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Computational investigation of the comparative analysis of cylindrical barns subjected to earthquake

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Abstract. The structural behaviors of cylindrical barns as a specific engineering structure have been considered as a complicated computing process. The structure design against the earthquake load, to protect by using the code, is an urgency avoiding unexpected damages. The situation has been subjected to the applied design method if there would be no failure across the construction procedures. The purpose of the current study is to clarify the behaviors of cylindrical reinforced concrete barns through the analytic methods across the mass and Lagrangian approaches through the whole outcomes comparison indicating that the isoparametric element obtained from the Lagrangian approach has been successfully applied in the barns earthquake analysis when the slosh effects have been discarded. The form of stress distributions is equal with s_z closed distributions to one another.

Keywords: analysis of cylindrical barns; earthquake load; added mass; Lagrangian approach; analytical methods

1. Introduction

Reducing all earthquake damages has provoked new solutions to dissipate the earthquake energy. (Shariati *et al*. 2010, Andalib 2011, Bazzaz *et al*. 2012, Toghroli *et al*. 2014, Shariati *et al*. 2015, Andalib *et al*. 2018, Li *et al*. 2017, Khorramian *et al*. 2017). In order to determine the dynamic behaviors of barns, are scarce, unrealistic assumptions of existing studies about this subject like assuming the silo membranes as rigid so disregard the interaction and assuming the earth movements as harmonic, always exist (Gholhaki *et al*. 2008, Bazzaz *et al*. 2015a, Fanaie *et al*. 2015, Zahrai 2015, Shah *et al*. 2016).

It is obvious that doing such kind of studies by considering the silo membrane-material and ground interactions will be more realistic. 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 (Rammerstorfer *et al*. 1990, Doğangün *et al*. 1996, Fanaie *et al*. 2012, Fanaie and Dizaj 2014, Mohammadhassani *et al*. 2014a, Shariati *et al*. 2015, Fanaie *et al*. 2016, Safa *et al*. 2016, Shah *et al*. 2016, Rehab *et al*. 2018, Takin *et al*. 2016).

Regarding the properties of the barns, in this study, isoparametric element which is used at the analytical solutions realized by Lagrangian approximation, is assumed to be an elastic solid whose bulk elastic modulus is equal to the bulk elastic modulus of the material and as the slosh effects created by the earth movement at the granular material contained at the barns are neglected; only the impulse pressure is taken into consideration at analytical methods (Yang *et al*. 2009, Andalib *et al*. 2010, Bazzaz *et al*. 2014, Bazzaz *et al*. 2015b, Khorami *et al*. 2017a, b, Mohammadhassani *et al*. 2014b). And the silo-material interaction is examined according to the East-West component of Erzincan earthquake (1992) with the utilization of Lagrange formulation by adapting the mentioned eight nodded three-dimensional isoparametric element to the structural analysis program (SAPIV) (Bathe

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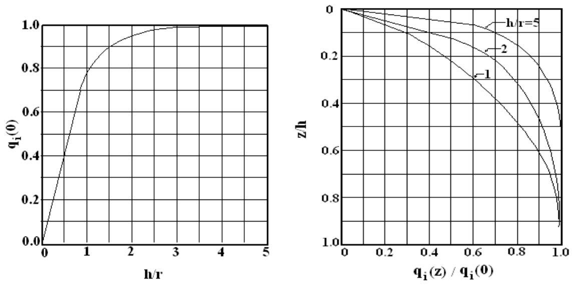
Table 1 Analytical methods used for determining dynamic pressure distribution

Method	Dynamic pressure distribution
Westergaard	$p(z) = 0.875 a_m \rho \sqrt{h\,z}$
Karman	$p(z) = 0.7071 a_m \rho \sqrt{z(2h-z)}$
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	$p(z) = a_m \rho h \sqrt{3}[(z/h) - 0.5(z/h)^2]\tanh[\sqrt{3}r/h]$



(a) (b)

Fig. 1 $q_i(0)$ and $q_i(z)$ values for the estimation of impulse pressure

et al. 1974). 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 barns.

2. Determination of dynamic pressure distributions using some analytical and numerical methods

2.1 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, Adapted Housner and Adapted Veletsos methods considering both effects are adapted to barns in case only the impulse component is considered. The relations used at calculations are given at Table 1. At these relations, a 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 barns (Housner 1957, Keyvanfar *et al*. 2014, Armaghani *et al*. 2016, Khanouki *et al*. 2016, Wang *et al*. 2018, Zahrai *et al*. 2015).

In adapted veletsos method (Priestley *et al*. 1986), the impulse pressure can be estimated from the following equation by obtaining the dimensions $q_i(0)$ value from Fig. 1(a) according to *h/r* ratio and the dimensionless $q_i(z)$ value from the chart of Fig. 1(b)

$$p_i(z) = q_i(z) \cdot a \cdot \rho \cdot r \tag{1}$$

2.2 Numerical methods

2.2.1 Added mass approach

The principle of added mass approach is based on the study made by Westergaard in1931 (Westergaard 1933). 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

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

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

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

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

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

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 barns in which the impulsive effects dominates, by adding the membrane to the finite elements model at the membrane-material interface of the material mass (Hangai *et al*. 1983, Mansouri and Kisi 2015, Mansouri *et al*. 2016).

2.2.2 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:

(1) Neglecting the slosh effects caused by base motion at the granular material in the silo, only the impulsive effects are taken into consideration.
(2) The contained material is assumed to be compac-

table, 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

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

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 $E_{44} = \psi_z E_v$.

$$\begin{aligned} p_{xr} &= E_{22}\ \varepsilon_{\mathrm{xr}} \\ p_{yr} &= E_{33}\ \varepsilon_{\mathrm{yr}} \\ p_{zr} &= E_{44}\ \varepsilon_{\mathrm{zr}} \end{aligned} \tag{8}$$

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

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

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

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

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 (Hangai *et al*. 1983).

2.2.2.1 Utilization of the three dimensional isoparametric element by finite element modeling

In this paper, the selected three dimensional isoparametric element with eight node points and general

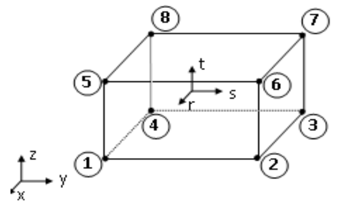


Fig. 2 Isoparametric element

(x, y, z) and local (r, s, t) axes groups which are considered for this element, are given in Fig. 2.

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

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

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

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

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

$$U = \frac{1}{2}\ u^T\ Ku, \qquad T = \frac{1}{2}\ v^T Mv \tag{13}$$

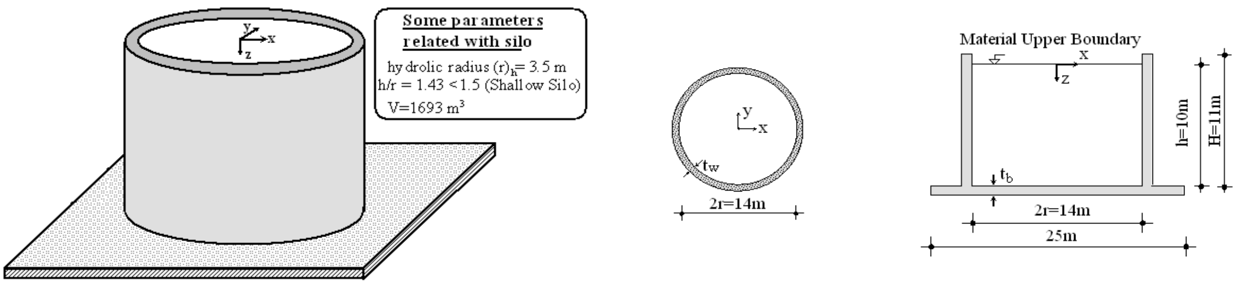
According to finite elements method, it is seen from this equation, as only the impulse effects are taken into consideration in granular material, no term related with surface slosh takes place in potential energy expression. If the mentioned energy expressions are replaced in the Lagrange equation of number (Hangai *et al*. 1983), the motion equation of the undamped system can be obtained as

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

3. Silo application

3.1 General

Here, adapting the three dimensional isoparametric element whose formulation was given before, to the structural analysis program SAPIV (Bathe *et al*. 1974), such that the 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 (Fig. 4), In this computation, the bulk modulus, Poisson ratio and the unit mass of the



(a) Silo (b) Plan (c) Vertical section

Fig. 3 Silo plan and vertical section

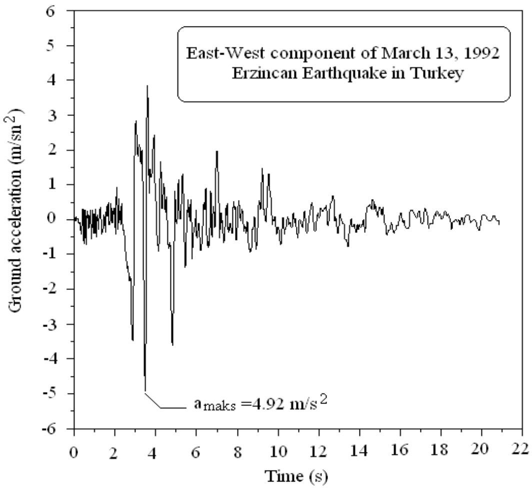


Fig. 4 Earthquake acceleration of the March 13, 1992 Erzincan Earthquake in Turkey

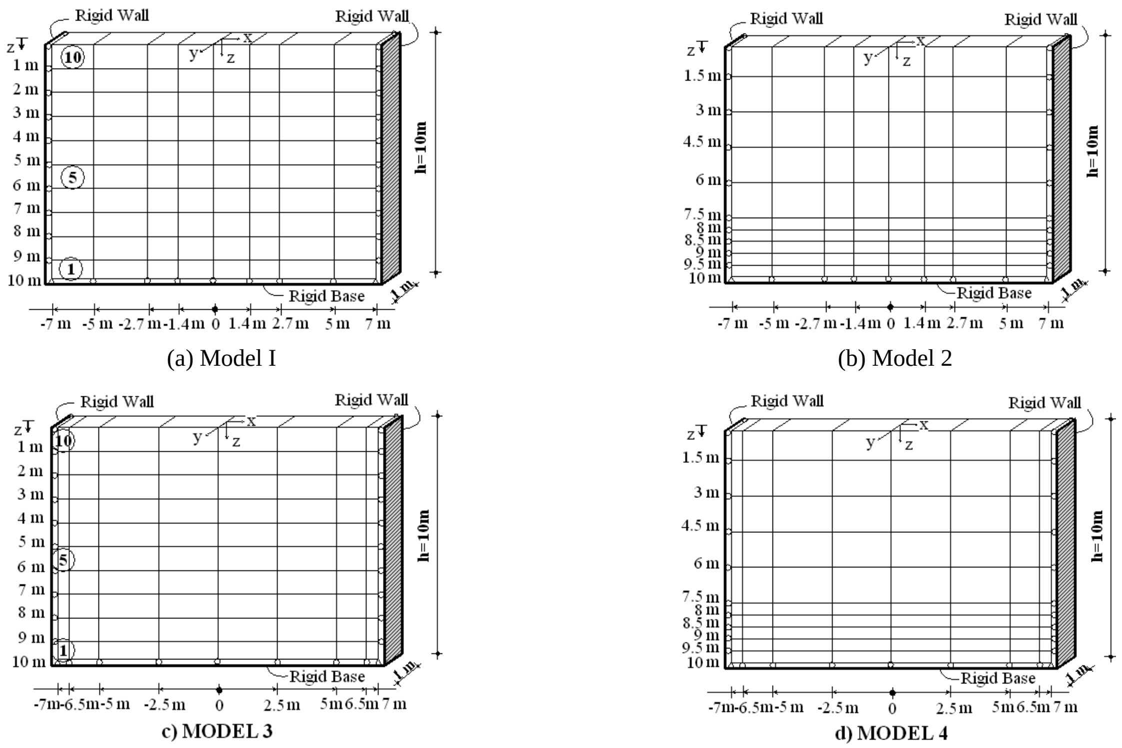
contained wheat is taken as E_v = 4,167×10^7 N/m^2, ν = 0.30 and ρ = 800 kg/m^3, respectively and unit mass, Poisson ratio and elasticity modulus of silo wall material is taken as ρ = 2500 kg/m^3, ν = 0.2 and E = 285×10^8 N/m^2, respectively.

3.2 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.

Material dynamic pressure distributions obtained by analytical methods and finite elements method (FEM) by using Lagrangian approach is given in Fig. 6.

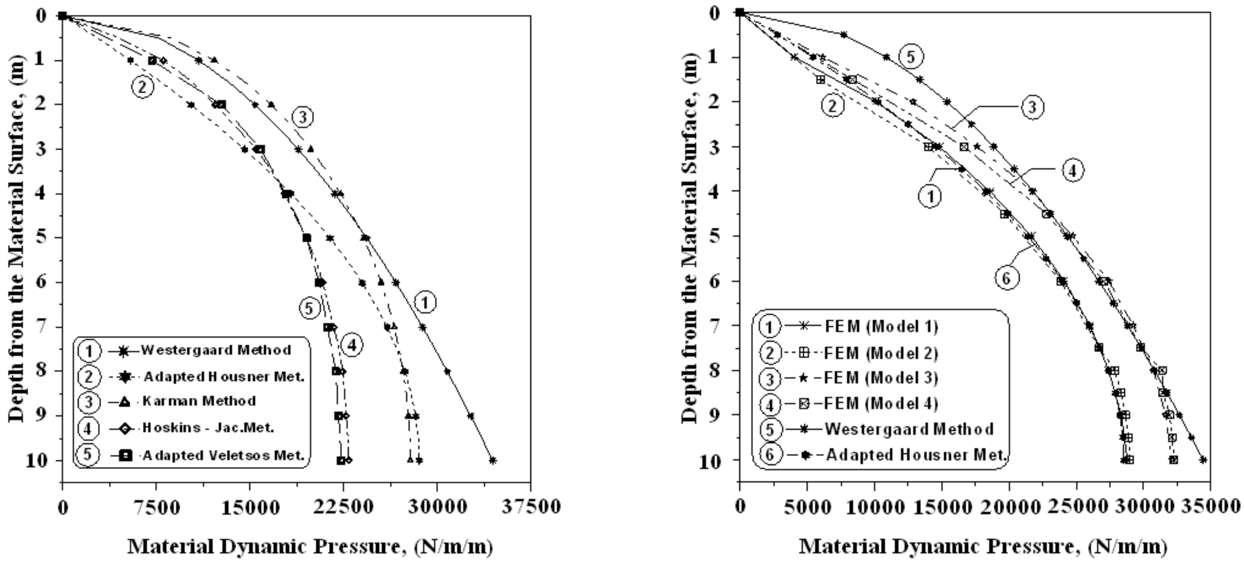
From this figure it is seen that the difference between material dynamic pressure values estimated by finite



(a) Model I (b) Model 2

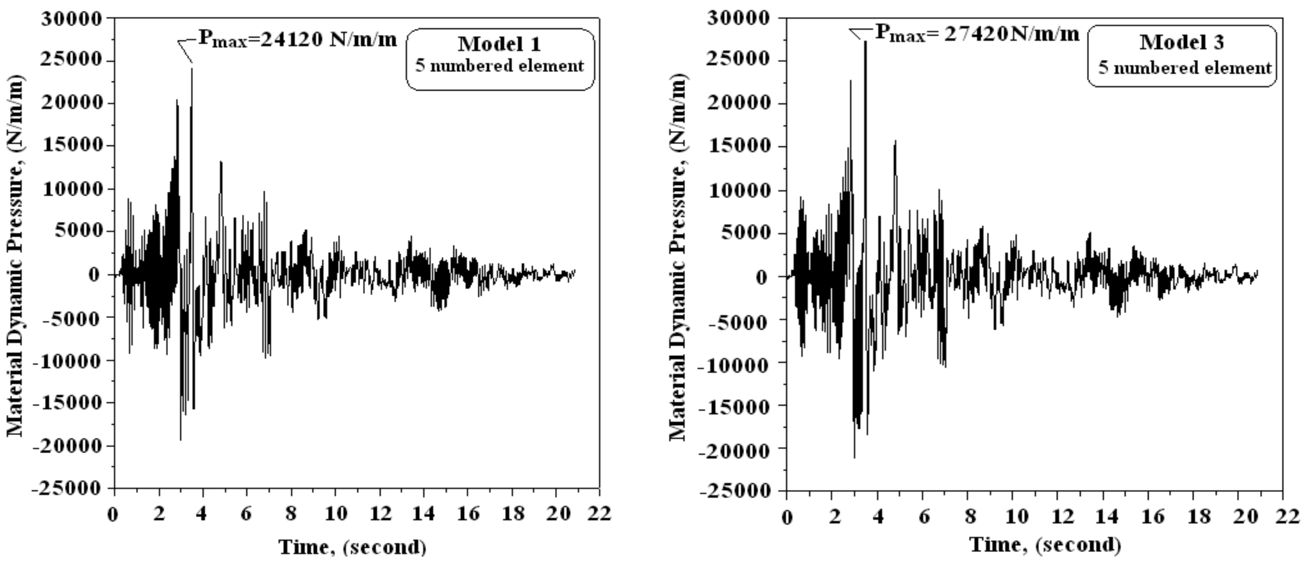
(c) Model 3 (d) Model 4

Fig. 5 Finite element meshes considered at rigid analysis of the silo



(a) (b)

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



(a) (b)

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

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 he 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 according to four models are close to the ones obtained by Westergaard and Adapted Housner analytical methods. 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 barns.

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. Looking at these details the deformation of materials can be realized and can be concluded that variation of material dynamic pressure due to time is the same of earthquake ccelogram (Hangai *et al*. 1983).

3.3 Flexible solution according to model considering the entirety of the silo

3.3.1 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

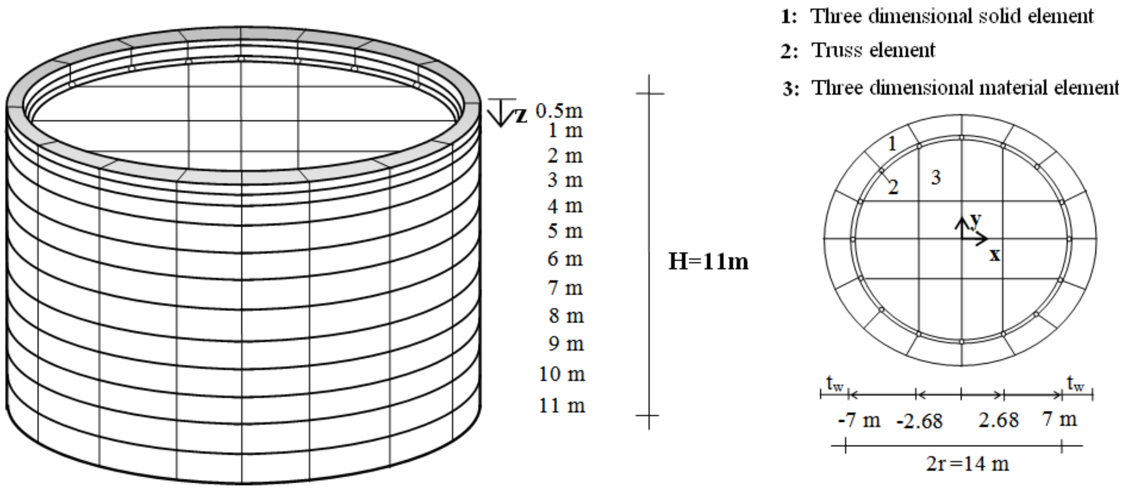


Fig. 8 Silo model used for the entirety of the silo at the solution by Lagrangian approach

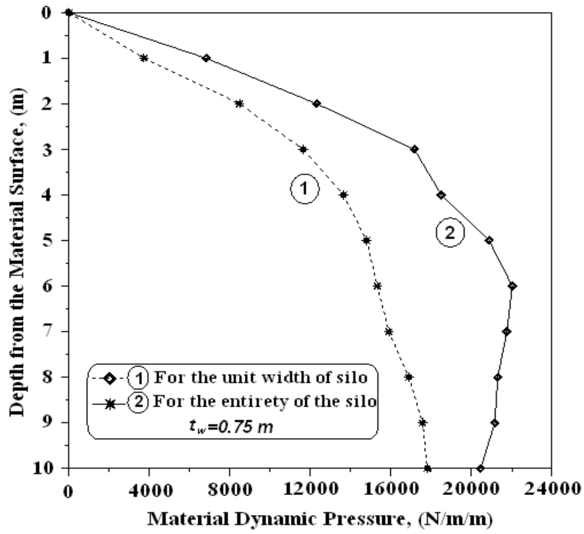


Fig. 9 Material dynamic pressures for the entirety and the unit width of the silo

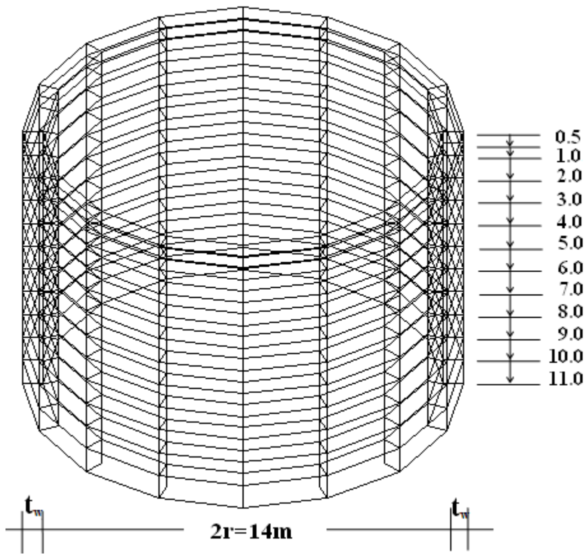


Fig. 11 Finite element mesh used at added mass approach analysis

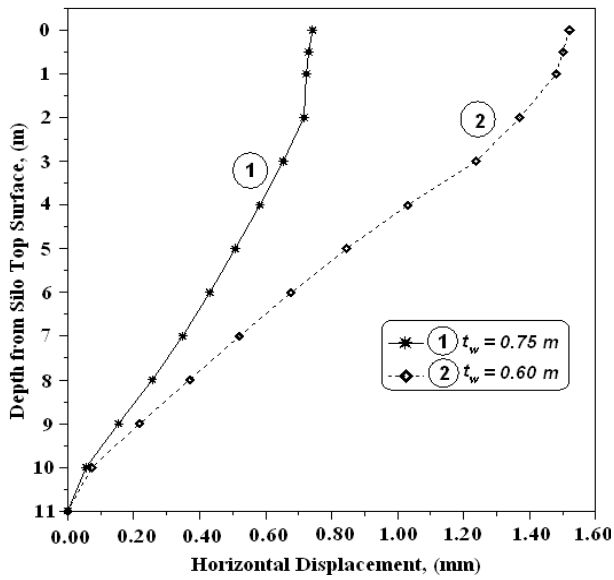


Fig. 10 Variation with membrane thickness of displacement

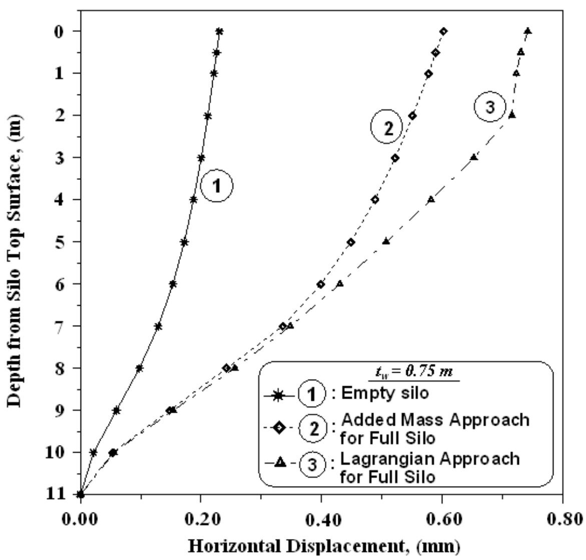
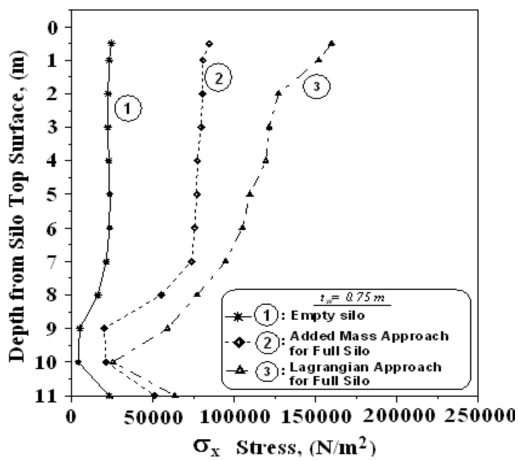
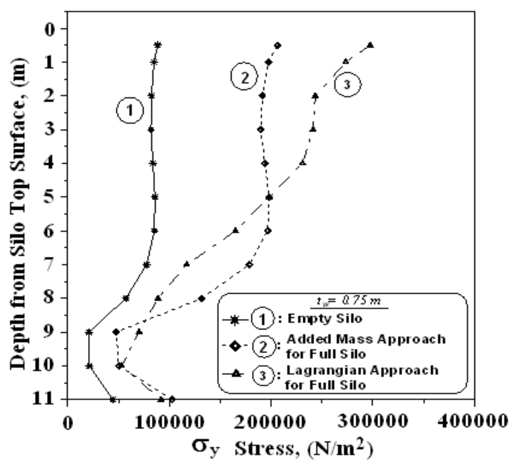


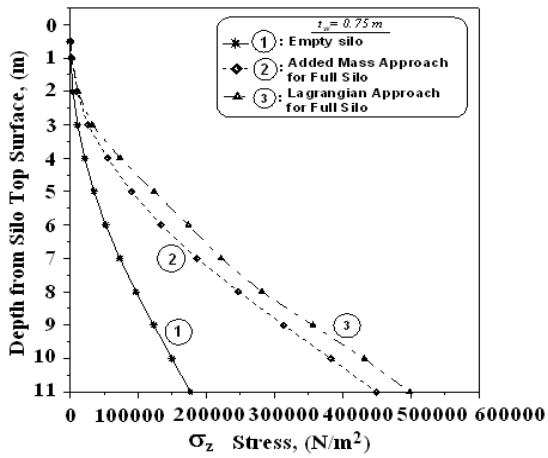
Fig. 12 Horizontal displacement distributions



(a)



(b)



(c)

Fig. 13 Normal stress (σ_x, σ_y, σ_z) distributions obtained by lagrange and added mass methods

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.

These figures 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 barns designed according to silo analysis with unit width might have remained at insecure side and as the membrane thickness increase, horizontal displacements decrease.

3.3.2 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.

Normal stress distributions obtained from both of the two methods are given in Fig. 13. It is seen from these igures 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.

4. Conclusions

It is concluded from this research, 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 barns. 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 barns 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.

To sum up, the current study has confirmed that the iso-parametric element gained from the Lagrangian approach has been effectively used in the earthquake reinforced concrete cylindrical barns' analysis discarding the slosh impacts when the results have been compared to both the analytic methods and added mass approach. The conclusion has been derived from the numerical examples of the current study. In order to generalize the results, theoretical and experimental studies have been done on few models in which all the assemblage results might be evaluated altogether.

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CC

Nomenclature

$a(t)$	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