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INVESTIGATION OF GROUND IMPROVEMENT BY HPI COLUMNS ON SOIL-STRUCTURE INTERACTION AND THE RESULTING FLOOR RESPONSE SPECTRA

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ABSTRACT

The aim of this paper is to show the analytical differences between ground improvement using high-pressure injection columns (HPI) and given soil on floor response spectra (FRS). This is being conducted based on an ongoing planning project for a long-term storage facility for medium and low-level radioactive waste.
The original planning for this long-term storage facility was started in the early 1990s but was not completed at that time. The seismic requirements have increased considerably in recent years.
Two models are being developed to decide the possible differences in effects. One with HPI columns and one without this ground improvement. The subsoil is not varied and only one soil model, minimally soft (G_{min}), is considered.
The FRS are calculated for both models at selected locations.

INTRODUCTION

A deep geological repository is regarded to provide a stable environment for the safe storage of radioactive waste. The above-ground repository is a reinforced concrete structure with a steel winding tower, designed in the early 1990s at a former mining site as a long-term storage facility for low- and intermediate-level radioactive waste with negligible heat generation. Since the original design was not fully completed, a new seismic assessment is needed to meet modern standards. The governing earthquake is now defined by an elastic free-field spectrum with amplitudes three times higher at resonance frequencies than initially assumed. To avoid conservative assumptions, detailed soil-structure interaction (SSI) is included in the analysis. A general overview about the structure and analysis is given in Hildmann et al. (2024) and in Karapetrou et al. (2024).

For the new seismic design and this study, two three-dimensional numerical models were developed, both considering the soil-structure interaction. Due to the lack of detailed data on the dynamic soil properties, on-site measurements were conducted, particularly crosshole measurements, to figure out the dynamic soil parameters. Because of significant and uneven settlements of the foundation slab caused by static loads, the soil conditions were improved using high-pressure injection (HPI) technology. The HPI columns are integrated into the SSI models to reliably assess their impact on dynamic soil response.
The modelling of SSI effects is performed using the SASSI software. Two analysis cases are considered. Figure 1 illustrates the workflow of the analysis.

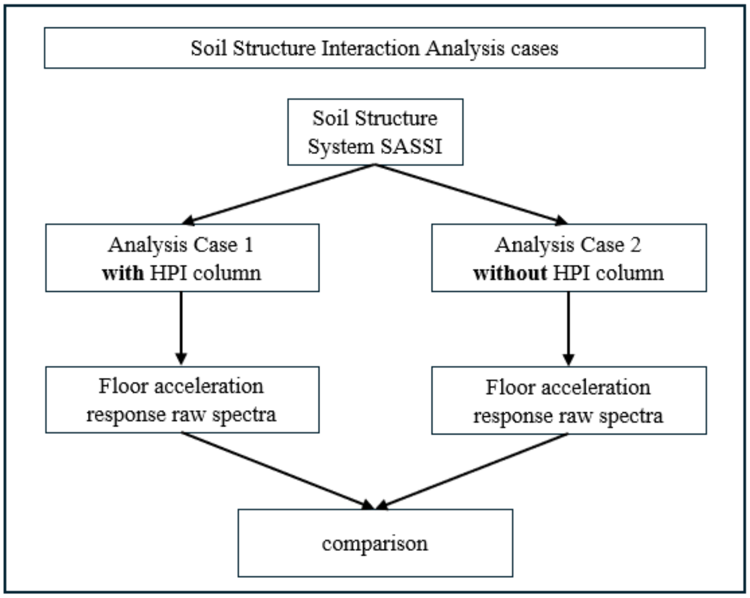

Figure 1. Workflow of the implemented analysis cases of the repository model considering SSI effects

DESCRIPTION OF THE ABOVE-GROUND BUILDING COMPONENTS

The investigated repository is a reinforced concrete structure comprising multiple parts (see Figure 2): the shaft with a basement and hall (A), the shaft hall extension (B), the main control centre (C), the steel winding tower (D), the elevator tower (E1), and the staircase (E2). Except for the winding tower, all parts are rectangular reinforced concrete structures with concrete walls. The steel winding tower consists of steel frames with reinforced concrete slabs.

The shaft basement (L/B/H = 23.30/20.30/6.80 m) and shaft hall (L/B/H = 23.30/20.30/40.00 m, including the winding tower) are founded on a reinforced concrete slab at -6.80 m. Structural joints vertically separate the shaft hall walls from the shaft hall extension and main control centre. The shaft hall extension (L/B/H = 23.30/12.87/15.84 m) is built on a strip foundation at -0.70 m, while the main control centre (L/B/H = 19.90/6.80/12.50 m) is found partially on a slab and a strip foundation at -3.00 m. The main control centre foundation, at -3.35 m to -0.04 m, is connected to the shaft cellar’s outer walls.

Structural joints provide vertical separation between building parts. The materials used include concrete types C20/25, C25/30, and C30/37, reinforcing steel B500, and structural steel S235 and S355. The 3D Finite Element Model (FEM) was created with Femap, employing beam and shell elements. Elastic material properties were considered. The total structural mass, including dead weight and equipment, is 12,500 t.

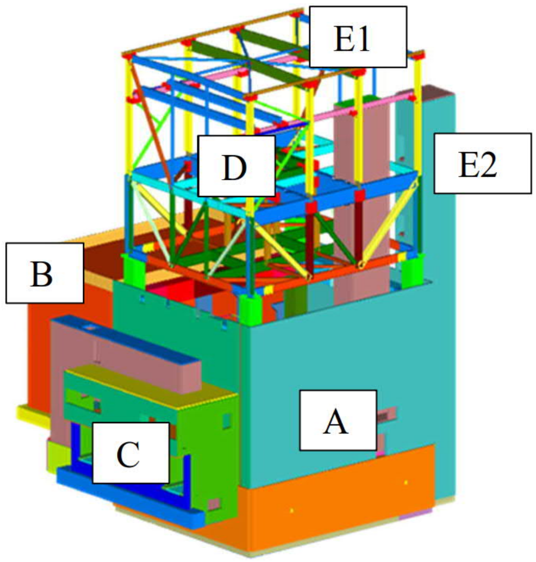

Figure 2. Isometric view of the repository construction

SOIL MODELLING

The geotechnical survey showed a soil profile composed of silty and sandy gravel layers. Due to the absence of detailed dynamic property data, crosshole measurements were conducted to achieve shear wave velocities and damping values down to a depth of 45 meters. To account for uncertainties in soil stiffness the parameters are varied, but only one boundary condition is reported here:

- G_{min} (soft soil): Shear modulus G_{medium} reduced by a factor of 1.5.

The numerical modelling of the soil-structure interaction was performed using SASSI2000, which conducts dynamic analyses in the frequency domain, incorporating subsoil characteristics. The soil was modelled as linear elastic, but seismic effects were integrated through a 1D equivalent linear analysis using SHAKE91, which allowed for the consideration of:

- Reduction in shear modules due to seismic excitation.
- Increase in soil damping resulting from dynamic loading.

The analysis showed a reduction in shear modulus ranging from 0.50 – 0.99 for G_{min} damping values varied between 0.03 – 0.10 for G_{min}, based on G-γ-D curves from Seed and Idriss (1970).
Because of expected significant and uneven settlements of the foundation slab, HPI columns were implemented to enhance the subsoil and control settlements. A total of 156 HPI columns were strategically placed beneath the shaft basement, but not directly under the foundation slab. Instead, an intermediate capillary-breaking soil layer with a uniform modelled thickness of 1.35 meters was introduced and backfilled with compacted sandy soil.

Although the primary purpose of HPI columns was to mitigate static settlement issues, their potential impact on dynamic earthquake analysis was also considered.

By combining geotechnical investigations, numerical modelling, and soil improvement techniques, the study ensured a comprehensive assessment of both static and seismic effects, leading to an optimized and stable foundation design.

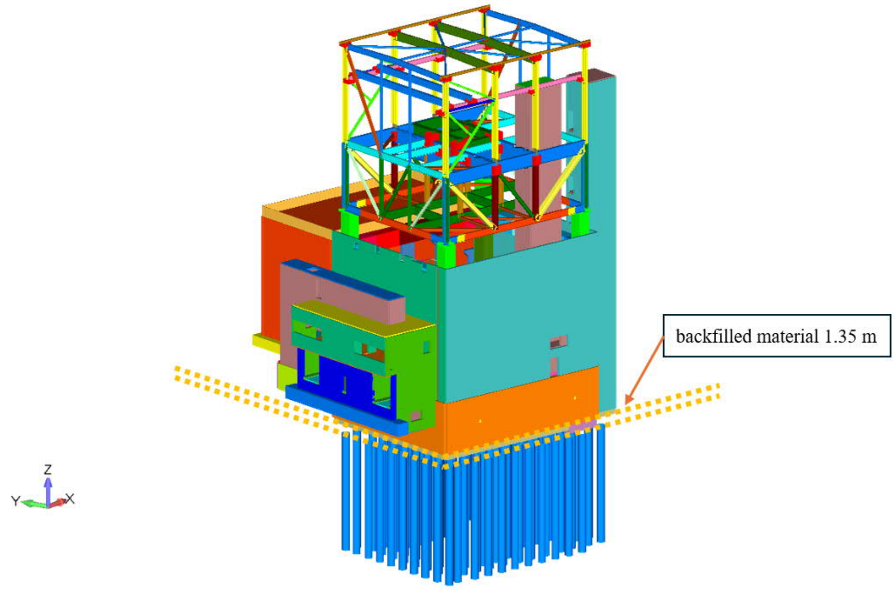

Figure 3. Isometric view of the repository construction including the ground improvement and the winding tower (the soil layers are not shown but included).

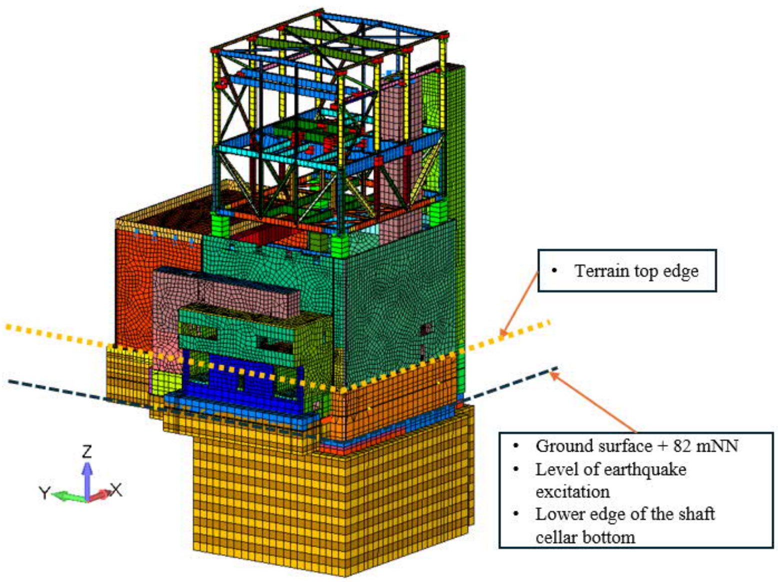

Figure 4. Isometric view of the repository construction includes soil layers without ground improvement and the winding tower.

SEISMIC REQUIREMENTS

A new seismic design is needed to meet modern standards. The normalized free-field acceleration spectrum (5 % damping) defines the design spectrum, with the vertical part set at 2/3 of the horizontal per KTA 2201.1. Three independent acceleration time histories were generated using IRIS for seismic analysis in SASSI, with a 10-second total duration and 5-second strong motion. Figure 3 compares the acceleration response spectra of the selected records to the design spectrum.

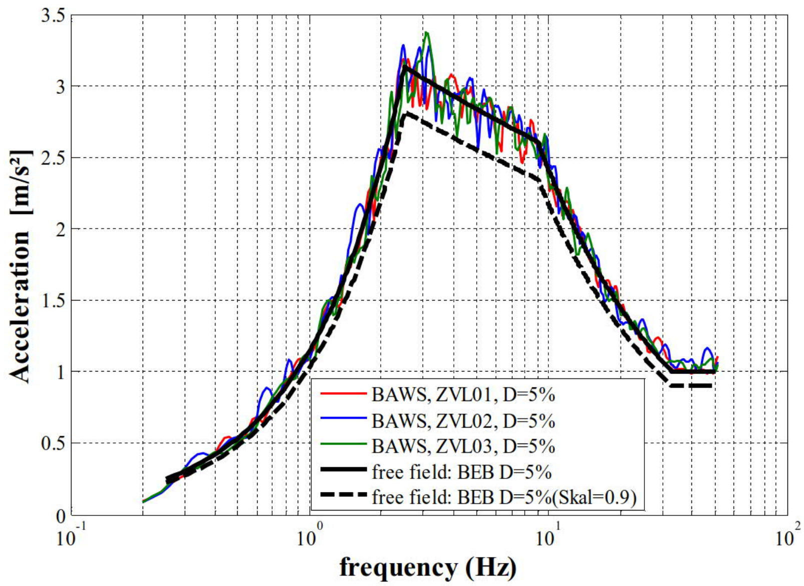

Figure 5. Acceleration response spectra of the selected seismic records in comparison to the free field design spectrum.

ANALYSIS CASE

The complete soil-structure model is computed in SASSI for a defined frequency range of approximately 100 Hz and analyzed up to 20 Hz. This analysis aims to assess the dynamic behavior of the structure under seismic excitation. Transfer functions are figured out for the three earthquake directions, which include two horizontal and one vertical component. These transfer functions characterize how seismic waves propagate through the soil and interact with the structural system.

In the post-processing phase, the calculated transfer functions are combined with selected time histories to generate response acceleration spectra. These spectra provide essential insights into the structural response under seismic loads. The analyses are conducted for different input motions.

At specific nodes within the finite element (FE) model, raw spectra are determined for soil models both with and without HPI columns. These analyses help assess the influence of HPI columns on the overall structural response. A total of 22 representative nodes are selected across various structural areas, including the base slab, the decoupled shaft basement ceiling, the outer wall of the shaft hall, and the main control room. The acceleration values at these nodes are compared within the same frequency range to evaluate variations in seismic response.

The damping ratio for the evaluation is set at 4 %, which is a typical value for components. The locations of the evaluation points are illustrated in Figures 6, 10, and 14. Additionally, Figures 7 to 9, 11 to 13, and 15 to 17 present the acceleration values in three spatial directions for a selected evaluation point. These graphical representations provide a comprehensive overview of how different structural components respond to seismic excitation.

Outer wall of the shaft hall

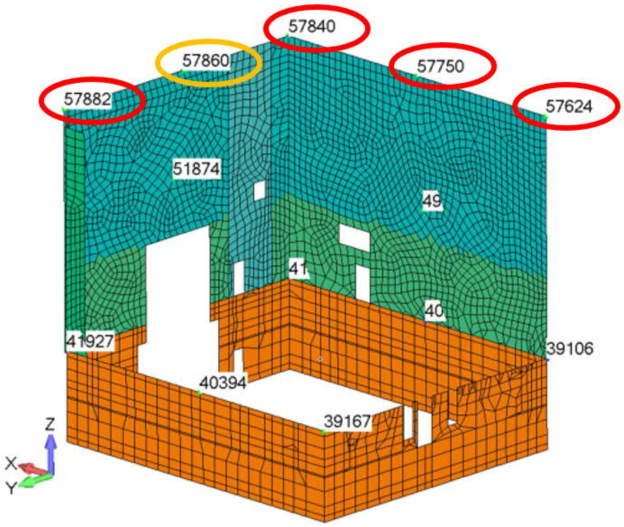

Figure 6. Isometric view of the outer of the shaft hall with the evaluation points (circled in red).

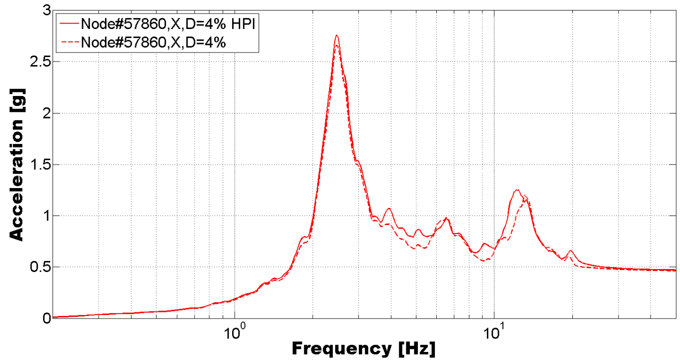

Figure 7. Node 57860; acceleration [g] in x direction.

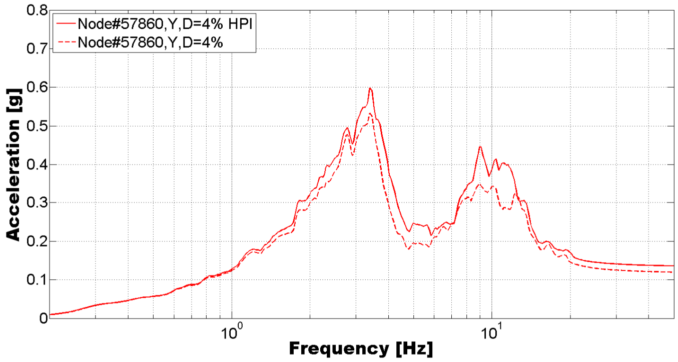

Figure 8. Node 57860; acceleration [g] in y direction.

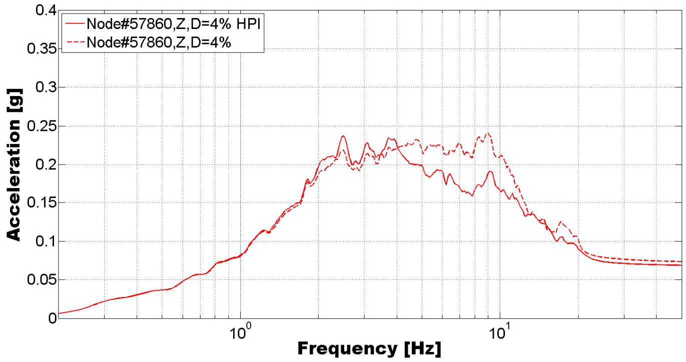

Figure 9. Node 57860; acceleration [g] in z direction.

The HPI columns noticeably reduce the response spectra in the z-direction (vertical), especially between 4 Hz and 12 Hz. In the x- and y-directions, the influence is minimal. The reduction of the response spectra over a wide frequency range shows a moderate but structurally relevant influence of the soil improvement.

Decoupled shaft cellar ceiling

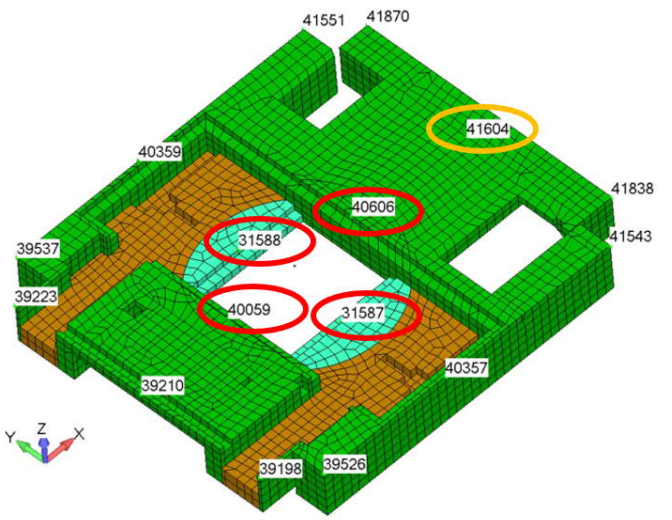

Figure 10. Isometric view of the outer of the decoupled shaft cellar ceilings with the evaluation points (circled in red).

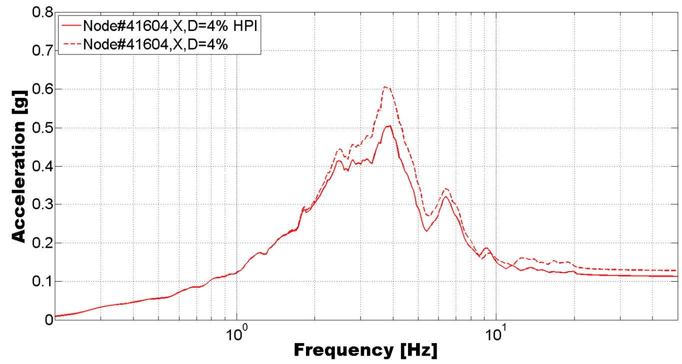

Figure 11. Node 41604; acceleration [g] in x direction.

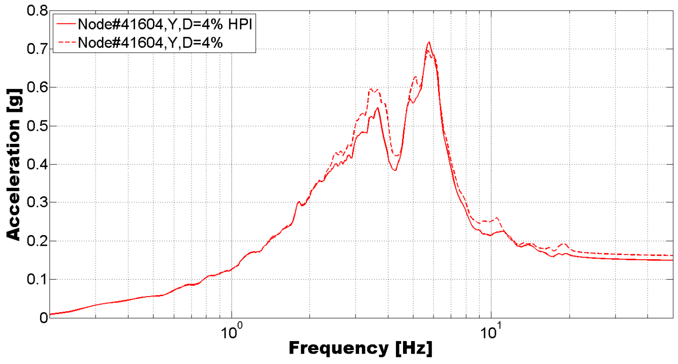

Figure 12. Node 41604; acceleration [g] in y direction.

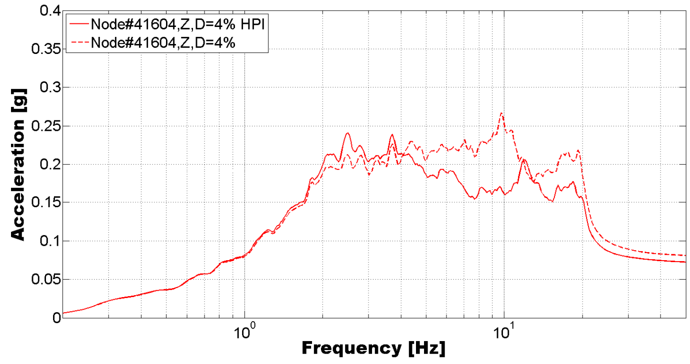

Figure 13. Node 41604; acceleration [g] in z direction.

The HPI columns noticeably reduce the response spectra in the z-direction (vertical), particularly between 4 Hz and 12 Hz. In the x-direction, a reduction is noticeable between 2.5 Hz and 6 Hz. In the y-direction, the influence is minimal. The reduction of the horizontal response spectra over a wide frequency range shows a moderate but structurally relevant influence of soil improvement.

Base plate

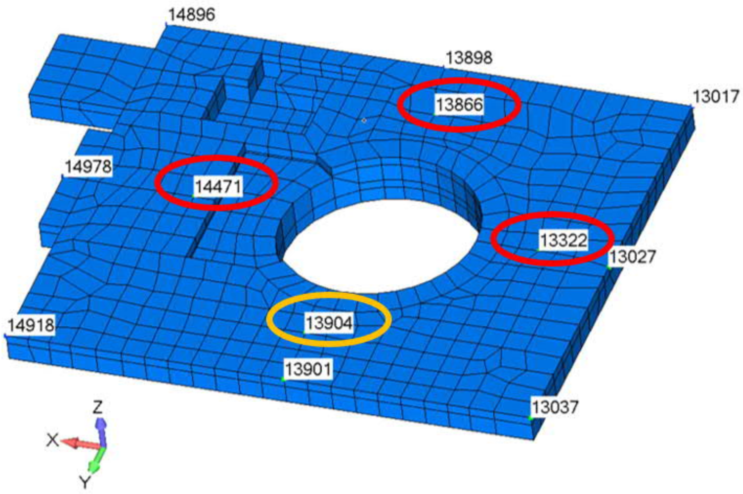

Figure 14. isometric view of the outer of the base plate with the evaluation points (circled in red)

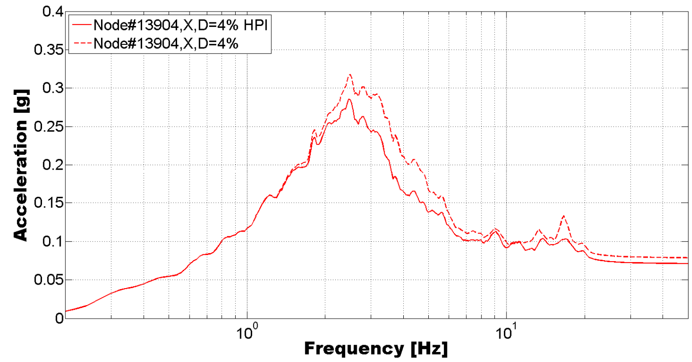

Figure 15. Node 13904; acceleration [g] in x direction

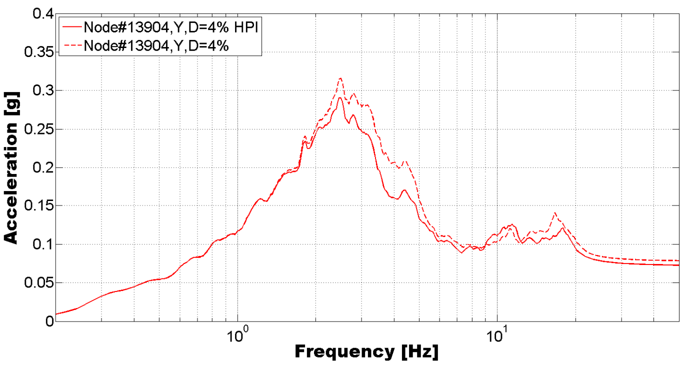

Figure 16. Node 13904; acceleration [g] in y direction

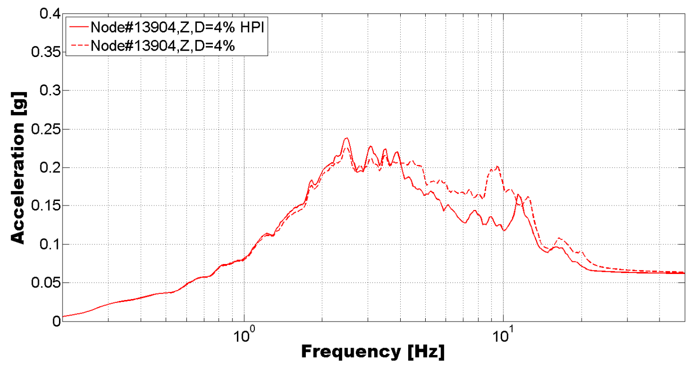

Figure 17. Node 13904; acceleration [g] in z direction

The HPI columns noticeably reduce the response spectra in the z-direction (vertical), particularly between 4 Hz and 12 Hz. In the x-direction, a reduction is noticeable between 2 Hz and 6 Hz. In the y-direction, the influence is minimal. The reduction of the response spectra over a wide frequency range shows a moderate but structurally relevant influence of soil improvement.

CONCLUSION

Due to the high computationally determined static settlement values, the presented project decided to improve the subsoil using 156 high-pressure injection (HPI) columns to reduce potential settlements. These HPI columns were integrated into the numerical subsoil model. The question arose regarding their impact on the FRS, particularly concerning their decoupling from the foundation slab.

To investigate this, two numerical calculation models were created for the minimum soft soil and compared. The FRS was determined in three spatial directions at selected points and evaluated both numerically and graphically. The comparison of the results shows that the differences in the computed FRS values due to the subsoil improvement with high-pressure injection and the decoupling of the building structure are small in horizontal directions, in the vertical direction HPI leads to reduce response Spectra in the frequency range from approximately 4 Hz to 12 Hz.

Through the systematic analysis of these response spectra, the study aims to enhance the understanding of seismic behavior in complex soil-structure interaction scenarios, thereby contributing to improved structural safety and optimized design.

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