Seismic Behavior of Reinforced Concrete Silos Considering Granular Material-Structure Interaction

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Abstract

Silos are structures that are used for storing different types of granular materials. Due to nonlinearity of reinforced concrete walls of silo and incrementally nonlinear behavior of granular material, overall seismic behavior of reinforced concrete silos is very complex, in this paper we have used ABAQUS finite element package for modeling of earthquake effect on a reinforced concrete silo, reinforced concrete silo walls are modeled by shell elements and their nonlinear behavior is considered by concrete damaged plasticity model, seismic behavior of granular material inside silo is highly nonlinear and requires a complex nonlinear description of the granular material, the behavior of granular material is incrementally nonlinear even at low strains. The hypoplasticity theory describes the stress rate as a function of stress, strain rate and void ratio. It can model the nonlinear and inelastic behavior of granular materials due to its rate-type formulation. Granular material inside silo is modeled by solid elements and its nonlinear behavior is considered with a hypoplastic constitutive model, for modeling of interaction between silo walls and granular material, surface to surface contact with coulomb friction law is considered between silo walls and granular material. After modeling, the behavior of reinforced concrete silo under earthquake excitation is compared with a model without considering granular material-structure interaction.

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Keywords: Reinforced Concrete Silo, Seismic behavior, Concrete Damaged Plasticity, Hypoplasticity, Surface to Surface Contact

1. INTRODUCTION

Silos are structures which are used for storing granular materials. In common silo design based on ACI 313 (1997) wall pressures from earthquake effects are not taken into account and the system is reduced to

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a cantilever beam with several point masses being situated on top of each other to calculate appropriate additional static horizontal loads, 80 percent of actual mass of stored material should be considered as effective mass for calculating masses. But Eurocode 8 part 4 (2003) considers additional horizontal pressures resulting from earthquake effects with simple relations, there are few researches that have tried to investigate the behavior of silos under earthquake loading with considering granular material-structure interaction, Braun and Ebil (1995), Meskouris and Holler (2006) have tried to investigate the behavior of silos under earthquake loading, they have used different hypoplastic models for modeling of granular material inside silo, but in all of these researches the behavior of silo wall is elastic, in this paper we have tried to compare the seismic behavior of a reinforced concrete silo with and without considering granular material-structure interaction. The hypoplasticity theory was used for modeling of granular material behavior. The nonlinear behavior of silo walls was modeled by concrete damaged plasticity model (Lubliner 1989; Lee and Fenves 1998).

2. MODELING OF GRANULAR MATERIAL BEHAVIOR

Hypoplasticity is a class of incrementally nonlinear constitutive models that are developed to predict the behavior of soils. The basic structure of the hypoplastic models has been developed during 1990’s at the University of Karlsruhe. The hypoplastic material laws describe the stress rate as a function of stress, strain rate and void ratio and are well for modeling of cohesionless, granular materials. VonWolffersdorff’s hypoplastic constitutive model (1996) can model the nonlinear behavior of granular materials very well but it has some drawbacks for application to cyclic loadings. The most significant shortcoming of this model is an excessive accumulation of deformations for small stress cycles that is called ratcheting. To solve this significant shortcoming, Niemunis and Herle (1997) presented an extension for VonWolffersdorff’s constitutive model by introducing the intergranular strain concept. In this paper VonWolffersdorff’s hypoplastic constitutive model with intergranular strain extension was used for modeling of granular material inside silo. VonWolffersdorff’s hypoplastic model requires eight material parameters. $\phi_c$ is critical friction angle, $e_{c,0}$ is the conventional maximum void ratio, $e_{d,0}$ is conventional minimum void ratio, $e_{i,0}$ is maximum possible void ratio at zero pressure. $h_s$ is granular hardness that is a pressure-independent stiffness, $n$ is an exponent, appearing in the power law for proportional compression. $\alpha$ and $\beta$ are exponents to be calculated from the triaxial peak friction angle. Five additional material parameters are required for the intergranular strain extension. $R$, $m_T$, $m_R$, $\beta_r$ and $\chi$ are intergranular strain parameters, The parameter $R$ is maximum intergranular strain, factors $m_R$ and $m_T$ are the increase factors of stiffness for each load reversal in the 180 degrees and 90 degrees directions compared to the stiffness in the 0 degrees direction. The parameters $\chi$ and $\beta_r$ are used for smoothing of stiffness change.

3. MODELING OF REINFORCED CONCRETE BEHAVIOR

The concrete damaged plasticity model was used for modeling of silo walls. This model is a continuum, plasticity-based, damage model for concrete. It assumes that the main two failure mechanisms are tensile cracking and compressive crushing of the concrete material. The model assumes that the uniaxial tensile and compressive response of concrete is characterized by damaged plasticity. Under uniaxial tension the stress-strain response follows a linear elastic relationship until the value of the failure stress, $\sigma_{f,t}$, is reached. The failure stress corresponds to the onset of micro-cracking in the concrete material. Beyond the failure stress the formation of micro-cracks is represented macroscopically with a softening stress-strain response. When the concrete is unloaded from any point on the strain softening branch of the stress-strain curves, the unloading response is weakened and the elastic stiffness of the
material appears to be degraded. The degradation of the elastic stiffness is characterized by two damage variables, $d_t$ and $d_c$, which are assumed to be functions of the plastic strains. The damage variables can take values from zero, representing the undamaged material, to one, which represents total loss of strength. Stiffness recovery is an important aspect of the mechanical response of concrete under cyclic loading. The experimental observations in materials like concrete show that the compressive stiffness is recovered upon crack closure as the load changes from tension to compression. On the other hand, the tensile stiffness is not recovered as the load changes from compression to tension once crushing micro-cracks have developed. In this modeling approach, the concrete behavior is considered independently of the rebar. Effects associated with the rebar/concrete interface, such as bond slip and dowel action, are modeled approximately by introducing some “tension stiffening” into the concrete modeling to simulate load transfer across cracks through the rebar. Plasticity parameters of concrete damaged plasticity model include, dilation angle, flow potential eccentricity which implies that the material has almost the same dilation angle over a wide range of confining pressure stress values. Increasing the value of flow potential eccentricity provides more curvature to the flow potential, implying that the dilation angle increases more rapidly as the confining pressure decreases, $\sigma_{bo}/\sigma_{c0}$, which is the ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress, $K$ which is the ratio of the second stress invariant on the tensile meridian, to that on the compressive meridian, at initial yield for any given value of the pressure invariant, such that the maximum principal stress is negative.

4. MODELING

In this paper we have considered two models of a reinforced concrete silo. The silo dimensions are presented in table 1. In the first model the granular material inside silo was modeled by VonWolffersdorff’s hypoplastic constitutive model with intergranular strain extension. The granular material inside silo was considered to be sand with mass density equal to 1500 kg/m$^3$. 8-noded solid element C3D8R was used for modeling of granular material. The parameters of hypoplastic model are presented in tables 2 and 3. In the second model the effect of granular material-structure interaction was neglected and 80 percent of the mass of granular material inside silo was applied to the silo walls uniformly, the silo pressures and vertical friction loads under static conditions were also applied to silo walls based on ACI 313 (1997). In both models the concrete damaged plasticity model in ABAQUS (2009) was used for modeling of reinforced concrete silo walls, 4-noded shell element S4R was used for modeling of silo walls and silo bottom. Silo bottom was considered to behave elastically, circumferential and meridional rebars were defined as layers of uniaxial reinforcement in shell elements, rebars were assumed to have yield stress equal to 400 Mpa, ultimate tensile stress equal to 600 Mpa and ultimate tensile strain equal to 0.14, Modulus of elasticity of rebars was considered equal to $2\times10^5$ Mpa. For decreasing the computation time only half of silo was modeled and symmetric boundary conditions were used at the center of silo and granular material. The finite element mesh of silo models and material inside first model is shown in figure 1. The plasticity parameters of concrete damaged plasticity model considered for modeling of silo walls are presented in table 4. The uniaxial tension and compression stress-strain curves of concrete and the uniaxial tension and compression damage variables, $d_t$ and $d_c$ that are defined as a function of cracking and inelastic (crushing) strains are presented in figure 2.

In the first model the interface between silo walls, silo bottom and material inside silo was modeled by the “contact pair” algorithm provided in ABAQUS. ABAQUS standard uses pure master-slave contact. In pure master-slave contact one of the two surfaces comprising a contact pair is assigned as the master surface, and the other as the slave one. Coulomb’s friction law was used for the modeling of friction. The friction coefficient was set to be 0.4. For the contact constraint, the penalty contact algorithm was
considered, which is similar to introducing stiff springs between the two surfaces to prevent them from penetration.

Table 1: Dimensions of the silo

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Silo height (m)</td>
<td>20</td>
</tr>
<tr>
<td>Internal diameter (m)</td>
<td>10</td>
</tr>
<tr>
<td>Silo wall thickness (m)</td>
<td>0.3</td>
</tr>
<tr>
<td>Meridional reinforcement</td>
<td>2 layers of Φ 18 @ 200 mm</td>
</tr>
<tr>
<td>Circumferential reinforcement</td>
<td>2 layers of Φ 18 @ 150 mm</td>
</tr>
</tbody>
</table>

Table 2: The parameters of VonWolfersdorff hypoplastic model

<table>
<thead>
<tr>
<th>Granular material</th>
<th>φc</th>
<th>h_{0} (N/m²)</th>
<th>n</th>
<th>e_{d0}</th>
<th>ec0</th>
<th>e_{i0}</th>
<th>α</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hochstetten sand</td>
<td>33</td>
<td>1500×10^6</td>
<td>0.28</td>
<td>0.55</td>
<td>0.95</td>
<td>1.05</td>
<td>0.25</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 3: Additional parameters for intergranular strain concept

<table>
<thead>
<tr>
<th>R</th>
<th>mR</th>
<th>mT</th>
<th>βr</th>
<th>χ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>5</td>
<td>2</td>
<td>0.5</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 4: Plasticity parameters of concrete

<table>
<thead>
<tr>
<th>Dilation angle</th>
<th>Flow potential eccentricity</th>
<th>σ_{00}/σ_{c0}</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.1</td>
<td>1.16</td>
<td>0.667</td>
</tr>
</tbody>
</table>

5. ANALYTICAL PROCEDURE

The analysis includes two steps. Theses steps were performed by ABAQUS standard, which uses an implicit solver, gravity loads in the first model and gravity loads, silo pressures and vertical friction loads under static conditions in the second model were applied statically in the first step. In the first model the surfaces on the silo wall and silo bottom were considered as master surface and the external surfaces on the granular material that are in contact with silo wall and silo bottom were considered as slave surface. Hypoplastic material with intergranular strain extension implemented in the form of UMAT by Professor Niemunis for ABAQUS standard was used for modeling of granular material inside silo. After the first step earthquake excitation was applied to the silo. Implicit dynamic analysis in ABAQUS standard was used for applying earthquake excitation. The earthquake accelerogram applied to the models is shown in figure 3. The PGA value of accelerogram is 0.4g.
4-noded shell elements (S4R) used in both models
8-noded solid elements (C3D8R) used in the first model

Figure 1: The Finite element mesh of silo models and granular material inside the first model

Figure 2: Uniaxial tension and compression stress-strain curves of concrete and the uniaxial tension and compression damage variables, \( d_t \) and \( d_c \).
6. ANALITICAL RESULTS

For comparison, the time history of base shear is plotted for two models in figure 4. Base shear is computed considering the whole silo. Due to high distortion of granular material at the top of silo in the first model which considers granular material-structure interaction convergence problem has occurred in the middle of analysis. As shown in figure 4 the maximum base shear in the second model is 12237 KN while maximum base shear in the first model is 10929.4 KN, therefore maximum value of base shear in model 2 is greater than maximum value of base shear in model 1. Propagation of tension damage in silo walls is shown in figure 5 for both models. As shown is this figure tension damage in the first model has only occurred in the lowest part of silo walls but in the second model that the effect of granular material-structure interaction is not considered tension damage has propagated in the height of silo.

Cracking initiates at points where tensile equivalent plastic strain is greater than zero and maximum principal plastic strain is positive. Direction of the vector normal to the crack plane is assumed to be parallel to the direction of the maximum principal plastic strain.
Figure 5: Propagation of tension damage with respect to time in silo walls
The direction of maximum principal plastic strain in parts that tensile equivalent plastic strain is greater than zero is plotted in figure 6 at the $t=2.97$ sec for both models. As shown in this figure, flexural cracks have developed in the lowest part of silo walls near the symmetry plane in both models and by moving around perimeter the cracks developed in the lowest part of silo walls transform to shear cracks, in the second model shear cracks have developed in the height of silo.

7. CONCLUSIONS

In this paper we have tried to see the effect of granular material-structure interaction in seismic behavior of reinforced concrete silos, the results show that considering the effective mass of granular material equal to 80 percent of granular material total mass results in more severe tension damage in silo walls. In both models flexural cracks have developed in the lowest part of silo walls near the symmetry plane and by moving around perimeter the cracks developed in the lowest part of silo walls transform to shear cracks, in addition in the second model that granular material-structure interaction is neglected shear cracks have developed in the height of silo.

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References


