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APPLICATION OF THE DOMAIN REDUCTION METHOD IN SEISMIC ANALYSES OF NUCLEAR POWER PLANTS

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ABSTRACT

A Domain Reduction Method (DRM) procedure is developed for the seismic analysis of the reactor building of a nuclear power plant. In the first step, the frequency domain software DESOIL/BAUBOW is used to determine the seismic wave field. In the second step, the software ANSYS was used for calculations in the time domain in order to be able to consider non-linear effects in the installation equipment, building or soil.

This paper reports on experiences and findings in the practical implementation of the DRM. Among other things, the size of the reduced domain, the mesh resolution and the frequency range that can be mapped are discussed. The developed DRM procedure is being verified in two benchmark analyses. For this purpose the results of pure frequency domain analyses are compared with the results of the developed DRM procedure (e.g. floor response spectra).

INTRODUCTION

This paper presents a practical application of the Domain Reduction Method (DRM) for a nuclear project in practice. The DRM is described and recommended in ASCE/SEI 4-16 (2017) for the application of SSI analyses of nuclear power plants.

First, the theory of DRM is briefly discussed. Then, the implementation of the method is presented with the corresponding background of the incorporated software applications. The individual steps of the implementation are explained in detail using the seismic analysis of a reactor building embedded in the soil. Thereby, hints are given how to validate the single implementation steps by checks. Finally, both the implementation steps of the DRM and the modeling are evaluated in two benchmark studies: one considers the free-field seismic motion, the other the induced vibrations within the reactor building.

DOMAIN REDUCTION METHOD

The Domain Reduction Method (DRM) is a numerical two-step method for modelling earthquake induced ground motion in three- dimensional problems. The method was developed and verified by Bielak et al. (2003) and Yoshimura et al. (2003) to overcome the problem of multiple physical scales which are present when considering the earthquake source, the wave propagation path and the region of interest at the surface.

The DRM divides the entire problem, consisting of the seismic wave field at large scale and of the structure under consideration, into two simpler ones.

The first is an auxiliary problem where a domain of large scale is simulated which contains the seismic wave field, probably including the seismic source, as well as the region of interest, i.e., the neighbourhood of the structure to be analysed. This domain contains a rough reproduction of the composition of the global substrate, i.e., the wave propagation path in subsoil and bedrock, but neither the structure of interest itself nor a detailed mapping of the near-field is modelled (Figure 1(a)). Since all localized features are removed in this first step of simulation, it is referred to as background problem. The complete seismic wave field is simulated in the large-scale substrate including the region of interest. For the first step of the DRM, any appropriate method can be utilized. The aim is to compute motions that can be transferred to a seismic excitation for the second step.

In this second step, the domain is reduced to the neighbourhood of the structure of interest (Figure 1(b)) and loaded with forces equivalent to the initial seismic excitation from the first step. These forces induce the seismic waves into the considered domain, which contains now the structure of interest that can be analysed in detail (e.g. considering non-linear effects). The reduction of the analysed domain in this second step is enabled since the equivalent seismic forces act only within one single layer of elements adjacent to the interface between the region of interest and the exterior domain. Through this method, the wave propagation from the large-scale simulation can be transferred to a model, which describes only the near-field of the structure. The aim is to analyse the response of the structure and the region of interest.

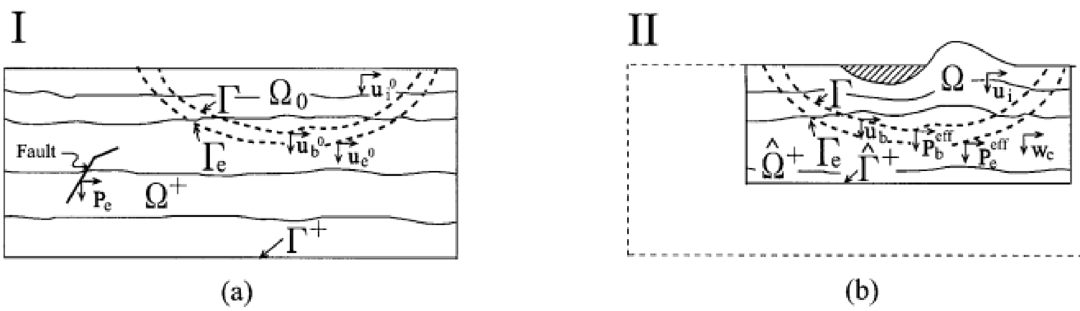

Figure 1. Schematic sketch of the two steps of the domain reduction method (from Bielak et al. (2003)).

DEVELOPED 2-STEP DRM APPLICATION

Starting from these theoretical basics, a two-step DRM application for analysing the earthquake response of a region containing a structure of interest and other localized features is established. In the version of the DRM developed here, a one-dimensional deconvolution analysis in frequency domain is applied for the first step of the DRM. In the second step a three-dimensional finite element analysis in time domain is performed.

DRM-Step I: DESOIL

In the first step (see Figure 1(a)) a background problem is analysed which embraces the domains Ω_0 and Ω^+. The interface Γ between the two domains Ω_0 and Ω^+ defines the boundary of the region of interest in the second step. Then, the free-field motions u_e^0 and u_b^0 are computed on the adjacent surfaces Γ and Γ_e and stored for the respective nodes. For this step, any appropriate method can be used by which the wave propagation between the seismic source and the region of interest can be simulated. The usage of the finite element method is computational expensive in this case and requires the implementation of absorbing boundaries. More efficient alternatives are, amongst others, the thin layer method, as employed in the present application in software DESOIL (2016).

DESOIL computes transfer functions of horizontal and vertical acceleration in horizontally layered soil profiles based on a rigid or elastic halfspace. Total or incident waves of seismic excitation at base can be considered. The earthquake is idealized as vertically propagating shear- or compression waves in a one-dimensional subsurface structure. The seismic wave response in the frequency domain is calculated linear-elastically using the multiple reflection theory. By means of the transfer functions between different soil layers determined with DESOIL and the Fourier transformations, the displacement and acceleration time histories at different soil depths can be determined within a deconvolution analysis with given response time histories at the soil surface. The thus determined time histories in the soil profile represent the seismic wave field in the free field.

DRM Step II: ANSYS

In the second step (see Figure 1(b)) the region of interest Ω is now modelled with the structure as well as all localized features. At the same time, the outer domain Ω^+ is reduced to a domain $\Omega^{\wedge+}$ which does not need to include the seismic source. This reduction is possible since the effective forces P^{eff} of the seismic excitation are solely acting on the bounding layers Γ and Γ_e adjacent to the region of interest. These equivalent forces are computed from the free-field motion u_e^0 and u_b^0. Hereupon, the total fields of motion u_i, u_b and the residual field we can be derived. Those fields of motion describe the behaviour of the region of interest, i.e., of the detailed modelled soil and of the structure connected to it.

In the second DRM step, the commercially distributed and widely used software ANSYS (2019) is employed. Initially, a soil model is generated with 3D volume elements, in which the same layering of the soil as in the first DRM step is considered. The linear-elastic material parameters of the solid elements of the soil correspond to those from the DESOIL analysis. Only with regard to the hysteretic material damping, different assumptions have to be made, since it is possible to specify the damping frequency-independent for analyses in the frequency domain (Step I), but not in the time domain (Step II).

After the soil model has been created, the adjacent surfaces Γ and Γ_e, the so-called DRM crust, are defined. When choosing the crust, the issue of residual waves has to be considered. If necessary, appropriate absorbing conditions at the boundary of the soil model have to be provided. For the volume elements of the crust, the element matrices are now read out and multiplied by the motion quantities located at the edges Γ and Γ_e that are determined in Step I. The results are the equivalent time-dependent force vectors P^{eff} acting on the nodes of the crust. In principle, these equivalent forces induce the same wave field in the inner area as that determined in Step I. Deviations can occur due to the use of different program systems and the associated different numerical solution of the problem (different numerical methods, solution algorithms, discretization, etc.).

In the final calculation step, the local structure, i.e. the structure under investigation, is inserted into the ANSYS-model and the analysis is performed in the time domain under the load of the time-dependent force vectors P^{eff} on the DRM crust. With them, the basic equation of motion is solved by a direct time-integration. During the transient analysis, inertia or damping effects are considered.

BENCHMARK CASE: SSI-ANALYSIS OF REACTOR BUILDING

The DRM application procedure described above is applied to the seismic analysis of a reactor building of a nuclear power plant.

The reactor building is founded embedded in the subsoil. The stratified soil in the upper 10 m consists of gravel with underlying opalinus clay. The bedrock is present at a depth of about 80 m. Due to the site situation with respect to the foundation and the typical design of the reactor building (high stiffness, large mass), the soil-structure interaction has a significant influence on the seismic response of the building. For the analyses performed here, best estimate values are adopted for the soil parameters.

The reactor building is a typical boiling water reactor with a height of ~66 m and a diameter of ~38m. The foundation base is ~15 m below terrain level. Figure 2 shows the soil profile with the embedment as well as a model view of the building, from which the rough dimensions can be seen.

The seismic excitation is given in the form of a ground response spectrum defined at terrain level and compatible acceleration time histories.

In the benchmark analyses presented here, the previously presented DRM application procedure is applied. First, the wave field in the ground, that induces the given seismic motion at the ground surface, has to be determined. This is accomplished with DESOIL as described above by computing the seismic free field motion at the distinct layer boundaries in the soil in terms of displacement and acceleration time histories in the spatial directions. Second, by means of the DRM time histories of effective forces are calculated at the DRM crust. The forces are based on the displacement and acceleration time histories computed by DESOIL. Third, a 3-D transient analysis is performed, using the ANSYS-model and the time histories of the forces, which are acting at the DRM crust inside the soil.

In the first benchmark analysis, the ANSYS model consists only of the soil model. In the second benchmark analysis, the soil model is supplemented by the model of the reactor building.

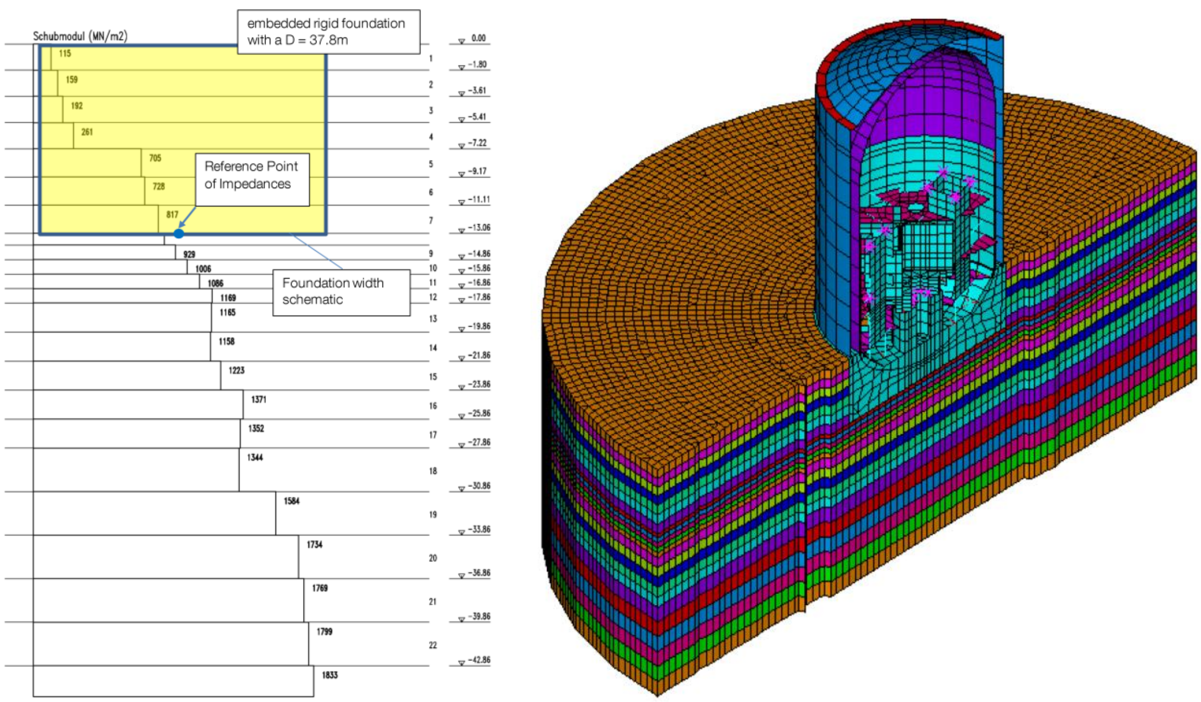

Figure 2. Benchmark case: Soil profile with the embedment (left), model view of the embedded reactor building (right).

BENCHMARK ANALYSIS 1: FREE FIELD

In the first benchmark analysis, it is checked whether the developed DRM application is able to reproduce Step I of the DRM correctly. In other words, it is to be checked whether the undisturbed seismic wave field is correctly transferred to the ANSYS model.

For this purpose, the wave field is first recalculated into the deeper layers of the soil by means of a deconvolution analysis. A vertically propagating shear wave field is assumed. With the displacement and acceleration quantities of the wave field in the soil, the DRM forces on the neighboring boundaries (the "DRM crust") are determined according to the procedure described above. These forces are used to excite the soil. In this Benchmark Analysis 1, they are intended to produce the same motion of the soil as initially entered.

The specific implementation of the DRM steps (Step I, Intermediate Step and Step II) is schematically outlined in Figures 3 and 5 and proceeds as follows.

Step I: Seismic motion in free-field (DESOIL)

Starting point is a seed of time histories which are compatible to the ground response spectra in the three spatial directions. With this seed of input time histories, the acceleration and displacement time histories in the different soil depths are determined using the transfer functions derived by DESOIL. The frequency-dependent transfer functions from the soil surface to the respective soil layers are calculated up to 40 Hz. For the further processing in the DRM only the time histories of the accelerations and displacements at the layer boundaries are needed, however, for verification purposes the response spectra of the accelerations are also determined. The transfer functions of the acceleration in horizontal direction and the corresponding response spectra are shown exemplarily for the upper eight soil layers in Figure 4 (layer 1 is the soil surface).

The increasing reduction of the acceleration with increasing depth can be clearly observed. While the reduction in the upper soil layers takes place in the upper frequency range (>30 Hz), the reduction in layer 8 (at a depth of ~8 m) shifts to the range of 5-15 Hz, which is relevant for earthquakes.

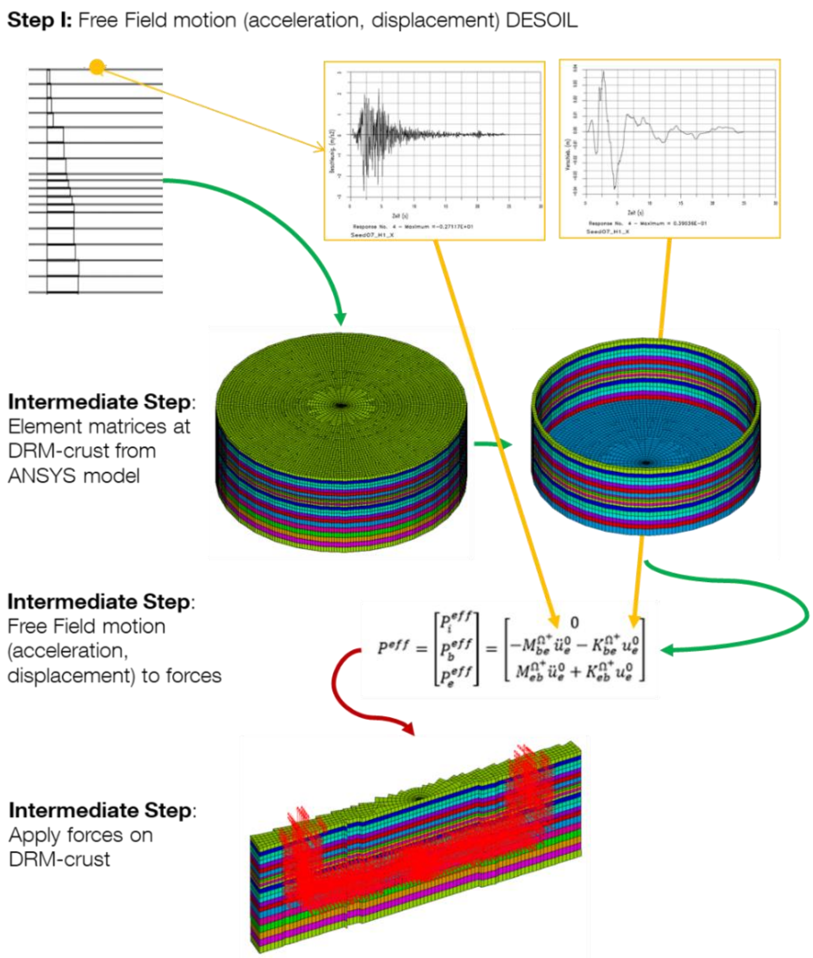

Figure 3. Schematic sketch of Step I and Intermediate Step (both apply for Benchmark Analysis 1 and 2)

Intermediate Step: Effective force vectors on DRM crust

In the Intermediate Step, the ANSYS model of the soil is needed to derive the element matrices of the elements of the DRM crust. With those the effective force vectors on the DRM crust are calculated with the acceleration and displacement time histories derived in DESOIL.

Step II: Free-field analysis with DRM-ANSYS

As described above, it shall first be verified that the developed DRM procedure is capable of correctly mapping the seismic wavefield. Therefore, it shall be checked whether the seismic wave field computed with ANSYS and using the effective force vectors in the free field, corresponds to the wave field from DESOIL (DRM Step I). For this purpose, the pure soil model without the reactor building is analysed.

The hysteretic damping for the soil layers is defined in the soil profile as frequency-independent parameter. Since frequency-independent damping parameters are not provided for time domain analysis, frequency-dependent Rayleigh damping is defined in the ANSYS model. The damping values given for each soil layer are transferred to Rayleigh parameter using support frequencies, which cover the relevant range of the eigenfrequencies.

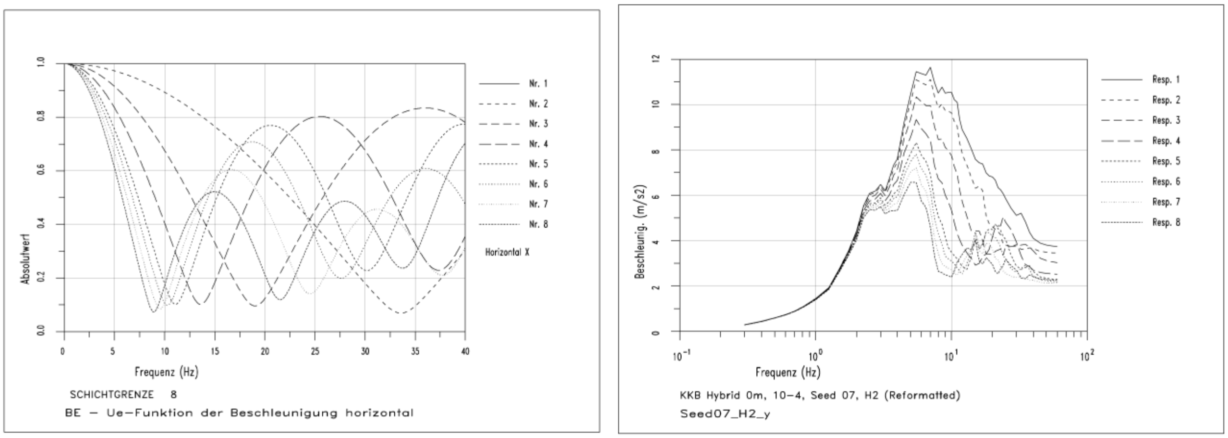

Figure 4. Transfer functions from soil surface to layer 1-8 (left), response spectra of acceleration for soil layers 1-8 (right)

Based on the soil profile, a layered soil body is created with volume elements in order to carry out the transient analysis. The idea is to build the soil model in the shape of a cylinder adapted to the base area of the reactor building. The cylindrical body has a height of 46 m and a radius of 64 m. The modelled solid elements have a maximum dimension of about 1.5 m x 1.5 m in horizontal direction. In vertical direction, the element size is defined by the thickness of the soil layers. The model is supported at the bottom (translational degrees of freedom are fixed), all other model boundaries are free.

The DRM crust is chosen to be cylindrical at a radial distance from the center of the reactor building. In addition, a buffer zone at the periphery of the model is provided. This zone should absorb the residual waves leaving the DRM area (this effect occurs when inserting the building). The size of the buffer zone and the chosen boundaries of the model should be sufficient to absorb the residual waves. For the case considered here, this is shown in the transient analysis including the reactor building (Benchmark Analysis 2).

The entire soil model has a radius of ~63 m. In vertical direction, the model measures ~45 m. Overall, the whole soil model contains ~144000 volume elements and ~151000 nodes.

The dimension of the DRM domain is a sensitive parameter in the DRM analysis. To evaluate the influence of the size of the DRM domain, the free-field study is carried out for two different sizes of the DRM domain:

- Model FF1: DRM-domain (inside DRM crust): $R \approx 44$ m, $H \approx 28$ m
- Model FF2: DRM-domain (inside DRM crust): $R \approx 34$ m, $H \approx 14$ m

Figure 5 shows the deformation of the two models excited by the effective seismic forces at one time step. It can be seen that in both cases only the area within the DRM crust is deformed. No significant displacements occur in the outer area. It is therefore not necessary to apply absorbing boundary conditions at the boundary of the model. Nevertheless, absorbing boundary conditions were introduced into the model FF1. The results differ only insignificantly, which confirms the previous statement about the necessity of absorbing boundary conditions.

To verify the free field motion, the horizontal accelerations and displacements at the central surface point of the soil model are compared with the corresponding values of the DESOIL analysis for both models (see Figure 6). Apparently, the time histories are in good agreement. Slight deviations occur for both models in the vertical acceleration time histories.

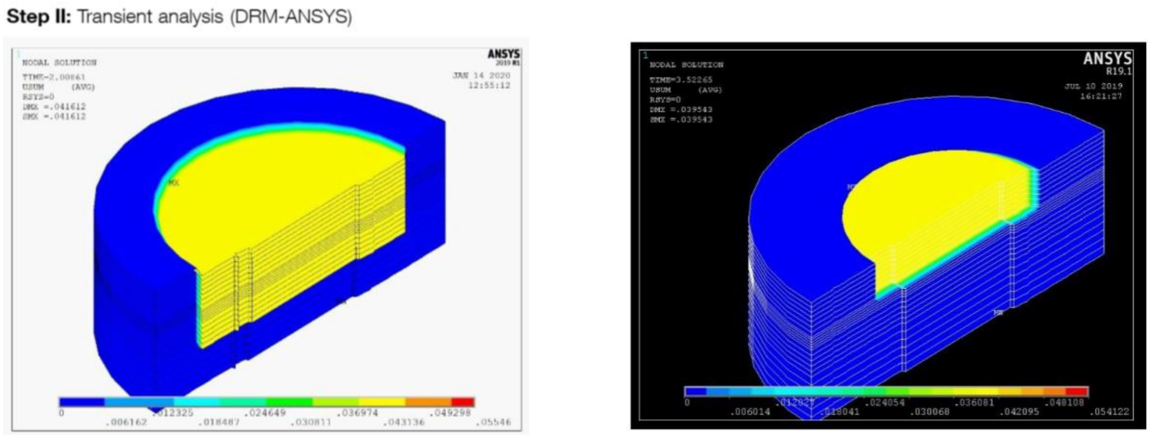

Figure 5. Benchmark Analysis 1, Step II: Displacement field in soil body for model FF1 (left) and FF2 (right)

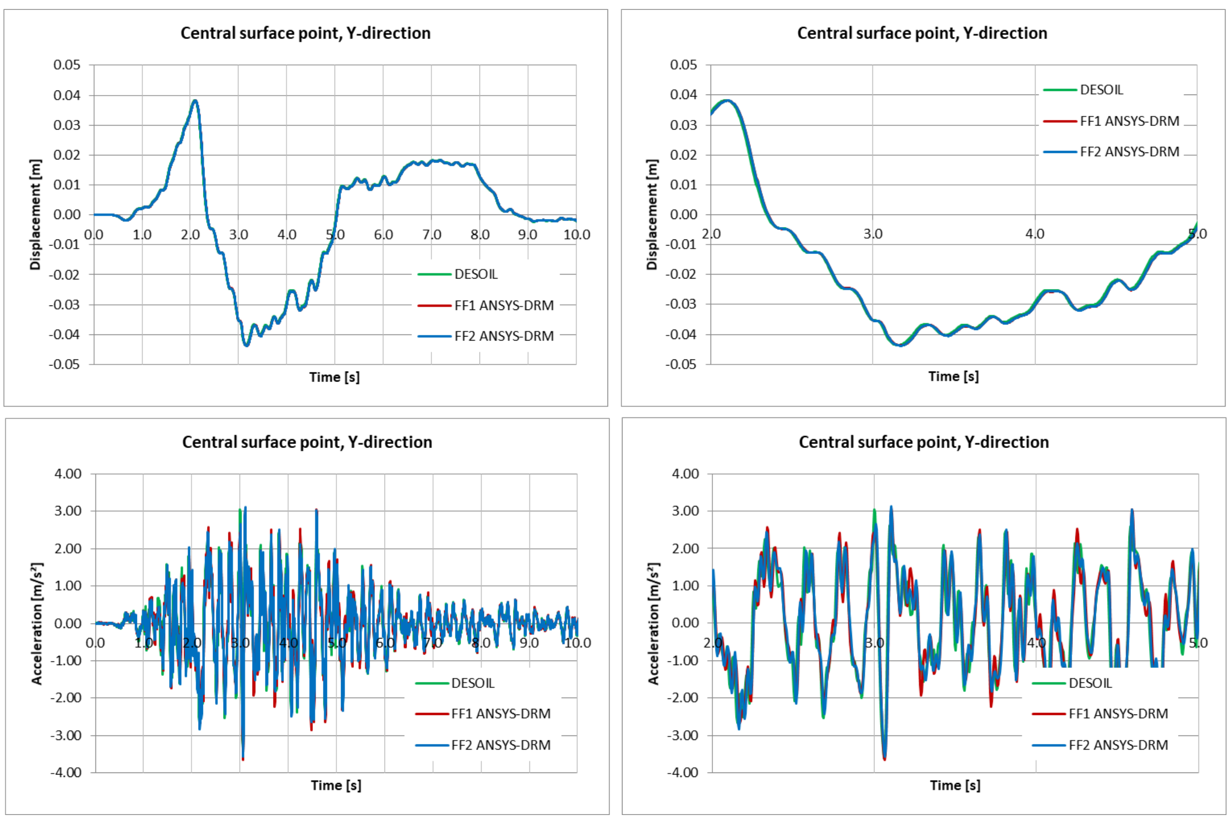

Figure 6. Comparison of time histories of displacement and acceleration for the central surface point (DESOIL and ANSYS-DRM models FF1 and FF2)

In addition, the acceleration response spectra are compared with each other. The results are shown in Figure 7 for the two models. The spectra are also generally in good agreement. In the frequency range up to 15 Hz, the values of the spectral accelerations correspond very well. In model FF1 - and to a lesser extent in model FF2 - deviations are found in the higher frequency range.

For both model variations, it is to be expected that these high-frequency acceleration peaks will no longer be observed in the model containing the building, since the building on the soil amplifies the low-frequency excitation and reduces the higher-frequency components. Regarding this aspect, both models are therefore considered suitable for further analysis including the building.

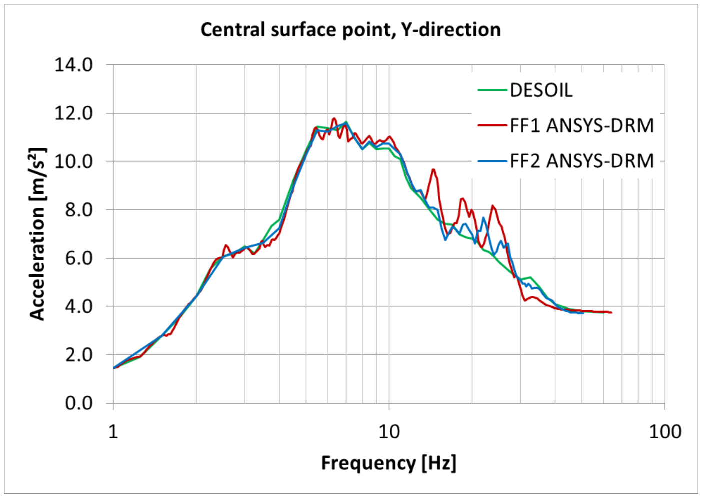

Figure 7. Comparison of horizontal acceleration response spectra (D=5%) for the central surface point (DESOIL and ANSYS-DRM models FF1 and FF2)

Another aspect, however, is the effects of the altered wave field caused by the building introduced into the DRM domain. These waves, additional to the free field motion, can cause problems in too small DRM domains if they are reflected outside the DRM crust and re-enter the DRM domain. In a sufficiently large DRM domain, these effects are damped due to the geometrical dimensions such that their influence on the overall performance is negligible. For this reason, the larger DRM domain (model FF1) is chosen for further analyses.

BENCHMARK ANALYSIS 2: MODEL CONTAINING SOIL AND BUILDING

In the second benchmark analysis, the seismic behavior of the reactor building is analyzed, taking into account the soil-structure interaction. The reactor building is introduced into the soil model for the DRM-ANSYS analysis (see Figure 2, right). The first DRM step (DESOIL analysis) and the Intermediate Step (generation of DRM forces at the DRM crust) are the same of the benchmark analysis in the free field (model FF1). The second DRM step follows the same procedure as in Benchmark Analysis 1, i.e., a transient analysis with excitation by the DRM forces, except with the combined model of soil and building.

Two SSI analyses performed in the frequency domain are used here as benchmarks for the DRM analysis. In the frequency domain, the radiation damping into the soil can be determined very realistically. The radiation damping is of decisive importance for the problem under consideration in this paper.

The one frequency domain analysis is performed with the software SASSI (2018) originally developed at UC Berkeley, the other with the software BAUBOW (2018) used in combination with the software SAP2000 (2019). BAUBOW developed by HOCHTIEF is based on similar assumptions as the SASSI programs (thin-layer method) and has been employed in continuously developed versions since the 1980s, especially in the analysis of nuclear structures. Details on BAUBOW can be found in Waas et al. (1985) and Borsutzky et al. (2019).

The benchmarking is performed by comparing selected floor response spectra inside the reactor building. The comparison is based on the same conditions regarding soil, building and excitation.

Concrete and steel structures in the reactor building are damped with D = 7% resp. 4%. In the frequency domain analyses, these ratios can be applied directly without any dependence on the frequency.

For the transient analysis (DRM-ANSYS) both damping ratios are converted to the appropriate Rayleigh damping values with appropriate support frequencies. As mentioned above, the modelled soil layers include Rayleigh damping, too.

Figure 8 shows the deformation of the combined model excited by the effective seismic forces for a certain time step. It can be seen that only the area within the DRM crust is deformed. The displacement time histories are checked for selected control points inside and outside the DRM crust: as desired no significant displacements occur in the outer area.

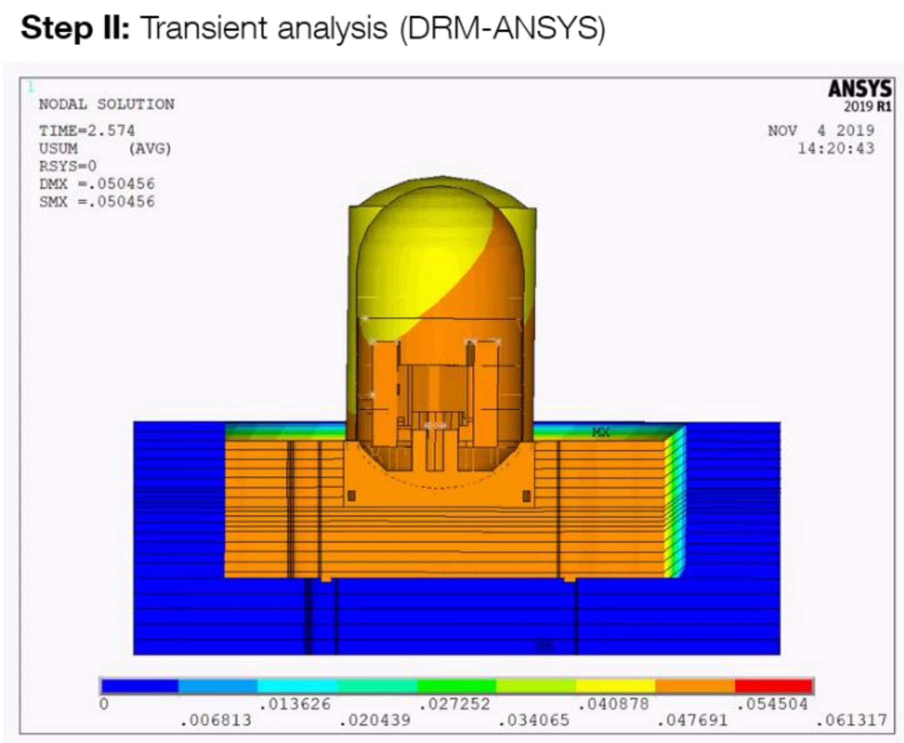

Figure 8. Benchmark Analysis 2, Step II: Displacement field in soil and building

For the benchmarking, the floor response spectra (FRS) at selected nodes in the reactor building are compared. Exemplary a comparative plot of the FRS for a node in the building is shown in Figure 9. The comparison of the floor response spectra for this and the other selected nodes show a good agreement between the results of the three methods.

Thus, this study shows that the developed DRM application can solve SSI problems equivalently to the methods in the frequency domain.

CONCLUSION

The presented benchmark analyses demonstrate the capability of the developed DRM application procedure to solve the soil-structure interaction problem equivalently to frequency domain analysis. Moreover, the DRM-ANSYS procedure provides the opportunity to capture nonlinear effects. Consequently, the models presented here were supplemented in a further step by plant components in the reactor building, which then were analyzed nonlinearly with the presented procedure.

In summary, the DRM method is a well suited approach to combine the advantages of a frequency domain analysis (proper mapping of radiation damping) with the advantages of a transient analysis (e.g. capturing nonlinear effects). The developed DRM application procedure provides an efficient tool for the application of the DRM.

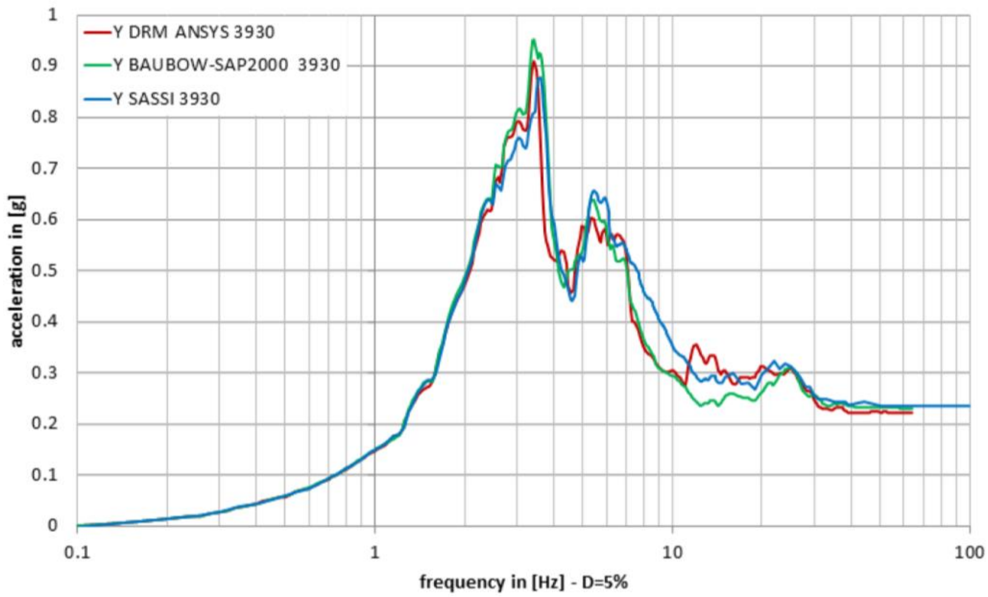

Figure 9. Exemplary comparison of horizontal FRS (D=5%) for the three methods

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