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CASKS (STACKS) UNDER EARTHQUAKE LOADS

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ABSTRACT

Cylindrical casks in interim storage facilities excited by loads resulting from design basis earthquake can be susceptible to trundle movements, which may necessitate minimum distances between the casks to prevent colliding of adjacent ones. This characteristic cannot be identified by means of quasi-static analysis. Hence, stability proofs for casks and cask stacks by means of time history analyses on nonlinear FEM models are performed demonstrating that the casks do not collide in case of design basis earthquakes based on the German safety standards KTA 2201.1 and 2201.4.

Numerical contact definitions are applied to a FEM model containing the cask and, respectively, cask stack as well as a cut out of the baseplate of the building. Thus, not only overturning and improper sliding of the cask/cask stack on the baseplate can be examined but also relative displacements between the casks within a stack can be determined. Within the numerical analyses, the applied friction coefficients are varied between upper and lower bounds, and various mass distributions for the cask stack are taken into account.

The earthquake excitation is applied following two different approaches valid according to the German safety standard KTA 2201.1: The first approach follows time histories corresponding to the floor response spectra of the baseplate, the second approach follows time histories taken directly from the priory performed building analyses.

INTERIM STORAGE OF CASKS

In Germany, there are three central interim storage facilities for spent nuclear fuel and radioactive waste sited in Ahaus, Gorleben and near Lubmin, as well as interim storage facilities built directly next to nuclear power plants. These interim storage facilities differ in the classification of casks stored, differentiating between radioactive waste with negligible heat generation and dry cask storage of spent fuel and heat-generating waste. Depending on the type of waste, different types of casks are stored. Besides containers of various types, cylindrical casks like e.g. shipping and storage casks of type CASTOR® V/19, V/52 and MTR3 for spent nuclear fuel and cast iron casks of type MOSAIK® for radioactive waste are used. The containers and casks are stored separately as well as stacked, whereat common ISO edges are used for containers. The casks are stacked directly or with stacking aids. As mentioned above, this paper focusses on cylindrical casks stored separately as well as stacked.

STANDARDS AND GUIDELINES

For our work in Germany, we use the applicable German standards and guidelines as a basis. Concerning seismic events and the resulting loads, this is the KTA series 2201. However, the methods and approaches can also be applied based on other standards.

The KTA series 2201 consists of six parts and deals with the design of nuclear power plants against seismic events. Nevertheless, its scope of application is extended to interim storage facilities by the ESK guidelines (2013, 2013a). As this paper focuses on numerical analyses, parts 2201.1, 2201.3 and 2201.4 are consulted dealing with general requirements concerning the design basis earthquake (DBE) and the verification (2201.1) as well as detailed requirements concerning the verification of civil structures (2201.3) and components (2201.4). All six parts had been amended successively from 2011 to 2015. Especially with the new version of KTA 2201.1, the requirements regarding the DBE were augmented compared to the previous version. Thus, the DBE has to be specified with an intensity of at least VI and a probability of exceedance of at least 10^{-5}/a.

EARTHQUAKE LOADS

Design Basis Earthquake (DBE)

With the DBE the seismic load for the load case earthquake is given. For interim storage facilities, seismological expert`s reports define a site-specific DBE and seismo-engineering parameters based on KTA 2201.1 such as e.g. intensity, probability of exceedance and strong motion duration as well as soil parameters like e.g. shear modulus, density, Poisson`s ratio, damping ratio. According to KTA 2201.1, the DBE is defined as a free field response spectrum, meaning a ground acceleration response spectrum for a reference horizon in the subsoil, where the oscillation properties are not influenced by building structures. No soil-structure interaction is considered at this step of the analysis. Generally, the reference horizon is equal to the ground level or the geological layer boundary of a sufficiently stiff ground layer. According to KTA 2201.1, the scatter band of the soil profile as well as uncertainties are covered within the computations. The DBE results from smoothed, broadened and enveloped spectra and is defined for the horizontal resultant as well as the horizontal and vertical component. Figure 1 (left) contains exemplarily free field response spectra for a damping ratio of 5 % for an arbitrary site in Germany. The peak ground acceleration (PGA) for the horizontally resultant direction a_{hr} is 0.26 g, for the vertical component a_v it is 50 % of a_{hr} (0.13 g).

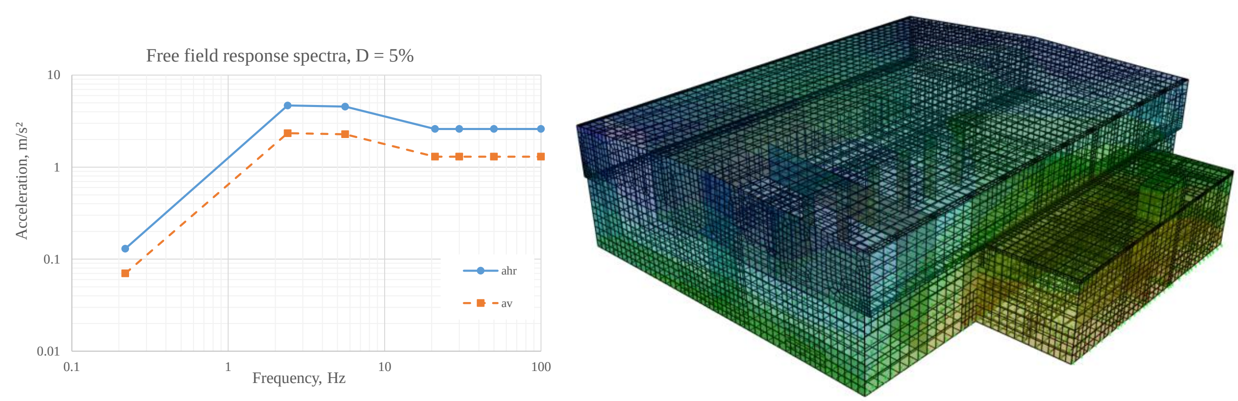

Figure 1. Free field response spectra for a site (left) and FEM model of an interim storage facility (right) in Germany.

Determination of Design or Required Response Spectra (DRS / RRS)

KTA 2201.4 defines the design response spectrum (DRS) to be enveloping, broadened and smoothed, whereat one has to differentiate between ground acceleration spectrum as primary spectrum, building response spectrum as secondary spectrum, and component response spectrum as tertiary spectrum.

Generally, based on the site-specific DBE, floor response spectra (FRS) for the base plate are computed on a FEM model of the interim storage facility for each of the three main directions, exemplarily shown in Figure 1 (right). According to KTA 2201.3, the soil-structure interaction has to be considered. For a homogenous soil, the elastic half-space model representing a simple spring-mass-damper is sufficient. For a layered soil with widely differing dynamic characteristics or for foundations differing from a spread foundation, like pile foundation, more accurate analyses have to be performed, e.g. by impedance functions.

According to KTA 2201.1 and 2201.3, the excitation is applied in all three main directions as time histories compatible with the DBE whereat for linear analyses at least three statistically independent time histories have to be combined resulting in three load situations. The resulting response spectra for each main direction can be averaged.

In order to consider the scatter band of the existing soil profile and the various loading conditions, KTA 2201.1 and 2201.3 demand diverse variations of the reference model, each subjected to the three load situations. Hence, concerning the soil, the average shear modulus (G_{mid}) is varied between a lower (G_{min}) and upper (G_{max}) bound and the various loading conditions are considered by additional masses ranging from a lower (M_{min}) and upper bound (M_{max}) as well. The resulting response spectra for each main direction have to be enveloped.

Afterwards, FRS are enveloped, broadened and smoothed for each main direction and identified as DRS, which are also named required response spectra (RRS). Figure 2 (left) contains exemplarily a RRS with a damping ratio of 4 % for the x-direction of the base plate of an interim storage facility as well as response spectra transformed back from time histories pictured in Figure 2 (right) compatible with the RRS according to KTA 2201.1 and 2201.3. These time histories can be taken as a basis for component verification as explained further below.

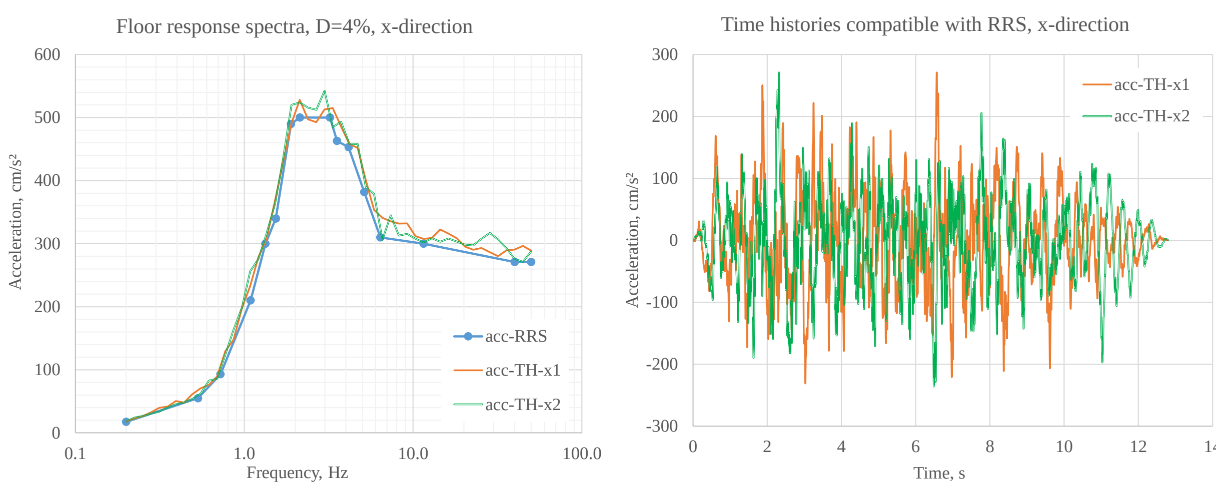

Figure 2. Required response spectrum (RRS) and two floor response spectra transformed back from time histories (TH) compatible with the RRS for the x-direction and a damping ratio of 4 % (left); two corresponding time histories (right).

NUMERICAL MODEL AND NONLINEAR ANALYSES

FEM Model of a Cask / Cask Stack

Modelling and computations are performed with the commercial FEM program ANSYS including the LS-DYNA solver. In order to represent relative displacements of the cask/cask stack on the base plate, including tilting, trundling and sliding, the numerical model also contains a section of the base plate of the building, besides the cask/cask stack. Between the (bottom) cask and the base plate and between the casks in a stack with or without stacking aids contact definitions are applied to the FEM model. For the contact pairs the friction coefficient is varied, respectively, between a lower and an upper bound depending on the material. Hence, the friction coefficient between a cask and the base plate is varied between $\mu_{\text{cask-base, min}} = 0.2$ and $\mu_{\text{cask-base, max}} = 0.6$, while the friction coefficient in a stack is varied between $\mu_{\text{cask-cask/stacking aid, min}} = 0.1$ and $\mu_{\text{cask-cask/stacking aid, max}} = 0.3$. The lower bound allows a conservative approach concerning sliding, while the upper bound allows a conservative approach concerning tilting and trundling. Figure 3 shows FEM models of various casks and cask stacks of the types CASTOR® V/52, MTR3 and MOSAIK®, with and without stacking aids, which are investigated.

For nonlinear time history analyses, loading conditions of the single cask and within the cask stack are investigated. Furthermore, for a cask stack imperfections due to handling accuracy need to be considered as well.

Depending on the computed displacements of the cask/cask stack relative to the base plate section, minimum distances can be necessary in order to avoid collisions of adjacent casks for the load case DBE.

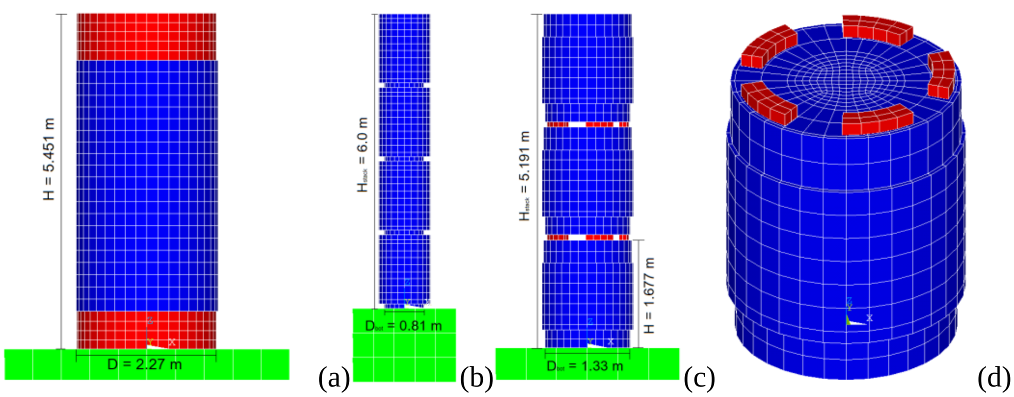

Figure 3. FEM model of a cask of type CASTOR® V/52 (a), stacked casks of type MOSAIK® without stacking aids (b), stacked casks of type CASTOR® MTR3 with stacking aids (c), stacked casks of type CASTOR® MTR3 with stacking aids (section of whole model) (d); (a) to (c) respectively with base plate section, (green).

Excitation by Time Histories

Within the nonlinear computations the excitation is applied to the base plate section in terms of acceleration time histories. Due to the nonlinearity, at least seven statistically independent time histories have to be combined resulting in seven load situations. As mentioned above, according to KTA 2201.1 the excitation may consist of time histories compatible with the RRS; see Figure 2. Besides KTA 2201.1 allows an alternative approach by applying time histories taken directly from the structural analyses of the building. Both approaches are taken into account for the verifications explained in the further.

Concerning the approach of time histories taken directly from the structural analyses of the building, one has to make sure that the scatter band of structural analyses is covered to comply with KTA 2201.1.

That is, in analogy to the structural analyses and the determination of DRS, the consideration of the variation of soil stiffness (G_{min}, G_{max}) and loading conditions (M_{min}, M_{max}).

Figure 4 contrasts both approaches in the frequency and time domain: The FRS transformed back from a time history compatible with the RRS covers the RRS in a conservative way. One can see that generating these time histories may lead to an overestimation of the zero peak acceleration (ZPA) in the frequency domain, which equals the maximum acceleration in the time domain. This, of course, is a sensitive parameter concerning time history analysis for component verification. Figure 4 (left) also contains FRS taken from various result nodes of the FEM model of the building for four model variants. The FRS of each model variant represents only the dynamic characteristic of this variant, respectively. Taking the corresponding time histories, exemplarily shown in Figure 4 (right), as excitation for the FEM analyses of the component leads to a lower excitation level, but results in an increase of computational cost in order to cover the scatter band of structural analyses.

Time history analyses for the load case DBE are performed on FEM models of various casks and cask stacks of the types CASTOR® V/52, MTR3 and MOSAIK®, with and without stacking aids; see Figure 3. Hence, both approaches, time histories compatible with the respective RRS and time histories taken directly from the structural analyses of the respective building, are pursued. In the following, results from a range of computations for two cask types are presented, CASTOR® V/52 (single; see Figure 3 (a)) and MOSAIK® (stack of four casks; see Figure 3 (b)).

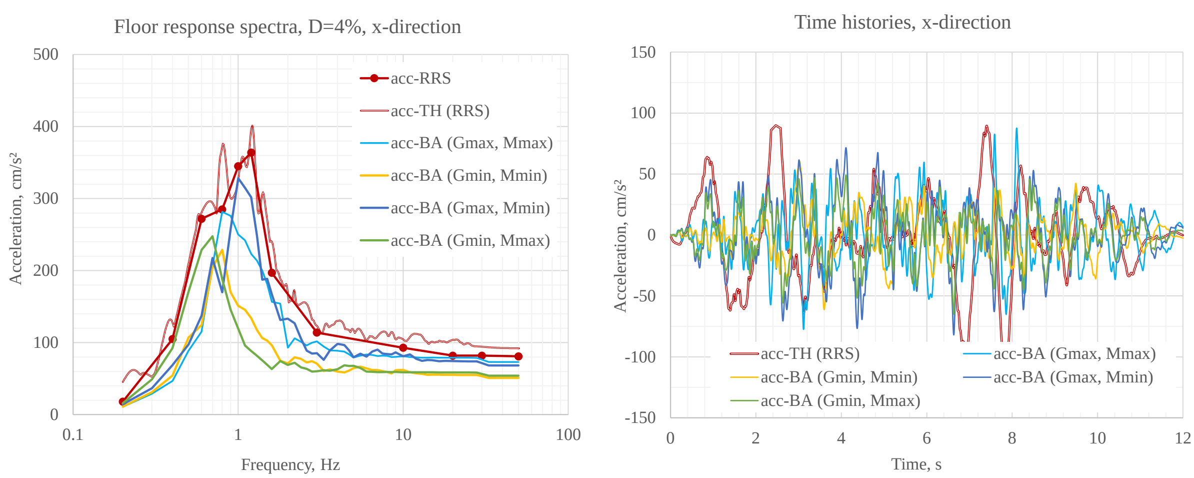

Figure 4. Required response spectrum (RRS) and floor response spectrum transformed back from time history (TH) compatible with the RRS for the x-direction and a damping ratio of 4 % versus floor response spectra resulting from building analyses, respectively for upper and lower scatter band of soil stiffness and loading conditions (left); comparison of the corresponding time histories (right).

Results – Trundling of a Cask / Cask Stack

Starting with a single cask of type CASTOR® V/52 excited by time histories of a duration of 12 s compatible with the respective RRS, Figure 5 contains trundling displacements relative to the base plate section applying an average friction coefficient ($\mu_{cask\text{-}base} = 0.4$) for the contact pair cask/base plate. The left diagram in Figure 5 opposes the two horizontal components for a result node at the top of the cask, while there are time histories of resultant displacements in the middle and on the right of Figure 5. One can see that observing result nodes of the centre line (bottom, middle and top) the horizontally resultant displacements increase with the height of the cask leading to a maximum horizontal displacement of approx. 70 mm; see Figure 5 (middle). The maximum vertical displacement of the bottom of the cask is approx. 25 mm, whereat there is a phase shift visible by the displacements of two orthogonal result nodes plotted in Figure 5 (right). The characteristics of the displacements exemplarily shown in Figure 5 give proof for not only trundling movements initialized by the earthquake excitation but also slight rolling, since the displacement of the bottom plate center (middle of Figure 5) is approx. 8 mm. As the vertical displacements are not zero after 12 s, the movement has not stopped yet but will resulting in horizontal displacements of the center of gravity and the center of the cover plate equal to the center of the bottom plate. Within the entity of performed computations both, trundling as well as a combination of trundling and rolling appears.

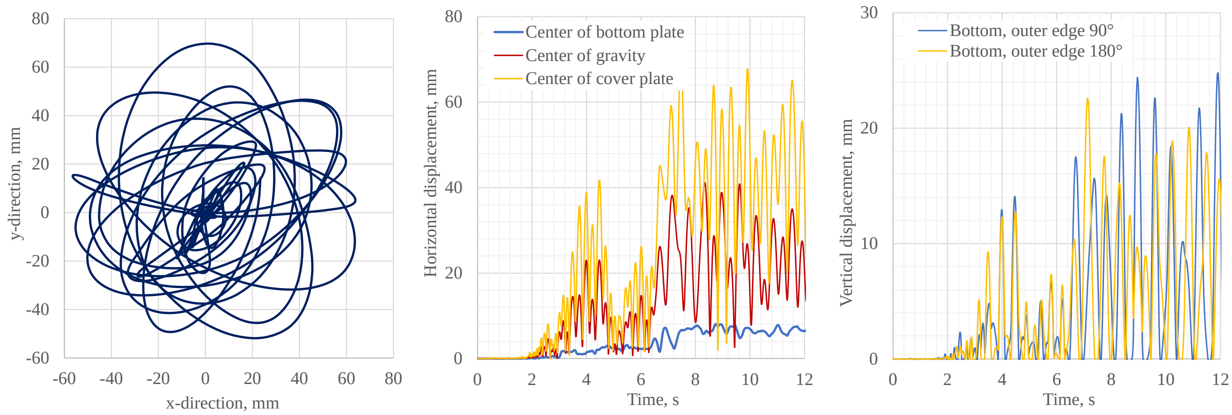

Figure 5. Displacements of a cask of type CASTOR® V/52 relative to the base plate applying a friction coefficient of $\mu_{\text{cask-base}} = 0.4$ (cask/base plate), and excited by time histories compatible with the RRS in Figure 2; displacements of both horizontal components at the top of the cask (left), horizontally resultant displacements of nodes on the middle axis (middle) and vertical displacements of nodes on the outer radius of the bottom of the cask (right).

The second example is given by a cask stack of four casks of type MOSAIK® without stacking aids. Exemplarily, horizontal displacements relative to the base plate are plotted for friction coefficients between the bottom cask and the base plate of $\mu_{\text{cask-base, max}} = 0.6$ and between the casks in the stack of $\mu_{\text{cask-cask, max}} = 0.3$ in Figures 6 and 7. In order to demonstrate the results from the two approaches explained above two load situations are chosen representing the wide range of resulting displacements including the respective maximum. Again, the duration of excitation is 12 s.

For the approach of time histories compatible with the RRS the maximum horizontal displacement of the stack top is approx. 250 mm for the load situation “TH combi. 1”, and approx. 430 mm for the load situation “TH combi. 2”, as shown in Figure 6, whereat “TH combi x” describes the respective combination of the statistically independent time histories as explained above. One can see that the influence of the combination of the generated time histories on the displacements of the stack is significant. Despite the relatively high displacements, the stack does not tilt. For the approach of time histories taken directly from the structural analyses the maximum horizontal displacements of the stack top are way lower, approx. 115 mm for the load situation “BA-TH 1”, and approx. 220 mm for the load situation “BA-TH 2”, as shown in Figure 7. (“BA-TH x” names the time history set taken from the building analyses, respectively). Even though the costs concerning the number of computations in order to cover the scatter band of structural analyses as demanded by KTA 2201.1 are high compared to the first approach, the benefit is given with the calculation of significant lower displacements. Hence, the minimum distance of two adjacent casks/cask stacks in order to avoid collision can be reduced.

Nevertheless, no matter which approach is chosen, just like with the single cask shown in Figure 5 the whole stack trundles. In analogy to the results of the single cask of type CASTOR® V/52, within the entity of the performed computations of this cask stack, the two movement characteristics described above appear as well, whereat it does not matter which approach is applied; see Figures 6 and 7. The displacements depicted in Figure 6 and the right side of Figure7 characterize a trundling where the stack trundles but ends after 12 s of excitation at its starting position as shown with nearly zero displacement. The left side of Figure 7 shows a combination of trundling and rolling ending after 12 s of excitation with a displacement of approx. 40 mm.

Since the relative displacements of the casks in the stack are negligible, even for the lower bound of friction coefficient, those are not discussed here.

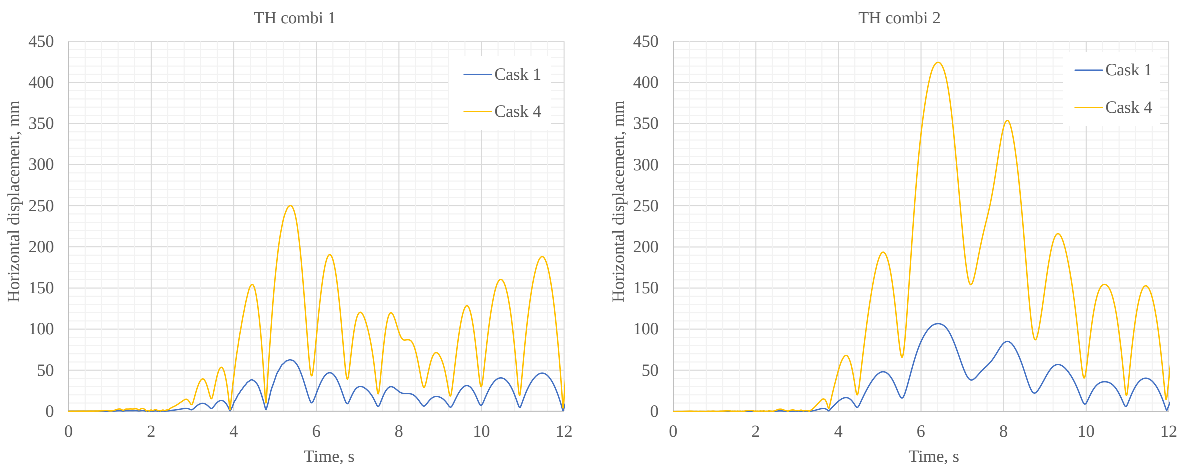

Figure 6. Cask stack of four casks of type MOSAIK®; horizontally resultant displacements of the cover plate center of the bottom cask (cask no. 1) and the top cask (cask no. 4), respectively; the friction coefficient between the bottom cask and the base plate is $\mu_{\text{cask-base, max}} = 0.6$ and between the casks in the stack $\mu_{\text{cask-cask, max}} = 0.3$; excited by time history combinations compatible with the RRS (TH combi 1 (left) and TH combi 2 (right)).

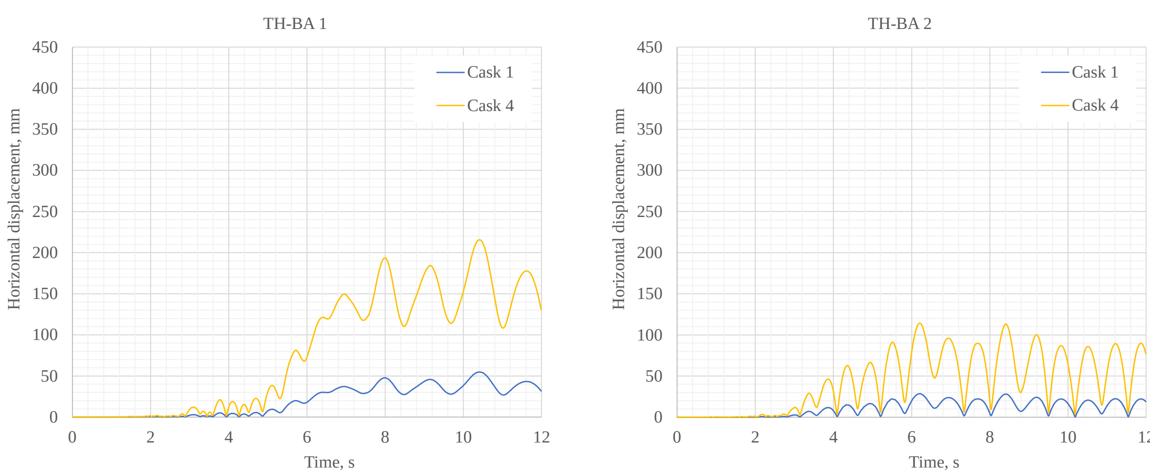

Figure 7. Cask stack of four casks of type MOSAIK®; horizontally resultant displacements of the cover plate center of the bottom cask (cask no. 1) and the top cask (cask no. 4), respectively; friction coefficient between the bottom cask and the base plate is $\mu_{\text{cask-base, max}} = 0.6$ and between the casks in the stack $\mu_{\text{cask-cask, max}} = 0.3$; excited by time histories taken directly from the building analyses (TH-BA 1 (left) and TH-BA 2 (right)).

Results – Sliding

Within the computations performed for both approaches, applying the lower bound of the friction coefficient ($\mu_{cask\text{-}base,\,min} = 0.2$) generally leads to sliding movements of the cask/cask stack which are small compared to the trundling movements. Exemplarily, Figure 8 contains the relative displacements of a stack of four casks of type MOSAIK® applying both load approaches excited by load situations equal to Figures 6 and 7. Applying time history combinations based on the RRS the maximum sliding movement is approx. 33 mm for “TH combi. 1”, while the stack slides approx. 30 mm for “TH combi. 2”. Contrary to the trundling movements discussed above, the influence of the combination of the generated time histories on the sliding movements of the stack is negligible; see Figure 8 (left). The same is true for applying time histories taken directly from the building analyses, whereat the displacements are below 8 mm (“BA-TH 1”) and 6 mm (“BA-TH 2”), respectively; see Figure 8 (right). Summing up, compared to the trundle movement the sliding is small.

When trundling becomes a problem because the minimum distance between adjacent casks/cask stacks cannot be increased, forcing sliding movements may be a way to solve this problem. In general, compared to trundling sliding is a more predictable movement. If it is possible to provide a low friction coefficient between the casks and the base plate by means of technical measures that is known as well as constant for the whole area of storage a more predictable and nearly synchronous movement of the casks can be induced.

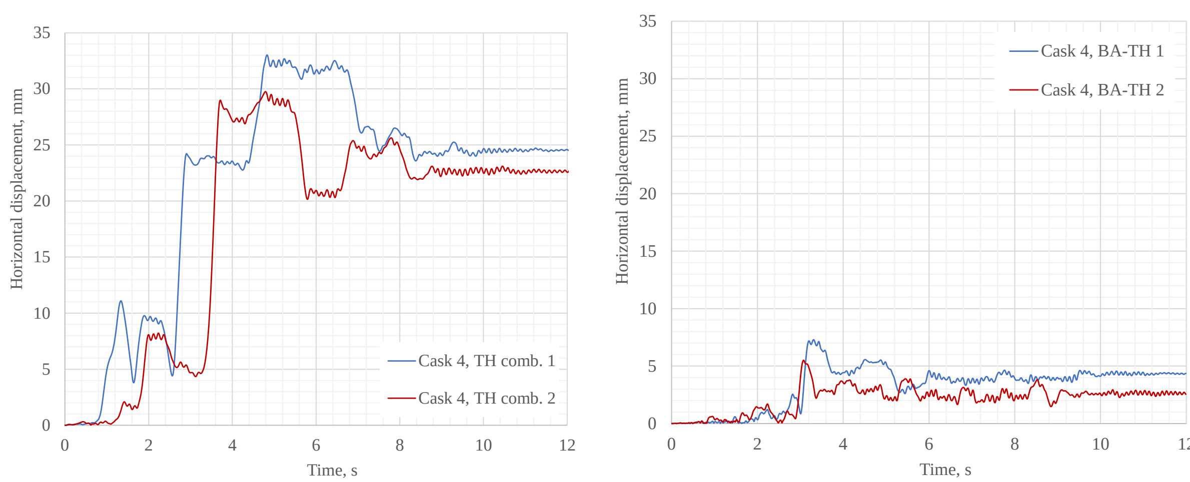

Figure 8. Cask stack of four casks of type MOSAIK®; horizontally resultant displacements of cover plate center of the top cask (cask no. 4); friction coefficient between the bottom cask and the base plate is $\mu_{cask\text{-}base,\,max} = 0.2$ and between the casks in the stack $\mu_{cask\text{-}cask,\,max} = 0.1$; excited by time history combinations compatible with the RRS (TH combi 1 and TH combi 2) (left) and time histories taken directly from the building analyses (TH-BA 1 and TH-BA 2) (right).

CONCLUSION

In order to proof stability of casks/cask stacks in interim storage facilities for the load case DBE tilting, trundling and sliding of the cask/cask stack need to be investigated. With means of FEM, various computations on a suitable numerical model can be carried out applying time histories. In doing so, the numerical model needs to contain not only the cask/cask stack, stacking aids if utilised and a section of the base plate, but also contact definitions representing the friction between the cask and the base plate as well as within the stack, respectively. In order to consider tilting, trundling and sliding appropriately, the friction coefficients need to be varied between an upper and lower bound.

Summing up, within the examples discussed in this paper the numerical results show that not the sliding of the cask/cask stack is significant but the trundling that may lead to a predefinition of a minimum distance between adjacent casks/cask stacks. If this predefinition will not meet the layout of the interim storage facility, inducing sliding movements by technical means providing a low friction coefficient between the cask and the base plate may be constructive.

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