MECHANICS OF GRANULAR MATERIALS ARCHING THEORIES AND EXPERIMENTS

Bela Csizmadia, Istvan Keppler

SZIE Faculty of Mechanics, H-2103 Gödöllő Páter K. 1., Hungary

Abstract: *The arching action in granular mass – formation, stability and damage of self-supporting stagnant arch like structures inside the bulk material – investigated here with our quasi-triaxial-, arching examiner- and optical measurement apparatus. Measurement of the flow function using our quasi-triaxial apparatus discussed. Definition of bilinear material model and fabric damage also discussed here. With the use of the flow function and bilinear material model we designate upper and lower borderlines of the region where self supporting bulk material – the so called disturbed region – can be found. Our research was supported by OTKA* 035022

Keywords: *granular material, arching, triaxial apparatus, bilinear model, flow function, fabric damage, disturbed region*

1. INTRODUCTION

All the experts working in agricultural engineering, food industry, pharmaceutical or chemical industry and the geotechnical- or mining engineers are facing themselves with the problems caused by the special properties of granular materials. Every operation – storage, mixing or shipping –, made with theses materials causes problems, which cannot be found in the same operations with liquid or solid materials.

During the discharge of granular material from silos – or other storage facilities – under some special circumstances, a so-called disturbed region is taking form within the granular material. Mechanical properties of granular material within this region are changing and the region became capable of bearing of it's own weight, and the pressure originate from the weight of granular mass above it. This phenomena is called arching action. The shape of the arches inside the granular mass is unknown, and this makes the prediction of the formation and stability of these structures extremely difficult.

In what follows, – beside the general outline of this problem – we will discuss the subject of arching action in granular mass. We will also study the methods of determination of those material properties that are important for the investigation in the field of arching.

2. FAILURE CRITERIONS

To determine the stresses within the disturbed region – or the arch –, we have to measure the granular materials material- and failure properties.

2.1. Quasitriaxial measurement apparatus

The load acting on a prismatic sample inside the granular mass is triaxial. The vertical load is caused by the granular mass above the specimen. The reason of the horizontal load is that the material lying in the prism's neighbourhood prohibits the sidelong movement of the prismatic specimens horizontal boundary. The reason of this can be the silo wall (which has a sort of stiffness), or the neighbourhood of the specimen. It is obvious that we need to use triaxial apparatus, to determine the material constants and failure criterions of granular material.

The classical triaxial testing apparatus uses cylindrical specimen. The vertical load and the horizontal pressure can be adjusted by the user.

We developed a quasi-triaxial measurement apparatus, which is capable to model the real circumstances better like the classical one. In our apparatus, the horizontal pressure acting on the prismatic specimen is caused by the wall, which has variable spring constant. This side force is measurable. However, the magnitude of these forces is not controlled by the researcher, but evolves because of the (adjustable) rigidity of the side wall.

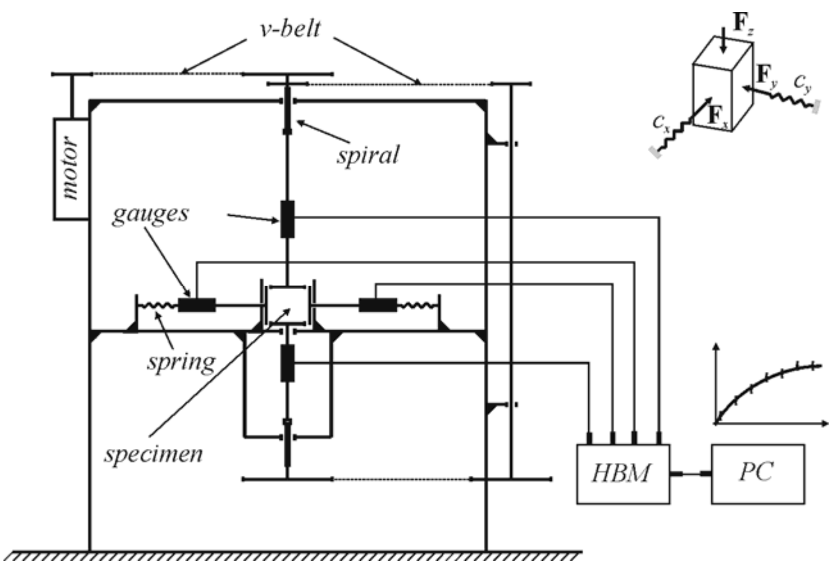

Fig. 1: Quasi-triaxial apparatus

The vertical force is generated by an electric motor, rotating a spiral shaft with a plate on its end. The side wall can be supported with springs, having variable spring constants.

The forces acting on the top and sides of the specimen can be measured with gauges having known spring constant, or gauges that supposed to be rigid. The electronic signals coming from the gauges are processed with the use of HBM Hottinger measurement system.

It is possible to take into account the friction forces acting on the side walls, with the measurement of forces acting on the bottom plate.

The quasi-triaxial apparatus is appropriate to measure the material constants belonging to the linear models [3]. In the next chapter, we discuss those failure criterions that are necessary for the investigation of the arching action and can be evaluated using the quasi-triaxial apparatus.

2.2. Flow function, an arching parameter

The quasitriaxial testing apparatus is suitable for the determination of the flow function, which determines the arching capability of granular materials. For the determination of the flow function, the specimen is pre-compressed in the quasitriaxial apparatus by the force belonging to the normal stress σ_1, while σ_2 horizontal stress prevents the specimen from collapse.

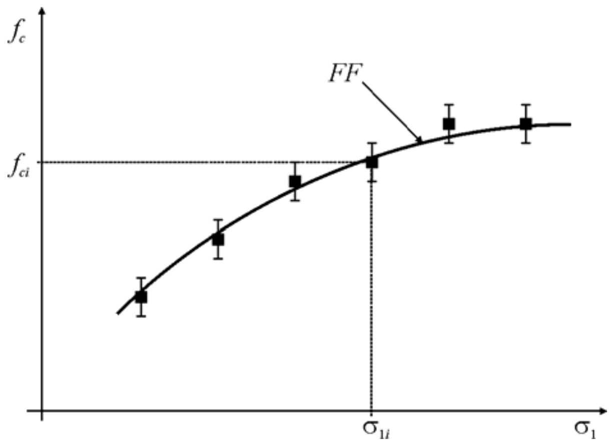

Fig. 2: Flow function

In a subsequent step, the normal stress is halted, and the walls of the specimen's container are removed. In the next step, the compression of the specimen continues until its collapse. The consolidating stress σ_1 and the force f_c belonging to the collapse are recorded. The function, which fits the pairs of stresses called flow function.

2.3. Bilinear approach

Results of quasi triaxial measurements show that the use of bilinear functions to fit on the triaxial test results gives better accuracy than simple linear fit.

The bilinear function is derived from two linear functions as it can be seen in the figure. With the use of bilinear model, we gain more accuracy, and do not loose the simplicity of linear functions.

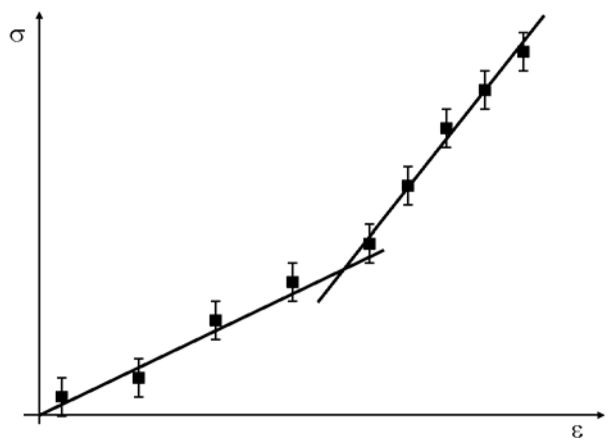

Fig. 3: Bilinear approach

2.4. Fabric damage

The use of bilinear material enables us to define the fabric damage phenomenon. This is the process when inside the material there are microstructural rearrangements because of the increasing stresses. The result of these rearrangements is the abrupt change in the material properties, beside small deformation. The connection point between the two linear functions in the bilinear model indicates this microstructural rearrangement, called fabric damage.

3. EXPERIMENTAL AND NUMERICAL INVESTIGATIONS

With our arching examination apparatus we are investigating the process of formation, damage and the stability of arches inside the granular material.

Our numerical investigations – with the use of finite element method programs – shows that it is important to designate the disturbed region within the granular material, to go on further and determine the stress field within this region. The disturbed region is that region within the granular material, in which the stress state is changed so – because of the change in the boundary conditions (e.g., the opening of the lower part of the hopper) – that the region is capable to wear it's own weight, and support the material lying above it.

To designate the disturbed region, we use the failure criteria defined above, the flow function used widely in the literature and the fabric damage defined by us. We assume that with the use of these failure criterions, it is possible to designate three different regions within the granular material inside a silo. These three regions are:

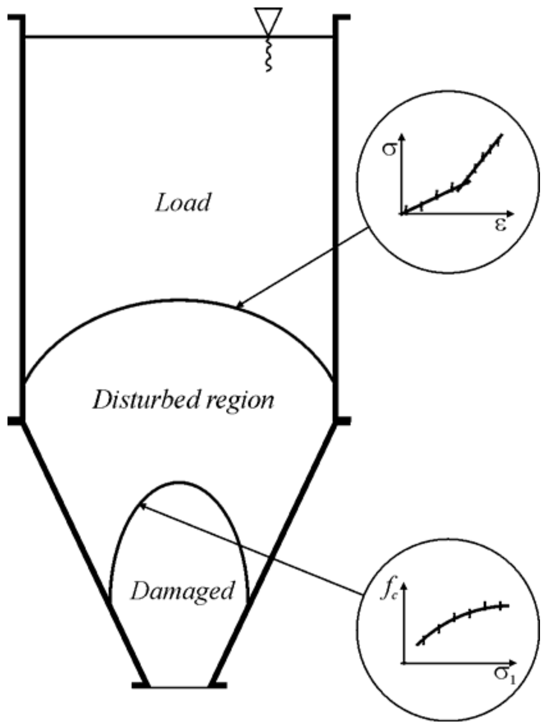

Fig. 4: The three regions

1. In the neighbourhood of the granular materials free surface and below, there vertical pressure is not high enough to bring the material in the state, where the fabric damage begins. The material is not consolidated enough to support its own weight, or the weight of the material above it. This region means only the load of the regions below.
2. Deeper inside the granular material the vertical pressure is growing. At one point, the pressure is high enough to consolidate the material in a state, where the fabric damage occurs. Here, because of the microstructural changes inside the granular mass, the

consolidated region is capable to wear it's own weight, and support the material lying above it. This is the disturbed region.

3. In the neighbourhood of the silo's bottom, the stress state is entirely different from the stress state can be found in the disturbed region. This is because the stress state is biaxial here (the lower part of the hopper is open). The bearing capacity of granular material in biaxial stress state is defined by the flow function. Therefore, if before the opening of the silo's bottom, the stresses were higher than the stresses defined by the flow function, the granular material is starting to pour out from the silo. The entire region, where the stresses were higher than those defined by the flow function, is pouring out from the hopper. This region is called the damaged region.

After the formation of the initial arches depicted above, there are two possibilities. The disturbed region is capable to support the structure; this means arching. It is possible, that the stresses are developing inside the disturbed region in a form, where Coulomb's classical yield conditions are satisfied, and the arch collapses.

4. FURTHER RESEARCH

We are working on an optical measurement system, which will be able to investigate the microstructural changes inside the granular material. Transparent, optically sensitive material (crushed glass) is used, with the pores between the particles filled with liquid, which has the same refractive index as glass. Without pressure on it, the whole assembly is transparent. Because glass becomes anisotropic to shear stress, the stress distribution is made visible with this method. We assume, that the structure of the force chains – made visible with the method explained above – is changing significantly in the neighbourhood of the fabric damage.

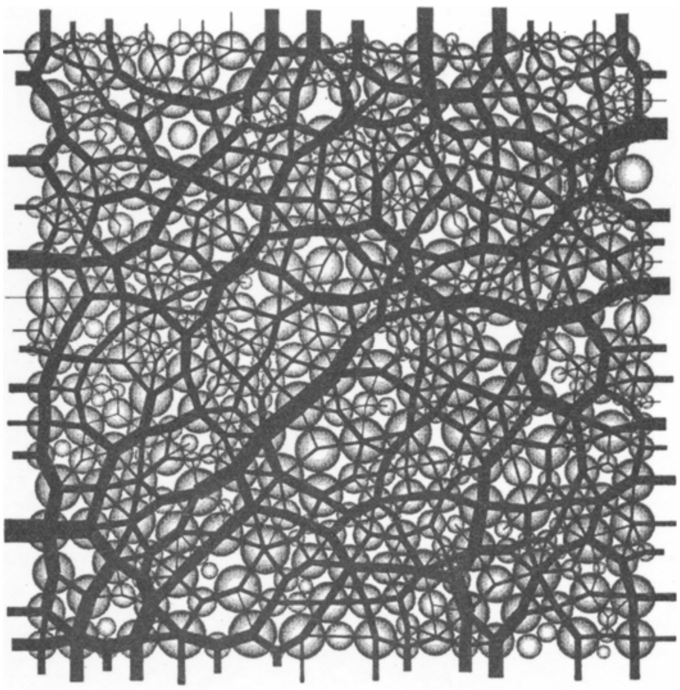

Fig. 5: Force chains

With the use of material properties measured with the quasitriaxial apparatus, we will be able to create a more accurate finite element model using homogenous, bilinear material model. With this more accurate model, it will be possible to designate –

numerically – the boundaries of the disturbed region. If we know the boundaries of this region, it will be possible to determine the stresses developing inside the arches, during the arching action. The results of the numerical investigations can be verified wit our modified arching action testing apparatus experimentally.

5. REFERENCES

1. **A. Drescher, A. J. Waters, C. A. Rhoades**: *Arching in Hoppers I-II.*, Powder Technology, 84, (1995), pp. 165-183
2. **Csorba L., Balássy Z.Huszár I., Csizmadia B.**: *Determination of Poisson's ratio in elastic oedometer*, 4th ICCPAM Int., Conf., Rostock, 1989, Proceeding, Volume 1, pp. 26–30
3. **Gabriel I. Tardos**: *Stresses in Bins and Hoppers*, www.erpt.org/992Q/tard-00.htm
4. **Huszár I., Csizmadia B.**: *Biotechnológiai [...] folyamatokban résztvevő anyagok mechanikai tulajdonságainak vizsgálata*, OTKA 881 zárójelentése, GATE MGK MECT, 1990
5. **Janssen, H. A.**: *Getreidedruck in Silozellen,* Z. Ver. Dt. Ing., 39, (1895), pp. 1045-1049
6. **Keppler I.**: *Szemcsés anyagok természetes boltozódása és a tönkremeneteli jellemzők kapcsolata,* Fiatal Műszakiak Tudományos Ülésszaka, 2003, a konferencia kiadványa pp. 161-164