The Effects of Soil-Foundation-Structure Interaction on the Dynamic Response of Delijan Cement-Storage Silo under Earthquake Loading

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ABSTRACT

In this study the influence of foundation-soil-structure interaction on the non-linear dynamic behavior of a cement-storage silo structure is investigated. Delijan's silo is studied as a case which is a 3-cell type silo newly built cement storage structure near the city of Delijan in Isfahan province in the central part of Iran. Silo structure has been modeled using solid45, cubic type 3D-finite elements in ANSYS computer program[1]. The Silo's foundation and also the underlying soil have been modeled using non-linear elasto-plastic type solid65 3D-finite elements in ANSYS program[1]. Actual soil profile is modeled which was Type I in seismic design code 2800 of Iran[4]. To perform an extensive parametric study on the soil type effects, the soil type is also varied from stiff (type I) to softer soil (type IV) according to the seismic design code2800. The effects of structure-soil-structure interaction (SSSI) on the silo's response are also studied during the course of this research work. Both near-field and far-field soil effects are considered. The results show that inclusion of soil-structure interaction may have a considerable effect on the dynamic response of the silo structure. In particular, the SSI is shown to have more significant effect on the base-shear and overturning response of silo structure supported on softer soil (type IV). It is also observed that the softer soil as Type IV may increase the acceleration response of the silo while reducing the maximum overturning moments at the base. However, the effect on the base shear response is observed to be somewhat mixed depending on the EQ-record and the direction of seismic wave. It is also observed that SSSI effect might increase the maximum base shear response at silo's base while reducing the peak overturning moment and the maximum displacement values.

KEYWORDS: Delijan's Cement Silo, Soil-Foundation-Structure interaction, Structure-Soil-Structure Interaction, Non-linear Dynamic Response

INTRODUCTION

In the recent decades, the importance of structure-soil-structure interaction on dynamic response of key structures such as silos, storage tanks, offshore structures and also other types of structures have been presented in various studies such as works by Emami Azadi[6,7,8,9], Godbole et al,[10], Holler *et al.* [11,24,26], Li *et al.* [12], Livaoglu et al [13,14], Maharaj *et al.* [17], Mangal *et al.* [18], Mylonakis *et al.* [19], Naserdin[20], Novak *et al.* [21], Oner *et al.* [22] Wolf *et al.* [28,29,30] and Yang *et al.* [31] and Yue *et al.* [32]. In particular, the SSI effect on the silo structures partly have been addressed in the recent studies[11] but the effects of SSSI have not been modeled. Also, in most of these studies,the influence of varying ground conditions (i.e. seismicity) has not been considered. In the current study, the effect of seismic records on the silo's dynamic behavior has been taken into account. The structure's dynamic response is also studied for both the case of empty silo and also silo filled with cement material.

Most of the previous studies use either lumped spring type models or 2D and 3D type continuum mechanics models. In particular, Winkler spring type models, single or double cone models have also been used recently to idealize the foundation-soil interaction [28,29,30]. Also associated or non-associated full plasticity models have been recently used to model foundation-soil interaction [6,8,9]. These models often use soil softening or hardening rules. In the current study, Drucker-Prager constitutive model [1,5] is applied for interaction between the silo's large and thick plate type mat foundation with the supporting soil.

In other previous studies, infinite type elements, boundary elements, cell-elements and semi-infinite elements have also been used to model the far-field of soil [28,29,30]. Method of finite element has been used in most of foundation-soil interaction studies to model the soil medium see for e.g. [6,7,8,16,22,28,29,30]. Although this approach has some shortcomings in soil far-field modeling, but nonetheless, it is capable of modeling the whole system of structure-foundation-soil and hence performing an integrated analysis of the system. Sub-structure method has been also applied to analyze soil-structure interaction problem in finite element codes such as ANSYS [1]. Also interface analysis approach was earlier used in some other geotechnical finite element analysis programs such as PLAXIS [23] for soil-structure interaction problems.

For seismic analysis of the system, Elcentro, Tabas and Naghan earthquake records [25] have been used to represent characteristics of three different seismic events. Although, the site specific seismic input motion was not generated here due to limited scope of the research but the effects of varying ground conditions have been studied together with the obtained soil profilesin the Delijan silo's building site [24].

THEORETICAL BACKGROUND DYNAMIC SYSTEM MODELING

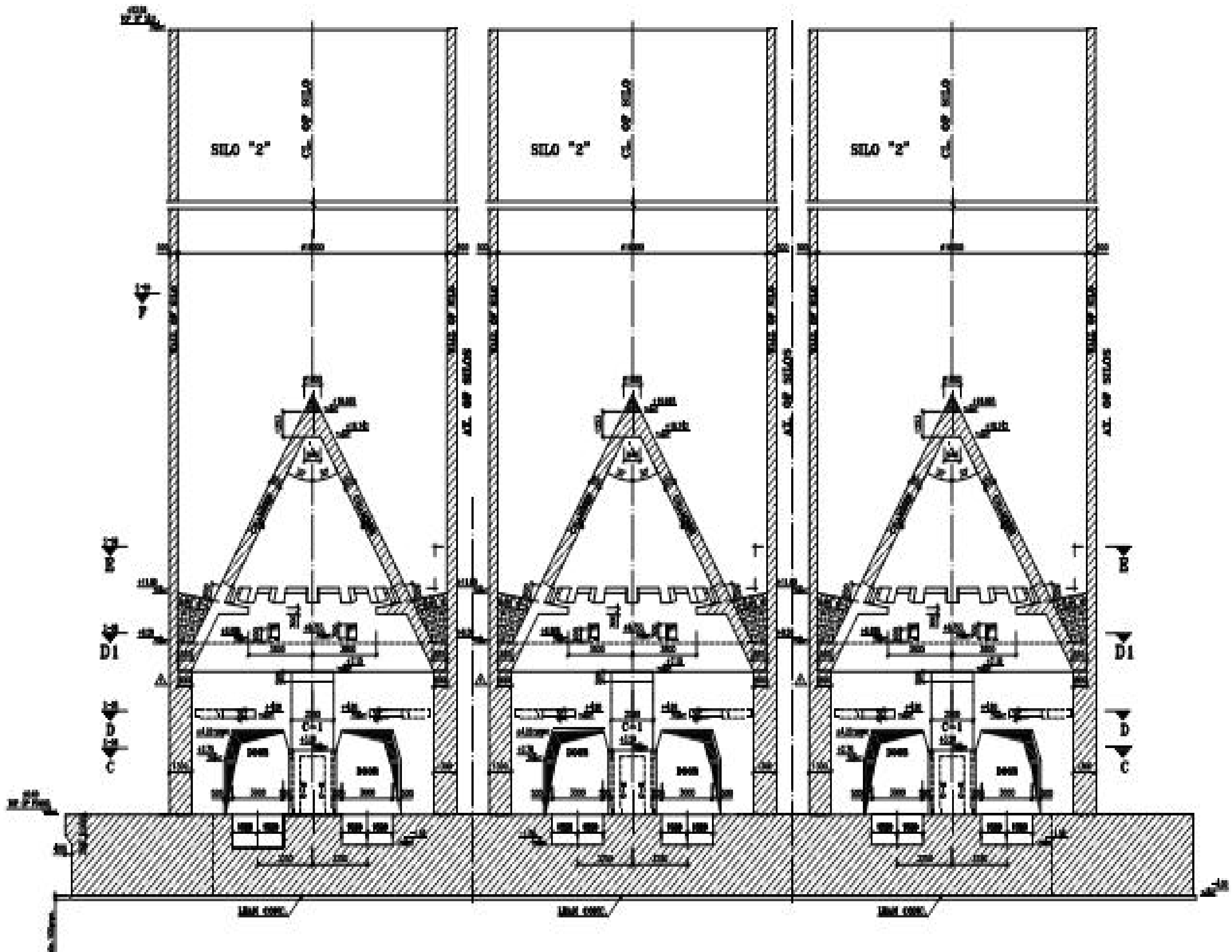
The dynamic equation of motion of system in an incremental form can be written as:

$$\Delta F_i + \Delta F_d + \Delta F_r = \Delta F_e \quad (1)$$

where ΔF_i, ΔF_r, ΔF_d and ΔF_e represent the inertia force, the restoring force, the hysteretic damping force and the excitation force increments, respectively. A consistent mass matrix [M] approach is used to model the silo system mass and to compute the inertia component ΔF_i. A tangent stiffness matrix [K_t] approach was adopted to compute the restoring force component ΔF_r. A Rayleigh (proportional) system damping matrix [C] method was applied to compute the damping force component ΔF_d[3,24]. Each increment of any force component in Eq.1 above can then be computed from the following general equation[24]:

$$\Delta F(t) = F(t + \Delta t) - F(t) \tag{2}$$

here, each time increment size is taken so that the stability and accuracy criteria in the adopted numerical solution algorithm which is discussed in the following subsection are satisfied. [3,24].



Section A-A

Figure 1: A Cross-sectional detail of Delijan's cement storage Silo Structure and its Foundation

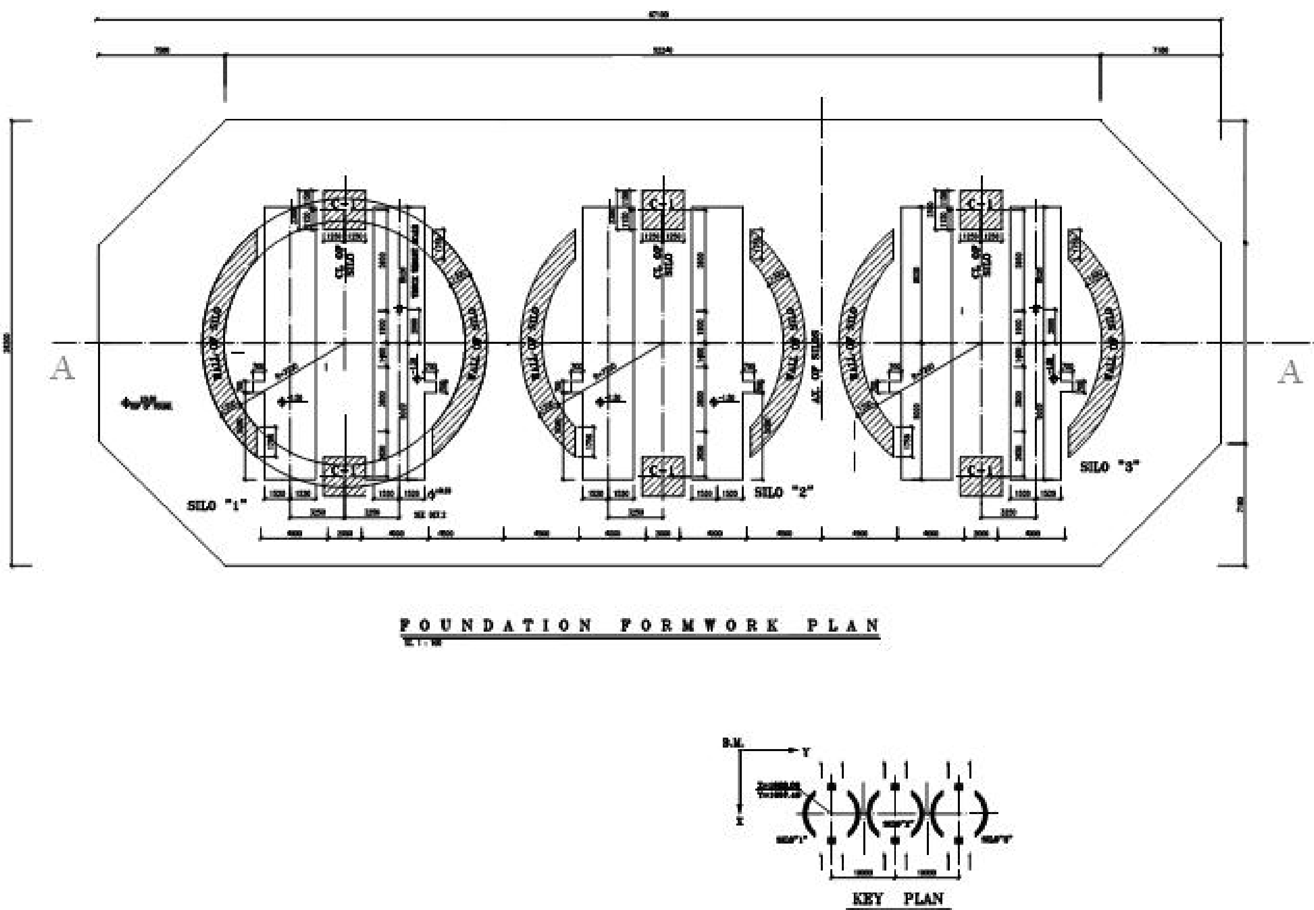


Figure 2: A Plan view of Delijan's Silo Structure and its Foundation

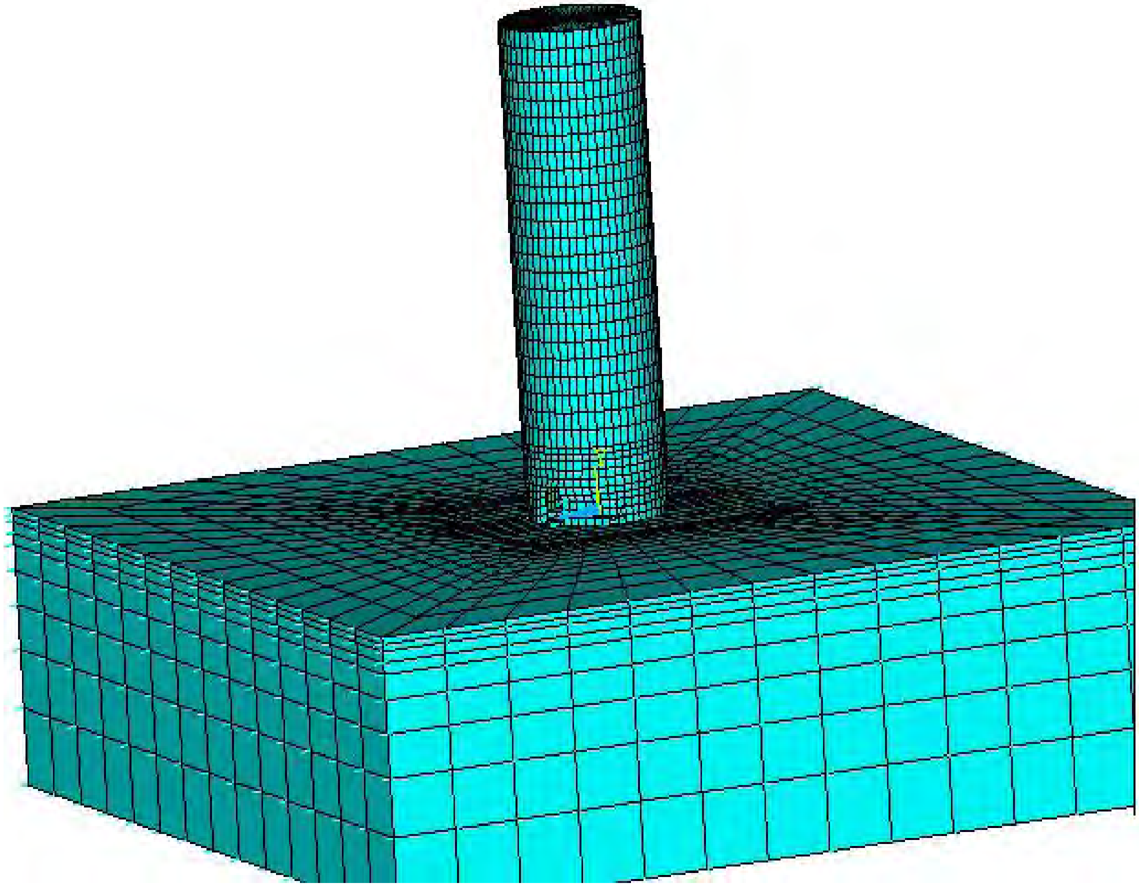


Figure 3: A Finite Element Model of Single Cell of Delijan's Silo Structure and its Foundation

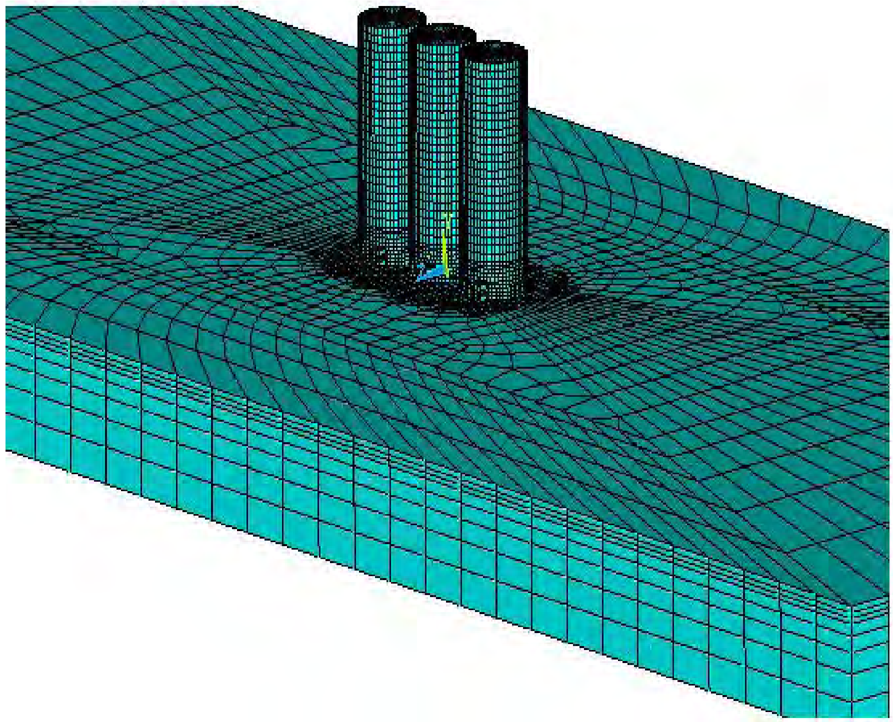


Figure 4: A Finite Element Model of three-Cell of Delijan's Silo Structure and its Foundation

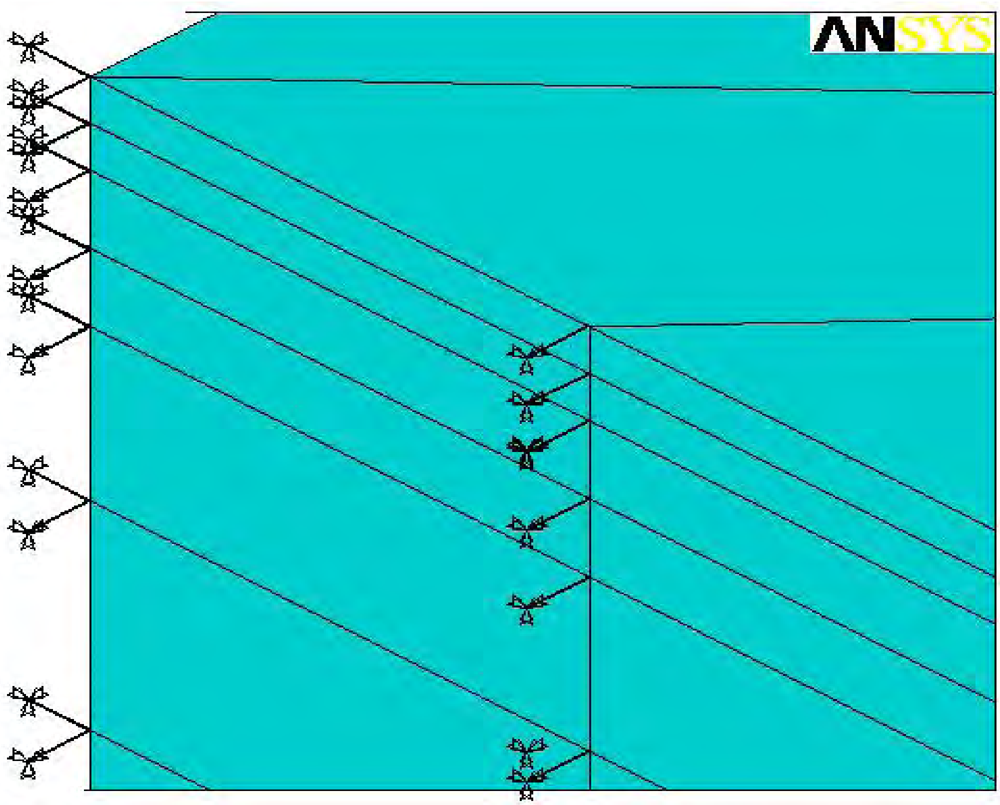


Figure 5: A Finite Element Modeling of Far-Field of Soil for Delijan's Cement Silo Foundation

STRUCTURAL MODELING

Delijan's silo structure consists of three main storage cells used in combination with the Portland cement production facilities nearby in Isfahan province of in Central Iran. Silo structure has a height of 53.5m above the foundation level. Fig.1 shows the cross sectional detail of the silo structure and its foundation. Fig.2 also shows the plan view of the Delijan's silo structure. The inner radius of the silo storage cell varies from 7.1m to 8.0m, while the outer radius is about 8.5m. A concrete funnel is built at 7.2m height above the footing. The concrete material of structure had a 28 day characteristic strength in cylindrical specimens of about 40MPa. The steel reinforcement used in the silo's structure was AIII type with a yield strength of 400MPa. Each cylindrical shape cell is modeled using 3D-type SOLID65 finite elements with 8 nodes as shown in Figs. 3 and 4. A linear elastic type constitutive model is used in SOLID65 elements to idealize the behavior of RC material used in the structure of the silo. The adopted finite element in ANSYS [1] has the capability of modeling any possible cracks in the concrete itself and also the reinforcement usage in the shell structure of the cylindrical storage cells. The other possible effects such as bonding and creep are also included in the SOLID65 elements used in the super-structure modeling. The detail drawings are used for the silo's design according to the engineering consultant company [24].

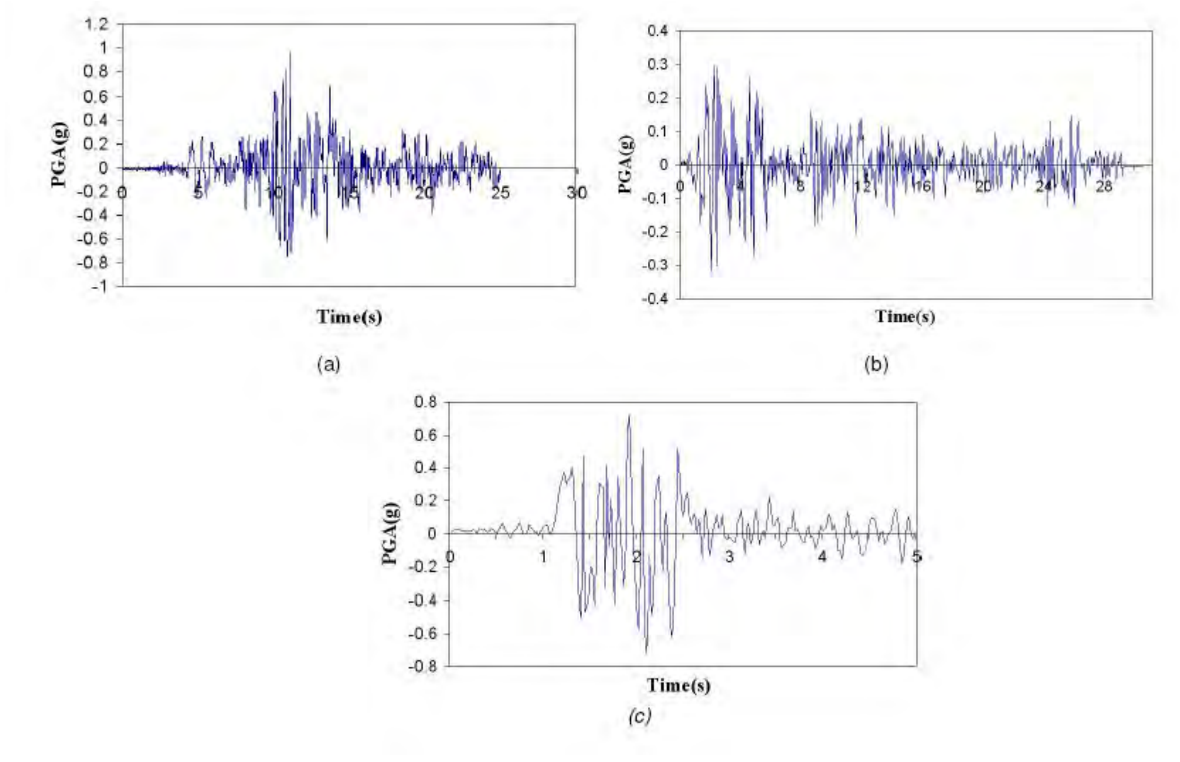


Figure 6: Seismic Records used for Analysis of Delijan's Cement Silo
(*a*) Tabas (*b*) El-Centro (*c*) Naghan

FOUNDATION AND SOIL DESCRIPTION

Foundation of the Delijan's cement silo as modeled using FEM in Figs.3 and 4 is a mat type (thick plate) built of reinforced concrete material with dimensions of 26m by 28m in plan view (as shown in Fig.2) and a thickness of about 4m.

Soil exploration study of the Delijan's silo site has been performed by the Iranian Consultant Eng. company (zamin Fannavaran). Soil profile is classified using British Soil Classification System (BSCS) as GML/GCL which mainly consists of sandy gravel mixed with silt layer and also clayey gravel mixed with silt particles.

Average wet Unit weight of the soil from borings is obtained as 20kN/m^3. Based on geotechnical studies, the soil at the building site of silo had a low permeability coefficient, less discharge rate and poor drainage[24].

Shear strength parameters related to a Mohr-Coulomb type failure criterion are computed to be c=40kPa, $\phi=35^o$. The Shear Modulus of soil (G_s) is obtained from tests as 687MPa and Poisson’s ratio as $\nu=0.27$. The constrained elastic modulus of soil may be computed as E_c=1745MPa[24].

Shear wave velocity in the soil is found from tests to be about 586m/sec which is in the range of: (375m/sec< V_s < 750m/sec). Hence, the soil type at the Delijan's silo site is classified as type-II according to seismic design code 2800[4].

Site seismicity study for the Delijan's silo has also revealed that the most probable peak ground acceleration (PGA) could be around 0.3g[24]. In addition to the site specific soil type, two other soil types III, IV were also considered for study of the SSI effects on softer soils with shear wave velocities in the range of (375m/sec< V_s < 175m/sec) and (V_s < 175m/sec), respectively. Fig.7 shows the stress-strain behavior of the three different soil types used in this study.

Table 1. Soil Types Parameters used in addition to the Site Soil Parameters

Soil Type	v_s (m/sec)	ν	γ (kN/m^3)	G (MPa)	(M
III	272	0.4	18.0	136.12	38
IV	150	0.4	17.0	38.25	1

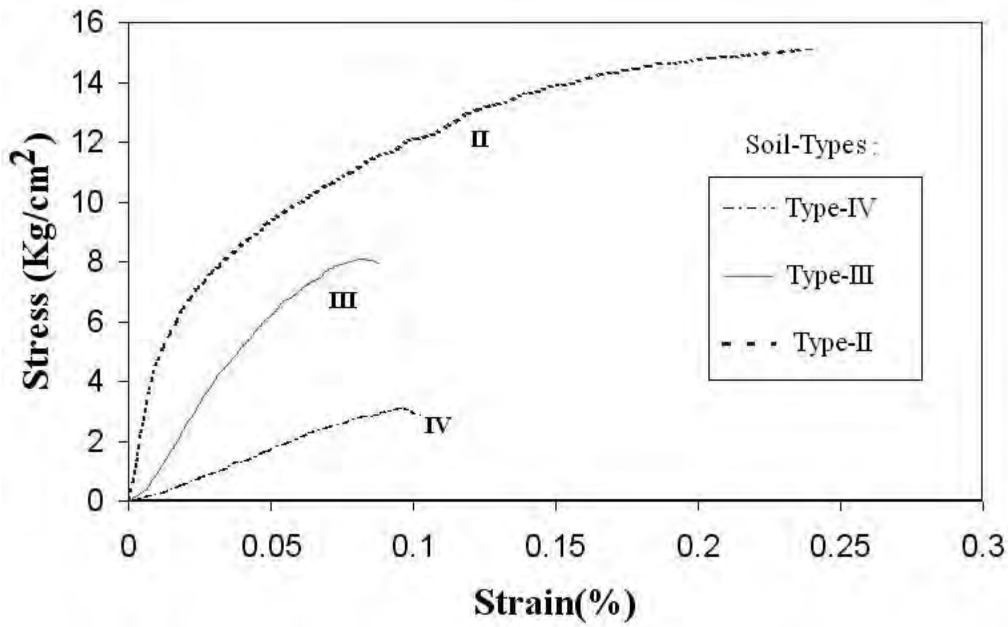


Figure 7: Stress-strain behavior of the Type-II, III, IV soil used for Analyses of SSI effect on Delijan's Silo

LOAD DESCRIPTION

The gravity, functional and environmental (seismic) loading are applied on the silo system. The gravity load consists of self-weight of silo structure and the mat foundation. The self-weight of silo is applied on each element as distributed load and also the weight of other parts are considered as equivalent nodal loads. Functional loads due to loading the storage cells with cement are considered as static dead load. While the foundation self-weight is also applied as distributed static type dead load on its base. However, three different earthquake induced loading on the system are considered. The seismic records (see Fig.6) used during this study are Tabas (N16W), Elcentro(N-S) and Naghan(N-S) records, respectively.

NUMERICAL SOLUTION METHOD

The incremental form of the dynamic equilibrium Eq.1 above can be re-written as:

$$[M]\Delta\ddot{u}(t)+[C]\Delta\dot{u}(t)+[K]\Delta u(t)=\Delta F_e \tag{3}$$

where [M], [C] and [K] represent the structural mass, the damping and the restoring force matrices, respectively. The numerical integration of Eq.3 can be performed by means of a conventional predictor-corrector scheme or a Newmark's integration method [1,3].

Summary of Results

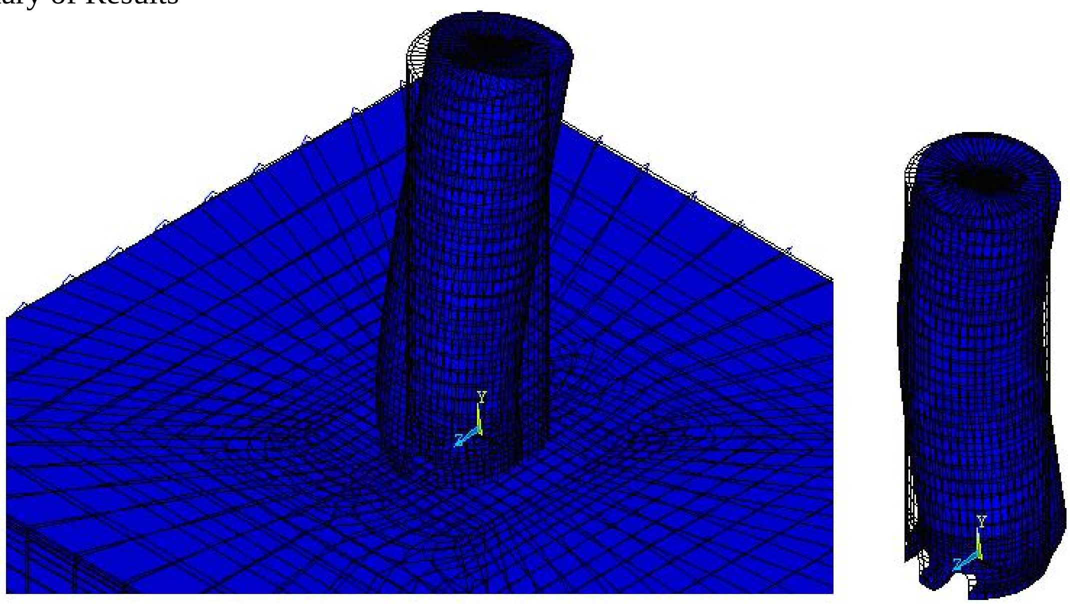


Figure 8: Shape of 7th Mode of Delijan’s Cement Silo System (Tabas, El-Centro, Naghan)

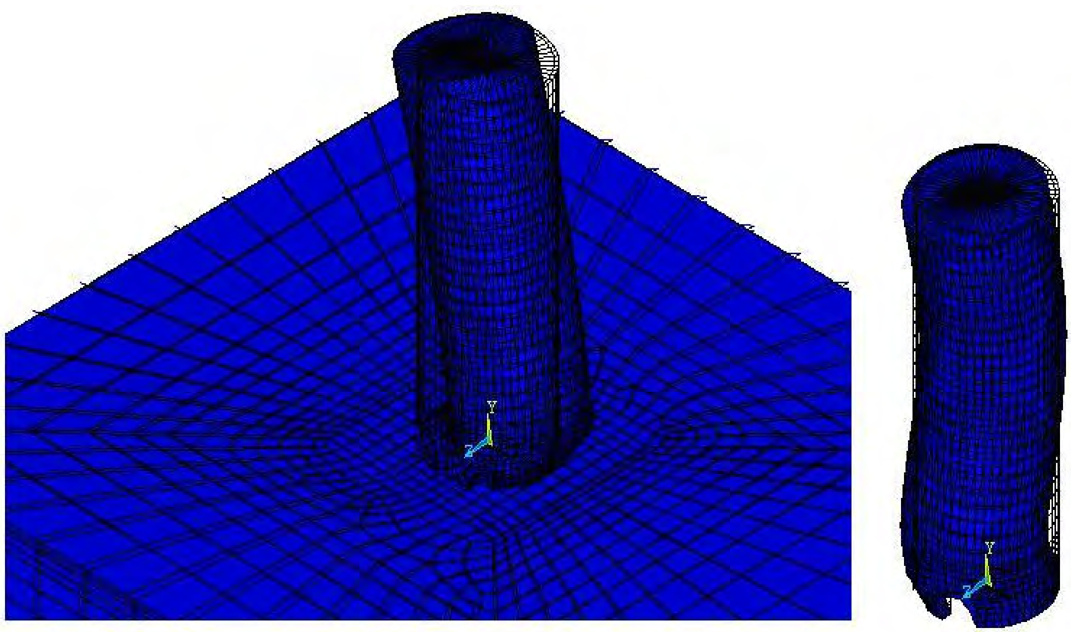


Figure 9: Shape of 8th Mode of Delijan’s Cement Silo System (SSI Effect vs. Fixed Base)

Figs. 8 and 9 show the 7th and 8th mode shapes of the Delija’s Silo as filled with fixed base and also supported on the local soil considering SSI effect, respectively. It can be seen that the considering the soil-structure interaction has changed the free vibration mode shapes of silo considerably. The deformation in the silo’s structure is somewhat reduced but the overall deformation with respect to the fixed base has increased due to foundation and soil near field’s deformation.

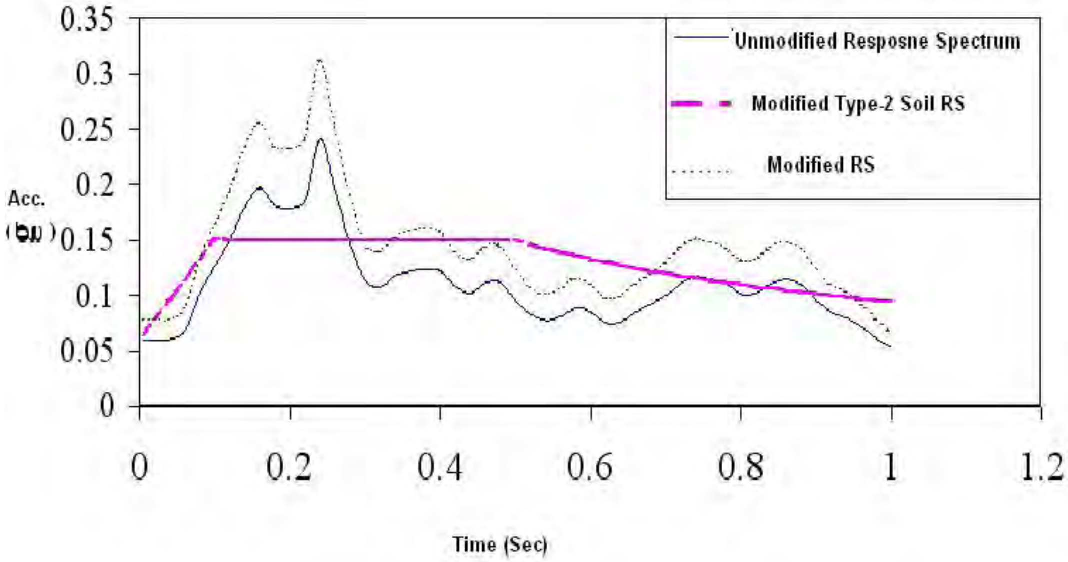


Figure 10: Response Spectra of Delijan's Cement Silo (Tabas EQ-Record)

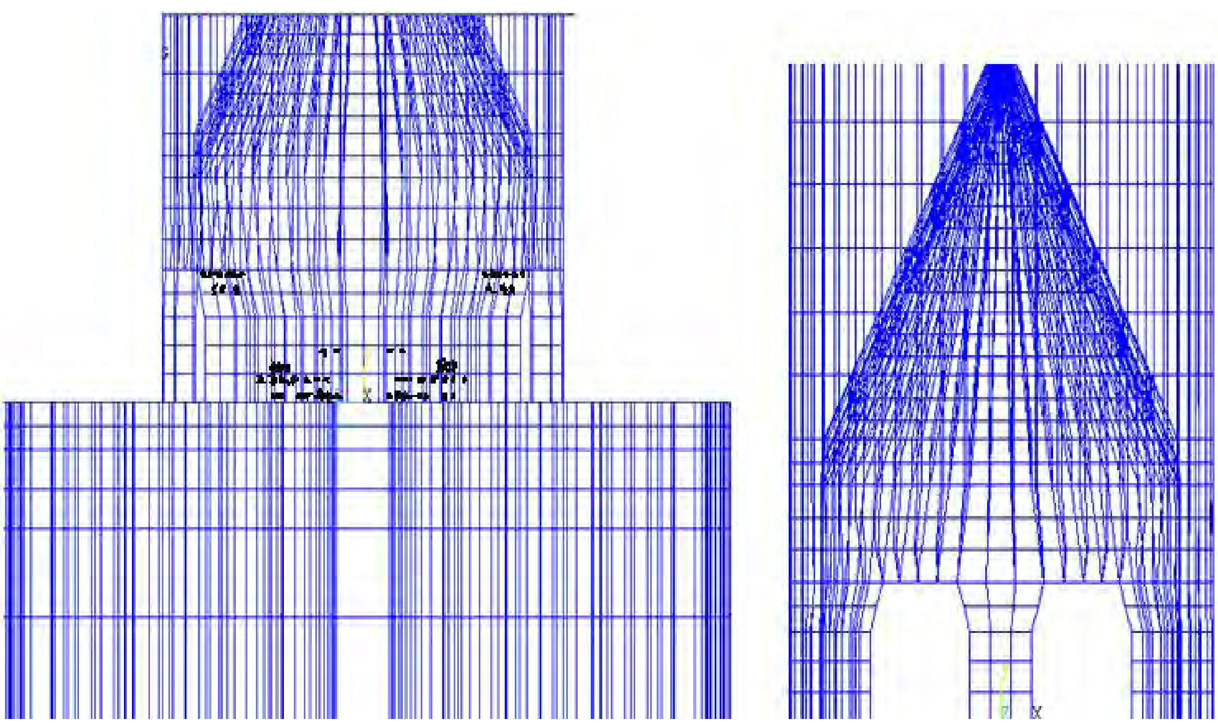


Figure 11: Cracks Development at Delijan's Cement Silo Structure (Tabas EQ-Record)

Fig. 10 represents the modified-RS and unmodified acceleration spectra generated for the Delijan's silo system [24]. It can be seen that the peak acceleration response in both modified and un-modified spectra are in the range of 0.1-0.4sec. The design spectrum for Type-II soil according to code 2800 of Iran is also plotted here which has a multi-linear form having a flat part between 0.1-0.5sec and a linear falling part from 0.5-1.0sec. Fig.11 shows a cracked section of the Delijan's silo structure under Tabas earthquake record as filled with cement. Deformed FE model indicates that the cracks mostly have occurred around the main openings in the lower part of the silo structure which are designed for unloading of the cement.

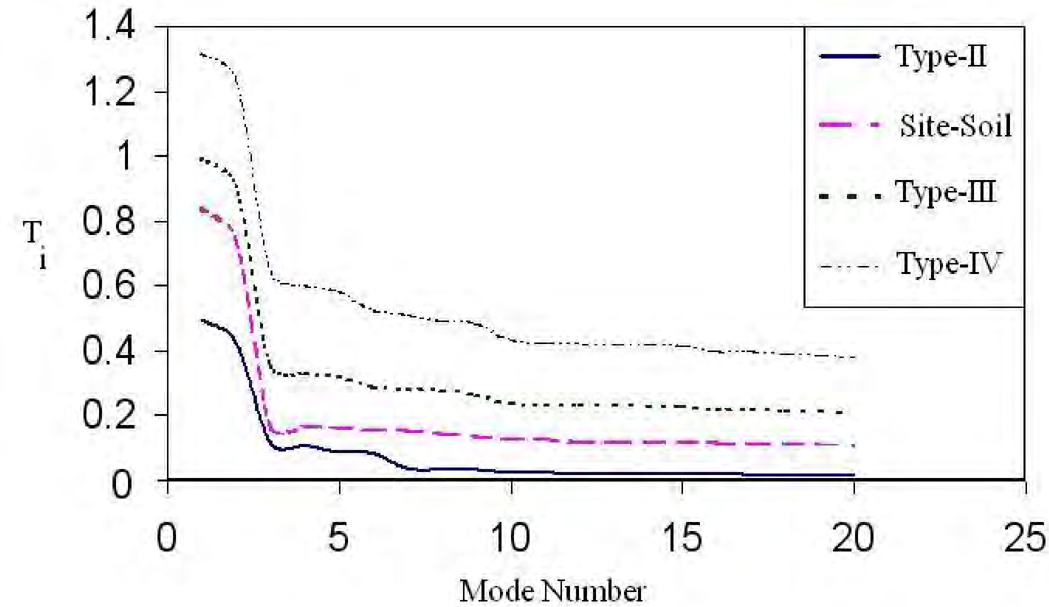


Figure 12: Variation of Modal Period vs. Mode Numbers for Delijan's Cement Silo with Various Supporting Soil Types

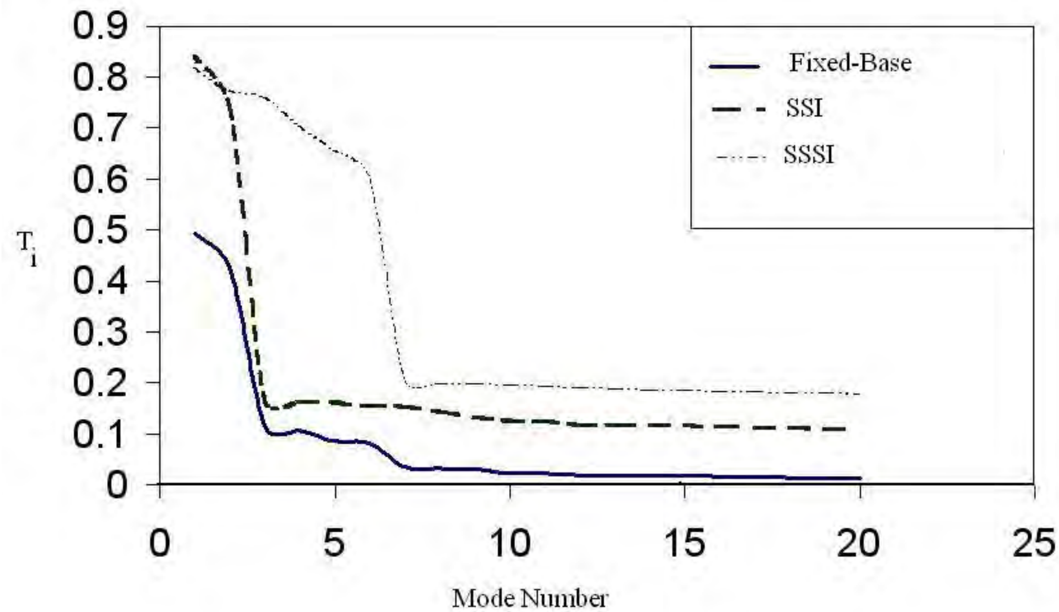


Figure 13: Variation of Modal Period vs. Mode Numbers for Delijan's Cement Silo with Various Support Conditions

Fig. 12 shows the influence of various soil types on the modal periods of the studied silo system considering the soil-structure interaction (SSI) effect. It is seen that for the site-specific soil and also softer soil type-IV the modal periods are higher than the those of soil types II and III. The results indicate that SSI effect for higher modes can not be neglected at all.

Fig. 13 shows the structure-soil-structure interaction(SSSI) effect on the modal periods of the Delijan's silo system. SSSI effect has increased considerably the modal period for higher modes (after 3rd mode up to 7th mode) as shown in this Figure.

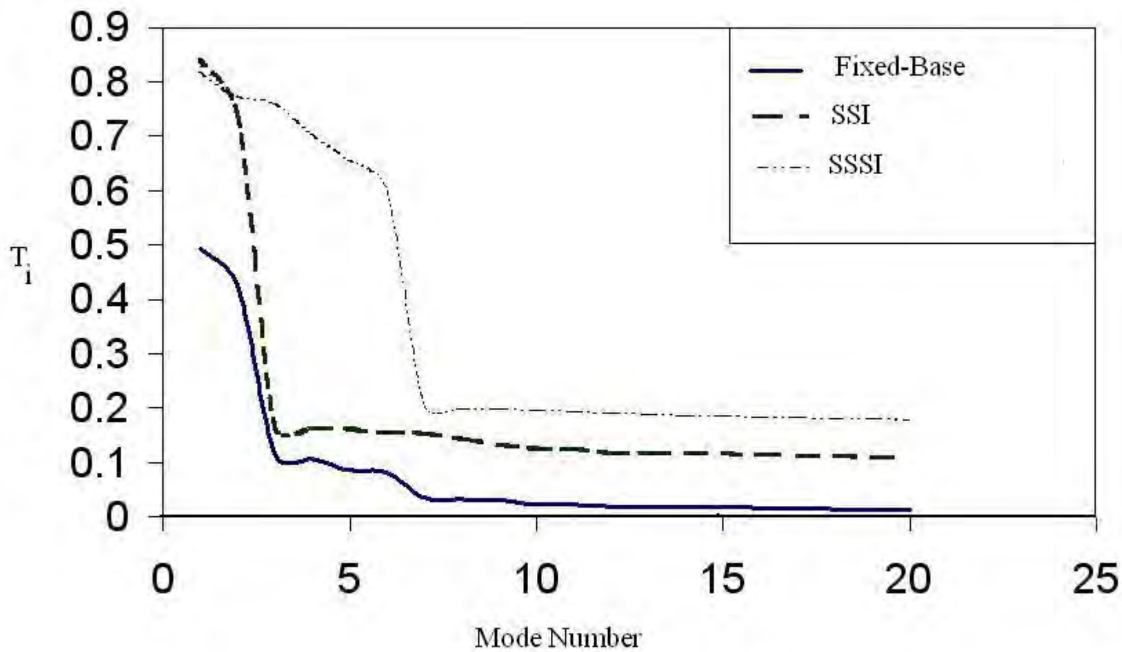


Figure 14: Ratios of Max Displacement considering SSI effect versus Shear Wave Velocity for Delijan’s Cement Silo under three different EQs

Fig. 14 shows the trend of decrease of U_{SSI}/U_{FB} ratio with shear wave velocity (Vs) for the studied single silo-foundation-soil system under all 6 earthquake components. This clearly indicates that the SSI effect on the displacement response of the silo-foundation-soil system is significantly higher for lower Vs500m/sec. This might also confirm to a great extent the previous findings on other type of structures[7,8,9].

Table 2: Maximum Overturning-Moments Values for Delijan’s Cement Silo as Filled Under Tabas, Elcentro, Naghan Records

EQ-RECORDS	M_{FB} (N.m)	M_{SSI} (N.m)	M_{SSSI} (N.m)
TABAS X	1478838000	1418509000	1371249000
TABAS Z	-1457702000	-1241869000	-1290081000
ELCENTRO X	918030400	910593000	909299800
ELCENTRO Z	-914448300	-868698200	-886298200
NAGHAN X	1465581000	1248811000	1378784000
NAGHANZ	-1420364000	-1179491000	-1171046000

Table 2 represents the peak O.M. response of the silo-foundation-soil system for all earthquake records in X- and Z-directions as the effective ground input motions with fixed base, with considering soil-structure interaction and also structure-soil-structure interaction effects. It is seen that the peak O.M. response for the case of SSI effect included is reduced say by about 4-17% while it has further decreased (say in the range of 0.5-3.4%) for the multi-cell silo-foundation-soil cases analyzed with SSSI effect included for earthquake records in X-direction. For Tabas and El-Centro earthquake components in Z-direction, however, peak O.M. response of the system has slightly increased (in the range of 2-7%) from the single silo-foundation-soil cases studied with considering only SSI effect. For Naghan earthquake in Z-direction a very slight decrease of about 0.6% has been observed for peak O.M response of multi-cell-silo-foundation-soil taking into account SSSI effect.

Table 3: Maximum Base-Shear Values for Delijan's Cement Silo as Filled Under Tabas, Elcentro, Naghan Records

EQ-RECORDS	V_{FB} (N)	V_{SSI} (N)	V_{SSSI} (N)
TABAS X	-48938260	-48124800	-46817000
TABAS Z	-48928480	-43369250	-44966930
ELCENTRO X	-30899960	-30464680	-30525070
ELCENTRO Z	-30791290	-29268070	-29654080
NAGHAN X	-49579520	-41234170	-45851920
NAGHANZ	-48394080	-38897910	-38642290

In Table 3 the peak base shear responses of the silo-foundation-soil system for various seismic records are presented with fixed base and also with considering soil-structure and structure-soil-structure effects, respectively. It can be seen that soil-structure interaction effect has reduced the peak base shear response for all 6 earthquake components while silo-soil-silo interaction effect has resulted in relatively less reduction of maximum base shear response.

It is observed that for the filled silo taking into account the SSI effect may reduce the maximum base shear at the silo's base in the range of 2-20%. More reduction in Maximum Base-Shear is observed for Z-Direction compared to X-Direction. The latter might be attributed to the openings in the X-Direction, which have reduced the stiffness of the silo structure in this direction. Also, the reduction is higher for the Naghan earthquake with shorter duration (impulsive) compared with Tabas and El-Centro seismic records. The reductions due to SSI effect in the case of empty silo are shown to be quite insignificant. The maximum reduction is observed to be in the range of 2-5%.

It can be seen that taking into account the soil-structure interaction effect has resulted in the peak base shear response of single cell silo-foundation-soil system supported on softer soil (type IV) to increase by 8.95% and 12% for Tabas-Z and Tabas-X components, respectively. In contrary, the SSI effect has caused a reduction of 4.7% and 4.3% in the peak base shear response of the single cell silo system on type IV soil under El-Centro-Z and El-Centro-X components, respectively. Comparatively, for Naghan-Z and Naghan-X components the peak base shear response of this system supported on type IV softer soil was reduced by 8.7% and 5.5%, respectively.

CONCLUDING REMARKS

It is shown that the support condition may have a profound effect on the global dynamic response of the filled silo system. In particular, it is found that the influence of the soil-structure interaction may increase the maximum overall displacement of the filled silo structure in Z-direction very significantly. In comparison, the maximum base-shear has been reduced by 5-20% due to soil-structure interaction effect in the Z-direction. The effect on the overall system response in X-direction was far less important.

It is found that the influence of soil-structure interaction (SSI) on the global base-shear response of empty silo system was quite insignificant. Similar trends have been observed for the global overturning moment of the filled silo. On the contrary, the effect of SSI on the overall displacement response of the empty silo was found to be somewhat considerable. This might show the deformation of foundationand soil near field which has affected the overall displacement.

It is also concluded that the influence of soil-structure interaction (SSI) on the silo's response can be higher for Naghan earthquake of impulsive nature with shorter duration of about 5-10sec compared to Tabas or El-Centro seismic records with longer durations of 10-30secs. It is also observed that the softer soil as Type IV may increase the acceleration response of the silo while reducing the maximum overturning moments at the base. However, the effect on the base shear response is Observed to be somewhat mixed depending on the EQ-record and the direction of seismic wave.

It is also observed that structure-soil-structure interaction (SSSI) effect might increase the maximum base shear response at silo's base while reducing the peak overturning moment and the maximum displacement values.

DISCUSSION

The findings of this paper on the soil-structure interaction effects on the studied case of cement storage silo's response and also those of other recent research works suggest that both foundation-soil modeling and also soil type may have quite significant influence on the response of the studied storage system. However, the recent reliability studies on other type of structures[8,9] also indicate that inclusion of the soil-foundation-structure interaction itself may have more profound effect on the reliability of the system than modeling parameters and uncertainties related to them. In fact, the soil type effect can also play more significant role in determining the dynamic base-shear, overturning moment and displacement response of the soil-foundation-silo structure systems. Nonetheless, more accurate soil data or more comprehensive site exploration program and also more refined soil-structure interaction modeling might improve further the reliability of the obtained results. More verification studies might also be needed to validate further the results of this study and those of other recent works on SSI effect on storage type silo systems.

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