TECHNOSCIENCE ARTICLE

Soil- structure Interaction of a Nuclear Reactor

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Coordinates: 27°11'N; 56°16'E

Key words: Solid foundation, Nuclear structure,
Collapse anchor

Abstract

Soil – structure interaction is one of the most important issues in seismic designs. It is assumed that the soil under the foundation is solid and separation doesn't occur between foundation and earth. While the soil has limited hardness and foundation is on the earth on the basis of gravity. If the collapsed anchor exceeds the resistant anchor resulted from gravity loads, the foundation would lift. The issues such as earth softness and the foundation lifting are some of the causes which affect significantly the analysis and designing the different structures. The current study investigates the soil – structure interaction effects on the nuclear structures dual frame nonlinear responses. Here, we examine the soil – structure interaction and clamped state with different records, considering the structure history analysis. The results show that soil – structure interaction influences the structure analysis and reduces the structure costs, considerably.

Introduction:

The soil–structure interaction is one of the most important issues in seismic design which soil–structure engineers encounter along with relevant researchers pay special attention. Most of the designs are on the basis of existing regulations and it is assumed that the earth movement transmits directly and with no change to the basic structure. In this method, we assume that the soil under the structure is completely rigid and the foundation separation is not possible, while the soil hardness is limited and the separation is possible. There are two assumptions impact the different structures analysis and design: the soil softness and the foundation–free soil. Soil–structure kinematic interaction and foundation flexibility reduce the earthquake force on the structure, especially in the structures with the low period (FEMA 440. 2005).

In recent years, several regulations contain different ways to show the foundation flexibility and the soil – structure system hardness reduction with the base shear reduction and increasing the structure lateral movements (FEMA 450. 2004). The methods in above-mentioned regulations are based on the soil – structure interaction but do not contain rocking movements (soil – foundation separation) or local destruction. Therefore we need explicit foundation elements for the linear and non-linear behaviour of structures in seismic design methods on the

basis of ASCE 43-03 (2005), FEMA 274 (1997) and ATC 40 (1996). Generally, Winkler model is used to model foundation and the beneath soil. In this model, the foundation is modelled by an arrow on the Winkler non-linear foundation (BNWF), because it is simple and able to model soil nonlinear behaviour (Raychowdhury & Hutchinson, 2009). The structure analysis does not lead to non-linear analysis, considering soil and structure interaction, but the rocking movement leads to non-linear analysis. The foundation rocking movements lead to foundation rise in one hand and the soil non-linearity in the other hand. But sustained deformations occur in the structure like rotation and permanent subsidence.

During the earthquake, overturning moment amount exceeds resistant moment amount resulted from gravity loads and rises some part of the foundation. Tower and oil tanks uplift are some of the milestone examples of the earthquakes like Imperial Valley (1952), Arvin Tehachapi (1964), and Alaska (1979) (Psycharis, 1986). It should be noted that the nuclear structures foundation uplift is rarely observable. This is because the uplift amount is low and the soil and foundation interface contact is invisible, due to the hemispheric shape. This point of view is explicit in ASCE 43-03 (2005) and CSA – A23.3 (2005).

Several numerical and analytical studies have been done about soil complex behavior and the seismic imposed structure (Wen *et al.*, 2002; Stewart *et al.*, 2003;

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Allotey & Naggar, 2007; Harden & Hutchinson, 2009; Raychowdhury & Hutchinson, 2010 & 2011; Saxena *et al.*, 2012). Housner (1963) studied the theory of structures with rocking movements, which investigated the response of rigid things free vibration with rocking movements. Meek tested the characteristics of a system composed of structure flexibility in 3 times. Aslam *et al.* (1980) reported that resistance against rocking movements improves by anchoring a rigid structure to the ground and putting the pre-stress element in it.

Yim & Chopra (1984a) investigated the fleeting rocking movement effects on the flexible structures. The effect of rocking movements, expanded foundation determined in the structure maximum response. They further assessed the dynamic response of rocking structures by the numerical method on the basis of Rayleigh – Ritz theory. They showed that the foundation rocking movement causes base shear reduction for the structures with a low period, more pronounced for lean structures.

Makris & Konstantinidis (2002) argued that Yin & Chopra (1984b) method, named as a simple way is not a good way to determine rocking movements. As per them, it is a simple way has a major disadvantage, especially in shorter structures and narrower blocks. Jeong *et al.*, (2003) tested the slide effects on the nonlinear, rocking behaviour of rigid things discrete under horizontal and vertical harmonic provocations. They portrayed a set of time history responses using Poincare cross-section and different kinds of rocking movement's responses and the effects of slide movements using bifurcation diagram. Qin & Chouw (2010) investigated soil–structure interaction experimentally and revealed that structures with allowable uplift can be used as a mitigation measure to reduce the activated forces in the structures. Also added that further investigations of the interrelation between the dynamic properties of ground excitation, flexible and nonlinear structure, SSI and uplift behaviour are necessary.

The study of dynamic SSI behaviour of a nuclear reactor building by Saxena *et al.* (2011), focused on effects of slip and separation due to SSI on seismic SSI response of nuclear reactor building using finite element analysis. It was observed that SSI allows slip and separation at the soil–foundation interface which has a significant effect on the behaviour and responses of the reactor.

In another study, Tang & Zhang (2011) focused on effect of SSI on the damage probability of amid-rise slender shear wall with a flexible foundation. SSI effect on the maximum interstory drift was found to be most sensitive to the soil friction angle.

Nuclear reactor's chamber holders are one of the most important atomic energy equipment. Vulnerability assessment of the holder in earthquake-prone regions is

very important. Proper knowledge regarding soil–structure interaction in the nuclear reactor's are very important and which cannot be neglected.

Finite element: the reactor nonlinear analysis performed by 2 limited component and the stresses; strains and displacement are reviewed in the related connection point. ABAQUS is used to analyse two and three-dimensional items. Generally to do nonlinear analysis, both material and geometric non-linear effects involved.

The related measures for concrete with 27.6 MPa compressive strength is 24.8 GPa elasticity model, 0.18 Poisson, and 0.0001 cracking strain. Steel cover sheet is based on A516 grade 60°. This structure is a cylindrical one with a hemisphere shape at the top. The cylinder inner height is 38.4 m and the structure total height (inner) is 56.4 m. Cylinder and structure thickness is 1.37 m and 0.76 m in the cap top. The foundation thickness is 3.1 m. The thickness of inner steel cover is 6.36 m. The finite element analysis is performed by ABAQUS and the analysis is based on Damage Plasticity.

The model contains 4177 analysis points and 3810 elements. Four – node meshes are used for linear elements and 8 – node elements are used for concrete. Figure 1 depicts the used model and the model meshing.

Figure-1: The used model and the model meshing

The above-mentioned models are investigated in this study in two modes: considering soil–structure interaction and the interaction – free mode, designed by ASCE 43-05 (2005). Soil models include cuboids in 200*200*50 and 2nd type ground. Nonlinear circuit elements (GAP) between soil and reinforced concrete is used to place the structure on the soil medium. These elements consist of springs with non-linear behaviour, so that undertake no force from tensile forces and show nonlinear behavior in the compression zone. There are 500 MPa adhesion and 36° friction angle in software modeling. Force – spatial changes characteristics of connection elements are as follows (eq (1)):

$$f = \begin{cases} K(d + \text{open}), & \text{if } (d + \text{open}) < 0 \\ 0, & \text{if } (d + \text{open}) \geq 0 \end{cases} \quad (1)$$

Where 'K' is spring stiffness and 'd' is spring deformation. The early openness is zero. In this study, GAP elements stiffness is 2921111 kgf/m for midsection and

2731111 kgf/m for end section, considering FEMA 356.

The relative horizontal movement of concrete foundation and soil is neglected. On the other hand, it is assumed that the concrete slip on the soil is prevented.

Boundary conditions modelling should be performed in the model edges so that it prevents the returning of seismic waves into the model and boxed model effects. For this purpose, we used unlimited elements in the model edges. Impedance functions (IF) is a soil-structure system and introduced by system stiffness and damping and is a function of vibration frequency and loading frequency function (driving force). In the current analysis, system stiffness performed in the form of lateral loading harmonic with Po domain and we measured the resulted spatial change in the same point and different vibration frequencies.

Accelerograms and their determination criteria: grab maps that are used to determine the earth movement effects should represent the real movements of the earth in the earthquake, as much as possible, according to ASCE.

The selected Accelerograms magnitude was 6 to 7 and the distance from the fault was 15 to 25 km, measured by design regulation spectrum for the ground, type 2. The used Accelerograms characteristics are depicted in table 1.

Table -1: The used Accelerograms characteristics

Earthquake	Date	Magnitude	R(km)	PGA(g)
Imperial Valley	1979	6.53	24.82	0.176
Northridge	1944	6.7	20.22	0.22
Loma Prieta	1989	6.93	16.00	0.382

Failure Criteria: in the third chapter of ASCE, the nuclear reactors inspection has been presented. The main tests on the structure components performed in the laboratories, therefore the plastic effective stress measure is obtained from the equation (2), in which failure happens:

$$\epsilon_{failure} = \epsilon_{uniaxial} * f_1 * f_2 * f_3 * f_4 \quad (2)$$

Where $\epsilon_{failure}$ is the effective plastic strain anticipated to happen in this strain, $\epsilon_{uniaxial}$ is the failure strain in the main test,

f_1 : effective impact factor in multi-axial stresses spectrum,

f_2 : effective impact factor for model analysis,

f_3 : effective impact factor for variables,

f_4 : effective impact factor for corrosion. The current study coefficients obtained from NUREG/CR-6706 values, considering the structure type and model geometry.

Models Analysis: in the current study, we modelled an item without considering interaction and then a model using interaction element in soil and structure junction point, three dimensionally. A tuned-mass dumper is used in the junction point of the structure to the foundation to consider the interaction effects. The elements are presented with 5% mortality. The results studied for three earthquake record including Imperial, Northridge and

Loma Prieta, considering the structure analysis in two forms: interaction free and considering interaction. Fig.-2 depicts the rigid state using the stresses cover outputs in the model with the mean of resulted stresses from three earthquake records. More sensitive stresses are formed in the middle point and the junction point of the cap to the structure cylinder.

Figure 3 depicts the structure body stresses, considering the soil – structure interaction. In this case, the maximum stresses occur in the structure body, as the free interaction mode but less than a solid foundation. In this manner, the applied loads to the structure in the foundation and structure point are more than other points. The applied stresses to the structure body reduce due to the load concentration and results in better function.

Figure-2: The maximum stresses cover by elements for solid state

Figure-3: Respectively a. the maximum stresses cover, b. load distribution, and c. structural deformation for soil-structure interaction modes

The structure response for mentioned earthquakes is 18 seconds. Table-2 presents the maximum stresses and displacements for the applied loads mean in two forms: interaction mode and interaction-free mode. In these forms, the stress and displacement maximum occur in Loma Prieta record wave.

The output means are good measures to evaluate the results from the applied earthquake on the structure.

The displacement output is one of the measures used to examine the structure stability against the applied loads. The structure crown horizontal displacement is proper for

dome-shaped structures to examine these displacements. According to the surveys on the structures, there are stresses more than concrete strength and structure body, in the interaction-free mode that is dangerous.

Table-2: The results of the analysis to the maximum amount

State	Earthquake	RD [cm]	CS [MPa]	TS [MPa]
Fix	Northridge	5.8	21	1.7
	Imperial	5	17	1.4
	Loma Prieta	10	36	2.8
	Average Earthquake	2.4	21	1.6
Flexible	Northridge	2.3	8.3	0.65
	Imperial	2.4	8.2	0.64
	Loma Prieta	3.3	12	0.9
	Average Earthquake	1.6	8.2	0.6

RD-Roof Displacement; CS-Compression Stress; TS-Tension Stress

The results of soil- structure interaction effects in solid mode; in this section, we present the results of compressive and tension stresses. In fact, these results are separated to review the results exactly. Response from 3 earthquake results is suitable to compare two structures interaction modes. Figure-4 shows the maximum compressive stresses for these two modes.

The compressive stresses reduce, comparing interaction mode (SSI) with the first mode, without soil – structure interaction. This case is better in the structure. In fact, our analysis is upstream regarding rigid structure. Considering the tension stresses (Fig.-5) in earthquake period, equal to 10 seconds, the tension stresses applied the load in interaction-free mode is more than interaction and flexible one. Tension stress is used structure failure measures. The tension crack occurs sooner in structure body and caused nuclear rays in the area, due to the low level of tension stresses in the concrete.

The displacements in the structured crown are good measures to analyse the resistance of the important structure against the seismic loads. Therefore, crown displacement analysis and comparing it in two modes (interaction and interaction – free mode) is important.

Figure-6 depicts the crown maximum displacements in two modes. The interaction effect in crown horizontal displacement is very important.

The applied acceleration on the structured crown is less in interaction – free mode, compared to SSI, considering Fig.- 7. Therefore, the soil – structure interaction mode is better to perform failure measures, because it is more economical.

Effects on the structure frequency time: it is very important to determine the system eigenvalues to estimate the ductility demand. In the common regulations, the structures frequency time is used to determine soil – structure interaction effects on the system seismic behaviour. In the current research, a frequency eigenvalues analysis performed to know the structure nonlinear behaviour, considering soil – structure interaction. In this section, the frequency time of three first modes presented for two modes: the structure with a rigid substrate and with flexible one and the way of changes.

As table 3 depicts, the stiffness reduction occurs in flexible substrate and the structure frequency time increases. In the first mode, the frequency-time increases 13%, but in the higher values 9% and 5% increment occurs.

Table-3: Period amounts in two models

Mode	Fixed Base T	Flexible Base	T' / T
1	0.188	0.213	1.13
2	0.073	0.081	1.09
3	0.068	0.072	1.05

Evaluation of performance levels: Table-4 depicts the steps taken in the structure to have triple performance levels. As the table shows, the base shear values in flexible substrate mode are less rigid than the solid substrate. But

the opposite condition is true for displacement. Flexible substrate structures get the performance level, comparing solid ones.

Table-4: The detail performance levels

State	Limit State	BS*[tonf]	RD**[cm]
fix	Immediate Occupancy(IO)	154	0.95
	Life Safety(LS)	189	1.25
	Collapse Prevention(CP)	201	1.36
Flexible	Immediate Occupancy(IO)	124	2.65
	Life Safety(LS)	146	3.85
	Collapse Prevention(CP)	165	5.01

*Base Shear; **Roof Displacement

Ductility factor changes: the structure capacity against the non-elastic and plastic deformations is called ductility factor (in no collapse state). On the other hands, ductility factor is the ability of structure in standing with non-elastic deformations and entering to plastic zone. Ductility is provided by the components of the structure system designed for energy dissipation.

Table-5 presents the demand ductility for different performance level. As it is clear, ductility increases with applied force and plastic hinge ductility demand. It is important to note that mentioned increment in the flexible substrate is more than the rigid one.

Table-5: The detail performance levels

State	Limit State	RD*[cm]	μ
Fix	Immediate Occupancy(IO)	0.95	1
	Life Safety(LS)	1.25	1.31
	Collapse Prevention(CP)	1.36	1.44
Flexible	Immediate Occupancy(IO)	2.65	1
	Life Safety(LS)	3.85	1.45
	Collapse Prevention(CP)	5.01	1.9

*Roof Displacement

Conclusion:

The current study investigates the soil-structure interaction effects on the nuclear structures nonlinear behaviours. We designed two models with and without interaction in three-dimension format, using ASCE 43-03 and the foundations designed regarding the bracing arrangement in a narrow band format. Then both models analysed separately. Followed by the results analysed in terms of cap displacement, performance level, maximum stress, plastic strain and the structure period.

The most important results of the study summarised as below:

1. As the results show soil-structure interaction influences the larger structures which are more than the normal ones. The system total hardness is affected by the softer element hardness because the soil-structure system is connected in series. In the other hand, the total hardness depends on the softer element hardness, in the case of high difference of soil and

structure. The system total hardness is affected by the soil hardness and is an important issue in the total response of soil – structure interaction system. Therefore, the soil-structure interaction has the high influence on the system response.

2. Request ductility is one on the important parameters of the structure behaviour after submission. As the results show in all cases the request ductility is more flexible in substrate mode, which depicts the structure ability in the tolerance of inelastic shapes and plastic zone entrance.
3. The results of the cap displacement show that interaction causes the displacement and more cost effective design.
4. Interaction tensions are less than the rigid mode. It is because these elements receive the earthquake energy in the energy connection point and the structure will have a better response.
5. In general, soil-structure interaction reduces the foundation shear and increases the structure oscillating period and drift uniformity.

Acknowledgements:

We acknowledge all the persons involved in this study right from the concerned in charge for providing permission to the person help in conducting the study.

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