Response to Reviewer #2
Title: Strength Characteristics of Sand-Silt Mixtures Subjected to Cyclic Freezing-Thawing-Repetitive Loading
Manuscript ID: sensors-935060
Authors: Jong-Sub Lee, Jung-Doung Yu, Kyungsoo Han, and Sang Yeob Kim

The authors are grateful to the reviewers for their valuable comments. We have modified the manuscript based on these comments (We have highlighted these changes in the revised manuscript).

Comments:

This paper is providing interesting data on the strength characteristics and micromechanics of sand-silt mixtures, when these are subjected to cyclic freezing-thawing-repetitive loading. The English is acceptable, but the writing style should be improved by the authors in their future papers, because it causes confusion, and it also demands from the reader great effort to read and re-read the paper many times, from the beginning, to finally understand what the authors want to say. There is too much text to explain some details, while the most relevant information is, in some parts, not revealed to the reader. The symbols (SF, theta_u, etc.) are defined in the beginning but their meaning is not recalled after several pages, which makes the reading difficult. Therefore, the authors should improve this aspect, following my specific recommendations (see below), and take additional comments (see below) in the revision of this manuscript into account, before I can recommend acceptance.

We are grateful to the reviewer for the crucial insights. We have edited the manuscript to include descriptions that address the reviewer’s comments. In addition, this manuscript has been edited by a professional English language editor from Editage.

1) Parameter definitions: It would be helpful if the authors could add, somewhere in the paper, a table with 3 columns, so that the reader can check it whenever a quantity is mentioned in the paper: parameter symbol unit silt-fraction SF % (...)

The authors added the section of “List of notations”, which defines symbol or abbreviation, unit, and meaning to improve the readability of the manuscript. The symbol or abbreviation of D_s, ΔD_r, N, S, θ_u, LVDT, SF, and TDR are summarized in the revised manuscript (LN 32) as follows:
List of notations

- $D_r$ [%] Relative density
- $\Delta D_r$ [%] Change in relative density
- $N$ [ ] Number of repetitive loading
- $S$ [%] Degree of saturation
- $\theta_u$ [%] Volumetric unfrozen water content
- LVDT [ ] Linear variable displacement transducer
- SF [%] Silt fraction
- TDR [ ] Time domain reflectometry

2) Figure 1: It is impossible for the reader to understand what this figure is actually showing, unless the reader is a co-author or knows a very similar paper where a similar figure has been shown. How many samples do you have for each value of the silt fraction? Only 1 sample per silt fraction? If yes, then what do you mean with "maximum" and "minimum" void ratio? Do you measure the void ratio at different positions in the sample, or do you measure one single void ratio for the sample, but have various samples to take an average (in this case, where are the error bars?)? Could you please describe in more detail when, approximately, the maximum and the minimum void ratio values occur during the experiment? In summary: The authors should add a new paragraph where these questions are answered explicitly.

The maximum and minimum void ratios should be determined based on the ASTM D4253 and D4254 standards. The maximum void ratio represents the loosest packing condition (i.e., minimum density state), and the minimum void ratio displays the densest packing condition (i.e., maximum density state) of a specimen. Thus, the maximum void ratio can be obtained by pouring the specimen from the spout as loosely as possible (ASTM D4254). On the other hand, the minimum void ratio can be attained by compacting and vibrating the specimen in the mold (ASTM D4253). Thus, the maximum and minimum void ratios displayed in Fig. 1 are the index properties of each singular sand-silt mixture, which do not change during the test. The authors added the explanation of maximum and minimum void ratios in the revised manuscript (LN 75-82) as follows:

The maximum and minimum void ratios of each sand-silt mixture with different SF were determined based on the ASTM D4253 and D4254 standards [17, 18], and they varied with the
SF owing to the role of fine particles [16] as shown in Figure 1. Note that the maximum void ratio presents the loosest packing condition (i.e., minimum density state), and the minimum void ratio displays the densest packing condition (i.e., maximum density state). Thus, the maximum void ratio can be obtained by pouring the specimen from the spout as loosely as possible, while the minimum void ratio can be attained by compacting and vibrating the specimen in the mold.


3) Line 130: "Previous studies have revealed that the relationship between the volumetric water content and relative permittivity can be expressed by a cubic equation [15, 21, 22]." Is this cubic equation too big to be mentioned in the paper? It would be helpful to display it, so that the reader can make a comparison between it and your results. Moreover, you should make this comparison explicitly, i.e., in some part of the paper you should explicitly write whether your results agree with or contradict the cubic equation.

The majority of previous studies have used relationships between volumetric water content and relative permittivity expressed as empirically cubic polynomial equations (Kim et al., 2018; Lee et al., 2018). Since a time domain reflectometry (TDR) probe was manufactured for this study, a calibration test was conducted to obtain the appropriate cubic polynomial equation. The authors displayed the equation in the revised manuscript (LN 147-160), so that the reader can compare the cubic polynomial equations from previous studies with the one in this study as follows:

From the estimation of the relative permittivity ($\varepsilon_r$) by substituting $\Delta t_2$ into Eq. (1), volumetric unfrozen water content ($\theta_u$) has been commonly estimated using a cubic polynomial relationship as follows:

$$\theta_u = a \cdot \varepsilon_r^3 + b \cdot \varepsilon_r^2 + c \cdot \varepsilon_r + d$$

where $a$, $b$, $c$, and $d$ have been experimentally obtained as shown in Table 2. The coefficients are determined as $a= 0.95$, $b= -12.99$, $c= 64.48$, and $d= -95.04$ through the calibration test.

**Table 2.** Coefficients of cubic polynomial relationships between volumetric unfrozen water content and relative permittivity.
<table>
<thead>
<tr>
<th>Relationship</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kim et al. [15]</td>
<td>0.79</td>
<td>-13.95</td>
<td>84.30</td>
<td>-153.70</td>
</tr>
<tr>
<td>Kim et al. [35]</td>
<td>0.25</td>
<td>-3.70</td>
<td>25.49</td>
<td>-43.13</td>
</tr>
<tr>
<td>Lee et al. [26]</td>
<td>0.11</td>
<td>-2.31</td>
<td>19.66</td>
<td>-33.41</td>
</tr>
</tbody>
</table>


4) **Line 137: What is \(\theta_u\)? Please include the definition of \(\theta_u\) again in the sentence.**

The authors added the meaning of the \(\theta_u\), which is a symbol of the volumetric unfrozen water content, to improve a readability as the reviewer commented.

5) **Figure 3: Please tell that this has been obtained from your measurements, or has this figure been taken from another work? In this case, please include the citation.**

Fig. 3 was created by the authors to show the conceptual change in the time domain reflectometry (TDR) signals for soils before and after freezing. The obtained TDR signals from the authors’ measurements are plotted in Figs. 6 and 7.

6) **Line 147: What is "SF"? Please include the definition of SF again in the sentence.**

The authors added the meaning of the SF, which is an abbreviation of the silt fraction, to improve a readability as the reviewer commented.

7) **Line 172: "because the mechanical characteristics of sand–silt mixtures, such as strength, are significantly affected by the \(D_r\) rather than the void ratio". This sentence is confusing because if \(D_r\) is the density (in %), then the void ratio (which I understand as "porosity") is equal to 1 - \(D_r\). Alternatively, if \(D_r\) is the density in g/cm3, then the void ratio is equal to 1 - \(D_r/D_{material}\), where \(D_{material}\) is the density of a single particle. Therefore, both quantities**
void ratio and Dr are directly related. How can the mechanical characteristics be then significantly affected by one rather than the other quantity, if both quantities are perfectly complementary to each other? Or is the void ratio something different from the porosity? Please also include again the definition of Dr in the sentence.

Soil is composed of solid and void, which consists of air and water. The void ratio and porosity are conceptually similar but have different indices as follows:

\[
\text{void ratio} = \frac{\text{volume of void (air + water)}}{\text{volume of solid}} \quad (1)
\]

\[
\text{porosity} = \frac{\text{volume of void (air + water)}}{\text{total volume (solid + air + water)}} \quad (2)
\]

The relative density is a ratio, expressed in terms of percentage, of the difference between the maximum void ratio and any given void ratio of soils to the difference between the maximum and minimum void ratios (ASTM D4254) as follows:

\[
D_r = \frac{e_{\text{max}} - e}{e_{\text{max}} - e_{\text{min}}} \times 100(\%) \quad (3)
\]

where \(D_r\), \(e_{\text{max}}\), \(e_{\text{min}}\), and \(e\) denote relative density, maximum void ratio, minimum void ratio, and void ratio of the specimen, respectively. Thus, the relative density is related to the void ratio as presented in Eq. (3), but not the relationship of \(e = 1 - D_r\) as reviewer commented. For binary mixtures such as the sand-silt mixtures used in this study, the fixed relative density rather than fixed initial void ratio is beneficial to estimate the effect of silt fraction since each sand-silt mixture with different silt fractions has different maximum and minimum void ratios. Thus, the authors fixed the relative density of 60% for all sand-silt mixtures, and the definition of \(D_r\) is added in the revised manuscript (LN 85-86) as follows:

Note that the \(D_r\) is a ratio of the difference between maximum and any given void ratios to that between maximum and minimum void ratios [18].

8) **Figure 6:** It is better to use dotted lines for the F1, F2, F3, and F4 curves, to better differentiate them from the R... curves.

To better distinguish between the Fn and Rn curves, the lines for the Fn curves have been replaced with dotted lines using smaller dots, while the lines for the Rn curves have been replaced by dash-dotted lines.

9) **Figure 7a, 7b:** It is better to use dotted lines for the F1, F2, F3, and F4 curves, to better differentiate them from the C... curves.

To better distinguish between the Fn and Cn curves, the lines for the Fn curves have been replaced with dotted lines using smaller dots, while the lines for the Cn curves have been replaced by dash-dotted lines.

10) **Section conclusions:** The most attentive reader will have difficulties to remember the meaning of all symbols that appear in the text of this section. Please recall their meaning, alternatively refer to a table where all symbols are explained (see my comment 1 above).

The authors added the meanings of all symbols and abbreviations in the first paragraph (e.g., relative density (D_r), change in relative density (ΔD_r), number of repetitive loading (N), degree of saturation (S), volumetric unfrozen water content (θ_u), linear variable displacement transducer (LVDT), silt fractions (SFs), and time domain reflectometry (TDR)) in the section of “5. Conclusions” to improve a readability in the revised manuscript. In addition, the authors added the section of “List of notations” to improve a readability of the manuscript as reviewer suggested in the first comment.

11) **Section conclusions:** Compared to previous studies, please cite 2-3 main novelties presented in your manuscript.

Thanks for the comment to improve the novelties of this study. The authors revised the section “5. Conclusions” (LN 389-394) as follows:

The sand-silt mixtures continuously and repeatedly undergo cyclic freezing-thawing-repetitive loading, and the number of repetitive loading (N) is subjected up to 1,000 in order to simulate a number of vehicle loads. During the cyclic
freezing-thawing-repetitive loading, linear variable displacement (LVDT) and time domain reflectometry (TDR) sensors monitor the volumetric change and volumetric unfrozen water content ($\theta_u$). This enables the understanding of the influences on the strength of specimens.

12) The weak part of this paper is that it doesn't connect well the experimental framework to the community of numerical simulation experts. Your results are really very important to improve particle-based models. In particular, great progress is being made in the model and application of granular materials with relevance for the industry, but your experiments show that the micromechanics of granular materials can change considerably depending on the boundary conditions to which they are subjected (and the level of polydispersity). Therefore, it would be pertinent to acknowledge the excellent progress in the particle-based simulation, e.g., by citing these papers: Wet granular flow control through liquid induced cohesion A Jarray, V Magnanimo, S Luding Powder technology 341, 126-139 (2019) Attractive particle interaction forces and packing density of fine glass powders EJR Parteli, J Schmidt, C Blümel, KE Wirth, W Peukert, T Poeschel Scientific Reports 4, 6227 (2014) and stress that it would be interesting to incorporate the insights presented in your paper into the particle-based models such as the ones of the papers above, to make these models stronger and better applicable to a broader range of environmental and industrial applications. Such a remark, including the suggested citations of particle-based simulations, would help to enhance the visibility of the article and also to connect the communities of experimentalists and modelers in this field that still demands so much research and (most importantly) the combined efforts of both communities.

The authors appreciate the reviewer’s helpful recommendation to enhance the visibility of this study and connect the communities of experiment and model fields. The authors cited the references that deal with particle-based models in the revised manuscript (LN 383-386) as follows: In further, to broaden the estimation and prediction of the behavior of granular materials, numerical studies that consider particle interaction [40] and capillary force induced by water [41] can be utilized to verify the effects of $\Delta D_r$ and $\theta_u$ estimated in this experimental study.