Evaluation of unit weight and strength of sand using electro-mechanical impedance

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ABSTRACT
In this study, the EMI (electro-mechanical impedance) of a small piezoelectric sensor was applied for measuring a unit weight and strength of sand. Three different sizes of uncemented Nakdong river sand were filled loosely or densely into a compaction mold. A piezoelectric sensor with 2 cm in diameter was installed into sand for EMI measurement. A small Nakdong river sand was mixed with cement ratios of 4, 8 12, 16% and then compacted into a specimen with 5 cm in diameter and 10 cm in height. The cemented specimen consisted of 6 layers with a sensor at the third layer. The EMI signal for 3 days and unconfined compressive strength at 3rd day was measured. As a unit weight of uncemented sand increased, a resonant frequency increased slightly from 102 to 105 kHz but a conductance at resonant frequency (peak conductance) decreased. For cemented sands, as a curing time and cement ratio increased, the resonant frequency increased significantly from 129 to 266 kHz but the peak conductance decreased. An unconfined compressive strength (UCS) of cemented sands was between 289 and 1,390kPa for different cement ratios. The relationship between UCS and resonant frequency linearly increased but one with peak conductance was in inverse proportion.

RÉSUMÉ
Dans cette étude, l'EMI (impédance électromécanique) d'un petit capteur piézoélectrique a été appliqué pour mesurer un poids unitaire et la force du sable. Trois tailles différentes de sable de rivière Nakdong non cimenté ont été remplies de façon lâche ou dense dans un moule de compactage. Un capteur piézoélectrique de 2 cm de diamètre a été installé dans le sable pour mesurer les interférences électromagnétiques. Un petit sable de rivière Nakdong a été mélangé avec des rapports de ciment de 4, 8 12, 16%, puis compacté en un échantillon de 5 cm de diamètre et de 10 cm de hauteur. L'échantillon cimenté se composait de 6 couches avec un capteur à la troisième couche. Le signal EMI pendant 3 jours et la résistance à la compression non confinée au 3ème jour ont été mesurés. À mesure que le poids unitaire du sable non cimenté augmentait, une fréquence de résonance augmentait légèrement de 102 à 105 kHz, mais une conductance à la fréquence de résonance (conductance de crête) diminuait. Pour les sables cimentés, à mesure que le temps de durcissement et le rapport de ciment augmentaient, la fréquence de résonance augmentait significativement de 129 à 266 kHz, mais la conductance de pointe diminuait. La résistance à la compression non confinée (UCS) des sables cimentés se situait entre 289 et 1 390 kPa pour différents taux de ciment. La relation entre l'UCS et la fréquence de résonance a augmenté linéairement, mais celle avec une conductance de crête était inversement proportionnelle.

1 ABSTRACT

Piezoelectric (PZT) materials are often applied for various civil engineering projects. One PZT sensor called a bender element has been used to generate a shear wave or compressive wave in laboratory testing (Dyvik and Madshus, 1985; Lee and Lee, 2006; Shirley and Hampton, 1978; Suwal and Kuwano, 2013). On the other hand, EMI (Electro-Mechanical Impedance) technique using PZT sensor has been widely used for monitoring concrete structure as a non-destructive testing technique. It has usually been attached to the surface of concrete and steel bridges and concrete structures to monitor its strength or deformation. Recently, it was inserted into a mortar to measure curing conditions (Lee et al., 2016).

Soil compaction is a fundamental procedure for soil engineering. The degree of soil compaction can be determined by measuring unit weight (density) of compacted soils. On the other hand, soil density around pipes or retaining walls can be loosened by soil washing due to leakage or ground water flow. Recently, this kind of ground failure related to soil density change is occurring more frequently. Therefore, it is necessary to monitor unit weight of soils in the field.

In this given study, a PZT patch was installed into three different sizes of Nakdong river sand, which was poured into a small compaction mold. Four different levels of surcharges were applied on the surface of each sand. Then, a frequency and conductance was measured for each sand with different surcharge. A resonant frequency and a conductance at resonant frequency were correlated with surcharge and corresponding unit weight. This kind of relationship can be used to predict a unit weight of soil followed by compaction, loosening, or cavitation in the field. The strength of cemented sand was also measured and correlated to EMI.

2 PIEZOELECTRIC PATCH AND SAMPLE PREPARATION

A PZT patch used in the testing was shown in Figure 1. It was coated with ceramic to protect a short circuit. Its dimension is also shown in Figure 1. The EMI measuring system used in this study consists of LCR (Inductance, Capacitance, and Resistance) meter, PZT patch, GP-IB (General Purpose Interface Bus), and software. This PZT patch without soil has three modes of resonant frequencies (130, 468, and 662 kHz) below 1 MHz. The frequency range from 50 to 350 kHz within 1st mode of resonance was selected to easily distinguish different soil densities.

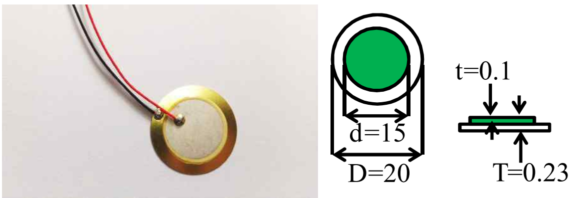


Figure 1. PZT patch after coating and dimensions (unit: mm)

A series of EMI sensing experiments for different surcharges were carried out on Nakdong river sand. The sand was dried and sieved into three different sizes, small (0.075-0.85 mm), medium (0.85-2.0 mm) and large (2.0-4.75 mm). Its grain size distribution curves are compared in Figure 2. Their specific gravity was the same as 2.65. It was loosely poured into a compaction mold with 15 cm in diameter and 17 cm in height as shown in Figure 3a. The PZT patch was located at the 1/3rd of a mold and then four different levels of surcharges were applied on the surface of sand. The ratios of a diameter of PZT patch (D_{PZT}) to a mean grain size of sand (D_{50}) are 47, 17, and 6 for three sands, respectively.

For strength testing, the small sand was mixed with different cement ratios, 4, 8, 12, and 16%. As shown in Figure 3b, a specimen was 5 cm in diameter and 10 cm in height and a PZT patch was located in the middle of the specimen. It was air cured for 3 days and then tested for unconfined compression tests.

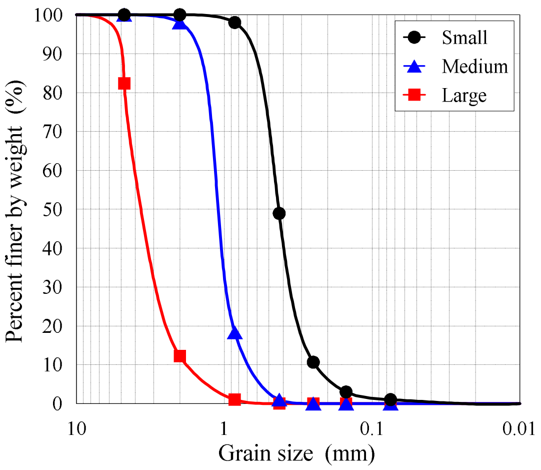


Figure 2. Grain size distribution curves of Nakdong river sand

3 RESULTS OF EMI SENSING

The initial dry unit weights of the three sands were 14.45, 15.74, and 16.83 kN/m^3 without a surcharge. The unit weight of sand after applying surcharge was calculated by considering settled surface. As a surcharge increased, the unit weight gradually increased. The variation was most dominant at the small grain size of sand from 14.45 to 17.49 kN/m^3.

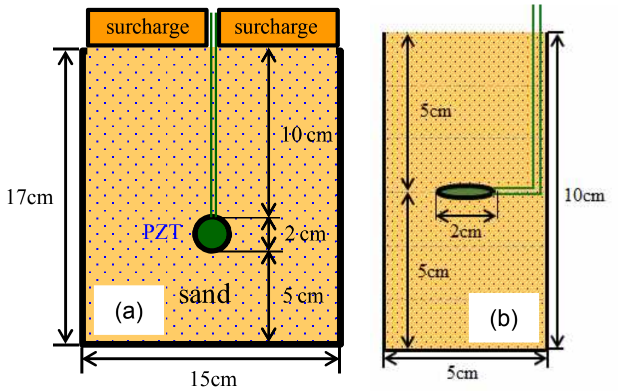
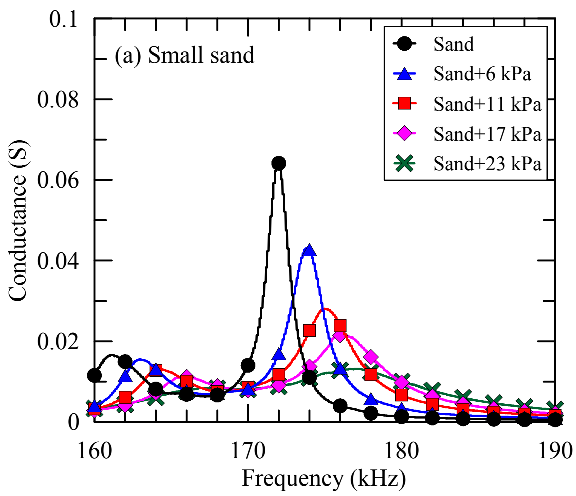


Figure 3. Experimental setup for EMI measurement for (a) uncemented sand and (b) cemented sand

3.1 Effect of surcharge on EMI sensing

The effects of surcharge applied for uncemented sand on EMI sensing were investigated in terms of a resonant frequency and a peak conductance. Figure 4 shows the relationship between frequency and conductance on three sands. As a surcharge on sand increased, the resonant frequency gradually increased for three sands. It is because sand became stiffer due to unit weight increase caused by surcharge. As a result of that, the vibration became less and a resonant frequency increased. On the other hand, a peak conductance was slightly decreased as a surcharge increased. Similarly, Lee et al. (2015) also showed that the resonant frequency increased and the peak conductance decreased as a mortar became harder.



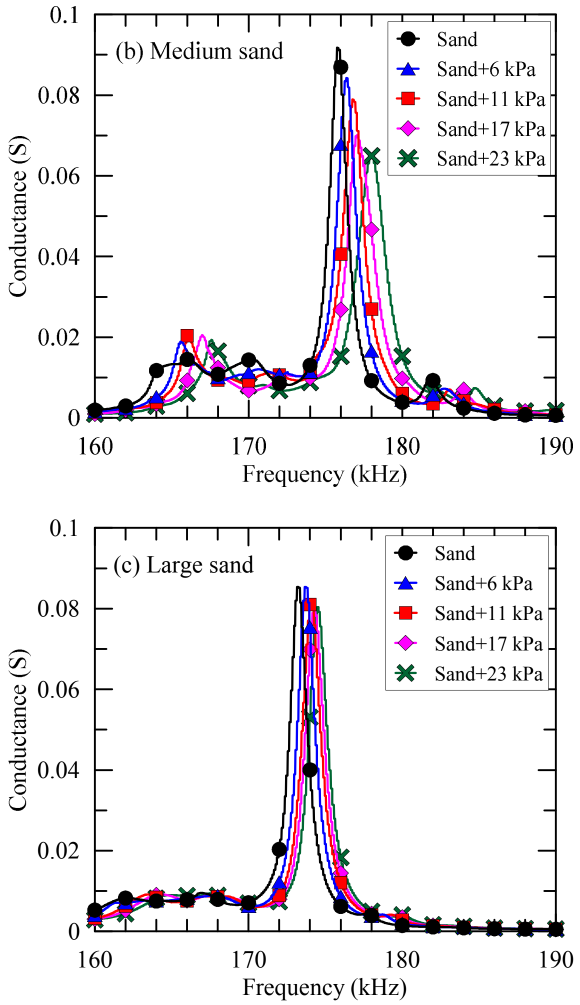


Figure 4. Relationship between frequency and conductance

In the field, soils consist of various grain sizes and therefore three different sizes of sands were used for EMI sensing. Compared to small size of the sand, the effect of unit weight increase caused by surcharge increase is not noticeable on medium and large sands. It seems to be related to the contact area of sand to PZT patch. The relative size of sand particle to PZT patch can influence on the frequency and conductance. For example, the ratio of a diameter of PZT patch to a mean grain size of large and medium sand (D_{PZT}/D_{50}) is 6 and 17. Compared to small size of the sand (D_{PZT}/D_{50} = 47), such large size of sand resulted in less change on EMI sensing.

3.2 Relationship between unit weight vs. frequency and conductance

As shown in Figure 5, a resonant frequency (Figure 5a) increased and a peak conductance (Figure 5b) decreased as a surcharge increased, regardless of a sand size. The variation of resonant frequency and peak conductance is most dominant on small size of Nakdong river sand. As a key finding of this study, the relationship between a dry unit weight (r_d) and a resonant frequency (f_0) of the small sand was derived to Eq. 1 from Figure 5(a). As shown in the figure, as a unit weight increased, the resonant frequency increased but peak conductance decreased. By using this kind of result, we can predict the variation of unit weight in the field due to compaction or surcharge loading.

$$f_0(\mathrm{kHz}) = 1.593 \times r_d(\mathrm{kN/m3}) + 148.71 \qquad [1]$$

For medium and large sands used in this study, the change of resonant frequency and peak conductance was small when a surcharge was applied on the top of specimen. It is because the amount of surcharge itself was low and the transferred load to sand particles was also small. This resulted in a small amount of unit weight change, which marginally influenced the measured frequency or conductance from the 20 mm of PZT patch.

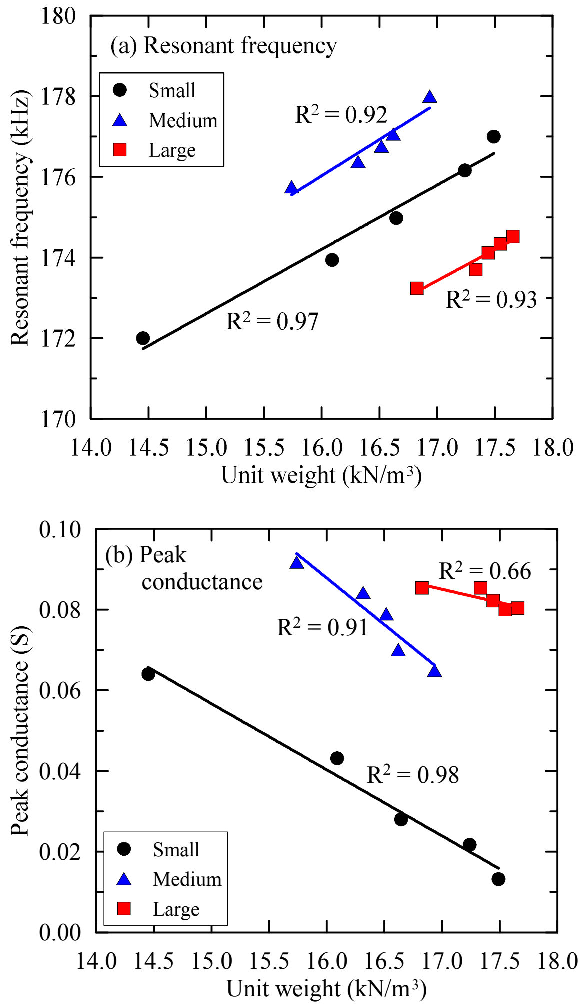


Figure 5. Effect of unit weight on frequency and conductance

3.3 Relationship between compressive strength vs. frequency and conductance

A series of unconfined compression tests were carried out for cemented small sand with different cement ratios. The unconfined compressive strength was 289, 520, 903, and 1,390 kPa for cement ratios of 4, 8, 12, and 16%. As shown in Figure 6, a resonant frequency (Figure 6a) increased but a peak conductance (Figure 6b) decreased as an unconfined compressive strength increased. It was shown that the compressive strength of cemented sand was strongly correlated to its resonant frequency.

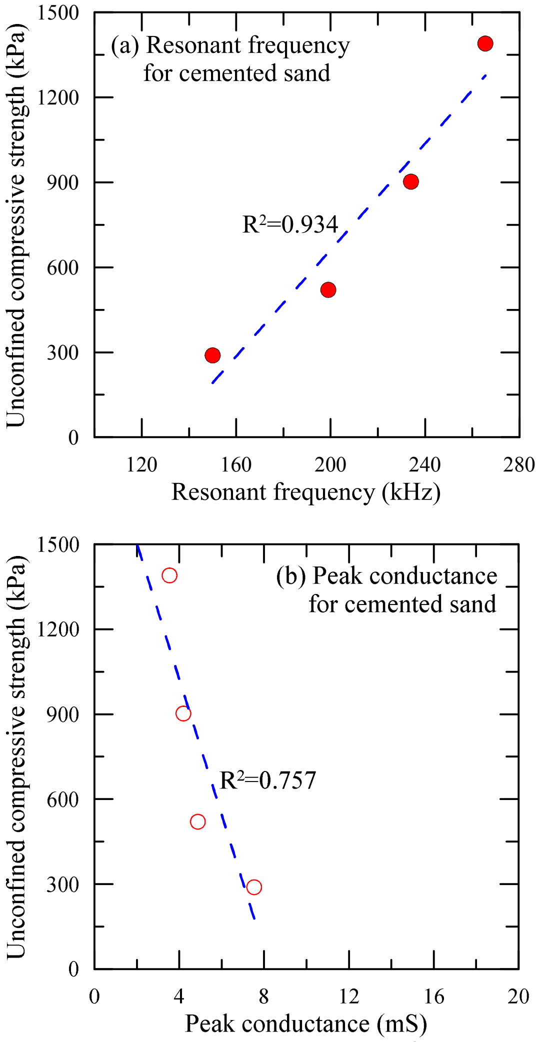


Figure 6. Relationship between unconfined compressive strength and frequency and conductance

4 CONCLUSIONS

The clean Nakdong river sand was poured into a small compaction mold and then applied with surcharge. A series of an EMI sensing experiment were carried out on three different sizes of sands. Four levels of surcharges (6, 11, 17, 23 kPa) were applied on the surface of sand. A small sand with a PZT patch was prepared with different cement ratio (4, 8, 12, and 16%) and tested for unconfined compression tests. The results were compared in terms of a resonant frequency and conductance. The following results were obtained.

As a surcharge increased, a resonant frequency increased but a peak conductance decreased due to the increase of a unit weight.

A unit weight of small size of Nakdong river sand was strongly correlated to the measured resonant frequency and peak conductance. On the other hand, the unit weight of medium and large sizes of Nakdong river sands was marginally correlated to the resonant frequency and peak conductance.

The relationship between a resonant frequency or peak conductance and a unit weight of sand could be capable of predicting the degree of soil compaction, loosening or cavitation in the field.

The compressive strength of cemented small sand was strongly correlated to its resonant frequency.

5 ACKNOWLEDGMENT

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