Experimental Examination of the Arching Mechanism on the Micro Level

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Abstract

The arching phenomenon is manifested through the reduction of stresses experienced by underground structures. Arching plays an important role in geotechnical engineering construction such as; excavations, retaining structures, pile groups, tunnel boring machines, culverts and underground facilities. The arching mechanism is intrinsic to granular material/rock mass independent of scale effect. Its fundamental mechanism relates to the ability of discrete units to transfer loads through interaction in a preferable geometry and, thus, to bridge between the zone (or point) of load application to the zone (or points) of reaction.

The testing results of an advanced experimental technique is presented and analyzed. A model of granular material made of photoelastic particles is utilized. The model and the sophisticated image and global data acquisition system allow to track the development of the arching within ideal granular material during a trap door experiment by following the motion of each particle and the contact forces between the particles. Visual and quantitative analyses are presented demonstrating the relationship between the global arching phenomenon and the particle interaction on the micro-level. The obtained information allows one to observe the changes associated with the arching mechanism and the stress variation resulting from it. The arching mechanism is observed in details that previously could not have been achieved.

Photoelastic Discrete Simulation (PDS)

De Josselin de Jong and Verruijt (1969) suggested that the interparticle contact force magnitude could be determined as a function of the relative size of the isochromatic fringes at the contact, and the corresponding contact force direction followed a line connecting the center of gravity of isochromatic fringe near the contact. The isochromatic fringes can be observed through a circular polariscope, which consist of quarter-wave plates and polarizers. Further development and testing of the above method has been presented by Paikowsky et. al. (1993). A calibration process establishing the relationship between the photoelastic isochromatic fringes and the contact force magnitude and direction were developed, allowing to accurately monitor the interparticle contact forces. Independent digital images acquired in parallel, enable to follow markings on the particles. These images allow to monitor the motion of each particle (translation and rotation) as presented by Paikowsky and Xi (2000). The two techniques were combined into an experimental system that enables the investigation of both, kinematic behavior and interparticle contact force variation of photoelastic particles. This experimental system was termed Photoelastic Discrete Simulation (PDS).

Experimental Setup

The PDS was used to construct a granular mass made of photoelastic particles, and conduct trap door experiments. A trap door testing system has been developed to study the

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arching behavior of particulate materials on the contact detail level. The system allows one to perform trap door tests under different boundaries (e.g. smooth or rough side boundaries), loading conditions, trap door movement (active or passive), and to accommodate different sizes of trap doors. One-inch diameter photoelastic particles with different aspect ratios (AR) were used (round AR=1, elliptical AR=1.25). The layout of the experimental system, and a flow chart describing the comprehensive image acquisition and analysis system is presented by Paikowsky and Xi (1997), and Tien and Paikowsky (2001).

Experiment Description

A detailed depiction of the loading and trap door systems is presented in Figure 1. Experiment #9 of active arching is presented in which 882 one-inch (9.5 mm thick) round photoelastic particles were used. The sample size before loading was 792.2 mm (H) by 635 mm (W) (see Figure 1). The trap door size was 317.5 mm (12.5 inches) wide. Experiment #10 had the same setup as Experiment #9, and some of the results presented for comparison with those of Experiment #9.

Test Results

Global Response

The global response of the tested sample was collected from six load cells located at the top, bottom, and two sides of the sample, and from two DCDTs placed at the top and bottom (see Figure 1).

The global response testing results related to vertical loads and displacements are presented in Figure 2. The force acting on the trap door is presented in Figure 2c. A constant load of 705.4 N acted on the door after the vertical seating load to the sample increased to 1550 N, and then the force dropped to 0 N when the displacement of the trap door was approximately 1 mm. Since the trap door width is 317.5 mm, a displacement of 1 mm is only 0.3% of the trap door width. This ratio is similar to the former results of trap door experiments that had the minimum force on the trap door with the door displacement under 1% of the trap door width (Terzaghi 1936, Tien 1996). The force on the trap door stayed close to 0 N till the trap door displacement reached 10 mm. At this point, the force started to increase, indicative of the unstable stresses of the particles’ forming the arch above the door.

Interparticle Behavior

Figure 3 presents the photoelastic images and the contact forces magnitude contours for frames #0 and #34 of experiment #9. These frames represent the state of the sample under seating vertical load before any movement (frame #0), and when no force is acting on the trap door as a result of its displacement (frame #34). A comparison between the trap door load cell measurements (figure 2), and the photoelastic interpretations (Figure 3) of the force acting on the door indicate on a difference of forces of 10.4% and 8.8% (load cell greater than photoelastic) for frames #0 and #34 respectively. Additional details depicting the particle’s interparticle forces, displacements, and rotations are presented by Tien and Paikowsky (2001).

Arch Formation

Utilizing the available information, the formation of an arch at a microscopic view is illustrated in Figure 4. A particle marked “C” (denoting the “center” particle) along the side of the triangular zone, is chosen to illustrate the arching mechanism. The center particle is originally in contact with six surrounding particles. Each surrounding particle interacts with a contact force to Particle C before the arching takes place. The contact forces are approximately 60° degree apart due to the geometry of the problem, dictated by
the uniformity of the particles. During arch formation, Particles #1 and #6 start to separate from the center particle C. Meanwhile, the contact forces from Particles #2 and #5 ($F_2$ and $F_5$) increase, and the contact forces from Particles #3 and #4 ($F_3$ and $F_4$) decrease. Following the arching formation, only $F_2$ and $F_5$ act on the center particle. The two contact forces between Particles #3 and #4 ($F'_3$ and $F'_4$), which are parallel to $F_2$ and $F_5$, also increase during the arch formation. The $60^\circ$ inclined axial forces remain, therefore, as the only forces acting on the particles along the sides of the triangular zone formed by the arching. The displacements of Particles C, #2, #3, #4, #5 are along a $60^\circ$ slip surface during the arching formation process. Particles #1 and #6 move in a downward direction approximately $90^\circ$ from the horizontal. The other particles within the triangular zone also move downward at approximately $90^\circ$ to the horizontal with the trap door (Illustrated are Particles #7 and #8). After the arching is generated, the interparticle forces and the slip surfaces create a mesh similar to the one in Figure 4. The angles within the mesh are $90^\circ+\phi$ (which is $45^\circ+\phi/2$ to the horizontal direction). The internal friction angle of 1” round particles is $40^\circ$. Therefore, the slip surface should be at $65^\circ$ (i.e. $45^\circ+\phi/2$) to the horizontal. However, since the testing particle system consists of homogeneous 1” round particles, the slip surfaces follow a generic $60^\circ$ plane instead of the $65^\circ$ plane.

Acknowledgment

The presented research was made possible through the support of the National Science Foundation (NSF, NYI Grant MSS-9358090) and the University of Massachusetts Lowell. Acknowledged for their technical support are Mr. Gary Howe, laboratory director of the Civil and Environmental Engineering Department at University of Massachusetts-Lowell. Mr. David Rondeau and Mr. Furui Tang, the machinists of the College of Engineering, manufactured the parts for the testing apparatus and photoelastic particles.

References

Figure 1. Testing Frame For the Trap Door Experiment Using Photoelastic Particles

Figure 2. Sample Global Responses as a Function of Time and Trap Door Displacement (EXP #9 & 10) (a) Vertical Load (b) Vertical Deformation (c) Force on the Trap Door
Figure 3 Interparticle Forces of EXP #9 Under Seating Load (left) and full arching development (right) (Frames #0 and #34) Respectively. (a) Photoelastic Fringe Image and (b) Contact Force Magnitude Contours
Figure 4 The Formation of Active Arching in A Microscopic View