Cyclic Behaviour of Palu Sandy Soils in Cyclic Simple Shear Test

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Abstract. A 7.5-moment magnitude earthquake hit Palu, Central Sulawesi, Indonesia, in September 2018. This earthquake caused many damages and casualties, including tsunami and liquefaction. Following these events, Palu sand’s cyclic properties were investigated under cyclic simple shear testing conditions, which could convincingly portray the real seismic ground shaking under repeated shear force. All the tests were performed under the frequency of 1.0Hz with varied relative densities and cyclic stress ratio (CSR). The results show that grain size distribution plays a significant role in liquefaction resistance of sandy soils tested—the soils tested under higher CSR need fewer cycles to liquefy. Furthermore, soils which in loose conditions tend to have lower liquefaction resistance.

1. Introduction
On 28th September 2018, the enormous 7.5-moment magnitude earthquake whose mainshock was 77-km from Palu and 20-km depth was felt in Central Sulawesi, Indonesia. It was followed by a tsunami, landslides, liquefaction, and caused casualties [1].

Soil liquefaction is a condition where enormous pore pressures occur due to the cyclic loading of granular soils and the soils’ consequent softening. Then, the soil behaves temporarily as a viscous liquid when the effective stress approach zero. It is one of the most critical geohazards that causes tremendous damage, according to Kramer (1996) [2]. Evaluating liquefaction potential during earthquakes is an essential subject for geotechnical engineers in the seismically active region [3]. The phenomenon itself has been observed over the past few decades. It was well observed during the notorious Niigata earthquake in 1964 [4–10].

Several studies have been performed in the laboratory to understand the behavior of soils subjected to cyclic loading. According to Mele et al. (2019), cyclic laboratory testing may have an essential role in exploring this phenomenon. One of the most common testing methods to evaluate the undrained cyclic resistance to liquefaction is the cyclic triaxial test. However, this test cannot replicate in the laboratory the complex cyclic simple shear stress path experienced by the soil during an earthquake [11]. According to Ulmer et al. (2019), simple shear is commonly accepted as the shear mode of deformation most closely associated with soil deposits’ response under earthquake loading.

This paper presents the result of a comprehensive study carried out on sandy soils collected from Central Sulawesi through cyclic simple shear testing. In particular, it addresses the effect of relative density and CSR on liquefaction resistance.
2. Testing Materials

Soil samples for the current study were collected from Palu, Central Sulawesi, Indonesia. Sand A represents coarse sand, while Sand B is uniform sand. The properties of both sand are presented in Table 1.

There are different ranges of grain-size distributions with a possibility of liquefaction, and it depends on the grading of the soils as to Sassa and Yamazaki (2017). When the grain-size distribution of soil falls in the areas with the possibility of liquefaction, it is assessed that liquefaction can occur and vice versa. As can be seen in grain size distribution curves in Figure 3, Sand A falls in the range with the low possibility of liquefaction while Sand E falls in the high possibility range. Once in the laboratory, sandy soils were sieved (<4.76mm) to separate bigger particles like gravel.

![Figure 1. Sand A](image1.png) ![Figure 2. Sand B](image2.png)

![Figure 3. The grain size distribution of specimens](image3.png)

| Properties          | Sand A | Sand B |
|---------------------|--------|--------|
| Specific Gravity, $G_s$ | 2.64   | 2.57   |
| $D_{50}$ (mm)       | 0.805  | 0.452  |
| $c_u$               | 2.01   | 1.77   |
| $e_{min}$           | 0.562  | 0.549  |
| $e_{max}$           | 0.841  | 1.108  |
3. Experimental Program
The cyclic simple shear test was used to study the response of soil due to cyclic loading. According to Seed et al. (1986), this test convincingly represents the real seismic ground shaking under repeated horizontal shear force [14]. It was performed on specimens with 20-mm in height and 70-mm in diameter. Samples were reconstituted using the dry deposition technique to make the sample uniform (Ishihara, 1993) [14]. It was involved by pouring oven-dry sandy soil using a funnel into a mold. The funnel was moved up gradually at zero drop height until the sand came out entirely from the funnel. Then, the top surface was smoothed, and the top cap was carefully placed upon it. Afterward, the specimen is placed in the CSS apparatus, as can be seen in Figure 4.

To generate in-situ ($K_0$) stress conditions, vertical consolidation stress was applied to the sample before shearing [15]. Specimens were consolidated under the initial sheer pressure of 100 kPa without saturation process. It was further subjected to stress-controlled loading with a frequency of 1.0 Hz for 50 cycles. During this test, equivalent pore pressure and shear strain were measured. Baxter et al. (2010) discovered that the pore pressure response can be inferred from the change in vertical stress observed throughout the test [15]. When the cyclic loading is applied undrained, the rubber membrane tends to expand and even extrude from a narrow space at the specimen’s upper periphery as to Ishihara (1996). To avoid this undesirable situation, the ring-surrounded membrane is used in this research. The tests were all conducted at three variances of relative density: 30%, 50%, and 70% for various CSR. Liquefaction is considered to occur when the excess pore pressure,

\[ r_u = \frac{\Delta u}{\sigma_{v0}} \]  

is equal or more than 0.90 (stress criterion), or when the value of shear strain in double amplitude is 7.5% (strain criterion).

![Figure 4. The specimen is placed in CSS apparatus](image)

![Figure 5. Consolidation process](image)

4. Results and discussions
Cyclic simple shear testing was done on three different CSRs values. They were 0.15, 0.20, and 0.25. The applied cyclic stress ratio (CSR) can also be calculated by:

\[ CSR = \frac{\tau_{cyc}}{\sigma_{v0}} \]
where $\tau_{cyc}$ is applied cyclic shear stress and $\sigma'_v$, the variable is the initial vertical effective stress of 100 kPa.

As shown in Table 2, unidirectional cyclic shearing was done on two sandy soils retrieved from Palu, Central Sulawesi. The number of cycles needed for soil to liquefy, $N_{liq}$ evaluated by criterion mentioned before is also reported in this table. From Table 2, it is clear that shear strain increases rapidly for higher CSRs. These results correspond with the outcomes Boulanger and Ziotopoulou (2015) had, where the higher CSR assigned to the samples, the number of cycles required to prompt initial liquefaction is fewer. However, if the specimen tested has a higher relative density, it will take more cycles to reach a liquefaction state.

| Sample | Relative Density (%) | CSR | $N_{liq}$ |
|--------|----------------------|-----|-----------|
| Sand A | 30                   | 0.15| 11.0      |
|        |                      | 0.20| 3.0       |
|        |                      | 0.25| 1.0 - 1.5 |
|        | 50                   | 0.15| 16.0 - 19.0|
|        |                      | 0.20| 8.0 - 10.0 |
|        |                      | 0.25| 3.0       |
|        | 70                   | 0.15| 40.0 - 47.0|
|        |                      | 0.20| 9.0       |
|        |                      | 0.25| 1.0 - 1.5 |
| Sand B | 30                   | 0.15| 8.0       |
|        |                      | 0.20| 4.0 - 5.0 |
|        |                      | 0.25| 1.0       |
|        | 50                   | 0.15| 6.0 - 10.0 |
|        |                      | 0.20| 2.0 - 3.0 |
|        |                      | 0.25| 1.0 - 2.0 |
|        | 70                   | 0.15| 22.0      |
|        |                      | 0.20| 5.0       |
|        |                      | 0.25| 3.0 - 4.0 |

As an example, Sand A’s results with 30% of relative density are shown in Figure 6. Figure 6a shows that the applied value of CSR for this sample is 0.25. Figure 6b shows that the number of shear strains getting higher, along with the development of pore pressure. Pore-water pressure was computed from the measured reductions in mean effective stress as to Kuhn et al. (2014). The cyclic number obtained for stress and strain criteria is similar for this specimen. Meanwhile, the hysteresis loop can be seen in Figure 6c.

For comparison, results from Sand B with the same parameters can be seen in Figure 7. Figure 7a shows that CSR value is constant throughout the test. Figure 7b represents that there is rapid pore-water pressure build-up along with shear strains that getting higher. Meanwhile, Figure 7c shows the hysteresis loop for this sample.

Both models show that the response of the soil is similar. The hysteresis loop trends for Sand A (Figure 6c) and Sand B (Figure 7c) are alike. However, favorable shear strains were more pronounced for Sand A, while negative shear strains were more pronounced for Sand B. Nevertheless, the amplitudes of shear strains obtained by Sand B are higher than Sand A. Despite the similarities of the range of $N_{liq}$ in high CSR value, Sand A showed a more excellent liquefaction resistance than Sand B. For Sand A with a relative density of 50% and CSR of 0.15, 16 to 19 cycles were required to liquefy the soil.

On the other hand, it required 6 to 10 processes to develop the same conditions for Sand B. The slight
difference in the liquefaction resistance on the two sandy sand could be associated with their different grain size composition. Their cyclic loads and relative densities were nominally the same.

Figure 8 shows the relationship of CSR with the number of cycles for Sand A and Sand B. For both specimens, the higher relative density, the more outstanding CSR was needed to reach the liquefaction phase. Sand A, with a relative density of 70%, had a broad range of Nc. Meanwhile, Sand B with the same parameters had a narrower scope. With CSR of 0.15, Sand A needed around 40 cycles to liquefy.
while Sand B only needs 22 cycles. This condition could be attributed to their grain size distributions, where Sand B falls in a high possibility range of liquefaction.

![Figure 8. Relationship of CSR and number of cycles](image)

5. Conclusion
A series of undrained cyclic simple shear tests on sandy soil from Palu, Central Sulawesi, Indonesia, are presented and discussed. The specimens were reconstituted with dry deposition technique at 30%, 50%, and 70% relative density. Sand A and Sand B exhibited different liquefaction resistance, attributed to their grain size distribution and particle shapes. If the soils were subjected to higher CSRs, they would likely be more prone to liquefaction. This condition also occurs in samples with loose conditions. For most of the conditions, Sand A showed higher liquefaction resistance than Sand B. It is shown from the number of cycles needed for Sand A to reach a liquefaction state, which is higher than Sand B. However, further research is still required to understand the cyclic properties of sandy soils collected from Palu, Central Sulawesi.

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