Transactions of the SMiRT 27
Yokohama, Japan, March 3-8, 2024
Division V

SEISMIC SOIL – STRUCTURE – INTERACTION ANALYSIS OF A RADIOACTIVE WASTE REPOSITORY CONSIDERING ON SITE MEASUREMENTS AND SUBSOIL IMPROVEMENT

Sotiria Karapetrou[1], Marco Hildmann[2], Fritz-Otto Henkel[3]

[1] Dr. Ing, Municipality of Nea Propontida, Greece, (sotiria.karapetrou@gmail.com)
[2] Dipl.-Ing. (FH), Woelfel Engineering GmbH + Co. KG, Hoechberg, Germany
[3] Senior Expert, Woelfel Engineering GmbH + Co. KG, Hoechberg, Germany

ABSTRACT

Aim of this paper is to present the modelling and analysis steps for the evaluation and design of a repository structure, which will be used as a long-term storage for low and intermediate radioactive waste. Its initial design began in the early 90ies but it was not concluded at that time. As the seismic requirements increased significantly over the past years, the new design of the construction is required. Two analysis cases are implemented considering both the soil – structure interaction effects. In the first case, the soil –structure system is considered in one single model implementing the substructuring method. In the second case the soil – structure interaction effects are determined in a two-step modelling procedure by generating at first appropriate soil springs and introducing them continuously to the numerical model of the structure. These two separate analysis procedures are required in order to achieve an integrated evaluation and design process not only of the repository structure itself but also for the various components.

INTRODUCTION

A deep geological repository is considered to provide a stable geologic environment that is required for storing hazardous or radioactive waste. The aboveground repository under investigation is a reinforced concrete construction with a steel winding tower, which was first designed in the early 90ies at the site of a former mine to be used as a long-term storage for solid and solidified low and intermediate radioactive waste with negligible heat generation. However, the initial design of the repository was not concluded at that time so that new seismic design is required to take into account the modern seismic standards. The earthquake is defined now by an elastic free field spectrum, which in the resonance frequencies is three times higher than the original one. Thus soil structure interaction (SSI) is taken into account in the analysis, in order to eliminate potential conservative effects resulting from the higher seismic design intensity.

Two separate three-dimensional numerical models were developed for the new seismic design, performing two analysis cases, which both take into account the soil-structure interaction. Due to the lack of additional data regarding the dynamic properties of the different soil layers, on site measurements were performed and more specifically crosshole measurements to gain insight on the dynamic soil characteristics. Additionally due to the relatively high and non-uniform settlements of the foundation slab caused by static loading, it was decided to improve the subsoil environment using the high-pressure injection (HPI) technique. The HPI columns are integrated in the SSI models in order to take into account in a reliable basis the impact of the soil improvement in the dynamic response of the soil.

The SASSI software is used for modelling the SSI effects and perform two separate analysis cases. In the first analysis case, the sub-structuring method is implemented to account for the soil –structure interaction effects. This modelling approach is used to define the floor acceleration response spectra in horizontal and vertical direction. In the second analysis case, the soil – structure interaction is considered through the introduction of impedance functions, which are used to generate soil springs distributed under the different foundation parts of the construction. This latter model is used for the general structural design of the repository using the program Sofistik. Figure 1 summarizes the workflow of the implemented cases of analysis as described above.

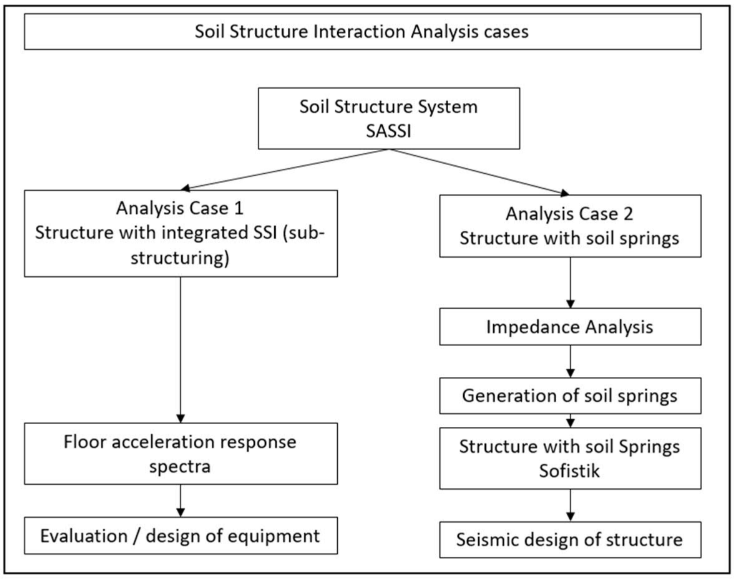

Figure 1. Workflow of the implemented analysis cases of the repository model considering SSI effects

DESCRIPTION OF THE RADIOACTIVE WASTE REPOSITORY

The repository under investigation is a reinforced concrete construction which consists of various building parts: the shaft consisting of a basement and a hall (A in Figure 2), the shaft hall extension part (B in Figure 2), the main control center building (C in Figure 2), the steel winding tower (D in Figure 2), an elevator tower (E1 in Figure 2) and the staircase (E2 in Figure 2). All building parts, except for the winding tower, are reinforced concrete structures and rectangular shaped with their structural systems comprising mainly concrete walls. The steel winding tower is a frame structure including steel frames with reinforced concrete slabs.

The dimensions of the shaft basement and shaft hall are L/B/H = 23,30/20,30/6,80 m and L/B/H = 23,30/20,30/40,00 m including the winding tower respectively. The basement has a foundation depth of -6,80 m. The shaft structure is founded on a reinforced concrete slab. The shaft hall walls are separated from the walls of the shaft hall extention and the main control center building vertically by strucural joints. The shaft hall extension has dimensions of L/B/H = 23,30/12,87/15,84 m and is founded on strip foundation at a depth of -0,70 m. Finally the main control center building has dimensions of L/B/H = 19,90/6,80/12,50 m and is founded partially on a slab and partially on a strip foundation at a depth of –3,00 m. At a depth of -3.35 m to -0.04 m, the foundation of the main control center building is connected to the outer walls of the shaft cellar. The different building parts are separated in the vertical direction through structural joints.

The concrete and steel material types defined for the different structural parts are: Beton C20/25; C25/30; C30/37, reinforcing steel B500 and structural steel S235; S355. The 3D Finite Element Modelling of the structure is conducted with the programs Sofistik and Femap. Beam and Shell elements were used to model the different structural components of the repository building. Elastic properties of the materials are considered. The total mass of the structure, including the dead weight of the structural components and the weight of the equipment, is 12.530,19 t

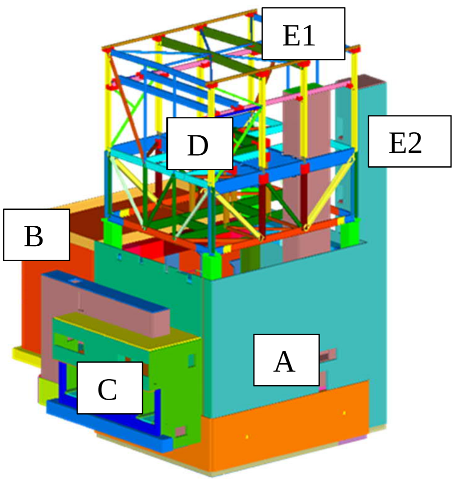

Figure 2. Isometric view of the repository construction

SEISMIC REQUIREMENTS

New seismic design of the repository is required to take into account the modern seismic standards. The shape of the new design spectrum is represented through the normalized free field acceleration spectrum for a damping value of 5%. According to KTA 2201.1, the design spectrum of the vertical component is defined as the 2/3 of the horizontal one.

The design spectrum was used to select a set of three statistically independent acceleration time history records to perform the seismic analysis in SASSI. The total duration of the excitation was selected to be approximately 10 sec with the strong motion duration to be 5 sec. The selection of the seismic records was made using the IRIS software. The acceleration response spectra of the selected records are shown in Figure 3 in comparison to the free field design spectrum.

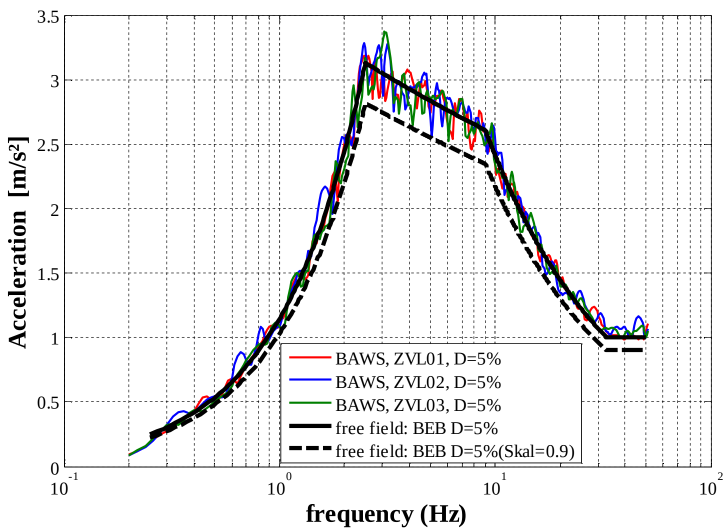

Figure 3. Acceleration response spectra of the selected seismic records in comparison to the free field design spectrum

SOIL STRUCTURE INTERACTION

Soil modelling

According to the available geotechnical survey, the soil profile consists of various silty and sandy gravel layers. Due to the lack of additional data regarding the dynamic properties of the different soil layers, it was decided to perform on site measurements. More specifically, crosshole measurements were conducted in order to gain a more realistic insight of the dynamic soil characteristics on site. Shear wave velocities and damping values are estimated up to a depth of approx. 45 m. The estimated shear modulus values from the experiment are adjusted to account for the increase in the soil stiffness as a result of the additional overburden pressure. Finally two boundary cases regarding the soil stiffness are considered in the computation process: a stiff soil profile “Gmax” and a soft soil profile “Gmin” which are defined by multiplying and dividing the shear moduli with a factor of 1,5 respectively. Thus uncertainties in the definition of the actual soil stiffness are taken into account in the final results.

The numerical modelling of the soil – structure model is conducted using the program SASSI2000 which performs dynamic analyses in the frequency domain including the subsoil characteristics (layered halfspace). The soil in SASSI is considered as linear elastic. However the impact of soil deformation due to seismic loading is taken into account, performing a 1D equivalent linear analysis using the program SHAKE91. This analysis allows to account for the reduction of the dynamic shear modulus and at the same time the increase of soil damping, which are induced due to the seismic excitation. The reduced shear moduli and the higher damping values are then introduced in the SASSI program for the 3D dynamic analysis of the complete soil – structure model. The G – γ – D curves after Seed and Idriss (1970) shown in Figure 4 were employed. According to the analyses results, the shear moduli of the soil layers are decreased with a factor of 0.50 – 0.99 for the soil profile Gmin and 0.65 – 1.00 for Gmax respectively, whereas the damping values are calculated as 0,03 – 0,10 for soil profile Gmin and 0.03 – 0.07 for Gmax. Figures 5 and 6 show the results of the SHAKE analysis for Gmax and Gmin soil profiles.

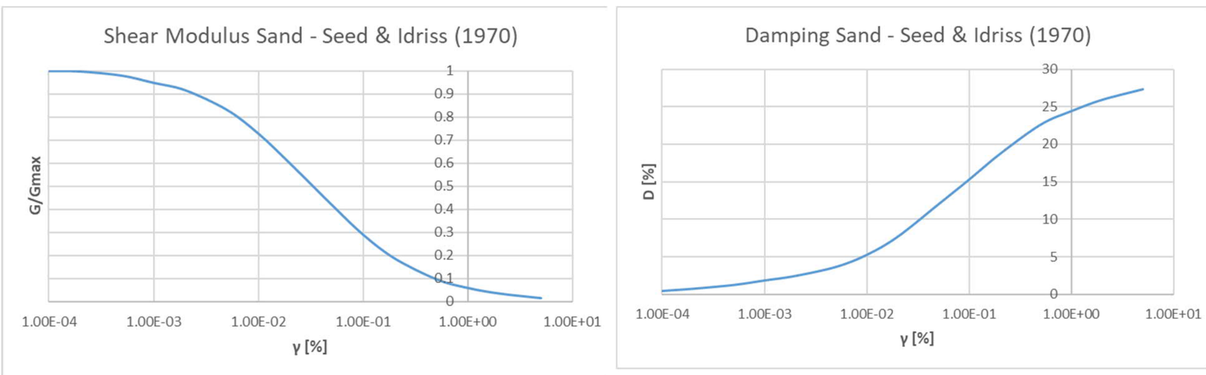

Figure 4. G – γ – D curves after Seed and Idriss (1970) for sand used for the SHAKE analysis

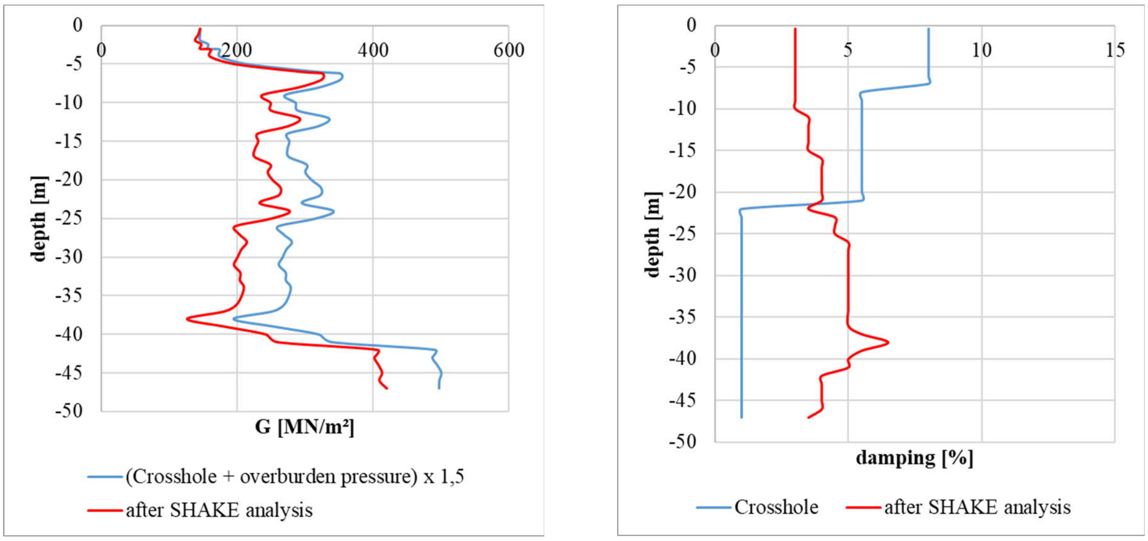

Figure 5. SHAKE analysis results for Gmax

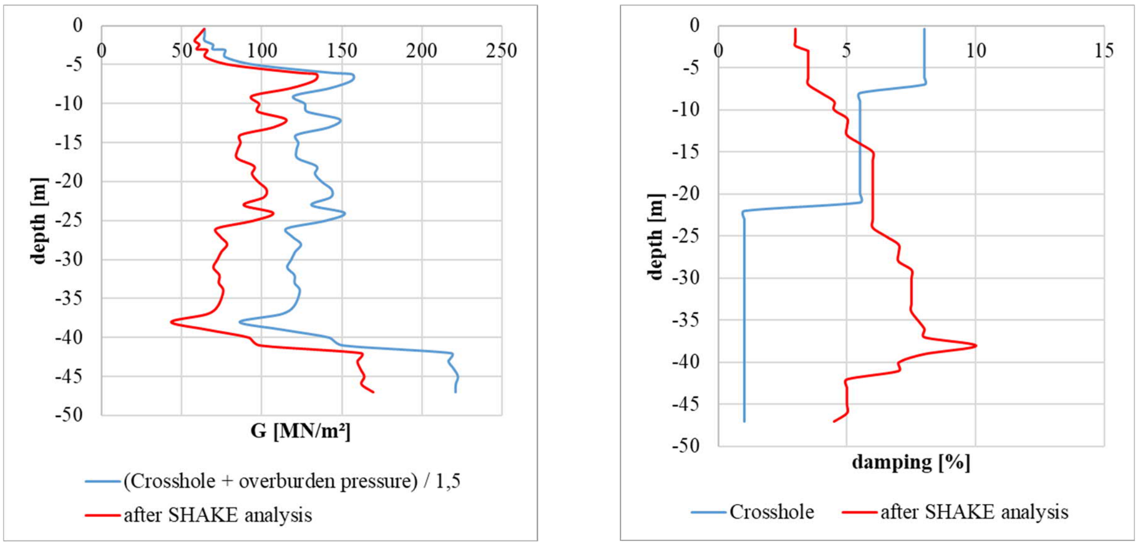

Figure 6. SHAKE analysis results for Gmin

Due to relatively high and non-uniform settlements of the foundation slab, which are expected to be caused by static loading, it was decided to improve the subsoil environment using the high-pressure injection (HPI) technique to remedy this issue and provide settlement control. The HPI columns are in general expected to have only a slight influence on the dynamic properties of the soil. However, because there are only limited data available regarding the impact of this particular improvement technique on the shear modulus and damping values of the soil, the “HPI columns” were also taken into account in the dynamic analysis of the soil-structure model. The number and the layout of the HPI columns under the shaft basement are defined based on static analysis, aiming at keeping the settlements and soil pressures under the acceptable limits. The HPI columns are not placed directly under the basement slab but under an intermediate capillary breaking soil layer with varying thickness. This intermediate soil layer should be backfilled with excavated material with compacted sandy soil propoerties. For modelling purposes an average uniform thickness for this soil layer between the basement slab and the HPI columns of 1.35 m was taken into account. In total 156 HPI columns were used in the final layout.

The Substructuring method

The soil – structure interaction problem is analysed in SASSI using the substructuring method. In this approach, the linear soil-structure interaction problem is subdivided into a series of simpler substructures: the free-field, the excavated soil volume and the structure. Each substructure is solved separately and the results are combined in the final step of the analysis to provide the complete solution using the principle of superposition. Transfer functions are generated for the predefined excitation frequencies which are then combined with the selected time histories in the post-processing phase to generate the response parameters.

In Figure 7.1 and 7.2 the finite element model of the repository is shown including also the HPI columns. In the SASSI model, the structural elements are modelled with beam and shell elements. The soil layers, which include both the embedded parts of the repository structure and the HPI columns, are simulated with 3D solid elements. The HPI columns are modelled using the SASSI module "Interpile Elements", which considers the interaction of the coupled soil – pile system in the analysis.

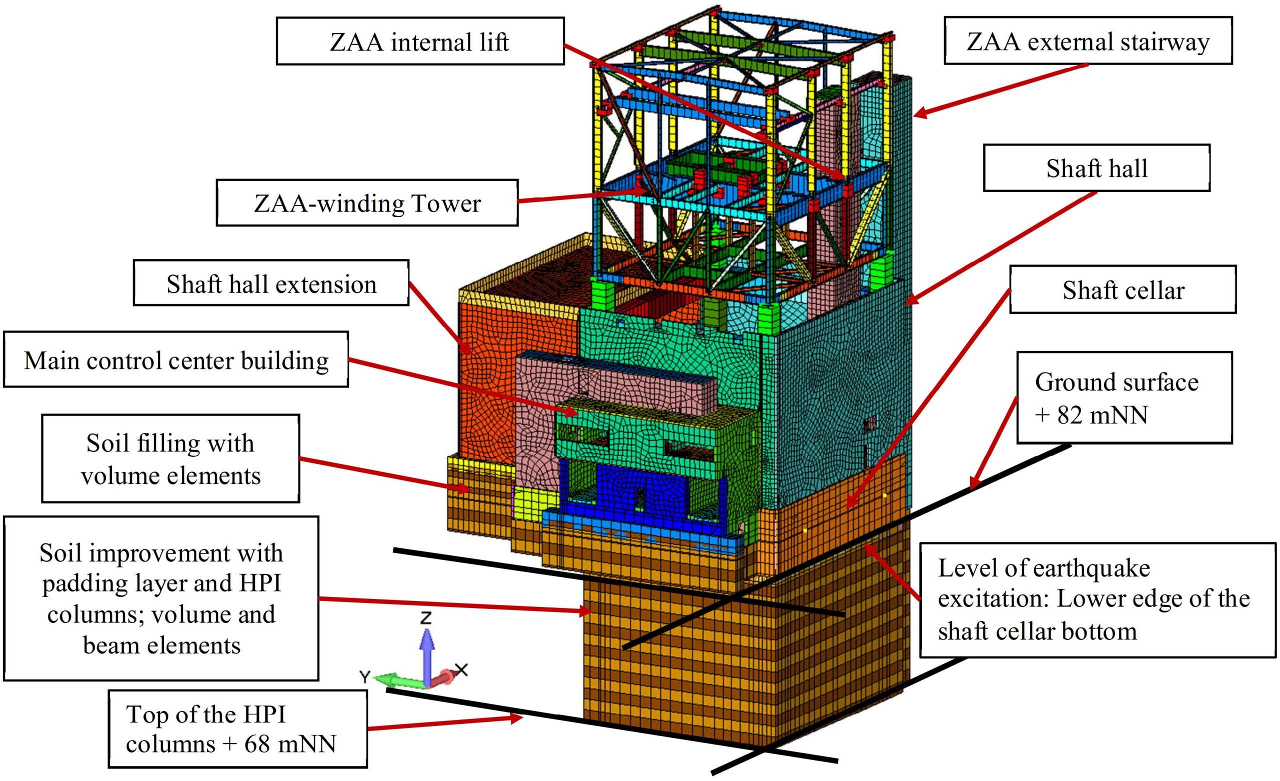

Figure 7.1 FE model of the soil – structure system in SASSI

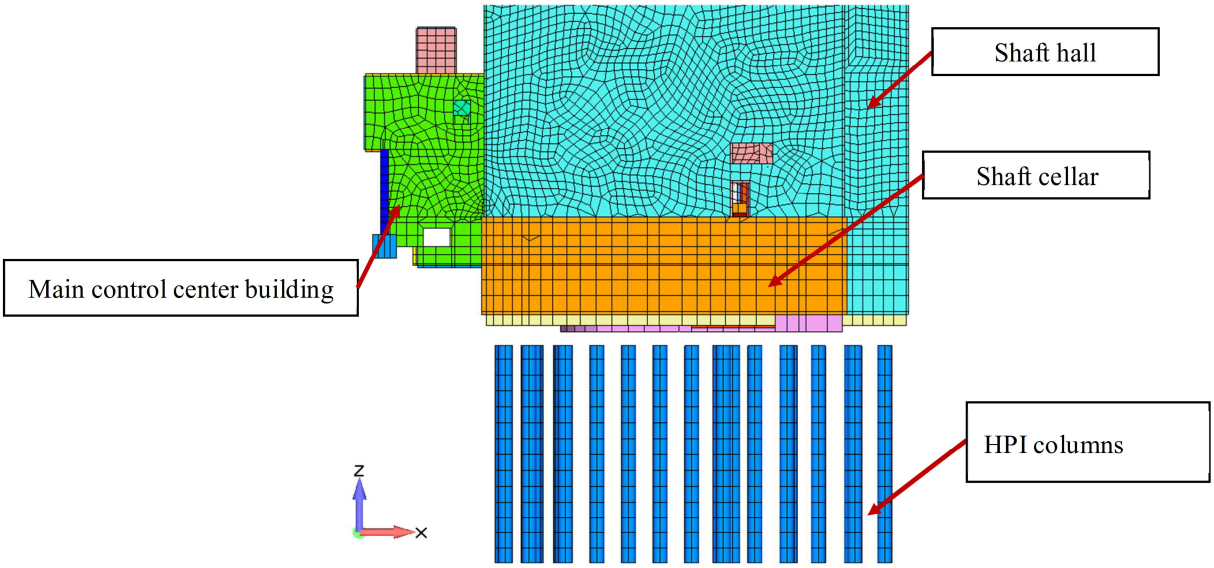

Figure 7.2 Side view with the HPI columns

Generation of Impedance functions

It is possible to generate dynamic impedance functions for a foundation system with the SASSI program. In this case, the foundation is modelled as massless and rigid and by applying harmonic excitation in the different directions (i.e. excitation of different degrees of freedom), the impedance functions for the different vibration modes (vertical, horizontal, rocking, torsional) are calculated.

The impedance functions are calculated for the ZAA, ZAA shaft hall extension and Main control center building are determined separately. These impedance functions are used to generate soil springs distributed under the different foundation parts of the repository construction. For the computation of the stiffness values of the soil springs the static impedance functions are used (f = 0 Hz).

The stiffness distribution of the translational springs under the foundation systems of the different building parts, is based on the geometry of each foundation type. Rotational springs are only used under the slab foundation. The delta springs –the difference between global rotational springs and resulting rotational springs from distributed translational springs - are distributed over the length of the outer edge of the respective foundation element.

ANALYSIS CASES AND RESULTS

Analysis case 1: Analysis of the soil – structure system in SASSI

The complete soil – structure model is analysed in SASSI for a defined frequency range of approximately 20 Hz. Transfer functions are calculated for seismic excitation for the three earthquake directions (two horizontal and vertical). In the post-processing phase the transfer functions are combined with the selected time histories to generate response acceleration spectra. The analyses are repeated accounting for the soil variability (Gmax, Gmin) and the different input motions resulting finally to envelop floor response spectra which represent the envelops of the results

Analysis case 2: Analysis of the structure with soil springs in SOFISTIK

The 3D Finite Element Modelling of the structure is conducted with the programs Sofistik. In this analysis case the finite element model is used for the general structural design of the repository. The impedance functions generated with SASSI software are used to define appropriate soil springs, which are distributed under the foundation systems of the different building parts of the repository as described analytically in the previous chapter.

The paper "Design and construction of building parts above ground of a repository" in this SMiRT describes the methodological procedure for the design of safety-relevant above-ground building components of a German repository.

CONCLUSION

Due to increase in the earthquake demand, the seismic design of a repository structure, which had initiated in the early 90ies but was not constructed at that time, had to be revaluated. In this paper the seismic evaluation and design process was shown, highlighting the modelling approaches which were implemented in order to take the soil – structure interaction effects into account, in order to eliminate potential conservative effects resulting from the higher seismic design intensity.

Two analysis approaches were performed in order to fulfil the design goals regarding the structure and components. In both approaches SSI effects were taken into account. The dynamic soil properties were defined based on crosshole measurements. The soil improvement through HPI column was included in the numerical model in order to account of the potential impact in the dynamic response of the soil profile.

In the first analysis case the soil – structure system was modelled in one step by analysing one single model. From these analysis, floor acceleration response spectra were generated which were continuously used in the design of the components. In the latter case, the soil – structure system was modelled in a two-step modelling approach. First the soil springs were defined based on an impedance analysis, which were then introduced in the finite element model of the structure. This model was used for the general structural design of the repository.

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