MICROZONATION MODEL FOR LIQUEFACTION POTENTIAL OF MAKASSAR COASTAL AREA

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ABSTRACT: The objectives of this research were to correlate liquefaction potential assessment using CPT and SPT data with NCEER method and using seismic vulnerability index of HVSR method, and then to develop microzonation of liquefaction vulnerability map on the coastal area of Makassar city. Brief descriptions of NCEER and HVSR methods were given. Data for HVSR method was obtained by using one set of short period seismograph of type TDS-303 (with three components), and one set of accelerograph of type TDQ 303S with sampling frequency of 100Hz. Results showed that: 1) the calculations of SF with NCEER and of shear strain with HVSR methods, both resulted in more or less similar evaluation of vulnerability level against liquefaction, 2) available earthquake record in Makassar give much smaller acceleration compared to the results based on Indonesian SNI 1726-2012 code, and 3) using the values of PGA as suggested in SNI 1726-2012 for both methods, some area in Makassar indicated as vulnerable to liquefaction particularly near river and coast in southern part of the city. It was also concluded that since the extend of area indicated vulnerable is different from both methods due to fewer number of data in CPT and SPT compared to HVSR data, a focus research on indicated area was suggested.

Keywords: Microzonation, liquefaction, earthquake, accelerograph.

INTRODUCTION

Makassar city is in earthquake zone between 3 and 4 (SNI 1726-2012-Indonesian code) which between 1950 and 1960 experienced earthquakes with a magnitude of around 6 on Richter scale with epicenter of 50 km. Located in the estuaries of Jeneberang and Tallo Rivers, and Makassar Strait, some area experience flood that causes saturation of mainly sandy and silty deposit. The city’s soft soil layer conditions could amplify ground acceleration due to earthquake. Therefore it is deemed necessary to develop a seismic microzonation as the basis for assessing liquefaction susceptibility.

The objectives of this research work are to correlate liquefaction potential assessment based on Cone Penetration Test (CPT) and Standard Penetration Test (SPT) with seismic vulnerability index and ground shear strain, and to develop microzonation of seismic liquefaction hazard on the coastal area of Makassar city.

EVALUATION OF LIQUEFACTION

Seismic liquefaction occurs when a saturated or partially saturated soil loses strength due to earthquake shaking that increases pore water pressure, and then decrease effective stress causing the soil to behave like liquid. The following procedures in evaluating safety factor against liquefaction were adopted from Youd et.al (2001), also called NCEER method. In this study, data from cone penetration test (CPT) and standard penetration test (SPT) were used to evaluate liquefaction.

Cyclic Stress Ratio (CSR)

Cyclic Stress Ratio (CSR) is a parameter to indicate the seismic demand on the soil layer. CSR is calculated by equation 1 as proposed by Seed and Idriss (1971) also in Youd et.al (2001).

\[
CSR = 0.65 * \left( \frac{a_{max} * 100}{g * \sigma_{vo}} \right) * r_d
\]

where:
- \(a_{max}\) = peak horizontal acceleration at ground surface
- \(g\) = gravity
- \(\sigma_{vo}\) = total overburden pressure
- \(\sigma_{vo}\) = effective overburden pressure
- \(r_d\) = stress reduction coefficient

Coefficient \(r_d\) in Eq. 1 is approximated by Equation 2, where \(z\) is the depth below ground surface in meter (Youd et.al, 2001):

\[
r_d = \frac{1.0-0.417 z^{1.5}+0.00173 z^{1.5}}{1.0-0.417 z^{1.5}+0.00173 z^{1.5}+0.00021 z^{2}}
\]

Cyclic Resistance Ratio (CRR) for CPT

Capacity of soil layers to resist liquefaction is expressed in term of cyclic resistance ratio (CRR). For CPT data, calculation of CRR is based on the curve shown in Fig 1. Therefore CPT values need to be adjusted to Corrected CPT Tip Resistance by Equations 3 and 4, and then for equivalent of clean sand by Equations 5 through 10.

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As the value of corrected cone resistant of equivalent clean sand obtained, CRR for 7.5 moment magnitude is obtained by Equations 11 or 12, Robertson and Wride (1998)

\[ CRR_{7.5} = 0.833 \left( \frac{q_{c1N}}{q_{c1N_{cs}}} \right) + 0.05 \]  
\[ CRR_{7.5} = 93 \left( \frac{q_{c1N}}{q_{c1N_{cs}}} \right)^2 + 0.08 \]

where:
CRR\(_{7.5}\) = cyclic resistance ratio for earthquake moment magnitude of 7.5

**Cyclic Resistance Ratio (CRR) for SPT**

Procedure of calculation was based on Fig. 2 for clean sand curve or could be determined by Equations 13 and 14.

\[ CRR_{7.5} = \frac{1}{34-(N_{60}) \cdot C_N} \cdot \frac{(N_{60}) \cdot C_E \cdot C_B \cdot C_R \cdot C_S}{100} \]  
\[ (N_1)_{60} = N_m \cdot C_N \cdot C_E \cdot C_B \cdot C_R \cdot C_S \]

where:
(N\(_1\))\(_{60}\) = corrected standard penetration resistant
N\(_m\) = measured penetration resistant
C\(_N\) = factor for normalize
C\(_E\) = correction factor for hammer energy ratio
C\(_B\) = correction factor for bore hole diameter
C\(_R\) = correction factor for rod length
C\(_S\) = correction factor for sampler with or without liner

In case the soil is not clean sand, to use the clean sand curve or equation, the (N\(_1\))\(_{60}\) values are adjusted to (N\(_1\))\(_{60cs}\) by using Equations 15 to 18 which depend on fine content (FC). Then value (N\(_1\))\(_{60cs}\) is used instead of (N\(_1\))\(_{60}\) in Equation 13.

\[ (N_1)_{60cs} = \alpha + \beta (N_1)_{60} \]

For FC \(\leq 5\%\)
\[ \alpha = 0 \quad \beta = 1 \]

For 5\% \(< FC \leq 35\%\)
\[ \alpha = \exp[1.76 - (190/FC^2)] \quad \beta = 0.99 + (FC^{1.5}/1000) \]
For $FC > 35\%$

$$\alpha = 5.0; \ \beta = 1.2$$ (18)

Fig. 2 SPT clean sand curve for earthquake Magnitude 7.5, from Youd et al. (2001)

Factor of Safety (FS)

Evaluation of safety factor against liquefaction is calculated by Equation 19 and 20 below. Values of CRR and CSR are either from CPT or SPT data.

$$FS = \left( \frac{\text{CRR}}{\text{CSR}} \right) \text{MSF}$$ (19)

$$\text{MSF} = \frac{10^{(\alpha^2 - 24)}}{M^2}$$ (20)

where MSF is the magnitude scaling factor for other value of moment magnitude.

EVALUATION WITH MICROTREMOR DATA

Microtremor is a low amplitude ambient vibration of the ground caused by man-made or natural sources such as wind, sea wave, traffic etc. Its amplitude ranges from 0.1 to 1 micron with velocity of 0.001-0.01 cm/s. The measurement of microtremor has been used to estimate seismic characteristics of surface geology.

HVSR Method

Nakamura (1989, 1997, 2000, and 2008) and Nakamura et. al (2007) introduced the Horizontal Vertical Spectral Ratio Method (HVSR). The H/V spectral ratio of microtremor measurement had been shown able to determine the predominant frequency ($f_0$) and amplification factor (A) of soil layers. From the two parameters a vulnerability indexes ($K_g$) can be determined.

In relation with earthquake motion, it was also shown that H/V spectral ratio of microtremor and that of earthquake are similar. Such characteristics are beneficial for research on seismicity. Fig 3 shows an example of result of HVSR analysis.

Seismic Vulnerability Indexes

Seismic Vulnerability Indexes ($K_g$) is an indication of easiness of ground deformation, Nakamura (1997). The indexes can be determined by Equation 21 as follows:

$$K_g = \frac{A^2}{f_0}$$ (21)

Ground Shear-Strain

When ground layer subjected to acceleration, the amount of shear strain of surface ground can be determined from the vulnerability index ($K_g$) and the acceleration ($\alpha$). The calculation of shear-strain ($\gamma'$) is performed with Equation 22, Nakamura (1997, 2000, and 2008).

$$\gamma' = K_g \times (10^{-6}) \times \alpha$$ (22)

The magnitude of shear strain occurs in soil body affect the deformation characteristics of soil. Ishihara (1996) compiled variation of the characteristics with respect to strain level as shown in Table 1.

Table 1 Variation of soil properties with strain (Ishihara, 1996)

<table>
<thead>
<tr>
<th>Strain</th>
<th>Dynamic</th>
<th>Static</th>
<th>Basic</th>
<th>Resilience</th>
<th>Plasticity</th>
<th>Liquefaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>None</td>
<td>None</td>
<td>0%</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
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<td>5%</td>
<td>None</td>
<td>None</td>
<td>5%</td>
<td>None</td>
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</tr>
<tr>
<td>10%</td>
<td>None</td>
<td>None</td>
<td>10%</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

With the data obtained from microtremor and a known acceleration, the shear strain can be calculated. Acceleration value used could be from measurement or from design code.
Area Investigated

Area investigated is around Makassar coast from 5.3° S to 5.26° S and from 119.20° E to 119.52° E. The number of data collected: 110 microtremors, 35 CPT, and 11 N-SPT as shown in Fig. 4.

Microtremor Equipment

Equipment used are one set of portable short period/velocity seismograph of type TDL-303S (3 components), and one set of portable accelerograph of type TDQ - 303S.

EVALUATION STEPS

Evaluation steps are as follows:
1. Calculate SF from CPT and SPT data by using NCEER method. Acceleration data are from earthquake history and from Indonesian design code SNI 1726-2012. Peak ground acceleration (PGA) from earthquake record of a particular point can be used to calculate PGA of other points by ratio of amplification factor (A).
2. Calculate Seismic Vulnerability Indexes (Kg) by HVSR method. Acceleration data are the same as step 1. Then calculate the shear strain to get soil properties from Table 1.

RESULTS

Comparing NCEER and HVSR results

Fig. 5 and Fig. 6 show example of typical results of evaluations for a particular location from both NCEER and HVSR methods respectively. In Fig. 5, SF values are between 1 and 2 which could mean soil is safe but near liquefaction condition. That SF results (Fig. 5) are more or less in agreement with the level of strain resulted from HVSR method (Fig. 6).

Mapping the HVSR results

Dominant frequencies ($f_0$) of ground layer in Makassar are ranging from 0.6 to 9.14 Hz as shown in Fig. 7. As indicated in the figure, area around the coast has dominant frequency that less (lighter shade) than that of area farther from the coast. In term of vulnerability index, smaller dominant frequency will result in higher index or more vulnerable.

Results for soil amplification factors (A) are plotted in Fig. 8. The magnitude of soil amplification factor in Makassar and vicinity could reach up to 16.4 times. Higher values are concentrated around river banks and closer to coast area. This result agrees with the geological characteristics of fluvial sediment. These higher values of amplification factors increase the vulnerability index of the area.
From dominant frequency \(f_o\) and amplification factor \(A\), the seismic vulnerability indexes \(K_v\) are calculated as plotted in Fig. 9. The index values for Makassar city are ranging from 0.254 to 179.194. Two areas in the map in particular show relatively higher values. Those high-index areas are near the coast and area around the river. In this area, small dominant frequency and high amplifications factors contribute to high vulnerability index.

Fig. 7 Map of dominant frequency \(f_o\)

Fig. 8 Map of soil amplification factor \(A\)

Fig. 9 Map of seismic vulnerability index \(K_v\)

Based on earthquake history data, the shear strain results are too small \((0.463 \times 10^{-6} \text{ to } 689.096 \times 10^{-6})\) to cause liquefaction as shown in Fig. 11. Since Makassar is in the border of zone 3 and 4 of SNI 1726-2012 the use of 2 code’s values were performed which gives larger results. Shear strains resulted by the use of code values of 0.15g (shear strain of \(39.258 \times 10^{-6} \text{ to } 26891.994 \times 10^{-6}\)) and 0.2 g (shear strain of \(39.258 \times 10^{-6} \text{ to } 4514.714 \times 10^{-6}\)) are shown in Fig. 12 and Fig. 13. Shear strain, with 0.2g, indicates that some areas are vulnerable to liquefaction as suggested in Table 1.
Shear strain in Fig. 13 of HVSR method suggest more vulnerable locations than those suggested by Fig. 15 of CPT based NCEER method. This difference could be caused by much fewer number of CPT data compared to HVSR data that affecting contour map. Therefore a further research focusing around these locations is recommended.

From CPT evaluation using values from SNI 1726-2012, the total thickness of soil layers vulnerable to liquefaction are shown in Fig. 14 (for 0.15g) and Fig. 15 (for 0.2g) with a range of from 2.3 to 6.8 meter. An increase of acceleration from 0.15g to 0.2g causes an increase of area affected, but not necessary an increase in the total layer thickness of affected point.

CONCLUSION
1. From the calculation of SF with NCEER and shear strain with HVSR methods, both resulted in more or less similar evaluation of vulnerability level against liquefaction.
2. Calculations based on available earthquake record in Makassar give much smaller acceleration compared to the values on Indonesian code which utilize statistical projection.
3. From using the values of PGA as suggested in SNI 1726-2012 for both methods, some area in Makassar indicated as vulnerable to liquefaction particularly near river and coast in southern part of the city.
4. Further research should be focus on the area indicated as vulnerable using both methods.

REFERENCES


SNI 1726:2012 Procedure for earthquake resistant design for building and non building (Indonesian code, in Indonesian)
