Experimental And Numerical Study Of The Response Of Granular Layer In The Trap-door Problem

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Abstract. Deriving from the traditional problem of behavior of granular materials in silos, the trap-door test is a very basic experimental test that reproduces solicitation met in a wide range of technological applications (soil reinforcement, granular material storage…). In spite of the fact that many analytical models exist for the description of this test, a large part of the behavior of granular layers submitted to a localized basal relative displacement remains obscure: influence of the displacement value, value of the friction angle of the granular matter… Carried out in quasi-static motion and involving several granular materials such as gravels and sands, the experimental study brought to light that trap-door tests systematically break down into three different successive phases depending on the amplitude of the trap-door. Pressure applied on the trap-door by the granular material decreased suddenly for very low displacement values. Then a progressive increase was observed coinciding with a progressive expansion of a subsiding zone from the bottom of the layer to its top. At last the pressure stabilized for the greater displacements of the trap-door. This last phase corresponded with the classical failure pattern used in analytical solutions: a vertical slipping plane at each edge of the trap-door. Because of very different response were obtained with sand and gravel, particularly in the transitional phase, a numerical study were carried out by means of Discrete Element Method. Involving simple spheres and complex shaped particles as clumps, a wide range of materials presenting various friction angles were tested. A neat influence of the peak friction angle on the maximal load transfer phase was observed whereas the last phase was associated with the residual friction angle. In addition, a micromechanical analysis, giving the localization of shear strains underlined the effect of the friction angle on the pattern of arching observed in the material.

Keywords: granular material, load transfers, Discrete Element Method.
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INTRODUCTION

Initially studied by Terzaghi [1,2], the trap-door problem consists in the description of mechanisms occurring in a granular material layer when a trap-door located below is moved downward.

The first analytical description of the failure mechanism [2,3] is based on the assumption that the column of granular material above the trap-door slides vertically with the trap-door while the remaining material is fixed. This assumption leads to the analogy with the problem of stresses in silos initially described by Janssen [4]. The problem of the trap-door has been commonly studied in a plan strain conditions [2,5-7]. However, even if aspects of the kinematics were mostly recognized in these experimental studies, there was a lack of quantitative results on the amplitude of load transfers.

In this paper, experimental tests carried out on two geomaterials showed a complex response which can not be reduced to the classical pattern mentioned previously. For better understanding of these phenomenons, a numerical study was carried out using Distinct Element Modeling.

EXPERIMENTAL STUDY

Experimental tests of the trap-door problem have been performed on several natural dry geomaterials such as gravels and sands. The physical properties and the mechanical characteristics of the material obtained with low confining pressure triaxial tests are given in Tab.1. The plane strain tests were carried out in a box 1.0x0.4m in plan (Fig.1). A 0.2x0.4m trap-door was placed on the bottom of this box, the thickness h of the granular layers ranging from 0.05 to 0.60m. During the trap-door tests, the vertical displacement δ and the vertical pressure p^{nc} acting on the central part of the trap door are measured.

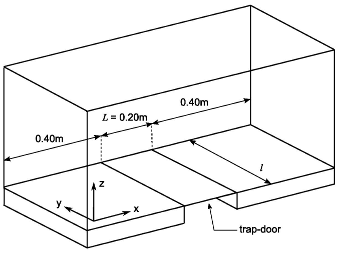
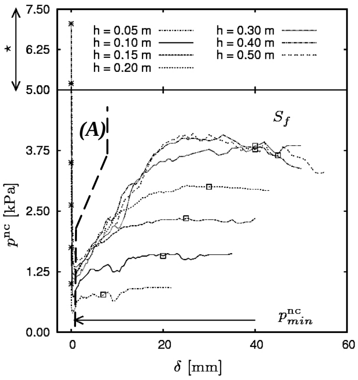


FIGURE 1. Diagram of the experimental test box.

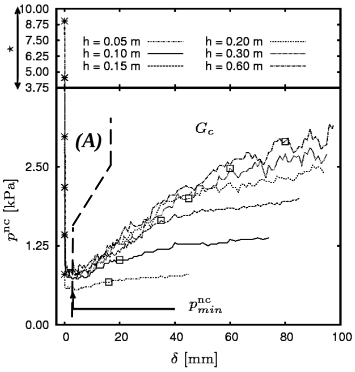
TABLE 1. Materials characteristics.

	Gravel G_c	Sand S_f
Diameter range	[5.0, 12.5]mm	[0.01, 6.3]mm
Mean diameter	8.0mm	0.5mm
Test density	15.2kN.m^{-3}	17.0kN.m^{-3}
Peak friction angle	53.6°	48.6°
Residual friction angle	40.1°	38.4°

Typical experimental results obtained with a granular layers of gravel or sand of thickness h are given on Fig.2 (p^{nc} versus trap-door displacement δ).



(a) sand



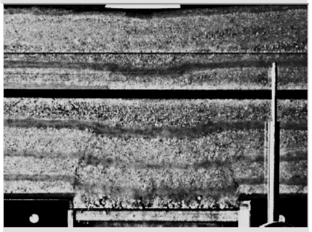
(b) gravel

FIGURE 2. Pressure p^{nc} versus trap-door displacement δ obtained with sand (a) and gravel (b) layers: ***(A)*** maximal load transfer phase, ***(B)*** transitional phase (ending with square boxes), ***(C)*** critical phase (beginning with square boxes).

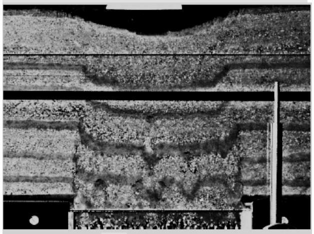
Three typical phases were systematically observed and can characterize the response of a granular layer in the trap-door problem with regard to load transfer amplitudes (Fig.2) and to kinematics (Fig.3):

- Maximal load transfer phase (***A***): corresponds to the minimal pressure p_{min} applied on the trap-door and occurs for very small trap-door displacements
- Transitory phase (***B***): two sliding planes gradually turn toward vertical direction (Fig.3.a, Fig.3.b); the pressure p^{nc} increases with the trap-door displacement δ.
- Critical phase (***C***): begins when the sliding planes became vertical (Fig.3.c), corresponds to the classical description of the trap-door problem.

(a) $\delta = 5$ mm



(b) $\delta = 10$ mm



(c) $\delta = 40$ mm

FIGURE 3. Kinematics observed with a 30cm thick layer of sand for each of the three phases.

NUMERICAL STUDY

The Distinct Element Model used in this study is a three dimensional method based on molecular dynamics approach [8]. The particles composing the modeled material interact with each other through linear normal and tangential contact laws. A Coulombian friction criterion bounds the tangential and the normal contact forces.

In order to reproduce high levels of shear strength (Tab. 1), complex particle shapes such as assemblies of two identical spheres – called clusters – were used in addition to simple spheres samples (Fig.4).

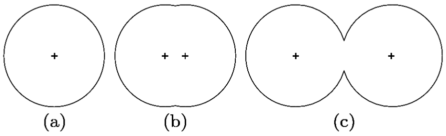


FIGURE 4. Particle shapes: spherical (S); cluster with 20% of diameter between centers (C^{20}); cluster with 95% diameter between centers (C^{95}).

A total of seven different numerical samples were tested, differing by particle shape, porosity, contact friction coefficient. The macro-mechanical characteristics of each sample were assessed from the modeling of triaxial tests on a representative elementary volume (8000 particles). Consequently, peak friction angles φ_p ranged between 24.5° and 49.0°. Residual friction angles φ_r ranged between 21.7° and 31.3°.

The trap-door test was carried out with each sample with a layer counting 23000 particles. The size of the test-box was the same as the experimental test box (except in the y-axis direction l=0.10m). The sample was set up by REDF [9] without gravity. Then gravity was applied and the trap-door was moved by 1mm increments.

Experimental and numerical responses were compared with static and kinematics points of view. The pressure p^{nc} versus the trap-door displacement δ is given on Fig.5. The displacement fields of the particles are given on Fig.6 for different values of δ.

The three typical phases described in the experimental study were observed in the numerical tests with Discrete Element layers.

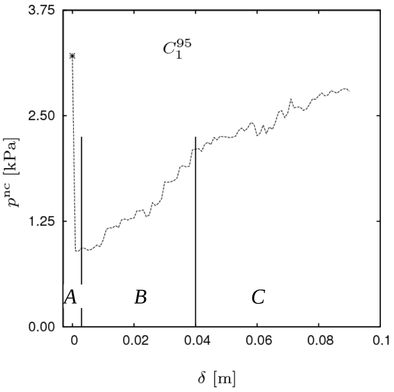
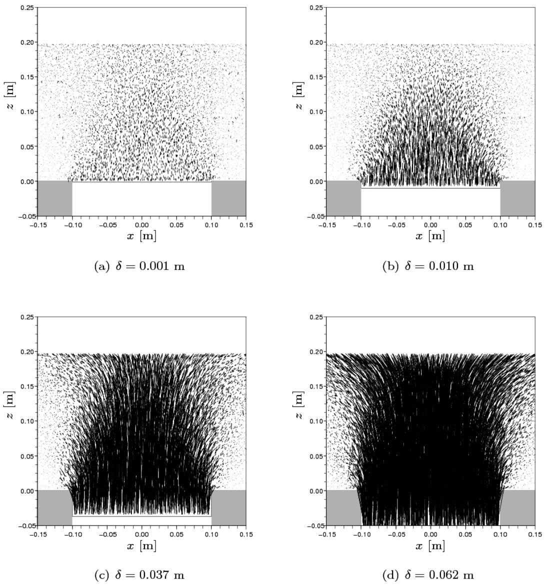


FIGURE 5. Numerical simulation: pressure p^{nc} versus trap-door displacement δ obtained with a sample of clusters (C^{95} C^{95}) with φ_p=46.2° and φ_r=31.3°.



(a) $\delta = 0.001$ m
(b) $\delta = 0.010$ m
(c) $\delta = 0.037$ m
(d) $\delta = 0.062$ m

FIGURE 6. Particle displacement fields for different values of the trap-door displacement δ. Sample of clusters (C^{95}).

After validating the ability of the numerical method to reproduce the physical mechanisms, the influence of several mechanical parameters of the layer was investigated.

The parametric study performed shows that the mechanisms involved in the trap-door problem could be related to the shear strength of the granular material composing the layer. Due to the very small displacement necessary to reach the first phase (maximal load transfer phase), the minimal pressure p_{min} was correlated to the peak friction angle φ_p (Fig.7) for the three types of particles used. It can be seen that there is a clear effect of the peak shear strength of the granular layer on the minimal pressure resulting in the trap-door test. We can note that the circled marks on Fig.7 show no effect of particle shape.

Due to the large displacements necessary to reach the critical state, the pressure p_c was correlated with the residual friction angle φ_r on Fig.8. The value of critical pressure was linked to the residual friction angle, even though the pressure range was more reduced for the critical phase than for the maximal load transfer phase.

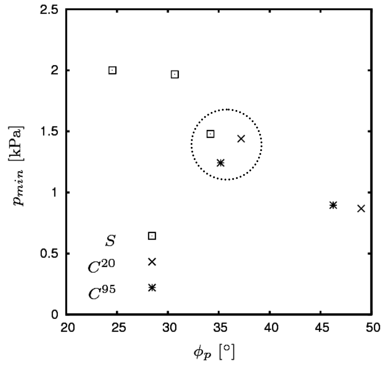


FIGURE 7. Minimal pressure p_{min} versus peak friction angle of the granular layer φ_p.

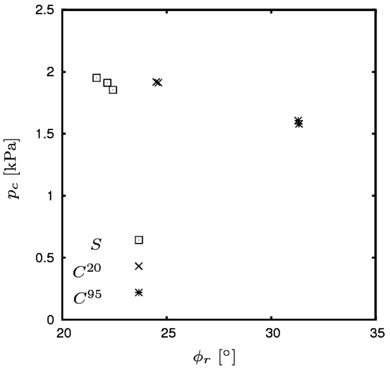


FIGURE 8. Critical pressure p_c versus residual friction angle of the granular layer φ_r.

To check the influence of the mechanical parameters on the arching mechanisms, strain tensors were calculated, using a Delaunay tessellation of the modeled granular layers, on each resulting tetrahedron [10,11].

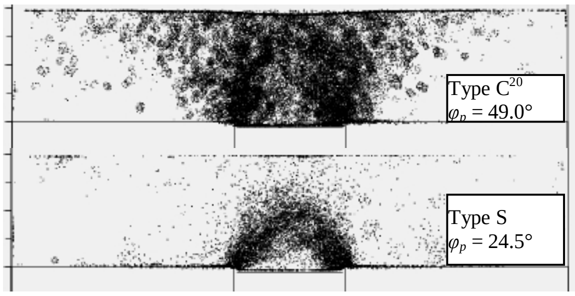


FIGURE 9. Points where the second invariant of strain tensor is greater than 1.5% (for δ=0.02m).

The second invariant of the strain tensor was deduced, representing the intensity of shear strain. The distribution of this invariant in the layer showed a great influence of the peak friction angle on the pattern of arching for the first phase (Fig.9).

CONCLUSION

Experimental and numerical results given by the Discrete Element Method show that the response of a granular layer on the trap-door problem breaks down into 3 different phases characterized by particular kinematics and load transfer amplitudes.

The results obtained with the DEM analysis allowed to link the maximal load transfer to the peak shear strength of the granular layer. The amplitude of load transfer during the critical phase was linked to the residual shear strength of the material. In addition, a micromechanical analysis made on the numerical results showed a great influence of the peak shear strength on the pattern of arching.

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