A hierarchical approach to soil arching problem via physical model test with photoelastic measurement and discrete element simulations

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ABSTRACT

Soil arching is a unique phenomenon in which soil grains plays an active role in efficiently resisting external load. A traditional trapdoor problem was investigated via a physical model test using bi-dimensional particles made of PTFE elastomer. Each particle was coated by trimmed thin photoelastic sheet such that force transmission can be visualized and their contact forces can be measured. A hierarchical approach for expanding the model size was taken. We attempted the discrete element method (DEM) to simulate existing photoelastic tests, from which microscopic model parameters for DEM were calibrated. The area of the trapdoor problem can easily be enlarged in the discrete element simulations, which overcomes practical limitation in physical model tests. The comparison of the results from the experiment and simulation reveals that the initial condition of the assembly prepared for the DEM is too perfect to reflect the local perturbation in the contact distribution that can be naturally expected in the experiment. Numerically enlarged discrete element model has successfully captured the general patterns of contact force distribution due to the soil arching.

Keywords: arching, trapdoor, photoelastic measurement, discrete element method

1. INTRODUCTION

Soil arching is a unique phenomenon in which soil grains plays an active role in efficiently resisting external load (Terzaghi, 1943). Soil arching is very attractive to geotechnical engineers because a design including an additional stability owed by the soil arching can greatly reduce the construction cost. However, quantitative evaluation of its effect is not straightforward because of the unseen nature of soil arching. This may contribute to very different design codes for the piled embankments that greatly rely on the geometric contribution of soil arching (van Eeleken et al., 2012; Karinski et al., 2003)

Quantifying load contribution and visualizing contact force distribution are two key factors in the design of geo-structure expecting the soil arching. In this study, a traditional “trapdoor” problem was investigated in the lab testing scale. To trace the distribution of the contact forces during trapdoor opening, two different approaches—photoelastic model tests and discrete element simulations—were conducted. Photoelastic model test is a physical test using a small-scale particulate assembly with the two-dimensional circular particles made of PTFE elastomer. Every particle was coated by trimmed thin photoelastic sheet that is optically sensitive to its mechanical deformation. The numerical analysis using the discrete element method for the same model geometry used in the photoelastic model test was concurrently conducted. The model parameters such as microscopic contact normal and tangential stiffnesses were calibrated by matching the macroscopic force-displacement curve with the curves obtained from the photoelastic model test.

To expand the size of the model for a real application that cannot be achieved easily in a physical model test, a hierarchical approach using the discrete element method was taken. The area of the trapdoor problem was enlarged in the discrete element simulations, which overcomes practical limitation in physical model tests. The change in the distributions of the contact force in the photoelastic tests and discrete element simulations during trapdoor opening are visually compared.

2. PHOTOELASTIC PHYSICAL MODEL TEST

To experimentally investigate the trapdoor problem, a granular assembly with the particles coated by optically sensitive photoelastic sheet was tested. To manufacture the cylindrical particles with the circular section, a circular PTFE elastomer rod was carefully cut...
Table 1. Material properties of photoelastic sheets and model particles

| Particle Material | Photo Sheet | Strain-optical Coefficient, K | Thickness of sheet | Fringe value, f |
|-------------------|-------------|-------------------------------|--------------------|----------------|
| PTFE              | PS-1C       | 0.15                          | 1.0 mm             | 3790           |

(a) Set-A with uniform 10-mm diameter particles

(b) Set-B with 10-mm diameter particles over a layer of 20-mm diameter particles.

Fig. 1. Loading frame containing two different sets of the granular assemblies.

to have 15-mm long cylindrical particles. Every particle was coated by the trimmed thin photoelastic sheet such that the force transmission can be visualized.

Table 1 summarizes physical properties of the coating sheets used in this study. The assembly was contained in the steel frame capable of the manual compression as shown in Fig. 1. For the trapdoor tests, two different sets of the particle assemblies were prepared. One set designated Set-A is a uniform assembly with single-sized 10-mm diameter particles. The other set designated Set-B is the similar assembly with 10-mm diameter particles but stacked over a layer with 20-mm diameter particles. As can be expected, Set-B initially contains a certain degree of perturbation in the upper region with 10-mm diameter particles due to the irregularity in the contact between 10-mm and 20-mm diameter particles. Fig. 1(a) and 1(b) compares the two different sets of the assemblies used in this study.

As shown in Fig. 1, overall size of the initial particle assembly was approximately 181.23-mm high and 780-mm wide. Approximately 1450 particles were stacked for the preparation of these assemblies. To study the soil arching, a 100-mm wide trapdoor modeled by a vertically movable steel segment was located at the center and bottom of the particle assembly. To apply the confining pressure, a rigid steel bar connected to the loading rod was placed on the top of the assembly. By manually rotating the gear that moves the loading rod and steel bar downward, a specific value of the confining pressure can be applied. The vertical displacement and its corresponding reaction force of the steel bar were monitored via the LVDT and load cell, respectively.

The trapdoor tests were performed in three stages. First, a granular assembly of either Set-A or Set-B was prepared. Second, under the fixed trapdoor condition the confining pressure was applied on the top of the granular assembly. Subsequently, the steel segment of the trapdoor slowly lowered until the downward displacement of the trapdoor reached 15 mm.

![Fig. 2. Confining force-displacement curves in the photoelastic tests.](image)

Fig. 2 shows the reaction force-applied displacement curves during the stage applying the confining pressure. For each case of the assembly set, three different external forces for the confining pressure, 1.96, 3.92, and 5.88 kN, were applied. The slopes of the curve are linear except for the initial exponential increase that might reflect the Hertz-type contact stiffness for the cylindrical particles. In contrast with the relatively consistent slopes for the Set-A, the curves for the Set-B have wide variation indicating the fractal nature of the contact system signified by the local perturbation.

After applying the confining pressure, the trapdoor was opened incrementally by 5 mm. Fig. 3 shows sequential images of photoelastic pattern of the contact force distribution in the Set-A under the confining force of 5.88 kN. At the initial stage, Stage 1, the oblique pattern of the contact force chains can be clearly observed. Immediately after lowering the trapdoor by 5 mm, Fig. 3(b) shows a dark triangular shape near the trapdoor region which indicates the loss of the contact forces. Subsequently, Fig. 3(c) and 3(d) show the expansion of the dark area retaining the triangle-like shape. Even though the area losing the contact forces gradually increased as the trapdoor moved downward, the oblique pattern of the contact force chains in the other area still remained in the Set-A.
Fig. 3. Photoelastic patterns of contact forces in the Set-A subjected to the confining force of 5.88 kN.

Fig. 4. Photoelastic patterns of contact forces in the Set-B subjected to the confining force of 5.88 kN.
For the Set-B, however, the contact force chains did not have a particular preferred pattern even at the initial configuration, as shown in Fig. 4(a). When the trapdoor started to be opened, the vertically straight force chains above the location of the trapdoor immediately disappeared and new force chains were generated next to the trapdoor. The brightness of these new contact force chains became strong as the trapdoor moved downward.

When the trapdoor moved, the overall confinement in the granular assembly was reduced because the steel bar confining the assembly remained at its position during trapdoor opening. Fig. 5 compares the reduction of the confining forces during trapdoor opening for the Set-A and Set-B assemblies. The obvious reduction was found in the Set-B where the confining force suddenly dropped at the first increment of the trapdoor opening. The rate of the subsequent reduction in the confining force for the Set-B is practically the same as those for the Set-A, as shown in Fig. 5. The sudden drop in the confining force observed in the Set-B is likely related to the dramatic change in the contact force chains in the first increment of trapdoor opening discussed previously.

3. DISCRETE ELEMENT ANALYSIS

To conduct the discrete element analyses, PFC2D software was used. The soft-contact approach that allows the artificial overlaps between particles was chosen. First set of the discrete element analyses was attempted to simulate the photoelastic lab test described in the previous section. The same geometry of the cylindrical particles and load frame shown in Fig. 1 was two-dimensionally modeled in the discrete element analyses. Table 3 summarizes the units used for the simulations.

| Length | Density | Force | Stress | Contact stiffness |
|--------|---------|-------|--------|-------------------|
| mm     | ton/mm³ | ton   | N      | N/mm             |

To model the nonlinear contact stiffness between particles with the circular section, the Hertz-Mindlin contact model was chosen. The model parameters for the Hertz-Mindlin model were calibrated until the simulated confining force-applied displacement was identical to that for the Set-A shown in Fig. 2. The final values of the elastic shear modulus, Poisson's ratio, and friction coefficient used in the contact stiffness model are 830 MPa, 0.2, and 0.1, respectively. For the stable numerical analyses, the time increment was calculated not to exceed the critical time step, \( t_{crit} \) (Bathe and Wilson, 1976),

\[
t_{crit} = \sqrt{\frac{m}{k}}
\]

where \( k \) is the average value of normal contact stiffness, and \( m \) is the mass. Applied value of \( t_{crit} \) was 0.00031 sec.

![Fig. 6. Discrete element models for the Set-A and Set-B.](image)

Once the model assembly was established, the same procedure used in the photoelastic lab test was simulated to lower the trapdoor downward. Fig. 7 shows the progressive change in the contact force distribution in the Set-A model obtained from the discrete element analyses. The oblique patterns of the contact forces in the simulations are very similar to those observed in the photoelastic lab tests. As shown in Fig. 4, the photoelastic test of the Set-B does not exhibit a unique and homogeneous pattern of the contact force distribution. However, the patterns from the discrete element simulations shown in Fig. 8 for the Set-B still preserve the oblique distributions of the contact forces during trapdoor opening.

Fig. 9 shows the confining force-displacement curves obtained from the discrete element simulations. During confinement, the slope of the curve for the Set-A is slightly greater than the slope for the Set-B. The curves in the simulations are not as linear as those in the photoelastic tests.
Fig. 7. Simulated contact force distributions in the Set-A subjected to the confining force of 5.88 kN.

Fig. 8. Simulated contact force distributions in the Set-B subjected to the confining force of 5.88 kN.

Fig. 9. Simulated confining force-displacement curves.

Fig. 10. Simulated confining force-trapdoor opening relationships

Fig. 11 shows expanded models of Set-A and B with an enlarged 500-mm wide trapdoor at the center on the bottom of the assembly. Fig. 12 and 13 show that the contact force distributions in the enlarged Set-A and Set-B during the trapdoor. As shown in Fig. 12 and 13, overall oblique pattern in the contact force distributions can be observed in the different two sets and practically the same as that observed in the original dimensions in Fig. 7 and 8.
4. CONCLUSIONS

To investigate the contact force distribution caused by the soil arching, a hierarchical approach using both photoelastic experiments and discrete element analyses were attempted. The traditional trapdoor problem was studied via photoelastic model tests using cylindrical particles made of PTFE elastomer that were coated by trimmed thin photoelastic sheet. We attempted the discrete element method (DEM) to simulate existing photoelastic tests, from which microscopic model parameters for DEM were calibrated. The comparative study on the results from the experiment and simulation reveals that the initial condition of the assembly prepared for the DEM is too perfect to reflect the local perturbation in the contact distribution that can be naturally expected in the experiment.

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