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An experimental investigating the width and height of a stable arch formed in granular materials by using a new developed trapdoor apparatus

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Abstract*—This paper discusses the formation of arching phenomenon as a stable arch in granular materials. A series of laboratory tests are performed to investigate the formation in granular materials. For this aim, a new trapdoor apparatus is designed to find the dimensions of arches formed over the door in cohesionless aggregates. This setup has two new important applications. In order to investigate the maximum width of the opening generated exactly on the verge of failure, the door can be open to an arbitrary size. On the other hand, the box containing granular materials (or base angle) is able to set on angles of zero to 90 degrees with respect to horizontal. Therefore, it is possible to understand the effect of different gravity accelerations on arching. It is observed that for all tested granular materials, increasing the door size and decreasing the base angle, both causes to increase the width and height of the arch. Moreover, the shape of all arches is governed by a parabola. Furthermore, the maximum door width is approximately five to 8.6 times the particle size, regarding to the internal friction angle and base angle of materials.

***Keywords*—Arching, Arch, Granular materials, Door width, Base angle**

I. Introduction

Arching is one of the most common phenomena encountered in materials both in the field and laboratory. Terzaghi [1] defined arching effect as the transfer of pressure from a yielding mass of soil onto adjoining stationary parts. In other words, arching is closely related to the mobilization of shear strength induced by the relative movement in materials. He used trapdoor tests to explain how stress transferred from yielding parts of a soil mass to adjacent stationary, nonyielding parts led to the formation of an arching zone.

By using this idea, several work have been carried out to investigate the arching effect as load transferring in different engineering problems, including earth pressure on retaining structures [2], stability analysis and design of tunnels [3-7], bearing resistance of piles [8], settlement of pile-supported embankments [9], load on buried structures [10], and granular flow in hoppers and silos [11, 12]. A literature study on the arching effect can be found in Tien [13]. More recently, the Discrete Element Method has been used to explore the application of arching in soil; for example [14, 15]. In some engineering problems, physical soil arches as stress-free surfaces may form, such as that in the flow and storage of granular materials for 30^o base angle of materials box [16]. In such a problem, the desirable outcome when an outlet at the bottom of a hopper is opened is that the material fl In out under gravity. However, it is well-known that if the size of the outlet is too small, a stable and self-supporting obstruction (arch or dome) may form to prevent the flow of materials. In this case, arching should be avoided via appropriate selection of the outlet size or using additional methods such as vibration. Approximate theories have been developed for the analysis of granular flow and the design of hoppers [16-19]. Motivated by the aformentioned literature review, this study tries to solve limitations of Gou and Zhou's (2012) setup (i.e. using different constant doors and a fixed 30^o base angle), and it focuses on the physical properties of arches formed in granular materials by using a developed trapdoor test in 2D stress condition. Exploring the maximum size of opening door related to critical width and height of the arch over the door, by consideration of various gravity acceleration (0^o to 90^o base angle of materials box) in spite of Gou and Zhou's setup that only studied 30^o base angle. Finding dimensions of a stable and self-supporting arch in granular materials, facilitates the analysis of load transfer mechanisms and may be attributed to stability of an unsupported structures like tunnels excavated without any support in sand under different surcharges. This developed setup also can help designers to select a precise size of hopper or silo outlet with various base angle of materials.

II. Experimental test

A. *Developed trapdoor test*

We can use the trapdoor apparatus in order to investigate the formation of arch in granular materials. Gou and Zhou's (2012) trapdoor test is only for different doors with constant size and a base angle of 30 degrees to horizontal. However, this new apparatus is a developed version of Gou and Zhou's (2012) setup, which has a shifting door.

Fig. 1 shows this setup. Apparatus has a box which can set on arbitrary angle from zero to 90 degrees with respect

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to the horizontal, so as to apply different gravity acceleration (g) into materials. Indeed, the box containing materials is considered as a space between MDF base plate, lateral frames (called shoulders) and a plexiglass inserted in the fissure existing on the lateral frames. The box is fixed on the base and it is a 30×40×t cm space. t value corresponds to the average grains diameter and for placing only one layer of particles in the box (i.e. distance between base plate and plexiglass), t value is about d_{50} + 1 mm, so that particles move down without any friction with plexiglass and negligible friction with base plate. The particles are stacked only in single layer such that it simulates the plane strain condition. Therefore, this spacing is 10mm and 13mm for rockfill (d_{50}=9mm) and beads (d_{50}=d=12mm), respectively. Moreover, two transitive segments (called trapdoor blocks), are contrived at the lowest level of materials to access different door width and also use as a stopper for granular materials. There is a container under these blocks to be as a rail for moving segments on it and also to reserve the discharged materials.

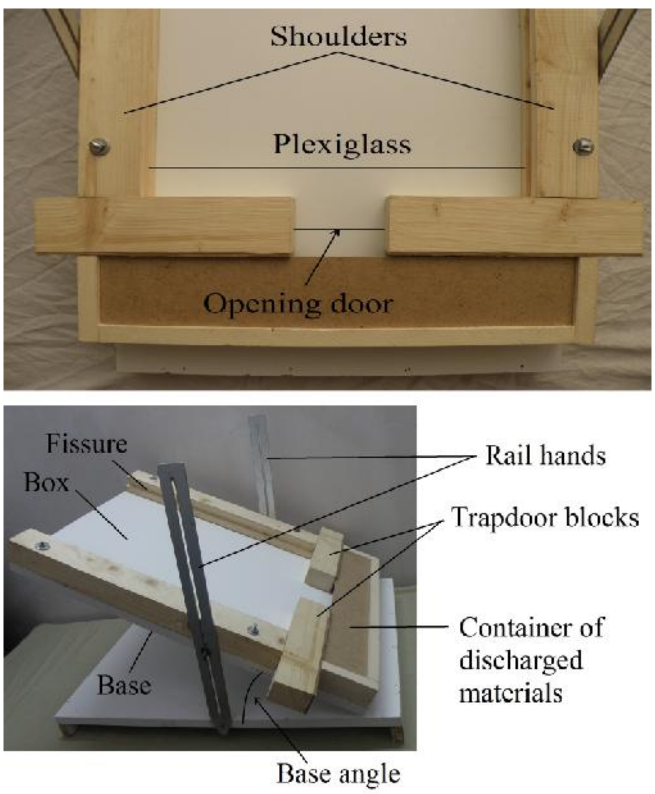


Figure 1. Developed trapdoor apparatus

B. *Selected granular materials*

Two kinds of granular materials were used in this study, including rockfills packing with the average size of 9mm and plastic spherical beads with the diameter of 12mm in two density conditions (i.e. loose and dense). The gradation curves of these materials are shown in Fig. 2.

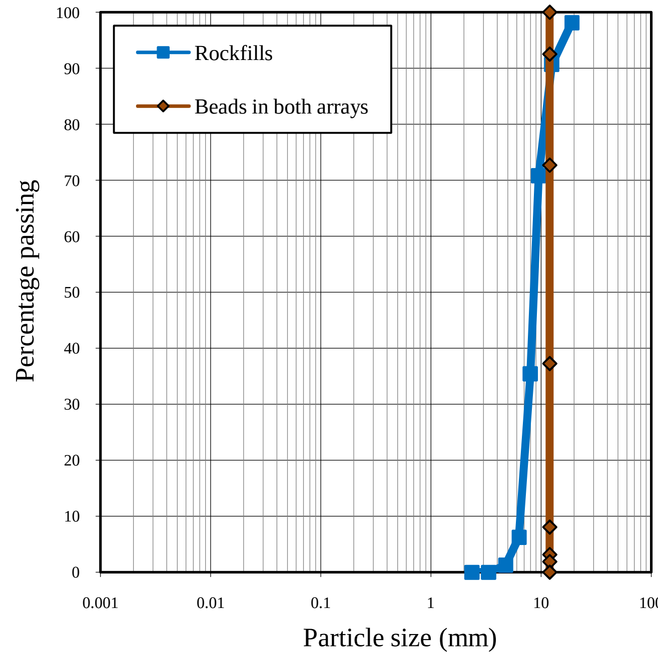


Figure 2. Gradation curve of granular materials (Rockfills: $d_{50}\approx$ 9mm, Beads: $d_{50}\approx$12mm)

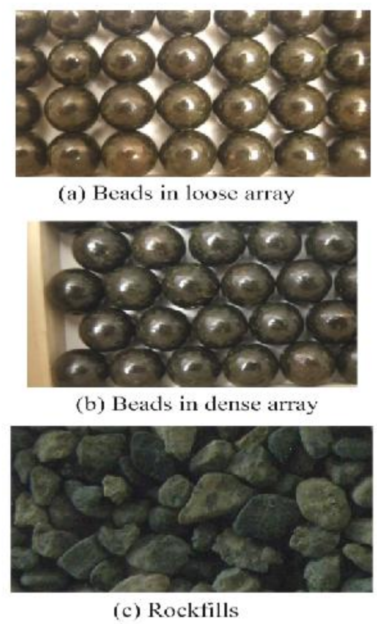


Figure 3. Tested granular materials

These granular materials are presented in Fig. 3. In order to access loose and dense packing of beads, two arrays of particles were arranged. In one that considered as loose array, each bead exactly sets on bead placed in lower row (Fig. 3(a)). Second arrangement or dense array is in the case of beads are located between those set in the nether layer (Fig. 3(b)). It is inevitable to consume much time and accuracy for attaining aforementioned arrays. The array for rockfills is shown in Fig. 3(c).

Since only one density ratio of rockfill is desirable in each stage of test, at first, materials were elected in amount that entirely fill the box, then density of packing is calculated regarding weight and volume of these rockfills. the weight of selected rockfills is 1900 gr distributed in $30\times40\times1\ \text{cm}^3$ box space, thus density can obtain from equation 1:

$$\rho_{(\text{Rockfills})} = \frac{\text{mass}}{\text{volume}} = \frac{1900}{30\times 40\times 1} = 1.58\,\frac{\text{gr}}{\text{cm}^3} \qquad (1)$$

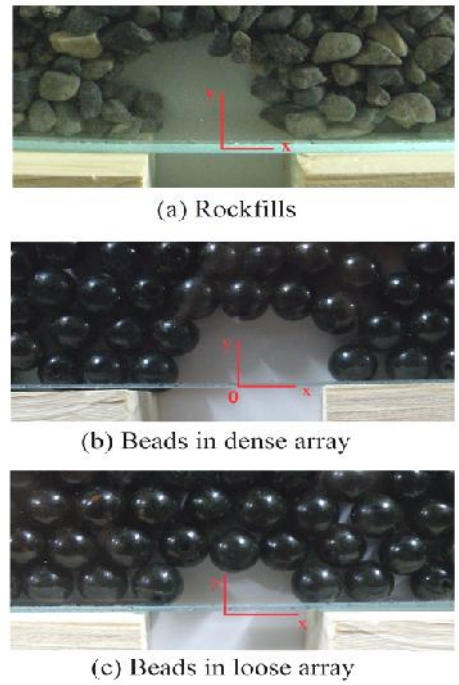
For the beads packing, the density values are $1.35\ \text{gr}/\text{cm}^3$ (dense) and $1.27\ \text{gr}/\text{cm}^3$ (loose). Note that these densities remain constant in all stages of the tests. The internal friction angles of tested materials were obtained from direct shear tests. Representative values of φ are 30.7°, 37.4° and 41.3° for loose, dense array and rockfills, respectively. These φ values were measuredby finding the angle of repose. It is obvious that using spherical grains and rockfills packing possessing irregular particles shape with different sizes results to way for finding out the effect of shape and size of granular ensembles in arching formation.

C. *Test performance*

First, the box is fixed on desired angle, then two trapdoor blocks move away and a distance is created between them, next a stiff rectangular rubber as the door fills this space. In second step, granular materials come in the box. It must be considered that entering the materials in the box, can be achieved by various manners. For example, rockfill is inserted in the box after fixing plexiglass, but beads first put in loose or dense array in the existing space between segments, shoulders and base plate, then plexiglass will be placed in fissures. This method facilitates process of arranging bead grains as loose or dense array. Finally, rubber door moves down and granular materials discharge and fall into the container. However, the whole materials do not discharge, but a stable arch forms over the door after a short time. This arch can carry static pressure of upper materials and transfers it to its two bottom supports by arching application. In every run of the test, distance between two blocks (*i.e.* opening door) increases 2mm as compared with previous stage, then width and height size of arch corresponding to door width are recorded in sheets relating to specific angle. This process is repeated so that no stable arch forms anymore. On the verge of arch collapse, we get maximum door width and the critical arch width and height in this study.

III. Experimental observations

By performing experimental tests on four base angles (θ) consisting 10°, 40°, 70° and 90°, numerous considerable results were observed. Fig. 4 shows typical arching photographs and Fig. 5 presents loci of each particle in stable arch formed over door widths (W) of 2.8 cm and 5.6 cm, on base angle of 40° and 90° for comaring results in three same conditions. A thorough investigation can help us to understand the simultaneous effect of both door width and base angle on arching. Note that in Fig. 5, x and y values represent the loci of particles forming arch.



(a) Rockfills

(b) Beads in dense array

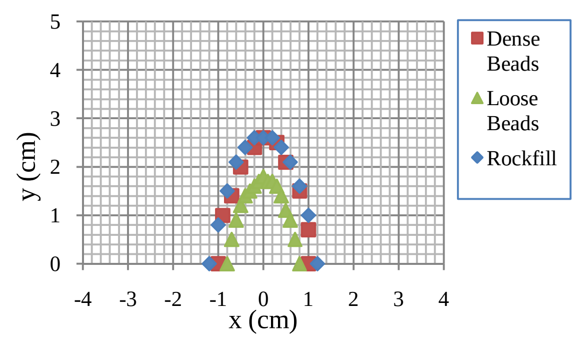
(c) Beads in loose array

Figure 4. Typical photographs of arching over door with W=5.6 cm

Arching effect makes a stable arch in each granular medium which transfers the load from surrounding materials into two its bases. All arches can be described as a parabola in the form of following:

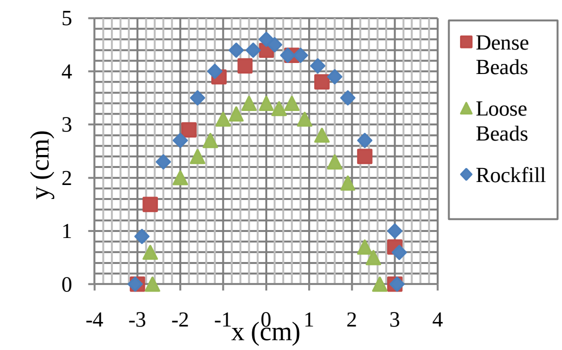
$$y = H\cdot[1-(2x/B)^2] \qquad (2)$$

where x and y are loci of each grain in the arch, B and H are the width and the height of arch, respectively.

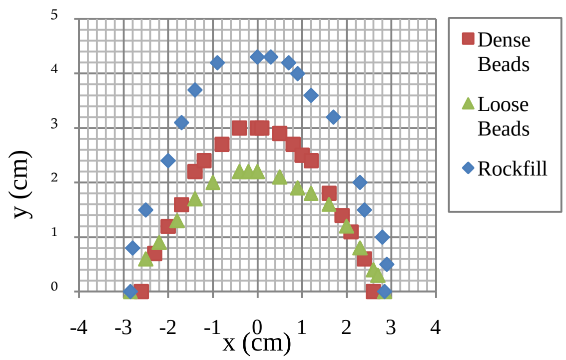


(a) θ=40°, W=2.8 cm

Figure 5. Comparison between arch shape formed on determined base angle and door width



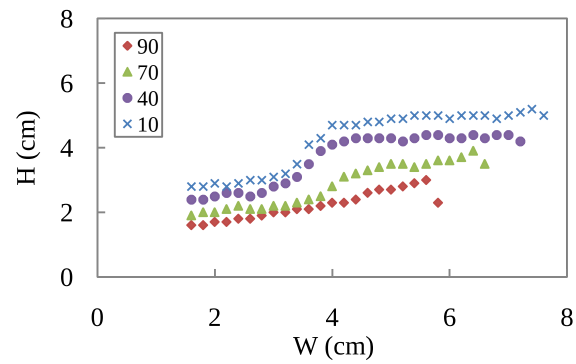
(b) θ=40°, W=5.6 cm



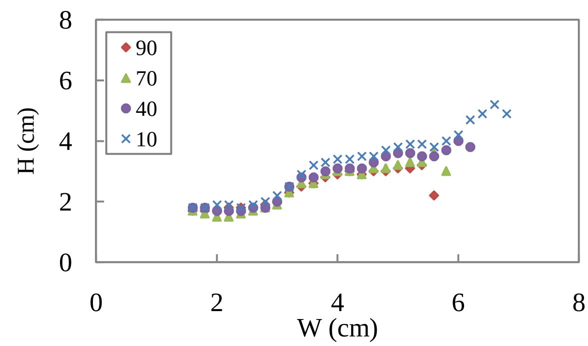
(c) θ=90°, W=5.6 cm

Figure 5. Comparison between arch shape formed on determined base angle and door width (continue)

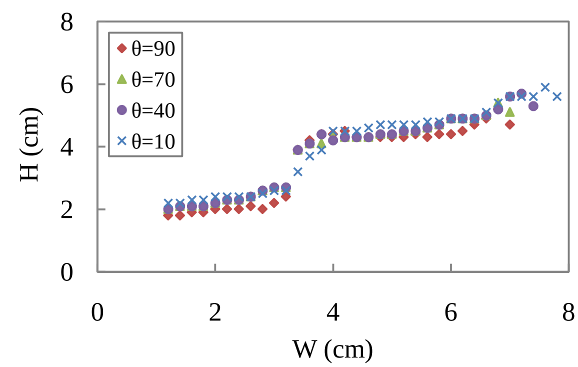
In fact, Fig. 5 presents the effect of door width and base angle, on the width and height of the arch. As shown in Fig. 5 for all materials, the arch width is smaller than door width. The arch height is greater for dense array ($\varphi = 37.4^o$) compared to loose array ($\varphi = 30.7^o$), although the diameter of bead grains is equal in both arrays (d=12mm). Meanwhile, the arch dimensions of rockfill (d_{50}= 9mm, $\varphi = 41.3^o$) is approximately greater than dense beads. This indicates that the internal friction angle of materials has mobilized the shear strength between particles and it is the most important factor in arch formation for granular materials. Increasing the the opening door width causes to discharge more materials and to decrease the surcharge. As presented in Fig. 6, the height of arch increase as the door width increases. This might be as a result of the reduction in surcharge on the arch that causes the arch to endure less pressure and consequently to have greater height. However, the arch height reduces with the increasing in the materials base angle. The more the base angle inclines, the more effective gravity acceleration ($g \times \sin\theta$) exerts on granular materials. This increases the effective surcharge on the arch and shortens its height. It is obvious that the arch supports the more loads in this condition. It is also observed that as the door width increases, the more materials is discharged and consequently the arch width is greater, until no stable arch can form. We call the arch forming on the verge of collapse as "critical arch". For this arch, the width of door and arch possess maximum possible size. On the contrary, the height of the arch is not the maximum, but it decreases slightly. The reason might be because that the arch cannot endure the materials have tendency to discharge, and for adoption this condition, the arch must decrease its height. Indeed, it is a new finding and needs to more discussion.



(a) Beads in dense array



(b) Beads in loose array



(c) Rockfills

Figure 6. Relation between door width and arch height for different base angles

According to authors' determination, the maximum door width (W_{max}) is the width of the door that no stable arch can form over the opening door with greater width than it. It is observed that the maximum door width is different for various base angles and the reason was discussed before. The W_{max}/d_{50} values versus different base angles for tested granular materials are presented in Fig. 7. As shown in Fig. 7, the W_{max} varies from five times the average particle size (d_{50}) for loose beads on the base angle of 90° to 8.6 times d_{50} for rockfills on the base angle of 10°. These observed data verify experimental results performed by Gou and Zhou (2012) for granular materials e.g., glass beads (with d_{50}=5.5 mm) and dense sand on the base angle of 30°. the results are presented in Fig. 7 for comparing results.

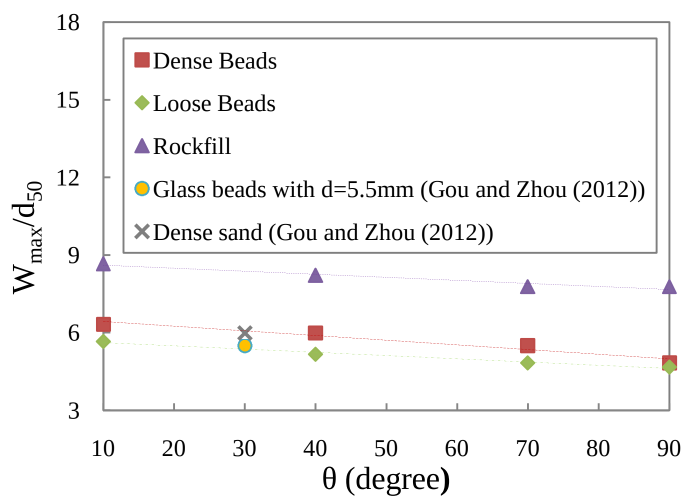


Figure 7. Maximum opening door size vs. different base angles

IV. Conclusion

A developed trapdoor apparatus is designed which is a new trapdoor setup in the world. An experimental analysis for ensembles of mono-sized particles of granular materials shows that stable arches may form, with the width varying with particle shape and the friction angle. For tested granular materials in this study, the critical width of opening door is approximately five to 8.6 times particle sizes. It is also observed that for all tested granular materials, increasing door size and decreasing base angle augment the width and height of the arch. However, on the verge of arch collapse, the height of critical arch decreases. Moreover, the shape of all arches is governed by a parabola. This finding may not be significant for geotechnical engineering practice owing to the small dimension of the arch, but is important for granular flow in silos or hoppers.

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