of a soil under a given seismic loading is generally defined as the ratio of cyclic resistance ratio (CRR), which is a measure of liquefaction resistance, over cyclic stress ratio (CSR), which is presentation of seismic loading that causes liquefaction, symbolically, \( \text{FS} = \text{CRR}/\text{CSR} \). The reader is referred to the research for the historical perspective of this approach.

2.1. Simplified method using probabilistic acceleration

The simplified methods described above are deterministic. The seismic hazard at the site is based on a known pair of parameters, \( M \) and \( a \). Therefore the MSF for \( M \) can be applied directly in the equation 2.

\[
\text{CSR} = 0.6g \frac{\sigma_{\text{max}}}{g} \frac{\sigma_{\text{dr}}}{\sigma_{\text{v0}}} \frac{r_d}{\text{MSF}}
\]  

(2)
However, if a probabilistic PGA is used, which is the result of the contributions of many magnitudes to PGA, what magnitude and hence what MSF should be used? In current practice, a single magnitude is often selected which tends towards the maximum magnitude expected in the governing seismic source zone and its weighting factor is used with the NBCC 2010 PGA.

Suggested Magnitude contributing to the probabilistic PGA demonstrated directly by two independent methods: (1) a probabilistic seismic hazard analysis using weighted magnitudes and (2) a procedure based on a magnitude – distance deaggregation for the BC code hazard level of a 2% exceedance rate in 50 years. The weighted magnitude probabilistic analysis approach is described in detail by the study [5]. It requires access to a seismic hazard analysis program. The deaggregation method is easy to implement because the magnitude – distance deaggregation is available from USGS. The study also has shown that both methods give the same results [6].

2.2. Resistance capacity
The cyclic resistance ratio, CRR as shown in figure 1, for cohesionless soils has been established as a function of normalized quantities: SPT-N, Qc and V and therefore can be determined from routine in situ field measurements. A similar database is not available for clays. There are three recognized methods for determining CRR for clays:
1. The direct method using cyclic loading tests on high-quality samples
2. Measure the monotonic undrained shear strength, S, in situ or by test on high-quality samples
3. Estimate Su based on the stress history of the soil profile

\[
r_c = \begin{cases} 
1-0.0076z & : z < 9.15 \\
1.174 - 0.0267z & : 9.15 \leq z \leq 23 \\
0.744 - 0.008z & : 23 < z \leq 30 \\
0.5 & : z > 30 
\end{cases} \tag{3}
\]

Figure 1. Flow diagram to evaluate CRR_{M7.5}. 

\[
CRR_{r,5} = 0.833 \left[ \left( \frac{q_{d,5}}{1000} \right) \right] + 0.05 \tag{4a}
\]

\[
CRR_{r,5} = 93 \left( \frac{q_{d,5}}{1000} \right)^2 + 0.08 \tag{4b}
\]
2.3. Vulnerability
The hazard susceptibility assessment makes use of and builds on a method proposed [7]. The research defined a Susceptibility Rating Factor (SRF) in which:

\[ SRF = F_{\text{hist}} \times F_{\text{geology}} \times F_{\text{comp}} \times F_{\text{gw}} \]  

(5)

where \( F_{\text{hist}} \) is a liquefaction history factor, \( F_{\text{geology}} \) is a geology factor, \( F_{\text{comp}} \) is a material composition factor, and \( F_{\text{gw}} \) is a groundwater factor. Each of factors is composed of a combination of contributing factors; for example, the historical liquefaction factor is a function of past occurrences and past levels of seismicity, and the geology factor is a function of the age of the materials, the environment in which they were deposited, and the reliability of the geologic classification. Note that the relationship proposed is multiplicative.

3. Results and discussion

3.1. Grain size distribution analysis
The fine grain content that passes the Filter #200 (0.074 mm) for each layer studied has values ranging from 20.38 to 99% with a sand content of 0.42 to 77.88%. Liquefaction tends to occur in sand-sized deposits as shown in figure 2.
Figure 2. Grain Size Diagram for potentially liquefiable soil.

The dominant sand content layer is occurs in DH-02 (5.5–6 m), DH-04 (2.5 - 3 m), DH-06 (2.5 - 3 m), DH-07 (2.5 - 3 m), DH-08 (2.5 - 3 m and 8.5 - 9 m), DH-11 (2.5 - 3 m and 8.6 - 9 m), DH-12 (8, 5 - 9 m and 11.6 - 12 m), DH-14 (2.5 - 3 m and 5.5 - 6 m) and DH-18 (5.5 - 6 m and 8.5 - 9 m) which is shown in the following pictures.

3.2. Level of the vulnerability of surface deposits analysis
The sediment that dominates the site plan area is sandy gravel, which results from weathering from the Serpong Formation rocks. The Serpong and surrounding areas do not have historical records that show that the area has experienced liquefaction or not, so it has an observation constant value of 2.5. Based on the 2017 Indonesia Earthquake Hazard Map, the site area has a PGA value of 0.4 g for a 2500-year return period, so it has a 1.2 seismic constant.

The type of sediment in the PUSPITEK site plan area is a river and swamp lanes, so it has a class 6 constant value. Based on a review of geological maps, surface sediment maps, and groundwater contour maps, the constant quality of the study area has a value of 1.2.

The determination of the composition factor is based on the type of sediment found in the Puspitek site plan area. Laboratory data on samples of undisturbed soil (UDS) depth of 8.5 - 9 meters in DH-08 was used to determine the values for parameters in the composition factor. The value of each parameter in the composition factor can be seen in the following table.

The value of historical factors, geological factors, composition factors, and groundwater factors are calculated to obtain SRF values. Based on the aforementioned values, using the Kramer equation it was found that the RDE site plan area had an SRF value of 15.39 with a moderate level of vulnerability to liquefaction.

3.3. Analysis of liquefaction safety factor
At each depth, the values of the CRR and CSR vary depending on the physical properties of the sediment deposits and the forces that influence them. The earthquake magnitude value (Mw) on which the calculation is based on 7.5. In the analysis of liquefaction in the RDE site plan area, PGA values are used for certain return periods. The RDE site plan area has a shear velocity value (Vs) of 268 m / s and is a type 3, i.e medium soil. The liquefaction analysis is carried out for each 1,000-year earthquake return period. We use stratigraphic data, N-SPT, laboratory data (normal content weight and saturated content weight), groundwater table, PGA, and seismic earthquake magnitude to analysis SF as shown in figure 3.
The main results are in the form of safety factor (SF) for each layer interval to a maximum depth of 20 meters are shown from the graphics in figure 4.

The value of the SF is equal to one is the standard for determining the level of safety of sediment deposits from the occurrence of liquefaction. In the sediment deposition layer with SF values, less than one has a tendency to easily experience liquefaction. Conversely, in sediment deposition layers with more than one SF value can be justified to be safe against liquefaction.

![Figure 3. Distribution of soil composition on site.](image)

Figure 3. Distribution of soil composition on site.

3.4. Analysis of Liquefaction Potential Index (LPI)

The results of the liquefaction potential index analysis on sediment deposition layers that have the potential to experience liquefaction for earthquakes with a 1000-year return period are shown in table 1 and figure 5. The data shows that the site plan area has a liquefaction potential index that does not occur (LPI = 0), low (0 < LPI < 5), medium (5 < LPI < 15), and high (LPI > 15). Based on the analysis of liquefaction factor based on Finn's method there are several zones in the soil that have the potential to experience liquefaction.

![Figure 4. Safety Factor Analysis on DH-10, DH-11 and DH-21, nearby turbine structure.](image)

Figure 4. Safety Factor Analysis on DH-10, DH-11 and DH-21, nearby turbine structure.
Table 1. LPI result for DH-01 to DH-23.

| DH    | LPI | Level of Strength | DH    | LPI | Level of Strength |
|-------|-----|-------------------|-------|-----|-------------------|
| DH-01 | 0   | Not Occur         | DH-13 | 6.25| Medium            |
| DH-02 | 12.77| Medium            | DH-14 | 8.79| Medium            |
| DH-03 | 6.16| Medium            | DH-15 | 3.25| Low               |
| DH-04 | 0   | Not Occur         | DH-16 | 37.47| High              |
| DH-05 | 12.51| Medium            | DH-17 | 24.72| High              |
| DH-06 | 0   | Not Occur         | DH-18 | 8.29| Medium            |
| DH-07 | 0   | Not Occur         | DH-19 | 0   | Not Occur         |
| DH-08 | 0.70| Low               | DH-20 | 0   | Not Occur         |
| DH-09 | 4.46| Low               | DH-21 | 0   | Not Occur         |
| DH-10 | 2.34| Low               | DH-22 | 0   | Not Occur         |
| DH-11 | 13.17| Medium           | DH-23 | 3.09| Low               |
| DH-12 | 4.45| Low               |       |     |                   |

Figure 5. The liquefaction potential index map for earthquake loads of 1000 years return period.
4. Conclusions
In general, based on the results of the analysis of the level of vulnerability of sediments surface, grain size distribution, potential liquefaction index, there is a possibility of low liquefaction. Based on the results of the analysis of liquefaction security factors based on Finn's method there are several zones in the soil potentially experiencing liquefaction. According to the map, DH-16 and DH-17 possibly have the high potential liquefaction yet in a small area which has sandy gravel sediment deposit of Serpong Formation.

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