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Influence of Soil-Structure Interaction on the Response of Nuclear Power Stations under Earthquake Excitation

J. Altes
Institut für Nukleare Sicherheitsforschung, Kernforschungsanlage Jülich GmbH, Germany

D. Koschmieder
Institut für Nukleare Sicherheitsforschung, Kernforschungsanlage Jülich GmbH, Germany

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J. Altes and D. Koschmieder

Institut für Nukleare Sicherheitsforschung, Kernforschungsanlage Jülich GmbH, Germany

SYNOPSIS

The influence of different soil properties on the response behaviour of buildings and components was investigated using the finite-element method. The first example is concerned with a high temperature reactor. Floor response spectra and rocking of the pre-stressed reactor pressure vessel are calculated. In another example the influence of soil-structure interaction on the response of embedded buildings is shown.

HIGH TEMPERATURE REACTOR

Response of the Containment

Within the scope of a transferal of an American risk study for high-temperature reactors (AIPA, General Atomic Company 1975 and 1978) to German design and site conditions, commissioned by the German Minister of the Interior (BMI), the highest licensing authority for nuclear power stations, also the seismic risk of the nuclear power station was analysed (KFA-GRS 1980). For this task it was necessary to determine the response of the plant as a result of earthquake intensities (0,2 g) exceeding those of the safe shutdown earthquake (0,1 g).

A three dimensional finite-element model was used to investigate the response of the buildings and components of the reference 3000 MW (t) GA-HTGR plant. Containment and prestressed concrete reactor pressure vessel (PCRV) are coupled with the subsoil by the base mat. Beam-elements with six degrees of freedom at each nodal point (3 translations and 3 rotations) are chosen to represent the dynamic behaviour of the structures.

The analyses are carried out for a mean value of the soil shear modulus of 355 MN/m^2 and the upper and lower fractile of 430 MN/m^2 resp. 280 MN/m^2 to take into consideration the naturally existing variation of the soil properties. The modal damping of the soil lies between 0,05 and 0,08. To provide a broader basis for the investigations and to make them more generally valid also weak soils with shear moduli between 90 and 220 MN/m^2 are considered. Weak soils are normally found at river sites.

The calculations are carried out for a measured and a artificially generated earthquake scaled to 0,1 g. The time-histories were baseline corrected (Koschmieder and Altes 1978). For German siting conditions the San Francisco Earthquake on March 22, 1957, measured at Golden Gate Park, is suited very well. The artificially generated earthquake circumscribes the given design spectrum. The FE-program ASKA was used for the response analyses. Frequencies up to 60 Hz were considered.

In the displacement time histories calculated, the initial natural frequency increasing with growing stiffness of the subsoil can be clearly identified in each specific case (Fig. 1).

The character of the excitation function has an increasing immediate effect in proportion to the growing stiffness of the soil (Fig. 2).

Maximum displacements decrease with increasing soil stiffness. The horizontal displacement increases in proportion to the height of the reactor containment, whereas the containment and prestressed concrete pressure vessel behave as rigid bodies in the vertical direction.

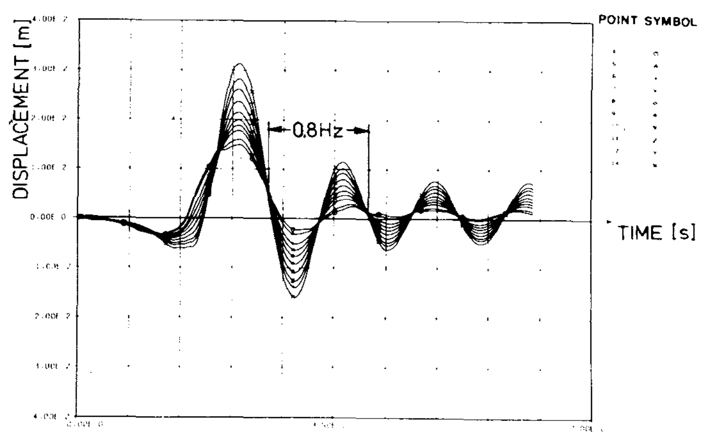

Fig. 1. Response of the containment-building (San Francisco earthquake, shear modulus of the soil 93 MN/m^2)

In the response spectra, the increase in accelerations with growing shear modulus can be observed (Fig. 3). An increase in damping becomes more evident only in connection with a greater shear modulus. The response spectra were used to determine the failure probability of components.

Response of the PCRV

In a separate investigation, the potential rocking of the PCRV was analysed using a very detailed model. In this connection, two variants were examined, i.e. rigid coupling of the PCRV to the base-mat in the two horizontal directions and in the vertical direction and on the other side coupling via prestressing cables in the vertical direction only. In the first case, minor rocking occurs in connection with the strong motion phase (Fig. 4); in the second case, there is only a rigid body movement in the vertical direction (Fig. 5).

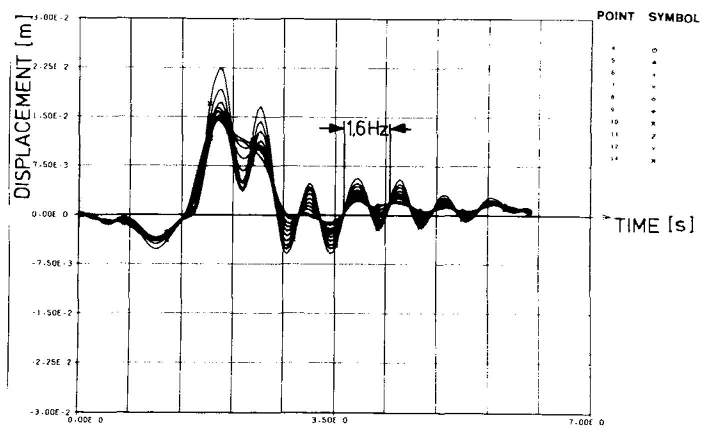

Fig. 2. Response of the containment-building (San Francisco earthquake, shear modulus of the soil 430 MN/m^2).

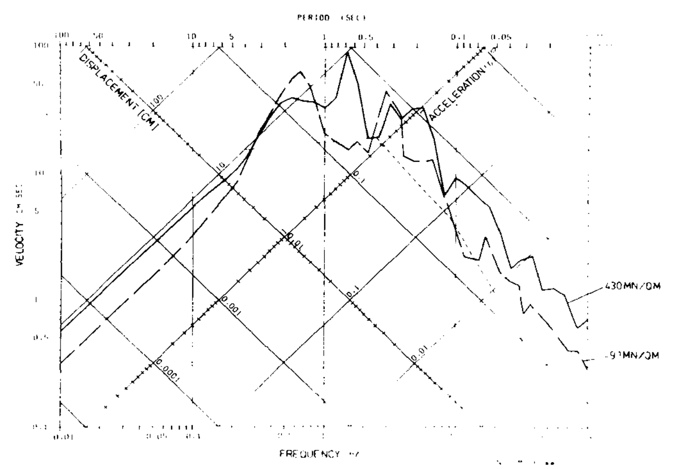

Fig. 3. Response spectra of a point of the containment building

UNDERGROUND SITED PWR-PLANT

In another study entitled "Assessment of Underground Siting of Nuclear Power Plants" (Altes and Koschmieder 1977; KFA-ISF 1978), which was also prepared for the German Minister of the Interior the seismic behaviour of embedded PWR-reactor buildings with the cut-and-cover technique in soil was investigated (Fig. 6). For the calculation of the response the LUSH-program was used. According to Berger et al. (1975) there is a good agreement of the response between two-dimensional and axisymmetric models for points below the ground surface, whereas deviations up to 30 % are observed in the structure above ground level due to differences in flexural strength. It is therefore possible to reproduce the behaviour of both soil and foundation by means of two-dimensional models with good approximation to the three-dimensional conditions.

The depth to be taken into account for the calculation is determined by the geological conditions of the site. The necessary distance between the lateral boundary of the model and the building is recommended to be at least 2 to 2.5 b (b = building width) in the case of high damping. Since it was intended to study only general tendencies in connection with the embedment effect on the response behaviour, a distance of 2 b was chosen in the present case. For frequencies up to 10-15 c/s to be transmitted and a mean shear wave velocity of the subsoil of 220 m/s, the element dimension in the vertical direction should be less than 4 m. The models were excited at the soil-rock interface by the acceleration-time history of the San Francisco earthquake on March 22, 1957 (Golden Gate Park).

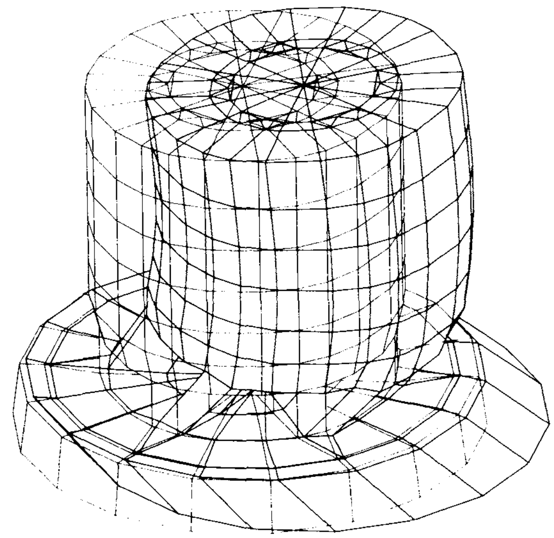

Fig. 4. Displacement of the PCRV, rigid coupling (time: 1,96 s, enlargement: 500 - fold)

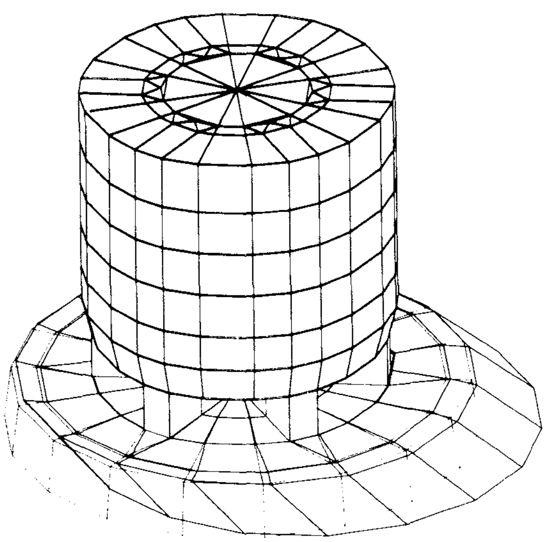

Fig. 5. Displacement of the PCRV, coupling by tendons (time: 1.96 s, enlargement: 500 - fold).

According to Whitman (1976) " the assumption that the motion at the soil-rock interface is independent of the type and the depth of overlying soil is not really correct, but is does serve as a good starting place for understanding general effects", and Kausel (1976) states: "If there is substantial internal damping in the soil or the soil properties are markedly different from those of the underlaying rock, specifying the motion at an outcropping of rock at bedrock would be essentially equivalent."

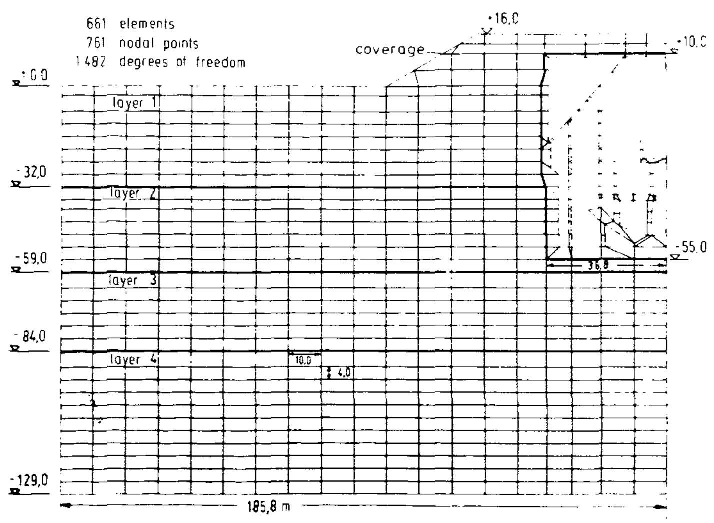

Fig. 6. Finite element model of the totally embedded reactor building

The main results of the investigations are:
The thickness of the subsoil, i.e. the thickness of the soil between the rigid base and building foundation, has a significant influence on the results obtained. With increasing thickness accelerations will substantially decrease towards the surface level at equal seismic intensity. In the case of lower stratum thicknesses, the accelerations will increase in relation to the reference value (Seed et al. 1975, Schnabel et al. 1972, Dezfulian and Seed 1970).

The accelerations calculated for the three models do not differ very much from each other (Fig. 7). At the respective base mat levels the values for total embedment, semi-embedment and surface installation are nearly the same. The same tendency may be observed when using other earthquakes. In the case of vertical excitation, accelerations are more or less constant from rigid base to surface. There is no big difference in the response of embedded buildings on deep soil layers compared with buildings sited aboveground, but the tendency is that the response of embedded buildings is more advantageous than that of buildings located aboveground. The shift of maximum response towards higher frequencies in connection with total embedment has been confirmed by these investigations (Fig. 8).

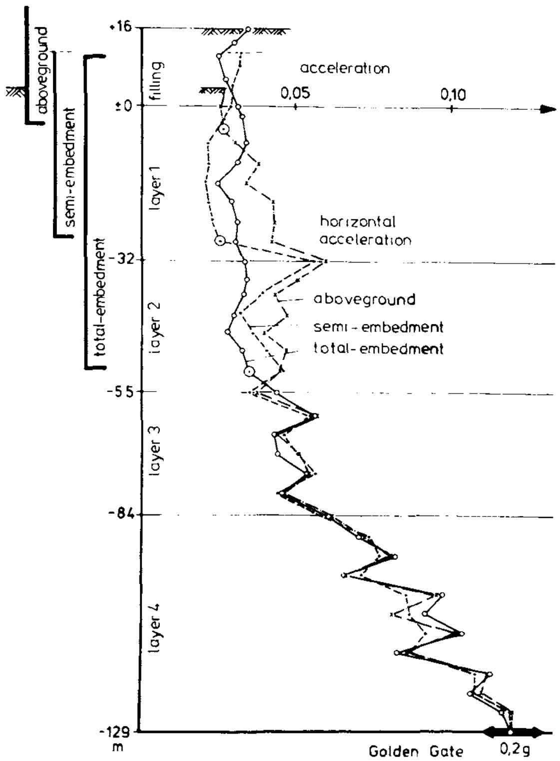

Fig. 7. Calculated accelerations for the three finite element models

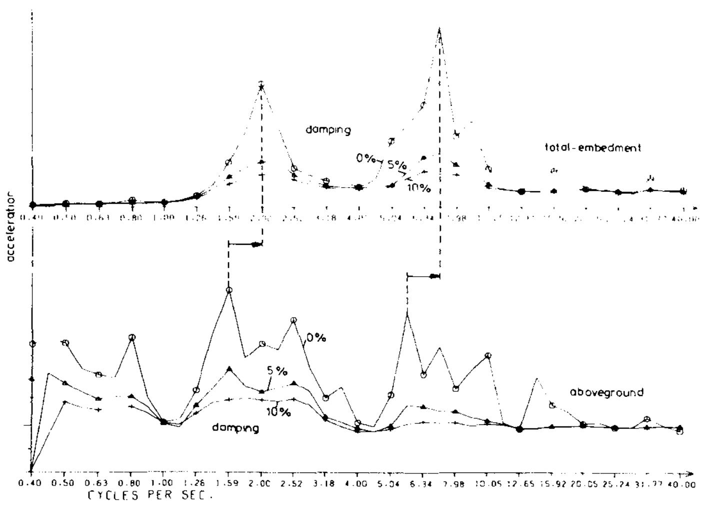

Fig. 8. Influence of embedment on the frequencies of maximum response