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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:

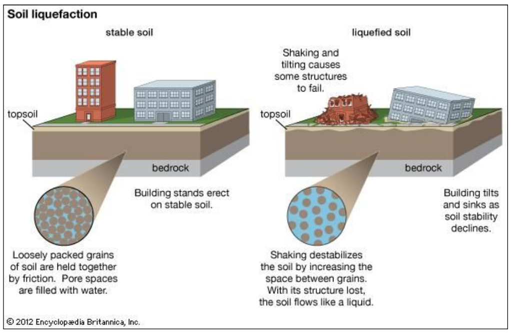

Fig 1. Process of liquefaction.

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.

Fig 2. Satellite Imagery of Petobo

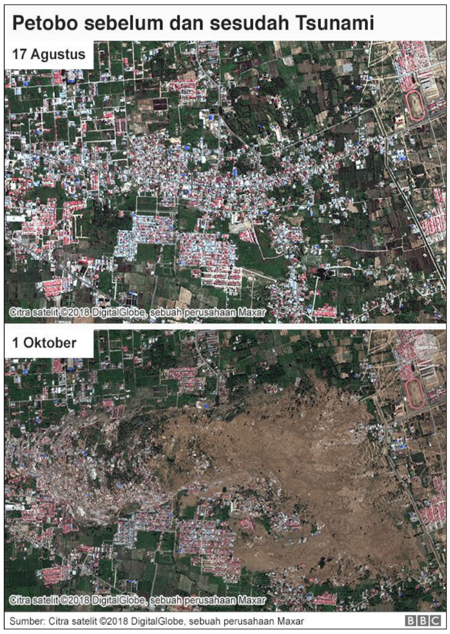

Fig 3. Conditions after liquefaction in Balaroa

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Fig 4. Conditions after liquefaction in Petobo

To mitigate such disasters, analysis of the potential of liquefaction in areas that may be vulnerable is necessary. There are various methods to analyze the potential for liquefaction in the field and in the laboratory including Cone Penetration Test data,and the Seed and Idriss calculation method [2],[3], [4], determined liquefaction potential using N-SPT data (Standard Penetration Test), and the Idriss and Boulanger method predicted the liquefaction that occurred in the Bengkulu city area from the September 12, 2007, magnitude 8.6 earthquake well [5], also found that N-SPT rather than Seed and Idriss predicted the liquefaction that occurred at Bitung pier in North Sulawesi [6], determined liquefaction risk in the laboratory- based on a grain size analysis using a sieve test from which gradient curves were constructed.

Liquefaction testing in the laboratory has also been conducted using a triaxial test, which can determine the potential for liquefaction from cyclic loads [7]. The potential of liquefaction can also be predicted by measuring the effective confining pressure for various CRR value and construction a graph of cyclic resistance ratio (CRR) against Fine Contents (FC) from which the safety factor for liquefaction can be calculated. The safety factor value is an important predictor of potential liquefaction in sandy soil. This method because it only requires shallow samples of soil. Hence, this is the method chosen for the present study.

2 METHODOLOGY

2.1 Preliminary Investigation

Samples were taken from 6 different locations where there are important structures such as school, mosque, or state-owned companies, where analysis of potential liquefaction could gauge the risk of damage to these buildings. The six sites were : 1) Pariaman Beach (Floating Mosque of Kota Pariaman), 2) Poltekpel School (Ketaping), 3) Rusunawa (Tabing), 4) Padang Beach (Behind UNP Campus) , 5) Teluk Bayur Port, 6) Pertamina, Bungus. Samples were taken to a depth of 30 cm.

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:

$$D_r = \frac{\left[\frac{1}{\gamma_{d\,(min)}}\right] - \left[\frac{1}{\gamma_d}\right]}{\left[\frac{1}{\gamma_{d(min)}}\right] - \left[\frac{1}{\gamma_{d(maks)}}\right]} = \left[\frac{\gamma_d - \gamma_{d(min)}}{\gamma_{d(maks)} - \gamma_{d(min)}}\right]\left[\frac{\gamma_{d(maks)}}{\gamma_d}\right] \tag{1}$$

Where :

$\gamma_{d(min)}$ is Dry unit weight in the *loosest* state; (that is,when the void ratio is,e $_{maks}$)

γ_d is *in situ* dry unit weight (*in situ* void ratio, e)

$\gamma_{d(maks)}$ is Dry unit weight in the *densest* state; (that is,when the void ratio is, e $_{min}$)

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

$$Moisture\ content = w\ \% = \left(\frac{W_w}{W_s}\right) x\ 100\% \tag{2}$$

Where:
Ws is Weight of the soil solids
Ww is Weight of water

$$Moist\ unit\ weight = \gamma = \frac{W}{V} \tag{3}$$

Where:
W is Total weight of the soil specimen = Ws + Ww
V is Total volume of soil

$$Dry\ unit\ weight = \gamma d = \frac{\gamma}{1+w} \tag{4}$$

Where:
γ 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 throught a filter no.200.

2.4 Eartquake Acceleration (a $_{max}$)

Earthquake acceleration of the bedrock can be calculated using the atenuase function which describes the correlation between the eartquake acceleration (a max), Earthquake Magnitude (Mw) and the distance (r) from the earthquake epicenter.

Atenuase function formula calculated by *Joyner & Boore*:

$$a = 10^{[\,0.71 + 0.23(M_w - 6) - \log(r) - 0.0027r\,]} \tag{5}$$

Where:
a is earthquake acceleration
M_w is earthquake magnitude
r $= \sqrt{ro^2 + 8^2}$
ro 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 formulae is:

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

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 formulae is:

$$CSR = \frac{\tau c}{\sigma'} = \frac{0{,}65.\gamma.z.\frac{amax}{g}.rd}{\sigma'} \qquad (7)$$

Where :

τc	is Cyclic Shear Stress (kPa)	
σ’	is Confining pressure	(kPa)
z	is Dept	(m)
γ	is Unit Weight	(g/cm^3)
g	is Gravitation	(m/s^2)
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.

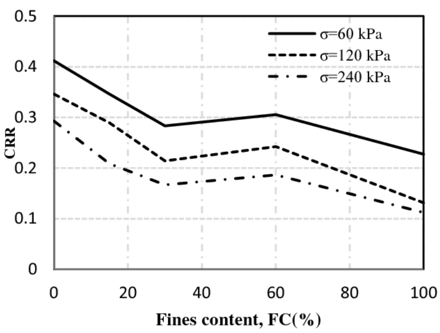

Fig 5: FC (Fine Contents) vs CRR (Cyclic Resistence Ratio) Baziar and Sharafi (2011).

2.8 FS (Safety Factor)

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

FS = 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	γ (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 σ' = 60 kPa	CRR σ' = 120 kPa	CRR σ'= 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

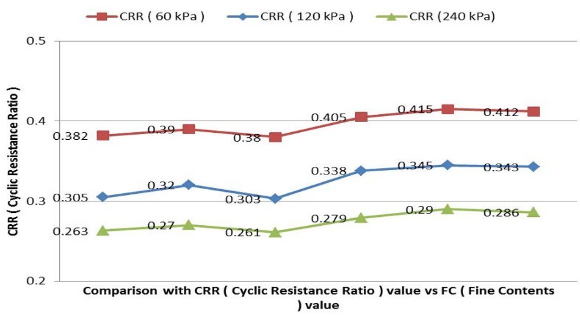

Fig 6: CRR value for containing pressure

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 (**τc**) obtained as follows:

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	4.566
4	1.200	0.106	4.157
5	1.200	0.087	3.091
6	1.200	0.092	3.559

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.

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 the if FS < 1, then the potential for liquefaction is very high.

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

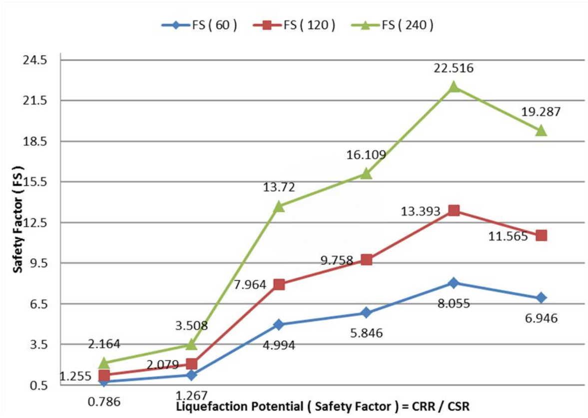

Fig 7: Safety Factor for containing pressure

From the FC vs CRR graph with confining pressure 60 kPa, (Baziar and Sharafi: 2011) the highest CRR value was for Fine Contents 0 %, (0,415 kPa). As the confining pressure increase to 120 kPa and then to 240 kPa, the CRR values dropped to 0,345 and 0,290 kPa respectively.

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.

The safety factor value for liquefaction at 60 kPa pressure was 0,786 for soil from one location (Floating Mosque of Kota Pariaman) tested indicating that site could be at risk of liquefaction in case of an earthquake.

4 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.

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