EXPERIMENTAL AND THEORETICAL INVESTIAGTIONS OF SILO MUSIC DURING GRANULAR FLOW

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1. Introduction

Dynamic effects can occur in granular bodies during confined flow in silos. Strong vibrations are accompanied by a booming sound, sometimes called silo music or by repeated shocks called silo quake. In dry cohesionless granular silo fills, only silo music has been observed. In cohesive silo fills, silo music and silo quake can take place. These strong dynamic effects have been recorded in various conditions, e.g., in large full scale silos, small experimental models, during mass, funnel or expanded flow, and during controlled or free outlet. The strong dynamic effects create noise pollution that disturbs the neighborhood (e.g. local population residing close to industrial plants) or can cause hearing damage of plant workers. They may cause earthquake type movements which endanger surrounding structures and contribute to fatigue of joints and connections. In the most extreme cases, rapid vibrations can cause silo failures. In spite of many experimental studies, the phenomenon of the silo music is still not well understood.

On the basis of experiments, several sources of extensive dynamic effects in silos have been proposed which include: slip-stick behavior between stored solids and silo walls, grain collisions and a frozen disorder of the bulk solid, insufficient flow ability of the silo fill, energy release by the fall of the bulk solid from the region of mass flow into the region of channel flow, propagating longitudinal stress waves due to a resonant interaction between the granular material and the silo structure which were induced at the outlet, alternating flow patterns during flow, non-linear change of the wall friction with flow velocity, acceleration and deceleration of the granular material at the transition between bin and hopper, internal slip-stick and solid dilation during flow.

The aim of these investigations is development of the mechanism of the phenomenon of the silo music understood as pronounced vibrations connected with loud sound [1]. The study is limited to dry cohesionless sand during gravitational outflow from a cylindrical model silo.

2. Silo model tests

First, silo experiments with dry cohesionless sand during gravitational outflow were performed in a cylindrical perspex model silo. Wall accelerations and acoustic signals were recorded and the evolution of mode shapes for different levels of the granular material in a silo were determined. In addition, both pressures along the wall and inside the material above the outlet were registered. The Perspex silo model had a height of 2.00 m, an outside diameter of 0.2 m and a thickness of the wall of 40 mm. A symmetric outlet with a diameter of 0.08 m in the flat bottom induced a discharging process due to gravity. The silo was fixed at the bottom (it was supported by a steel rigid frame structure) and free at the top. As a filling substance, initially medium dense dry sand with rough grains was used. The silo was excited by modal hammer, linear motor actuator and flowing sand during emptying (when the silo music was created). In the case of an empty silo, 9 mode shapes were identified. Three lowest modes were bending ones and for higher modes - ovalling ones (i.e. the radial displacements dominated the shape of the modes). In turn, for the silo containing sand up to 1.90 m, only 3 bending modes were identified since the inertia of the filling was very large and the energy transmitted to the structure through the modal hammer and actuator was not sufficient to excite higher modes. During silo discharge, in the case of the sound signal, the dominant frequency was about 100 Hz and it corresponded to the 1^{st} ovalling silo mode shape. For the radial acceleration signal, the dominant frequency was also about 100 Hz. The dominant frequency of the vertical signal was found to be 50 Hz (it corresponded to the 2nd bending mode).

3. Theoretical model

It is proposed that there are some similarities between the origin of the sound in the silo and the music of bells. The mode shapes of the silo are very similar to the modes of bells. In bells, the clapper striking the shell causes that bell walls undergo radial vibrations that are associated with vertical ones. In the case of the silo, the role of the clapper is taken on by radial forces generated by the silo fill hitting the hopper at the outlet. The dominant frequency of the sound signal during flow equals to 100 Hz and it corresponds to the 1st ovalling silo mode shape which is very similar to the first bell mode.

To qualitatively explain the presence of pulsations of radial stresses during silo flow at the hopper due to the change of the shearing direction, simple plane strain FE-simulations have been conducted. The behavior of the granular body subjected to the varying shearing force along silo walls at the outlet was approximately described by a cyclic quasi-static direct shearing along wall under a constant normal stiffness (*CNS*) condition (which simulates the surrounding material) [2]. The FE-calculations were carried out with a micropolar isotropic hypoplastic constitutive model which describes the evolution of effective stresses and couple stresses depending on the current void ratio, stress and couple stress state, rate of deformation and rate of curvature and a mean grain diameter by isotropic linear and non-linear tensorial functions. The obtained numerical results were qualitatively the same as those obtained in the experiment with different cohesionless sand [3].

4. Conclusions

The silo music phenomenon in tall narrow silos containing granular fills occurs during gravitational outflow in the form of strong vibrations of the structure connected with a loud booming sound. The silo music requires a dynamic interaction between the silo structure and moving granular fill (i.e. frequency accordance). It is produced mainly by the change of the shearing direction in the silo fill at the outlet. Vibrations of silo walls and moving granular body cause air oscillations with frequencies audible by human beings.

The dominant frequency of the oscillating sand is 50 Hz. The exciting force transmitted mainly through sand has both vertical and radial components. The dominant frequency of the sound signal during flow equals to 100 Hz and it corresponds to the 1st ovalling silo mode shape.

The silo music is not generated by the slip-stick phenomenon understood as the variable friction between the smooth wall and granular material subjected to constant normal force.

The silo music can be significantly reduced avoiding the change of the shearing direction at the silo outlet or a decrease of a pulsating material column by additional inserts.

5. References

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