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PRELIMINARY INVESTIGATIONS ON THE RESPONSE OF NUCLEAR POWER PLANTS TO AIRCRAFT IMPACT CONSIDERING SOIL-STRUCTURE INTERACTION

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ABSTRACT

The Soil-Structure-Interaction (SSI) has a significant influence on the overall response of many dynamically loaded structures and its consideration in numerical analysis represents a major challenge for engineers. Even with recent advances in computing power and the software capabilities today, the simulation of SSI is still time-consuming, complex and sophisticated. A rigorous analysis of the structural response, however, requires a correct consideration of the SSI.
This paper presents investigations of the influence of dynamic SSI in linear and non-linear simulations of induced vibrations caused by a load-time function of an aircraft impact using elastic and plastic material models. The soil is considered in a simple approach by static spring-damper-elements and in a more accurate approach by PML-elements (absorbing elements), enabling a fast calculation. The used configuration of soil and PML-elements is chosen based on parametric studies on element size, number of PML-Elements and distance to excitation source. A verification of the application of the PML method to simple models has been performed using a time domain (extended mesh) and a frequency domain method (Thin-Layer-Method).

INTRODUCTION

Structures of crucial importance for society, like critical infrastructure, military facilities, embassies as well as power plants require special consideration in design and conception and must satisfy very high safety standards. They must be able to withstand weapons fire, aircraft impact as well as explosions. Structures exposed to such high dynamic loads cause vibrations in the soil that propagates as shear-waves, compressional waves and their combinations (e.g. Rayleigh waves) (see Figure 1). The waves themselves change the dynamic behavior of the structure.
This phenomenon of dynamic SSI can have a considerable influence on the behavior of dynamically loaded structures and should be included in safety assessments. See for example Sadegh-Azar and Garg (2009), Sadegh-Azar and Hartmann (2011). Especially in the analysis of highly dynamic loads (e.g. explosions or aircraft impact) on stiff structures with large mass on soft soil (i.e. having shear wave velocity less than 700 m/s, Kausel (2017)) the influence of dynamic SSI cannot be neglected. For the design of safety-relevant plant components (mechanical or electrotechnical systems) and the assessment of their vulnerability, building response spectrum (floor response spectrum) or time history analysis due to induced vibrations are required (Sadegh-Azar and Hartmann 2011).

The state-of-the-art approach to considering SSI in dynamic analysis especially in design of nuclear power plants, is still SASSI (Ostadan 2007), a program developed in 1981 at the University of California, Berkeley. Since then, the program has been developed in various variations. It is considered an industry standard and is based on the Thin-Layer-Method (TLM), which works in the frequency domain. For small deformations in the linear elastic range, the calculations with this method are relatively accurate. The method is inadequate for large displacements, though. For instance, in the analysis involving damage i.e. non-linear effects of structural behavior, as they occur in the calculation of aircraft impacts, the accuracy is poor. For this purpose, direct transient time-domain methods are necessary, in which the soil and structure are modelled and analyzed together in one Finite-Element model. Since the focus of this contribution is on the analysis of aircraft impact, the latter method is of interest.

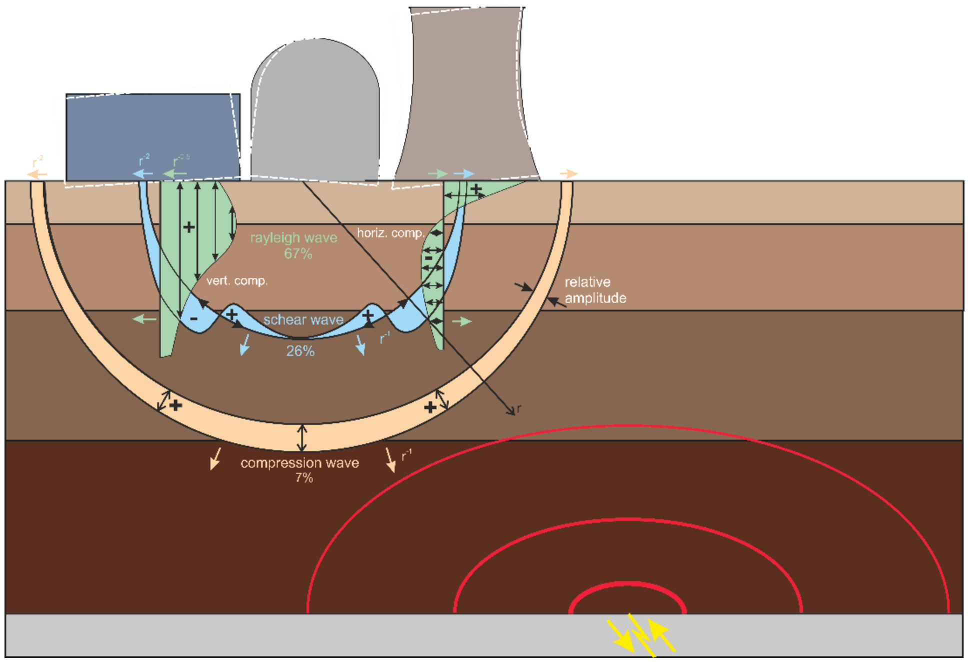


Figure 1. Principle of Soil-Structure Interaction cf. [5]

SOIL-STRUCTURE INTERACTION IN FINITE ELEMENT CALCULATIONS

A complex problem arises for the consideration of soil in Finite-Element analysis. In a static analysis, the boundary of the modelled soil is defined at a distance so that it no longer substantially influences the calculation results (e.g. in settlement calculations). Dynamic analysis is much more complex. Waves propagating in the soil are reflected at the boundary of the model and falsify the calculation results. For this reason, special elements the "Perfectly Matched Layers" (PML) were developed to absorb waves of all angles of inclination and all frequencies.

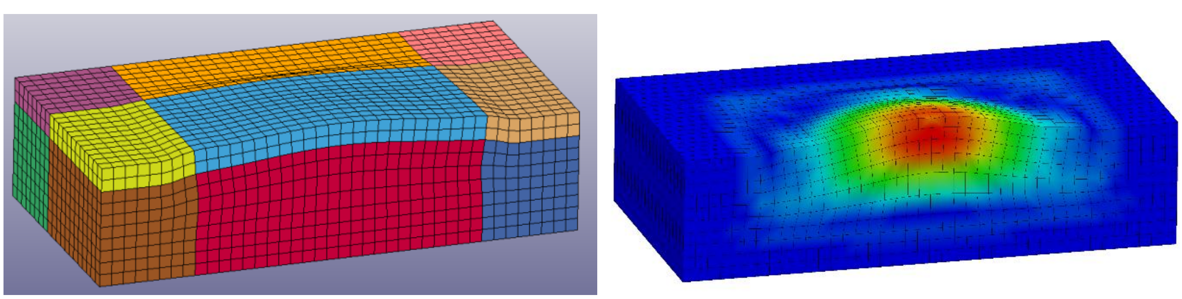


Figure 2. LS-Dyna-model of a harmonic excited flexible foundation on homogenous soil surrounded by PML-Elements: left – numerical model, right – resulting displacement

These PML elements, placed at the boundary of the Finite Element model, prevent the reflection of waves leaving the bounded area (Fig. 2). The properties of the layers are adjusted to fit perfectly to the bounded Finite-Element area ("perfectly matching"). A complex-valued coordinate stretching is used, which maps the natural coordinates to complex stretched coordinates using a stretching function that determines the damping profile.

The PML method was originally developed by Bérenger (1994) for electromagnetic waves and later adapted for elastic waves (Basu and Chopra 2003, Basu and Chopra 2004). By means of a displacement-based Finite-Element formulation and adaptation for explicit time integration, transient three-dimensional dynamic analyses including nonlinearities are possible (Basu 2009). The method is implemented in LS-Dyna (2019) and enables the use of nonlinear material models. This software is ideally suited for simulating highly dynamic events and also provides a number of nonlinear material models.

VALIDATION WITH EXTENDED MESH METHOD

For validation purposes, the response of a foundation resting on homogeneous soil is investigated by applying the extended mesh method and comparing the results to a model with PML-elements. In the extended mesh method, a large soil area is modelled, so that reflections at the boundaries do not return to the foundation during the calculating time (see Fig. 3).

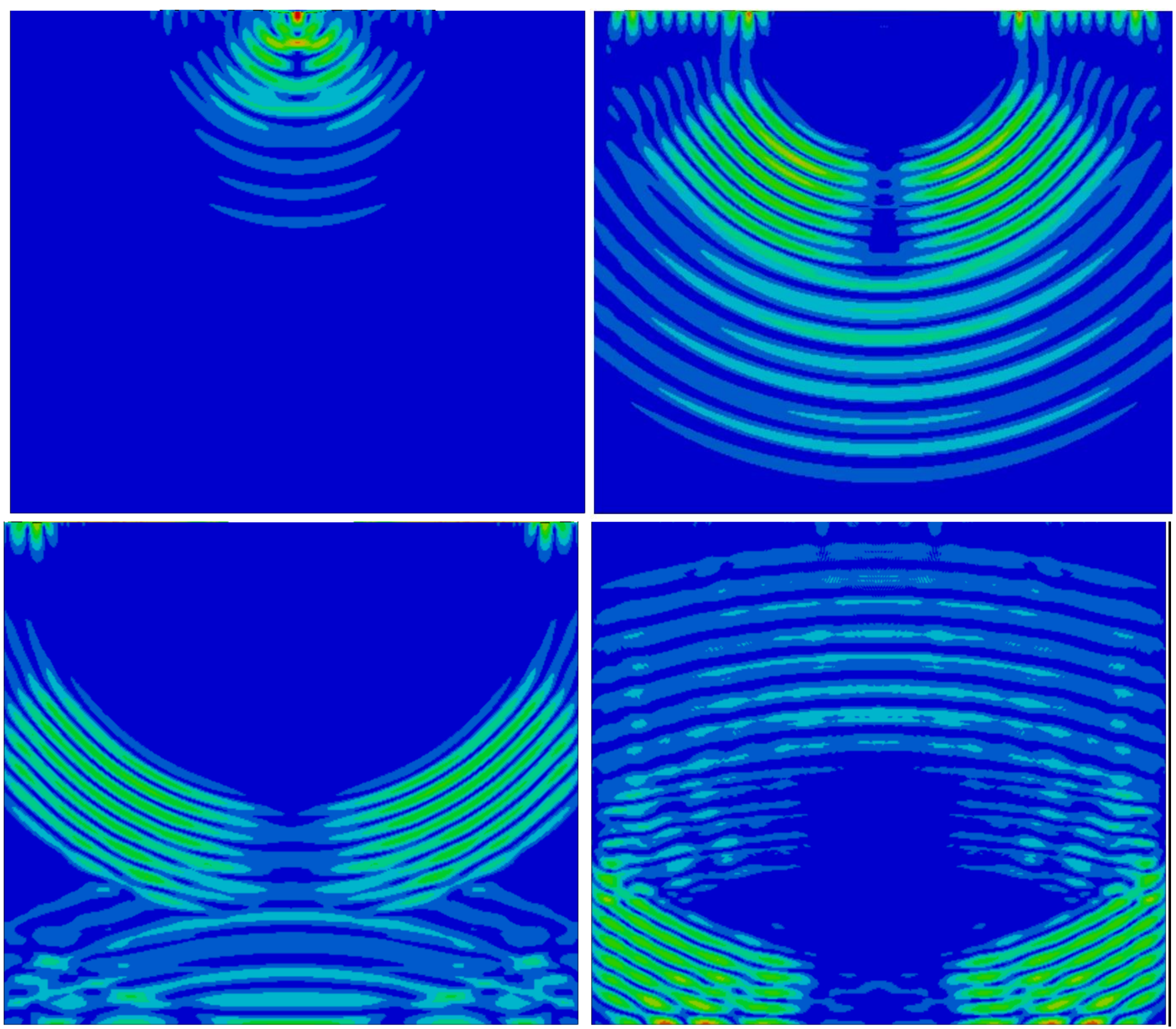


Figure 3. LS-Dyna-model of a harmonic excited flexible foundation on homogenous soil with extended mesh

Fig. 3 shows the model of an extended mesh. The vibration of the harmonically excited foundation propagates as waves in the soil area until the boundary of the FE-model is reached. Then reflections appear which return to the foundation and falsify the calculation results. In the model for the lateral boundaries, non-reflecting boundaries based on viscous dampers are used. Even though this is a simple and rough procedure, the absorbing effect is clearly evident compared to the simple boundary at the bottom.

This large model leads to an enormous memory requirement and a long calculation time. For complex non-linear three-dimensional dynamic analysis, the computation effort is unacceptable even for modern high-performance computers. Therefore, absorbing elements such as the PML-elements presented here are required.

The same calculation with PML-Elements were performed. However, this time only a small soil area is modelled (see Fig. 2). The results of the calculation with extended mesh and PML method were identical. For details see Basu (2009), a similar example was examined there using extended mesh, PML and viscous boundaries.

VALIDATION WITH THIN-LAYER METHOD IN FREQUENCY DOMAIN

Before performing complex non-linear dynamic analysis using PML, the method was verified with the, in the frequency domain working, aforementioned Thin Layer Method (TLM). The method was implemented by the author in MATLAB and validated by other software based on the TLM method.

The TLM is a very efficient and powerful semi-analytical procedure for considering SSI in linear-elastic calculations. It was first developed by Waas (1972) and extended for three-dimensional systems by Kausel (1982) and Waas-Werkle-Riggs (1985). In the TLM the soil is treated as a horizontally layered medium whose layers extend infinitely in a horizontal direction. Thus, Finite-Element discretization is performed only in vertical direction and analytical solutions are used for the horizontal direction. For the calculation linear displacement approaches in vertical direction are used, while for the horizontal direction Hankel and Bessel functions in cylindrical coordinates are used. The latter fulfill the differential equations of the continuum and capture the radiation exactly to infinity (Hartmann 1986).

The MATLAB tool developed according to the TLM approach enables to calculate the impedances (frequency dependent stiffness and damping coefficient) and the displacements resulting from time harmonic loads for a surface foundation. The computation in this tool can be summarized as follows: the calculation starts with assembling the stiffness- and mass matrices from submatrices of the single layers. It continues by solving the eigenvalue problems and the normalization of the orthogonality conditions of the resulting eigenvectors and finalizes with the calculation of displacements in the frequency domain by means of the green's function. From the latter the flexibility matrix and by its inversion the dynamic stiffness matrix (impedance matrix) is developed.

As a benchmark, a simple foundation of 2.0 x 2.0 m resting on 4 fictitious soil layers is examined. The properties of the layering are shown in Tab. 1. The layers rest on an elastic-homogeneous half-space, which is approximated by extending the layering. The properties of the half-space correspond to the last soil layer.

Table 1: Soil parameters used for configuration under investigation

Layer	**Thickness of layer [mm]**	**Density [t/mm³]**	**Shear modulus [N/mm²]**	**Poisson number [-]**	**Damping [-]**
1	100	1.8e-9	100	0.1	0.00
2	200	1.9e-9	150	0.2	0.05
3	300	2.0e-9	200	0.3	0.10
4	400	2.1e-9	250	0.4	0.15

The vertical displacement for a series of harmonic excitations up to a frequency of 100 Hz is calculated. The same system is modelled using LS-Dyna (Fig. 4) and the displacements for the harmonic excitations in the time domain are calculated.

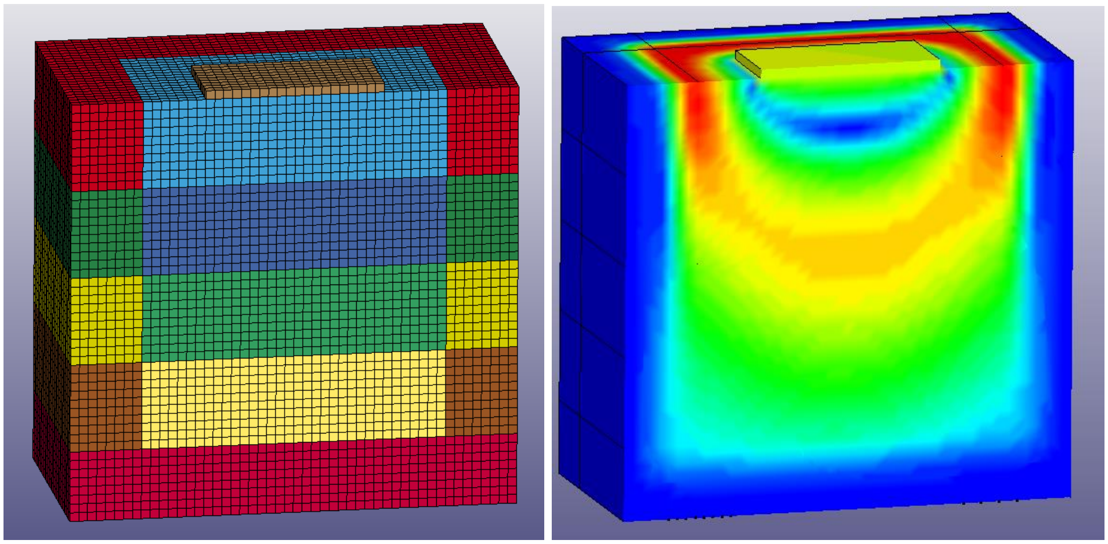


Figure 4. left - LS-Dyna-FE-model of surface foundation resting on soil-layering and half-space surrounded by PML-Elements, right - resulting displacement of harmonic excitation

The FE-model is surrounded by PML-elements that absorb all waves leaving the FEM region, as shown in Fig. 4. The diagram in Fig. 5 shows the good agreement between the results calculated by LS-Dyna in the time domain using PML and the TLM method calculated in the frequency domain.

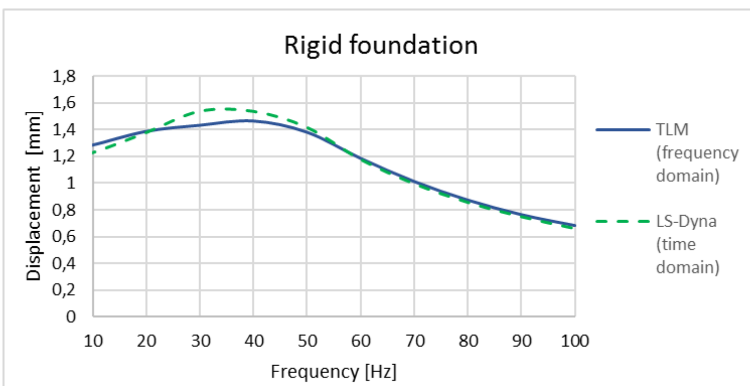


Figure 5. Vertical displacements of rigid foundation excited by harmonic load calculated in time and frequency domain

PARAMETER STUDIES BASED ON CALCULATIONS WITH PML-ELEMENTS

An extended investigation of the application of PML elements to simple soil-structure-configurations was cunducted to determine the accuracy and efficiency of the method. The influence of element size, layer thickness and number of elements as well as the distance to the excitation source were investigated. Rigid and flexible surface foundation on homogeneous and layered soil were examined excited by harmonic loads.

In various literature it is often recommended for Finite Element calculations to use an element edge length smaller than 1/6-1/8 of the shear wavelength λ in order to obtain satisfactory numerical accuracy (e.g. Kausel 2017). The shear wave length can be easily obtained by $\lambda = v_s/f$ while f is the exciting frequency of interest and v_s is the shear wave velocity that can be calculated by:

$$v_s = \sqrt{\left(\frac{G_s}{\rho}\right)} \tag{1}$$

where G_s is the shear modulus and ρ the density of the material. In the tested examples the element size of 1/8 λ was not sufficient for exact calculation due to the imperfect absorption quality. Good results were achieved with element sizes of 1/16 of the shear wavelength λ (Fig. 6).

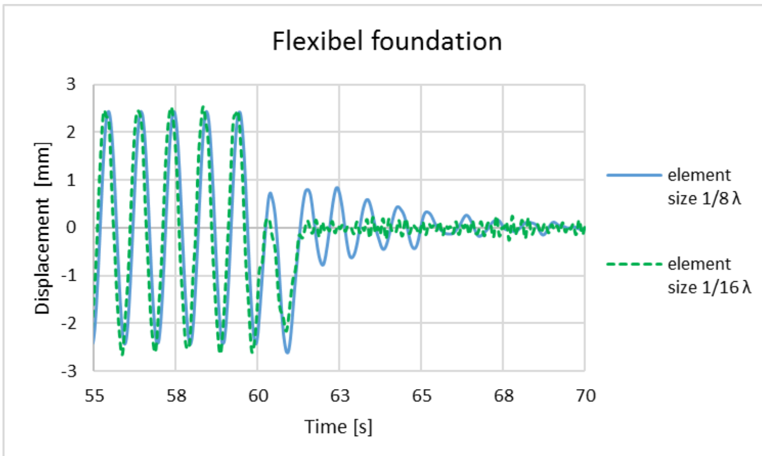


Figure 6. Results for flexible foundation with element length of 1/8 λ and 1/16 λ

The results with the element size of 1/8 λ indicate an overestimation of amplitudes during excitation. Even after the end of the excitation the system continues to move and shows that a complete absorption of the waves was not successful. The system calculated with an element size of 1/16 λ shows almost complete decay of the excitation.

The required size of the soil area to be modelled and the required number of PML-Elements were investigated. The results for a soil area of 0.2 m and 0.5 m thickness surrounding the excited foundation next to the adjacent PML layer are shown in Fig. 5. At a small distance of about 0.2 m, a thickness of up to 8 elements led to resonance phenomena (Fig.7). Using 10 elements the wave absorption was successful.

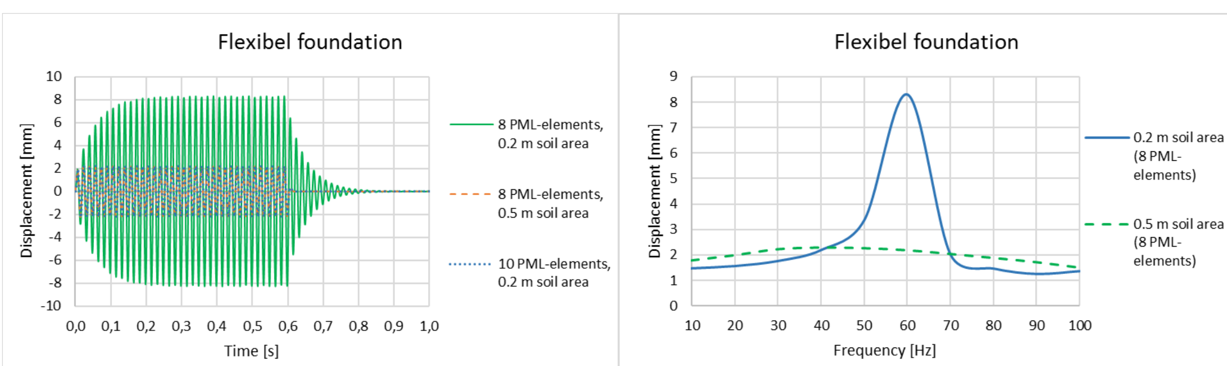


Figure 7. Displacements of foundation: left - with different thickness of PML-Layer and size of modeled soil area right - with different size of modeled soil area calculated in time domain and displayed in frequency domain

INVESTIGATION ON RESPONSE OF NUCLEAR POWER PLANT TO AIRCRAFT IMPACT

Based on the presented validation and findings PML-elements are used in a numerical analysis of a nuclear power plant due to aircraft impact.
First, the load-time-history of an aircraft impact is estimated by simulating the impact of an elastoplastic 3D-shell-beam-model of the airplane on the outer shell of the power plant model and integrating the pressures of the impact area. In this way, the flexibility and plasticization of the concrete structure are taken into account. This load function is than applied on a detailed power plant model. The soil is considered in a simple approach by static spring-damper elements (frequency independent impedances) and in a more accurate approach by PML-elements.
The crucial value for the estimation of induced vibrations is the total impulse (mass of aircraft x impact velocity). Thus, a high velocity is assumed at which a relatively low structure such as the containment building of a nuclear power plant can still be targeted for impact.

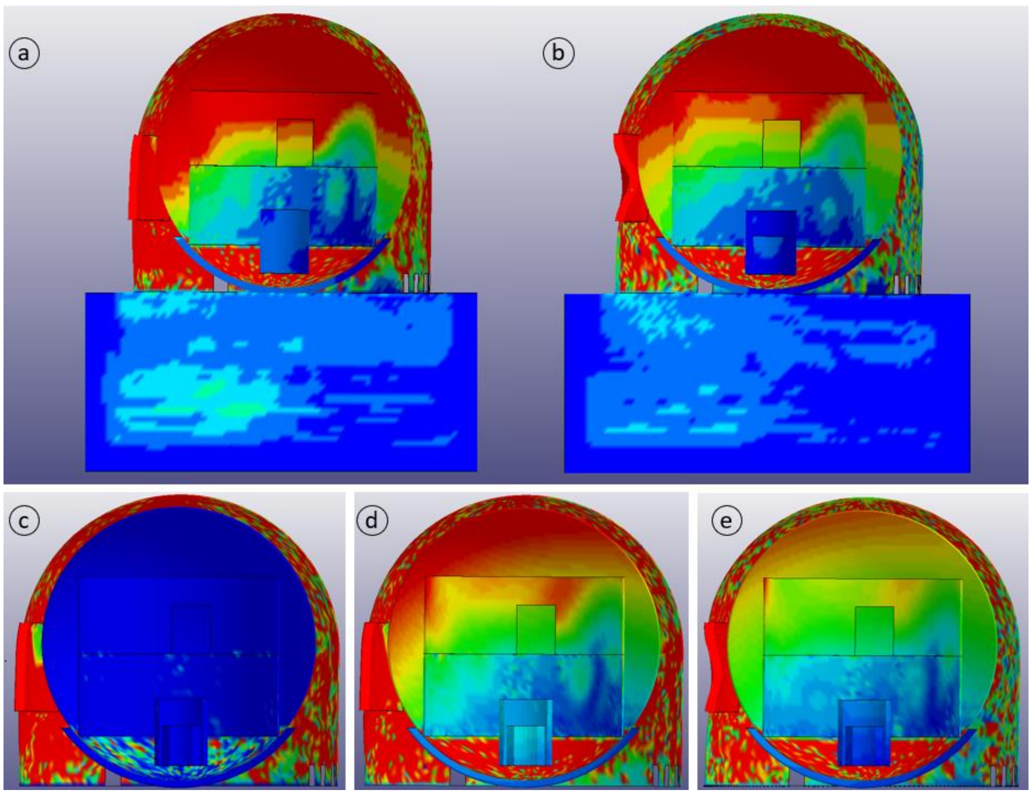
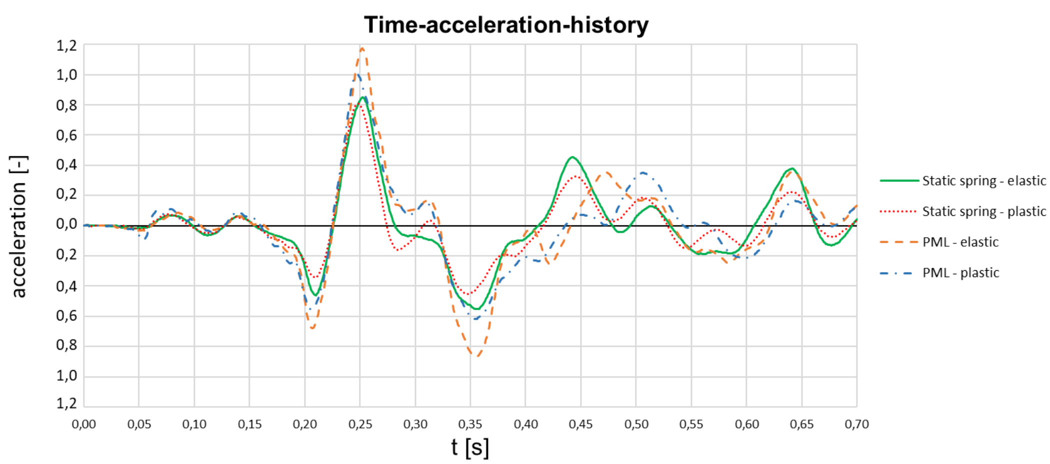


Figure 8. Resulting acceleration: a) elastic model with PML-elements, b) elastoplastic model with PML-elements c) model with fixed foundation d) elastic model with static spring-damper-elements, e) elastoplastic model with static spring-damper-elements

A linear-elastic and a non-linear-elastoplastic analysis is performed and compared. In the non-linear calculation the impact area is discretized by modelling the reinforcement with discrete beam elements. For the modelling of steel, the elasto-plastic material model "piecewise linear plasticity" is used. The coupling of the reinforcement with concrete is done with the command "constrainded_lagrange in solid". For concrete, the three-invariant plasticity and damage-based constitutive concrete model Karagozian & Case (K&C) release III is used. This model is widely used to compute the effects of quasi-static, blast and impact loads on concrete structures (Joseph M., Magallanes et al. 2010) and exhibits methods to reduce mesh-dependencies due to strain-softening. In order to consider strain-rate effects, which play an important role for high dynamic loadings, a special strain hardening curve is defined, for details see Malvar L. (1998).

The outer shell outside of the impact area is modelled as non-linear layered shell, which represents a smeared combination of concrete and reinforcement. The material model "Concrete_EC2" used includes concrete cracking in tension as well as crushing in compression and reinforcement yield, hardening and failure, (LS-Dyna 2019). The dynamic calculations are performed in the time domain with explicit integration methods and time steps adapted to the nonlinearities.
Based on the parameter studies presented above, the elements size of 1/16 λ is selected. A convergence study was carried out using smaller elements, which showed almost no change in the calculation results.
Figure 8 shows the acceleration response of the nuclear power plant model as a result of an aircraft impact. In a) and b) the calculation with elastic and elastoplastic material is shown. For both models the absorption by means of PML-elements works very fine. No reflections can be observed at the boudaries. In d) and e) static spring-damper elements are used to approximate the soil for the elastic and elastoplastic material model. In c) the foundation plate was fixed. The model shows that almost no accelerations appear in the internal area, indicating the proper functionality of the secondary containment protecting the internal components. Concluding the induced vibrations are transmitted via the foundation plate and soil. Therfore, the consideration of soil is essential for these calculations
In Figure 9 the acceleration response of the internal node where the reactor crane is mounted is displaced in time domain and frequency domain. The latter represents a floor response spectrum, which can be used for designing the component. The acceleration using the non-linear plastic model are in general smaller compared to the elastic calculation. The reduction achieved by using the plastic model are even larger for the model with PML-elements. The models with static springs are underestimating the amplitudes by about 40% for the elastic and 20% for the plastic calculation.



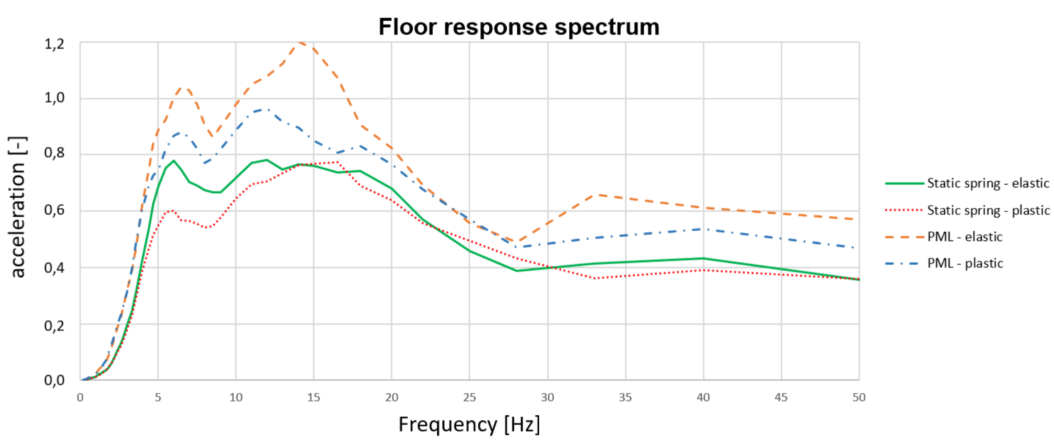


Figure 9. Acceleration response of internal node: top – Time-acceleration-history, bottom – Floor response spectrum

CONCLUSION AND OUTLOOK

The influence of dynamic Soil-Structure-Interaction cannot be neglected in safety assessments regarding aircraft impact. Induced vibrations are transmitted by the foundation and soil making the consideration of the interaction indispensable. The approximation of soil by static spring-damper-elements can underestimate the vibrations considerable. It is advisable to model the soil area and use PML-elements to capture the radiation properties of the soil in dynamic non-linear calculations. Investigations using PML-elements in a non-linear dynamic airplane impact analysis with elastoplastic material models were presented and show plausible results.

So far, the method was verified for elastic calculations by simple models with time (extended mesh) and frequency domain (TLM) methods. The verification of the complex nuclear-power-plant model is planned by means of the TLM method for the elastic calculation.

To verify the results of the nonlinear calculations with PML, a more common method in nuclear power plant design will be used. A linear elastic and an elastoplastic calculation will be performed without considering soil and the floor response spectra will be evaluated. A transfer function will be determined based on building response spectra (floor response spectra) of the linear and non-linear calculations. Then a linear calculation will be performed in the frequency domain considering soil using the Thin-Layer Method. The previously determined transfer function is used to derive the nonlinear response spectra from the linear calculation. This “pseudo”-non-linear-results will be compared to the response spectra obtained by the “real” non-linear calculation.

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REFERENCES

Basu, U., Chopra A. K. (2003). “Perfectly matched layers for time-harmonic elastodynamics of unbounded domains,” *Comput. Methods in Appl. Mech. and Engrg.*, 192, 1337-1375.

Basu, U., Chopra A. K. (2004). “Perfectly matched layers for transient elastodynamics of unbounded domains,” *Int. J. Numer. Meth. Engng*, 59, 1039–1074.

Basu, U., Chopra A. K. (2009). “Explicit finite element perfectly matched layer for transient three-dimensional elastic waves,” Int. J. *Numer. Meth. Engng*, 77, 151–176.

Bérenger, J. P. (1994). “A perfectly matched layer for the the absorption of electromagnetic waves”, *J. Computat. Phys.*, 144 (2), 185-200.

Bolisetti, C., Whittaker, A.S., Coleman J.L. (2015). “Frequency- and time-domain methods in soil-structure interaction analysis,” *SMIRT-23*, Manchester, Division V, Paper 526.

Borsutzky, R., Smoczynski, K.; Sadegh-Azar, H. (2013). “Ansätze im Zeitbereich zur Berücksichtigung der frequenzabhängigen Boden-Bauwerk-Wechselwirkung,“ 13. D-A-CH-Tagung, Wien.

Hartmann, G. (1986), “Pfahlgruppen in gesichertem Boden unter horizontaler dynamischer Belastung,” *Mitteilungen des Instituts für Grundbau, Boden- und Felsmechanik der Technischen Hochschule Darmstadt*.

Kausel, E., Peek, R. (1982). „Dynamic Loads in the interior of a layered stratum. An explicit solution,” *Bulletin of the Seismological Society of America.*

Kausel, E. (2017). *Advanced Structural Dynamics*, Cambridge University Press.

Livermore Software Technology Corporation (2019). LS-Dyna. Version: Livermore Software Technology Corporation.

Miller, G. F., Pursey, H. (1954). “The field and radiation impedance of mechanical radiators on the surface of a semi-infinite isotropic solid,” *Proc. Royal Society*, London, 223, 521–541.

Ostasan, F. (2006). SASSI 2000. *A system for analysis of soil-structure interaction. Theoretical Manual*, Berkeley.

Joseph M., Magallanes et al. (2010). “Recent improvements to release III of the K&C Concrete Model,” *11th International LS-Dyna Users Conference*, 2010.

Javier M. L., Crawford J.E. (1998). “Dynamic increase factors for concrete,” *Twenty-Eighth DDESB Seminar*, Orlando, FL.

Sadegh-Azar, H. (2007). “Die Bicentenario-Chiloe-Brücke: Seismische und dynamische Untersuchungen” *Bautechnik 84* (3), S. 157–168. DOI: 10.1002/bate.200710014.

Sadegh-Azar, H., Gorg, A. (2009). Bautechnische Auslegung von Kernkraftwerken für Erdbeben,“ atw 54 (12). 753-759.

Sadegh-Azar H., Hartmann H. G. (2011). “Grundlagen der seismischen Auslegung von Kernkraftwerken und Einfluss der Boden-Bauwerk Wechselwirkung“. *D-A-CH-Mitteilungsblatt (86)*, 3–10.

Waas, G., Riggs, H. R., Werkle H. (1985). “Displacement solutions for dynamic loads in transversely-isotropic stratified media,” *Earthquake engineering and structural dynamics (13)*, 173–193.

Waas, G. (1972). *Linear two-dimensional analysis of soil dynamic problems in semi-infinite layered media*. Ph.D. Dissertation.