Pressure profiles exerted by grain-like material on the silo walls in accelerated conditions

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SUMMARY:
This paper presents analytical developments devoted to the evaluation of the effective behaviour of grain in flat-bottom silos during an earthquake. Based on the results achieved from this study, the paper proposes an innovative methodology for the seismic design of flat-bottom silos containing granular and grain-like materials, which allow for substantial reductions in the design seismic actions for silos characterized by squat geometrical configuration. The analyses are developed by simulating the earthquake ground motion with constant vertical and horizontal accelerations and lead to the subdivision of the ensiled material into three different portions by means of plain dynamic equilibrium considerations that take into consideration the specific mutual actions developing in the ensiled grain. The findings indicate that, in the case of squat silos the portion of grain mass that interacts with the silo walls turns out to be noticeably lower than the total mass of the grain in the silo.

Keywords: flat-bottom silos, grain-like material, dynamic equilibrium, friction coefficient, seismic forces

1. INTRODUCTION

In the general issue of the action of grain-like materials, during earthquake ground motions, on the walls of flat-bottom silos, the assessment of the horizontal interaction is of particular interest. This interest is based on the possibility of providing more appropriate design rules closer to the effective seismic behaviour of silos. A careful evaluation of the forces produced by the material in the silos makes it possible to safely design silos in a seismic area without waste of material and excessive redundancy. The walls of the silos are typically subjected to both normal and tangential stresses (normal pressures and vertical and horizontal friction forces) produced by the material inside the silo. The magnitude and distribution of both shear and normal pressures over the height of the wall depend on the properties of the stored material and whether the silo is being filled or discharged. As it is the case for most structures, the effect of lateral loads can be significant especially on larger silos containing heavier material since the magnitude of the horizontal seismic load is directly proportional to the weight of the silo (Dogangun et al. 2009).

For the material inside the silos, the horizontal actions are usually evaluated using the following hypotheses (Eurocode 8 part 4):

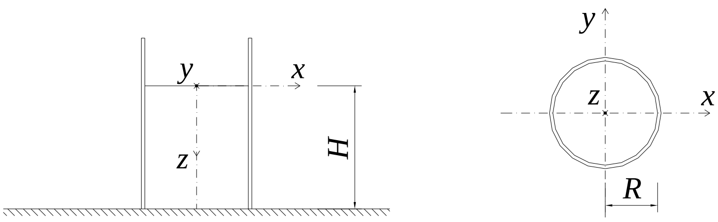
1. stiff behaviour of the silo and its contents (which means that the silo and its contents are subjected to the input ground accelerations; no amplification is taken into account);
2. the grain mass corresponding to the whole content of the silo with the exception of the base cone with an inclination equal to the internal friction angle of the grain is balanced by the horizontal actions provided by the walls (supposing that the seismic force coming from the base cone is balanced by friction and therefore does not push against the walls).

Although there are many papers on the behaviour of liquid silos under earthquake ground motion (Hamdan 2000, Nachtigall 2003), there are only few examples of scientific investigation into the dynamic behaviour of flat-bottom grain silos under earthquake ground motion.

The main goal of this paper is to present an analysis of the effective behaviour of flat-bottom silos containing grain when subjected to constant horizontal and vertical accelerations, which are here taken to simulate earthquake ground motion (time-history dynamic analyses are not carried out). In more detail, the developments presented here, keeping the validity of the hypothesis 1, is aimed at assessing, on the basis of plain dynamic equilibrium considerations, the effect of the horizontal actions that rise on the silo walls due to the applied accelerations. The results obtained show how these horizontal actions may be far lower with respect to those that can be obtained by adopting the Eurocode approach (i.e. using also the hypothesis 2), especially for silos characterized by squat geometrical configuration. To better understand the physical meaning of the results obtained, a three-dimensional representation of the results in terms of those portions of the grain mass that act (in terms of horizontal actions) upon the silo walls is also provided, in addition to the analytical expression of the horizontal actions. The results obtained are then used to formulate a procedure for the seismic design of silos.

2. PROBLEM FORMULATION

A silo with radius R and filled with grain-like material up to the height H, as represented in Fig. 2.1, is considered. The free surface of the grain is assumed to be horizontal. With the objective of obtaining an approximated estimation of the pressures which the grain-like material produces on the silo walls due to the earthquake acceleration, an idealised system is studied in idealised conditions.

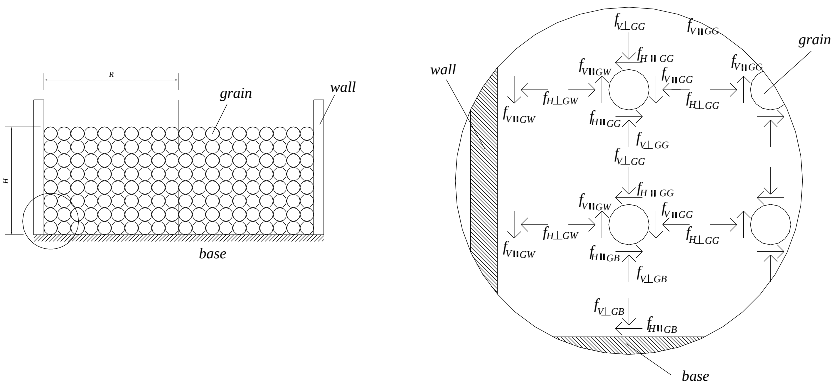


(a) (b)

Figure 2.1. Geometry of a flat-bottom grain silo and reference system adopted. (a) vertical view; (b) plan view.

The following idealised system is considered as representative of the flat-bottom silo filled with grain-like material:

- the silo walls are assumed to be infinitely stiff with respect to the ensiled grain;
- the grain-like material is assumed to be incompressible and compact, without voids, as it were be composed by a number of infinitely stiff and infinitely resistant spherical balls, as depicted in Fig. 2.2.



(a) (b)

Figure 2.2. (a) Idealised system. (b) Mutual forces which are exchanged between a grain and another one, between the grain and the silo wall, and between the grain and the silo base.

It is well known that the grain provides forces onto the silo walls (Pozzati an Ceccoli 1972). Fig. 2.2 represents the mutual forces of the schematic idealisation adopted:

- $f_{V,\perp,GG}$ is the vertical normal force, perpendicular to the grain surface, which is exchanged between a single grain and another one;
- $f_{H,\perp,GG}$ is the horizontal normal force, perpendicular to the grain surface, which is exchanged between a single grain and another one;
- $f_{H,\|,GG}$ is the horizontal tangential force, parallel to the grain surface, which is exchanged between a single grain and another one;
- $f_{V,\|,GG}$ is the vertical tangential force, parallel to the grain surface, which is exchanged between a single grain and another one;
- $f_{H,\perp,GW}$ is the horizontal normal force, perpendicular to the grain surface, which is exchanged between the grain and the silo wall;
- $f_{V,\|,GW}$ is the vertical tangential force, parallel to the grain surface, which is exchanged between a single grain and the silo wall;
- $f_{H,\|,GB}$ is the horizontal tangential force, parallel to the grain surface, which is exchanged between the grain and the silo base;
- $f_{V,\perp,GB}$ is the vertical normal force, perpendicular to the grain surface, which is exchanged between the grain and the silo base.

It is here assumed that:

- the normal forces ($f_{V,\perp,GG}$, $f_{H,\perp,GG}$, $f_{H,\perp,GW}$ and $f_{V,\perp,GB}$) do not have limitations;
- the tangential forces are limited by the friction law of the contact surface considered, i.e.:

$$f_{H,\|,GG} \le \mu_{GG} \cdot f_{V,\perp,GG} \qquad f_{V,\|,GG} \le \mu_{GG} \cdot f_{H,\perp,GG}$$

$$f_{H,\|,GB} \le \mu_{GB} \cdot f_{V,\perp,GB} \qquad f_{V,\|,GW} \le \mu_{GW} \cdot f_{H,\perp,GW}$$

where μ_{GG}, μ_{GB} and μ_{GW} are the friction coefficients of the contact surfaces grain-grain, grain-base and grain-wall, respectively. Note that, implicitly, Eurocode 8 assumes $f_{H,\|,GG} = 0$, which implies, under earthquake input, a lateral sliding behaviour of each grain layer upon the one below, so that the lateral equilibrium is ensured by the reaction of the walls which take all weight of the grain. In order to perform an integral evaluation of the global forces that the grain produces on the silo walls, the grain-like material is treated as a set of overlapped layers of infinitesimal height *dz* (passage from discrete treatment of grains to continuous treatment of grain-like material), and the above-mentioned concentrated forces becomes distributed normal pressures *p* and tangential stresses τ, respectively:

- $f_{V,\perp,GG}$ becomes $p_{v,GG}(z)$; $f_{H,\perp,GG}$ becomes $p_{h,GG}(z)$; $f_{H,\|,GG}$ becomes $\tau_{h,GG}(z)$;
- $f_{V,\|,GG}$ becomes $\tau_{v,GG}(z)$; $f_{H,\perp,GW}$ becomes $p_{h,GW}(z)$; $f_{V,\|,GW}$ becomes $\tau_{v,GW}(z)$;
- $f_{H,\|,GB}$ becomes $\tau_{h,GB}(z)$; $f_{V,\perp,GB}$ becomes $p_{v,GB}(z)$.

According to Janssen (1895) and Koenen (1896), for the vertical translational equilibrium of a grain portion at a generic height *z*, the vertical pressures, $p_{v,GG}(z)$, at the base of this portion are equally distributed over the whole surface.

However, it is reasonable to assume that the vertical pressures tend to diminish from the core of the grain portion towards the silo walls where their value is equal to zero. A limiting schematisation (that will be useful for the assessment of the actions induced on the silo walls by the applied accelerations and that lead to conservative results) is the one where each grain layer is divided into two "equivalent" portions composed of (*i*) grain completely leaning against the layers below (central portion) and (*ii*) grain completely sustained by the walls (and therefore characterised by a null vertical pressure between one grain and another). This schematisation requires that it exists a specific distance *s* from the silo wall, in correspondence of which $\tau_{v,GG}=0$ and such that $p_{v,GG}=0$ for all points which are distant less than *s* from the silo wall (Fig. 2.3).

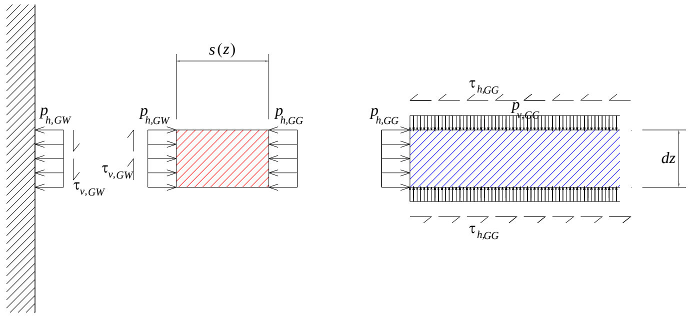


Figure 2.3. Subdivision of each grain layer: grain completely leaning against the layers below (internal disk) and grain completely sustained by the walls (external torus).

Therefore, with reference to a horizontal layer of grain characterised by height *dz* and placed at a generic distance *z* measured from the free surface, it can be divided into two portions:

- an "internal disk" with a diameter of *2r* (corresponding to the grain leaning on the layers below), highlighted in Fig. 5 with blue hatching;
- an "external torus" with a unknown thickness *s* (corresponding to the grain sustained by the walls), highlighted in Fig. 5 with red hatching.

The dimensions of the internal disk and the external torus vary with the distance *z* measured from the free surface of the grain, as the thickness *s* of the external torus varies with *z*.

The internal disk *D* is characterised by height *dz* and radius $r(z)=R-s(z)$ and is placed at a depth *z* measured from the free surface of the grain, namely at height *h* = *H-z* from the ground.

The external torus is subdivided into sectors (of circular annulus), each one of them, with central angle $d\theta$, is identified by the central angle θ measured clockwise from the negative semi-axis of *x*, as indicated in Fig. 5. Each sector of the external torus, which will be referred herein to as element *E*, is characterised by height *dz* and thickness $s(z)$. A system of auxiliary coordinates (O, $\xi-\eta$) on the horizontal plane is also defined, where ξ represents the radial direction (perpendicular to the lateral surface of the silo) and η represents the direction perpendicular to ξ**,** as indicated in Fig. 2.4.

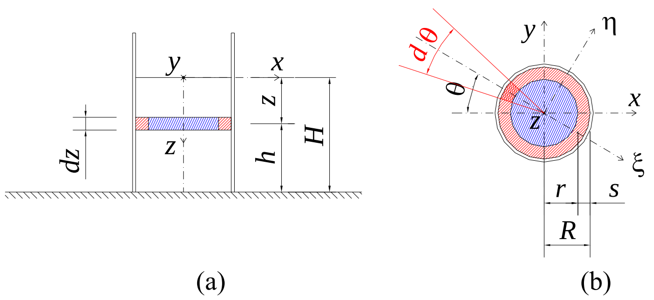


Figure 2.4. External torus (red hatching) and internal disk (blue hatching) of the grain.

The above-described idealised system is studied in the following idealised conditions. The earthquake ground motion is simulated with in time constant vertical and horizontal accelerations. Provided that the silo is assumed to be infinitely stiff, no amplification is here considered and thus spectral accelerations coincide with ground accelerations.

Accelerated conditions with both in time constant vertical ($a_{gv}\cdot g$) and horizontal ($a_{gh}\cdot g$) additional accelerations will be thus studied in detail (Fig. 6). Here, the expression "additional" means "additional with respect to the acceleration of gravity". Note that both a_{gv} and a_{gh} are expressed as fractions of g.

The objective of the following sections is to determine the value of the thickness of the external torus in accelerated conditions, by means of simple plain equilibrium equations, in order to quantitatively identify the portion of the grain which leans on the layers below and the one which pushes on the walls. Clearly, as intermediate results, information regarding normal pressures and tangential stresses will be also achieved.

3. ACCELERATED CONDITIONS

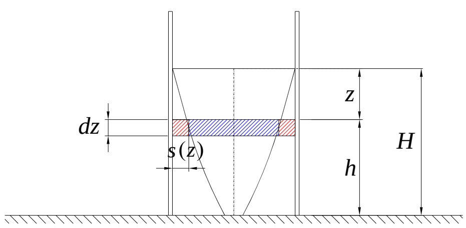
The following assumptions are considered:

- presence of in-time constant vertical additional acceleration a_{gv} towards z (positive upwards);
- presence of in-time constant horizontal additional acceleration a_{gh} towards x (positive to the right);
- the inertial forces acting on internal disk *D*, due to the horizontal additional acceleration, are completely balanced by the resultant of the shear (tangential) stresses developing on the lower surface of the disk (absence of horizontal sliding of the grain);
- the eventual negative variation (depression) of the horizontal pressure between element *E* and the silo wall, due to the effects of the horizontal additional acceleration, is so that it cannot completely annihilate the horizontal pressure, $p_{h,GW}(z)$, between element *E* and the silo wall (hypothesis of not annihilating the pressure).

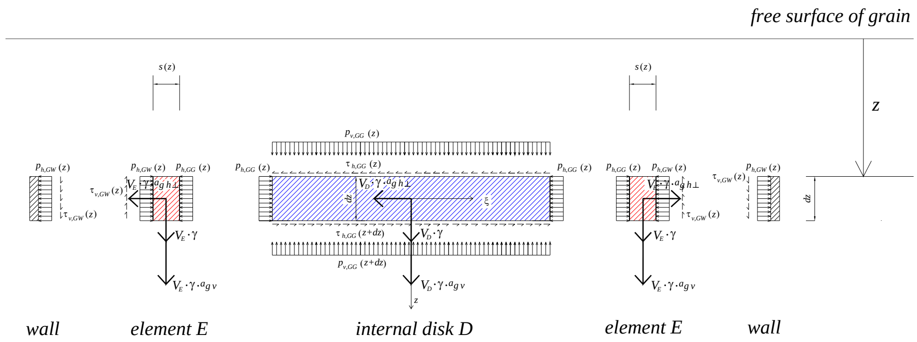
The direction of the additional acceleration (towards x) is rotated by an angle θ on the horizontal plane compared to the direction (towards ξ) perpendicular to the external vertical surface of element *E*.
The analyses are not carried out here with reference to Janssen and Koenen's hypothesis (Pozzati and Ceccoli 1972), but to the subdivision of the grain into disks and elements, which implies the generation of additional forces between the silo wall and the grain, in the presence of horizontal and vertical additional accelerations.
With reference to Figures 3.1 and 3.2, the unknown quantities of the problem are:

1. $p_{v,GG}(z)$ = vertical pressures acting on disk *D*;
2. $p_{h,GG}(z)$ = horizontal pressures which are exchanged between disk *D* and element *E*;
3. $\tau_{h,GG}(z)$ = horizontal tangential stresses acting on the surfaces of disk D;
4. $\tau_{v,GW}(z)$ = vertical tangential stresses acting on the silo wall.
5. $s(z)$ = thickness of element *E*;
6. $p_{h,GW}(z)$ = horizontal pressures which are exchanged between element *E* and the silo wall;
7. $\tau_{h,GW}(z)$ = horizontal tangential stresses acting on the silo wall.

The mutual actions exchanged between the grain and the silo walls are assessed here (as is usually done in seismic analyses where the effects of horizontal accelerations are evaluated), by the study of free-body diagrams which are representative of the dynamic equilibrium conditions.



(a)



(b)

Figure 3.1. Vertical longitudinal section: (a) schematic trend of $s(z)$; (b) vertical and horizontal actions operating on disk D and symmetrical elements E.

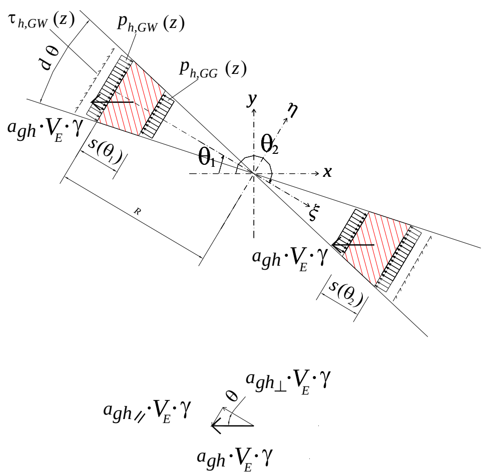


Figure 3.2. Horizontal cross-section: horizontal actions operating on symmetrical elements E.

Figures 3.1 and 3.2 show the mutual actions that disk *D*, elements *E* and the external walls of the silo exchange. It must be noticed that, in addition to the normal pressures and the shear stresses which are exchanged between the portions of grain and between the grain and the silo wall, there are the vertical and additional horizontal forces reported hereafter:

γV_D = self-weight of disk *D* and acting towards *z* due to the effect of the gravity acceleration (γ is the density of the grain-like material);

$a_{gv}\gamma V_D$ = inertial force coming from the centre of the mass of disk *D* and acting towards *z* due to the effect of the vertical acceleration a_{gv} (the inertial force is downward, as the acceleration a_{gv} has been assumed positive upwards);

$a_{gh}\gamma V_D$ = inertial force coming from the centre of the mass of disk *D* and acting towards *x*, due to the effect of the horizontal acceleration a_{gh} (inertial force to the left as the acceleration a_{gh} has been assumed to be positive to the right);

γV_E = self-weight of element *E* and acting towards *z* due to the effect of the gravity acceleration (γ is the density of the grain-like material);

$a_{gv}\gamma V_E$ = inertial force coming from the centre of the mass of element *E* and acting towards *z* due to the effect of the vertical acceleration a_{gv} (the inertial force is downward, as the acceleration a_{gv} has been assumed positive upwards);

$a_{gh}\gamma V_E$ = inertial force coming from the centre of the mass of element *E* and acting towards *x*, due to the effect of the horizontal acceleration a_{gh} (inertial force to the left as the acceleration a_{gh} has been assumed to be positive to the right).

Vertical translational equilibrium of disk *D* provides:

$$p_{v,GG}(z) = (1 + a_{gv}) \cdot \gamma \cdot z \tag{3.1}$$

If λ is the pressure ratio of the grain-like material, the following relationship holds between vertical and horizontal pressures inside the grain:

$$p_{h,GG}(z) = \lambda \cdot (1 + a_{gv}) \cdot \gamma \cdot z \tag{3.2}$$

Horizontal (radial) translational equilibrium of disk *D* provides:

$$\tau_{h,GG}(z) = a_{gh} \cdot \gamma \cdot z \tag{3.3}$$

If μ_{GW} is the friction coefficient of the contact surface grain-wall, the following relationship holds between the normal pressures and the vertical shear stresses along the contact surface between the grain of element *E* and the silo wall:

$$\tau_{v,GW}(z) = \mu_{GW} \cdot p_{h,GW}(z) \tag{3.4}$$

Vertical and horizontal translational equilibrium equations of element *E* are coupled in the following system of equations:

$$\begin{cases} \gamma \cdot V_E (1 + a_{gv}) = \tau_{v,GW}(z) \cdot A_E \\ p_{h,GW}(z) \cdot A_E = a_{gh\perp} \cdot \gamma \cdot V_E + p_{h,GG}(z) \cdot A_E \end{cases} \tag{3.5}$$

After some calculations, this system of equations provides the closed-form expressions of $p_{H,GW}(z)$ and $s(z)$:

$$p_{h,GW}(z) = \frac{\lambda \cdot \gamma \cdot z}{\nu (1 - \nu \cdot a_{gh} \cos\theta \cdot \mu_{GW})} \tag{3.6}$$

$$s(z) = R - \sqrt{R^2 - R \cdot \frac{2 \cdot \lambda \cdot \mu_{GW}}{1 - \nu \cdot a_{gh} \cos\theta \cdot \mu_{GW}} \cdot z} \tag{3.7}$$

Horizontal (tangential) translational equilibrium of element *E* provides:

$$\tau_{h,GW}(z) = \left(\frac{a_{gh} \sin\theta \cdot \gamma \cdot \lambda \cdot \mu_{GW}}{1 - \nu \cdot a_{gh} \cos\theta \cdot \mu_{GW}} \right) \cdot z \tag{3.8}$$

4. FUNDAMNETAL RESULTS

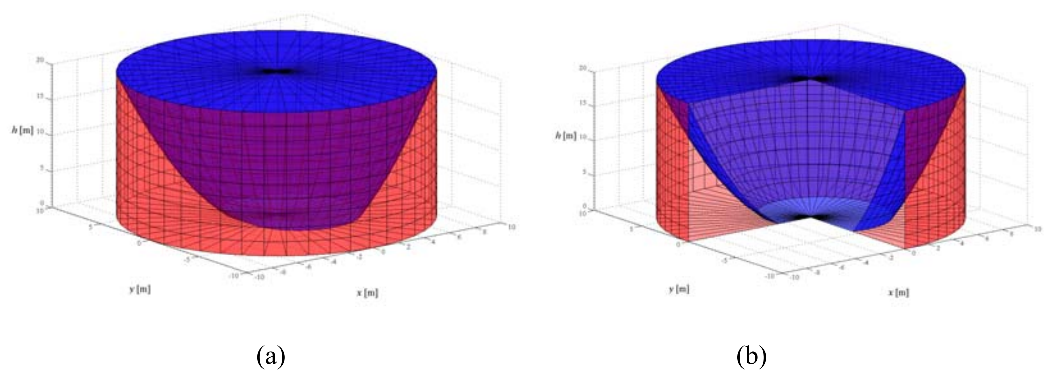
Eq. (3.6) represents the first fundamental result of this work: it provides, according to the assumptions of previous sections, the horizontal pressures which are exchanged between the grain, schematised as element *E*, and the silo wall, in seismic conditions. In the case of absence of the additional horizontal acceleration ($a_{gh} = 0$), Eq. (3.6) simplifies as follows:

$$p_{h0}\left(z\right) = \frac{\lambda \cdot \gamma \cdot z}{\nu} = \lambda \cdot \gamma \cdot \left(1 + a_{gv}\right) z \qquad (4.1)$$

Then, it can be interesting to define the overpressure (or depression), due to the effects of the horizontal accidental acceleration, between the grain and the silo wall, as follows:

$$\Delta p_h\left(z,\theta\right) = p_{h,GW}\left(z,\theta\right) - p_{h0}\left(z\right) \qquad (4.2)$$

Eq. (3.7) represents the second fundamental result of this work: $s\left(z,\theta\right)$ represents the thickness of the portion of grain which, according to the assumptions of previous sections, actually "pushes" on the silo walls in seismic conditions.
In order to give physical insight into this result and to facilitate the understanding of the mutual actions which develop between the grain and the silo walls under accelerated conditions, in this section three-dimensional graphical representations are provided of the volumes of the portions of grain which basically (i) are supported by the grain below and (ii) are sustained by the silo walls. Fig. 4.1 provide these graphical representations for a silo characterised by same parameters reported in the previous section.
Portion A1 is the amount of grain insisting on the lower portion of the material all the way to the silo foundation. This portion of the grain does not interact with the silo walls. From a geometrical point of view, it coincides with the vertical axis truncated cone (overturned) solid (Fig. 4.1, blue colour), with, as the minor base, the one obtained by drawing the curve $r\left(z,\theta\right) = R - s\left(z,\theta\right)$ for $0° \leq \theta \leq 360°$ on the plane $z = H$ (therefore at the silo foundation) and, as the major base, the silo circumference (placed at the top of the grain, i.e. $z = 0$).
Portion A2 is the amount of grain that is completely sustained by the lateral walls of the silo. This portion of the grain interacts with the silo walls. From a geometrical point of view, it coincides with the vertical axis cylindrical annulus (Fig. 4.1, red colour) and thickness $s\left(z,\theta\right)$, which is variable according to the height *z* and to the angle θ on the horizontal plane.



(a) (b)

Figure 4.1. Three-dimensional views of portion A1 (in blue) and of portion A2 (in red) of the flat-bottom grain silo: (a) overview and (b) sectioned view.

5. METHODOLOGY PROPOSED FOR THE ASSESSMENT OF THE SEISMIC ACTION ON FLAT-BOTTOM GRAIN SILOS

It can be reasonably assumed that structures characterized by high values of the vertical and horizontal stiffnesses, such as silos, do not amplify or diminish the acceleration induced by the earthquake ground motion at their base. They are therefore subjected to the stresses caused by the inertial forces that arise due to the accelerations at the base that, during the seismic events, vary continuously in time. It is clear that the highest stresses induced by the seismic action are those that derive from the peak ground acceleration. Therefore, the seismic design of silos can be based on the assumption that the action induced by earthquake ground motion is modeled as a couple of horizontal and vertical additional accelerations, $a_{gh} \cdot g$ and $a_{gv} \cdot g$, representative of the maximum shaking of the ground.

By approximating the seismic action on silos as two additional, constant, horizontal and vertical accelerations equal to $a_{gh} \cdot g$ and $a_{gv} \cdot g$, their effect can be evaluated with reference to the results obtained through the analytical elaborations described in the previous sections. It must be highlighted that the actions developing on the silo walls are not axial-symmetrical.

The base shear (at the bottom of the silo walls) is given by the integral, on the lateral surface of the grain, of the projection of the additional pressures towards *x* (namely, along the horizontal additional acceleration). The bending moment at the bottom of the silo walls is given by the integral, on the lateral surface of the silo, of the projection of the additional pressures towards *x* (namely, along the direction of the horizontal additional acceleration) multiplied by their height from the silo foundation Skipping all analytical passages, the base shear and the base bending moment is given by:

$$T = a_{gh} \cdot \gamma \cdot \pi R H^2 \left(\frac{\lambda \cdot \mu_{GW}}{1 - \nu^2 \cdot a_{gh}{}^2 \cdot \mu_{GW}{}^2} \right) \qquad M = \frac{1}{3} a_{gh} \cdot \gamma \cdot \pi R H^3 \left(\frac{\lambda \cdot \mu_{GW}}{1 - \nu^2 \cdot a_{gh}{}^2 \cdot \mu_{GW}{}^2} \right) \tag{5.1}$$

Eurocode 8 provisions would lead to the following actions at the base of silo walls:

$$T_{EC8} = a_{gh} \cdot \gamma \cdot \pi \cdot R^2 \cdot \left(H - \frac{R}{6} \right) \qquad M_{EC8} = a_{gh} \cdot \gamma \cdot \pi \cdot \frac{R^2}{2} \cdot \left(H^2 - \frac{R^2}{27} \right) \tag{5.2}$$

For the immediate assessment of the benefits that the methodology here presented gives with respect to calculation according to Eurocode 8, it is appropriate to define the following ratios between: (*i*) the shear obtained from the formulation presented and the one obtained from Eurocode calculations, (*ii*) the bending moment from the formulation presented and the one obtained from Eurocode calculations (where $\Delta = H / 2R$ is the slenderness ratio).

$$\rho_T = \frac{T}{T_{EC8}} = \frac{H^2 \left(\frac{\lambda \cdot \mu_{GW}}{1 - \nu^2 \cdot a_{gh}{}^2 \cdot \mu_{GW}{}^2} \right)}{R \cdot \left(H - \frac{R}{6} \right)} = \frac{2\Delta \left(\frac{\lambda \cdot \mu_{GW}}{1 - \nu^2 \cdot a_{gh}{}^2 \cdot \mu_{GW}{}^2} \right)}{\left(1 - \frac{1}{12\Delta} \right)} \tag{5.3}$$

$$\rho_M = \frac{M}{M_{EC8}} = \frac{2}{3} \frac{H^3 \left(\frac{\lambda \cdot \mu_{GW}}{1 - \nu^2 \cdot a_{gh}{}^2 \cdot \mu_{GW}{}^2} \right)}{R \cdot \left(H^2 - \frac{R^2}{27} \right)} = \frac{4}{3} \frac{\Delta \left(\frac{\lambda \cdot \mu_{GW}}{1 - \nu^2 \cdot a_{gh}{}^2 \cdot \mu_{GW}{}^2} \right)}{\left(1 - \frac{1}{108 \cdot \Delta^2} \right)} \tag{5.4}$$

For illustrative purposes, Fig. 13 reports the graphs of ρ_T and ρ_M ratios as functions of the slenderness ratio, for some specific values of the parameters: $\mu_{GB} = 0.40$, $\lambda = 0.50$, $a_{gh} = 0.15, 0.25, 0.35$, $a_{gv} = 0.10$, and $\mu_{GW} = 0.25, 0.40, 0.50, 0.60$.

Careful examination and inspection of the plots reported in Fig. 5.1 indicates that the difference between the results of the here proposed methodology and those of the Eurocode 8 procedure is maximum (i.e. low values of the ratios) for squat silos, characterised by lower values of slenderness ratio. Also:

- the advantages of the theory here presented are larger for the bending moment, rather than for the shear;
- among the parameters which govern the behaviour of silos, the most important one seems to be the grain-wall friction coefficient μ_{GW}: the beneficial effect in terms of base shear and base bending moment reduction, provided by the portion of grain which leans on the layers below and does not push on the silo walls, increases if μ_{GW} decreases;
- again, the beneficial effect in terms of base shear and base bending moment reduction increases (i.e. the ρ_T and ρ_M ratios decrease) with decreasing values of λ;
- the values of the additional accelerations (both horizontal and vertical) do not influence so much the trend of the ρ_T and ρ_M ratios.

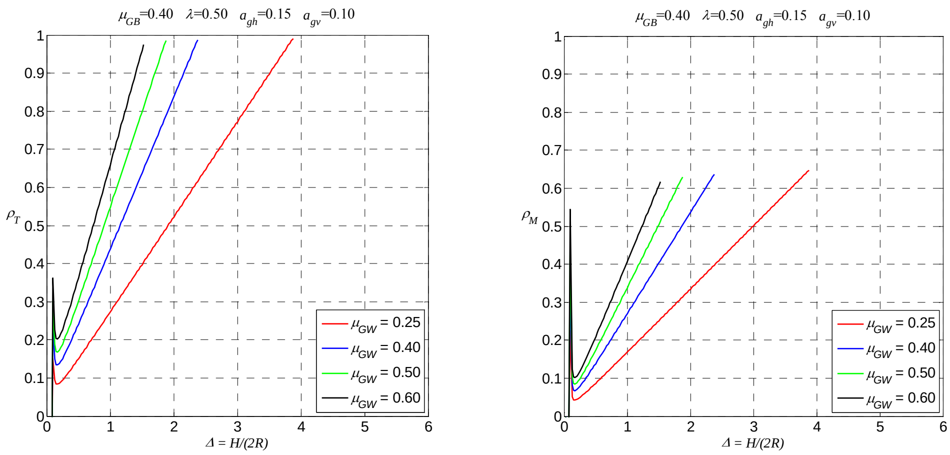


Figure 5.1. ρ_T and ρ_M ratios as function of the silo slenderness ratio $\Delta = H/(2R)$ for specific parameters.

6. CONCLUSIONS

In this paper, the actions of grain on the walls of flat-bottom grain silos during earthquake ground motions have been studied analytically.

First, the mutual actions exchanged between the grain and the silo walls under static and accelerated conditions (constant vertical acceleration and constant horizontal acceleration) have been assessed.

Then, the analytical results obtained in the first part have been used to formulate suggestions for assessing the seismic effects on the walls of flat-bottom grain silos. The results indicate that, in case of squat silos (characterized by low but common height/diameter slenderness ratios), the portion of grain mass interacting with the silo walls proves to be noticeably lower than the total grain mass contained in the silo.

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