Implementing Innovative Ideas in Structural Engineering and Project Management
Edited by Saha, S., Zhang, Y., Yazdani, S., and Singh, A.
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ISBN: 978-0-9960437-1-7

EFFECT OF THE GRAIN SLIDING ON THE SEISMIC BEHAVIOR OF CIRCULAR SILOS: A THEORETICAL FORMULATION

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Earthquakes frequently cause damage or collapse in silos, provoking significant financial loss and even loss of life. The effect of lateral seismic loads can damage the upper portion of the silo if the material contained can oscillate inside the silo during the ground motion. The contribution of the grain sliding in terms of wall stresses is not explicitly accounted neither in current design codes nor in scientific literature. In the present paper, the effect of the horizontal sliding of the grain layers is accounted in terms of additional overpressures, wall shear and bending moment during dynamic excitation and compared with theoretical formulations, code provisions and experimental evidence. Shaking table tests suggest that the grain sliding may be relevant in the evaluation of the wall base bending moment and that ACI 313-97 and Eurocode 8 provisions appear overly conservative. Finally, a design recommendation is drawn for reducing the effect of the seismic actions on the silo wall.

Keywords: Effective mass, Wall pressure, Shaking table test, Analytical developments.

1 INTRODUCTION

In circular silos, earthquakes impress vertical and horizontal structural loads, leading to additional non-uniform pressure distributions (potentially larger than the pressure due to the gravity loads), shear and bending actions on the silo wall. The effect of lateral seismic loads can damage the upper portion of the silo if the material contained can oscillate inside the silo during the ground motion. Therefore, it appears necessary to account for the simultaneous lateral loads due to material flow and lateral seismic loads (Dogangun *et al*. 2009). The contribution of the grain sliding in terms of wall stresses is not explicitly accounted in the current design codes nor in scientific literature.

In the present paper, the effect of the horizontal sliding of the top grain layers is accounted in the evaluation of the additional contributions in terms of overpressures, wall shear and bending moment during dynamic excitation and compared with code provisions and experimental evidence.

2 THEORETICAL STUDIES AND CODE PROVISIONS

The first analytical study aimed at estimating the actual distribution of the pressures on the wall of grain-silos was proposed by Janssen (1895) for the static case. During the last thirty years, through very different approaches, relevant studies have been performed to better understand the seismic behavior of grain-silos and to provide rational seismic design rules (Trahair *et al*. 1983, Hull and Rotter 1989, Veletsos and Younan 1998). Recently, Silvestri *et al*. (2012) and Pieraccini *et al*. (2014) proposed new formulations.

The earliest findings have been receipted by many current design codes, as ACI 313-97 (1998) and EC8 part 4 (EN 1998-4, 2006) and FEMA P-750 (NEHRP, 2009). It should be noted that both the ACI 313-97 code and the simplified method by EC8 provisions consider an effective mass equals to 80% of the ensiled content.

The effect of grain sliding is not explicitly accounted in design code and no specific investigation can be found in literature, although earthquakes can also damage the upper portion of the silo (Dogangun *et al*. 2009).

Shaking-table tests performed on circular ground-supported silo specimens (Chorro *et al*. 2014, Silvestri *et al*. 2014) shown that such phenomenon may significantly contribute in increasing the wall bending moment during dynamic excitation.

3 GRAIN SLIDING

Horizontal sliding of the top grain-layers always occurs in grain-containers, even for minimal, very low horizontal accelerations. This simple phenomenon is part of the common feeling. Despite the apparent simplicity, such phenomenon is still under investigation and subject of great practice importance. For all these reasons, the dynamics of granular material have recently attracted considerable attention. The two-dimension numerical model by Matthey and Hansen (1998) helps to better understand the dynamic of grain top layers. The experimental investigation by Siavoshi *et al*. (2006) points out that friction increases with layer thickness, demonstrating that grain-grain friction could be much lower at the top of the ensile content.

4 ASSUMPTIONS

The theoretical frameworks by Silvestri *et al*. (2012) refer to an idealized system. The analytical treatment requires specific assumptions in order to model the complex grain-silo interaction in dynamic conditions. In that regard, the granular content is considered as composed by incompressible, compact, without voids, infinitely resistant grains and the physical and frictional properties of ensiled mass and grain-system (unit weight γ, grain-grain friction coefficient μ_{GG} and grain-wall friction coefficient μ_{GW}, pressure ratio λ) are considered as uniform in the whole content.

In this research work, Assumption 7, which excludes any horizontal sliding of disk *D* on the layers below (with exception for the grain layers close to the free surface), is removed. Then, disk *D* slides on the silo base if its horizontal inertia exceeds the weakest friction resultant, considering that $\mu_{GB} < \mu_{GG}$ (Arnold *et al*. 1980), i.e. if $a_{eh}(z=H) \geq \mu_{GB}/v_0$ (see Eq. 50, Pieraccini *et al*. 2015). The sliding of the top grain-layers cannot be exactly molded, since the lower grain-grain friction for the grain-layers close to the free surface cannot be accounted by the adopted analytical framework.

Until the reduced horizontal acceleration $a_{eh,r} = a_{eh}(z=H) - \mu_{GB}$ is lower than μ_{GG}, disk *D* behaves as a unique rigid body. Then, no along-the-height dynamic amplification occurs and it pushes on the silo wall in-phase with $a_{eh}(z=H)$. Since the grain-base friction is fully mobilized, the silo wall balances the remaining fraction of the horizontal inertial force of the disk *D* (as referred as $\Delta T_{xx}(z)$).

The grain-sliding of the top layers (unavoidable, even for low magnitude of the horizontal accelerations) can be accounted for $a_{eh}(z=H) > \mu_{GB}/v_0$. Considering that the common mean values of grain-base friction (considering base surface as wall type D1 and D3, EN 1991-4 2006) hold to a 0.2-0.5 range, such contribution can be considered for a large class of cases, as for the most demanding earthquakes.

5 ANALYTICAL DEVELOPMENTS: THE EFFECT OF GRAIN SLIDING

From the framework proposed by Pieraccini *et al.* (2015), an integral evaluation of the global forces that the grain produces on the silo wall is obtained by means of simple free-body dynamic equilibrium equations. Eqs. (1)-(3) provide the additional normal and tangential overpressures acting on the silo wall due to grain-sliding:

$$\Delta p_{h,GW}(z,\vartheta)^* = \frac{1}{2}\gamma \cdot a_{eh,r} \cdot \left[R - s(z,\vartheta)\right]^2 \cdot \cos(\vartheta) \tag{1}$$

$$\tau_{r\vartheta,GW}(z,\vartheta) = \frac{1}{2}\gamma \cdot a_{eh,r} \cdot \left[R - s(z,\vartheta)\right]^2 \cdot \sin(\vartheta) \tag{2}$$

$$\Delta\tau_{v,GW}(z,\vartheta) = \mu_{GW} \cdot \Delta p_{h,GW}(z,\vartheta)^* \tag{3}$$

Eq. (4) provides the distributed shear action $\Delta q_{xx}(z)$ along the height of the wall:

$$\Delta q_{xx}(z) = \frac{1}{2}\gamma \cdot a_{eh,r} \cdot \int_0^{2\pi} \left[R - s(z,\vartheta)\right]^2 \cdot d\vartheta = \gamma \cdot a_{eh,r} \cdot A_{D,dyn}(z) \tag{4}$$

Eq. (5) provides the relative additional wall shear $\Delta T_{xx}(z)$:

$$\Delta T_{xx}(z) = \gamma \cdot a_{eh,r} \cdot \int_0^{z} A_{D,dyn}(z) \cdot dz = \gamma \cdot a_{eh,r} \cdot V_{D,dyn}(z) = \left[1 - a_{eh0}/\mu_{GB}\right] \cdot T_{xx}(z) \tag{5}$$

where $T_{xx}(z)$ is the wall shear action as reported in Eq. (16) of Pieraccini *et al.* (2014).

Eqs. (6) and (7) provide the additional wall bending moment $\Delta M_{yy,1}(z)$ and $\Delta M_{yy,2}(z)$, respectively:

$$\Delta M_{yy,1}(z) = \left[1 - a_{eh0}/\mu_{GB}\right] \cdot \int_0^{z} T_{xx}(z) \cdot dz = \left[1 - a_{eh0}/\mu_{GB}\right] \cdot M_{yy,1}(z) \tag{6}$$

$$\Delta M_{yy,2}(z) = \int_0^{2\pi}\int_0^{z} \Delta\tau_{v,GW}(z,\vartheta) \cdot R^2 \cdot \cos(\vartheta) \cdot d\vartheta \cdot dz \tag{7}$$

where $M_{yy,1}(z)$ is the first member in Eq. (17) of Pieraccini *et al*. (2014).

6 APPLICATIVE EXAMPLES

In the present section a brief comparison between the formulation given by theoretical formulations, ACI 313-97 and EC8 provisions presented. Applicative examples compare the along-the-height variation of the grain-wall normal overpressures, the wall shear and the bending moment in accelerated conditions (assuming a constant vertical profile for both the horizontal and vertical accelerations). A grain-silo system characterized by $\gamma = 15000\,N/m^3$, $\mu_{GW} = \mu_{GB} = 0.45$, and $\lambda = 0.70$ is subjected to horizontal accelerations $a_{eh0} = 0.60$ and null vertical acceleration ($v_0 = 1.00$).

6.1 Normal Overpressure, Shear And Bending Moment On The Wall

Figure 1 reports the normalized overpressure acting on the front side ($\vartheta = 0$) of the wall for the three grain-silos with different slenderness ratios ($H/R = 0.50, 1.00, 2.00$). The grain sliding involves additional overpressure, which presents highest magnitude close to the top of the silo wall. Figure 2a and b report the along-the-height profiles of the normalized wall shear and bending moment, respectively, as provided by EC8, the Pieraccini formulation and the proposed one.

6.2 The Experimental Evidence

Experimental results are provided by shaking-table tests performed on a circular silo specimen containing Ballottini glass particles (Chorro *et al.* 2014, Silvestri *et al.* 2014) with similar grain-system characteristics of the silos presented in previous sections ($\gamma = 14810\,N/m^3$, $\mu_{GW} = \mu_{GB} = 0.45, \lambda = 0.69$, $H/R = 2.00$). Figure 3 reports the wall base bending moment for increasing horizontal acceleration as provided by ACI 313-97 and EC8 provisions, the Pieraccini formulation, the proposed one (assuming a constant vertical profile for the horizontal acceleration and null vertical acceleration, $v_0 = 1.00$) and the experimental test. The experimental bending moment presents a sort of bilinear trend up to 0.80g. For a horizontal acceleration a_{eh0} ; 0.35 the slope suddenly increases, consistently with the limit value $a_{eh0} = 0.45$. The wall base bending moment M_{yy} obtained by the proposed formulation is in good agreement with the experimental evidence, at least up to a horizontal acceleration around 0.80g, suggesting that the grain-sliding may be relevant in the evaluation of the wall stresses. The wall base bending moment obtained by ACI 313-97 and EC8 provisions overestimates the experimental results, suggesting that the actual activated mass may result noticeably lower than the effective mass proposed by ACI 313-97 and EC8 (Silvestri *et al.* 2014).

7 CONCLUSIONS AND DESIGN RECOMMENDATIONS

This paper proposes an analytical formulation for the evaluation of the additional overpressures, shear and bending moment acting on the wall of circular ground-supported grain-silos due to grain sliding. A comparison of the proposed formulation with theoretical formulations, ACI 313-97 and EC8 provisions is performed.

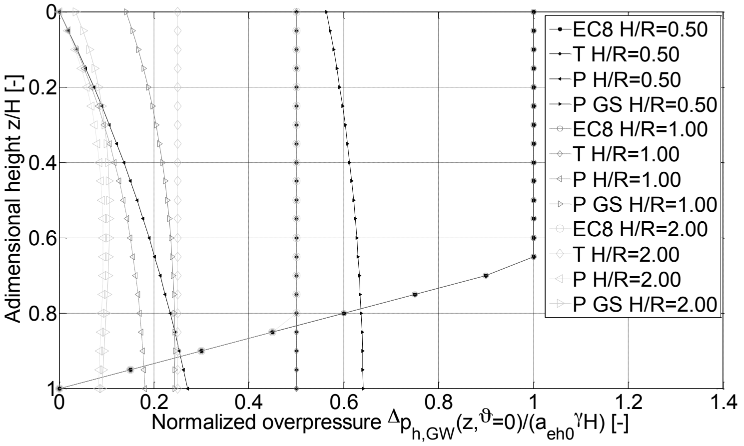
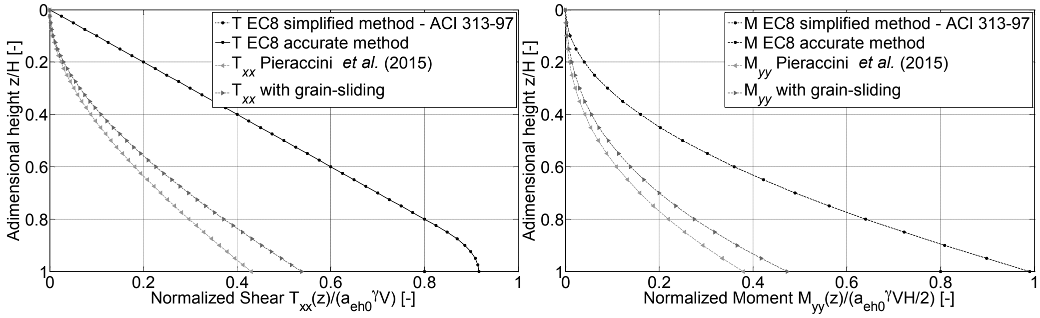


Figure 1. Height wise variation of the normalized overpressures on the wall for EC8 (accurate method), the Trahair (1983) and the Pieraccini (2015) formulation, and the proposed formulation.



(a) (b)

Figure 2. Height wise variation of the normalized wall shear (a) and bending moment (b) for the EC8, the Pieraccini formulation and the proposed one.

Furthermore, the analytical predictions of the wall base bending moment are compared with shaking-table test results (Chorro *et al.* 2014, Silvestri *et al.* 2014). The proposed formulation appears in good agreement with the shaking-table tests results and the experimental verification suggests that: (i) the grain sliding may be relevant for the evaluation of the wall base bending moment; (ii) the actual activated mass may result noticeably lower than the effective mass proposed by ACI 313-97 and EC8, which seem to be overly conservative. As design recommendation, a system of ribs inserted at the silo base could roughen the bottom surface and could prevent the sliding of the deep grain layers, reducing the seismic actions on the silo wall.

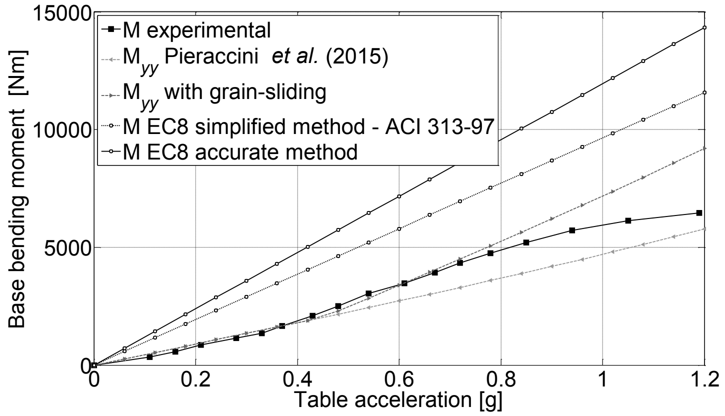


Figure 3. Comparison between the experimental bending moment and the predicted values by the Pieraccini formulation, the presented one and the EC8 methods.

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