Analysis of potential liquefaction of sandy soils using effective confining pressure

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Abstract. Earthquake disasters are some of the most frequent disasters in the world. One of the impacts of earthquakes is liquefaction. Indonesia is earthquake-prone and has been negatively impacted by liquefaction. Recently liquefaction resulting from an earthquake in Palu, Central Sulawesi caused losses in terms of material and lives motivating a more detailed study of this risk to reduce it in the future. In this study, an analysis of the liquefaction potential of sandy soil was carried out by varying the effective confining pressure to produce a graph relating fine contents (FC) to cyclic resistance ratio (CRR). The value of the cyclic resistance ratio is needed to determine the safety factor for potential liquefaction.

1 Introduction

Indonesia is located on the ‘Pacific Ring of Fire’ [1] so often experiences earthquakes of varying magnitudes. Some of these trigger liquefaction. Liquefaction of the soil is a phenomenon where the soil becomes saturated so that it loses rigidity due to stress, such as from earthquakes, which suddenly causes the soil to turn into a liquid like material. As illustrated in Fig. 1:

Fig 1. Process of liquefaction.

Liquefaction can result in the movement of soil burying victims, damaging buildings and infrastructure and causing collapse of buildings as the strength of the land supporting them is lost. One liquefaction disaster that claimed many lives occurred in Palu on 28 September 2018, especially in Petobo and Balaroa Sub-districts in conjunction with an earthquake of magnitude 7,4 SR.

In Balaroa 82 people died and 1,405 houses were destroyed, while in Petobo 104 people were killed and 2,050 houses damaged. Fig. 2 shows, a comparison of satellite images in Petobo, after and before the liquefaction. Fig.s 3 and 4 show damage caused by liquefaction disasters.
2.2 Index Properties of Soil

Relative density (Dr) can also be expressed in terms of maximum and minimum dry unit weight, which can be calculated by the formula:

\[
D_r = \frac{\frac{1}{\gamma_d} - \frac{1}{\gamma_d(\text{min})}}{\frac{1}{\gamma_d(\text{max})} - \frac{1}{\gamma_d(\text{min})}}
\]

Where:

\( \gamma_d(\text{min}) \) is Dry unit weight in the loosest state; (that is, when the void ratio is \( e_{\text{max}} \))

\( \gamma_d \) is in situ dry unit weight (in situ void ratio, \( e \))

\( \gamma_d(\text{max}) \) is Dry unit weight in the densest state; (that is, when the void ratio is \( e_{\text{min}} \))

The weight relationships are moisture content, moist unit weight, dry unit weight, often defined as follows:

\[
\text{Moisture content} = w \% = \left( \frac{W_s}{W_w} \right) \times 100\%
\]

Where:

\( W_s \) is Weight of the soil solids

\( W_w \) is Weight of water

\[
\text{Moist unit weight} = \gamma = \frac{W}{V}
\]

Where:

\( W \) is Total weight of the soil specimen = \( W_s + W_w \)

\( V \) is Total volume of soil

\[
\text{Dry unit weight} = \gamma_d = \frac{\gamma}{1 + w}
\]

Where:

\( \gamma \) is Moist unit weight

\( w \) is Moisture content

2.3 Sieve Analysis Test

The sieve analysis test determined the value of FC (Fine Contents) from sand soil samples by determining the percent of the sample which passed through a filter no.200.

2.4 Earthquake Acceleration (\( a_{\text{max}} \))

Earthquake acceleration of the bedrock can be calculated using the atenuas function which describes the correlation between the earthquake acceleration (\( a_{\text{max}} \)), Earthquake Magnitude (\( M_w \)) and the distance (\( r \)) from the earthquake epicenter.

Atenuas function formula calculated by Joyner & Boore:

\[
a = 10^{\left[ 0.71 + 0.23(M_w - 6) - \log(r) - 0.0027r \right]}
\]

Where:

\( a \) is earthquake acceleration

\( M_w \) is earthquake magnitude

\( r \) = \( \sqrt{r_o^2 + 8^2} \)

\( r_o \) is range in location with epicenter
2.5 Reduction Factor \((rd)\)

The reduction factor is a value that can affect stresses in the soil. The deeper the soil, the smaller the reduction factor [8]. Following is the formula \((rd)\) proposed by T. F. Blake.

The formula is:

\[
rd = \frac{1.0 - 0.4113 z^{1.5} + 0.04052 z + 0.001753 z^{1.5}}{1.0 - 0.4117 z^{0.5} + 0.05729 - 0.006205 z^{1.5} + 0.00121 z^2} \quad (6)
\]

where \(z\) is the depth of the soil layer

2.6 Cyclic Stress Ratio (CSR)

Cyclic Stress Ratio is a cyclic stress due to an earthquake divided by effective stress. Seed and Idriss (1971) calculated the equation for the ratio cyclic stress (CSR), the formula is:

\[
CSR = \frac{\tau_c - \sigma^* \cdot \frac{g_{max} \cdot a_{max}}{\gamma} \cdot rd}{\sigma^*} \quad (7)
\]

Where :
- \(\tau_c\) is Cyclic Shear Stress (kPa)
- \(\sigma^*\) is Confining pressure (kPa)
- \(z\) is Depth (m)
- \(\gamma\) is Unit Weight (g/cm³)
- \(g\) is Gravitation (m/s²)
- \(a_{max}\) is Earthquake acceleration

The effective confining pressure that were used were between 60 kPa, 120 kPa, and 240 kPa [9].

2.7 CRR (Cyclic Resistance Ratio)

Several formulae can be used to determine CRR value, including N-SPT data, Artificial Neural Networks [10], but for this research, CRR was obtained from the CRR vs FC graphs, according to Baziar and Sharafi (2011) who obtained CRR values from these graphs as below.

2.8 FS (Safety Factor)

To determine the liquefaction potential, you can use the following formula:

\[
FS = \frac{CRR}{CSR}
\]

When:
- If FS value is < 1 = liquefaction
- If FS value is > 1 = no liquefaction

3 Result and Discussion

Data of the sand based on index properties as follows:

**Table 1**: Index properties of soil

| Sampel | \(\gamma\) (gr/cm³) | W (%) | Dr | GS |
|--------|---------------------|-------|----|----|
| 1      | 1.778               | 8.820 | 3.712 | 2.658 |
| 2      | 1.611               | 5.450 | 2.196 | 2.660 |
| 3      | 1.473               | 8.870 | 1.819 | 2.659 |
| 4      | 1.644               | 9.410 | 1.668 | 2.655 |
| 5      | 1.490               | 7.870 | 1.697 | 2.654 |
| 6      | 1.622               | 5.480 | 1.303 | 2.664 |

CRR value was obtained of the graph Fig. 5, by Baziar and Sharafi (2011):

**Table 2**: CRR value from confining pressure

| Sampel | FC% | CRR \(\sigma^* = 60\) kPa | CRR \(\sigma^* = 120\) kPa | CRR \(\sigma^* = 240\) kPa |
|--------|-----|----------------------------|--------------------------|--------------------------|
| 1      | 3   | 0.382                      | 0.305                    | 0.263                    |
| 2      | 2.47| 0.390                      | 0.320                    | 0.270                    |
| 3      | 3.03| 0.380                      | 0.303                    | 0.261                    |
| 4      | 1.17| 0.405                      | 0.338                    | 0.279                    |
| 5      | 0   | 0.415                      | 0.345                    | 0.290                    |
| 6      | 0.07| 0.412                      | 0.343                    | 0.286                    |

![Fig 5: FC (Fine Contents) vs CRR (Cyclic Resistance Ratio) Baziar and Sharafi (2011)](image)

![Fig 6: CRR value for containing pressure](image)

The higher the value of the pressure produced, the smaller the potential for liquefaction because with high pressure, the soil becomes dense and the bond between the granules gets stronger which results in smaller soil pores, so liquefaction is less likely to occur.

The value of earthquake acceleration \((a_{max})\), reduction factors \((rd)\) and cyclic stresses \((\tau_c)\) obtained as follows:
 liquefaction is very high. To determine liquefaction potential in soil samples, the value of safety factor (FS) at each pressure is calculated, if the value of FS > 1, then liquefaction will not occur, and if FS < 1, then the potential for liquefaction is very high. 

### Table 3: Reduction factor, earthquake acceleration, and cyclic stress

| Sampel | rd   | a max | τc  |
|--------|------|-------|-----|
| 1      | 0.994| 0.249 | 29.164 |
| 2      | 0.994| 0.174 | 18.470 |
| 3      | 1.200| 0.130 | 456.6 |
| 4      | 1.200| 0.106 | 415.7 |
| 5      | 1.200| 0.087 | 309.1 |
| 6      | 1.200| 0.092 | 355.9 |

The farther the distance of the epicenter, the smaller the earthquake acceleration. Facilities / infrastructure such as schools, hospitals, government offices, close to potential earthquake epicenters needs to be designed with consideration of the possibility of liquefaction.

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### Table 4: Confining pressure σ' = 60 kPa

| Sampel | σ' (kPa) | CSR | CRR | FS | Ket |
|--------|---------|-----|-----|----|-----|
| 1      | 60      | 0.486| 0.382| 0.786| yes |
| 2      | 60      | 0.308| 0.390| 1.267| no  |
| 3      | 60      | 0.076| 0.380| 4.994| no  |
| 4      | 60      | 0.069| 0.405| 5.846| no  |
| 5      | 60      | 0.052| 0.415| 8.055| no  |
| 6      | 60      | 0.059| 0.412| 6.946| no  |

### Table 5: Confining pressure σ' = 120 kPa

| Sampel | σ' (kPa) | CSR | CRR | FS | Ket |
|--------|---------|-----|-----|----|-----|
| 1      | 120     | 0.243| 0.305| 1.255| no  |
| 2      | 120     | 0.154| 0.320| 2.079| no  |
| 3      | 120     | 0.038| 0.303| 7.964| no  |
| 4      | 120     | 0.035| 0.338| 9.758| no  |
| 5      | 120     | 0.026| 0.345| 13.393| no  |
| 6      | 120     | 0.030| 0.343| 11.565| no  |

### Table 6: Confining pressure σ' = 240 kPa

| Sampel | σ' (kPa) | CSR | CRR | FS | Ket |
|--------|---------|-----|-----|----|-----|
| 1      | 240     | 0.122| 0.263| 2.164| no  |
| 2      | 240     | 0.077| 0.270| 3.508| no  |
| 3      | 240     | 0.019| 0.261| 13.720| no  |
| 4      | 240     | 0.017| 0.279| 16.109| no  |
| 5      | 240     | 0.013| 0.290| 22.516| no  |
| 6      | 240     | 0.015| 0.286| 19.287| no  |

The highest CSR value was 0.486 kPa for confining pressure 60 kPa which dropped to 0.243 kPa for 120 kPa and 0.122 kPa for 240 kPa. CSR is inversely proportional to CRR and it was found that if the CRR value is higher than the CSR value the potential for liquefaction is low.

Conclusion

The results of this study indicate that several of the large public buildings in the coastal area around Padang and Pariaman city are build on soil that could experience liquefaction in case of an earthquake. As this area is also earthquake-prone it could be suggested that future construction of such public structures be conducted further inland in areas with soils that are less likely to suffer from liquefaction under pressure. Failing that construction methods that are less vulnerable to liquefaction need to be investigated for buildings in these areas.

References

1. F. Pratama, A. S. Budi, Wibowo, Jnl Oln Mtrak Tnk, 2 (2014)
2. A. Hakam, H. G. Putra, D. Lastaruna, Jnl Rkys Spl 5 (2009)
3. H. Warman, D. Y. Jumas, Jnl Rkys Spl 9 (2013)
4. L. Z. Mase, Jnl Trts Trpn Bdg Rkya Spl 24, 11-16 (2017)
5. K. C. Tijow, O. B. A. Sompie, J. H. Tico, Jnl Spl Sik 6, 491-500 (2018)
6. S. P. O. Siahaan, Tugas Akhir SI, 60-61 (Padang, 2015)
7. L. Bjerrum, S. Kringstad, O. Kummeneje, *The Shear Strength of a Fine Sand* (NGI, 1961)
8. T. L. Youd, Jnl Gtchncl Gevrmnt Engg 127, 817-833 (2001)
9. M. Baziar, H. Sharafi, S Dnmc Ertqke Engg 31, 857-865 (2011)
10. H. Sharafi, S. Jalili, Opn Jnl Cvl Engg 4, 217-228 (2014)