Effect of the Flexibility of the Base Mat on Seismic Response of a PWR-Reactor Building

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SUMMARY

Soil-structure interaction analyses are commonly performed by substructure techniques assuming, for simplicity, that the foundation mat is rigid. This facilitates the easy use of soil springs and dashpots (or compliance functions) for the rigid body modes of the foundation.

The flexibility of the base mat influences the stiffness and the radiation damping of foundations. In this paper its effect on the seismic response of an axisymmetric PWR-reactor building is investigated. The base mat of the building is stiffened by cylindrical concrete walls and by a rigid block in the center. Soft and stiff soil conditions are considered.

The structure and its foundation are modelled by axisymmetric shell and volume elements with Fourier expansions in the circumferential direction. The soil is treated as a horizontally layered viscoelastic medium. Soil and structure are coupled along nodal rings. The stiffness matrix of the soil is computed using an explicit semi-analytic solution for displacements caused by ring loads acting on the surface or within a layered medium. The analysis is performed in the frequency domain, and the response in the time domain is computed by the fast Fourier transformation.

The earthquake response of the PWR-reactor building is computed with and without including the flexibility of the relatively stiff base mat. The comparison shows that including the flexibility of the mat has hardly any effect on the resonant frequencies and the damping of the fundamental rocking and vertical modes. This is the case for soft and stiff soil conditions. However, the flexibility of the mat strongly affects the first structural deformation mode, in which the external and internal structures deflect in opposite directions.

1. Introduction

It is common practice in the dynamic analysis of soil-structure interaction problems to model the structural foundation as rigid. This assumption allows the soil to be modeled by soil springs and dashpots, one for each degree of freedom of the rigid foundation. The assumption of a rigid foundation is acceptable for a majority of machine foundations and for structures with a very stiff basement. However, for many structures it may not be a realistic assumption, and hence, there has been considerable interest in recent years in determining the effect of the flexibility on the dynamic stiffness of the foundation.

Previous investigations of flexible foundations have generally been concerned with either determining the frequency dependent complex dynamic stiffness (impedance functions) of a massless plate, or with the response of a plate under dynamic loading. Lin /1/ has computed the dynamic vertical and rocking stiffnesses for massless circular plates which rest on a viscoelastic half-space and have a rigid outer ring. Iguchi and Luco /2/ have considered the circular plate with a rigid core and resting on a viscoelastic half-space. In both investigations the load was applied to the rigid section of the plate. Hence, it was possible to express the dynamic stiffness in terms of a complex scalar. Rectangular plates have been considered by Iguchi and Luco /3/, and by Whittaker and Christiano /10, 11/. In the latter two references uniform square plates with and without mass were considered.

The results of these investigations are difficult to apply to the case of a circular PWR-reactor building. In this case the base mat is stiffened by stiff circumferential walls and by a concrete block at the center. The inertia loads of the structure are transmitted to the base mat by the walls and the center block. The distribution of the inertia loading will affect the dynamic stiffness of the foundation.

The purpose of the present study is to investigate the effect of the mat flexibility on the earthquake response of an actual PWR-reactor building. The structure and its foundation are modeled by axisymmetric shell and volume elements. The soil is modeled as a viscoelastic layered medium. The responses to an earthquake ground motion are compared for a flexible and a rigid foundation. The cases of a medium soft soil and a soft rock are considered.

2. Modelling and numerical procedure

2.1 Soil model

The soil is horizontally layered. It extends laterally to infinity and is bounded in the vertical direction by a rigid base at a finite depth. In the case study of this paper, the depth of the base is chosen such that the model represents soil layers with variable material properties underlain by a thick homogeneous layer which can well approximate the effect of a halfspace /6/. The thickness of the homogeneous layer is chosen to be about 1.5 Rayleigh wave lengths, and therefore is frequency dependent. Material damping is included by the use of complex moduli.

The numerical procedure used has been presented by the first author in /8, 9/ and later by Kausel /5/ with a different derivation and in more detail. It is an extension of earlier work on transmitting boundaries /7, 4/. Explicit semi-analytic solutions for point loads or ring loads acting within a layered medium or on its surface are obtained in the frequency domain. The medium is discretized only in the vertical direction (normal to the layering) by assuming a piecewise linear variation of the displacement field. In the radial (horizontal) direction of a cylindrical coordinate system, Bessel and Hankel functions are used to describe the displacement field. They are solutions to the pertinent differential equations which are obtained from the general equations of motion by separation of variables. A Fourier expansion takes care of the variation in the tangential direction. In the presented applications, only the N = 0 term of the Fourier expansion is needed to describe the vertical motion of the axisymmetric model, and only the N = 1 term is necessary to simulate the horizontal and rocking motion. This results from the assumption that the free field earthquake motion consists of vertically propagating waves.

The evalution of the displacements caused by point or ring loads at a given frequency involves the solution of two uncoupled algebraic eigenvalue problems, one for displacements in vertical planes (Rayleigh wave type) and one for displacements in horizontal planes (Love wave type) /7/. In addition, Bessel and Hankel functions have to be computed. The necessary computations can be performed rapidly and with high precision /7/.

The dynamic flexibility matrix of the nodal rings, at which the soil is to be connected to the structural model, contains the nodal displacements that are produced by unit loads applied at each of the nodal rings. For each Fourier term, there are three degrees of freedom per nodal ring, i.e., radial, vertical and tangential. Inversion of the flexibility matrix yields the complex dynamic stiffness matrix of the layered medium. As the explicit ring load solutions are valid for a horizontally layered medium without an excavation for the structure, the excavation has to be considered separately. To this end, the stiffness, inertia, and material damping of the excavated soil mass is represented by axisymmetric volume elements (torus elements), and a dynamic stiffness matrix is computed for these elements. This matrix is then subtracted from the dynamic stiffness matrix of the layered medium to account for the excavation.

2.2 Structural model

The structure is modeled by axisymmetric shell and volume elements. Consistent with the analysis of the soil model, a Fourier expansion is used in the circumferential direction. The response to the earthquake excitation is first computed in the frequency domain with complex moduli representing the hysteretic material behaviour of the structure. The time history response is then obtained by fast Fourier transformations.

The structure is connected to the soil at several nodal rings as indicated in Fig. 1 by nodes along the soil-structure interface. Equal displacements and equilibrium are enforced at these nodal rings.

3. Case study

3.1 PWR-reactor building

The PWR-reactor building weighs approximately 180 MN. It is a concrete structure with a spherical steel containment. Its outer cylindrical wall has a radius of 32,5 m and is 1,8 m thick. It is topped by a spherical dome and supported by a base mat which has a thickness of 3 m. The external structure as well as most parts of the internal structure are basically axisymmetric. The external and the internal structures are coupled primarily through the base mat. Other slabs which span from the internal structure to the external cylindrical wall (see Fig. 1) rest on sliding supports at the external wall in order to reduce the transmission of airplane impact forces to the internal structure and the equipment.

The foundation mat is relatively stiff due to its thickness and the stiffening cylindrical walls: the 1.8 m thick outer wall, the inner ring wall at radius 21 m with a thickness of 1.0 m, and a third ring wall (which is, however, a relatively ineffective stiffener because of many openings). The central part of the foundation mat is an almost rigid block.

There are actually several radial walls that also contribute to the stiffening of the foundation mat. They are not included in the model, however, because they are not designed to carry a significant portion of the earthquake forces.

The concrete properties are taken for the uncracked condition: Young's modulus is 30 000 MN/m², and Poisson's ratio is 0.2. The Young's modulus of the spherical steel containment is $2.1 \cdot 10^5$ MN/m², and its Poisson's ratio is 0.3. The structural damping of concrete and steel are 7% and 2%, respectively.

The assumption of uncracked concrete will partly compensate for neglecting the stiffening effect of the radial walls on the base mat. It is likely that the overall stiffness of the mat foundation is slightly underestimated in the analyses which include the flexibility of the base mat.

In order to show the effect of the mat flexibility on the structural response, analyses are also performed assuming a perfectly rigid base mat.

3.2 Soil conditions

Two different soil conditions are considered: a "soft" condition (e.g. sand and gravel layers) and a "stiff" condition (e.g. soft to medium soft sedimentary rock). In both cases the shear modulus increases linearly with depth from the foundation at -6m to -146m and then remains constant.

		soft	stiff
Shear modulus in MN/m² (-6m to -146m)		180 to 600	1800 to 6000
Shear wave velocity in m/s (-6m to -146m)		293 to 535	929 to 1690
Poisson's ratio	throughout	0.47	0.4
Material damping	throughout	0.05	0.02

In both cases, the backfill is 6m high. It has a shear modulus of 80 MN/m², a Poisson's ratio of 0.4, and a mass of 2 t/m³.

3.3 Earthquake ground motion

The assumed earthquake ground motion consists of vertically propagating shear and compression waves. Kinematic interaction effects which result from the shallow embedment of the structure are negligible. The time history of the free field horizontal motion at the foundation level is shown in Fig. 2. The peak horizontal acceleration is 0.2 g (peak vertical acceleration is 0.1 g). The response spectra for 2, 7, and 15% damping are also shown. The spectra are similar to the USNRC standard spectra (Reg. Guide 1.60). The spectrum for 15% damping is relatively smooth.

3.4 Response analysis in the frequency and time domain

The dynamic stiffness matrix of the soil and the transfer functions for the structural response to ground motion are computed at about 60 different frequencies between 0 and 13 Hz and 0 and 18 Hz in the soft and stiff soil cases, respectively. The transfer functions are then interpolated automatically by a four point scheme (with a subsequent visual inspection). The interpolation frequencies are those used by the fast Fourier transform for 4096 time steps of 0.01 seconds.

4. Response to ground motion

4.1 Vertical response

Fig. 3a shows transfer functions for vertical acceleration at Points A and C (Fig. 1), caused by a unit vertical ground acceleration, for the soft soil condition and the cases of a flexible and a rigid base mat. The first peak at about 2 Hz corresponds to the rigid body mode of the structure on the flexible soil. The damping of this mode is large (small peak), and is hardly affected by the flexibility of the base mat. At higher frequencies the transfer functions for the flexible and the rigid mat are quite different. Because of the flexibility of the mat, the first deflection mode of the external structure (Point C) is shifted from 11 to 4.7 Hz. The damping of this mode results mainly from radiation damping resulting from soil-structure interaction. The equivalent viscous damping ratio is about 15% for the rigid and 20% for the flexible base mat case.

The response spectra in Fig. 3b show little amplification of the ground motion because of the large damping of the vertical modes. Therefore, the differences in the spectra between the flexible and the rigid base mat cases are not important for practical design purposes.

4.2 Horizontal and rocking response

Fig. 4 shows transfer functions for horizontal structural accelerations, caused by a unit horizontal ground motion, for the soft and stiff soil conditions. The rigid body rocking mode in the soft soil case is at 1.8 Hz. Its equivalent viscous damping ratio is between 15% and 20% for the rigid and the flexible base. In the stiff soil case this mode is at about 4 Hz and shows less damping (between 7% and 10%). In this case the mode is more affected by structural deformations than by soil-structure interaction. However, the effect of the flexibility of the base mat on the rocking mode is still negligible.

The second response peaks for Point A and B in Fig. 4 are strongly influenced by the flexibility of the base mat. In the soft soil case they are shifted from 5.5 to 3.2 Hz and in the stiff soil case from 5.7 to 4.7 Hz. The peaks are increased in both cases by the flexibility of the mat. The mode consists of deflections of the internal and external structure in opposite directions and bending of the base mat.

The response spectra presented in Fig. 5 show that the general response level is not raised by the flexibility of the base mat. However, the peak of the first structural deflection mode is shifted to lower frequencies and amplified. The amplification is more pronounced in the stiff soil case. The response level for the stiff soil condition is about twice as high as for the soft soil condition. This is due to the effects of soil-structure interaction and the loss of radiation damping as the subgrade becomes stiffer.

5. Conclusions

The base mat of the PWR-reactor building, which is actually very stiff, may be considered as rigid in earthquake response analyses. The assumption of a perfectly rigid base mat is fully justified for the computation of the response of the fundamental rocking and vertical modes. This holds for soft and stiff soil conditions. The first deflection modes of the building, in which the internal and external structures deform in opposite directions, are strongly influenced by the flexibility of the base mat. In more detailed analyses one should therefore consider the mat flexibility, even though its effect with respect to soil-structure interaction is small in the investigated cases.

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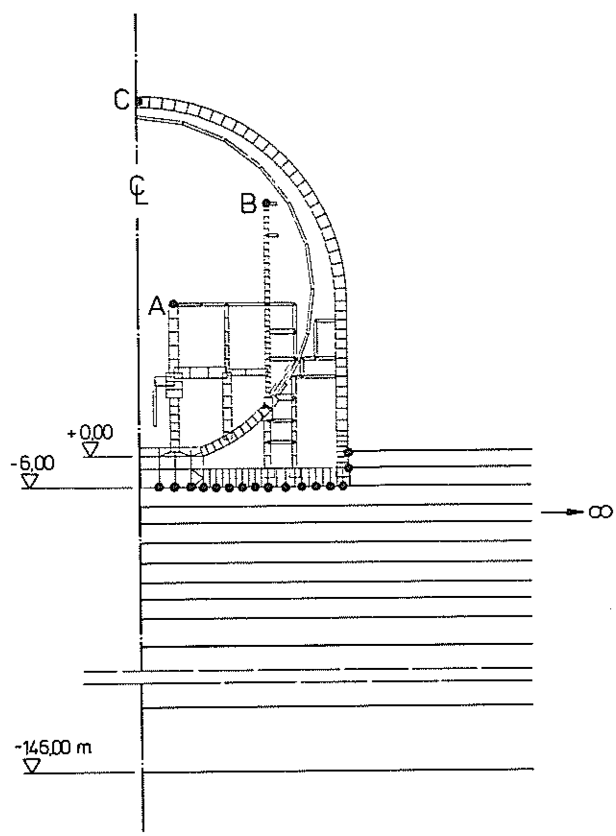
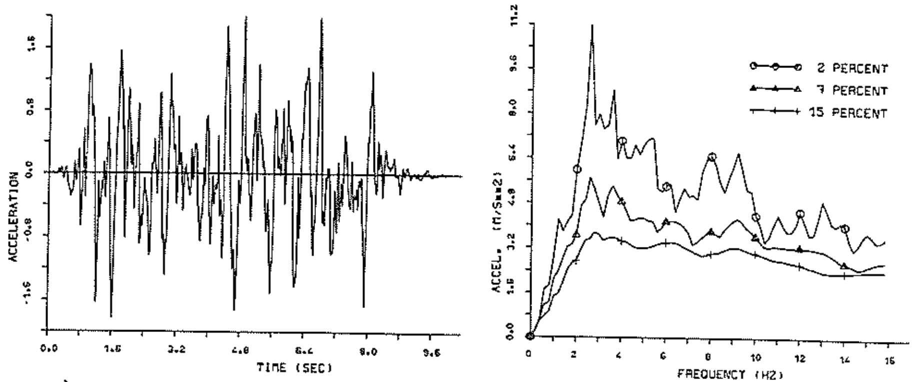


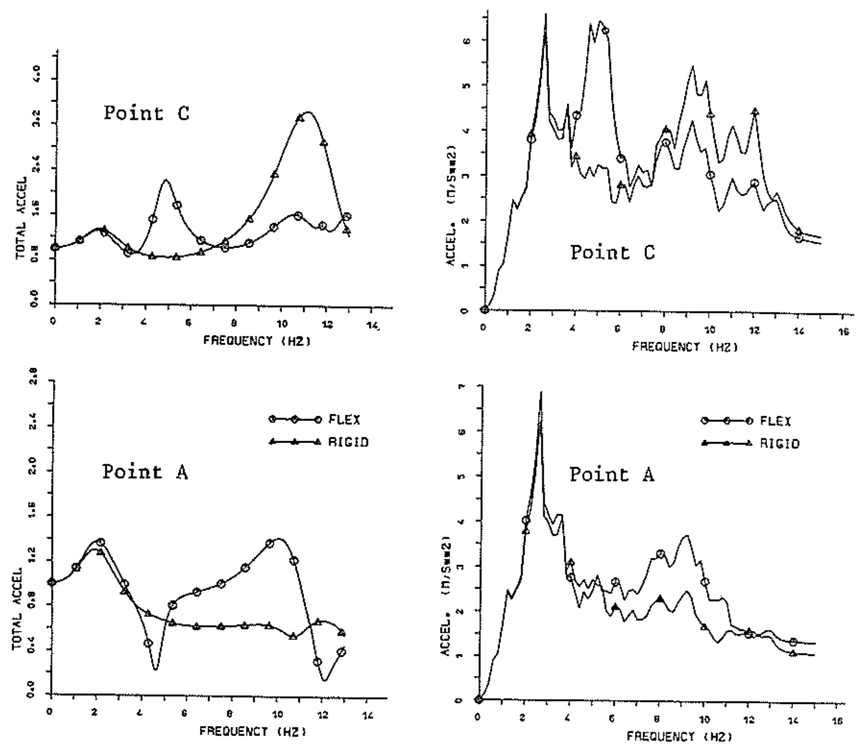
Fig. 1 Axisymmetric model of PWR-reactor building on layered soil



a) ACCELERATION TIME HISTORY

b) RESPONSE SPECTRUM

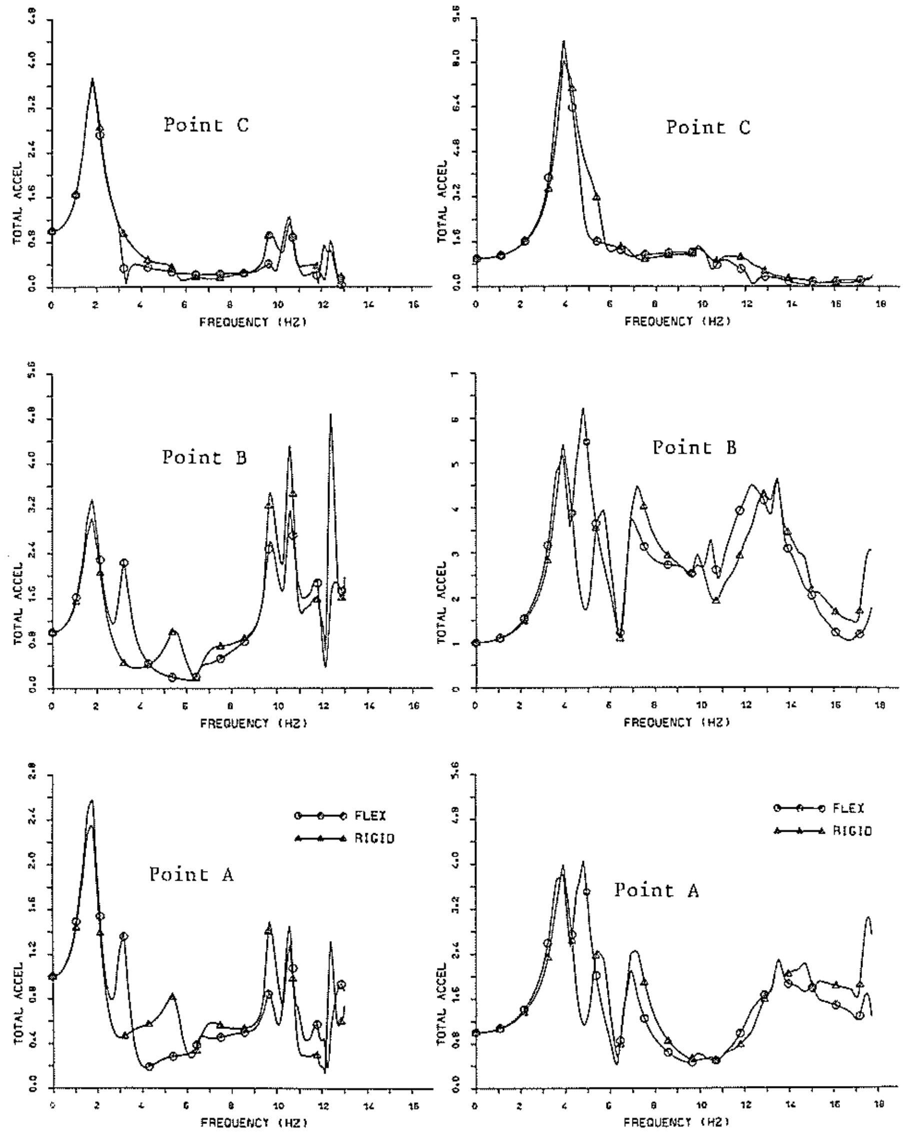
Fig. 2 Horizontal ground motion



a) TRANSFER FUNCTION

b) RESPONSE SPECTRUM at 2% damping

Fig. 3 Vertical acceleration caused by vertical ground motion with max a_v = 0.1g, soft soil condition



a) soft soil condition   b) stiff soil condition

Fig. 4 Transfer functions of horizontal structural acceleration caused by horizontal ground acceleration

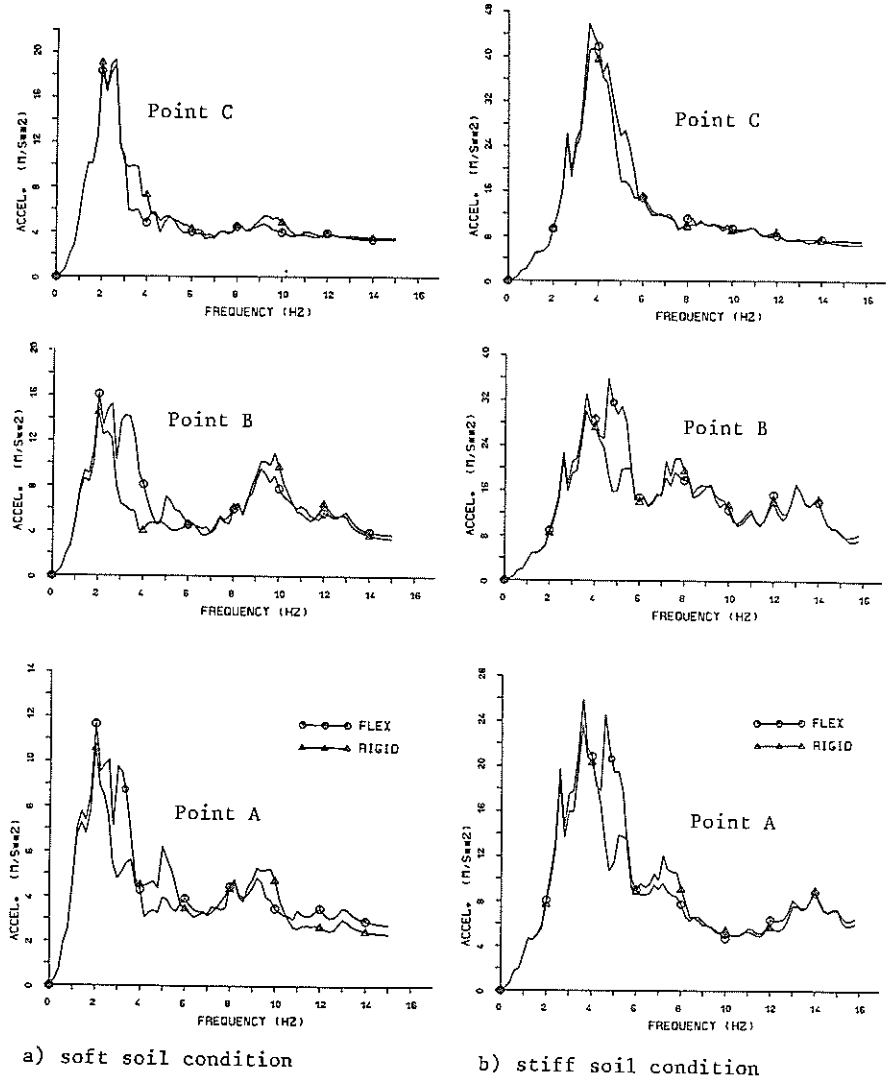


Fig. 5 Response spectra of horizontal structural acceleration caused by horizontal ground acceleration with a_h = 0.2 g; 2% damping