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Effects of grain properties on loads in model silo**

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A b s t r a c t. This work addresses the variation in wall loads in thin, smooth walled, flat floor metal silos caused by the variation in the mechanical properties of the grain bedding and friction forces acting on the grain-wall interface. Experimental effects shown and discussed are not fully covered by standard design codes. Background of some of these phenomena is still poorly understood, and as such a satisfactory theoretical description for the causes of these phenomena cannot be offered. As illustrated by experimental results, these effects can cause additional loads to occur on silo walls.

K e y w o r d s: grain silo, mechanical properties, silo loads

INTRODUCTION

Silos present the structural engineers with one of the most complicated design challenges they must face (Rotter, 1998). Not only must a silo designer understand the structural aspects of the design, but also understand and take into account the properties of the material stored within, which can vary significantly not only between different locations in the silo but also from one loading regime to another. Standard design procedures currently used to estimate the loads in silos assume constant grain properties throughout the silo and do not take into account the variation that can occur caused by the frictional interaction between grains, particle deformation and/or elasticity. Sundaresan (2001) suggested that significant gaps exist in our understanding of particulate systems, translation of the behaviour of these systems into mathematical models and the solution of such models. In the area of storage and discharge of granular materials, several seemingly simple problems continue to remain challenges. One of these is our inability to characterize how seemingly secondary variables, such as small changes in humidity level or moisture content of the material, affect the deformation characteristics of the bedding.

The majority of granular mechanics theory was formulated for mineral materials. However, bulk or cereal grains are different in that they are comprised of particles that are deformable under operational loads, and their mechanical properties vary significantly with moisture content. The results presented in this paper were selected from several different completed projects and concern the variation in wall loads in thin, smooth-walled metal silos caused by the variation in the mechanical properties of the grain bedding and friction forces acting on the grain-wall interface.

EQUIPMENT AND PROCEDURES

The majority of silo model tests reported in this paper were conducted using a model silo 2.44 m in diameter and 7.3 m high. The wall and flat floor of the model silo were each supported on three load cells evenly spaced around the circumference of the silo. The silo was centrally filled from a spout up to an initial height-to-diameter ratio (H/D) of 2.75 (if not stated otherwise). The model was then discharged through a centric discharge orifice. The wall and floor loads were measured during loading, detention and discharge at 1 min intervals until discharge was completed. Soft red winter wheat was used for all tests.

The coefficient of wall friction and the stress ratio were determined in a cylindrical model silo 0.6 m in diameter and 0.6 m high. The wall of the test apparatus was constructed in two semicircular halves cut along the axis. The two

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semicircular halves were connected with four load cells installed in pairs on the two connection lines. The model silo had a flat bottom consisting of five concentric rings, each of equal area, which were used to measure the radial variation in vertical pressure acting on the silo floor. The wall and each ring in the model silo were supported on three load cells evenly spaced around the circumference. The experimental set-up allowed for determination of the mean lateral pressure, vertical wall stress, and mean vertical pressure. The coefficient of wall friction, μ^*, was determined as the ratio of mean vertical wall stress, σ_t, to mean lateral pressure, σ_x. The average value of the stress ratio, k, was calculated utilizing a numerical solution of Janssen's (1895) equation for the mean vertical pressure on the bottom of the silo. The model was also equipped with a air humidifier system which was used during tests involving the swelling pressure of grain. A perforated cylindrical air plenum located centrally in the silo supplied grain with moist air. The silo was centrally filled and precompressed. Following precompression, the vertical pressure was decreased to a value of 3 kPa, created by the weight of the top cover of the silo. During testing, wet air with relative humidity of up to 95% and the temperature of 36°C was blown through the grain for 24 hours and swelling pressures were measured. The initial moisture content of the grain, u_o, was approximately 7% (wet basis). This value was chosen to increase the rate of moisture absorption from the conditioned air.

RESULTS

Swelling pressure of wetted grain

The mean lateral pressure, σ_x, on the silo wall is shown in Fig. 1 for two initial moisture contents: 6.8 and 7.1% (wet basis) (Horabik and Molenda, 2000). The swelling pressure increased linearly with changes in moisture content. The swelling pressures were found to be highly influenced by the initial moisture content of grain. The bedding structure also influenced both the pore structure and distribution and, ultimately, the permeability of the layer of grain. Although the same filling procedure was followed throughout this experiment, relatively large variations in the swelling pressures were observed between different replications. This variation is believed to be caused by the variation in bedding from one replication to another. The initial bulk density was also a major factor influencing swelling pressure. The results of the tests performed on the model silo (small precompression – σ_z =10 kPa, ρ_0= 780 kg m^{-3}) as compared to the results of an oedometric test (strong precompression – p =500 kPa, ρ_0= 835 kg m^{-3}) indicate that the swelling pressure is strongly influenced by the initial bulk density of the grain.

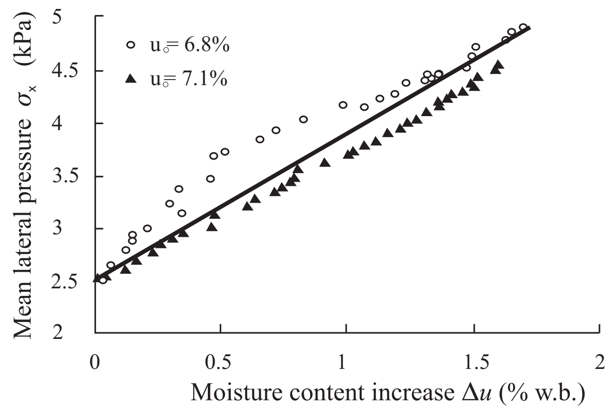

Fig. 1. Mean lateral pressure on the silo wall as influenced by moisture content increase.

Accumulation and relief of elastic energy

Stress-strain curves for uniaxial compression of wheat at five different moisture contents during both loading and unloading are shown in Fig. 2 (Molenda and Stasiak, 2001). Changes in moisture content resulted in large variations in the loading curves, which were reflected in values of

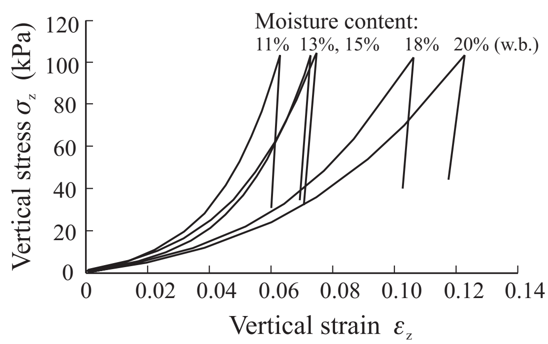

Fig. 2. Stress-strain relationships for uniaxial compression tests of wheat grain.

modulus of elasticity, E, and Poisson's ratio, ν. The modulus of elasticity, E, decreased with an increase in grain moisture content and varied from 22.4 MPa at a moisture content of 10% (w.b.) down to 11.1 MPa at a moisture content of 20% (w.b.) The maximum pressure of 100 kPa exceeded that in typical grain storage structures. Poisson's ratio, ν was found to not have a clear relationship with moisture content and varied over a range from 0.22 to 0.18.

Horabik *et al.* (1992) determined that during the final stages of discharge the vertical frictional forces acting on the walls of a model silo, 0.4 m in diameter and 1.6 m high equipped with a flat bottom, changed their direction from a normal downward direction to an upward direction (Fig. 3). This reversal in the direction of the vertical frictional force was first observed during unloading at the height-to-diameter ratio of approximately 1 and was believed caused

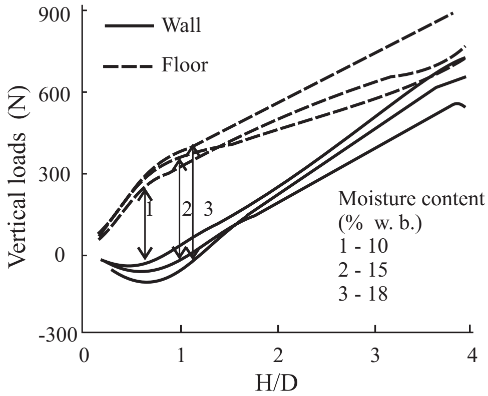

Fig. 3. Vertical wall and floor loads as affected by the height-to-diameter ratio (H/D) during discharge for wheat at three moisture contents.

by the viscoelastic response of the grain, which occurred because of a decrease in consolidation pressure produced by the overbearing grain. During this response the particles 'rebound', resulting in an upward movement of the grain mass and a change in the direction of the vertical frictional forces acting on the wall. This recoverable part of the total volumetric strain were found to vary with changes in the moisture content of the stored grain. The maximum upward friction force on the silo wall increased from 40 N for a moisture content of 10% (w.b.) up to 96 N for a moisture content of 18% (w.b.).

Elasto-plastic hysteresis of grain

Typical hysterestic behaviour was observed during the determination of the coefficient of wall friction, μ^*, and pressure ratio, k, in a 60 cm diameter model silo (Horabik and Rusinek, 2000). The largest differences in the pressure ratio, k, were observed during the first loading cycle (Fig. 4a). Subsequent loops of the pressure ratio followed approximately the same path from one loading cycle to the next. Values of the pressure ratio for wheat obtained in this experiment varied from 0.31 to 0.44 during the first loading cycle and were much lower than 0.5 recommended by Eurocode 1 (2003). These experimental values were also lower than the range of values (0.46 to 0.62), which can be obtained by using the angle of internal friction, φ, and an equation for the stress ratio recommended by Eurocode 1.

The coefficient of wall friction, μ^*, also varied with changes in the vertical load (Fig. 4b). During the first phase of loading its value decreased from 0.4 to 0.27. During unloading, the value of μ^* decreased down to 0.11. In subsequent loading cycles, hardening of the grain bedding occurred in which increased vertical pressures were observed. This resulted in a further decrease in the coefficient of wall friction.

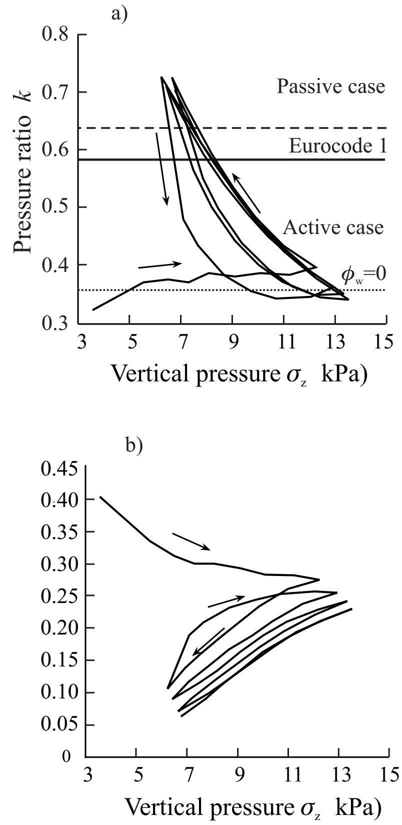

Fig. 4. The pressure ratio (a) and the coefficient of wall friction (b) versus the vertical pressure for wheat in succeeding loading-unloading cycles.

Hysteresis effects were also observed in tests conducted in a 2.44 m diameter model silo 7.3 m high in which the effects of partial emptying and refilling of the bin were studied (Horabik *at al.*, 1999). During these experiments, the silo was loaded to an H/D ratio of 2.75 and then unloaded until the vertical wall load (VWL) decreased to zero. The silo was then reloaded to an H/D ratio of 2.75 and then unloaded. This cycle of loading and unloading was repeated five times. Figure 5 shows a comparison of the experimental and predicted relations of the vertical wall load-to-gross grain load ratio (VWL/GGL) as a function of the height-to-diameter ratio during fill and unload cycles. The largest irreversible rearrangement of intergranular forces occurred during the first fill and unload cycle. In each succeeding fill and unload cycle, the hysteresis loop is several times smaller than that found for the first cycle. During each rest period, the VWL/GGL ratio decreased as a result of intergranular forces rearrangement. At the beginning of unloading (the bottom 'dot' on the vertical unload line) a dynamic load shift from the silo floor to the silo wall was observed. A significant decrease in the dynamic load shift was observed with an increasing number of fill-unload cycles.

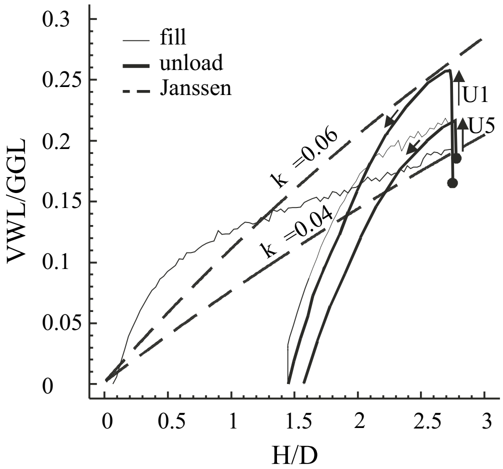

Fig. 5. Comparisons of experimental and predicted (Janssen) relations of vertical wall load-to-gross grain load ratio (VWL/GGL) to the height-to-diameter ratio (H/D) during fill and unload (U1 – first, U5 – fifth) cycles.

CONCLUSIONS

1. Seemingly simple problems of predicting stresses exerted by grain on silo walls continue to remain challenges. Two basic challenges are the complicated mechanics of the shell constituting the silo wall and the variability of the stored material. In particular, for grain a wide range of variability of material parameters has to be accepted as an inherent feature of the material because of the considerable number of factors which can influence these types of materials. In this work some reasons for variability of grain properties and their influence on silo loads has been shown.

2. Experimental effects shown and discussed above are not covered by standard design codes. However, these effects are frequently observed for flat floor, smooth wall metal silos storing grain. Background of some of these phenomena is still poorly understood, and as such satisfactory theoretical description for the causes of this phenomena cannot be explained. Consideration should be made in the design of silos for these effects, in particular where operational conditions promote these higher loads.

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