Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

Transferring SSI from Frequency to Time Domain: Integrating Non-Linear Effects

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ABSTRACT

This paper describes a straightforward approach to introduce nonlinear effects in a seismic calculation of a structure, particularly in or close to the building.

The method used builds upon the Domain Reduction Method (DRM), which combines a large-scale calculation with a near field analysis. This is achieved by extracting a subdomain and applying seismic waves of the large-scale model to the edge of the extracted domain. The proposed approach features several key differences from the standard DRM application:

- The calculation of the large-scale model is solved in the frequency domain.
- The large-scale model already includes the building itself (SSI).
- Displacement (Dirichlet) boundary conditions are used at the interface between the large and the subdomain.
- The size of the subdomain is verified without relying on iterative procedures.

This work extends a procedure presented at SMiRT27 (Linneweber et al., 2024) that proposed to extract displacements at the base of the model from the calculation in the frequency domain (ACS SASSI) directly and apply them as boundary conditions in the time domain (ANSYS). While that method yielded sufficiently accurate structural responses, it was limited to linear behavior.

The research addresses this shortcoming and includes non-linear effects. This demonstrates that a transition from SASSI to a transient time-domain analysis is feasible, with the potential to incorporate nonlinear effects within the building to a certain extent.

INTRODUCTION

Introducing nonlinear effects in seismic calculations remains a challenging problem. While nonlinear behavior is well understood, performing a full nonlinear simulation in the time domain is computationally expensive, and defining wave propagation at artificial boundaries is not analytically solvable. In contrast, frequency-domain methods offer an elegant solution by providing analytical representations of infinite boundaries, making them computationally efficient for seismic analysis. However, incorporating nonlinear effects in frequency-domain calculations is cumbersome and remains an open issue.

A promising approach is to combine both methods and their respective advantages. Here, we propose a procedure based on the **Domain Reduction Method (DRM)**. Our approach follows a two-step process:

1. **Solving the entire problem in the frequency domain (including the structure)**, where only linear effects are considered (far field).
2. **Extracting a localized subdomain** that includes the structure and a surrounding portion of the soil, and solving it in the time domain while incorporating nonlinear effects (near field).

By comparing the reaction forces at the interface between the linear model and the nonlinear model, we can quantify the error introduced by nonlinear effects. At its core, this approach is based on the DRM, but instead of prescribing forces, we apply Dirichlet boundary conditions (displacements) from the frequency-domain solution to the localized time-domain model. We include the structure in the far field analysis, to calculate theoretically exact boundary conditions for the near field analysis.

The underlying assumption is that a linear structure and a nonlinear structure influence the surrounding soil similarly beyond a certain distance. Therefore, solving the full system in the frequency domain provides a valid approximation. Extracting a sufficiently large soil region along with the structure and applying frequency-domain displacements as boundary conditions in the time-domain simulation allows for an efficient and accurate analysis while incorporating nonlinear effects.

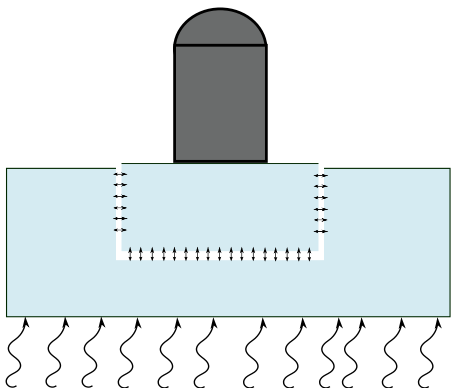

Figure 1. Calculation of the complete model in the frequency domain.

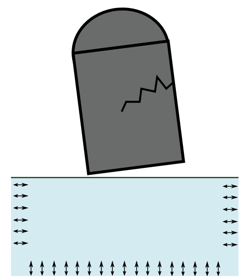

Figure 2. Extraction of a localized region and solving it in the time domain with introduced nonlinear effects in or close to the structure.

STEPWISE VALIDATION OF THE EXTRACTION PROCESS IN THE TIME DOMAIN

The first key element is to determine the size of the area to be extracted. The fundamental idea is that, since displacements are prescribed at the boundary, each interaction node experiences a specific reaction force. By comparing these reaction forces (here in x-direction) while varying the size of the extracted soil domain, it should become evident that a larger soil domain results in smaller deviations between a linear and a nonlinear calculation.

To investigate this, a disk with a central beam and a mass is modelled (Figure 3) in ANSYS, that can slide (nonlinear)/cannot slide (linear) on the underlying soil. The soil is then excited by a displacement history. By systematically increasing the soil size in the time domain (r = 10 m, r = 20 m, r = 40 m, r = 80 m) and computing the difference in reaction forces at characteristic boundary nodes the influence of the domain size is analyzed. The influence of nonlinearity - the contact between the soil and the structure - diminishes as the soil size increases (Figure 4).

For a numerical comparison the correlation coefficient and the mean squared error is computed. The correlation factor between the curves already depicts for all curves a perfect correlation (=1). However, the mean squared error shrinks from MSE = 17961 (r=10 m) to MSE = 7 (r=80 m).

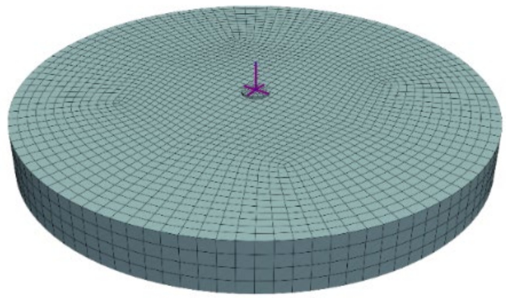

Figure 3. Centrally aligned plate, reinforced with beams and the underlying soil.

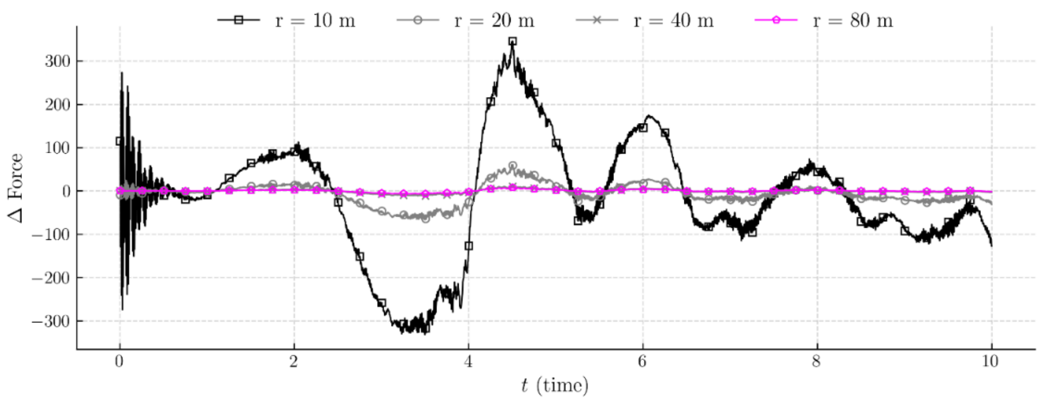

Figure 4. Delta reaction force (x-direction) between the linear and nonlinear calculations.

Artificial Waves or "Bathtub Effect"

The second key element is the investigation of artificial waves and their influence. These artificial waves should strongly depend on the size of the extracted soil domain. To examine this, the displacement of the mass node at the top of the structure is analyzed.

In the simplified model, which includes damping, the displacement curves at the top node remain identical, indicating that no significant artificial wave reflections are introduced.

To further investigate this, additional simulations were performed:

- The **displacement boundary conditions** were modified (sinus displacement history).
- **Damping was removed**.
- A **softer soil** was introduced.

When a sudden "jump" is applied in the sinusoidal displacement history at t = 5 s, the linear model now displays high-frequency wave generation, which becomes stronger as the soil domain increases (Figure 5). The nonvisible artificial waves in the first simplified model indicate that damping in both the soil and the structure has the beneficial side effect of suppressing artificial wave reflections. Since damping is a necessary component of any realistic model, this ensures feasible results. However, Figure 5 shows that removement of the damping introduces artificial waves that depend on the size of the extracted soil. Thereby a larger domain means more artificial waves. Thus, these waves limit the maximum size of the extraction in this simplified model.

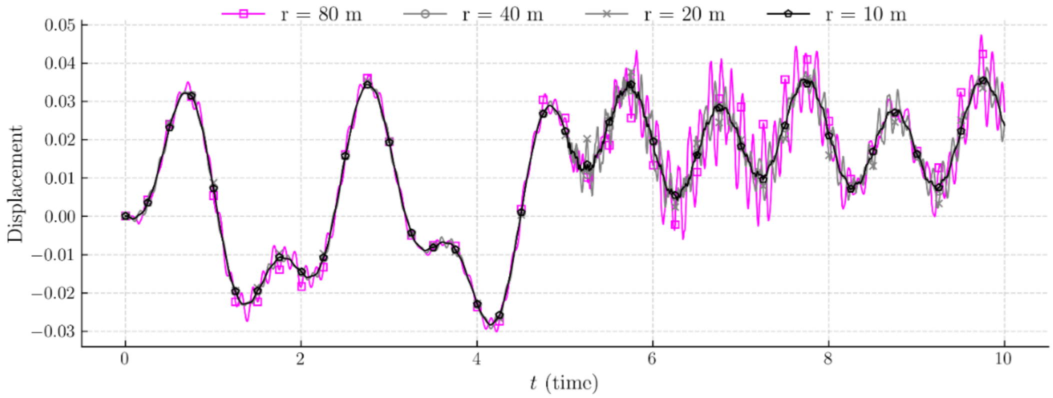

Figure 5. Displacement curves at the upper beam node in x-direction.

Generalization of the Approach

It is worth noting that this methodology is not limited to the introduction of nonlinear effects. It can also be extended to incorporate other significant model modifications, such as the addition of heavy tanks or structural reinforcements.

Based on these results, a structured workflow has been developed for transition from a linear frequency-domain model to a nonlinear time-domain model. Importantly, in the case of a purely linear transition, no additional soil extraction is required.

Workflow for Model Calculation and Validation for linear localized regions

1. Linear calculation of the full model in the frequency domain
2. Extraction of just the building, applying the displacements at the interface
3. Linear calculation of the local part in the time domain
    a. Adjusting the damping coefficients (soil/structure)

Workflow for Model Calculation and Validation for nonlinear localized regions

1. Linear calculation of the full model in the frequency domain
2. Extraction of a local part of the model, applying the displacements at the interface
3. Linear calculation of the local part in the time domain. Comparison between the time and frequency domain
    a. Adjusting the damping coefficients (soil/structure)
    b. Artificial waves still observable? Subdomain size is too large.
4. Introduction of nonlinear effects in the localized subdomain
5. Comparison of reaction forces between the nonlinear and linear models
    a. Good agreement of reaction forces = Model is adequate
    b. Significant differences between models = Increase the size of the local domain

Remark 1: Since the displacements are calculated in the frequency domain, a Fourier transformation must be performed to extract the time history displacements. This is already performed automatically in ACS-SASSI.
Remark 2: ACS-SASSI provides the relative movements to the free field. These displacements are baseline corrected. Here the accelaration excitations (also with a zero baseline) are integrated twice and added to the relative displacement to get the absolute displacements. A direct integration of the absolute acceleration would need an additional base line correction – this was avoided by this approach.

VALIDATION IN A MORE COMPLEX MODEL: INFLUENCE OF SOIL VARIATIONS AND REACTION FORCES

Until now, the focus was the time history calculations and the validation of the general assumption. In the following chapter the complete workflow is done for a more complex model. This includes in the first step the frequency domain calculation and in the second step the localized time domain calculation.

Model Setup and Frequency Domain Calculation

To validate the approach, three models with increasing soil domain sizes are compared. The frequency-domain calculations are performed using ACS-SASSI, where the soil is modeled as excavated material. The layer properties are transformed into material parameters under the assumption of isotropic behavior.

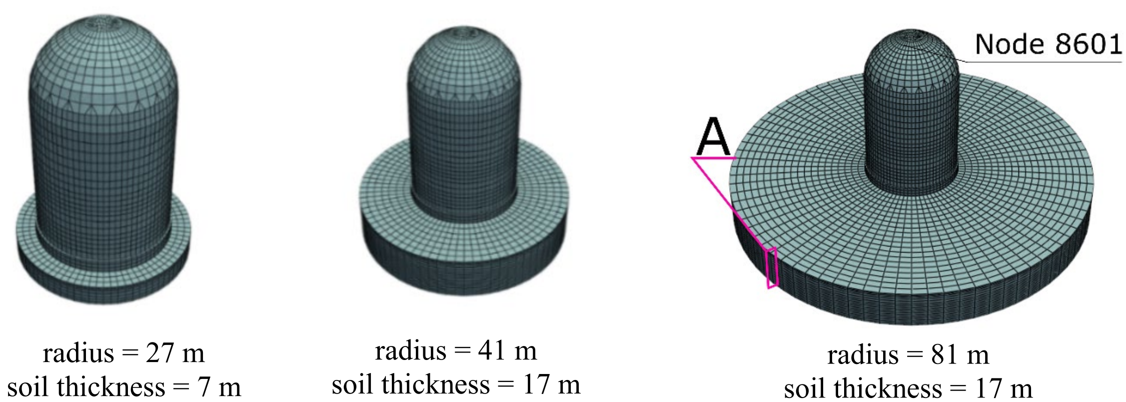

Figure 6. Investigated models of a reactor building with increasing soil size. Area "A" circles nodes used for the reaction force comparison.

The displacement response at the upper node (Node 8601) is in good agreement across all models (Figure 7). Minor deviations are observed, which can be attributed to the finite element size influencing the transmission of certain wave frequencies. However, these differences remain small, confirming the consistency of the frequency-domain calculations (Figure 7).

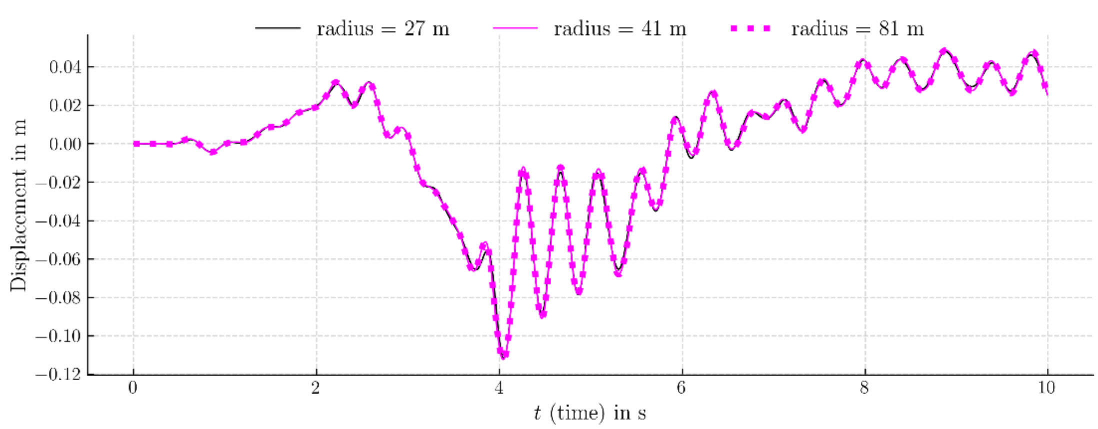

Figure 7. The displacements at a characteristic upper node (8601) in x-direction.

Comparison of Global and Localized Model Response

Since the frequency-domain analysis yields reliable results, we proceed with the calculation of the localized model in the time domain. Initially, no nonlinearities are introduced to validate the transition between the two domains.

For an accurate transformation, the linear response of the extracted local model (time-domain calculation) should closely match the full-model displacement (frequency-domain results). As depicted in Figure 8, the general agreement is maintained, although discrepancies emerge due to the damping coefficients (see Figure 9). These differences highlight the need for careful damping parameter calibration to ensure consistency (compare Linneweber et al., 2024). In this validation case, no additional adjustment was performed, leading to visible deviations, yet the overall motion trends remain similar.

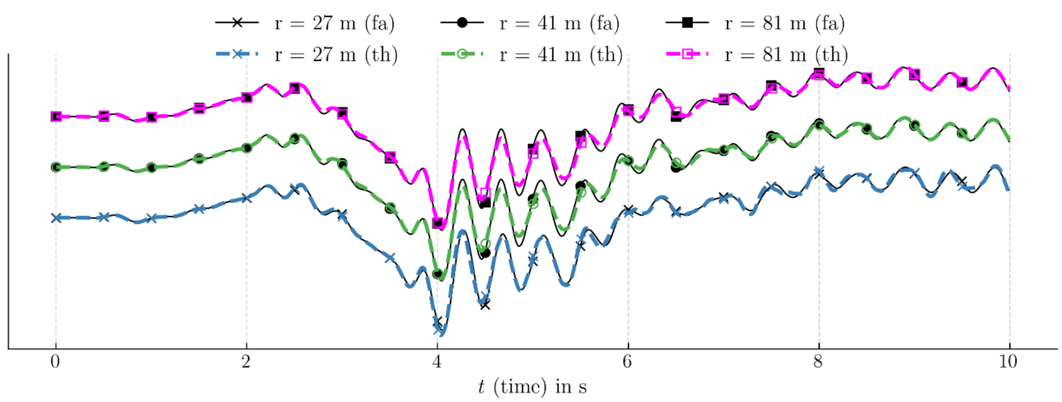

Figure 8. Comparison between the movements of the characteristic node 8601 at the top of the building in x-direction. fa = frequency analysis, th = time history analysis. The curves are shifted vertically to ensure visibility.

Introduction of Nonlinearities

In the next step, nonlinearities are incorporated into the model (sliding, uplifting). Contact is implemented between the soil and the foundation, allowing separation and sliding effects. Unlike in the simplified model, where the building merely rests on the soil, the structure in this case is partially embedded. This requires an additional contact condition between the foundation sides and the surrounding soil, ensuring realistic interaction. Due to an error in the model building, a linearly increasing gravitational acceleration is applied instead of a static one. Since this effect supports uplifting behavior and does not affect the overall conclusions, it was retained.

Effect of Soil Domain Size on Reaction Forces

A quantitative analysis of reaction force (Figure 9, 10, 11) correlations confirms the necessity of a sufficiently large soil domain:

- For a radius of 27 m, the (negative) correlation is -0.24, mean squared error: 295871 (Figure 9)
- For a radius of 41 m, the correlation increases to 0.16, mean squared error: 16562 (Figure 9)
- For a radius of 81 m, the correlation reaches 0.92, mean squared error: 2148 (Figure 9)
- Figure 10 shows, that for a radius of 81 m, the correlation factor is above 0.9 independent of the depth.
- Figure 11 shows, that for a radius of 81 m, the correlation factor is only 0.76 at the center of the soil (directly below the building), while at greater distance to the building it becomes 1.0.

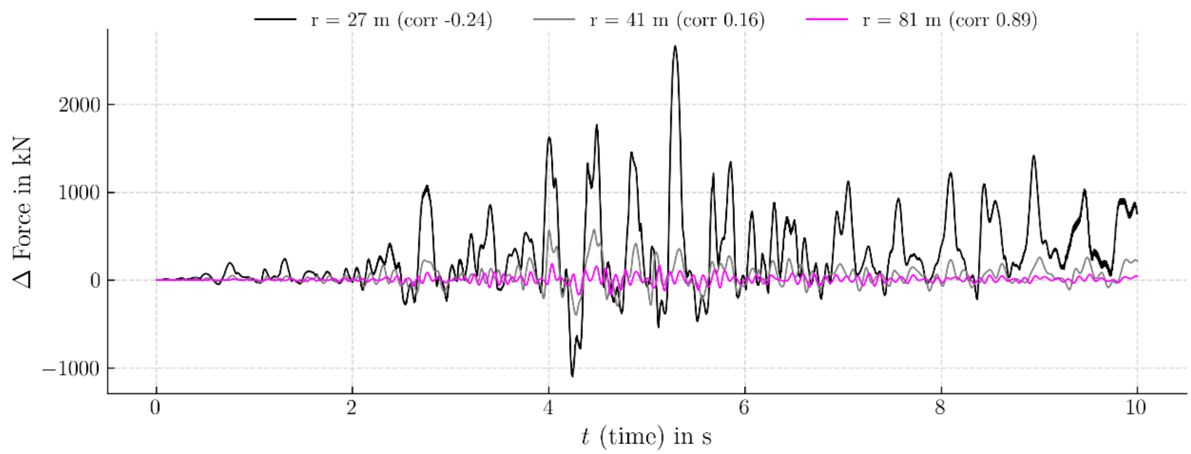

Figure 9. Delta reaction force at the characteristic interface node in x-direction (-12.5 m).

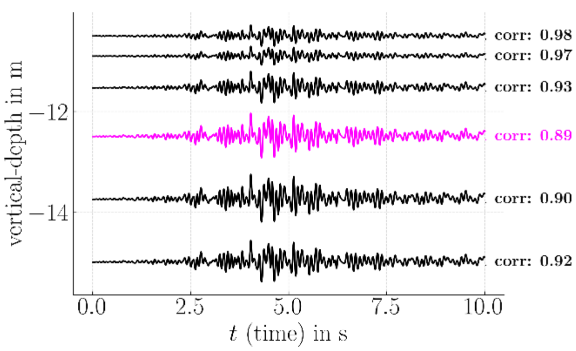

Figure 10. Delta reaction forces in x-direction at the boundary of the soil over the depth (starting at -10 m, model: r = 81 m, area "A" - Figure 6).

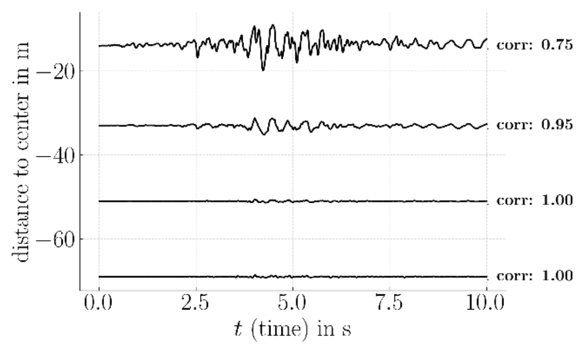

Figure 11. Delta reaction forces in z-direction over the distance to the soil center center taken from the bottom boundary of the soil (model: r = 81 m).

The correlation values indicate that increasing the soil domain size leads to a progressive improvement in agreement between the localized and full-model reaction forces. The Pearson correlation coefficient further illustrates that the waveform similarity improves with larger soil domains. However, while correlation captures shape consistency, it does not reflect absolute magnitude differences, and a residual mean error remains. This error shrinks visibly over the size of the soil radius (Figure 9). Additionally, Figure 10 shows that the strong correlation is present in all layers, while Figure 11 shows a growing correlation from the center of the model to its outer diameter in z-direction.

Effect of Soil Domain Size on the Displacement of the Top Node

Since it has been demonstrated that a radius of 27 m results in no or even in a negative correlation, while a radius of 81 m yields a strong correlation, it follows that the nonlinear system's response should also converge as the domain size increases. In Figure 12 three curves for the nonlinear calculations at the characteristic node 8601 are plotted. Additionally, the result for the linear calculation is added to depict the influence of nonlinearities.

Key observations:

- Figure 12 shows that the results for r = 41 m and r = 81 m are already very similar. By comparing the accelerations of those displacement curves the difference becomes more visible (Figure 13).
- As expected, the linear response differs from the nonlinear response (figure 12).
- The result for r = 27 m deviates but is consistent with the expected trend.

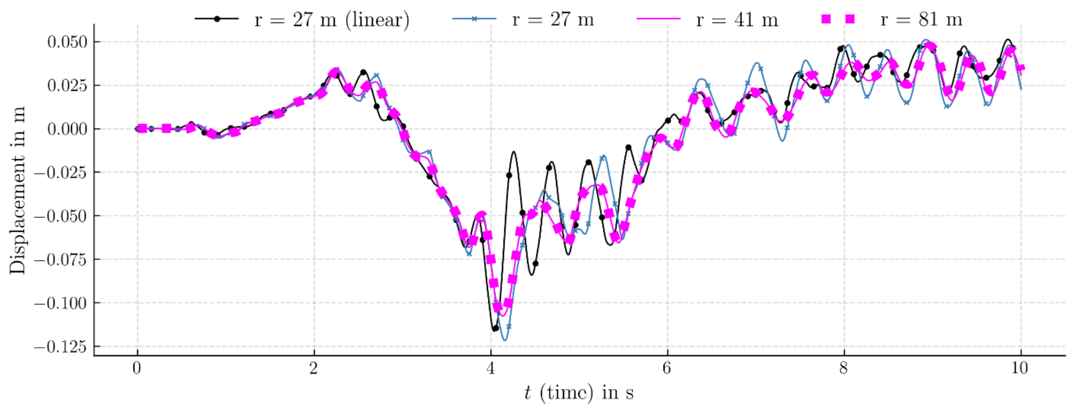

Figure 12. Displacement at the upper node 8601 in x-direction.

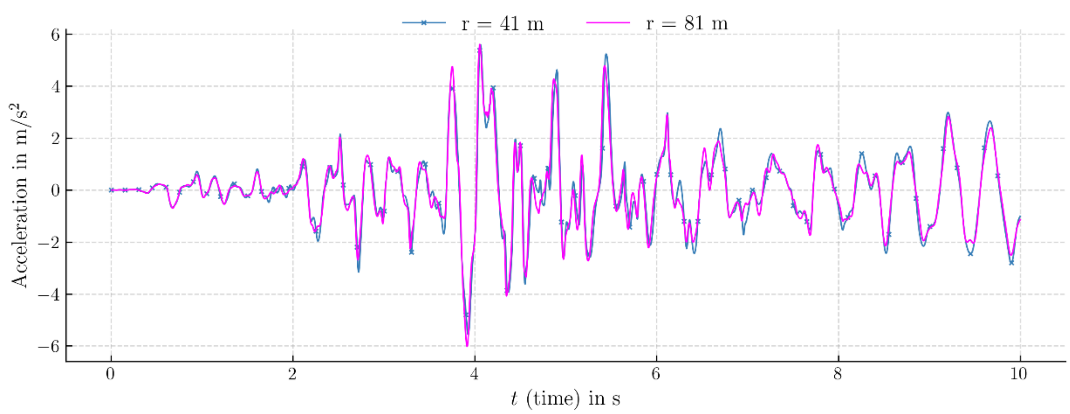

Figure 13. Acceleration at the upper node 8601 in x-direction for r = 41 m and r=81 m.

This demonstrates that, although artificial waves are introduced (see next section) and the reaction force comparison does not indicate a correlation for r = 41 m, the results at the structure are much better, yet not as accurate as the results with r = 81 m and small differences are still visible (Figure 13).

The "Bathtub-Effect" in the Complex Model

Since the frequency-domain model includes both the structure and the surrounding soil, the prescribed displacements at the boundary of the localized time-domain model should theoretically represent the complete wavefield. However, in practice, differences in damping and numerical errors (or discretization) introduce deviations between the time-domain and frequency-domain responses.

To investigate these effects, the vertical displacement difference at a central node is analyzed (Figure 14). All configurations show deviations, with the largest error with r = 27 m (a perfect match would be a zero line).

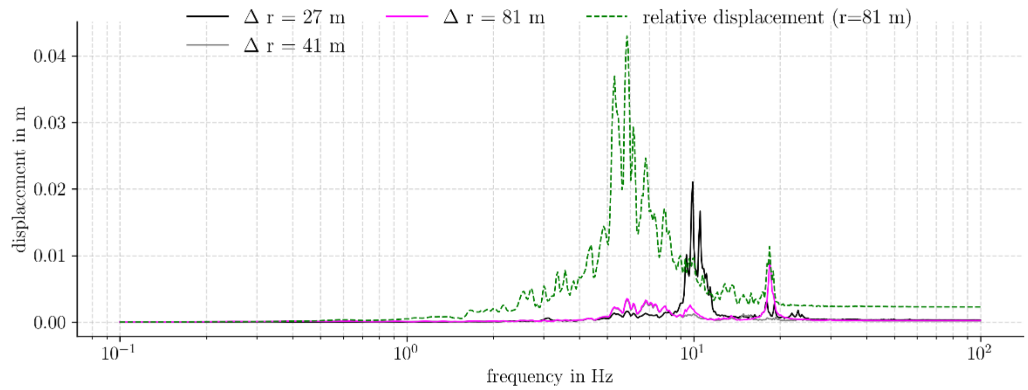

Figure 14. Response Spectrum (damping 0.001) of the delta displacement between the frequency analysis and the time integration at a central node at the foundation. For comparison the spectrum of the relative displacement is additionally plotted.

The effect should increase between the linear calculations, when the wave field is not ideal anymore. To simulate this, the building is removed, and the response is compared. In Figure 14 the difference between the following simulations is plotted:

1. **Calculation 1:** Soil + Building + Damping
2. **Calculation 2:** Soil + Damping (**Building Removed**)

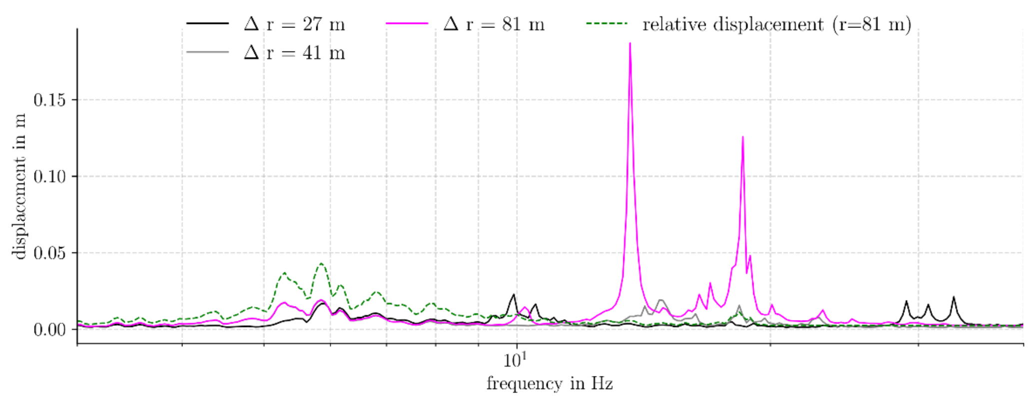

Figure 15. Response Spectrum (damping 0.001) of the delta Displacement between calculation 1 and calculation 2 in z-Direction at the center of the soil. For comparison the spectrum of the relative displacement is additionally plotted (see Figure 14).

Visibly a larger domain leads to a greater deviation. The artificial waves in the r = 81 m model may be attributed to the fact that larger domains provide more degrees of freedom and more waves can propagate. While the imposed displacement boundary conditions represent the far-field motion, a mismatch with the internal response can cause localized reflections, which appear as high-frequency artifacts. These effects are limited in smaller domains due to geometric confinement but become visible in larger systems.

This analysis demonstrates that artificial wave effects are not only a function of the displacement mismatch but also depend on the domain size. While moderate domain sizes are necessary to capture nonlinear interaction, further enlargement can amplify artificial wave content, which may distort the local response if not properly damped. Further it demonstrates that the large-scale simulation should already be as close to the subdomain calculation as possible.

CONCLUSION

The method presented in this study offers a practical and simplified approach for considering nonlinear effects in seismic analysis. The concept is based on the Domain Reduction Method (DRM), but is simplified in the following ways:

- Application of displacement boundary conditions from the frequency-based SASSI calculation instead of forces
- Use of a straightforward verification step of the subdomain size within the time domain

The proposed displacement-based variant of the DRM is particularly suitable for extending existing frequency-domain models. It enables the incorporation of nonlinearities while preserving the efficiency and verification potential of established linear models, by introducing a way to assess the appropriate soil region required for the reduction. This eliminates the need for iterative adjustments other than damping. Additionally, the side-by-side calculation in both the frequency and time domain provides an inherent verification of the response. With the subdomain size calculated appropriately, the linear results remain valid and the cascaded structure of the DRM—solving the global model first, followed by the local model—can be maintained. While other hybrid methods, such as those based on the Spectral Boundary Method (e.g., Albertini et al., 2021; Ma et al., 2019), also aim to model global wave propagation efficiently, the approach presented here focuses on practicality and reuse of existing frequency-domain results without requiring direct coupling.

In summary, the proposed method reduces computational and modeling effort in comparison to the classical DRM, allows existing frequency-domain models to be extended with local nonlinear effects, and provides an internal verification. Its main limitation is that only localized nonlinearities in or near the structure can be captured, and the size of the structure and surrounding soil domain is constrained.

Future studies could focus on sensitivity analyses to determine a suitable subdomain size and to evaluate the influence of different types of nonlinearities. Additionally, the evolution of the correlation factor with respect to subdomain size is of particular interest.

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