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The role of slenderness on the seismic behavior of ground-supported cylindrical silos

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Abstract. This paper reports on the results of a parametric study, which examines the effects of varying aspect ratios on the dynamic response of cylindrical silos directly supported on the ground under earthquake loading. Previous research has shown that numerical models can provide considerably realistic simulations when it comes to the behavior of silos by using correct boundary conditions, appropriate element types and material models. To this end, a three dimensional numerical model, taking into account the bulk material-silo wall interaction, was produced by the ANSYS commercial program, which is in turn based on the finite element method. The results obtained from the numerical analysis are discussed comparatively in terms of dynamic material pressure, horizontal displacement, equivalent base shear force and equivalent bending moment responses for considered aspect ratios. The effects experienced because of the slenderness of the silo in regards to the seismic response were evaluated along with the effectiveness of the classification system proposed by Eurocode in evaluating the loads on the vertical walls. Results clearly show that slenderness directly affects the seismic response of such structures especially in terms of behavior and the magnitude of the responses. Furthermore the aspect ratio value of 2.0, given as a behavioral changing limit in the technical literature, can be used as a valid limit for seismic behavior.

Keywords: cylindrical silos; bulk material-silo wall interaction; seismic response; dynamic; slenderness

1. Introduction

Silos are built for many purposes including the storage of raw, processed food materials and industrial materials such as coal, sand, cement, etc. Increased population sizes influences the need for more silos to be constructed, particularly bigger and taller silos. Seismic zones present a particular problem for silo construction as the behavior of these dynamic sensitive structures, under earthquake loading, must be taken into consideration. The construction of such structures in earthquake prone regions and subsequent failures of silos in recent earthquakes indicates that the mechanism of silos' seismic behavior is still not well understood (Iwatsubo 1998, Mori *et al*. 2000, Bechtoula and Ousalem 2005, Doğangün *et al*. 2009, Villalobos *et al*. 2011, Fierro *et al*. 2011, Whitman *et al*. 2013). Therefore, earthquake resistant design for silos is crucial in ensuring silos remain intact and undamaged if faced with an earthquake. Moreover, areas that do experience earthquakes need silos in place that can withstand, as much as possible, damage in order to meet a population's basic needs such as food, heating, etc., which becomes all the more crucial after an earthquake and other resources have been damaged.

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Silos that have a special structural system to interact more effectively with bulk material systems have notably complex dynamic behavior, unlike many other structural systems. Dynamic effects are different in character in terms of distribution patterns and their magnitudes when compared with the static effects This case depends on not only physical and mechanical properties of the stored material but also on the geometrical properties of the silo's structure. The lack of research available about the seismic behavior of silos, and the effects of the above mentioned parameters on the seismic responses of silos, shows a critical gap in the technical literature.

In the late eighties a few tests were performed on silo models that were exposed to dynamic, earthquake typical loads to determine the influence of bulk material effective mass on the dynamic response of silos (Shimamoto *et al*. 1982, Harris and von Nad 1985, Sasaki *et al*. 1986, Sasaki and Yoshimura 1992). However, little information can be found about the seismic behavior of cylindrical silos. Rotter and Hull (1989) modeled a cylindrical silo structure containing bulk solid using elastic finite element analysis for solids with axi-symmetrical geometry and where the earthquake load was represented by a quasi-static horizontal body force. Consequently, they outlined a few recommendations for silo design. Braun and Eibl (1995) performed a numerical analysis and more recently, Holler and Meskouris (2006) conducted a numerical and experimental study aimed at describing the seismic behavior of silos. Tatko and Kobielak (2008) performed an experimental study on a silo model subjected to impulsive loads while being supported on a spring system in order to

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investigate the subsoil vibration effects on dynamic material pressure. Durmus (2013) carried out a parametric study on the seismic behavior of silos, focusing specifically on soil/foundation and bulk material interaction effects. Livaoglu and Durmus (2015) performed a numerical study concerned with effects of the wall flexibility on the seismic behavior of ground supported cylindrical silos. Durmus and Livaoglu (2015) conducted an analytical and numerical study for the evaluation of dynamic behavior induced by seismic activity on a silo system, containing bulk material, with a soil foundation. Livaoglu and Durmus (2016) proposed a simplified approximation for seismic analysis of silo-bulk material system.

The seismic design of silos is usually implemented by obtaining additional static loads from many simplifications. These simplifications can include: a disregard for silo geometry (despite the differing slenderness and shape of the silos, the same equations and numeric data are used to find a solution); rigid wall assumption; and an assumption that the bulk material and silo wall act together. These simplifications can lead to unrealistic results. Large amounts of repair and/or reinforcement or replacement costs, loss of stored material and environmental damage give rise to the necessity in doing more research on the seismic behavior of such structures in order to get a reliable design procedure. Indeed, at this time there are no agreed upon calculation procedures when it comes to the consideration of earthquake effects on silos. Very few national and international standards include explicit requirements concerning the seismic design of silos. Most silo standards do not cover the subject at all or they refer a designer to general building codes (Briassoulis 2009). It should be noted that recently Eurocode has introduced a simple seismic procedure for seismic actions in silos and tanks with a general suggestion (EN1998-4 2006). EN1998-4 (2006) includes criteria and rules required for the seismic design of silos without restrictions on their size, structural type and other functional characteristics. For some types of tanks and silos, however, it also provides detailed methods. This code does emphasize, however, that this standard may not be sufficient for facilities associated with large risks to the population or the environment, meaning that additional requirements should be established by the competent authorities.

Silos may be divided into two main groups, either as on-ground or elevated for seismic design, since their seismic responses are completely different (Trahair *et al*. 1983). The Eurocode makes the same distinction between these two main groups. The main effect of seismic action on on-ground silos is the stress induced in the silo wall due to the response of the bulk material. As for elevated silos, the main concern is the supporting structure and its ductility and energy dissipation capacity. This study focuses on directly ground-supported silos.

In addition to the structural type of silos (on-ground or elevated), the relationship between the height and the diameter of the largest inscribed circle within the silo cross-section, in other words the aspect ratio (H/d_c), has a major role in determining the loading on the silo walls. The aspect ratio is termed as the slenderness of the silo, with categories from very slender to squat and retaining geometries in EN1991-4 (2006) for flowing patterns (Nielsen *et al*. 2012). Several studies have been performed on the slenderness effects on dynamic loads that stem either from the filling of or discharging of the bulk material (Kusiñska 2000, Kozicki and Tejchman 2005, Sadowski and Rotter 2011a, Sadowski and Rotter 2011b). As for the determination of seismic loads, a distinction is made between rectangular and circular silos only in EN1998-4 (2006), however, no distinction is made between slender or squat silos. Moreover, slenderness effects on effective mass calculation are not taken into account in any standards when it comes to the seismic design of these structures.

Table 1 Classification of silos according to their dimensions by different approaches

Silo type	Dishinger (Fischer 1966)	Soviet Code (Safarian ve Harris 1974)		Eurocode (EN1991-4 2006)
	Cross-section type			
	All	Circular	Rectangular	All
Slender	$H>1.5\cdot\sqrt{A}$	$H>1.5\cdot d_c$	$H>1.5\cdot a$	$2\leq H/d_c$
Squat silo	$H<1.5\cdot\sqrt{A}$	$H<1.5\cdot d_c$	$H<1.5\cdot a$	$0.4<H/d_c\leq 1.0$
Intermediate slender silo	-	-		$1.0<H/d_c<2.0$
Retaining silos (with flat-bottom)	-	-		$H/d_c\leq 0.4$

The above mentioned previous studies indicate that very limited research has been performed on the seismic behavior of silos, particularly when it comes to the slenderness of a given silo. Thus, this paper aims to investigate the effects of silo slenderness on the seismic response of directly ground supported cylindrical silos while also considering bulk material-silo interaction in order to determine the different behavioral limits. These limits may help in proposing different calculation methods for different ranges of aspect ratios in estimating additional dynamic loads. To this end, a three dimensional numerical model is constituted for the seismic design of the bulk material-silo system and the results then evaluated for six different aspect ratios parametrically.

2. Classification of silos according to aspect ratio

The relationship between the basic dimensions of a structure and its height has significant effects on seismic behavior of the structure. The interaction between the bulk material and silo may exhibit considerable differences in behavior according to aspect ratio and depending on the silo geometry. Therefore, it is possible to examine silos in two main classes, as slender or squat, based on this ratio. Basically, slenderness affects the behavior of bulk material. This behavior can be affected by the geometry of the silo and the physical and mechanical properties of the bulk material. Also material pressures on the silo walls and at the bottom may show significant changes depending on slenderness. In addition to this basic distinction, this classification can be expanded in certain standards such as

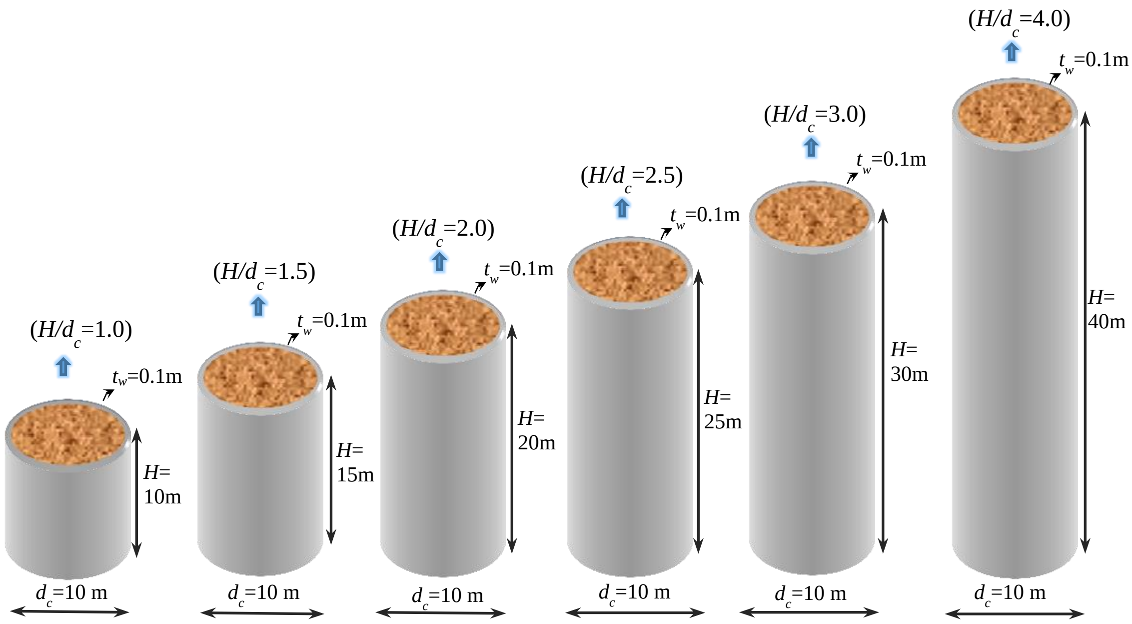


Fig. 1 Geometrical properties of the considered silos

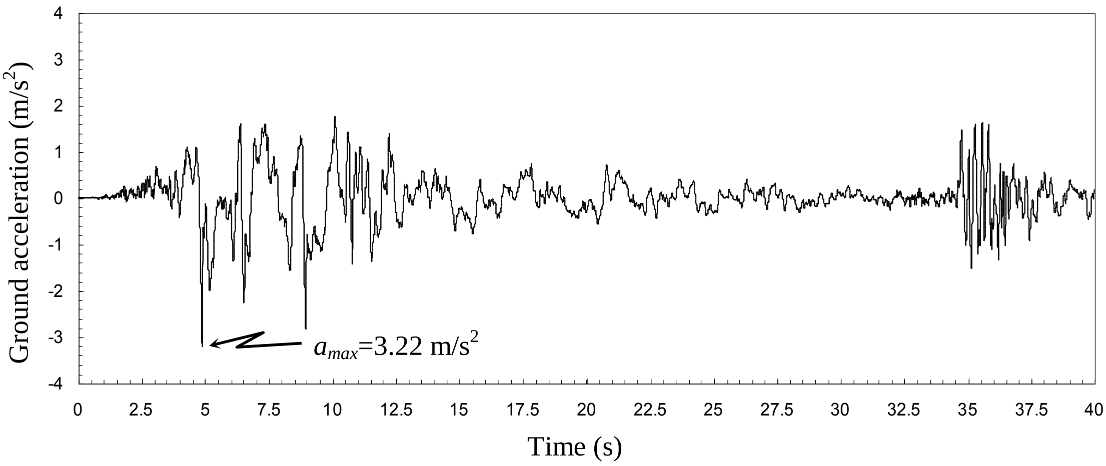


Fig. 2 Considered ground motions N-S component of Yarimca Station- Izmit Earthquake

in EN1991-4 (2006) where four silo classes are identified. The classifications of silos according to their dimensions by different researchers and codes are presented in Table 1 (Durmus 2013). These dimensions are the height of the vertical silo wall, H, the plan cross-sectional area of the silo, *A*, the width of the rectangular silo, *a*, and the characteristic dimension of inside of the silo's cross-section, d_c, respectively.

Silos can also be classified according to the position of the plane of rupture of the stored material as determined by the Coulomb theory. If the rupture plane intersects the top surface of the stored material, it is a squat silo, if not, it is a slender silo. Although the exact classification is not critical for borderline structures, engineers have different opinions for the starting point of the rupture plane for silos that have a hopper. Thus, a silo could be classified as either squat or shallow according to the assumed location of the rupture plane (Safarian and Harris 1974).

3. Description of the considered systems

In this study, the dynamic responses of six reinforced concrete on-ground silos with different aspect ratios (H/d_c) were studied in order to investigate the slenderness effects on the seismic behavior of such structures. These systems were assumed as having a fixed base. All silos have 10 m radius and their heights are 10 m, 15 m, 20 m, 25 m, 30 m and 40 m, respectively (Fig. 1). The Young's modulus, unit mass, Poisson ratio and the material damping ratio of RC were taken to be 28000 MPa, 2500 kg/m^3, 0.2 and 5%, respectively. All the silos were calculated as being filled with granular materials such as wheat. Young's modulus, unit mass, Poisson ratio and the material damping ratio were interpreted as 5 MPa, 900 kg/m^3, 0.3 and 10%, respectively (EN1991-4 2006, Ayuga *et al*. 2001, Hardin *et al*. 1999).

The interaction between the silo wall and the stored

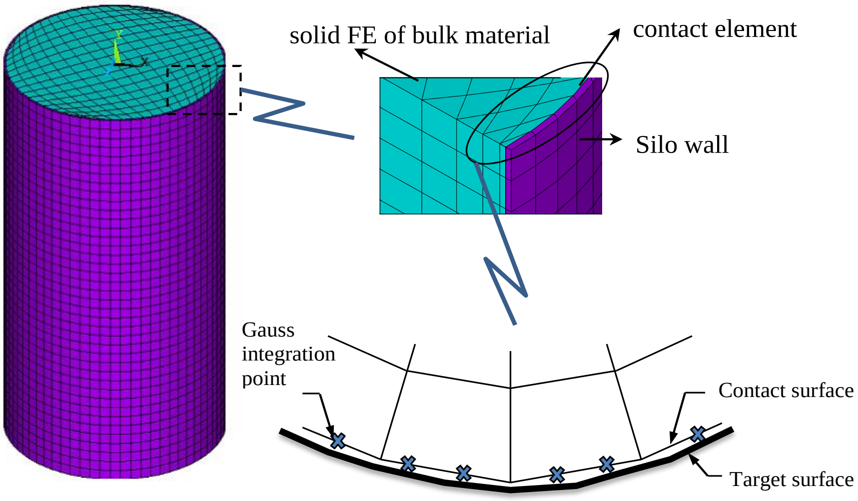


Fig. 3 Finite element model for silos (Durmus 2013)

material was considered by using interface elements in the numerical model. The wall friction coefficient between concret *e* and wheat was selected at 0.57 as proposed in Eurocode (EN1991-4 2006). A full time history analysis was conducted for these silo systems. In the transient analysis, the 1999 Marmara Earthquake, İzmit-Yarimca station N-S component was considered. The considered acceleration history of the ground motion is shown in Fig. 2. The horizontal earthquake time history was applied to the base of the model shown in Fig. 3.

4. Finite element model

A three-dimensional finite-element model was used for the simulation of a reinforced concrete silo containing wheat (Fig. 3). The silo base was presumed to be fixed. The silo structure, the stored material and the interface between them are the components of the numerical model. The silo wall and the bulk material were modeled using isoparametric eight-node-brick elements and with three degrees of freedom per node. The seismic action effects were calculated on the basis of an elastic approximation. The interaction between the silo wall and stored material was modeled using interface (contact) elements. A surface-to-surface contact algorithm was selected to simulate the contact mechanism between the reciprocal surfaces of these two different materials for such a three dimensional analysis of a silo. In such problems these two boundaries are named as target and contact surfaces. Due to greater rigidity, the target surface was selected as the inside of the silo wall while the surface of the bulk material was assumed as the contact surface (Fig. 3). The contact status between these two surfaces was regularly determined at Gauss integration points. The Coulomb friction model was used to model the interaction between the bulk material and the silo wall. In accordance with the chosen contact behavior, local separation of the surfaces is allowed and normal pressure equals zero if separation occurs.

Finally, to determine the seismic behavior and response of the bulk material-silo system full transient dynamic analysis was carried out using the ANSYS. In this analysis, the Rayleigh damping approximation was utilized to take damping into account. Static loads were neglected in the analyses and additional dynamic pressures stemming from the horizontal earthquake loading were obtained.

5. Results of analysis and discussion

Slenderness, defined as the height/diameter ratio, can have major effects on the seismic behavior of silos just as it does on many other similar structural systems. Taking into consideration the evaluation of silos in the technical literature of two main classes, squat and slender, this study analyzes six different aspect ratios. Results show that slenderness also affects the dominant modes of the silo wall in addition to the behavior of the bulk material. The behavior of the system is also affected by the geometry of the silo, the mechanical properties of the stored material and the silo wall. Therefore, in addition to the interaction between the bulk material and the silo wall, material pressures on the silo wall and the effects on the silo bottom may show significant changes based on the slenderness. Moreover, the literature shows that classification according to slenderness can be expanded upon as in the EN1991-4 (2006) (see Table 1). As noted above, the analyses were carried out considering six different aspect ratios, including 1.0, 1.5, 2.0, 2.5, 3.0 and 4.0, respectively. The aspect ratio limit between a squat and a slender silo is usually accepted as 2.0. In this study, all systems analyzed via the numerical model are represented by the abbreviation of NM where NM_10 symbolizes the silo model with a height of 10 .

In order to examine the effects of slenderness on seismic behavior, obtained results are discussed parametrically in terms of dynamic material pressure, horizontal displacement, equivalent base shear force and the overturning moment in the following sections.

4.1 Dynamic material pressures

Table 2 reports the obtained peak values of the

Table 2 Maximum dynamic material pressures, their occurrence instants and heights for six different aspect ratios

Aspect Ratio (H/d_c)	Maximum dynamic material pressure, p_{hs}^{max} (kN/m^2)					
	left side			right side		
	t (s)	H_o (m)	p_{hs}^{max}	t (s)	H_o (m)	p_{hs}^{max}
1.0	7.00	8.0 (0.80H)	24.55	9.00	10.0 (1.00H)	38.20
1.5	7.00	9.5 (0.63H)	24.97	9.00	8.5 (0.57H)	38.86
2.0	7.00	9.0 (0.45H)	23.47	9.00	8.0 (0.40H)	38.38
2.5	7.00	9.5 (0.38H)	25.22	9.00	7.5 (0.30H)	38.02
3.0	6.40	13.5 (0.45H)	20.56	9.00	6.5 (0.22H)	36.26
4.0	7.35	40.0 (1.00H)	22.20	4.90	7.5 (0.19H)	32.02

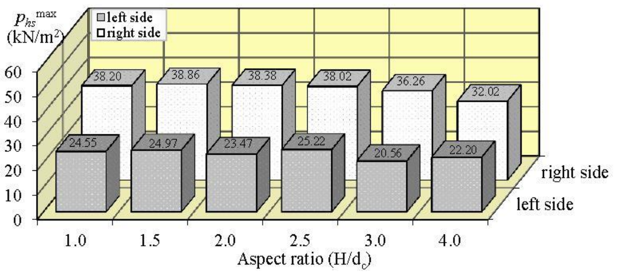
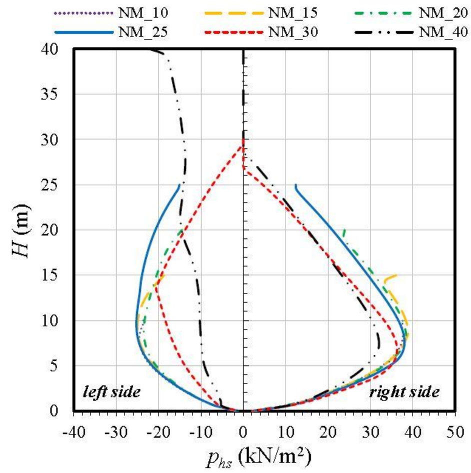


Fig. 4 Maximum dynamic material pressure variations for six different aspect ratios at opposite sides of the silo wall

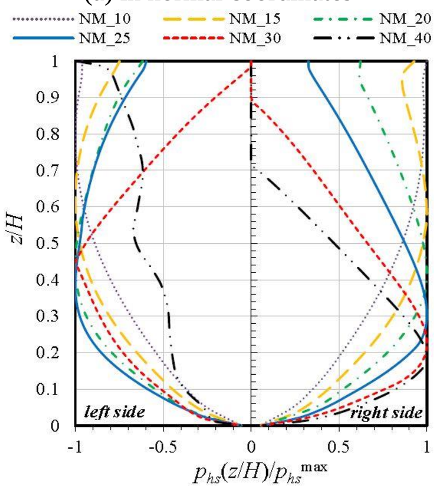
horizontal dynamic material pressures (p_{hs}^{max}) at opposite sides of the wall in relation to the direction of the earthquake, and their occurrence instants (t) and heights from the bottom of the silo (H_o) for six different aspect ratios. It is worth mentioning that the opposite sides of the silo walls in the earthquake direction are entitled as the left and right side, respectively, according to a cross-sectional area of the center. It can be seen from Table 2 that different response values, occurrence instants and heights were obtained for the opposite sides of the wall by reason of taking into consideration the contact mechanism between bulk material and silo wall.

The deviations of the maximum dynamic material pressure responses at the opposite sides of the silo wall are shown in Fig. 4. The maximum dynamic pressures along the height of the silo for six different aspect ratios are illustrated in Fig. 5. Two basic comparisons are given in this figure, which shows the heightwise variations of the obtained response values for each aspect ratio (Fig. 5(a)) and the normalized response values along the normalized height in respect to the maximum values for the considered aspect ratios comparatively (Fig. 5(b)). The dynamic material pressure variations along the silo height that gives the maximum base shear force were considered for these comparisons. The occurrence instants of these variations were determined for each aspect ratio and accordingly these occurrence instants are the same as those of equivalent base shear forces.

As mentioned above, different dynamic material pressure values were obtained at the opposite sides of the silo wall in the earthquake direction because of the considered interface between the bulk material and the silo wall, allowing the bulk material's independent movement from the silo wall to be taken into consideration. As it can be seen from Fig. 5, the possible separation of these two



(a) in normal coordinates



(b) in dimensionless coordinates

Fig. 5 Comparison of the maximum dynamic material pressures throughout the height of the silo wall for six different aspect ratios at opposite sides of the silo wall

different materials may result in the dynamic material pressure equaling zero at a specific height of the silo by increasing slenderness due to the effects of the dominant modes. It is possible to say from this comparison that the first four aspect ratios (H/d_c=1.0, 1.5, 2.0, 2.5) show similar behavior in dynamic material pressure distribution, for both sides of the wall, at the instant that the maximum shear force is obtained. As for the aspect ratios 3.0 and 4.0, the effects of the silo wall on the bulk material behavior increase due to the relatively large displacements that come

Table 3 Maximum horizontal displacements and their occurrence instants for six different aspect ratios

Aspect Ratio (H/d_c)	Maximum horizontal displacement, u^{max} (m)			
	left side		right side	
	t (s)	u^{max}	t (s)	u^{max}
1.0	7.05	-0.0013	4.95	0.0020
1.5	7.05	-0.0032	4.95	0.0051
2.0	7.05	-0.0057	9.05	0.0089
2.5	7.10	-0.0101	9.10	0.0148
3.0	7.15	-0.0196	9.15	0.0259
4.0	7.40	-0.0603	9.30	0.0667

about because of the increase in flexibility. The research conducted here suggests that the bulk material behavior is particularly subject to change at a large slenderness ratio of 4.0 because of the nature of its composition. Increasing the aspect ratio means more horizontal displacement of the silo wall and the bulk material shearing stiffness decreasing by increasing aspect ratio (H/d_c). Thus, the transmitted inertia forces at the bottom of the silo increases. In this case, the peak values of these responses, particularly in silos with greater slenderness, can be seen generally at the levels close to the bottom. Large increases in the aspect ratio can lead to the emergence of rather different dominant modes of the bulk material and the silo wall from each other. This may significantly affect the distribution of the dynamic material pressure throughout the silo height.

The dynamic material pressure distributions along the height of the silo at normalized coordinates for six different aspect ratios given in Fig. 5(b) shows that the occurrence height of the maximum dynamic material pressure from the bottom of the silo (H_o) changes with the increasing aspect ratio. In other words, the resultant location of these pressures from the bottom of the silo changes with the increasing aspect ratio. In almost all silos, except the left side of the silo with H/d_c=4.0, the occurrence height of the dynamic material pressure decreases by the increasing slenderness.

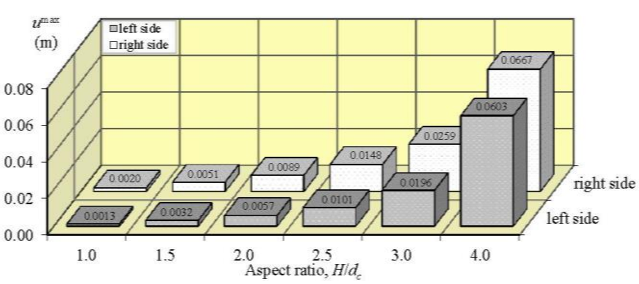


Fig. 6 Maximum horizontal displacement variations for six different aspect ratios at opposite sides of the silo wall

5.2 Horizontal displacements

The obtained peak values of lateral displacements (u^{max}) at the opposite sides of the wall in the earthquake direction and their occurrence instants (t) for six different aspect ratios are presented in Table 3. Table 3 illustrates that the maximum displacements are estimated as 0.0013 m~0.0603 m around 7. sec, on the left side, for all aspect ratios. These responses are captured at 4.95 sec for the first two aspect ratios, around 9. sec for the other aspect ratios, and as 0.0020 m~0.0667 m on the right side. In fact, these horizontal displacements at opposite sides are expected to happen in the opposite direction to each other, at different instants and values due to the interaction between the bulk material and silo wall.

The deviations of the maximum horizontal displacements at the opposite sides of the silo wall are shown in Fig. 6.

The difference in the maximum horizontal displacements between the opposite sides of the silo wall for 1.0, 1.5, 2.0, 2.5, 3.0 and 4.0 are 53%, 59%, 56%, 47%, 32% and 10%, respectively. As Fig. 6 shows, this ratio tends to decrease with the increasing aspect ratio. This result can be attributed to the varying dominant modes according to the slenderness. The obtained horizontal displacement responses are quite small especially for squat silos and these response values are negligible for these types of structures. However, as would be expected this response gets higher

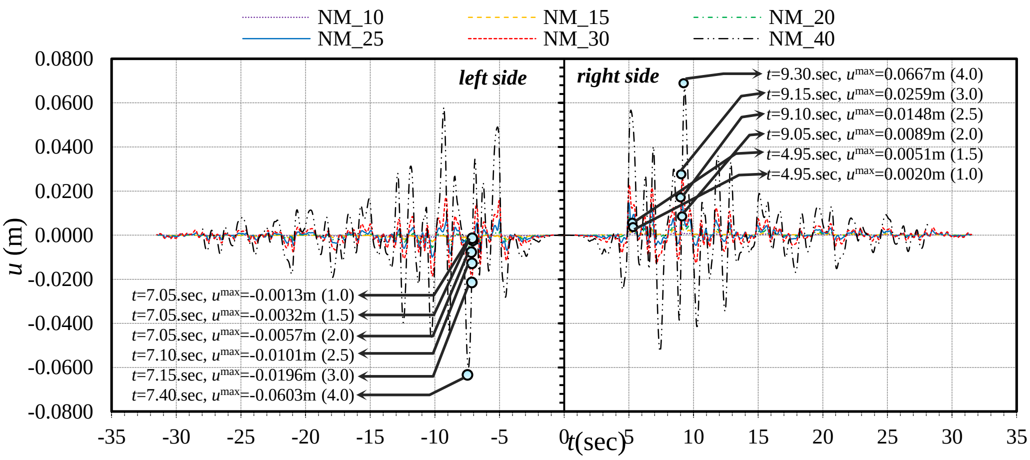


Fig. 7 Variations of horizontal displacements in time at opposite sides of the silo wall in the earthquake direction for six different aspect ratios

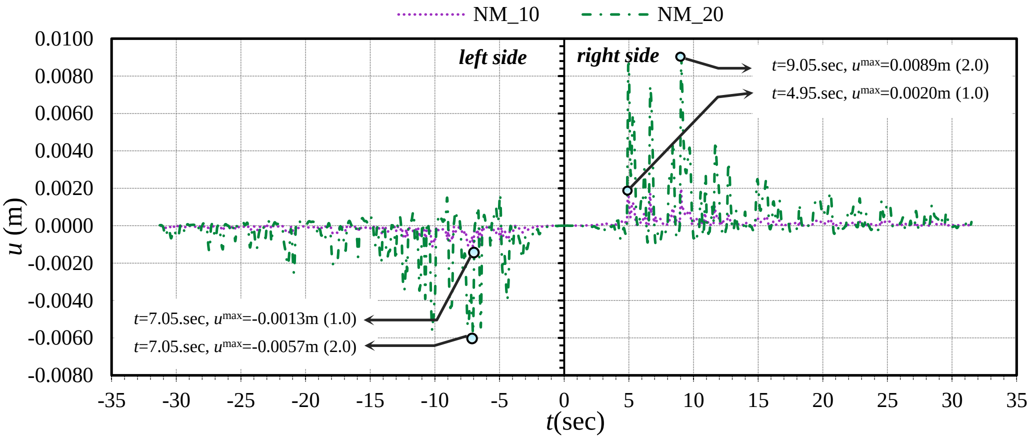


Fig. 8 Variations of horizontal displacements in time at opposite sides of the silo wall in the earthquake direction for aspect ratios 1.0 and 2.0

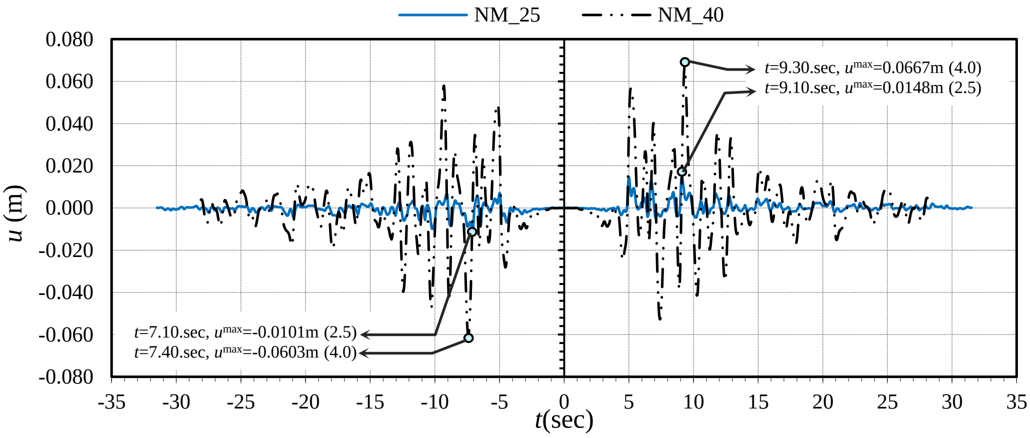


Fig. 9 Variations of horizontal displacements in time at opposite sides of the silo wall in the earthquake direction for aspect ratios 2.5 and 4.0

values with an increasing aspect ratio, however, these values did not reach remarkable levels.

The variations of maximum horizontal displacement responses obtained for considered aspect ratios in time are given in Fig. 7, comparatively.

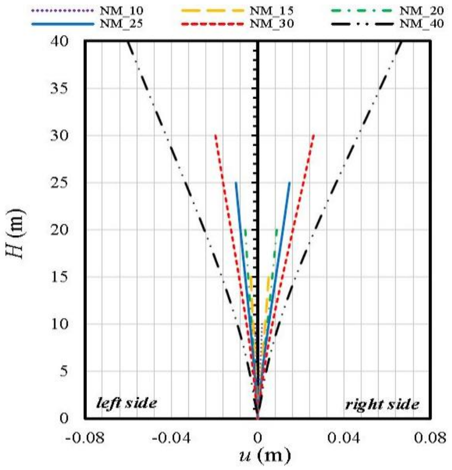
The definition of the slender silos in the technical literature, where $2.0<H/d_c$, indicates that the behavioral changes of these systems occur where the aspect ratio is greater than 2.0. This change can be seen explicitly by examining the variations of horizontal displacement responses in time. It is observed from Fig. 7 that the horizontal displacements of the silo wall proved to be normal for both sides on the outside of the silo, however, horizontal displacement results inside the silo were not found during ground movements experienced by squat silos (H/d_c=1.0, 1.5). This is a fact that arises due to the aspect ratios. This case based on the silo dominant modes related to their cylindrical geometry. Analyses showed that displacements occur in both directions (outside and inside the silo) for the slenderness ratios that are greater than 2.0 during seismic loading. Therefore, it can be stated that the cantilever behavior becomes dominant after this aspect ratio of 2.0. Thus, the aspect ratio limit of 2.0 defined in the technical literature is also meaningful for horizontal displacement responses. The comparison between the aspect ratios of 1.0 and 2.0, where an aspect ratio with a limit of 2.0 shows the limit of behavioral change, is given in Fig. 8.

As it can be also seen from Fig. 7, quite small response values are obtained for lower aspect ratios. Therefore, the comparison of a slenderness ratio of 2.5 and 4.0 are illustrated separately in Fig. 9 for a better understanding of the difference.

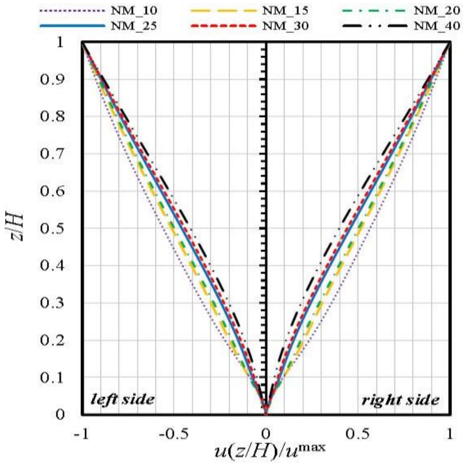
The information represented in Fig. 9 shows that there is no significant difference in terms of behavior. Moreover, the biggest differences obtained are in terms of the magnitude of responses for these silo systems that have aspect ratios in the slender silo class.

The heightwise variations of obtained lateral displacement values for each aspect ratio are shown in Fig. 10(a) and the same responses in normalized coordinates with respect to the maximum values are illustrated in Fig. 10(b), comparatively.

As it can be understood from Fig. 10 (a) horizontal displacement responses increase significantly with increasing slenderness of the silo. However, the main point



(a) in normal coordinates



(b) in dimensionless coordinates

Fig. 10 Comparison of the maximum horizontal displacements throughout the height of the silo wall via NM for six different aspect ratios at the opposite sides of the silo wall

to be addressed is that the obtained heightwise variations of horizontal displacements for squat silos are remote from the cantilever behavior while also showing rigid behavior. Silos exhibit a behavior similar to the cantilever beam behavior with the increase of the slenderness ratio. Obtaining greater response values of horizontal displacement in each case at the right side of the silo wall does not depend on any structural item. The relationship between the dynamic characteristics of the load and the bulk material and the silo structure, result in obtaining greater responses on the right side of the silo wall, in many cases.

5.3 Equivalent base shear forces

The obtained peak values and their occurrence instants for the maximum equivalent base shear are given in Table 4. In this study, equivalent means the force that occurs throughout the unit width of the silos' wall and not the total base shear force. However, it acts the same as the behavior and character of the total base shear force. It is worth mentioning that these responses are obtained from the maximum dynamic pressure throughout the height of the silo for each time step.

Table 4 Maximum equivalent base shear forces and their occurrence instants for six different aspect ratios

Aspect Ratio (H/d_c)	Maximum Equivalent Base Shear Force, V_e^{max} (kN/m)			
	left side		right side	
	t (sec)	V_e^{max}	t (s)	V_e^{max}
1.0	7.00	190.30	9.00	288.73
1.5	7.00	301.69	9.00	471.53
2.0	7.00	381.85	9.00	598.09
2.5	7.00	516.08	9.00	671.18
3.0	6.40	379.59	9.00	587.09
4.0	7.35	503.09	4.90	552.93

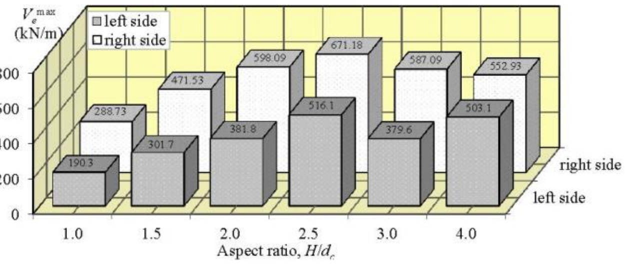


Fig. 11 Maximum equivalent base shear force variations for six different aspect ratios at opposite sides of the silo wall

The deviations of maximum equivalent base shear responses obtained for six different aspect ratios at both sides are given in Fig. 11.

It is clear that the mass increases with the increasing silo height and accordingly it is normal to expect an increase in base shear force. However, this case is not always valid in regards to dynamic behavior. A reduction in base shear forces between the aspect ratios of 2.5 and 3.0 can be seen from Fig. 11. It is appropriate to say that despite the increasing mass, such a reduction can occur due to the bulk materials behavior and accordingly the change in the common behavior of the whole system.

The variations of maximum equivalent base shear responses obtained for considered aspect ratios in time are given in Fig. 12, comparatively. As it can be seen from Fig. 12, equivalent base shear forces take their maximum values at one direction and at the opposite direction they take the value of zero due to taking into account bulk material silo interaction.

5.4 Equivalent overturning moments

The obtained peak values and their occurrence instants for the maximum equivalent overturning moment are given in Table 5. It is worth mentioning that the equivalent overturning moment is obtained by calculating the effect of the maximum dynamic pressures along the height for every 0.5 m to the base.

The deviations of maximum equivalent overturning moments obtained for six different aspect ratios at both sides of the silo wall are given in Fig. 13. As illustrated in Figs. 11 and 13, similar overturning moment responses obtained with the base shear force responses.

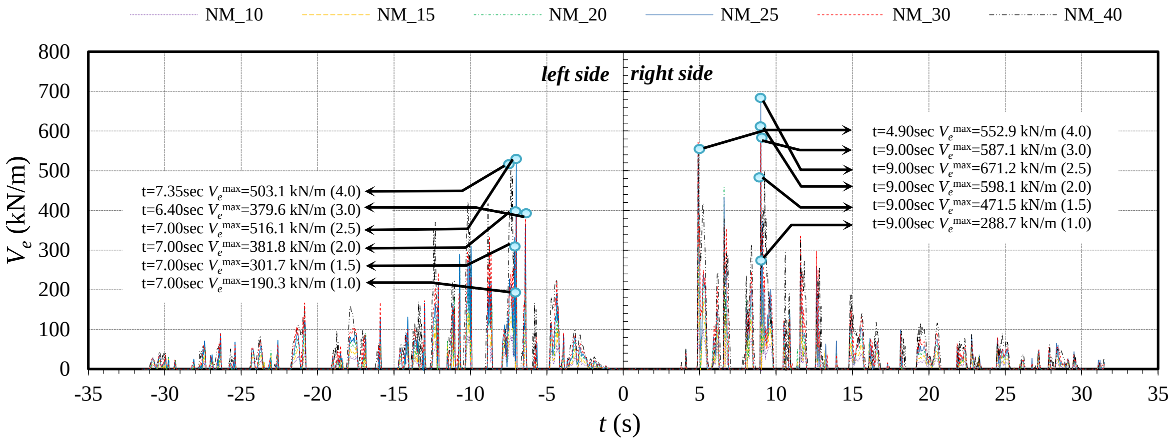


Fig. 12 Variations of equivalent base shear forces in time at opposite sides of the silo wall in the earthquake direction for six different aspect ratios

Table 5 Maximum equivalent overturning moments and their occurrence instants for six different aspect ratios

Aspect Ratio (H/d_c)	Maximum Equivalent Overturning Moment, M_e^{max} (kN/m)m)			
	left side		right side	
	t (sec)	M_e^{max}	t (sec)	M_e^{max}
1.0	7.00	1115.73	9.00	1707.13
1.5	7.00	2515.28	9.00	3957.05
2.0	7.00	3996.84	9.00	6193.08
2.5	7.00	6632.80	9.00	7800.90
3.0	8.75	5655.48	4.90	6761.26
4.0	7.35	11501.98	9.25	12113.49

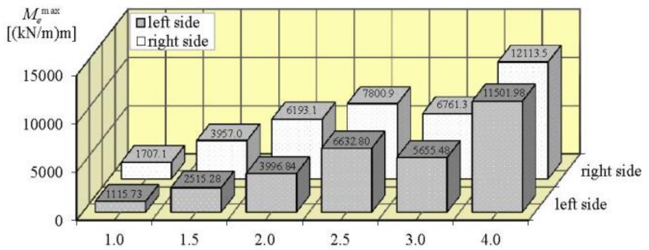


Fig. 13 Maximum equivalent overturning moment variations for six different aspect ratios at opposite sides of the silo wall

6. Conclusions

This paper presents a three-dimensional finite element model considering the interaction between bulk material and silo wall constituted to evaluate the effects of slenderness on seismic behavior of a bulk material-silo system. The aspect ratio is thought to be effective on the seismic behavior of such structures. In order to remedy the deficiency in the technical literature about this subject a parametric study was performed for six different aspect ratios to determine whether it is actually effective. The following conclusions may be drawn, based on the results of this study:

- After analyses of the considered systems, that slenderness may cause considerable effects on the response of the system in terms of behavior and magnitude. The maximum dynamic material pressures tend to decrease when slenderness of the silo increases. However, this trend may vary for very close aspect ratios due to the dynamic properties of the silo and the bulk material and their relation with the dynamic properties of the load.
- The distribution of the dynamic material pressure at the instant of the maximum equivalent base shear force obtained is that the seismic behavior of the silo exhibits similar characteristics for the first four aspect ratios (H/d_c=1.0, 1.5, 2.0, 2.5) and these similarities are valid for opposite sides of the silo wall. On the other hand, the heightwise dynamic material pressure variations for H/d_c=3.0 and 4.0 can vary in contrast with the lower aspect ratios. This can be attributed to the separation of the bulk material from the silo wall and thus the different dynamic properties of the bulk material and the silo wall. This result can occur according to the different dominant frequencies of both interacting mediums and the phase differences between their horizontal displacement responses. Obtaining zero dynamic material pressure values along a greater depth of the silo from the top surface of the silo for the considered heightwise distribution of dynamic material pressure response indicates a trend where change occurs due to increasing slenderness.
- Results show that displacement responses are quite small, especially for squat silos, and that these values are negligible for this structural system. However, for slender silos, despite a great increase in these responses proportional to squat silos, these values do not reach levels that cannot be ignored.
- Horizontal displacements of the silo wall prove to be normal for both sides on the outside of the silo, however, horizontal displacement results, inside the silo, are not found during ground movements experienced by squat silos (H/d_c=1.0, 1.5). This is a fact that arises due to the aspect ratio of the silo. Clearly, this case based on the silo dominant modes related to their cylindrical geometry. Moreover, it can be seen that cantilever behavior is dominant for slender silos. Thus, the

mechanism that controls the displacement response of the silo is the modes of the silo wall.

- The results from the parametric analysis performed in this study showed that the aspect ratio limit of 2.0, as given in the literature, is also a critical point in the change of silo seismic behavior.
- A different behavior arises for high aspect ratios bigger than H/d_c=3.5. So it can be said that in addition to a squat and a slender silo, a different classification should be performed for such an aspect ratio.

Briefly, this study shows that slenderness parameter changes the seismic behavior of reinforced concrete cylindrical silos significantly. Moreover, bulk material-silo interaction effects on the seismic behavior of such systems are not negligible. In order to generalize these results, similar studies should be undertaken with different earthquake records.

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