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STABILITY OF CASK AND CONTAINER STACKS IN AN INTERIM STORAGE HALL UNDER INDUCED VIBRATIONS FROM SEISMIC AND BLAST PRESSURE WAVE LOADING

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ABSTRACT

Interim storage halls at nuclear power plant (NPP) sites can store low- and intermediate-level radioactive waste. The waste is typically kept in different types of casks or box-shaped metal containers, which are typically stacked, requiring stability analysis under external events such as earthquakes and blast pressure waves (BPW).

This paper examines the stability of cask and container stacks under seismic and BPW loading. For this purpose, the structural response of the interim storage hall was determined by using finite element (FE) models. The induced vibrations at the base slab are determined by response spectra and time histories. These are used to perform static and non-linear numerical analysis to assess the stability of the container and cask stacks.

Both static and numerical calculations demonstrate the stability of the stacks with sufficient safety margins, while non-linear time history simulation provides additional insight into the transient behavior of the casks and containers, being able to demonstrate the motion of each element and determining remaining displacements.

INTRODUCTION

Interim storage hall halls are erected at a nuclear power plant (NPP) sites to collect the low- and intermediate-level radioactive waste produced locally, e.g. during the decommissioning of the NPP. The waste is collected in casks and containers and made available for later onward transportation to the final storage facility Konrad. During their storage in the hall, the casks and containers are stacked by an overhead crane. As part of the planning and design of an interim storage hall, load cases from external events (EE) have to be considered. EE include exceptional natural load cases such as floods or earthquakes, but also human induced load cases such as blast pressure wave. According to the recommendation of the German Nuclear Waste Management Commission (ESK), the blast pressure wave load case is considered beyond-design-basis event, see ESK (2021) and ESK (2023).

In Ries (2024) the load case blast pressure wave (BPW) was considered for this building in detail, addressing on the characteristics of the loading itself as the structural response of the building due to the nearby deflagration of an LNG vapor cloud. The resulting vibrations were evaluated as floor response spectra of the base slab. These spectra were compared to corresponding spectra from seismic investigations showing that the seismic are enveloping at the evaluated locations on the base slab.

For the site of a NPP, the paper briefly presents the procedure and result of the design under the effect of the design basis earthquake (DBE) and a blast pressure wave (BPW), with the focus on the stability of the stacked casks respectively the stacked containers.

BUILDING

The finite element model of the interim storage hall is depicted in Figure *1*. The hall consists of the storage hall itself and a small adjoining neighboring office building. Both buildings share a common base slab. Below the base slab the pile foundation is modelled. The FE model was originally built for seismic qualification according to KTA 2201.1 (2011) and KTA 2201.3 (2013). Variations in container loading, container distribution as well as variations in soil properties are considered by using model variants. The analysis is done by using the software SASSI (2019), for further details, see Ries, Müller-Petersen, Henkel, (2024).

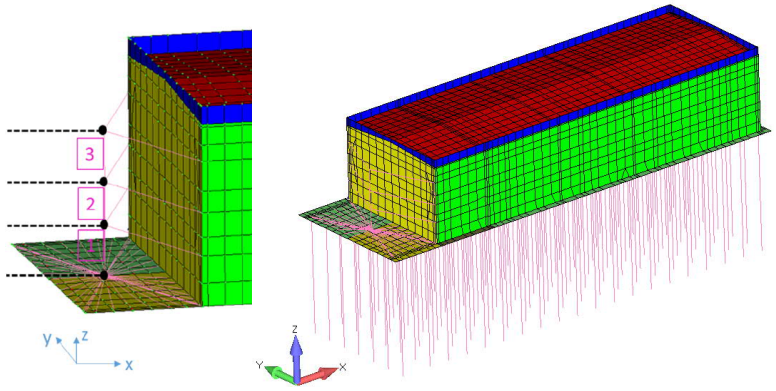

Figure 1. FE model of interim storage hall:
detail of modeling of office building (left), overall model (right).

CASKS AND CONTAINERS

In general, two different types of containers are stored in the considered interim storage facility for low- and intermediate-level radioactive waste. On the one hand, these are cylindrical casks made of reinforced concrete or cast iron, approx. 1.5 m high and 1.06 m in diameter. On the other hand, different sized box-shaped containers, so called Konrad containers (KC) from LxWxH 1.6 x 1.7 x1.7 m to 3.2 x 2 x1.7 m are used. These are made from sheet steel, all eight corners are equipped with ISO corners for container handling, with max. allowable total mass of 20 tons. Additionally, 20'-containers are used with an even higher total mass. The different container types are stored in separate areas, for reasons of space, containers of the same type are also stacked.

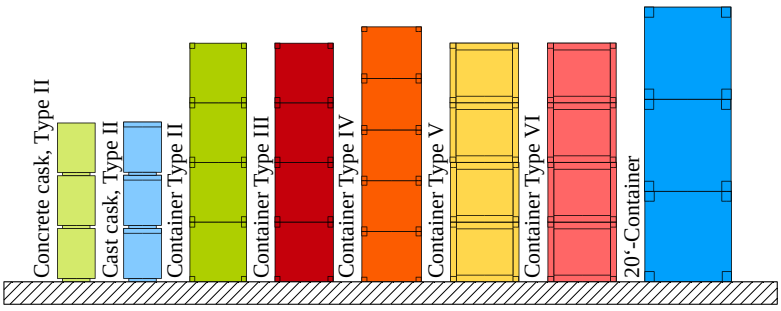

Figure 2. Illustration of stacking of different containers.

The stored containers of low- and intermediate-level radioactive waste can already be conditioned (according to Konrad conditions BfS (2015), for later forwarding to Konrad) or only buffered temporarily for later local handling.

The container stacks are placed on the base slab. Between the container stacks themselves and the building structure distinct gaps are to be observed. By using stacking cones, placed between the container corners, a gap between two stacked containers is created, allowing for heat removal and preventing horizontal slipping. The maximum number of containers of the individual types which can be stacked to top of each other is defined it ranges from three to five, see Figure 2.

All containers are filled with low- and intermediate-level radioactive waste, but their individual content is varying. Which means each container has its individual total mass, center of gravity and radiation characteristics.

LOAD CASES EARTHQUAKE AND BLAST PRESSURE WAVE

The effects of earthquake loading and BPW on the stability of the container stacks must be analyzed and assessed. Below both loadings are characterized.

Seismic loading

As illustrated in Figure 3 (on the left), the horizontal design spectrum (Design Basis Earthquake, DBE) from the site report is displayed. For illustrative purposes, Figure 3 (on the right) shows a spectrum-compatible time signal, normalized to the rigid body acceleration (ZPA).

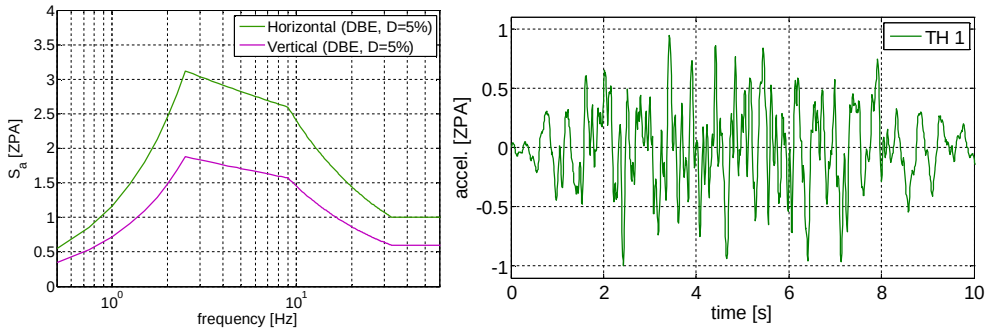

Figure 3. Design basis earthquake at the site: spectra (left), time history (right).

Blast pressure wave

There are various causes for blast pressure waves / explosions at the site. The leading load case scenario is a vapor cloud explosion caused by a postulated damaged Q-Max LNG vessel on the nearby waterway. The vessel leaks liquefied natural gas (LNG) from one of its tanks, causing a vapor cloud drifting towards the site. Near the site the vapor cloud is ignited, resulting in a vapor cloud explosion (VCE).

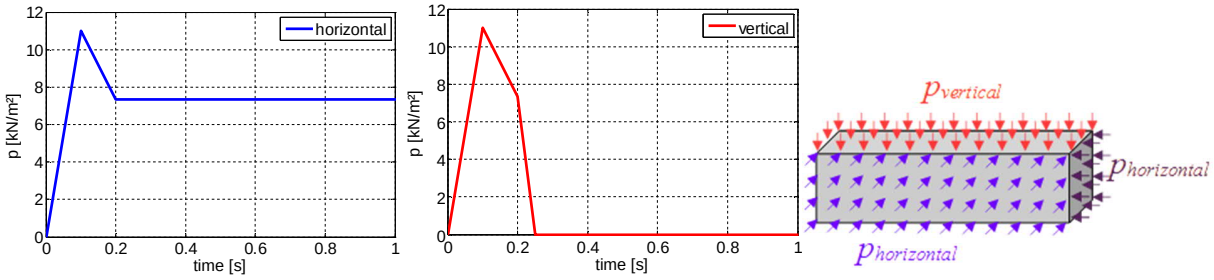

Figure 4. BPW, pressure loading: vertical (left), horizontal (mid), application ‘across the corner’ for box-shaped building.

There are different approaches to determine the overpressure time history that affects the structure. Here the peak value is determined by the multi-energy-method (MEM), the course of the time histories is determined by DIN 25449 (2022), for further details see Ries (2024). The resulting time histories of the pressure loading are depicted in Figure *4*.

INDUCED VIBRATIONS FROM EARTHQUAKE AND BLAST PRESSURE WAVE

As the containers are located on the base slab, the induced vibration from both load cases seismic and BPW must be numerically determined at that location.

In the first step the load case earthquake is fully analyzed. The time histories are calculated and evaluated in accordance with KTA 2201.3 (2011) by averaging spectra-compatible time history sets, enveloping over the soil and mass variation and smoothing. The results are the vibrations induced by DBE, which are given in the form of building response spectra. As an example, the result is shown in Figure *5* for a selected area on the floor slab. The calculations are also done for BPW, the spectra are enveloped over the model variants and the evaluation nodes, afterwards a spectral design is established. This design is also shown in Figure *5*, in comparison to the response spectra of a seismic calculation.

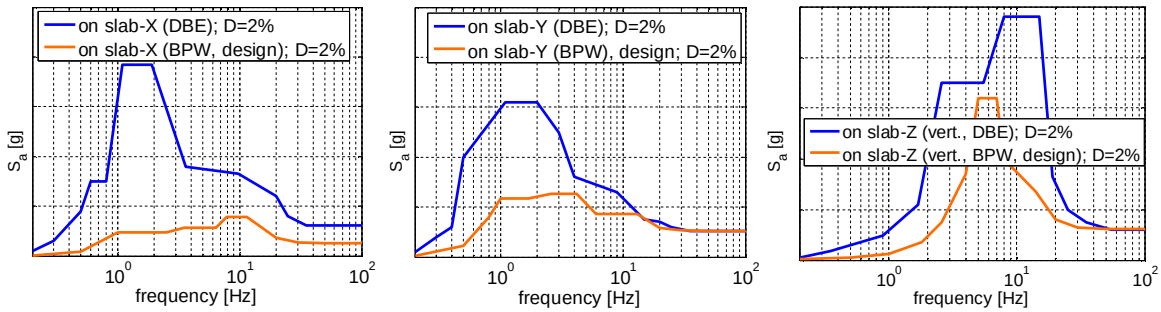

Figure 5. Induced vibrations on base slab: DBE (selected area) and BPW.

It can be seen that the BPW spectra are below the seismic spectra, especially in the frequency range up to 20 to 30 Hz.

VERIFICATION OF CONTAINER STABILITY

With knowing the induced vibrations / responses (i.e. time histories from numerical analyses or response spectra calculated from the time histories) of the base slab, the verification of the stability of the container stacks can be done. This is accomplished by showing the slipping and tilting safety und ensure that no collision with neighboring stacks or the building structure occurs in the event of slippage.

In addition to the container types (see FE model of two types in Figure 8, left), parameters such as stack height of the containers, mass occupancy with imperfections, use of intermediate elements (e.g. ISO stacking cones), contact points and time history combinations must also be taken into account. One addtional key parameter influencing the results is the friction coefficients of the different material pairings. For the material pairing ‘steel/steel’, ‘steel/concrete’ and ‘concrete/concrete’ the minimum and maximum friction coefficient have to be considered.

To effectively verify the stability of all container stacks and its variants under induced vibration combined with dead load loading, a covering analysis is carried out wherever possible.

Firstly the verification is tried to be carried out by simple static calculations. If container stacks’ stability cannot be verified by these calculations, non-linear time history calculations are used to verify the stability of the stacks. Both methods are addressed below.

Static calculations

Stacks with maximum stack height are considered for each container type. As a first assumption, it can be assumed that containers and their stacks will behave quasi-rigidly. Using the specified spectra (see Figure *5*), the stability of each container stack is investigated with respect to slipping and tilting safety.

In the static analytical verification, dead load *DL* is superimposed with the earthquake load $EQ_{hor,res}$ combination of horizontal resulting loading

$$EQ_{hor,res} = \sqrt{{EQ_X}^2 + {EQ_Y}^2} \qquad (1)$$

and the associated vertical excitation EQ_{vert}. It is conservatively assumed that the maximum accelerations in the horizontal and vertical directions occur at the same time, resulting in one conservative load combination to be considered

$$(DL - EQ_{vert}) + EQ_{hor,res}. \qquad (2)$$

The verifications are initially performed quasi-statically for all systems. The slipping safety is verified as shown in Figure 6.

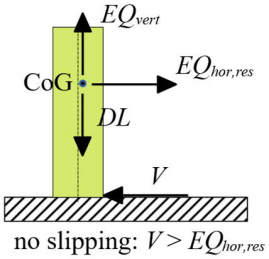

Figure 6. Slipping

According to Figure 6 the safety factor for slipping α_{slip} is calculated by

$$\alpha_{slip} = \frac{V}{EQ_{hor,res}} = \frac{\mu \cdot (DL - EQ_{vert})}{EQ_{hor,res}} \qquad (3)$$

The highest risk of slipping exists with the steel/steel friction combination, for which a minimum coefficient of friction of μ_{min} = 0.15 is used in accordance with KTA 3205.1 (2018), giving a minimum safety factor for slipping for all containers of $\alpha_{slip,min}$. As this value is significantly higher than the required safety (according to KTA 2201.4 (2012)) of 1.05, no slipping exists for all container stacks for the loading considered.

For the verification against tilting of the container stacks, only the smaller length dimensions are considered conservatively, as these have the highest sensitivity to tilting. The tilting safety is determined per container by considering various stacks with varying masses over the stack height. The maximum total mass of the individual containers is either assumed to be 100% or a reduced value is applied. This means that different stacks with varying total masses, mass distributions and different center of gravity positions are considered for each container type. For example, in the case of containers stacked four high, four different mass distributions are analyzed. For example, such as a top-heavy distribution of 60/60/60/100% filling within a container stack.

In the case of rectangular containers, in addition to flatness tolerances of the base, manufacturing tolerances (both in the mm range) as well as eccentric center of gravity positions in length, width and height are considered, which amount to up to 10% of the dimensions.

The analytical calculation of the tilting verification is carried out according to Figure 7.

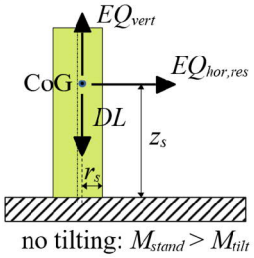

Figure 7. Tilting

If the standing moment M_{stand} is greater than the tilting moment M_{tilt}, tilting will not occur. With this condition, the safety factor against tilting α_{tilt} is calculated as follows

$$\alpha_{tilt} = \frac{M_{stand}}{M_{tilt}} = \frac{g \cdot r_s}{\left(EQ_{hor,res} \cdot z_s + EQ_{vert} \cdot r_s\right)} \qquad (4)$$

For tilting the same minimum safety factor is applied as for slipping. The tilt safety is lowest at maximum stacking height for the stack of three type II concrete casks, assuming the most unfavorable mass distribution.

Non-linear time history calculations

The tilting and slipping safety of the most unfavorable type II concrete container cask stack and the unfavorable container type IV is investigated using non-linear time history analyses.
For this purpose, seven load scenarios were selected by breaking down the spectra averaged over combinations of time histories and enveloped by models with different soil stiffnesses and several response points. The selected acceleration time histories of the seven scenarios determine the spectra (e.g. Figure 5, DBE). This number of seven load situations also corresponds to the specification of KTA 2201.4 (2012). As the container stack represents an anchored component, the stabilizing dead load has to be applied with a safety factor of 0.95 according to KTA 2201.4 (2012) (9.81 m/s² x 0.95 = 9.32 m/s²).

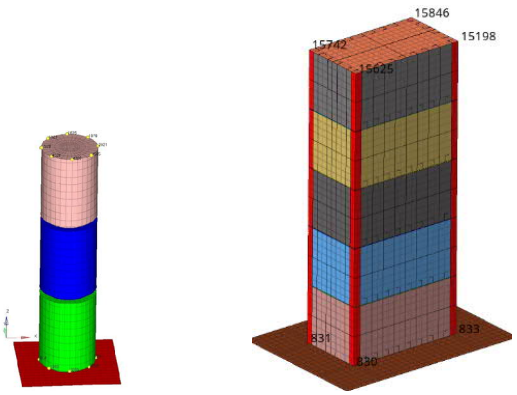

Figure 8. FE-Model of type II concrete cask stack (left) and type IV container stack (right).

The FE model of the cask stack is depicted in Figure 8, left. The most unfavorable mass distribution is used. The model of each cask consists of volume elements for container and filling with elastic material behavior and material damping.

The floor is defined as a rigid surface. Among the casks themselves and between the lowest cask and the floor contact pairs with appropriate friction values are defined.

The FE model of the type IV container stack, see Figure 8 (right), consists of elastic shell elements for the container itself and elastic volume elements for the filling, which reflect the eccentricity of the container filling with different raw densities. Stacking cones as well as geometric imperfections are considered in the model. Contact among the containers or the bottom container and the floor is taken into account with the *CONTACT PAIR option in the ABAQUS software, so the containers can tilt and slip during the induced vibrations.

Results of non-linear time history calculations

An example of the numerical calculations is shown in Figure 9 (left), which shows the resulting relative displacement of the nodes the top of casks compared to an earthquake excitation.

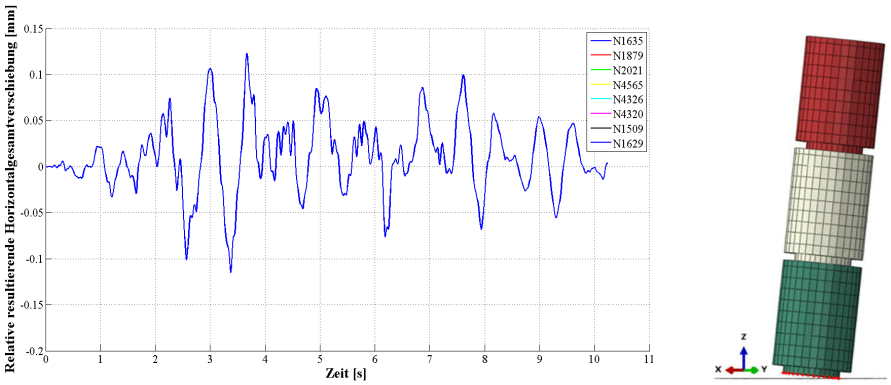

Figure 9. Concrete cask stack Type II: resulting relative displacement for μ_{min} (left) and short opening of the floor gap with heavily exaggerated representation (right).

This results, for example, in a maximum resulting relative horizontal displacement at the top edge of the uppermost concrete container of 0.125 mm for μ_{min} and 0.123 mm for μ_{max}. During the simulation also a short opening of the floor gap occurs, see Figure 9 (right).

The same parameter is shown for container type IV in Figure 10 (left).

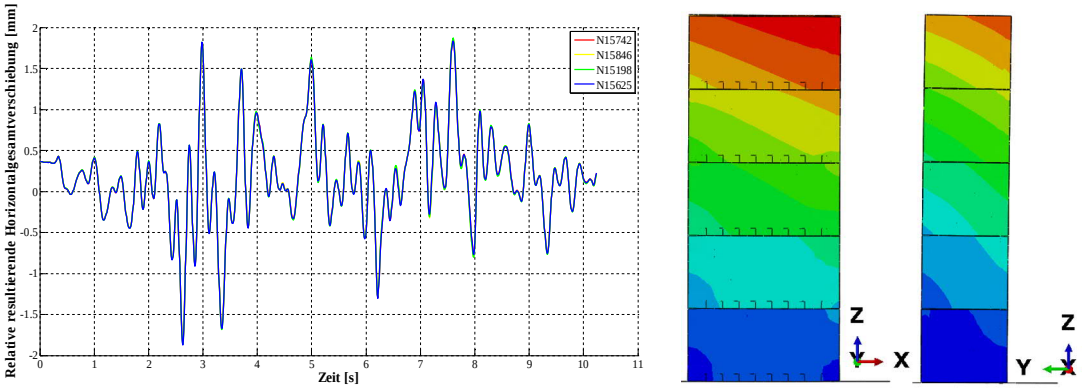

Figure 10. Container stack Type IV: resulting relative displacement for μ_{min} (left), remaining permanent displacement (right).

The stack of five Type IV containers has a maximum relative displacement of its top relative to the floor of 1.87 mm for μ_{min} and 1.38 mm for μ_{max}. After the container stack has experienced the motion a permanent displacement of the individual containers remain, see Figure 10 (right).

It can be noted that, as a result of the induced vibrations considered, the maximum relative displacements are present but small. The non-linear stability verifications for the most unfavorable container stacks cover all other waste container stacks examined. As the spectra for BPW are covered by DBE, see Figure *5*, this results hold as well for BPW.

CONCLUSION

The interim storage hall at a German NPP site is used to store and buffer different types of casks and containers. To save space the casks und containers are stacked. For safety reasons the stability of the stacks has to be verified during external events like earthquake of blast pressure wave loading. By using FE models, the dynamic response under these external loads is determined, resulting in time histories and/or response spectra of at least the floor slab of the interim storage hall, where the stacks are stored.

As a result of the low induced vibrations on earthquakes and BPW, the stability of the various cask and container stacks can be verified both by static calculations and by more elaborate numerical time history simulations. The results of comprehensive numerical calculations give additional insight into the effects of the induced vibrations on the container stacks, for example the remaining permanent displacement can be determined.

The verifications cover all other systems; thus the stability of the stacks is always ensured and there are no collisions among the stack and the building structure.

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