Influence of Different Foundation Depths on the Seismic Response of a Next Generation Nuclear Reactor*

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Abstract
The simultaneous occurrence of different load conditions such as gravity loads, lateral and vertical loads due to seismic event in various combinations should be considered to generate most critical design conditions on Nuclear Power Plant (NPP) components. The aim of this paper is to evaluate the behaviour and the structural response in form of response spectra of the reactor building internal structures, under site specific seismic loading, and to determine whether these ones satisfy current international safety regulations. A preliminary conceptual analysis and design of a nuclear building with different foundation embedding depths for the most critical conditions were discussed with reference to solutions considered for a Near Term generation Nuclear Power Plant. The seismic input motion was considered as a free field response spectrum with 0.2 g PGA, while the Soil-Structure Interaction (SSI) effects were taken into account through appropriate features. To achieve the purpose of this study, the foundations can be seen as a stable base for the superstructure able to transfer safely all loads from ground to the internals. The general approach was consistent with up-to-date design conditions for evaluation and upgrade of NPP facilities. The project’s major steps and objectives may be summarized as follows: study of available data for preliminary design and as built conditions, creation of 3-D detailed finite element models, determination of dynamic characteristics, verification of capability of structure to resist relevant design load combinations, determination of possible feature and components mostly affected by the assumed seismic loads. The results of the performed analyses, the possible effects of SSI and the response of internal components (e.g. Nuclear Building, Vessel-SGs etc.) seem to confirm the possibility to achieve an upgrading of the geometry and the performances of the proposed solutions for the considered NPP.

Key words: Nuclear Power Plant, Seismic Loading, Embedding Depth, Response Spectra, Soil Structure Interaction

1. Introduction

The philosophy of structure and the foundation substructure is influenced to a great extent by the sizes of the foundation soil characteristic and by the mechanical and rheological properties of the ground.  
The great variability of the foundation soils lead to the assumption of many mechanical
models which idealize the ground as a supporting medium [1]. Integrity of structures, systems and components of a nuclear power plant must be ensured in case of any design condition in particular in the event of an earthquake. Under earthquake loads, not specifically designed buildings have known to suffer extensive damage and even total collapse, as evidenced during earthquakes in Iran, Turkey, Taiwan, Greece, Italy and USA [2]. The seismic analysis coupled with the soil-structure interaction is required as one of the conditions for the design and construction approval of the Nuclear Power Plants (NPPs) structures and is also necessary to evaluate their real capacity of dynamic loads bearing. In fact, when a structure is subjected to dynamic loads, as seismic ones, the behaviour of the structural material may be significantly different from the one characteristic of static load applications [3]. A seismic evaluation is one of the most important and complicated regulatory requirements [4].

It should be considered that the proposed analyses are an example of what may be performed for this type of reactor case that is partially embedded in the soil (also for safety/security reasons). In this context the soil itself was modelled by means of a specific FEM model in the place of more widely adopted lumped mass, spring and dashpot schematization. Moreover the presence of Soil Structure Interaction is considered to be important for the induced uncertainty due to the nonlinear behaviour of soil and to the possible dynamic interaction between buildings through the soil during earthquakes. In this paper a preliminary application of the methodology to an innovative LWR reactor International Reactor Innovative and Secure (IRIS) structure is presented. This preliminary analysis is intended to evaluate the influence of different foundation depth on the dynamic loads propagation from the ground to the Internals (e.g. Reactor Pressure Vessel (RPV) or Steam Generators (SG)), taking into account also the soil-structure interaction for various soil characteristics.

2. Structure and model description

The standard design of a LWR refers to an envelopment of site conditions, in this way the reference reactor would be suitable for construction on any given site without necessity of site specific analysis and design. Between the new LWR concept IRIS is one of the most interesting next generation reactor under study at present. The IRIS integral vessel RPV is larger than a traditional PWR pressure vessel, but the size of the IRIS spherical containment is a fraction of that of corresponding loop reactors, resulting in a significant reduction in the overall reactor size [5-6]. This size reduction, combined with the spherical geometry results in a containment pressure capability at least three times higher than a typical loop reactor cylindrical containment, with the same metal thickness and stress level (Fig.1).

Fig. 1 -Containment system (CS)
Nuclear power plants are always composed of a number of adjacent structures, so in order to ensure adequate treatment of interaction effects the main buildings should be considered. All relevant reactor structural components are present in the proposed example model, with their real geometry and material characteristics. To the purpose of this study a system constituted with three mutually interacting components were considered: the foundation, the substructure and the superstructure. Apart from structural integrity, the foundation should be able to transfer all the forces to the sub-soil in an effective manner.

2.1 Structure description

The first task in structural modelling is to develop fixed-base models of each structure in as much detail as necessary to define adequately the building response at all desired locations. The Nuclear Island (NI) is the global model of the NPP considered (Fig. 2), which is characterized by a thick concrete basement and by:

- External building (EB) or outer containment;
- Inner containment or containment system (CS);
- Reactor pressure vessel (RPV) with its internal structures

The complete first mathematical model and the degree of discretization were chosen such that the natural behaviour of the structure in the relevant frequency range could be computed with good reliability. Modelling of EB (the External Building corresponds to the nuclear island shown in Fig.2 without the reactor pressure vessel), CS and RPV internal structures required the setting up of appropriate meshes assembled with suitable elements (as e.g. 3-D solid brick and/or shell type elements, available in the used finite element modelling code (FEM)) to represent the behaviour of each structure [7]. At appropriate locations within the RPV, nodes were chosen to lump the masses of the internal structures. The criterion for choosing the mass location points was to provide for accurate representation of the dynamically significant modes of vibration for each of the internal components.

The analyses were performed with some simplified assumptions. In the reactor type the considered EB surrounds the containment system. The structure is assumed to be founded on rigid foundation at the base, which joints the inner structures to the top soil deposit, and was characterised by a free top plate. The available preliminary structural drawing, in the following Fig. 2, shows that the foundations are located on the ground surface and are assumed closely bed to the soil.

The Soil was modelled as a homogeneous loose sand zone. The thin layer of soil and its material properties influence in different ways the horizontal and vertical propagation wave and the rocking vibration effects [8-9]. To the mentioned purpose the soil-structures interaction has been also considered and three different embedment foundations were analysed:

1. Superficial depth;
2. Intermediate depth;
3. Full depths;

The hypotheses assumed to setup the model were:

- Non linearity of soil mass: this feature is accounted for assuming an elasto-plastic material behaviour based on a yield surface that exhibits hydrostatic stress dependence. This characteristic is observed in a wide class of soil and rock-like materials that are generally classified as Mohr-Coulomb materials (generalized Von Mises materials).
The Containment System (Fig. 3) was one of the main superstructures studied, which was characterized by different mass and stiffness distribution over the height; due mainly to the upper hemispherical steel structure and to the bottom concrete wall structure. The containment system was linked to the external building by means of a single foundation which was grounded to the soil. The hypotheses assumed to setup the model were:

- The concrete containment is considered so stiff compared with the upper steel shell one that its local effect is negligible;
- The reactor pressure vessel, the water contained in the wet-well, and the upper containment shell are considered as lumped masses connected to the containment wall nodes.

The Reactor Pressure Vessel (Fig. 4) was the other main superstructure considered, which was characterized by the following assumptions:
The secondary loop pipes were not considered in the study;
• The core, SG tubes, water mass, primary coolant pumps and internals are considered as a set of point free masses linked respectively to the lower core plate, central SG column, pressurizer separator and barrel;
• The attachments of the SG headers to the RPV internal wall were considered as rigid restraints without mass.

Materials used in modelling the nuclear island are concrete and steel. Almost the whole building is made by concrete.

The material properties for the Containment System, the Substructure and the Soil in terms of Young’s modulus $E$, Poisson’s ratio $\nu$ and mass density $\rho$ are shown in Table 1[10].

In order to ensure adequate treatment of interaction effects, firstly the main structures were modelled in only one 3D finite element model, and subsequently the seismic analysis was carried out by means of the Substructure model approach.

<table>
<thead>
<tr>
<th>Material property</th>
<th>Material</th>
<th>Steel</th>
<th>Concrete</th>
<th>Loose Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young Modulus $E$ (MPa)</td>
<td>2.1E+5</td>
<td>2.3E+4</td>
<td>10÷23</td>
<td></td>
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<tr>
<td>Poisson Coef. $\nu$</td>
<td>0,3</td>
<td>0,2</td>
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<tr>
<td>Density $\rho$ (Kg/m$^3$)</td>
<td>7850</td>
<td>2.500</td>
<td>1.900</td>
<td></td>
</tr>
</tbody>
</table>

2.2 Substructures model approach

This analysis approach was based on appropriately separated models for the building structures as well as frequency-independent soil [11]. The nuclear reactor was considered as formed by external building, connected to a rigid base mat, containment system and RPV which represent the internal and external substructures.

The target response spectra for vertical and horizontal motions however are normally described in codes for several damping coefficients. In Regulatory Guide 1.60 (US Atomic Energy Commission, d1973), the given spectra are for 0.5, 2, 5, 7 and 10% damping. [12]

The Time History approach was used in all analyses to evaluate the effects of a Safety Shutdown Earthquake (SSE). The acceleration data were derived from the original horizontal response spectra (Fig.5) where the maximum Peak Ground Acceleration (PGA) was equal to 0.2 g, calculated for an appropriate damping, in according to the previous mentioned Regulatory Guide.
Seismic excitation was represented by an artificial time history compatible with the given free-field spectra applied at the base of the considered nuclear island. In the application example only the horizontal translation direction is considered. In general, as it is well known, earthquakes have different properties such as peak acceleration, duration of strong motion and different ranges of dominant frequencies and therefore have different effects on a structure. In the example the seismic loading was considered as applied at the soil as a W-E acceleration whose max amplitude was equal to 0.2 g, as previously mentioned, and the excitation duration was 30s (Fig. 6). The response of the structure was obtained for selected time steps of the input earthquake time history.

Before the development of the dynamic transient analysis, a modal analysis was carried out to evaluate the natural frequencies and modes of all the most relevant components of the considered system. The seismic analysis was performed assuming a proportional damping for each structure, in accordance with the Equivalent Rayleigh damping [13-14]. Damping values used for the internal component are 5 % and 7 % of critical ones, respectively for the welded steel and reinforced concrete structures. These values are in agreement with the NRC Regulatory Guide 1.61 (USNRC, 1973) that gives acceptable damping value to be used in the seismic analysis for operating (OBE) and shut down (SSE) earthquakes.

3. Numerical results

The substructure approach separates the NPP seismic analysis problem into a series of simpler ones that can be solved each independently. The substructure approach has been also validated considering the influence of the mesh sized [15]. The models structures, described previously, were implemented with MSC.MARC FEM Code, which allowed to assemble the mass, stiffness and damping matrices and to solve the
equations of dynamic equilibrium at each point and time step. The non-linear characteristics of soil and steel, when the structure is deformed under seismic excitation, could change the stiffness of the structure and could result in a change in its fundamental vibration period. The non-linearity in the model was dealt with an appropriate elastic-perfectly plastic option. The input Acceleration Time History (ATH) of the SSE is used to get the reactor vessel and SGs tube bundle responses. The real structural models of each building (lumped masses and stiffness) were then coupled with the previous mathematical models.

In order to analyze the soil influence (SSI) and obtain the amplification (or decreasing) factors which may influence the seismic response, accounting for the energy dissipated for the soil and system structural damping, some preliminary in depth examination with non linear analyses have been carried out on the EB model, in considering also different embedment depths.

The hypothetical NI adopted in this study, is symmetrically located on the concrete foundation resting on a thin layer of soil elements to account for the softening effect of the structure embedment.

Geometrical characteristics of the structures were developed in according to the specifications carried out from the above drawings. The EB is assumed to be a cylindrical reinforced concrete structure, with different thickness of walls and slabs up to the elevation 47 m. It is founded on a common foundation with an average depth of 1.5 m, which increase up to 2.0 m in the lateral walls. The building foundation is assumed to be superficial on the top of the soil in the first case (Figures 7a, b, and c).

The depth was assumed at an intermediate depth in the second one (Fig. 7b) and increased up to the external building full eight in the third one (Fig. 7c). In order to obtain the time response for seismic excitations, the free-field motion (time domain) is transformed into the frequency domain. The response functions, in terms of acceleration and displacement, transferred from the soil through the EB and the CS to the RPV for the considered depth foundations are represented respectively in Figs. 8-9-10 (a) and (b).

![Figs. 7 – Superficial (a) Intermediate (b) and Full (c) depth EB foundation](image_url)

![Figs. 8 -Acceleration and displacement transferred to RPV (Superficial foundation)](image_url)
One of the main results of this study is the comparison of the three different levels of embedment of the plant foundation. In particular as far as the general shape of response diagrams (in term of acceleration versus time) is similar for the considered embedment levels, while from a quantitative point of view, it was observed significant differences. It was observed that both intermediate and full depth foundation acceleration behaviours are apparently quite similar. This “similarity” may be due to the assumed hypotheses and NI layout as well as soil geometrical characterization, which could not highlight all SSI damping influence on the acceleration propagation (further in depth-examination are going study and not presented in this report).

From the results carried out with the analyses on NI, it appears that the containment system may be considered as a rigid body, which transfers almost directly the input motion from the ground to the reactor vessel, while the top plate cover may be considered as well as an elastic body. The rigid body assumption of CS has been validated by the previously mentioned modal analysis results which were not quoted in this paper (the first CS frequency resulted to be larger than the external building ones).

Moreover the ATH seems to be propagated through the NI in different way depending by depth building foundation.

All the acceleration results may be used to determine the response spectra of the above mentioned substructure and evaluate the type of the seismic loading propagation.

In the following Fig. 11 it is possible to evaluate the improvement introduced by the intermediate and full depth foundation embedment; in fact, the observed maximum acceleration values for the superficial foundation decrease of about 15% at the vessel skirt support level. The observed effects among the different embedments result more clear in the following showed comparison among the spectral acceleration at the bottom and upper SG-Vessel restraints (Figs. 17(a) and (b)).
Amplification of the peak acceleration between the structures ground and roof levels was observed due to the top plate building in-plane flexibility. These accelerations were used as input time histories for the next RPV substructure analyses. The obtained results at the upper and bottom SGs headers have indicated that the reactor pressure vessel may be considered as a rigid body too, which allowed the transfer of the input motion through the internals and steam generators to the tube bundle. Numerical results are obtained at both tube bundle end restraints for the needs of stress level evaluation in helicoidally tube successive analyses. In Figs. 12, 13 and 14 (a) and (b) respectively the response in term of acceleration and displacement were represented as transferred through the reactor pressure vessel to the upper and bottom SGs tube bundle restraints (SG_upper and SG_bottom respectively).
An overview of the acceleration and displacement time histories, depicted in the previous and following figures, highlighted that the frequency of the accelerations and displacements remains relatively unchanged even if then follow the largest portion of the base motion.

Figs. 14 - Acceleration and displacement transferred to SG tube bundle (Full depth building foundation)

The mentioned results for the two level in SG tube bundle, even if quite similar apparently, corresponds to really different acceleration time histories, due to the influence of the kinematic interaction and filtering effect of internals structures as well as soil, mainly when material is going into the nonlinear fields.

As a check of those conclusions the values of acceleration of the outer containment system and reactor pressure vessel were used to determine the response spectra, according to the Regulatory Guide 1.122 (USNRC, 1978). The response spectra transferred to the upper and bottom SG tube bundle restrains indicated that it was an increase of seismic acceleration propagated from the ground due to the excitation of the masses of the structure and equipment located inside the NI, as it is shown in Figs. 17 (a) and (b) respectively.

Figs. 17 – Calculated acceleration spectra at the upper (a) and bottom (b) SGs tube bundle comparison

Analysing the calculated response spectra it can be generally observed that the SSI and adjacent building interaction results in rather slight shift in the fundamental frequency of the building. They also depend on the dynamic properties of each structure such as strength, rigidity, and modal characteristics. Therefore, higher responses may be due to the excitation of the masses influenced by different embedment foundation geometry and EB top cover plate. These accelerations were used as input for the following SGs helicoidally tube substructure analyses.

The dynamic transient results indicated that on the SGs tubes the displacements were about 20 cm both on external and inner helicoidally tubes, while the stress intensity was almost negligible. It should be noted that the SG tube bundle were assumed without intermediate helicoidally tube support plates.
4. Conclusion

Analysis and design of the NPP structures involve considerations not only on the available geometry but also on the capacity of the most important structural members that transfer the seismic inertial loads from their application points to the SGs tube bundle extremity supports. The showed preliminary results were carried out with the Time History Method applied to the EB and RPV 3-D FEM models, in order to evaluate the seismic response of the single element of the SG helical tube bundle. These seem to indicate that steam generators tubes undergo a relatively low stress level in SSE conditions; also considering the SSI effects (accounted for in a more realistic assessment of structures behaviour). In general, the model analysis (considering the frequency dependency of the structural parameters) yielded accelerations values rather greater than the ground seismic motion. The differences are due to the influence of real damping characteristics, SSI, kinematic interaction effects by the complex mathematical model, filtering effects of the internals structures, etc.

On the base of all very preliminary analyses, the effects of three alternatives nuclear building in soil embedment have been considered in order to check the possible reference system criticalities and obtain a feed back on the critical design features (if any).

On the basis of this study, it can be concluded that the results of the performed analyses make evident the effects of SSI on the response of internal components (e.g. Nuclear Building, Vessel-SGs and SG-tubes system) and highlight the criticality of the external building top plate cover confirming also the possibility to achieve an upgrading of the NPP geometry.

References

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