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Investigation of wall flexibility effects on seismic behavior of cylindrical silos

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Abstract. This paper is concerned with effects of the wall flexibility on the seismic behavior of ground-supported cylindrical silos. It is a well-known fact that almost all analytical approximations in the literature to determine the dynamic pressure stemming from the bulk material assume silo structure as rigid. However, it is expected that the horizontal dynamic material pressures can be modified due to varying horizontal extensional stiffness of the bulk material which depends on the wall stiffness. In this study, finite element analyses were performed for six different slenderness ratios according to both rigid and flexible wall approximations. A three dimensional numerical model, taking into account bulk material-silo wall interaction, constituted by ANSYS commercial program was used. The findings obtained from the numerical analyses were discussed comparatively for rigid and flexible wall approximations in terms of the dynamic material pressure, equivalent base shear and bending moment. The numerical results clearly show that the wall flexibility may significantly affects the characteristics behavior of the reinforced concrete (RC) cylindrical silos and magnitudes of the responses under strong ground motions.

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

1. Introduction

Silos are special engineering structures for storing granular materials. Increasing needs of population give rise to increase construction of such structures. On the other hand, silos subjected to many loading types due to filling and discharging of bulk material, thermal conditions, differential settlements, dust explosions, internal structure collapse, wind loads especially for empty silos, earthquakes etc. Most of them differ from the loading types of other structures; their responses to common loading types also differ from those of many other structures due to bulk material-silo interaction. Therefore, design of silos becomes quite complicated and unfortunately a global theory is not available. As a result of high failure rate of silos, especially for seismic loads among aforementioned cases, still maintain their importance as a research subject. However, in spite of their vital importance, very few studies can be found in the technical literature concerning seismic response of such structures. Moreover, very few national or international standards include

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explicit requirements concerning the seismic design of the silos. Most silo standards do not cover the subject at all, or they refer to general building codes (Briassoulis 2009). On the other hand, Eurocode has recently introduced a simple seismic procedure for seismic actions in silos and tanks with a general suggestion (EN1998-4 2006). As a consequence, in practice, silos are designed against strong ground motions according to the corresponding codes for buildings and equipment (Briassoulis 2009).

As it can be seen from the technical literature a few tests performed on silo models exposed to dynamic, earthquake typical loads for determining the influence of bulk material effective mass on the dynamic response of silos at the end of the 20th century (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) modelled a cylindrical silo structure containing bulk solid by using an elastic finite element analysis for solid with axi-symetrical geometry and the earthquake loading is represented by a quasi-static horizontal body force and they provided some recommendations for silo design. Braun and Eibl (1995) performed a numerical analysis and recently, Holler and Meskouris (2006) conducted a numerical and experimental study for describing the seismic behavior ofsilos. Tatko and Kobielak (2008) performed an experimental study on a silo model subjected to impulsive load and supporting on a spring system for investigating subsoil vibration effects on dynamic material pressure. Nateghi and Yakhchalian (2011) tried to determine the effect of bulk material-silo interaction on crack propagation and damage mechanism of silo walls. Silvestri *et al*. (2012) investigated the effective mass of the bulk material in flat-bottom silos during earthquake ground motion analytically. Zandi *et al*. (2012) investigates the behavior of cylindrical silos subjected to earthquake by analytical and numerical methods. Durmuş (2013) carried out a parametric study about seismic behavior of the silos considering soil/foundation and bulk material interaction effects. Finally, Abdel-Rahim (2014) evaluated the seismic response of a cylindrical elevated silo under earthquake loading.

Seismic behavior of a silo can be affected by many parameters such as physical and mechanical properties of granular material, its interaction with silo wall, soil-structure interaction stemming from a great mass of a full of silo, the silo's aspect ratio, cross sectional geometry and type (elevated or ground supported), filling rate, wall flexibility, etc. Nevertheless, the seismic design of silos is generally performed by obtaining additional static loads by the help of many simplifications. Therefore, it is clear that rough estimates can be obtained according to these simplifications, such as disregarding silo geometry. Large amount of repair and/or reinforcement or replacement costs, loss of stored material, environmental damage and probable injury or loss of life give rise to thought that a lot more attention must be paid to research the seismic behavior of such structures to gain a better understanding of the silo seismic response and get a reliable design procedure (Doğangün *et al*. 2009). Although effects of the each abovementioned parameters on the seismic response of silos are still maintain their importance, in this study wall flexibility effects on the seismic response of silos were investigated.

Several studies have been performed about wall flexibility effects on the dynamic loads stemming from filling and/or discharging of the bulk material (Hawkins and Messer 1977, Mahmoud 1981, Ooi and Rotter 1990, Wu 1990, Jarrett 1991, Jarrett *et al*. 1995, Chen *et al*. 2001, Guines *et al*. 2001, Martinez *et al*. 2002, Goodey *et al*. 2003, 2006, Vidal *et al*. 2008). In most of them it is mentioned that wall flexibility has a marked effect on the filling and discharging pressures in non-cylindrical silo structures, especially in square and rectangular silos. In addition to these studies an approximate method for estimating the responses to horizontal base shaking of vertical, rigid and flexible circular cylindrical tanks that are filled with a uniform viscoelastic material was proposed by Veletsos and Younan (1998a, b). They mentioned that this proposed approximation is also applicable to the evaluation of the dynamic response of grain-storage silos.

The response of the silo wall to the strong ground motions can affect the wall pressures due to its flexibility. In this case an interaction problem between the bulk solid and silo wall arises. Also when the silo is filled, the presence of the stored material modifies the system rigidity. Therefore, direct use of practical methods from other kinds of structures can cause misleading results for earthquake loading. Hence, the solution requires numerical simulations (Rombach and Martinez 2009). As a result of its versatility a wide range of silo problems can be studied by the finite element method, which has become well established in silo research (Rombach and Eibl 2009). So, a three dimensional numerical model was constituted for the dynamic response of bulk material-silo system under earthquake loading. The parametric study in order to determine the effect of wall flexibility on the seismic response of directly ground supported cylindrical silos considering bulk material-silo interaction according to rigid and flexible wall assumptions for six different aspect ratios was carried out in the scope of this study.

2. Finite element modelling of seismic process simulation and considered bulk material-silo systems

A three dimensional finite-element model was used to represent bulk material-silo system as shown in Fig. 1. As it can be seen from Fig. 1, a flat bottom directly ground supported cylindrical type silo was selected for investigation and six different aspect ratios were considered for determining the effectiveness rate of wall flexibility according to the slenderness. All silos have 10 m diameter, 10 cm wall thickness and their heights are 10 m, 15 m, 20 m, 25 m, 30 m and 40 m, respectively (Fig. 1). The silo structure was considered as reinforced concrete and it was assumed to be filled with wheat. 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. Those of wheat were interpreted as 5 MPa, 900 kg/m^3, 0.3 and 10%, respectively (EN1991-4 2006, Ayuga *et al*. 2001).

The numerical model consists of three components that are the silo structure, the stored material and the interface between these two different medium. Isoperimetric eight-node-brick elements (SOLID 185) with three degrees of freedom per node were used for modelling both the silo wall and the bulk material. The seismic action effects were estimated on the basis of an elastic approximation. On the other hand, describing the contact mechanism between silo wall and bulk material is an important problem for the analysis of such structures. The interaction between the silo wall and stored material was modelled using interface (contact) elements (CONTA 174 and TARGE 170). Surface-to-surface contact algorithm is generally preferred to simulate the contact mechanism between the reciprocal surfaces of these two different materials. Therefore, such a three dimensional analysis of silos carried out in this study, accordingly this method was used. Because of being more rigid, inside of the silo wall was selected as target surface and the surface of the bulk material was assigned as contact surface (Fig. 1). The contact status between these two surfaces is regularly determined at Gauss integration points (ANSYS Inc. 2009a, b) The contact between the bulk material and the silo wall was modelled by simple Coulomb friction with a constant wall friction coefficient μ as 0.57 according to EN1991-4 (2006) for reinforced concrete silo wall and wheat. In accordance with the chosen contact behavior, local separation of the

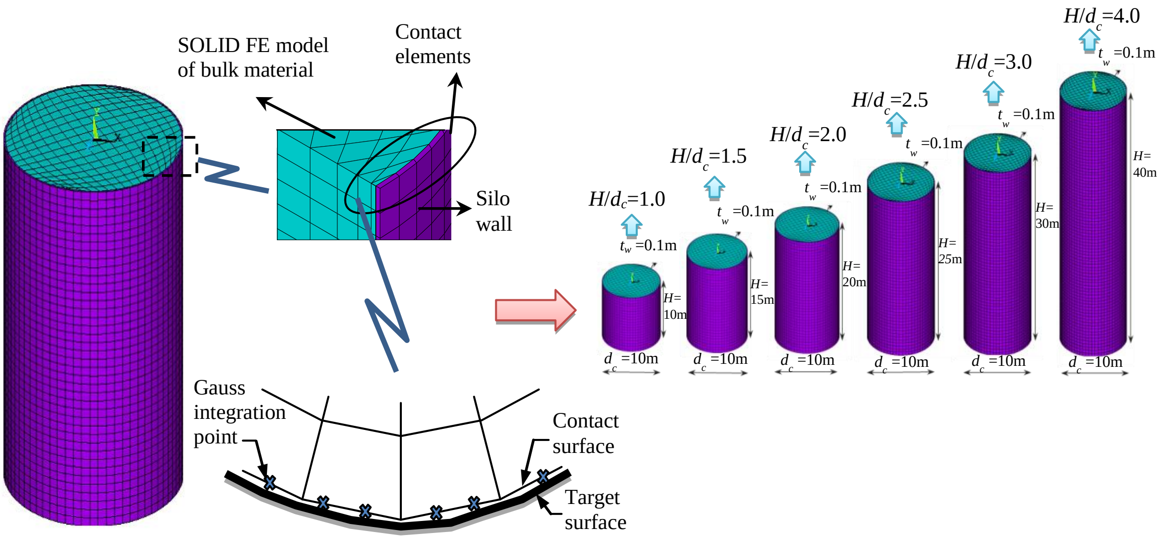


Fig. 1 Finite element model for silos and schematic view for their dimensions (Durmuş 2013)

surfaces is allowed and normal pressure equals to zero if the separation occurs. Due to the changeable contact status between the bulk solid and the silo wall during earthquake, the performed analyses are nonlinear. The 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 horizontal earthquake time history was applied to the base of models shown in Fig. 1.

3. Results of analyses and discussion

Totally twelve analyses were carried out by considering six different slenderness ratios and using rigid and flexible wall assumptions via three dimensional finite element models to investigate the wall flexibility effects on the seismic response of bulk material-silo system. These numerical models with rigid wall assumption are represented with abbreviation of NMR, on the other hand, the numerical models with flexible wall approximation are named as NMF in this study. i.e., NMR_10 represent the model with 10 m height of silo.

The obtained dynamic material pressure, equivalent base shear force and overturning moment response results are discussed parametrically in the following titles. It is worth mentioning that the opposed sides of the silo wall in the earthquake direction according to the center of cross-sectional area of silos were entitled as left and right side. By the reason of changing in the dynamic responses due to consideration of the contact mechanism between bulk material and silo wall, occurrence times and their heights for the opposed sides of the wall were given separately under the following subtitles.

3.1 Dynamic material pressures

Table 1 shows the obtained peak values of the dynamic material pressures ($p_{hs}^{\max}$), their occurrence times (t) and heights (H_o) from the bottom of the silos for the considered models. When evaluating these findings, the effects of rigid wall and flexible wall assumptions on the behavior of structure and accordingly those on the response of bulk material should be considered.

According to rigid wall approximation it was assumed that rigid body motion is only valid for silo's wall and dynamic material pressures completely depend on the inertia effects of the stock material. On the other hand, by the assumption of flexible wall it is clear that this behavior may vary due to the wall flexibility and interaction, due to slenderness of the silo, between silo wall and stock material as well. In other words, for rigid wall assumption the dynamic material pressures are shaped by behavior of the bulk material due to its slenderness ratio, as for flexible wall assumption additionally the interaction between the bulk material and the silo wall is raised as another parameter that affects the behavior. Therefore, when the occurrence times of the maximum dynamic material pressures are examined comparatively, behavior can be understood more clearly. While the occurrence times of these pressures change for the slenderness ratios of 3.0 and 4.0 via flexible wall assumption, conversely this case is different for rigid wall assumption. This alteration occurs at slenderness ratio of 4.0 at left side via rigid wall assumption. Thus, it is understood from this difference that both approaches change the behavior in different directions. As mentioned above, bulk material geometry, here increasing height of the bulk material is the only parameter that affects the behavior for rigid wall assumption. However, the geometrical changes of the silo wall are also effective on the total behavior for flexible wall assumption.

Another issue to be concerned here is that increasing bulk material mass and slenderness enhance the dynamic material pressures at both sides of the silo wall according to rigid wall approximation because bulk material motion is restricted by the silo wall at one direction normal to the wall. The total mass of the stock material is transmitted to the silo wall by the translational motion due to its inertia and this total mass is effective in this motion for slender silos (H/dc>2).

Table 1 Maximum dynamic pressures, their occurrence times and heights for six different slenderness ratios according to rigid and flexible wall assumptions

Slenderness 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)	$p_{hs}^{\max}$
NMR	1.0	7.00	8.0 (0.80*H*)	26.71	9.00	10.0 (1.00*H*)	43.44
	1.5	7.00	9.5 (0.63*H*)	31.73	9.00	11.0 (0.73*H*)	46.70
	2.0	7.00	13.0(0.65*H*)	34.27	9.00	13.5 (0.68*H*)	48.84
	2.5	7.00	17.0 (0.68*H*)	34.49	9.00	17.0 (0.68*H*)	49.28
	3.0	7.00	22.0 (0.73*H*)	33.78	9.00	22.0 (0.73*H*)	49.00
	4.0	11.00	16.5 (0.28*H*)	35.16	9.00	33.0 (0.83*H*)	48.95
NMF	1.0	7.00	8.0 (0.80*H*)	24.55	9.00	10.0 (1.0*H*)	38.20
	1.5	7.00	9.5 (0.63*H*)	24.97	9.00	8.5 (0.57*H*)	38.86
	2.0	7.00	9.0 (0.45*H*)	23.47	9.00	8.0 (0.40*H*)	38.38
	2.5	7.00	9.5 (0.38*H*)	25.22	9.00	7.5 (0.30*H*)	38.02
	3.0	6.40	13.5 (0.45*H*)	20.56	9.00	6.5 (0.22*H*)	36.26
	4.0	7.35	40.0 (1.00*H*)	22.20	4.90	7.5 (0.19*H*)	32.02

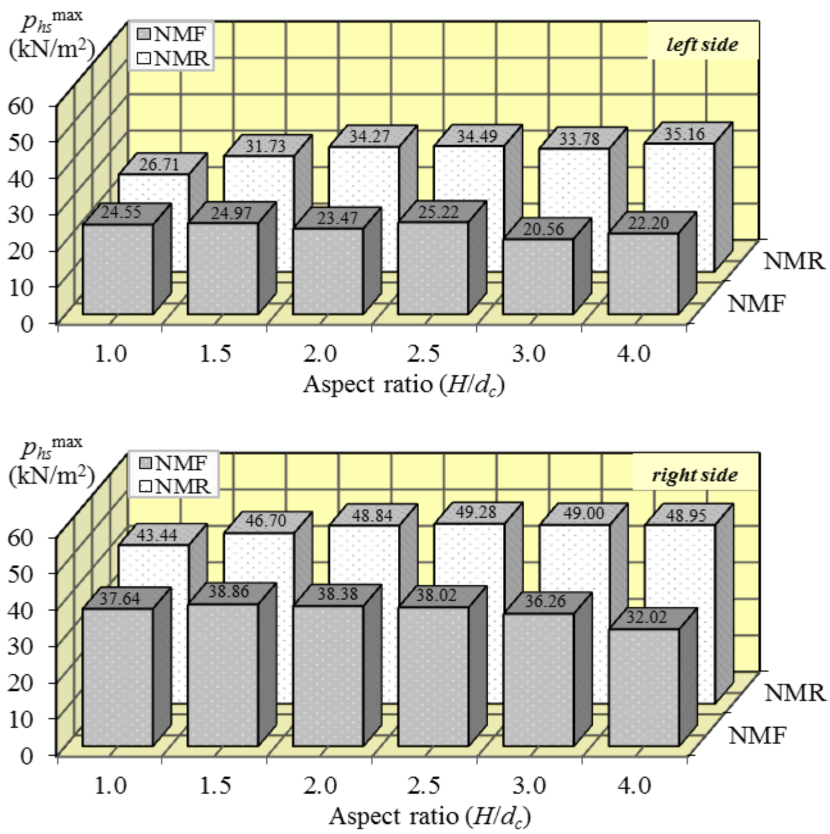


Fig. 2 Maximum dynamic material pressure variations with increasing slenderness ratio via NMF and NMR

On the other hand, for squat silos (H/d_c<2) a portion of inertia forces is transmitted to the base by shearing motion. The portion transmitted to the base increases with the decreasing slenderness ratio. In this case, the mass that affects the forces on the silo walls decreases, so the maximum dynamic material pressure values are less in squat silos compared to slender ones. Silo with a slenderness ratio of 4.0 gives 32% and 13% larger dynamic material pressure values compared to silo with a slenderness ratio of 1.0 at left and right side of the silo wall via rigid wall approximation, respectively.

The wall flexibility decreases the inertia forces transmitted to the silo wall by the horizontal translational motion and increases the portion of the bulk material mass transmitted to the base by shearing action via reducing the horizontal extensional stiffness compared to shear stiffness of the material ensiled. In this case, reduction takes place in the values of maximum responses with increasing slenderness ratios owing to the fact that slenderness increases the wall flexibility. Silo with a slenderness ratio of 4.0 gives 10% and 13% less dynamic material pressure values compared to silos with a slenderness ratio of 1.0 at left and right side of the silo wall, respectively via flexible wall approximation. So this reduction can be clearly explains the above mentioned situation (Fig. 2).

As it can be seen from Fig. 2, when the obtained maximum dynamic material pressures for six different slenderness ratios are compared according to rigid and flexible wall assumptions, NMR

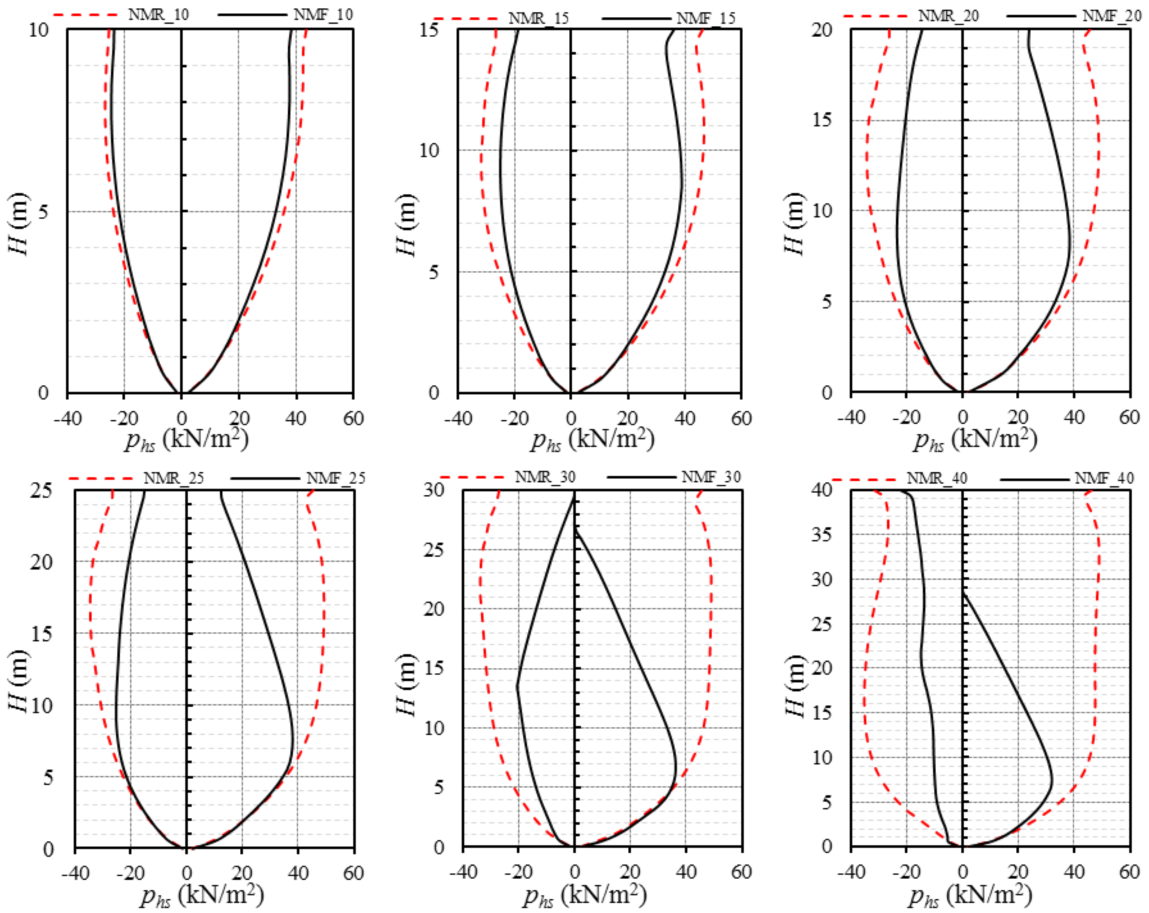


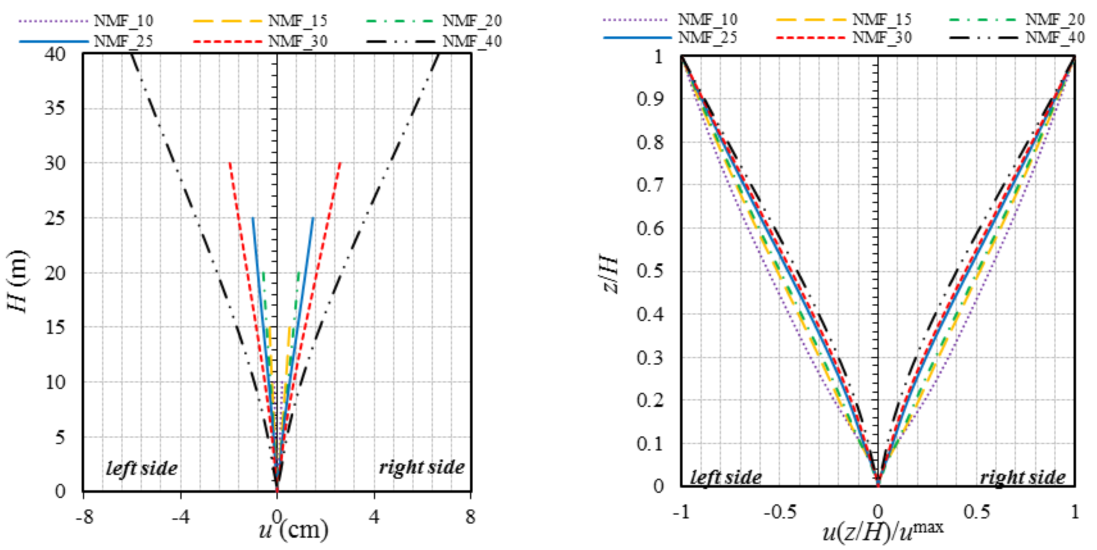
Fig. 3 Comparison of the dynamic material pressures along the height of the silo wall for six different slenderness ratios according to NMR and NMF

gives larger values as 9%, 27%, 46%, 37%, 64% and 58% at left side and 14%, 20%, 27%, 30%, 35% and 53% at right side compared to NMF for the six slenderness ratios, respectively. Here, it can be understood that the difference between the results obtained from NMR and NMF tends to increase with the increasing slenderness ratio at both sides. In this case, it can be said that this increase that occurs with increasing slenderness ratio results from the above described mechanism.

As it can be seen from Fig. 3, the difference between NMR and NMF solutions in terms of heightwise variations of dynamic material pressures began to form at the slenderness ratio limit of 2.0 given in the literature and as for H/d_c>2.0, this difference become quite apparent. As a result of the fact that the horizontal displacements fade in after the slenderness ratio limit of 2.0, increasing wall flexibility due to slenderness ratio reveals more clearly the dynamic pressures and stock material behavior. For a better understanding of this mechanism the increment in the horizontal displacement of the silos for bigger values of the slenderness ratio of 2.5 can be evaluated. While the horizontal displacement of the silo wall is obtained as around 1 cm up to the slenderness ratio of 2.5, this value reaches to 2 cm and 6 cm for H/d_c=3.0 and H/d_c=4.0, respectively. This deviation explains clearly the behavioral change (Fig. 4 a). In addition to this when the horizontal displacements illustrated in dimensionless coordinates (Fig. 4(b)), it is clear that console behavior be dominant after slenderness ratio of 2.0.

3.2 Equivalent base shear forces

Table 2 gives the obtained peak values of equivalent base shear forces (V_e^{max}) and their occurrence times (t) at the opposed sides of the silo wall for the considered models via rigid and flexible wall assumptions. It would be appropriate to indicate that equivalent base shear forces were calculated from the unit width heightwise variation of the dynamic material pressures by finding resultant force for each time step and the equivalent base shear was chosen at the time step which gives the maximum resultant force. It is also worth mentioning that equivalent base shear force is the same as the behavior and character of the total base shear force.



(a) Normal coordinates (b) Dimensionless coordinates

Fig. 4 Comparison of the maximum horizontal displacements along the height of the silo wall via NMF

Table 2 Maximum equivalent base shear forces and their occurrence times for six different slenderness ratios according to rigid and flexible wall assumptions

Slenderness Ratio (H/d_c)	Maximum Equivalent Base Shear Force, V_e^{max} (kN/m)							
	Rigid (NMF)				Flexible (NMF)			
	left side		right side		left side		right side	
	t (s)	V_e^{max}	t (s)	V_e^{max}	t (s)	V_e^{max}	t (s)	V_e^{max}
1.0	7.00	206.17	9.00	315.90	7.00	190.30	9.00	288.73
1.5	7.00	376.00	9.00	555.15	7.00	301.69	9.00	471.53
2.0	7.00	538.15	9.00	796.70	7.00	381.85	9.00	598.09
2.5	7.00	692.14	9.00	1037.82	7.00	516.08	9.00	671.18
3.0	7.00	829.51	9.00	1274.91	6.40	379.59	9.00	587.09
4.0	11.00	1155.51	9.00	1742.84	7.35	503.09	4.90	552.93

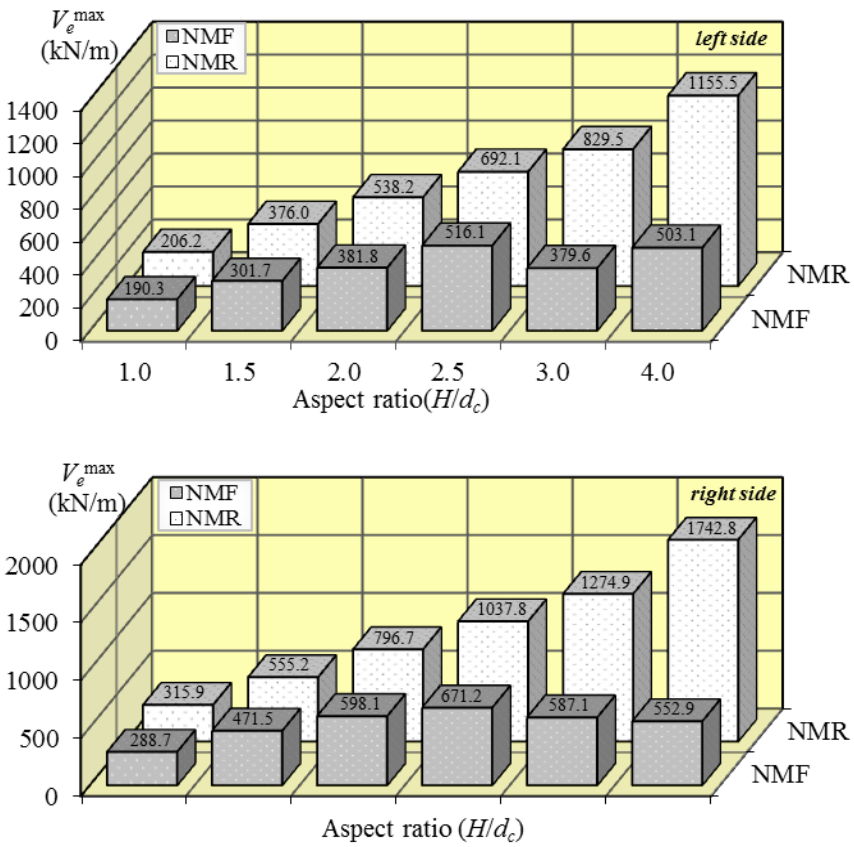


Fig. 5 Maximum equivalent base shear force variations with increasing slenderness ratio via NMF and NMR

The deviations of maximum equivalent base shear forces obtained from two different approximations, NMR and NMF, for considered models are illustrated in Fig. 5.

As it can be seen from the Fig. 5, equivalent base shear forces increases with the increasing slenderness ratio for the rigid solutions as expected. As for flexible solution, this increase is not valid for the slenderness ratios; 3.0 and 4.0. Dynamic characteristic of the system changed at the slenderness ratios of 3.0 and 4.0 and accordingly heightwise variations of the dynamic material pressures change. Therefore reductions occurred in the equivalent base shear responses for the slenderness ratios of 3.0 and 4.0 via flexible wall assumption. In this case, the flexible solution decreased the rate of increase of shear force. When the obtained results from NMR and NMF are compared for each slenderness ratio, at left side of the silo wall NMR gives 8%, 25%, 41%, 34%, 119% and 130%; at right side of the silo wall 9%, 18%, 33%, 55%, 117% and 215% larger values for the considered slenderness ratios, respectively. As it can also be understood from these values that prescribing silos as rigid can cause to obtain gradually increasing and significant amount of additional base shear forces with increasing slenderness ratio compared to the flexible solutions.

When the obtained variations of equivalent base shear forces in time according to rigid and flexible wall approximations are evaluated, for rigid solution at left side of the silo wall, the peak response values were obtained at 7. sec as 206~830 kN/m for first five slenderness ratios.

However, for H/d_c=4.0 this peak response value was occurred at 11. sec as 1155.5kN/m and at right side of the silo wall for all slenderness ratios they were obtained at 9. sec as 315~1743 kN/m. For flexible solution at left side of the silo wall for first four slenderness ratios the peak response values were obtained at 7. sec as 190~516 kN/m, for H/d_c=3.0 at 6.40. sec as 379.59kN/m and for H/d_c=4.0 at 7.35.s as 503.09kN/m. When the similar consideration was made at right side of the silo wall, for first five slenderness ratio these values were occurred at 9. sec as 288~587 kN/m and for H/d_c=4.0 at 4.9. sec as 552.93kN/m. As it can be understood from here that behaviors obtained via flexible and rigid solutions overlapped for first four slenderness ratios, difference occurs only in terms of maximum response values. Therefore, representing the first four slenderness ratios, only the comparison of the variation of equivalent base shear forces in time via both assumptions for slenderness ratio of 1.0 is illustrated in Fig. 6. The difference began to occur between rigid and flexible solutions for H/d_c=3.0 and this difference was more marked for H/d_c=4.0. Aforementioned comparisons for slenderness ratio of 3.0 and 4.0 are given in Fig.7 and Fig. 8.

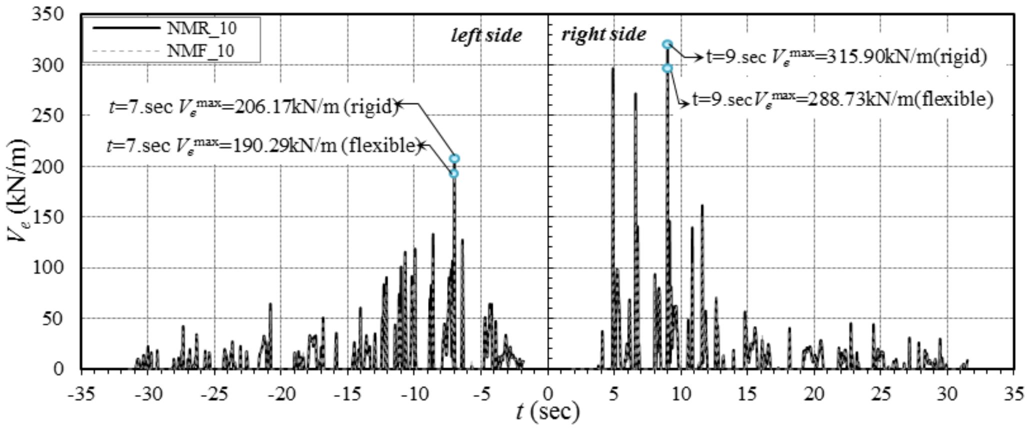


Fig. 6 Variations of equivalent base shears with time at opposed sides of the silo wall for slenderness ratio of 1.0 via NMR and NMF

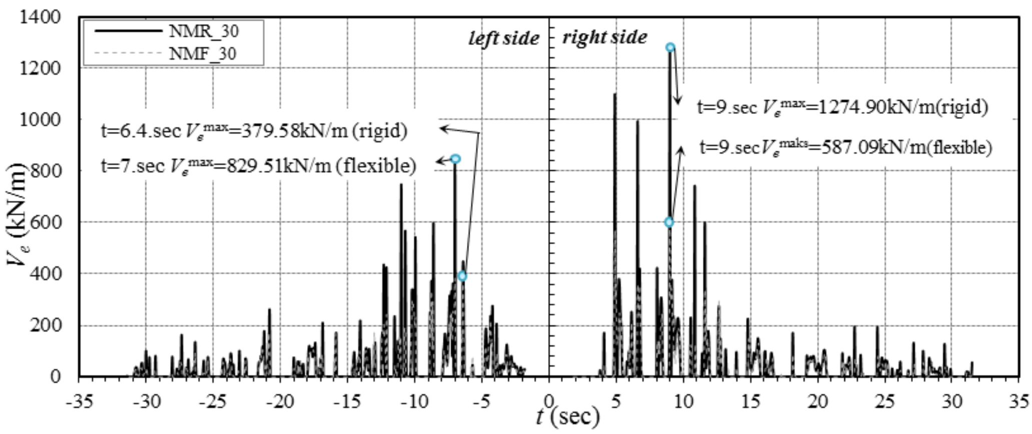


Fig. 7 Variations of equivalent base shears with time at opposed sides of the silo wall for slenderness ratio of 3.0 via NMR and NMF

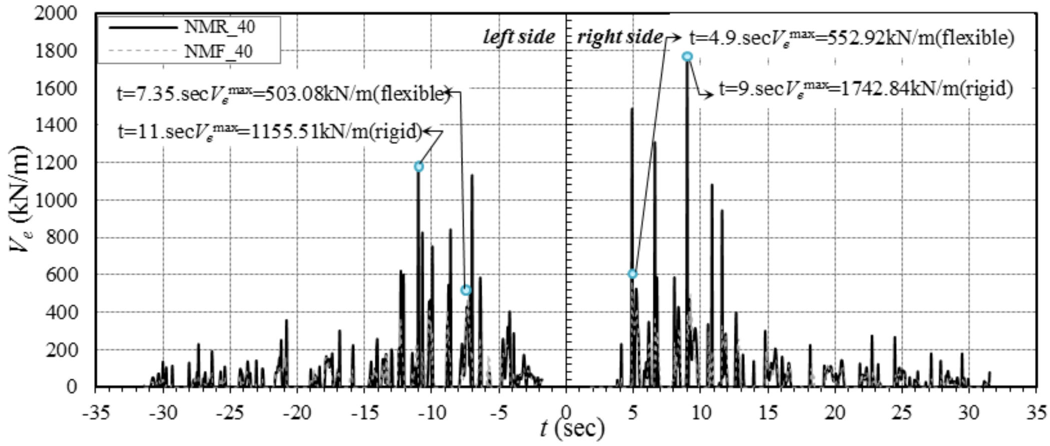


Fig. 8 Variations of equivalent base shears with time at opposed sides of the silo wall for for slenderness ratio of 4.0 via NMR and NMF

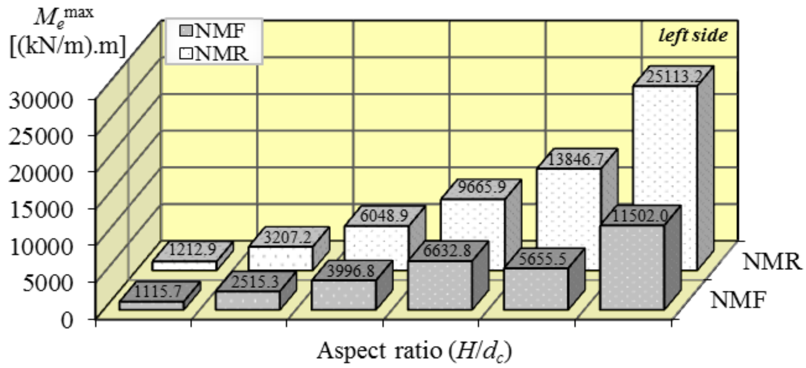
Table 3 Maximum equivalent overturning moments and their occurrence times for six different slenderness ratios according to rigid and flexible wall assumptions

Slenderness ratio (H/d_c)	Maximum Equivalent Overturning Moment, M_e^{max} [(kN/m).m]							
	Rigid (NMR)				Flexible (NMF)			
	left side		right side		left side		right side	
	t (s)	M_e^{max}	t (s)	M_e^{max}	t (s)	M_e^{max}	t (s)	M_e^{max}
1.0	7.00	1212.88	9.00	1890.98	7.00	1115.73	9.00	1707.13
1.5	7.00	3207.17	9.00	4826.54	7.00	2515.28	9.00	3957.05
2.0	7.00	6048.92	9.00	9003.77	7.00	3996.84	9.00	6193.08
2.5	7.00	9665.90	9.00	14397.85	7.00	6632.80	9.00	7800.90
3.0	7.00	13846.72	9.00	20980.08	8.75	5655.48	4.90	6761.26
4.0	7.00	25113.18	9.00	37572.71	7.35	11501.98	9.25	12113.49

3.3 Equivalent overturning moments

The obtained peak values of equivalent overturning moments (M_e^{max}) and their occurrence times (t) at the opposed sides of the silo wall in the earthquake direction for the considered models are given in Table 3. Rigid and flexible solution shows the same tendency for the first four slenderness ratios, however for slenderness ratios of 3.0 and 4.0 behaviors become different from those. As the considerations for equivalent overturning moments is similar with those of equivalent base shear, in order not to repeat same comparison, here Fig. 9 is given where the changes are clearly visible.

When the differences between the results of equivalent overturning moments are examined according to rigid and flexible solutions, NMR gives 9%, 28%, 51%, 46%, 145% and 118% at left side; these values are computed at right side as 11%, 22%, 45%, 85%, 210% and 210% larger compared to NMF for the considered slenderness ratios, respectively. These ratios indicate that under the same inertial forces, if we assume that the silo is rigid, gradually increasing and a significant amount of gaps can be obtained with the increasing slenderness ratio. Moreover,



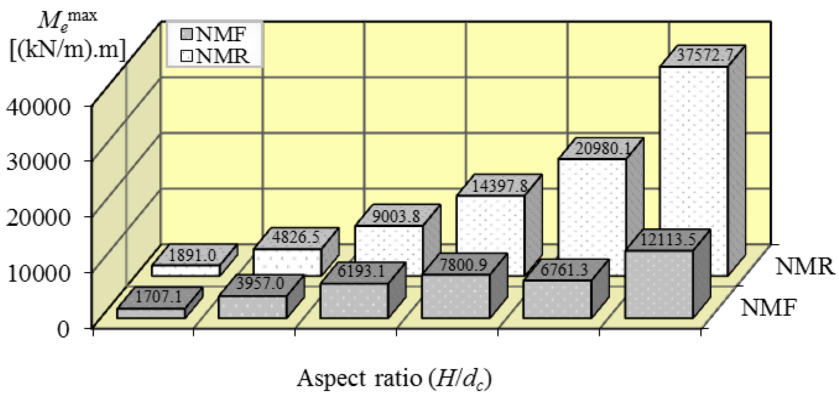


Fig. 9 Maximum equivalent overturning moment variations with increasing slenderness ratio via NMF and NMR

obtaining similar difference ratios between flexible and rigid wall approximations for overturning moments to those for base shear forces also refer that there is not any significant difference between obtained dynamic material pressure variations along the height according to both assumptions in terms of geometric center.

4. Conclusions

The most general conclusions obtained from the analysis carried out and their discussion given subtitles in this study can be summarized as follows:

It was determined that wall flexibility and silo-bulk material interaction are significantly effective on the seismic behavior of such systems and the magnitudes of the responses. So the flexibility of the silos must be accounted for the design purposes. More economical design can be made whereby the misleading result may be prevented. Thus, more realistic design can be realized.

Dynamic material pressures depend on the slenderness ratio of stored material in the case of rigid wall assumption. As for flexible wall approximation dynamic material pressures are also affected by the interaction between the stock material and silo wall. Because changes that occur in the silo wall affect the behavior of the whole system. Increasing slenderness ratio, accordingly increasing stock material mass amplifies the dynamic material pressures in the solutions with rigid wall approximation. This is because stock material's motion in the direction of the normal to the silo wall is restricted rigidly by the wall.

It was determined that wall flexibility decreases the inertia forces transmitted to the wall by the horizontal translational motion and increases the inertia forces transmitted to the base by horizontal shearing motion due to the fact that wall flexibility decreases horizontal stiffness of the stored material relative to its shearing stiffness.

The slenderness ratio value of 2.0 given in the technical literature as a distinction limit of squat and slender silos may also be assumed a valid limit for distinction between the seismic solution with rigid and flexible wall assumptions. The obtained heightwise variations of dynamic material pressures from these solutions becomes different at the slenderness ratio (H/d_c) of 2.0 and this difference is quite apparent for $H/d_c>2.0$. The difference between the responses of the solutions with rigid and flexible wall assumptions tends to increase by the increasing slenderness ratio.

When the silo structure prescribed as rigid, gradually increasing and a significant amount of additional responses with increasing slenderness obtained for the same systems compared to flexible wall approximation. As it can also be understood from these results that prescribing silos as rigid can cause overestimation of the responses except displacement response.

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