Vs and CPT based evaluation of location with high liquefaction damage during 2018 Palu earthquake

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Abstract. Palu earthquake occurred on 28 September 2018 caused severe liquefaction damages for the city. Based on field surface damage survey by Indonesia Geology Agency, a location was classified within the high liquefaction damage area. The pre-event soil characteristics of this location was provided by results of MASW (Multichannel Analysis of Surface Wave) and CPT (Cone Penetration Test) surveys. The soil deposit could characterized by relatively low shear wave velocity (Vs) and low of cone resistance (qc) values. The potential liquefaction presented by safety factor (0.6 to 0.9) obtained based on both methods was consistent to depths from 2.0 m to 5.0 m. This safety factor appears to be consistent with the high liquefaction damage reported by the Agency.

1. Introduction
The 28 September 2018 Palu earthquake with magnitude of 7.4 caused severe damages in the City of Palu. Liquefaction is a phenomenon in which sandy soils lose their shear strength due to the increase in porewater pressures induced by seismic shaking (e.g., [1]). Ishihara [2] presented the liquefaction phenomenon with a simulation of vibration of sand and water in an aquarium; the results included the compaction of sand and the increase in the water level.

It has been shown (e.g., [3]) that the liquefaction phenomenon depends on the type of soil, relative density, initial confining pressure, as well as the intensity and duration of seismic vibration. The soil type most prone to liquefaction is low density sandy soils in low confining pressure conditions subjected to a large magnitude earthquake. In addition, poorly graded sands tend to be more vulnerable compared to well graded sands. Furthermore, it has been shown (e.g., [4]) that a higher fines content would provide a higher resistance to liquefaction.

A number of field tests have been suggested to evaluate the liquefaction potential, including standard penetration tests (e.g., [3]), cone penetration tests (e.g., [5]), and shear wave velocity (e.g., [4]). Figure 1 shows the relationship between the normalized shear wave velocity and the liquefaction resistance, represented by the cyclic resistance ratio [4]. It is noted that shear wave velocity could be measured using the MASW (Multichannel Analysis of Surface Waves) geophysical method.

The Indonesia Geology Agency has developed the liquefaction potential map based on the post 2018 event field survey [6]. The red, orange, and yellow colored areas are areas with very high, high, and medium liquefaction potential, respectively. The white areas were not mapped during the survey.
Concrete cracking is known to have a knock-on effect on the durability performance and long-term service life of reinforced concrete structures [1, 2]. This phenomenon is primarily attributed to complex loading conditions that may arise from external loading under day-to-day service in addition to environmental exposures, creating even more complex physical and chemical changes in concrete properties [3]. This will cause not only localised distress and stiffness degradation of structural members but also poor resistance of penetration from aggressive agents (e.g. alkali-silica reaction and chloride transport) which will result in further significant deterioration [4, 5].
2. Research Method

The research method employed is summarized as a flowchart shown as Figure 4. The shear wave velocity data ($V_s$) and the cone resistance data ($q_c$) are used to calculate their respective Cyclic Resistance Ratio (CRR) using the methods summarized in [7]. Both the $V_s$ data and the $q_c$ data are subsequently normalized to 1 atm confining pressure, as the methods employ the $V_{s1}$ data and the $q_{c1}$ data. It is noted that the groundwater level was about 2.0 m below the ground surface.

The seismic demand represented by the Cyclic Stress Ratio (CSR) is also calculated based on the method suggested in [7]. The CSR is a function of soil vertical effective and total pressures, as well as the peak ground acceleration (PGA) of the considered earthquake. In this paper, the PGA value is estimated based on the average PGA calculated based on the methods proposed by the number of PGA was 0.462, calculated average empirical equation by Boore et al. [8] and Campbell and Bozorgnia [9].

The liquefaction potential is then determined based on the safety factor (SF), defined as the ratio of CRR to CSR. SF less than or equal to 1.0 would indicate that liquefaction would occur, while SF greater than 1.0 would indicate otherwise.

3. Liquefaction Assessment Result
Figure 5a presents the distribution of $V_s$ with depth. The $V_s$ values in general increase with depth, indicating an increase in soil compaction level with depth (e.g., [10]). Figure 5b presents the distribution of $q_c$ with depth. In general, the $q_c$ values were less than 10 MPa to a depth of 10.0 m, and they tend to increase with depth as well. It is noted that, based on data from a nearby bore hole, the particle size distribution of soil in this location is predominantly coarse grained sands.

Figure 6a presents the cyclic resistance ratio (CRR) from the PKA10 MASW data and the CPT7 data. Figure 6a alsos shows the cyclic stress ratio (CSR) for the research location. The values of $q_c$ based CRR are between 0.08 and 0.60, while those of $V_s$ based CRR are between 0.09 and 0.60. The values of CSR above ground water level are lower than those below the ground water level, because of the difference in effective soil vertical stresses. The values of CSR decreases with an increase of soil depth.

Overall, the liquefaction safety factor for the research location is between 0.30 and 1.20, and the depths of which $SF < 1.0$ are between 1.0 m and 12.0 m as shown in Figure 6b. It can be seen that, to a depth of 5.0 m, the SF based on $q_c$ is similar to that based on $V_s$. However, for depths greater than 6.0 m, the SF based on $q_c$ is much lower than that based on $V_s$.

Based on liquefaction potential analysis proposed by Andrus and Stokoe [4], liquefaction would occur at depths from 2.0 m to 12.0 m. A comparison between Figures 5a and 6a, the liquefaction SF is much less than 1.0 for depths up to 6.0 m, and the SF is about or greater than 1.0 for $V_s$ values of 180 m/s or greater.

Figure 5. Liquefaction potential by depth (a) Graph of Shear wave velocity of PKA 10 (b) CPT Survey Result of CPT07.
Based on liquefaction potential analysis proposed by Robertson and Wride [5], liquefaction would occur at depths from 2.0 m to 12.0 m. A comparison between Figures 5b and 6b, the liquefaction SF is much less than 1.0 for $q_c$ values of about 10 MPa or less. Furthermore, the friction ratio of CPT7 was used to estimate the soil types using the method proposed by Robertson [11]; the soil types are suggested to be silts and sands. This is in accordance with Ishihara [2] proposal, that liquefaction occurs in silt and sand materials which would be affected by pore water pressure below ground water level.

The liquefaction SF is consistently lower than 1.0 (between 0.6 and 0.9) for depths between 2.0 m and 5.0 m based on both tests. This appears to be consistent with the results of the field survey reported in [6]. This location is within high liquefaction damage area, characterized by crack more than 5 cm, settlement more than 10 cm, and lateral spreading more than 5 cm. Although this is an indirect comparison, the liquefaction field survey [6] could be used to validate the liquefaction SF obtained by the methods based on the shear wave velocity and the cone resistance.

4. Conclusions
This paper reported liquefaction analysis results employing the pre-event shear wave velocity $V_s$ obtained from MASW survey and the pre-event cone penetration $q_c$ data for a location in Balaroa area, Palu. This location is within the high liquefaction damage area as reported by the a field survey after the 28 September 2018 Palu earthquake. The liquefaction safety factor indicated by both data sets was consistent for depths up to about 5.0 m, and the safety factor was between 0.6 and 0.9. The safety factor indicated by the $V_s$ data was higher for depths greater than 6.0 m. This low liquefaction safety factor appears to be consistent with the reported high liquefaction damage class, suggesting a good correlation between the analysis and the field survey results.
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