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Injection of Granular Material

Visualization of Stress and Grain Flow

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Abstract : Some civil engineering projects require the injection of granular matter such as sand into the ground. However, granular matter resists pumping through tubes and thus it is difficult to inject such matter into the ground. With the help of several methods forces and movements of grains were visualized. Force chains and arches in a two dimensional granular matter model were visualized with polarized light and photo-elastic material. The movement of sand grains was visualized on a glass plate in a half-space ground model. With the particle image velocimetry (PIV) method the vector field of the movement and the field of the resulting shear rate were assessed. In this way a new method for the injection of granular material, such as, sand into the ground was devised. The method appears to be applicable to lift a building to counter subsidence.

Keywords : Force chains, Injection of sand, Granular matter Flow, PIV, Subsidence.

1. Introduction

Some tasks in civil engineering require the injection of solids into the ground. This is needed to stabilize a foundation by the ground compacting or to raise the ground level. Usually the injected solid is comprised of fine particles, about 20 microns in diameter, which are mixed with water and in this way a thick fluid is generated. Due to the small size of the particles the injected volume mostly fills the intergranular space of the ground. Only a small part - about 5 to 10% - is effective in the ground compacting or raising the ground. An example of this approach is the attempt to raise an area of about 1000 square meters with a building on it in Poveglia in 1970 (Marchini et al., 1976). This is a small island near Venice which was subject to land subsidence (Ammerman et al., 2000; Carbognin et al., 2000). The method was successful and this building was lifted up by 10 cm. However, the raised volume was only 8% of the injected volume, as most of the latter went into the intergranular space. This attempt showed that this technology is too costly and not effective enough.

Much more effective would be the injection of solids with diameters which are larger than the average diameter of the intergranular space. It would then not dissipate in the intergranular space, but would displace volume, thus rendered useful for compacting or raising. In practice such a solid is sand. However, sand is a granular matter and resists a transport through tubes, which is required for injection. Sand cannot be pumped through tubes because it blocks. This blockage is a specific property of granular matters and was first observed in silos. In these vertical tubular vessels the pressure at the bottom, which is generated by the weight of the granular matter does not rise over a certain limit. The weight mostly is transmitted to the tubular walls through friction. This behavior is called the Janssen effect (Janssen, 1895). It has been explained by the formation of force chains in the granular matter. These force chains can go in straight lines or form arches, leading the pressure or gravity forces into the tubular structure.

The objective of this paper is to show that the injection of sand into the ground is possible, if the force-chains are properly guided.

2. Methods and Materials

2.1 Visualization of Force-Chains

The force-chains, which create the blockage of the granular matter transport through tubes, can be made visible in a set-up of a model granular matter, which has photo elastic properties. The model of a granular matter is made of a multitude of Plexiglas cylinders having a diameter of 5 mm and a thickness of 3 mm. They form the particles which are subject to forces. When under stress, Plexiglas twists polarized light. Thus, stresses can be visualized (Liu et al., 1995; Geng et al., 2001; Matsumoto et al., 2003). For this the model particles are illuminated by polarized light and viewed through a polarizing filter. The stressed particles light up and visualize the force-chain (see Fig. 1).

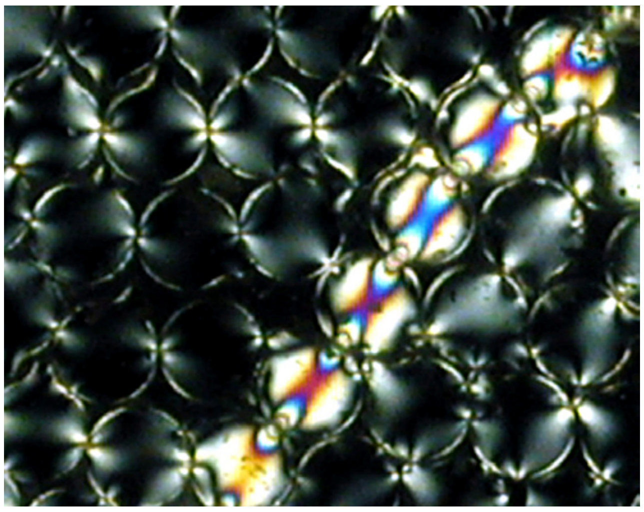

Fig. 1. Model particles under load – when compressed by a force the photo-elastic effect twists the polarized light and the stressed particles light up.

This is a two-dimensional model of granular material. The Plexiglas cylinders are positioned between two rectangular glass plates of 170 x 110 mm (see Fig. 2). Their distance is slightly larger than the thickness of the Plexiglas cylinders to ensure a free two-dimensional mobility. At each side of the glass plates polarizing filters are positioned. Their polarizing planes are set at 90 degrees to each other, thus blocking the light to pass through the model. If a stress is put on to a model particle the Plexiglas twists the light plane and light can pass through. It appears as if the particle lights up (see Fig. 1). The light pattern also contains information on the magnitude of the acting forces. Here, however, the evolving pattern of the force chains was in the center of interest and not the force as such.

Three models were investigated:

a model of a piston between walls - this simulates the blockage of sand in a tube,

a model of a piston in a confined space - this simulates the injection of sand into the soil,

a model of a piston in a confined space between walls - this simulates how force chains can act as valve.

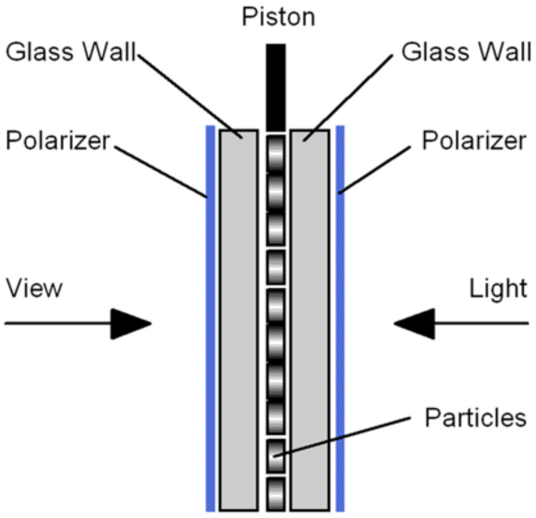

Fig. 2. Cross-section of the two-dimensional model. The glass walls confine the movement of the particles to two dimensions.

The tube was modeled with two walls restricting the movement of the particles in the lateral direction. A piston is modeled with another plate, applying a force onto the particles. The confined space was modeled with walls at the edges limiting the movement of particles. This was photographed (Nikon Coolpix 990, NIKON Corp., Japan) and filmed with a standard video camera (Canon MV30, CANON Inc., Japan).

2.2 Visualization of Sand Grain Movements in a Three-Dimensional Model

A three-dimensional model was made with a glass tank with a base of 200 x 400 mm and a height of 400 mm. It was halfway filled with sand (0.2 mm < grain size < 1 mm). With this model a half space is experimentally approximated, if the deformation is kept in the center and in addition kept small enough. If the deformation of the sand is generated right at the glass wall, this glass wall can be considered as a symmetry plane, thus rendering a cross section of the half space. The glass wall introduces only a small error, because the coefficient of friction of sand on glass is much smaller than the coefficient of inner friction of sand.

To avoid capillary effects the sand was covered with water. In the center a half-tube with an inner diameter of 30 mm was attached to the front wall of the tank. Inside the half tube another half-tube with 15 mm inner diameter was attached. In the latter the piston with a D-shaped cross-section is moving up and down. This is a representation of the geometry of the third model - piston in a confined space at the end of a tube – and a realization of a sand injecting piston. The piston is driven with a linear drive. It permits a slow movement (13 mm/s) and a travel of 40 mm. Sand was fed into the upper end of the outer half-tube. It sinks to the end of the piston by gravity forces and replaces the sand which is consumed at the lower end by the injecting piston. The sand grain movement was observed through the glass wall, filmed with a standard video camera (Canon MV30) and analyzed with a PIV program (DaVis 6.2.3, LaVision GmbH, Germany).

3. Results

3.1 Force-Chains

Piston between walls

When no load is applied, all particles appear dark (see Fig. 3, left). When the piston is pressed onto the particles, the force-chains become visible. The force chains lead from the base of the piston to the walls and form arches. These arches direct the force of the piston onto the walls. The lower part of the granular material is not affected and stays dark. In this way blockage is created and a further movement of the piston is impeded. In such way the Janssen-effect is created and made visible (see Fig. 3, right).

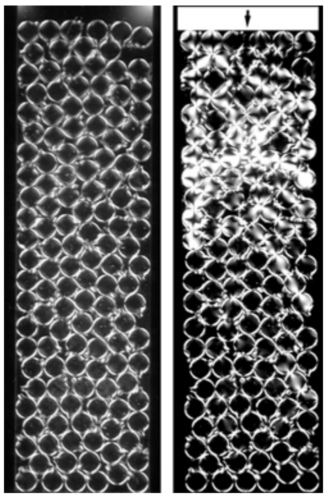

Fig. 3. Particles between walls – a slender confined space. All particles appear dark, left. Under the load of the piston acting on the top, force chains become visible, right. They lead the force of the piston into the side walls. In the lower part the particles are unstressed. This effect is found in silos, the so called Janssen-effect.

Piston in a confined space

If, however, walls of the cylinder are absent, the force chains spread out and act on the surrounding mass of particles and displace them (see Fig. 4).

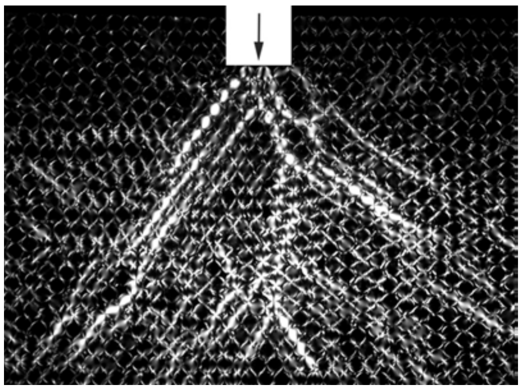

Fig. 4. Particles in a rectangular confined space. The force-chains generated by the piston in the top center distribute the force till the force-chains reach the walls. The upper corners remain free and thus unloaded. Arrow shows a force direction generated by piston.

Piston in a confined space between walls

To make the injection of granular material possible, a new arrangement of piston and walls is proposed. The walls represent the tube in the three-dimensional case. This arrangement assures that the force chains generated by the moving piston are directed away from the surrounding walls. In this way arching is avoided and a movement of granular matter is achieved. To achieve this, the piston is smaller than the distance of the walls and it is positioned somewhat retracted from the end of the walls. Thus the force-chains do not reach the walls and act directly on the surrounding ground, which is to be displaced. The piston does not create the Janssen-effect and expels the granular material (see Fig. 5, left). When the piston is reversed, force-chains are generated by the granular material pressure, which acts on the end of the tube. These force-chains are desired because they prevent the entrance of the surrounding granular material into the space between the walls. In such a way the force-chains act as a valve (see Fig. 5, right). The injection of sand is thus possible by a simple oscillating piston at the end of the tube.

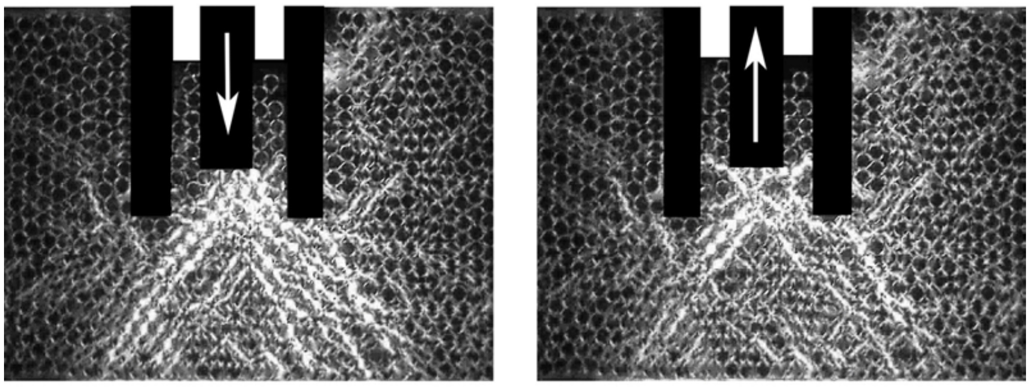

Fig. 5. Piston at the end of a cylinder. Left the piston moves down and the force chains distribute the force to the surrounding granules. Right the piston moves up. New force chains appear and form an arch at the end of the cylinder. This arch leads the forces into the walls and impedes the movement of granules into the cylinder. Thus the grains act as a valve.

3.2 Sand Movement

When the piston moves down, it displaces the sand and injects it. When the piston reverses and moves up, the surrounding sand does not follow it, as a fluid would do, but remains in its displaced position. The pressure of the surrounding sand is directed to the tube and the sand acts as a valve. Such a space is created, which is filled from the sand in the tube. This filling is gravity-driven like the outflow of granular matter out of a silo. In this way a pumping action is generated by only the up and down movement of the piston. Valves are not needed, because the geometric arrangement of piston and tube makes use of the force chains, as it is shown in the Plexiglas model.

After some time of the injection sand accumulates at the end of the tube and a spheroid of injected sand forms. By feeding of sand of different colors, the distribution and growth of the growing spheroid was made visible (see Fig. 6).

To form such a spheroid, the sand must move in curves. This was visualized with the help of the PIV - Particle Image Velocimetry method (Stanislas, 2000; Best, 2001). This method permits the analysis of images with a time lapse and delivers fields of the velocity vectors (see Fig. 7 above).

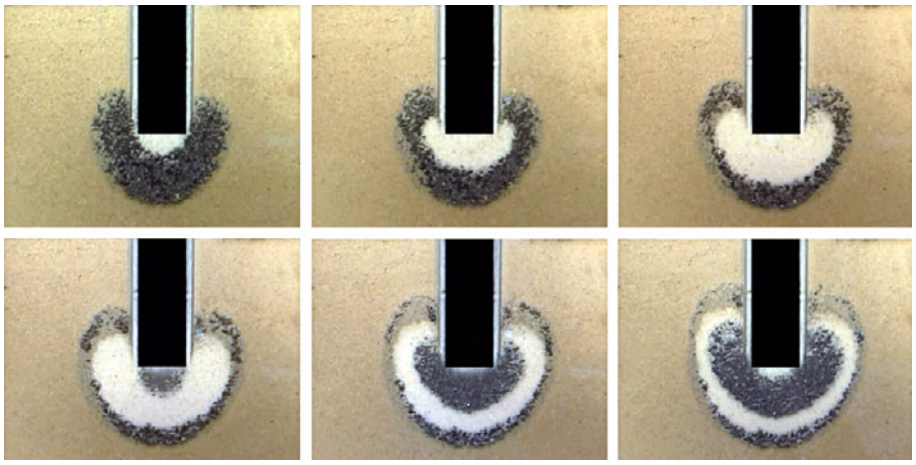

Fig. 6. Injection of sand into the surrounding sand. The accumulated sand takes up the form of a spheroid. This development is made visible with sand of different colors.

The result resembles the vector field of a flow of a viscous fluid out of a source. But how can this similarity be explained, since sand is not a fluid? For an analysis the sand volume can be divided in two domains: domain one is the one of small deformations which can be described by the classical theory of an elastic half space with Hooke's deformation law of an elastic continuum:

$$\tau = G \cdot \gamma \tag{1}$$

with τ being the shear stress, G the shear modulus and γ the deformation angle. Domain one thus is the domain of elastic deformation and the shear stress is below the sand´s shear stress limit. Domain two, however, is the domain of a viscous fluid because here the sand is stressed at its shear stress level and every increase in shear stress will result in a deformation. Hence, it can be described by the deformation law of a fluid continuum:

$$\tau = \eta \cdot \omega \tag{2}$$

where η is the viscosity and $\omega = d\gamma/dt$ is the shear rate. The latter is known as Newton´s shear stress law and characterizes a viscous fluid. However, in this case η is not a constant, but a function of ω. In this experimental analysis we do not know this function, but the shear rate ω can be visualized: it is determined by the function:

$$\left|\omega_z\right| = \frac{dv}{dx} - \frac{du}{dy} \tag{3}$$

where u and v are velocity components of the sand movement in the x and y direction respectively (see Fig. 7). This describes an angular movement around the axis vertical to the glass plate – the image plane, (see Fig. 7 below right). In civil engineering it is desirable to stay in the domain one – the elastic deformations of the soil and tries to avoid the domain two - the fluid state of the soil. In applying our method this fluid state of the soil is created: the sand is subjected to shear stress, until its shear strength is reached. Every increase of shear stress leads to a deformation; now this continuum resembles a fluid. However, at all times the sand can take up loads. This feature makes it safe and effective for the purpose of raising a building. In addition, by choosing a sufficient distance - depth - of the injection site to the building one can keep the angular deformation of the surface controlled and small.

4. Conclusion

In the development of the new method to inject granular matter methods of visualization were instrumental. They permitted a deeper understanding of the role of force lines to overcome the blocking effect – the Janssen effect. The force line experiments were successfully transferred to an actual granular material – sand. These experiments show that injection of sand into the ground is feasible. With the proper selection of the tube and piston geometry sand can be injected into the ground, where it accumulates in the form of a spherical body. Although the sand in the vicinity of the piston is sheared and thus a flow of sand is observed, the sand is load-bearing at all times. This discriminates our method from the well-known grout injection, where a fluid – a mixture of water and very small particles - is injected and the ground partially is destabilized. Further work will be needed to show the feasibility of the method for civil engineering tasks, such as actually raising the ground with buildings on it. In order to prevent any slanting of the buildings on the ground, an even uplift has to be achieved. For this several boreholes need to be drilled into the soil. The required depth is not yet defined and depends on the area to be raised. The borehole depth defines the injection pressure. Preliminary experiments show the pressure at the piston is about hundredfold the ground pressure. This is a high pressure, but for a borehole depth of 10 meters this is well in the working range of hydraulic pistons.

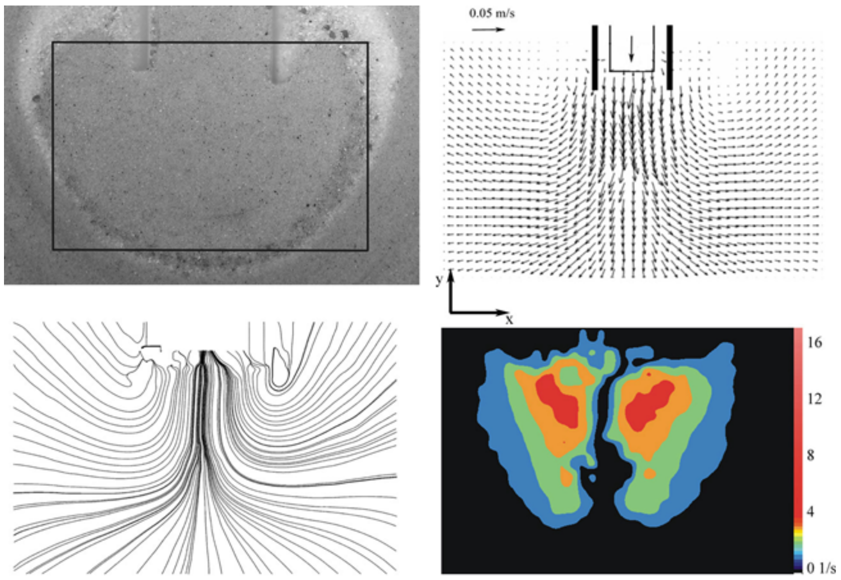

Fig. 7. Visualization of the sand movement close to the piston with the PIV method. Above left is a photo of the sand used for PIV is shown with a marked region evaluated by PIV. Above right a vector field is shown, in the down left the path lines of the sand grains and right the shear rate of the sand – the angular movement. The color red denotes the highest shear rates.

There is a great need for a method to raise the ground to counteract subsidence. Subsidence is a world wide problem, not only in Venice, but in many other cities. For many port cities this will be further aggravated by the rise of sea level, which is expected to happen in this century due to global warming.

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Author Profile

Klaus Affeld: He received his diploma degree in Aircraft Engineering in 1962 and his doctorate (Eng.) in fluid mechanics in 1969 from the Technical University Berlin. He worked at the institute of aircraft engineering in Berlin before starting his doctorate. After obtaining his doctorate, he worked as a researcher in Biofluidmechanics, focusing on the development of an artificial heart and taught Biofluidmechanics at the Technical University Berlin. In 1987, he founded the Biofluidmechanics Laboratory within the Charité. His research interests are blood flow, including flow in artificial organs, experimental methods in fluid mechanics, biomedical engineering and biomechanics.

Felix Affeld: He studied architecture at the Technical University Berlin. He studied also at the University of Venice and did his diploma thesis on Venice. In Venice he became aware of the cities problem of subsidence. He is the initiator of this project – to find a countermeasure to the subsidence.

Perrine Debaene: She received her Diploma in Biomedical Engineering - Biomechanics/Biomaterials from the Technological University of Compiègne, France, in 2001. Since 2001 Perrine Debaene works as a research assistant at the Biofluidmechanics Laboratory, Charite Berlin. She finished her Ph.D. thesis, that was supported by the German National Academic Foundation and received her doctorate in Engineering from the Technical University of Berlin in 2005. Her research interests are quantitative visualization, PIV, flow in natural and artificial organs and biomechanics.

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