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# Quantitative Comparison between Settlement Observed in MSW Biodegradation and Sand-Salt Dissolution Tests

Yuliang Guo[1], Xunchang Fei[2], XiaoQing Pi[1],

*[1]PhD candidate, school of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Residues and Resource Reclamation Centre, Nanyang Environment and Water Research Institute, 1 Cleantech Loop, Singapore 637141*

*[2]Assistant professor, school of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Residues and Resource Reclamation Centre, Nanyang Environment and Water Research Institute, 1 Cleantech Loop, Singapore 637141, email: xcfei@ntu.edu.sg*

## ABSTRACT

The in situ and laboratory MSW biodegradation is a long-term process, thus the assessment of its performance can be arduous. A sand-salt mixture is often used to replace an MSW specimen for simplification or approximation, with dissolution representing biodegradation. However, the effectiveness of this approximation still needs to be confirmed, and the effects of the initial properties and test conditions such as unstable fraction, size ratio, initial compaction, and vertical stress on the accuracy of this approximation are unknown. In this study, supplementary dissolution tests of sand-salt mixtures are first conducted to construct a dataset for sand-salt mixtures and MSW specimens. Then, the settlement, one of the most important characteristics in practice, is chosen to be the indicator to compare the suitability of this approximation based on test groups with different unstable fractions, while the effects of other initial properties and conditions are also investigated. Overall, the effectiveness of the approximation largely depends on the biodegradable fraction and salt fraction, while other properties only pose limited effects.

*Keywords: MSW, biodegradation, sand-salt mixture, settlement*

## 1 INTRODUCTION

In classic soil mechanics, solid mass is often considered conservative. In reality, geomaterials often contain constituents that are reactive in the environment. Examples include salts and minerals in natural soil that are reacting with migrating fluids (Abduljauwad & Al-Amoudi, 1995; AlNouri & Saleam, 1994; Frydman, Charrach, & Goretsky, 2014; Warren, 2010; Yong, Elmonayeri, & Chong, 1985) and biodegradable constituents in peats, organic clays, and landfilled municipal solid wastes (MSW) (Barlaz, Staley, & de los Reyes, 2010; Fei & Zekkos, 2018; Kalbitz & Geyer, 2002). Hence, dissolution and biodegradation in geomaterials are two common coupled processes leading to mass loss and instability. These two mass loss processes eventually alter the physical, mechanical, biochemical, and hydraulic properties of the materials and their subsequent behaviors (Brimhall et al., 1992; Fei & Zekkos, 2018; Ke & Takahashi, 2014; J. McDougall, 2007; Zheng & Elsworth, 2012).

The similarity of the two processes is observed in macroscopic engineering applications and microscopic mechanisms. For instance, slope failures and excess foundation settlement in karst structures and landfills can be attributed to dissolution (Minsu Cha & Santamarina, 2016; Rothwell, Thomson, & Kähler, 1998; Sultan et al., 2004; Vogt & Jung, 2002) and biodegradation (Zhang et al., 2020). Also, particle migration and permeability change occur not only in soluble soil (Minsu Cha, 2012; Gutiérrez, Desir, & Gutiérrez, 2003; Man, Graham, & Blatz, 2011; Taron & Elsworth, 2009) but also landfilled MSW (Cooke, Rowe, & Rittmann, 2005; Hunter & Bowman, 2018). Similar laboratory tests have been conducted on soluble and biodegradable geomaterials. Major consequences of dissolution and biodegradation in geomaterials include changes in shear-wave velocity (Fam, Cascante, & Dusseault, 2002; Truong, Eom, & Lee, 2010; Truong, Lee, Kim, & Lee, 2012), shear modulus (Espinoza, Kim, & Santamarina, 2011), compressibility (Abduljauwad & Al-Amoudi, 1995; AlNouri & Saleam, 1994; Fei & Zekkos, 2013), cone penetration resistance (Minsu Cha & Santamarina, 2013), shear strength (C. A. Bareither, Benson, & Edil, 2012; M. Cha & Santamarina, 2014; Fam et al., 2002; Fei & Zekkos, 2015; Gratchev & Towhata, 2013; Ismael & Mollah, 1998; Tran, Shin, Byun, & Lee, 2012), horizontal stress ratio (Shin & Santamarina, 2009), and fluid permeability (M. Cha & Santamarina, 2014; Zheng & Elsworth, 2012).

Conducting a long-term biodegradation test for MSW specimens in the laboratory can be arduous. Some studies have used soluble sand-salt mixtures to approximate the behaviors of biodegradable MSW (J. R. McDougall et al., 2018). However, the suitability of this simplification still needs to be investigated. The performances of a geomaterial in mass loss are highly dependent on the initial properties. The previous studies addressed the impacts of unstable mass fractions (Bowen, Gregorich, & Hopkins, 2009; Minsu Cha & Santamarina, 2013; Fei & Zekkos, 2018; Shin & Santamarina, 2009), sizes of unstable particles (John McDougall, Kelly, & Barreto, 2013; J. R. McDougall et al., 2018), and geomaterial compaction levels (Minsu Cha & Santamarina, 2013). Therefore, the objective of this study is to first construct a series of soil dissolution tests to supplement the dataset containing the behaviors of soluble soil and biodegradable MSW collected from the literature review. Then, the effects of different initial properties on the suitability or applicability of approximating MSW by sand-salt mixtures are explored.

## 2 METHODOLOGY

### 2.1 Specimen preparations of sand-salt mixtures

To supplement the existing data, dissolution tests on sand-salt mixtures with salt fractions higher than 20% were conducted. The silica sand used in this study has relatively uniform grain sizes of between 0.4-0.7 mm and a mean grain size of 0.5 mm. The air pluviation and standard compaction methods determined the void ratio (ASTM, 2012). A mixture of 75% silica sand and 25% sodium chloride (NaCl) by mass acted as a model soluble soil in this study. Given the specific gravity of 2.65 and 2.17 for the sand and salt, respectively, the volume fraction was 71% sand and 29% salt. There were two types of salt grains used in the experiment (Figure. 1a). One type was commercial coarse-grain salt, which has grain sizes of between 0.3-1.0 mm and a mean grain size of 0.7 mm. The other type was a laboratory-grade fine-grain salt, which has grain sizes of between 0.2-0.4 mm and a mean grain size of 0.3 mm. Three types of mixtures with different initial structures were used in the dissolution test, i.e., the loose mixture of sand and coarse-grain salt (loose-coarse), the loose mixture of sand and fine-grain salt (loose-fine), and the sand and coarse-grain salt mixture with extensive compaction (dense-coarse). Figure. 1b presents the grain size distribution curves of the sand and salt used in this study. The fine salt grains are mostly smaller than the sand grains, whereas the sizes of the coarse-grain salt and sand are comparable.

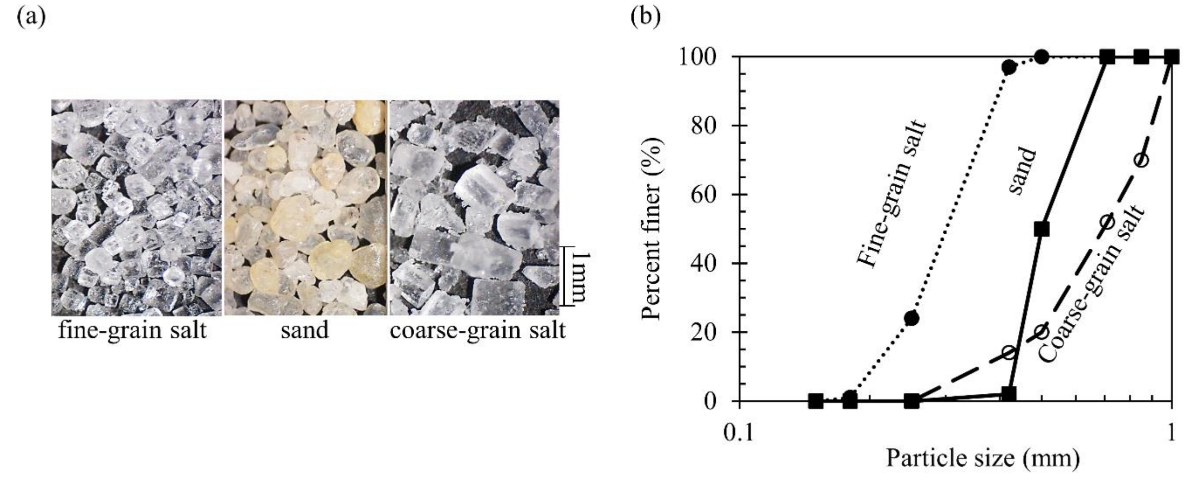

***Figure 1.*** *Tested materials: sand, coarse-grain salt, and fine-grain salt: (a) microphotographs, and (b) grain size distributions*

### 2.2 Test procedures of sand-salt mixture dissolution tests

A one-dimensional consolidation apparatus applied step-wise vertical loads to each sand-salt specimen and measured its vertical strain (ε) with time with a linear variable differential transformer (LVDT). A metal floating ring with a diameter of 50 mm and a height of 20 mm contained the specimen. Two porous stones above and beneath the specimen allowed double drainage pathways. The specimen was located in a water reservoir and the schematic of the apparatus is shown in Figure. 2. We prepared the three types of sand-salt mixtures as previously described and loaded them according to different stress histories. Table 1 summarizes the testing program for the 9 specimens, which have vertical effective stress (σ') at dissolution ($\sigma_{diss}$') of 50, 1000, or 1500 kPa. After the pre-loading steps, the specimen was loaded at the target $\sigma_{diss}$' for one hour. 500 mL of deionized water was then added rapidly to the reservoir to completely submerge the specimen. The specimen was loaded at $\sigma_{diss}$' for another 2-3 hours after the water addition. Based on the reading of the electrical conductivity probe and a pre-established calibration curve converting the electrical conductivity measurement to the corresponding salt concentration, we observed the complete dissolution of salt grains in the specimens after the one-time-only water addition. The potential breakage of a salt particle was disregarded for three reasons: firstly, the probability of breakage within this loading range was less than 10% (Portnikov, Kalman, Aman, & Tomas, 2013); secondly, any effect on the size ratio caused by breakage was only minor; and finally, it only had an impact on the preloading stage.

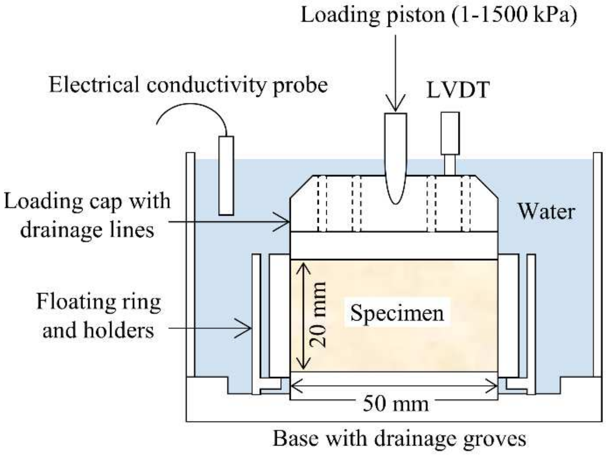

***Figure 2.*** *Schematic for testing apparatus of one-dimensional consolidation and dissolution tests*

***Table 1.*** *Summary of specimens and characteristic values of 1D consolidation and dissolution tests*

| Mixture | Preloading σ' (kPa) | $\sigma_{diss}$' (kPa) | $e_0$ | ε (%) |
|---|---|---|---|---|
| **Loose:<br>75% sand+25% coarse salt** | 50 | 50 | 0.77 | 21.9 |
| | 50-1000 | 1000 | 0.76 | 25.5 |
| | 50-1500 | 1500 | 0.74 | 25.3 |
| **Dense:<br>75% sand +25% coarse salt** | 50 | 50 | 0.58 | 19.7 |
| | 50-1000 | 1000 | 0.59 | 22.2 |
| | 50-1500 | 1500 | 0.59 | 18.8 |
| **Loose:<br>75% sand +25% fine salt** | 50 | 50 | 0.67 | 20.1 |
| | 50-1000 | 1000 | 0.65 | 21.3 |
| | 50-1500 | 1500 | 0.62 | 22.1 |

## 3 RESULTS AND DISCUSSIONS

### 3.1 Dataset of MSW specimens and sand-salt mixtures

To validate the performance of approximating the MSW by sand-salt mixture, the test results of the two types of specimens need to be collected and compared. A series of laboratory tests have been conducted on soluble and biodegradable geomaterials, as summarized in Table 2. The values of the three initial properties of all the specimens were then examined, and recalculated, if necessary. Initial void ratio ($e_0$), size ratio, i.e., the mean size of non-biodegradable or sand particles divided by the biodegradable or salt particles, and unstable fraction, i.e., soluble fraction or biodegradable fraction, are regarded as three significant initial properties while the loading condition and time history are also important factors in the mass loss process. For sand-salt mixtures, their size ratios were calculated by dividing the mean sand grain size by the mean salt grain size. For MSW specimens, the size ratios equaled the mean size of non-biodegradable particles divided by the mean size of biodegradable particles, which are dependent on initial MSW composition. According to the dataset, since the two types of unstable geomaterials experienced various test conditions, there might be some relative importance between these different influencing factors.

### 3.2 Unstable fractions

Based on previous studies, the effect of unstable fractions is usually the dominant one when it comes to the mass loss behavior of geomaterials. The experiment conducted in this study effectively supplements the dataset by providing the results of highly soluble soil specimens, i.e., soluble fraction >20%, so that all test results from the dataset can first be summarized by the unstable fraction in Figure 3. In Figure 3, one of the most important performance indicators, settlement, is chosen to show the effects brought by unstable fractions. The test results from this study and the literature of Table 2 are divided into four levels according to the unstable fractions, and the results of MSW and sand-salt mixtures are shown separately to provide comparisons. Regardless of other influencing factors, with the increase of unstable fractions, the differences between the real settlements of MSW and the ones approximated by the sand-salt mixture effectively decrease. The approximation can be suitable for the MSW specimens and sand-salt mixtures with unstable fractions of more than 20%.

The discrepancy of the approximation for the groups with low unstable fractions is attributed to the exclusive long-term creep of MSW specimens. Based on the available literature, even in the laboratory, the whole procedure of MSW biodegradation lasts much longer compared to sand-salt mixture dissolution. Therefore, the long-term settlement of MSW is jointly induced by biodegradation and long-term mechanical creep, which are not easily separated. Mechanical creep steadily contributes to settlement changes in the long term, while the settlement change due to biodegradation decelerates and eventually ceases (Fei & Zekkos, 2013). Some studies found that, under constant loading conditions, biodegradation remains the major contributor to MSW settlement changes compared to creep (O'Kelly & Pichan, 2013; X. B. Xu, Zhan, Chen, & Guo, 2015). However, according to the hypothesis proposed by the study of MSW and peat deposits, the decreasing biodegradable fraction might reduce the contribution of biodegradation but increase the contribution of creep (O'Kelly & Pichan, 2013; H. Xu et al., 2020). Therefore, the settlement results of MSW cannot be solely reflected by the biodegradation, especially for specimens with low degradable fraction, i.e., when creep becomes comparable to biodegradation and causes implicit compression. For instance, the settlement results of MSW specimens with 10% degradable fraction are seriously underestimated by the sand-salt mixture with the same soluble fraction, as shown in Figure 3. When the unstable fraction exceeds 20%, biodegradation becomes dominant in MSW specimens and shares a similar mechanism with salt dissolution, resulting in the similarity of settlement results.

### 3.3 Other influencing factors

Besides the unstable fraction, other initial properties and test conditions, i.e., initial size ratio, void ratio ($e_0$), and vertical stress, might also have effects on the effectiveness of the approximation. Following the same principle in Figure 3, the dataset is also divided into four levels of unstable fraction while indicating the secondary effects of initial properties and test conditions in Figure 4.

The effect of the size ratio is limited and can be neglected for the groups with high unstable fractions. In Figure 4a, though the scales of the size ratio are 0.60, 0.54, and 2.46 for groups of 20%, 25%, and 35% respectively, the most effective approximation is provided by the group of 35%. It indicates that the group with a high unstable fraction correspondingly has a high tolerance for the differences brought by other influencing factors. On the other hand, the similarity of size ratio still can improve the accuracy of the approximation. The size ratio of MSW specimens in the laboratory is often less than 1 due to the shredding or manual picking, therefore the sand-salt mixtures which have size ratios ≤1 will have better performance when conducting the approximation. For example, it can be seen from the sand-salt mixtures of the 10% group that the decreasing size ratios result in increasing settlement and thus slightly improve the settlement approximation, given the settlement of 10% MSW is underestimated by the sand-salt.

The differences in $e_0$ and external loading conditions between the MSW specimens and sand-salt mixtures do not noticeably affect the effectiveness of the approximation. Because of the low density of biodegradable grains in MSW specimens, it is inherently difficult to model the compaction level of MSW specimens by sand-salt mixtures. As shown in Figure 4b, the $e_0$ is universally smaller for sand-salt mixtures compared to the MSW specimens, and the differences can be as large as 3.27, 1.94, and 2.89 for the 20%, 25%, and 35% groups respectively. However, these large discrepancies of $e_0$ have very limited effects and are compensated by the high unstable fractions. A similar trend is also found for the vertical stress, as indicated in Figure 4c. The maximum difference of stress is nearly 1500 kPa between the sand-salt mixture and MSW specimens, but the 25% group does not reflect such a significant difference in the settlement approximation. It is assumed that after the preloading or preliminary consolidation, external stress might not significantly affect the subsequent mass loss process. A similar conclusion has been drawn in the MSW studies that the stress effect is not as important as the time effect for long-term biodegradation. Although the unstable fraction seems to be the significant factor while other properties and conditions only pose limited effects, which is similar to the conclusion in previous studies (John McDougall et al., 2013; J. R. McDougall et al., 2018), further confirmation is still needed since there is a lack of control groups on other factors. For example, the factors in Figure 4 might compensate each other to provide a seemingly negligible effect on the settlement. This requires future investigation and is beyond the scope of this study.

***Table 2.*** *Summary of available laboratory studies on mass loss processes in unstable geomaterials*

| Type of geomaterial | Significant properties | Testing conditions |
|---|---|---|
| **Soluble soil**[a] | Void ratio = 0.37-0.77<br>Soluble fraction = 1-35%<br>Stable-to-unstable size ratio = 0.40-9.00 | Vertical stress = 40-1500 kPa<br>Water addition: upward or downward flow |
| **Biodegradable MSW**[b] | Void ratio = 0.45-3.72<br>Biodegradable fraction = 4-51%<br>Stable-to-unstable size ratio = 0.11-1.00 | Vertical stress = 10-400 kPa<br>Elapsed Time = 57-850 days<br>Biodegradation conditions: inhibited or stimulated |

[a] (Bate et al., 2021; Minsu Cha & Santamarina, 2013; M. Cha & Santamarina, 2014; John McDougall et al., 2013; Tran et al., 2012; Truong et al., 2010).

[b] (Christopher A. Bareither, Benson, & Edil, 2013; Christopher A. Bareither, Benson, Edil, & Barlaz, 2012; Fei & Zekkos, 2018; Gourc, Staub, & Conte, 2010; Ivanova, Richards, & Smallman, 2008; Mali Sandip, Khare Kanchan, & Biradar Ashok, 2012; Shi, Qian, Liu, Sun, & Liao, 2016; Siddiqui, Powrie, & Richards, 2013; Woodman et al., 2013; X. B. Xu et al., 2015).

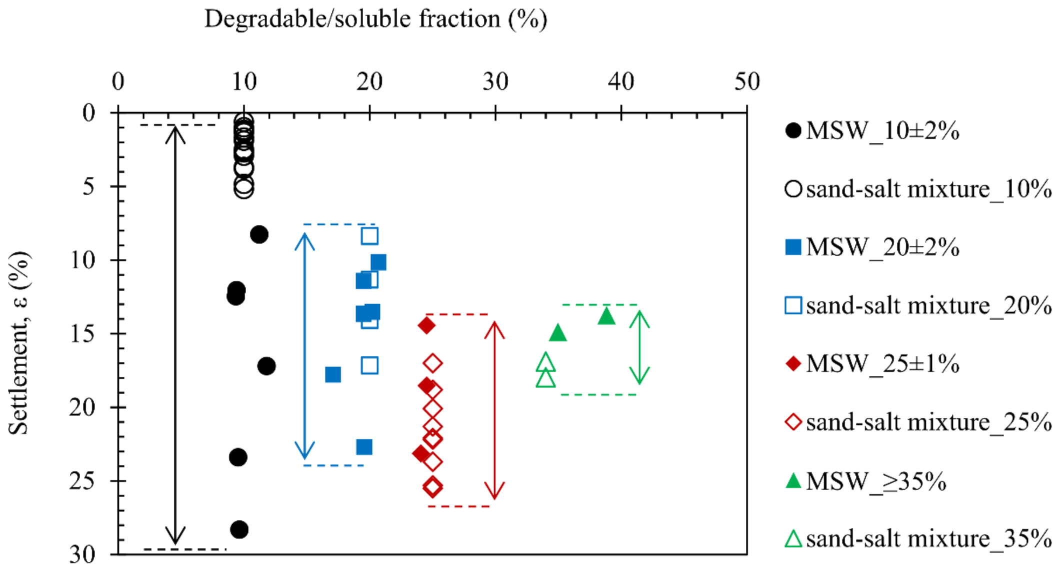

***Figure 3.*** *Effects of the unstable fraction on the approximation of settlement*

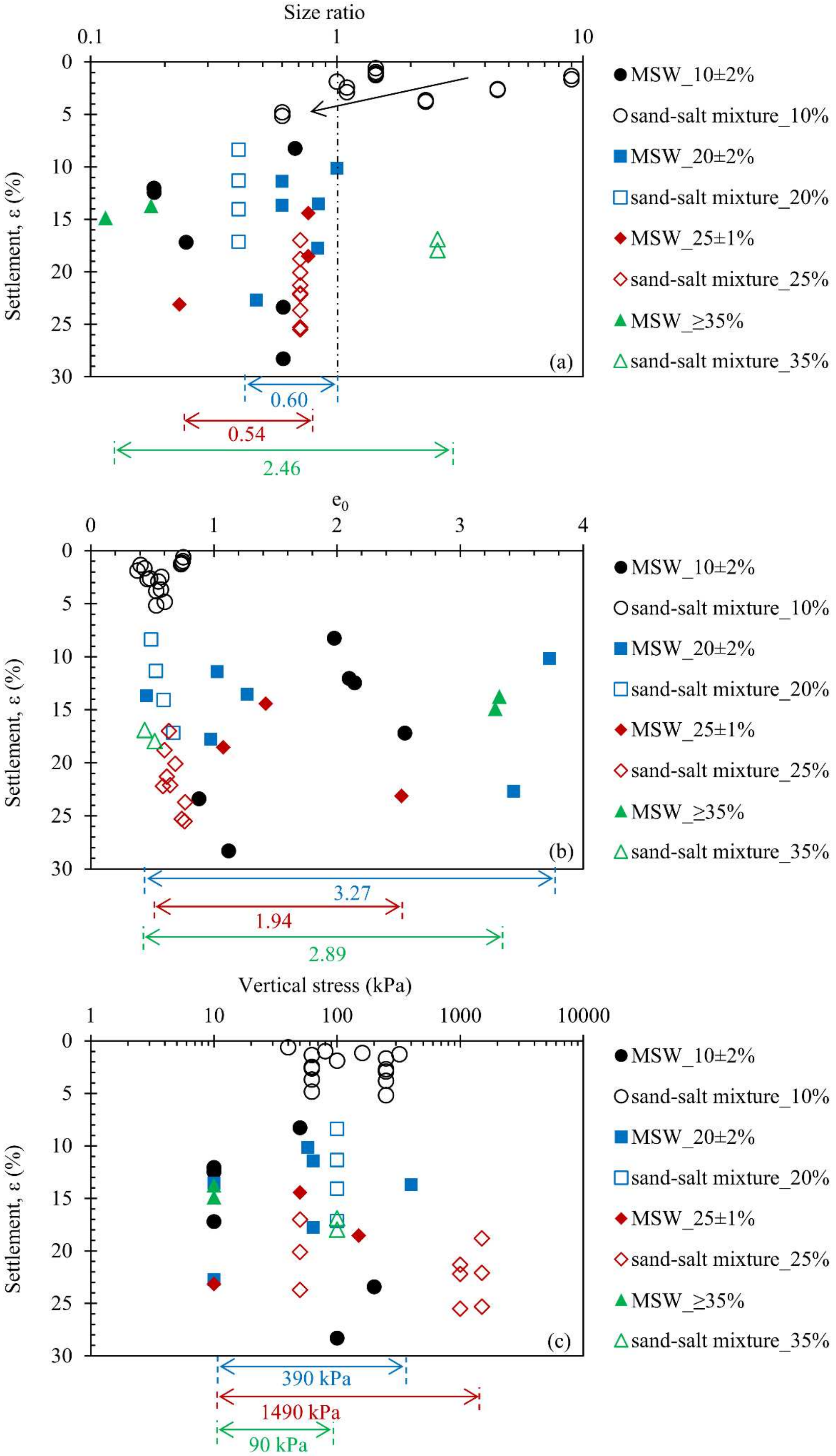

***Figure 4.*** *Effects of the size ratio (a), initial void ratio (b), and vertical stress (c) on approximation of settlement*

## 4 CONCLUSIONS

In this study, to supplement the existing data and construct a dataset for sand-salt mixtures and MSW specimens, dissolution tests on sand-salt mixtures with salt fractions of 25% were conducted. The dissolution tests can fulfill the gap and provide ample information for comparisons between the MSW specimens and sand-salt mixtures with high unstable fractions. Then, the settlement, one of the most important characteristics in practice, is chosen to be the indicator to compare the suitability of this approximation based on test groups with different unstable fractions, while the effects of other initial properties and conditions are also investigated.

Overall, the applicability of the approximation depends highly on the unstable fractions, i.e., biodegradable fractions and salt fractions, with other factors such as size ratio, $e_0$, and vertical stress posing limited effects. With the unstable fractions increasing, the differences between the settlement of MSW and the ones approximated by the sand-salt mixture effectively decrease. The approximation can be suitable for the MSW specimen and sand-salt mixture with an unstable fraction of more than 20%. The inaccuracy of the approximation for the groups with low unstable fractions perhaps results from the exclusive long-term creep of MSW specimens. The impact of unstable fraction >20% masks the impacts from other factors, though the relationships between other factors require further confirmation.

## 5 ACKNOWLEDGEMENTS

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