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Measurements of pressure and frictional tractions along walls of a large-scale conical shallow hopper and comparison with Eurocode 1991-4:2006

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ABSTRACT

A silo's hopper supports the majority loads induced by the stored particulate solids. Such loads vary from filling to discharging provided the hopper is steep enough to secure a mass flow; when the hopper is too shallow to promote a mass flow, funnel flow usually prevails – where how loads develop along walls of a shallow hopper remains to be addressed. In the paper, normal pressure and frictional traction were measured with pressure transducers as imposed by testing material sand along the walls of a full-scale conical shallow hopper. The transducers were carefully mounted in the designated positions of hopper walls along a generator. To make the measurement results representative, a concentric filling was carried out to ensure the sand depositing into the hopper axi-symmetrically; the filling normal pressure and frictional traction as developed along the hopper walls were then measured. The normal pressure and frictional traction during discharging were also measured when the sand was discharged centrically in a free discharge mode. Results from measurements showed that the normal pressure at the commencement of discharge changed only slightly from that as developed at the end of filling. Both the filling and discharging normal pressure, as demonstrated in the paper, could be evaluated based on the mechanics of steep hopper filling pressures by adopting an effective friction coefficient as proposed in Eurocode 1-4:2006 for a shallow hopper. Measurement also showed that the frictional traction was not fully developed either in filling or during discharging; a friction coefficient was only partially mobilised as an effective friction coefficient, and might vary very significantly from one location to another along the wall.

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1. Introduction

A silo with a shallow hopper is designed to meet the storage capacity if the available headroom is limited. This arrangement achieves a high volumetric capacity without the total height of the silo being large. A shallow hopper may also be chosen to avoid abrasive particulate solids sliding against the wall, since the flow mode will normally be internal [25,18,19,26].

The hopper usually supports the majority of the weight of stored solids; an correct estimation of loading as action on its walls is important for structural integrity assessments [40,42,21,39,32,34–36,20,28]. It is known that such loads vary from the process of filling to discharging if hopper is steep enough to bring a mass flow during discharge, where the pressures are governed by fully mobilised frictional sliding of the solid against the hopper wall, and could be calculated using theories as proposed by Dabrowski [12], Walker [40] etc. In shallow hoppers, the wall friction is not fully mobilised by consolidation of the solids during filling, pressures is recommended to be evaluated using the same relationships as in steep hopper, but adopting an effective hopper wall friction coefficient μ_{eff} [35,33,20,15]. The pressures which occur during discharge are still imperfectly understood; based on the fact that shallow hopper contains a large body of cushioning solid during discharge, silos with internal pipe flows appear to show little change in normal pressures, the discharge loads may be taken as identical to the filling values (Eurocode 1-4:2006). However, such a recommendation lacks of convincing theoretical evidences or experimental verification at the present time.

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In the present study, a straightforward measurement was carried out to investigate the loads along the wall of a large-scale conical shallow hopper exerted by testing material sand during filling and discharging.

Experimental measurement of loads on silo walls has been undertaken by a great variety of researchers as reviewed [31]. The objective of measurement is to determine the pressure and frictional traction exerted on the walls and bottom of the silo during filling and discharge. Two methods are available for the determination of these parameters: local direct measurement using pressure cells or measurement of the strains in the silo wall using strain gauges. In practice, pressure cells mounted in the silo walls have been most widely used for wall pressure measurements [31,24,17,14,41,6,29]. It must point out that these measurements are rather difficult to perform [3,4,27] and the pressure cells must satisfy very strict conditions [1,2,37,43,22,29]. Measurement of the strains in the silo wall using strain gauges (or other similar devices) was also used. This method is usually prone to temperature variations and temperature gradients, leading to error in an order of magnitude as those due to the internal pressure [11,10]. Great caution is required when applying either method.

A large-scale conical shallow hopper was built and used for measurement. Pressure transducers (cells) were mounted in specific locations on its wall. In the experiment, a concentric-filling was implemented with an aid of a small feeding hopper (a small outlet) to fill testing material sand axi-symmetrically into the hopper. With this symmetrical filling, the development of filling loads on the wall were measured, the discharging loads on the hopper wall were then measured in a free centrically discharging condition. Results thus obtained were used to verify the action as proposed for shallow hopper in Eurocode 1991-4:2006: silos and tanks.

2. Experimental set-up and testing material sand

2.1. Experimental set-up

An experimental apparatus as sketched in Fig. 1 was used to perform the measurements. It consisted of three parts: a material handling system (1 and 5 in Fig. 1), a test hopper (2) and a data acquisition system (3 and 4).

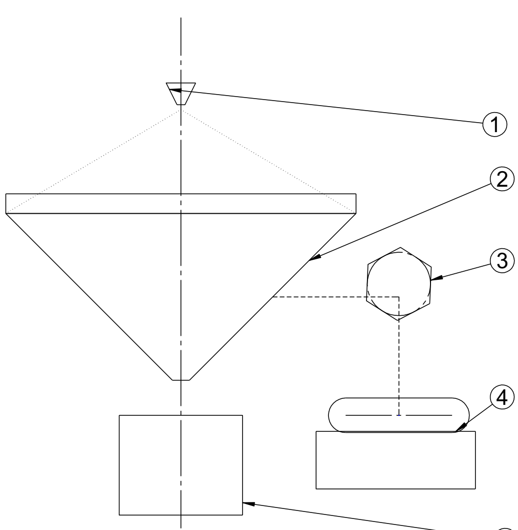

Fig. 1. Experimental arrangement in sketch.

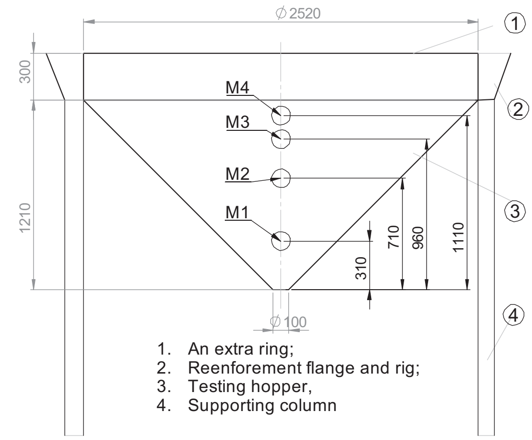

Fig. 2. A large-test hopper, and designated locations of pressure transducers.

The material handling system included a material feeding unit and a material discharging unit. The feeding unit was utilised to carry out a concentric filling. A small extra funnel was placed above the hopper, aligning with the axis of the hopper. This funnel was 400 mm in height, with a ⌀ 400 mm inlet a ⌀ 50 mm outlet. Sufficient amount of testing material (sand) was first fed into this small funnel, and then discharged into the hopper through its outlet. The feeding rate was quite stable, around 300 kg/min as measured. The discharging unit was designed to perform a free discharge from the outlet of the test hopper, and collected the sand in a receiving container. It was measured that the discharging rate was around 580 kg/min.

Dimensions of the test hopper are shown in Fig. 2. It was a large-scale conical shallow hopper with a 45° inclination angle, 1210 mm in height with ⌀ 2520 mm ($r=1260$) inlet and ⌀ 100 mm outlet. It was made of stainless steel plate of $t=6$ mm in thickness. The hopper aspect ratio h/r was therefore 1.0, where h is the height from cone apex to the top ($h=1260$) and r is the maximum radius, its maximum radius to thickness ratio was $r/t=210$.

An extra ring of 300 mm in height was attached at the top end of the test hopper to prevent the material from overflowing during filling. This ring was also reinforced with flanges and ribs in such a way to reduce the effect of supporting methods on the measurement results. The test hopper was via flanges supported with four steel columns; this arrangement was regarded to have a negligible effects on measurement results.

The data acquisition comprised pressure transducers mounted to the wall, Hydra data logger/converter and a PC. The pressure transducers were designed for both normal pressure and frictional traction measurement (see Fig. 3), and are to be counted as action along the walls of hopper. Four pressure transducers were used, and were mounted in designated locations on the hopper wall along a generator (see Fig. 2). Great care was taken to minimise protrusion of the transducers' interacting faces (see the disc as in Fig. 3). The disc was in fact cut from the walls of hopper, 120 mm in diameter. The perimeter of the discs was sealed with silicon-paste (to be dry). Calibrations were thereafter carefully carried out for the normal pressure and the friction traction according to the instructions specified by the manufacture [13] (DEKA Sensor & Technologie, GmbH, Germany); effects of sealing was taken into account.

The accuracy of each individual transducer was acceptable, with a maximum error of 5.3% on M4 on friction tractions component (see Appendix B). The reader is referred to Ding [14] for a description in more details. The calibrated data was used as input to set up the data acquisition system.

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