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Investigating the Comparative Analysis of Cylindrical Silos Subjected to Earthquake by Analytical and Numerical Methods

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ABSTRACT

The events occurring in silos which are classified as special engineering structures from construction and usage point of view are too complicated to solve with simple equations and perceptions. On the other hand, it is quite clear that they also have to be designed for earthquake loads to provide a required safety by the codes. However, it is known that this type of structures is damaged beyond the acceptable damages. This case might be attributed to the calculation methods used in their designs if no mistakes were made in construction processes. Therefore, the main purpose of this study was to investigate the behaviours of cylindrical reinforced concrete silos with analytical methods, added mass and Lagrangian approaches and to compare the results of these methods. While comparing to the results of analytical methods and added mass approach, the results obtained indicate that isoparametric element chosen by the Lagrangian approach can successfully be used in earthquake analysis of silos when sloshing effects are ignored.

Key words: Analysis of cylindrical silos, earthquake load, added mass, Lagrangian approach, analytical methods

INTRODUCTION

In order to determine the dynamic behaviors of soils, are scarce, unrealistic assumptions of existing studies about this subject like assuming the soils membranes as rigid so disregard the interaction and assuming the earth movements as harmonic, always exist. One of the numerical methods, finite element method is used at the structural analysis which considers the mentioned interactions. This method is applied to the interaction problem in the form of Euler and Lagrangian approaches with Westergaard's added mass approach (Karaca and Durmus, 2000; Dogangun *et al*., 1996; Rammerstorfer *et al*., 1990; Bathe, 1982; Adedeji and Ige, 2011; Azizpour and Hosseini, 2009; Alsulayfani and Saaed, 2009).

One of the new techniques in seismic design were based on changing the dynamic characteristics of buildings by dissipating the energy with lower damage in structural components of the system (Sharbatdar and Saatcioglu, 2009; Adedeji and Ige, 2011).

Regarding the properties of the soils, in this study, isoparametric element which is used at the analytical solutions is assumed to be an elastic solid; only the impulse pressure is taken into consideration at analytical methods. And the silo-material interaction is examined according to the East-West component of Erzincan in 1992 earthquake with the utilization of Lagrange formulation by adapting the mentioned eight nodded three-dimensional isoparametric element to the Structural Analysis Program (SAPIV) (Bathe *et al.*, 1973; Alsouki *et al.*, 2008; Alfaaouri *et al.*, 2009). Fallah *et al.* (2009). The application of modern control to diminish the effects of seismic loads on structures offers an appealing alternative to traditional earthquake resistant design approaches (Adedeji and Ige, 2011; Alsulayfani and Saaed, 2009). Finally, the data obtained from the analysis of silo is compared in-between them by many aspects and some justifications are reached about the utility of Lagrange Approach at the cylindrical silos.

DETERMINATION OF DYNAMIC PRESSURE DISTRIBUTIONS USING SOME ANALYTICAL AND NUMERICAL METHODS

Some analytical methods: With the assumption that the slosh effects at granular material could be neglected, besides Westergaard, Karman and Hoskins-Jacobsen methods which are used at liquid containers and only consider the impulse effects, The relations used at calculations are given at Table 1. At these relations is the maximum acceleration of earth movement ρ is the material unit mass, h is the height of the contained material and r is the radius of the silo. Here it should be stated that these relations are appropriate for rigid silos (Karaca and Durmus, 2000; Housner, 1957; Nasserasadi *et al.*, 2008).

In adapted Veletsos method (Jardaneh, 2004), the impulse pressure can be estimated from the following equation by obtaining the dimensions $q_i(0)$ value from Fig. 1a according to h/r ratio and the dimensionless $q_i(z)$ value from the chart of Fig. 1b.

Table 1: Analytical methods used for determining dynamic pressure distribution

Method	Dynamic pressure distribution
Westergaard	$p(z) = 0.875\ a_m\ ?\sqrt{h\ z}$
Karman	$p(z) = 0.7071\,a_m\ ?\ \sqrt{z\,(2h - z)}$
Hoskins-Jacobsen	$p(z) = \frac{8}{\pi^2} \cdot a_m \cdot \rho \cdot h \cdot \sum_{j=1,3,5}^{\infty} (-1)^{\frac{j-1}{2}} \cdot \frac{1}{j^2} \cdot \cos\frac{j\pi(h-z)}{2h} \cdot \tanh\frac{j\pi 2r}{4h}$
Adapted Housner	$p(z) = a_m\ \rho\ h\sqrt{3}\ \left[(z/h) - 0.5(z/h)^2\right] \tanh\left[\sqrt{3}\ r/h\right]$

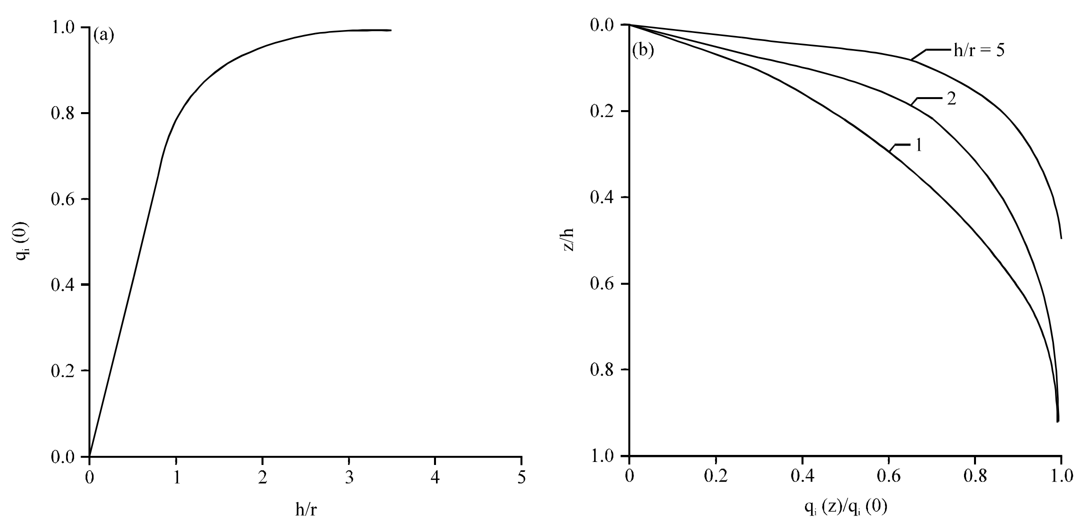

Fig. 1(a-b): q_i (0) and q_i (z) values for the estimation of impulse pressure

$$p_i(z) = q_i(z) \times a \times \rho \times r \quad (1)$$

Some numerical methods

Added mass approach: The principle of added mass approach is based on the study made by Westergaard (1931) and Priestley *et al.* (1986). In that study, Westergaard added a mass which creates the dynamic pressure, to the structural mass at the interface of fluid-structure. The value of added mass which has parabolic distribution from the material surface to bottom can be obtained by the following expression:

$$m(z) = \frac{7}{8} \times \rho \times \sqrt{h \times z} \quad (2)$$

where, h is totals material height, z is the depth of the material from the surface and ρ is the unit mass of the material.

In this study, the use of added mass approach with finite element method is made by adding an impulse mass determined using different methods for the materials to the mass of solid elements.

For this purpose, equation of motion given as:

$$M\ddot{u} + C\dot{u} + Ku = Ma(t) \quad (3)$$

can be written in the following form for the added mass approach:

$$M^{*}\ddot{u} + C\dot{u} + Ku = -M^{*}a(t) \quad (4)$$

The equation of the damped impulsive motion is known to be as following, where, M is mass matrix, C is damping matrix, K is rigidity matrix, u is displacement vector and a(t) is the acceleration of base motion.

In the added mass approach, this motion equation takes the following form, where, M_a is added mass matrix and M* (= $M+M_a$) is total mass matrix.

As it is seen from this relation, according to this approach it has been assumed that M_a mass vibrates simultaneously with the structure and because of the contained material, only the mass in the motion equation increases and the damping does not change.

This method which is not able to consider the slosh effects, can be practically used at engineering structures like silos in which the impulsive effects dominates, by adding the membrane to the finite elements model at the membrane-material interface of the material mass (Celep and Kumbasar, 1992; Hangai *et al.*, 1983; Ching *et al.*, 2011).

Lagrangian approach: In this approach, material behaviour is expressed by the displacement term at the finite element node points and thus the equilibrium-appropriateness conditions are provided at the points of membrane-material interface automatically.

Assumptions made for this study are given below:

- Neglecting the slosh effects caused by base motion at the granular material in the silo, only the impulsive effects are taken into consideration
- The contained material is assumed to be compactable, behaves linearly elastic, whose viscosity effects are negligible and at which the rotation is constraint

For the three dimensional model, the equation can be written as follows where, ε_v is the unit volumetric strain, u_x, u_y and u_z are the material displacements along x, y and z axes, respectively, p is pressure and E_v is the bulk modulus of material:

$$\varepsilon_v = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} \tag{5}$$

$$p = E_v \cdot \varepsilon_v \tag{6}$$

Rotations about x, y and z axes which are necessary in order to supply rotation constraints are, respectively expressed as:

$$\varepsilon_{xr} = \frac{1}{2}\left[\frac{\partial u_z}{\partial y} - \frac{\partial u_y}{\partial z}\right] \varepsilon_{yr} = \frac{1}{2}\left[\frac{\partial u_x}{\partial z} - \frac{\partial u_z}{\partial x}\right] \varepsilon_{zr} = \frac{1}{2}\left[\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}\right] \tag{7}$$

From here, the rotation pressures, p_{xr}, p_{yr} and p_{zr} can be as the following; where, Ψ_x, Ψ_y and Ψ_z shows constraint parameter coefficients for the axes orientations of x, y and z and $E_{22} = \Psi_x E_v$, $E_{33} = \Psi_y E_v$ and $E_{44} = \Psi_z E_v$.

$$p_{xr} = E_{22}\ \varepsilon_{xr}\ p_{yr} = E_{33}\ \varepsilon_{yr}\ p_{zr} = E_{44}\ \varepsilon_{zr} \tag{8}$$

Accordingly, the total potential (U) and kinetic energy (T) of the system is determined by the equations of:

$$U = \frac{1}{2}\int \varepsilon^T\ E\ \varepsilon\ dv\ T = \frac{1}{2}\int \rho\ v^T\ v\ dv \tag{9}$$

where, E, ε and v shows elasticity matrix, strain and velocity vectors, respectively. Therefore, the Lagrange equation can be written as:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{u}_i}\right) - \frac{\partial T}{\partial u_i} + \frac{\partial U}{\partial u_i} = F_i \qquad i = 1,2,3,4.... \tag{10}$$

where, here u_i and F_i show i numbered displacement component and external load corresponding to this component, respectively and this equation behaviors can be applied to the nonlinear systems as well as to the linear systems (Karaca and Durmus, 2000; Celep and Kumbasar, 1992; Hangai *et al*., 1983).

Utilization of the three dimensional isoparametric element by finite element modeling: In this study, the selected three dimensional isoparametric element with eight node points and general (x, y, z) and local (r, s, t) axes groups which are considered for this element, are given in Fig. 2.

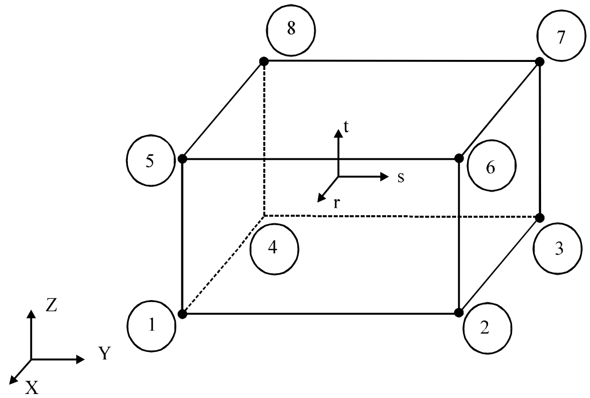

Fig. 2: Isoparametric element

Mass and stiffness matrices of this element should be known in order to determine the motion equations. Mass matrix of the element can be expressed as:

$$M = \rho \int_v Q^T\, Q\, dV \rightarrow M = \sum_i \sum_j \sum_k \eta_i \eta_j \eta_k\, Q^T_{ijk}\, Q_{ijk}\, \det J_{ijk} \tag{11}$$

where, J is the Jacobian matrix, Q is the interpolation functions and η_i, η_j, η_k are weight coefficients.

In order to obtain the stiffness matrix, the elasticity matrix (E) whose diagonal elements are E_{11}, E_{22}, E_{33} and E_{44}, respectively and the other elements are zero and the strain-displacement matrix (B) at the equation $\varepsilon = B.u$, where, $\varepsilon^T = [\varepsilon_v, \varepsilon_{xr}, \varepsilon_{yr}, \varepsilon_{zr}]$, should be known. Thus, the element stiffness matrix is as:

$$K = \int_v B^T\, E\, B\, dV \rightarrow K = \sum_i \sum_j \sum_k \eta_i \eta_j \eta_k\, B^T_{ijk}\, E\, B_{ijk}\, \det J_{ijk} \tag{12}$$

After the mass and stiffness matrices of the selected element was determined by the equations of (11, 12), potential and kinetic energy expressions can be written as:

$$U = \frac{1}{2} u^T\, K\, u, \quad T = \frac{1}{2} v^T\, M\, v \tag{13}$$

according to finite elements method. As it is seen from this equation, as only the impulse effects are taken into consideration in granular material, no term related with surface slosh takes place in potential energy expression. If the mentioned energy expressions are replaced in the Lagrange equation of number (10), the motion equation of the undamped system can be obtained as:

$$M\ddot{u} + K u = R \tag{14}$$

Silo application: Here, adapting the three dimensional isoparametric element whose formulation was given before, to the structural analysis program SAPIV (Bathe *et al.*, 1973), such that the

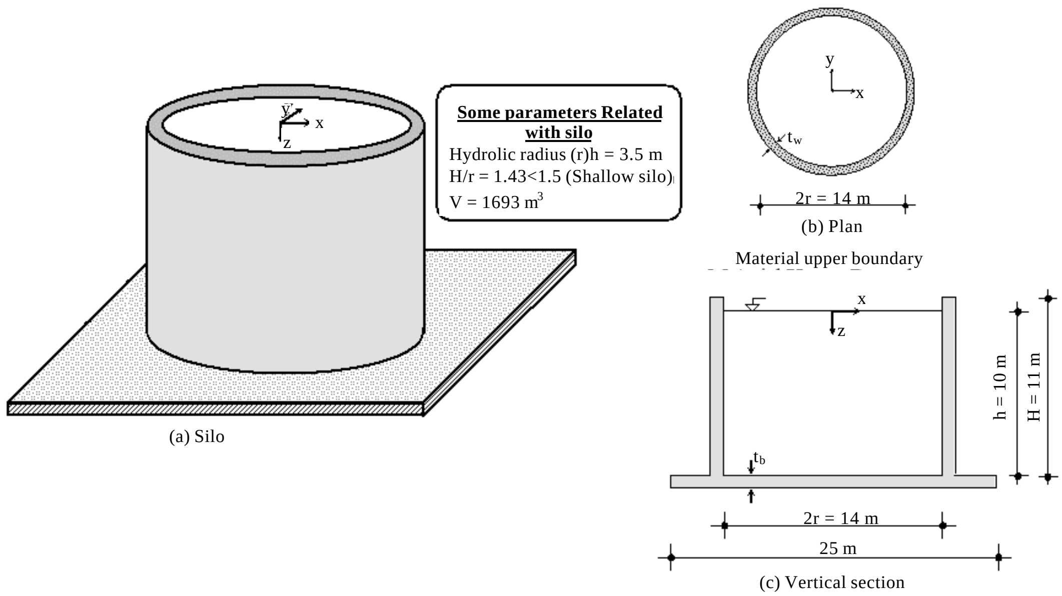

Fig. 3: Silo plan and vertical section

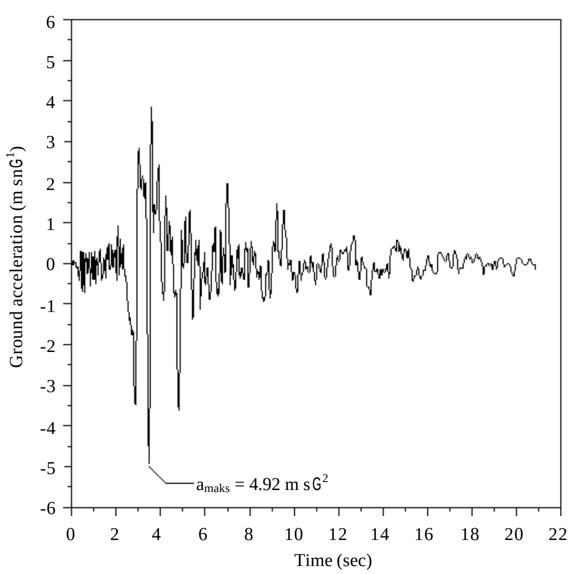

Fig. 4: Earthquake acceleration of the March 13, 1992 Erzincan earthquake in Turkey

surface slosh elements could not be used, computation of the silo whose characteristics are given in Fig. 3, is done according to the East-West component of the 1992 Erzincan Earthquake (Karaca and Durmus, 2000) (Fig. 4). In this computation, the bulk modulus, Poisson ratio and the unit mass of the contained wheat is taken as $E_v = 4{,}167\times10^7$ N/m^2, $\nu = 0.30$ and $\rho = 800$ kg m^{-3}, respectively and unit mass, Poisson ratio and elasticity modulus of silo wall material is taken as $\rho = 2500$ kg m^{-3}, $\nu = 0.2$ and $E = 285\times10^8$ N m^{-2}, respectively.

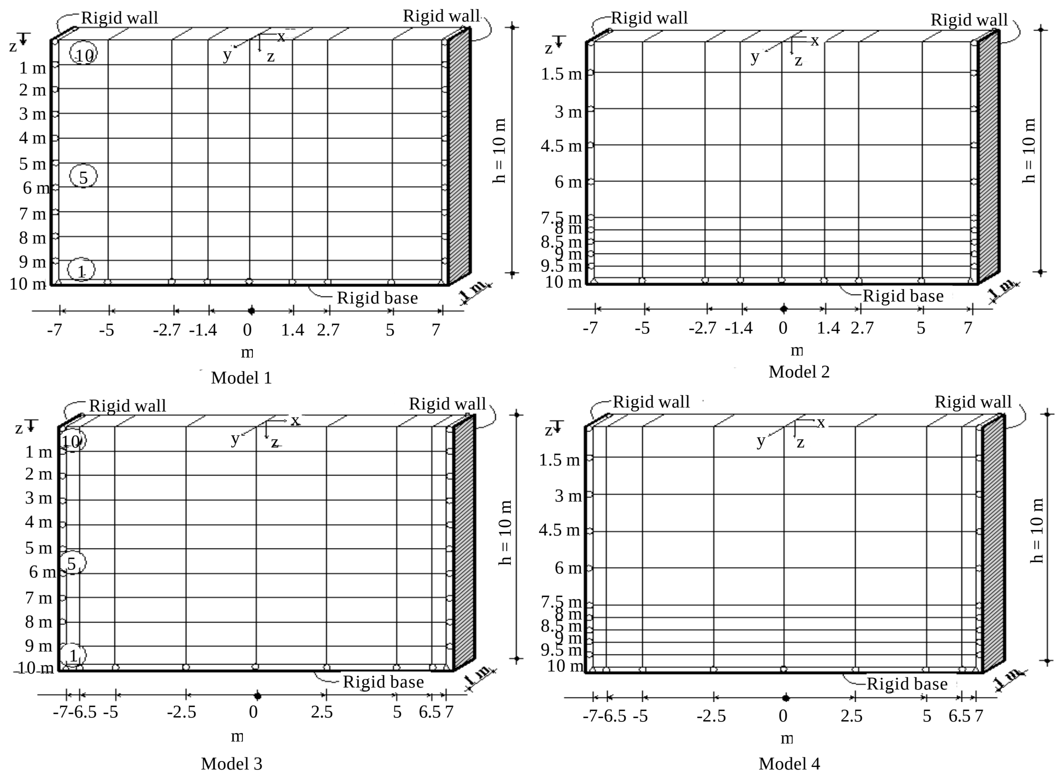

Fig. 5: Finite element meshes considered at rigid analysis of the silo material dynamic pressure distributions obtained by analytical methods and Finite Elements Method (FEM) by using Lagrangian approach is given in Fig. 6

Solution by assuming the silo to be rigid: In this solution, it is assumed that the silo base and walls are rigid and four models of the silo which are shown in Fig. 5 with unit width at diameter length in the direction perpendicular to base motion created by the earthquake, is considered in order to compare the obtained results with the ones obtained from analytical methods.

From this Fig. 6, it is seen that the difference between material dynamic pressure values estimated by finite elements method according to four different models does not exceed 12% at the base, pressures increase in case the finite element mesh is densed about the membrane considering a determined convergence, distribution obtained by the help of Model 1 practically coincides with the one obtained by.

Adapted Housner method, Westergaard method gives larger values at a maximum of 19% from all of the models at the base and the distributions obtained by finite elements method. This situation indicates that finite elements method which uses the element selected by Lagrangian approach can be used effectively as analytical methods at the rigid analysis of silos (Karaca and Durmus, 2000).

Variation of the material dynamic pressure formed during earthquake at the 5 numbered element of Model 1 and Model 3 by finite elements method is given in Fig. 7. As it is seen, variation of material dynamic pressure due to time is the same of earthquake accelerogram (Karaca and Durmus, 2000; Hangai *et al.*, 1983; Durmus, 1997, 1993; Dogangun and Durmus, 1993).

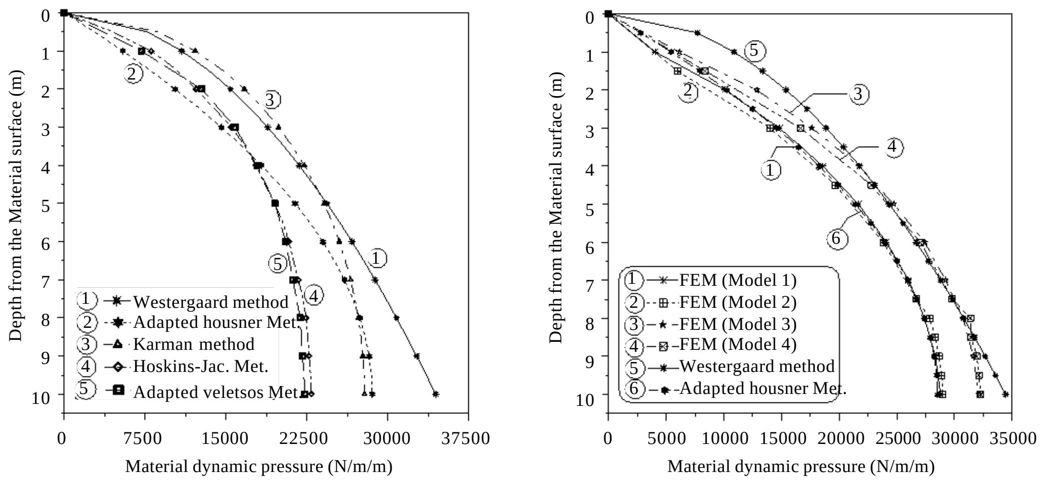

Fig. 6: Material dynamic pressure distributions estimated by analytical and Lagrangian approach

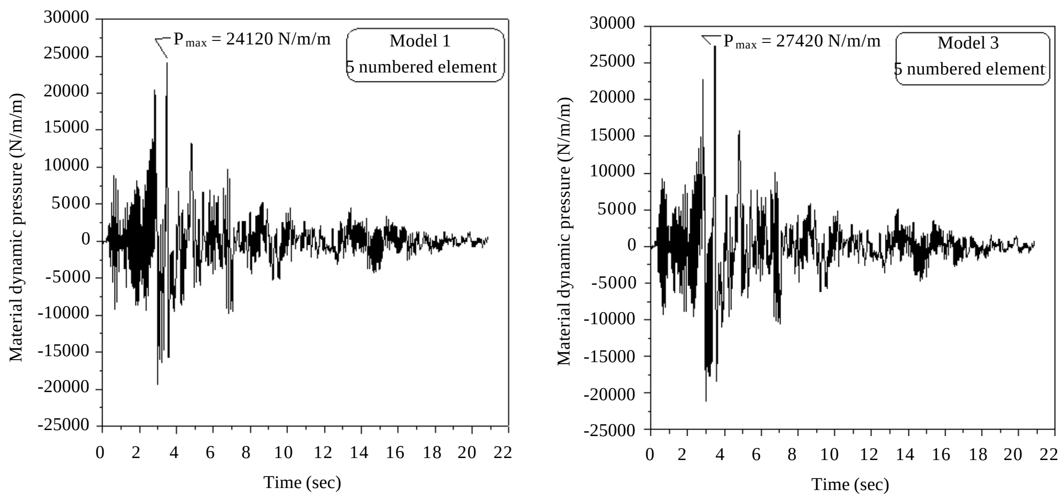

Fig. 7: Variation of material dynamic pressure at the 5 numbered element of silo during earthquake

Flexible solution according to model considering the entirety of the silo

Lagrangian approach: In this solution, wall thickness (t_w) is taken to be 0.75 m. It is assumed that the walls have a prescribed flexibility depending on material and geometric characteristics. The silo model for the analysis by the finite element method by assuming walls to be flexible is given in Fig. 8. In this model, it is assumed that the silo is fixed to the base, so that all degrees of freedom at the silo base are zero. Truss element is used for material's free vertical movement and equal horizontal displacement with wall.

Considering the entirety of the silo, material dynamic pressure distribution, obtained from the analysis realized on the model seen in Fig. 8, is given in Fig. 9 with the pressure distribution obtained for silo model having a unit width with the same element dimensions and the variation of horizontal displacement with the silo membrane thickness is given in Fig. 10.

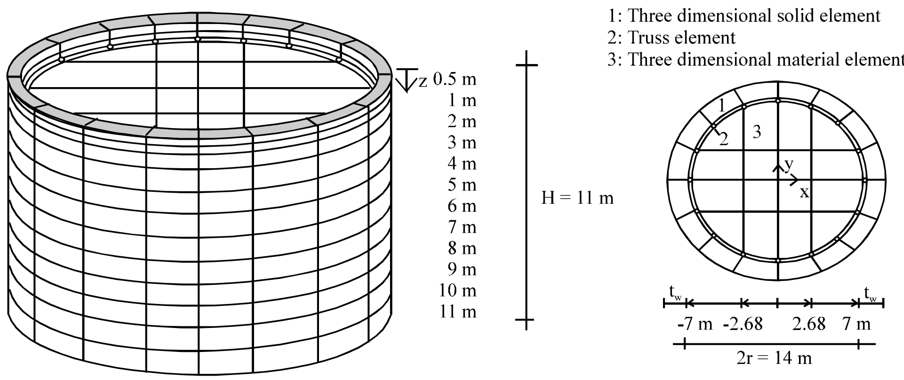

Fig. 8: Silo model used for the entirety of the silo at the solution by Lagrangian approach

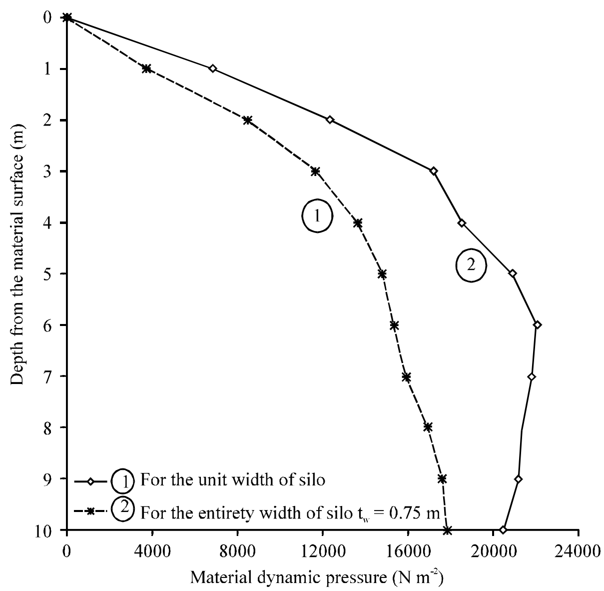

Fig. 9: Material dynamic pressures for the entirety and unit width of the silo

These Fig. 9 and 10 show that material dynamic pressures obtained from the analysis of silo model with unit width, are smaller than the ones obtained from the analysis of the entirety of the silo, such kind of silos designed according to silo analysis with unit width might have remained at insecure side and as the membrane thickness increase, horizontal displacements decrease.

Added mass approach: Finite element mesh considered at added mass approach used in the comparison of displacement and stress values obtained from Lagrangian Approach is given in Fig. 11. The unit weight of the wall which is 25 kN m^{-3} with the use of this method is taken as 57.21 kN m^{-3}. Horizontal displacement distributions obtained according to both of the two methods are given in Fig. 12.

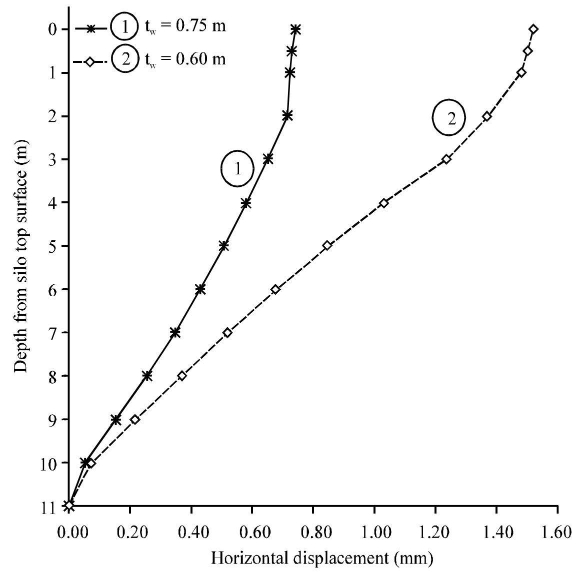

Fig. 10: Variation with membrane thickness of displacement

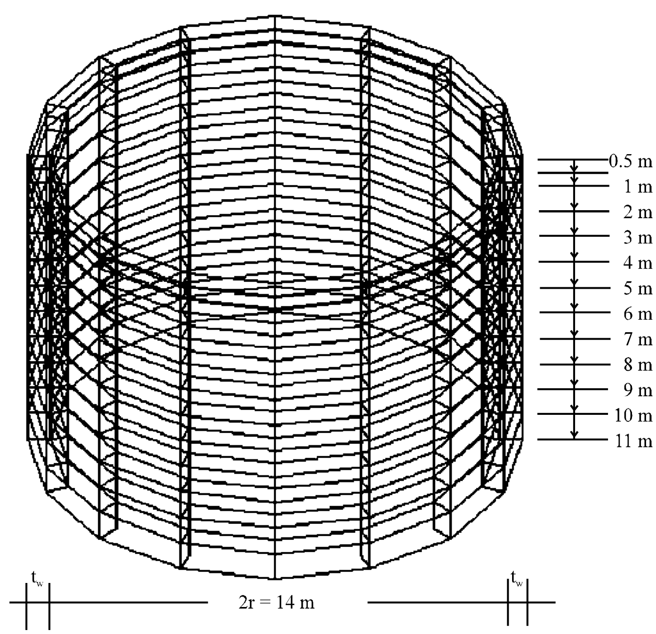

Fig. 11: Finite element mesh used at added mass approach analysis

Normal stress distributions obtained from both of the two methods are given in Fig. 13. It is seen from Fig. 13 that horizontal displacement distributions obtained by Lagrange and Added mass approaches coincide up to half of the height from base, later Lagrangian approach gives 23% greater values at silo top end, stress distributions are similar to each other in form and the σ_z distributions obtained by both of the two methods give very close values to each other.

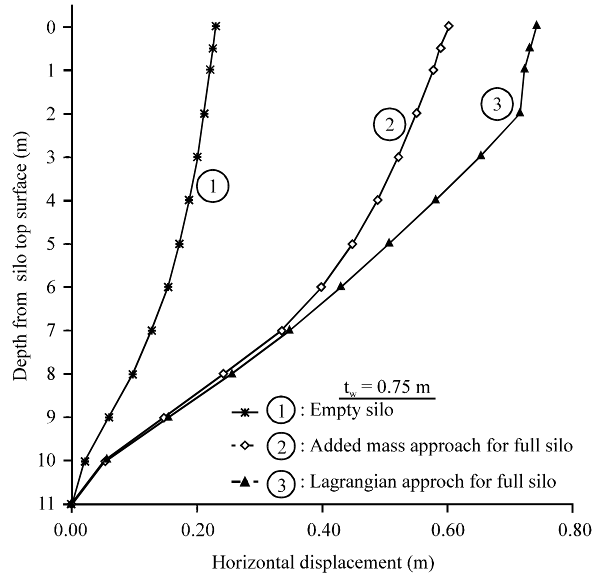

Fig. 12: Horizontal displacement distributions

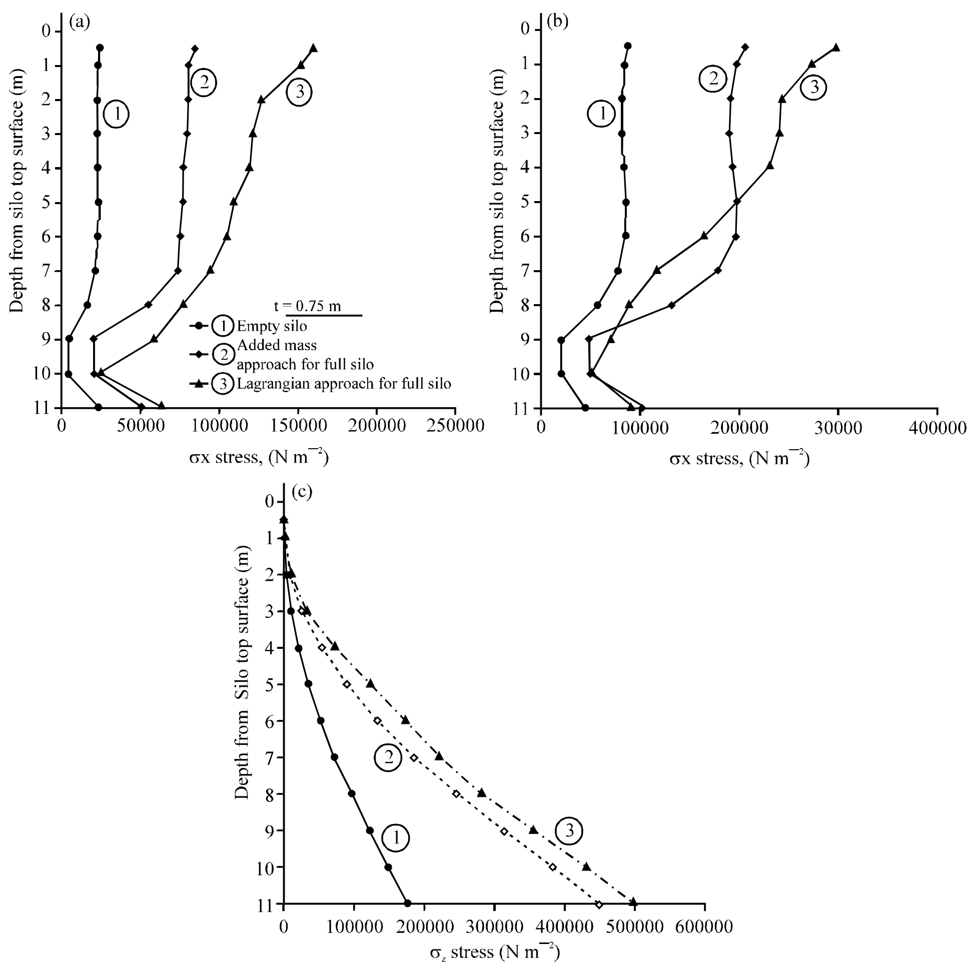

Fig. 13(a-c): Normal stress (σ_x, σ_y, σ_z) distributions obtained by Lagrange and added mass methods

CONCLUSION

Some conclusions and proposals which can be deduced from this study are summarized below:

Material dynamic pressure distributions, obtained from the rigid solution by Lagrangian Approach according to four different models of silo which are subjects to numerical applications, locate between the distributions which are determined by analytical methods. And this demonstrates that finite elements method which uses the element selected by Lagrangian Approach can be used effectively as the analytical methods at the rigid analysis of silos.

According to the results obtained from the flexible analysis of silo, on the contrary for the ones obtained from rigid analysis, material dynamic pressure reaches to maximum at the mid of the approximate depth, not at the silo base, and then the decrease in dynamic pressures.

Material dynamic pressure obtained from the flexible analysis with unit width of the silo are smaller than the ones obtained from the flexible analysis entirety of the silo and this demonstrates that such kind of silos which are designed according to silo analysis with unit width can remain at unsafe side.

It is seen that, stress distributions, obtained by Lagrange and Added Mass Approaches which are used at the flexible analysis of the entirety of silo, are similar to each other in form and σ_z distributions obtained by both of the two methods are very close to each other.

In summary, this study shows that isoparametric element selected by Lagrangian approach can be used efficiently in the earthquake estimation of reinforced concrete cylindrical silos by neglecting the slosh effects in compare with the analytical methods and added mass approach.

These conclusions are drawn from the numerical examples considered in this study. In order to generalize them, theoretical and experimental studies should be made on many models and the results of assemblage of models should be evaluated all together.

NOTATION

a(t)	:	Acceleration of base motion
a_m	:	Maximum acceleration of earth movement
B	:	Strain-displacement matrix
C	:	Damping matrix
E	:	Elasticity modulus of silo
E_v	:	Bulk modulus of material
F_i	:	External load
h	:	Height of the contained material
J	:	Jacobian matrix
K	:	Rigidity matrix
M	:	Mass matrix
M^*	:	Total mass matrix
M_a	:	Added mass matrix
p	:	Dynamic Pressure
p_{xr}, p_{yr}, p_{zr}	:	Rotation pressures
Q	:	Interpolation functions
R	:	General time varying load vector
r	:	Radius of the silo
T	:	Kinetic energy

U	:	Potential energy
u	:	Displacement vector
u_x, u_y, u_z	:	Material displacements along x, y and z axes
ρ	:	Material unit mass
ν	:	Poisson ratio
η_i, η_j, η_k	:	Weight coefficients
ε_v	:	Unit volumetric strain
Ψ_x, Ψ_y, Ψ_z	:	Constraint parameter coefficients for the axes orientations of x, y and z

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