An experimental investigation on ejecta-induced settlement in sand with varying fines contents and densities

M.-C. Chu
Postdoctoral Fellow, Department of Civil Engineering National Chung Hsing University

C.-C. Tsai
Professor, Department of Civil Engineering National Chung Hsing University

ABSTRACT: Ground settlement may occur due to ejecta during soil liquefaction and consequently cause damages to structures and lifelines. To investigate factors that affect the settlement induced by sand boil, an experimental investigation by the special design apparatus is conducted in this study. Sandy deposit is prepared by filling in transparent acrylic cylinder with varying densities and fines contents. An acrylic circular plate, acting as a non-liquefied layer, is placed on the top of sandy deposit (specimen). Then, the cylinder is subjected to torsional shaking to produce soil liquefaction and sand boil. Soil particles are ejected out from the gap between the circular plate and cylinder and the plate starts to sink simultaneously. The thickness of ejecta can be observed from the accumulated sand particles on the plate. The influences of varying densities and fines contents on the ejecta amount as well as the settlement are quantitatively analyzed. It is found that the larger density of clean sand deposit results in smaller ejecta amount and associated settlement. However, the influence of density on the ejecta amount of sand and silt mixture is not as obvious as that of clean sand. Moreover, the ejecta contains more silt than the prepared specimen from the sieve analysis results.

Keywords: Sand Boil, Liquefaction, Settlement, Fines content, Ejecta, Density

1 INTRODUCTION

Liquefaction settlement is an important issue in geotechnical engineering, and many researches have been conducted to evaluate the liquefaction settlement. The mechanism of liquefaction settlement has been discussed by Bray & Dashti (2014) that including three types: ejecta-induced settlement, shear-induced settlement, and consolidation settlement. The ejecta-induced settlement could be more significant compared the other two. However, the ejecta-induced settlement is hard to be captured by continuum analyses (Bray & Macedo 2017). Hence, an experimental investigation by the special design apparatus is used in this study. Effects of non-liquefied thickness, gap size, overburden weight on the amount of ejecta have been investigated in the model experiment by Tsai et al. (2022). In this study, the effects of fines and densities on the ejecta amount is further evaluated.

2 TEST PROGRAM

2.1 Test system

The experimental apparatus in this study is presented in Figure 1. The 2500g loading system (Figure 2) is placed on the top of soils. The laser distance transducer is installed on the top to
measure the total settlement. The transparent acrylic cylinder is designed to observe soil response during the test and to measure the pore water pressure changes by pore water pressure transducers installed at different depths on the cylinder. The acrylic cylinder is fixed on the shaking table during tests, and acceleration is measured by accelerometer through the tests. Torsional shaking is applied to induce liquefaction. During liquefaction, soil particles are ejected out from the 2mm gap between the loading system and acrylic cylinder (Figure 2) during the test. The ejecta amount could be observed and recorded by the monitoring camera.

### 2.2 Specimen preparation and testing procedure

The clean sand and non-plastic silt (Figure 3) were used as the test materials in this study (Table 1). The 5% silt is added in pure sand to investigate the effect of fines on sand boils. Clean sand specimens are produced by water pluviation method which has been adopted in previous researches (Ueng et al. 2006, Tsai et al. 2022). However, water pluviation method may lead to severe segregation of coarse and fine particles in the specimens of dirty sand. On the other hand, the dry deposition method and wet tamping method may also cause non-uniformity in specimens. Therefore, a modified deposition method is proposed herein for preparing specimens with fines after Carraro & Monica (2008) with the following steps.

1. The sand is first mixed with fines in the dry condition.
2. An acrylic tube is filled with de-air water to 1/5 height of tube.
3. Mixed soil is slowly filled in tube, and water is added to until it merges the soil.
4. The rubber stoppers are installed on the tube and the tube is placed upside down for allowing air bubbles to move up toward the top of tube.
5. Extra water is added to replace the space occupied by air bubbles. Previous step could be repeated several times until no visible air bubble.
6. Plastic wrap is installed on one side of tube.
7. The tube is suspended in sedimentation apparatus, and plastic wrap is penetrated to let soils flow out the tube and deposit in the transparent acrylic cylinder.

The proposed method effectively reduces the amount of air bubbles, and improve the uniformity. A pre-test small shaking is applied to achieve the desired densities. The settlement and porewater pressure are recorded and measured through the tests.

### Table 1. Basic properties of used materials.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Sand</th>
<th>Silt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity of solids</td>
<td>2.65</td>
<td>2.66</td>
</tr>
<tr>
<td>Median size $D_{50}$ (mm)</td>
<td>0.193</td>
<td>0.012</td>
</tr>
<tr>
<td>Effective size $D_{10}$ (mm)</td>
<td>0.147</td>
<td>0.002</td>
</tr>
<tr>
<td>Coefficient of uniformity $C_u$</td>
<td>1.36</td>
<td>7.58</td>
</tr>
<tr>
<td>Coefficient of curvature $C_d$</td>
<td>1.1</td>
<td>2.07</td>
</tr>
<tr>
<td>Hydraulic conductivity k(cm/s)</td>
<td>0.034</td>
<td>0.0056</td>
</tr>
<tr>
<td>$e_{\text{max}}$</td>
<td>0.922</td>
<td>2.102</td>
</tr>
<tr>
<td>$e_{\text{min}}$</td>
<td>0.598</td>
<td>1.182</td>
</tr>
</tbody>
</table>

Figure 3. Photos of materials.

#### 3 TEST RESULTS

The measured total settlement is contributed by ejecta-induced and consolidation settlement. The observed thickness of ejecta is considered as the same as the ejecta-induced settlement but is corrected to for the density difference between the ejecta and the specimen. Therefore, the consolidation settlement is estimated by the total settlement subtracting the ejecta-induced settlement.

##### 3.1 Density effect

The test results on clean sand of different densities (relative densities, Drs) are collected and shown in Figure 4. As the density increases, the total settlement (Figure 4 (a)), ejecta-induced settlement (Figure 4 (b)), and consolidation settlement (Figure 4 (c)) decrease. Moreover, the total settlement is mainly contributed by the ejecta-induced settlement as the density decreases. The excess pore water pressures in tests are shown in Figure 4 (d). It could be observed that the duration of excess pore water pressure maintaining around 2kPa is longer as densities is lower.
3.2 Fines effect

Figure 4 also shows the tests results of adding fines. It could be seen that density have a more obvious influence on liquefaction settlement in clean sand than dirty sand specimens. With the similar relative density, the ejecta (Figure 4 (b)) and consolidation (Figure 4 (c)) settlement of dirty sand specimens are less than clean sand. The excess pore water pressure dissipates right after the shaking stops in the dirty sand specimen as shown in Figure 5(a). With the similar density, pore water pressure maintains (PWP time) in 2kPa is longer in the clean sand than the dirty sand. In Figure 5(b), it could be seen that the PWP time reduces with the increasing relative density. It is also found that the fines contents in ejecta is around 15% to 25%, which is higher than the fines content (5%) in designated specimens. This shows that the fines are easier to be ejected out.

Table 2. Test information.

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Test No.</th>
<th>e</th>
<th>Dr</th>
<th>Gap size</th>
<th>Shaking duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>12</td>
<td>0.75</td>
<td>0.75</td>
<td>54</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>M2</td>
<td>0.71</td>
<td>0.71</td>
<td>52</td>
<td>2</td>
</tr>
<tr>
<td>Sand+5% silt</td>
<td>M3</td>
<td>0.76</td>
<td>0.76</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>M5</td>
<td>0.73</td>
<td>0.73</td>
<td>49</td>
<td>2</td>
</tr>
</tbody>
</table>

4 CONCLUDING REMARKS

Through the series of test results, it is concluded that density is influential on the amount of ejecta on both clean and dirty sand specimens. As density increase, the total settlement, ejecta-induced settlement, and consolidation settlement are reduced. However, the influence is more obvious in clean sand than dirty sand. On the other hand, the excess pore water pressure dissipates right after the shaking stops in the dirty sand specimen. The PWP time reduces as the density increases, which is more profound in the clean sand than the dirty sand specimens.
Figure 5. Test result of adding fines specimens.

REFERENCES


