Silo emptying in aspect of the non-desctructive detection methods application

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Summary: The paper presents results of concentration measurements in non-cohesive sand during free flow in rectangular and cylindrical silos using different non-invasive methods like thermography, X-ray photography, X-ray tomography and electrical capacitance tomography. The effect of the initial bulk solid density and roughness of silo walls on the concentration changes were investigated. Advantages and disadvantages of all presented methods were outlined. The possibility of application of the Electrical Capacitance Tomography (ECT) for observation the porosity changes of the bulk solid was pointed out.

Keywords: silo, concentration, granular material, flow, non-invasive methods, tomography, ECT

1. Introduction

Operational safety of silo construction is strictly connected with knowledge of the distribution of the bulk solid pressure on the silo walls and on the hopper. In case of emptying slender steel and aluminium silos strong dynamic effects occurs as a result of resonance between shaking, flowing bulk solid and silo structure (Tejchman, 1996). The resonance increases the silo wall and hopper pressure, causes the pre-failure, failure or the building colapse (Niedostatkiewicz, 2003; Niedostatkiewicz and Tejchman, 2003, 2008). The real description of the distribution of the pressure on the silo wall is very complicated due to the presence of localization in form of shear bands, where the band thickness directly influences silo wall pressure distribution. More over, the shear zone inside the bulk solids causes non-symmetric flow. The thickness of the shear zones depends mainly on the initial bulk solid density, wall roughness, pressure level and emptying velocity. Analysis of the bulk solid concentration, in the shear zones is also possible by using non-invasive methods which are not intrusive inside to the flowing bulk solid of any imperfection. Formerly and presently different measurement techniques are used to reach the concentration changes in granular materials during silo flow: coloured layers, X-ray radiation, γ-ray radiation, stereophotogrametry, termography, X-ray tomography, electrical tomography and optoelectronic methods like DIC or PIV. In the paper the results from the application of thermography, X-ray radiation, X-ray tomography and electrical capacitance tomography (ECT) methods to the validation of the changes in the flowing bulk solid will be published. The results will be presented due to tests formed with model cylindrical and rectangular silos, in laboratory and semi-industrial scales. The advantages and disadvantages of the mentioned methods will be outlined. The topic of the paper will be the discussion about the possibility of the ECT application method to the diagnosis of bulk solid flow as one which gives the possibility to estimate the thickness of shear zones in flowing bulk solid and validation of the concentration changes at the cross-sections and close to the wall profiles (Chaniecki, 2006; Chaniecki et al., 2006; Chaniecki et al. 2007).

2. Methods of silo flow diagnosis

Explanation of the reasons of the bulk solid behaviour during silo flow needs the knowledge of processes inside the granular material, mainly the concentration changes. Application of the invasive methods, like direct pressure measurement, improve the imperfection into the tender bulk solids, which causes the changes of the mechanical proportions of the granular system. Therefore the results of measurements with the invasive methods will be not presented in this paper, the discussion will be concentrated only with non-invasive one.

3. Non-invasive methods of silo flow analysis

3.1. Thermography

Thermography is based on emission of electromagnetic waves by the specimen with a temperature higher than the temperature of absolute zero (-273^{0}C). Thermography uses the spectrum of the infrared band by the registration of the differences of the absorbtion and emission of different areas. For thermography measurements, the reflection of the very short infrared waves is very importent. The infrared waves are produced by the external sources of the thermal radiation, which are hotter than the measured specimen.

Experiments with application of the thermo-camera were performed using the cylindrical model of the silo (h = 0.5 m, d = 0.06 m, t_w = 0.05 m). Tests were performed with medium grain sand d_{50} = 0.8 mm: loose (γ= 14.8 kN/m^3, e_o = 0.79) and dense (γ= 17.0 kN/m^3, e_o = 0.56). Also some tests were done with the usage of a loose sugar and a rice. Smooth and a very rough walls along the whole height of the silo were used. Very rough walls were created by sticking the sand paper to the wall. The silo was filled by a hopper montage at the top part of the silo, and throw the sieve montage at the some place (so called "rain method" of silo filling). The model was emptying gravitationally by the outlet with the diameter d_o = 0.02 m, located at the middle of the bottom.

For dense sand and smooth walls the temperature in the middle of the silo, both during the mass (Fig.1a) and funnel (Fig. 1b) flow was in practice similar, equal to

25.8^{0}C. For dense sand and rough walls the temperature in the middle of the silo during the mass flow was 25.9^{0}C (Fig. 1c). During funnel flow the temperature increased to 26.2^{0}C (Fig. 1d) as a result of internal grain friction. The temperature at the contact surface between the sand and silo wall was equal to 26.3^{0}C (Fig. 1c, d). Distribution of temperature in the case of tests with loose sand were similar to one during tests with dense granular material, both for experiment with smooth and with rough walls.

The main advantages of thermography is precision needed for measurement which is equal to 0.1^{0}C and easy of reproducting the experiments. The disadvantage is the fact that only the upper part of the flowing granular material can be analysed. Concentration changes and differences of the thickness of the shear zone along the silo wall can not be traced with termography. The contact line between bulk solid and wall can be traced with the measured temperature difference.

This method can be considered in our study as a quantitative measurement method with low attractive for silo flow analysis.

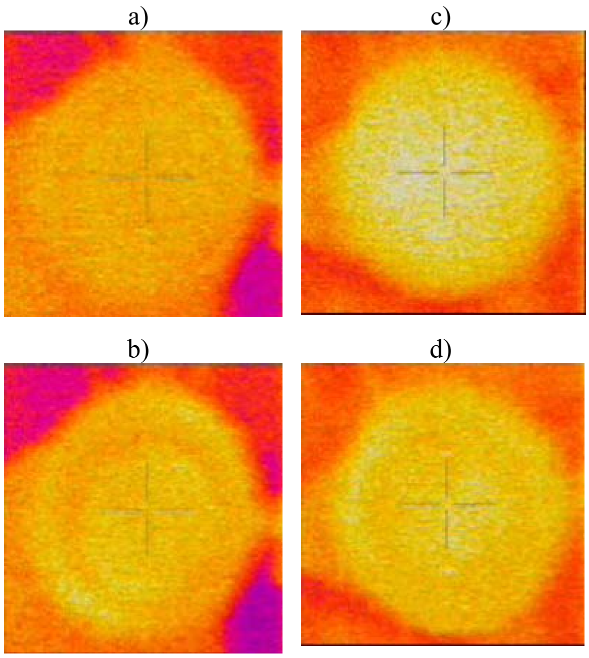

Fig.1. Measured temperature distribution of the top part of the dense sand during silo emptying at the time of mass and funnel flow for: a), b) smooth walls, c), d) rough walls

3.2. X-ray

The X-ray technique is based on different absorption of the radiation. Results are presented in positive and negative images. In case of positives image parts of granular material with smaller density and higher absorption are lighter, and areas with higher density and lower absorption are darker.

Experiments with the application of the X-ray method were performed with mass flow and funnel flow rectangular silos. The height of the mass flow silo was $h_m = 0.34$ m and the width $b_m = 0.09$ m. The height of the funnel flow silo was $h_f = 0.29$ m and the width $b_f = 0.15$ m. The wall thickness was $t_w = 0.01$ m. Tests were performed with medium grain sand $d_{50} = 0.8$ mm, similar to the previous tests with thermography: loose ($\gamma = 15.0$ kN/m^3, $e_o = 0.76$) and dense sand ($\gamma = 16.8$ kN/m^3, $e_o = 0.57$). Smooth and rough walls were also used. The silos were emptied gravitationally through the rectangular outlet with the width of $d_r = 0.005$ m and with the control flow. In the paper the results for mass flow are only presented. The loosening regions of the flowing sand were only detected during flow with an initially dense specimen.

The radiograms of silo flow of initially dense sand in a mass flow silo with smooth walls (Fig. 2a) revealed that a symmetrical pair of curvilinear dilatant rupture zones was created in the neighbourhood of the outlet (loosening is marked by a bright shadow). The zones propagated upward, crossed each other around the symmetry of the silo, reached the walls and subsequently were reflected from them. This process repeated itself until the zones reached the free boundary. In turn, in the case of the initial mass flow in a silo with rough walls and dense sand, curvilinear almost symmetric dilatant zones occurred in the material core above the outlet. They propagated upwards (some of them or crossed each other). Two different regions could be observed in the material (one core region in motion and two almost motionless regions at walls). The initial flow pattern was similar as this in a funnel flow silo. Later, during advanced flow, a pronounced loosening region above the outlet and dilatant shear zones along the walls appeared (Fig. 2b). During experiments with the sand paper (rough walls) the thickening of the shear band were noticed during the experiments with the dense material.

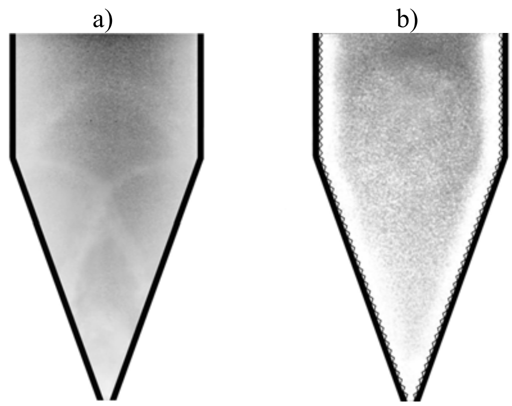

Fig.2. X-radiographs of initially dense sand during mass flow: a) with smooth walls, b) with rough walls

The main advantage of the X-ray measurement method is the possibility of observing changes inside the granular material. The disadvantages are facts that specialised apparatus is necessary for performing tests and the limitation that the specimen can not be too large.

This method can sbe considered here as a qualitative measurement method with medium attractive for silo flow analysis.

3.3. X-ray tomography

X-ray tomography hold its origin from the medicine. X-ray radiation is emitted by a source and is absorbed by the specimen, depending on the features and structure of the material. The remaining radiation travels to the detectors opposite the source. The next step of measurement is rotation of both the source and detector for the next projection. The complete reconstruction of the visualised image is possible in case of total rotation (360^0) of the source-detector. The image is reconstructed for different values of absorption coefficient received for different positions of the system source-detector system.

Experiments with application of the X-ray tomography were performed with cylindrical model of the silo ($h = 1.0$ m, $d = 0.075$ m, $t_w = 0.02$ m). Tests were performed with loose polymer granulate ($\gamma = 8.5$ kN/m^3). The measurement were connected with registration of the concentration changes of the horizontal pipe. During tests not only shear bands were not observed, but also the silo model could not be emptied due to the horizontal position of measured specimen.

The main advantage of the X-ray tomography is possibility of observation the changes of concentration at the cross sections. The disadvantages are that specialised apparatus is necessary and only horizontally moved specimen can be observed, as the tomograph is usually in the vertical plane.

This method can be regarded as a quantitative measurement method with low attractive for silo flow analysis.

a) b)

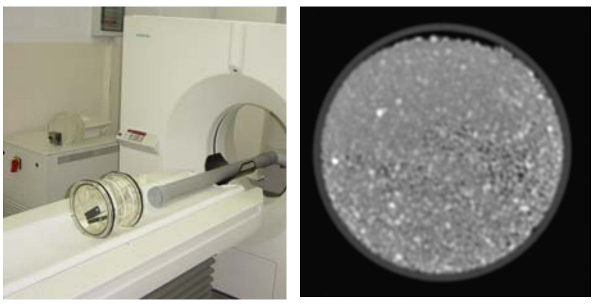

Fig.3. X-ray tomography: a) specimen prepared for test, b) tomogram (vertical cross-section)

3.4. Electrical Capacitance Tomography (ECT)

In the case of ECT, data is measured by the n_e electrodes which are located outside the pipe (silo) where the flow of the bulk solid take place (Fig. 4). As a result of those measurement N independent values of the electrode capacitancy c_i ($i = 0..N-1$) are received. They are the series of the M vectors of the between-electrode capacitancy $\mathbf{c}_m = \left[c_0, c_1, \ldots, c_{N-1}\right]$, where $m = 0..M-1$. This values allows for so called „raw data" analysis. Next procedure usually is performed on the basis of reconstructed image (32x32 pixels), received as a result of the reconstruction of the vectors $\mathbf{c}_m$. Reconstructed image is a description of the concentration of the dielectric permittivity $f(mT) = \left\{\varepsilon^m_{ij}\right\}$, where $i, j = 0..31$.

a) b)

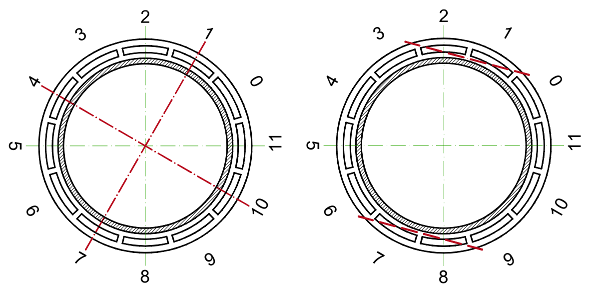

Fig.4. 12-electrode sensors used during experiments with ECT, examples of the cross-section profiles a) between electrodes 1-7 and 4-10; next close to the wall profiles b) between electrodes 1-2 and 7-8

Experiments with application of ECT tomography were performed with a cylindrical perspex model silo (diameter $d = 0.2$ m, height $h = 2.0$ m, wall thickness $t = 0.005$ m) containing non-cohesive, dry medium grain sand with a mean grain diameter of $d_{50} = 0.8$ mm, similar to that used in experiments with thermography and X-ray radiation. The silo was fixed at the bottom (it was supported by a steel rigid frame structure) and free at the top. Sand was initially loose ($\gamma = 15.0$ kN/m^3, $e_0 = 0.76$) or dense ($\gamma = 16.5$ kN/m^3, $e_0 = 0.61$). In the first case, sand was filled by hopper, and in the second case, the raining procedure by means of a sieve located above the silo top was used. Tests were performed for gravitational outflow (diameter of the symmetric outlet was $d_0 = 0.07$ m). Strong dynamic effects accompanied by a booming sound (called silo music) due to a dynamic interaction between solid and silo structure occurred in the upper part of the silo from the beginning of the silo discharge during mass flow (Tejchman 1996, Niedostatkiewicz 2003; Niedostatkiewicz and Tejchman 2003; Niedostatkiewicz and Tejchman 2008).

A 12-electrode ECT sensor was used in the tests. Measurements were performed at the heights of 0.3, 0.75, 0.85, 1.0 and 1.5 m from the bottom. During separate test tomographic data was measured only at the two heights: always at the 1.5 m and the second one varied from 0.3 to 1.0 m.

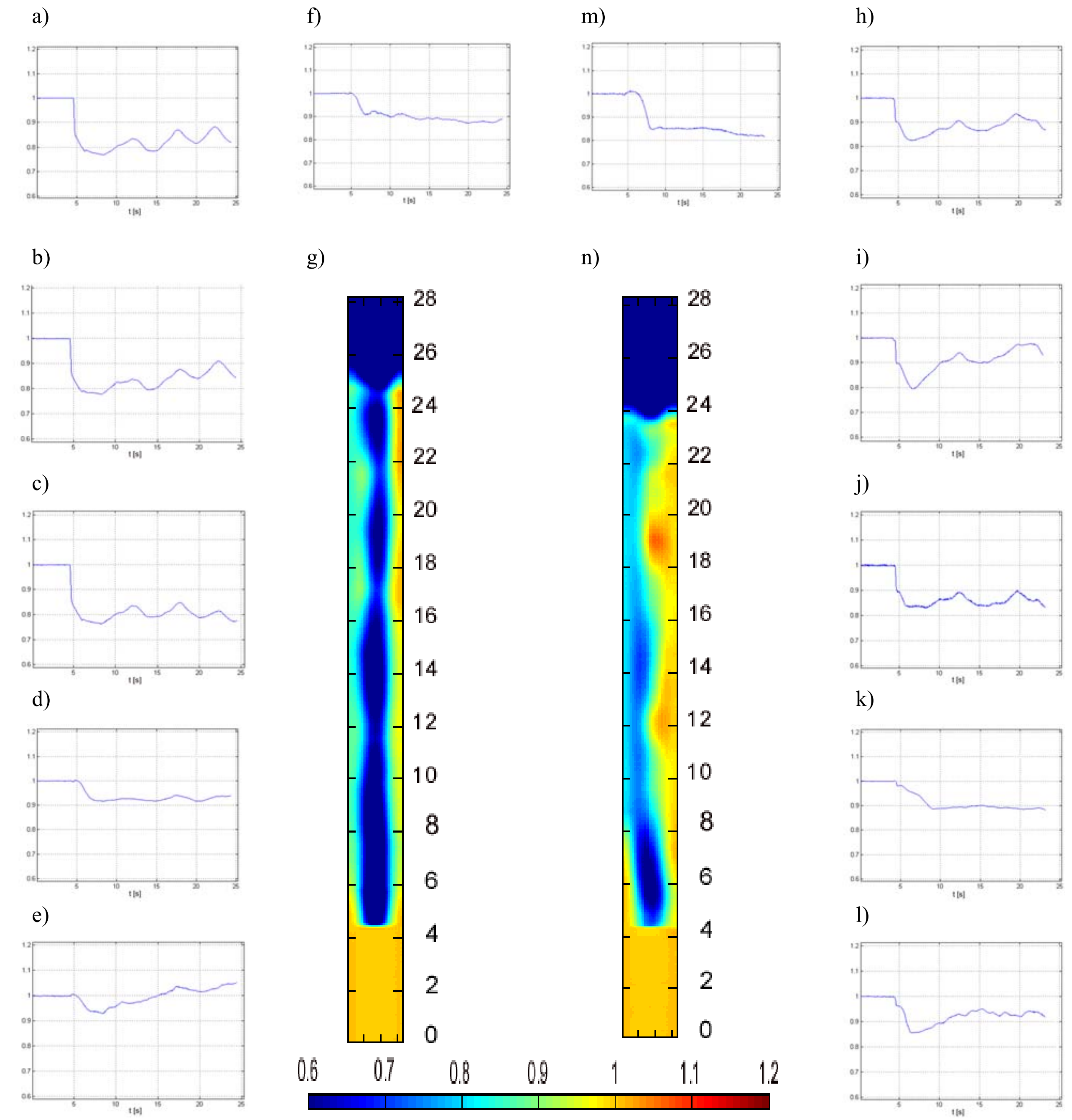

Fig.5. Measured at height h=0.3 m over the bottom of the silo distribution of the concentration of the bulk solid during silo emptying; at the cross-section profile: averaging, between electrodes 1-7 and between electrodes 4-10, close to the wall profile: averaging, between electrodes 1-2 and between electrodes 7-8, visualization of concentration changes at the horizontal cross-section in time function (topogram) for: a) b) c) d) e) f) g) smooth walls, h) i) j) k) l) m) n) rough walls

During the experiments vertical a_v, horizontal a_h and circumferential a_o accelerations on the silo wall were also measured. Results of the experiments were presented in 2 forms: as a graphs based on the "raw data" and as a reconstructed images in horizontal cross-section due to changes of the concentration at the measured height of the silo (topograms) ("reconstructed data").

Graphs, created on the basis of the "raw data" allows for local description of the behaviour of the sand during silo emptying and for the accurate description of the bulk solid at the characteristic locations: close to the wall profile and in the core of flow. Reconstructed images allows for determination of the concentration changes at the whole cross-section of the silos, but the values are with the reconstruction mistake. Furthermore reconstructed images allows for description of the thickness of the shear band close to the wall profile, and also allow to determinate the diameter of the core of flow.

For dense sand and smooth walls at height 0.3 m over the bottom in the cross-section profile in the moment of the beginning of emptying the silo the bulk solid surrenders the distinct dilatancy non-resident to

22% values of the initial state (Fig.5a). Afterwards in the cross-section profile the material shows slow contractancy during which alternant changes of the concentration of the no-resident bulk solid appear to 8% values of the initial state.

The flow in the cross-section profile is less symmetrical than in case of the material in the loose state (Fig. 5b, c). The profile close to the wall at the moment emptying of the silo commences the bulk solid the minimum dilatancy, then contractancy, and renewed dilatancy to 7% values of the initial state (Fig. 5d). The flow in the section is non-symmetrical (Fig. 5e, f). After the pronouncement of the dilatancy the material close to the wall profile contractanted, partly surrenders to the further looseness. In case of experiment with smooth walls the shear zone along the silo height was not observed, only the pulsation of the core of flow was noticed (Fig. 5g).

For dense sand and rough walls at height 0.3 m over the bottom in the cross-section profile in the moment of starting to empty the silo the bulk material surrenders the dilatancy non-resident at first to 9%, and then to 18% values of the initial state (Fig. 5h). Subsequently in cross-section the material surrenders the slow contractancy during which appear alternant changes of the concentration of the bulk material non-resident to 5% values of the initial state. The flow in cross-section profile is the resoluteness less symmetrical than in case of the material in the loose (Fig. 5i, j) state. In close to the wall profile in the moment of the beginning emptied of the silo the bulk solid surrenders the dilatancy to 11% values of the initial state (Fig.5 k). The flow in close to the wall profile is non-symmetrical (Fig. 5l, m), the maximum dilatancy carries out 18% values of the initial state. In case of experiment with rough walls shear zone with the thickness of ≈ 0.02 m was observed (Fig. 5n). More over the topograms allows for observation non symmetry of the flow.

The main advantages of the ECT tomography is low cost of experiments and possibility to easily reproduce. This method can be used both in laboratory and semi-industrial scale. The disadvantages are facts that special apparatus is needed and this method can not be applied commonly for rectangular silos.

This method can be considered as a quantitative measurement method with possibility to measure the values of the concentration changes of the bulk solid, which is highly attractive for silo flow analysis.

4. Conclusions

Description and visualisation of the bulk solid during silo flow for monitoring and diagnosis processes with the use of both invasive and non-invasive methods can be applied. Invasive one improves some imperfections into the granular material. This deforms the measured and visualised values. Therefore non-invasive methods are considered.

Termography allows for observation the behaviour only the upper part of the flowing bulk solid. There is no possibility for estimation the concentration changes inside the flowing granular material.

X-ray allows for observation the volume changes both along the silo walls and inside the bulk solid, but there is lot of problems with application of this method for dynamic silo flow. The influence of the initial density and wall roughness on bulk solid behaviour can be observed with booth of methods.

On the other hand application of the X-ray tomography allows only for estimation the concentration distribution in horizontal cylindrical pipe which moved quasi-static.

The trial of application of the Electrical Capacitance Tomography (ECT) is being very useful for measurements in model and semi-industrial silos. Concentration changes can be observed in horizontal and vertical cross sections, also continuous diagrams can be used for presentation of the concentration changes. Using ECT the thickness of the shear band and the diameter of the core of flow can be registered.

ECT measurement method seems to be the most useful from presented above for monitoring and diagnosis of the concentration changes during silos flow. Application of ECT method for silo flow analysis is further is being developed.

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