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REINFORCED CONCRETE SLABS UNDER DROP-WEIGHT IMPACT LOADS

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ABSTRACT

The reinforced concrete (RC) floor slabs of the waste disposal and storage facilities are critical for their safe operation. Design consideration should be taken for these structural elements for both operational and handling accidental conditions, including dropped loads.

The storage facility considered here is used as a storage for stacked up concrete low-level waste containers. The RC ground floor slab of the facility is designed, in addition to the operational conditions, to withstand drop-weight loading of a concrete waste container falling accidentally during handling. After such an accident, the concrete and reinforcement can locally be damaged and restored but the leak tightness of the structure should be ensured.

Three-dimensional dynamic non-linear finite element (FE) analyses are used to predict the structural response of the RC ground floor slab subjected to the accidental drop-weight impact loads of waste containers. In addition to the numerical analyses, a simplified method based on the energy balance check is used to validate the numerical results.

INTRODUCTION

Low-level waste disposal and storage facilities are important elements of the nuclear waste management and have to meet specific safety requirements. In Switzerland, there are several aboveground storage facilities for low-level waste, as well as for interim dry storage of high-level waste. Some of these facilities are designed for interim storage of low-level waste containers.

The reinforced concrete ground floor slabs of these storage facilities are critical for their safe operation. They should be designed so that they can withstand both operational and accidental conditions, including falling of the waste containers, without significant damage and leakage in case of such an accident. Furthermore, it should be possible to repair and restore the leak tightness of the floor slab after a drop-weight accident, if necessary.

DESCRIPTION OF THE INVESTIGATED FLOOR SLAB

The facility considered in this study is used as a storage for stacked up concrete low-level waste containers. The RC ground floor slab of the facility is designed to withstand drop-weight loading of a concrete waste container falling accidentally during handling. The waste containers can be considered as cubic elements with outer dimensions of 1.50 x 1.50 x 2.00 m and a maximum weight of 20 tons. The maximum possible drop-height based on the assembly of the overhead cranes is 6.5 m, which results in a kinetic impact energy of 1300 kJ.

The energy of the falling waste container can be absorbed through local damages of the container, deformation and damages of the RC ground floor slab, as well as deformation of the subground soil. The investigated RC ground floor slab has a thickness of 1.0 m. The reinforcement of the slab consists of 4 layers of longitudinal reinforcements in each direction and each face, and transverse shear reinforcement over the entire slab area.

NUMERICAL MODEL

Method and Assumptions

Three-dimensional dynamic nonlinear FE analyses are used for modeling drop-weight impact of a waste container on a RC ground floor slab, by an explicit time-domain integration method in the LS-DYNA software (R 11.0). The numerical analysis method used here has been calibrated against different experiments of impact on RC structures, e.g. Ghadimi Khasraghy et.al 2017, 2019a, and 2019b.

Element Types and Material Models

The investigated floor slab is represented by solid elements for the concrete and beam elements for the reinforcement. The subground soil and the waste container are modeled using solid elements. Only a selected area of the floor slab and the soil is represented. Due to symmetry, only a half of the selected area is modeled. A perfect bond is assumed between the concrete and the reinforcement.

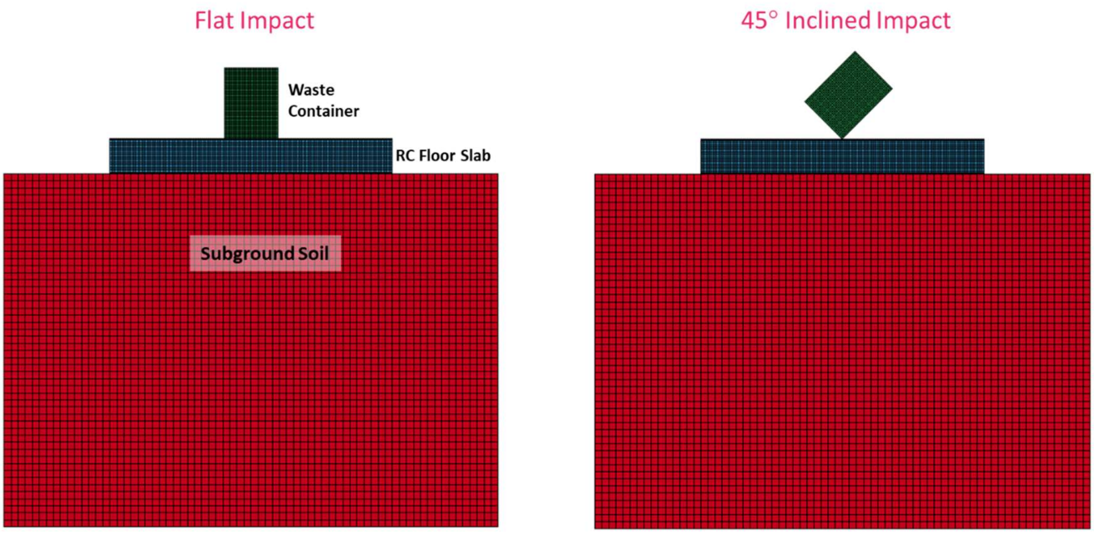


Figure 1. Finite element model geometry for a flat impact (left), and for an impact with 45° angle (right)

The continuous surface cap model (material model 159) of LS-DYNA is used for the concrete. This material model allows for definition of an erosion criterion for the concrete. An eroding constant of ERODE=1.2 is used, which allows erosion of the damaged concrete elements when the maximum principle strain exceeds 20%.

The constitutive model for the longitudinal bars and stirrups is bilinear with strain hardening. The reinforcement erodes when the strain in the beam elements exceeds 5%. The concrete and reinforcement elements are assumed to have a perfect bond where the concrete solid elements are connected to the reinforcement beam elements at nodal points.

The subground soil is represented using Drucker-Prager's yield criterion and the container is modeled as rigid material.

Loading and Support Conditions

The initial position of the falling waste container is defined at the surface of the concrete floor. The container is then subjected to a predefined initial velocity. Contact surfaces are defined between the container and the reinforced concrete floor, as well as between the concrete floor and the subground soil. The outer (bottom) nodal points of the subground soil elements are defined by fixed boundary conditions. Non-reflective boundary conditions are applied for the soil. Due to symmetry, only quarters of the test bodies are modelled.

SIMPLIFIED METHOD

The simplified method used here is developed based on the mass spring model according to Schlüter 1987 for the analysis of aircraft collisions with reactor containments. While considering the impact load carrying capacity of reinforced concrete slabs, two failure mechanisms are of importance, namely bending failure (global response) of the slabs, and punching shear under impact (local response). The simplified model, therefore, consisted of two masses and two springs for accommodating the local as well as the global response of the slabs. The impact energy could conservatively be compared with the deformation energy of the punching cone.

Three contributors control the punching response of the slab as shown in Figure 2:
$R_{2,1}$: Contribution of concrete
$R_{2,2}$: Contribution of stirrups if available, and
$R_{2,3}$: Contribution of the membrane effect of the bending reinforcement

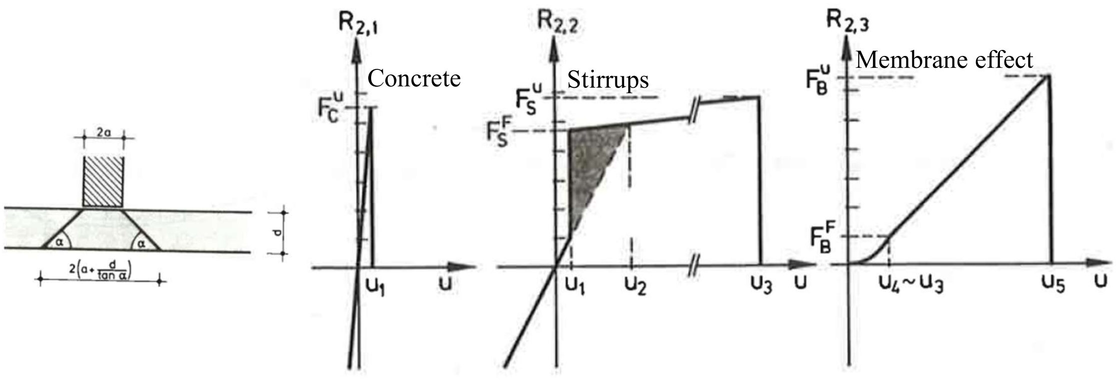


Figure 2. Spring properties for the punching cone according to Schlüter 1987

The concrete's contribution to the energy absorption is very small since concrete shear resistance is breached at very small displacements. After activation of the shear reinforcements (if available), the bending reinforcement will contribute to the punching resistance through membrane effects. The perforation limit will be reached in this case after the ultimate deflection (u_5 in Figure 2) is reached. It should be noted that for impact energies far beyond the punching capacity of the slab, for which perforation with high residual velocities are to be expected, this energy balance check may not be applicable since the membrane effects of the bending reinforcement may not be activated.

Fila et.al (2015) proposed a method to check the perforation resistance based on energy balance check considering only the contribution of the bending reinforcement. This formulation, however, includes some simplifications and assumptions.

The new formulation proposed in this paper is similar to the abovementioned proposal (Fila et.al 2015), but it provides an exact solution based on the geometry of the activated punching cone imposing the membrane effect. Additionally, the contribution of the shear reinforcement as proposed by Schlüter (1987) is included in the energy balance.

For the membrane forming a spherical sector, the maximum strain of the reinforcement can be estimated as a function of the effective membrane area. The effective strain can then be obtained and used for the calculation of the absorbed energy. The considered punching cone and the geometry of the mathematical model are shown in Figure 3.

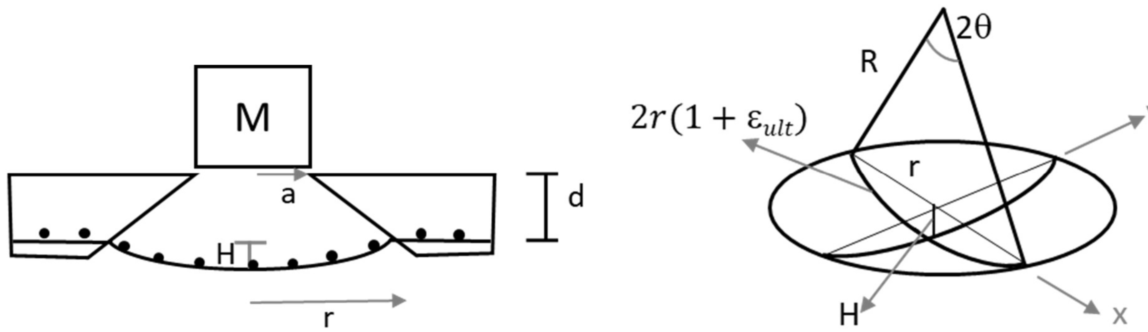


Figure 3. Considered punching cone (left) and the geometry of the mathematical model (right)

For the initial state ($\varepsilon_0 = 0.0$) the area of the membrane is:

$$A(\varepsilon_0) = \pi \cdot r^2$$

Where r is the radius of the punching cone.

Considering the cone geometry:

$$\theta / \sin\theta = 1 + \varepsilon_{ult}$$

It can be shown for the assumed ultimate strain of reinforcement steel $\varepsilon_{ult} = 5\%$ that an opening angle 2θ of the membrane surface is equal to 2×30.85°. The area of the membrane is then given by:

$$A(\varepsilon_{ult}) = 2 \cdot \pi \cdot R \cdot H$$

where $R = \frac{r}{\sin\theta}$ (radius of the surface of the membrane)

and $H = R \cdot (1 - \cos\theta)$ (sag of the membrane)

for an opening angle 2θ of the membrane surface equal to 2×30.85° ($\varepsilon_{ult} = 5\%$) the sag of the membrane is

$$H = \frac{\mathrm{r}}{\sin\theta} \cdot (1 - \cos\theta) = 0.276\, r$$

The effective medium strain of the reinforcement for the membrane with maximum strain of ε_{ult} can be calculated as follows:

$$\varepsilon_{eff}(\varepsilon_{ult}) = \sqrt{\frac{A(\varepsilon_{ult})}{A(\varepsilon_0)}} - 1 = 0.0374$$

The corresponding elastic effective strain for the membrane with $\varepsilon_y = 0.002$ (elastic strain) is:

$$\varepsilon_{eff}(\varepsilon_y) = 0.0015$$

Assuming the equivalent effective length L_{eff} of the reinforcement in one direction is equal to the length of a square having the same area as the punching cone:

$$L_{eff} = L_{eff_x} = L_{eff_y} = r \cdot \sqrt{\pi}$$

The reinforcement is to be considered as distributed in both directions over the same width of L_{eff}. The energy absorbed is equal to the total elongation of the reinforcement multiplied by the yield force.

$$W_{membrane} = 2\left(\varepsilon_{eff}(\varepsilon_{ult}) - \varepsilon_{eff}(\varepsilon_y)\right) \cdot (L_{eff}) \cdot \sigma_y \cdot a_s \cdot L_{eff} = 0.0359 \cdot 2 \cdot \pi \cdot r^2 \cdot \sigma_y \cdot a_s$$

or simplified deformation energy of the bending reinforcement for ($\varepsilon_{ult} = 0.05$)

$$\boldsymbol{W_{membrane} = 0.226 \cdot r^2 \cdot \sigma_y \cdot a_s} \quad \text{(J)} \qquad \text{(Equation 1)}$$

where:

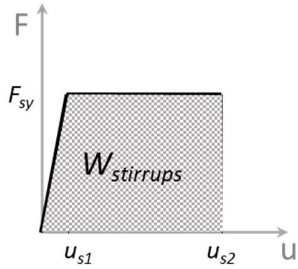
r	radius of the punching cone	(m)
a_s	tensile reinforcement area in one direction (for a_x=a_y)	(mm^2/m)
σ_y	yield stress of the reinforcement steel	(MPa)

The validity of the membrane energy according to the Equation 1 was investigated by comparing tests from different experimental series. The comparison for selected tests from three different experiments, in which the membrane effects were prominent, is shown in the Table 1. The “r” values in the table are obtained assuming $r = a + 2d$.

Table 1. Selected test impact energies compared to the calculated energy absorbed by membrane effects

Publication	Test	Mass [kg]	Velocity [m/s]	Impact energy [kJ]	r [m]	a_s [mm^2/m]	$W_{membrane}$ [kJ]
Just et.al 2016	S2P1	508	8.86	**20**	0.59	503	**19.8**
Fila et.al 2015	DL11	4000	7.2	**104**	0.69	1571	**84.5**
Xiao et.al 2017	10F-d	500	4.85	**5.9**	0.32	604	**7.0**

The energy absorption of the stirrups is assumed according to the Figure 4, which is a simplification of the stirrups contribution introduced by Schlüter 1987, see Figure 2.



$$F_{sy} = \pi(r^2 - a^2)a_{st}\sigma_{yst}$$
$$u_{s1} = \frac{d}{3}\varepsilon_{ys} \quad u_{s2} = 0.9d\varepsilon_{us}$$

Figure 4. Energy absorption of stirrups

$$\boldsymbol{W_{stirrups} = \pi \cdot (r^2 - a^2)\, a_{st}\sigma_{yst}d \cdot (-\tfrac{1}{6}\varepsilon_{ys} + 0.9\varepsilon_{us})} \text{ (J)} \qquad \text{(Equation 2)}$$

where,

a	radius of the impacting body	(m)
d	static depth of the slab	(m)
a_{st}	stirrups area	(mm^2/m^2)
σ_{yst}	yield stress of the stirrups	(MPa)
ε_{ys}	yield strain of the stirrups $= \frac{\sigma_{yst}}{E_s}$	(-)
ε_{us}	ultimate strain of the stirrups, e.g. 5%	(-)

RESULTS AND COMPARISON

Selected results of the numerical analyses used to predict the response of a RC ground floor slab subjected to drop-weight impact loads are shown here. To validate the numerical analysis results, a simplified method based on the energy balance check using the equations 1 and 2 is used.

Impact Forces

The calculated impact load time histories, defined as the contact forces between the waste container and the floor, as well as between the floor and the soil are shown in Figure 5.

The calculations show that contact forces are the highest in case of a flat impact. When the container hits the floor with an edge (45° angle), the energy is mostly absorbed locally due to the concrete and reinforcement damage on the upper slab surface. The maximum penetration depth of the container into the concrete slab is only 12 mm for the case of flat impact, whereas for the inclined impact the container penetrates about 131 mm with its edge into the slab.

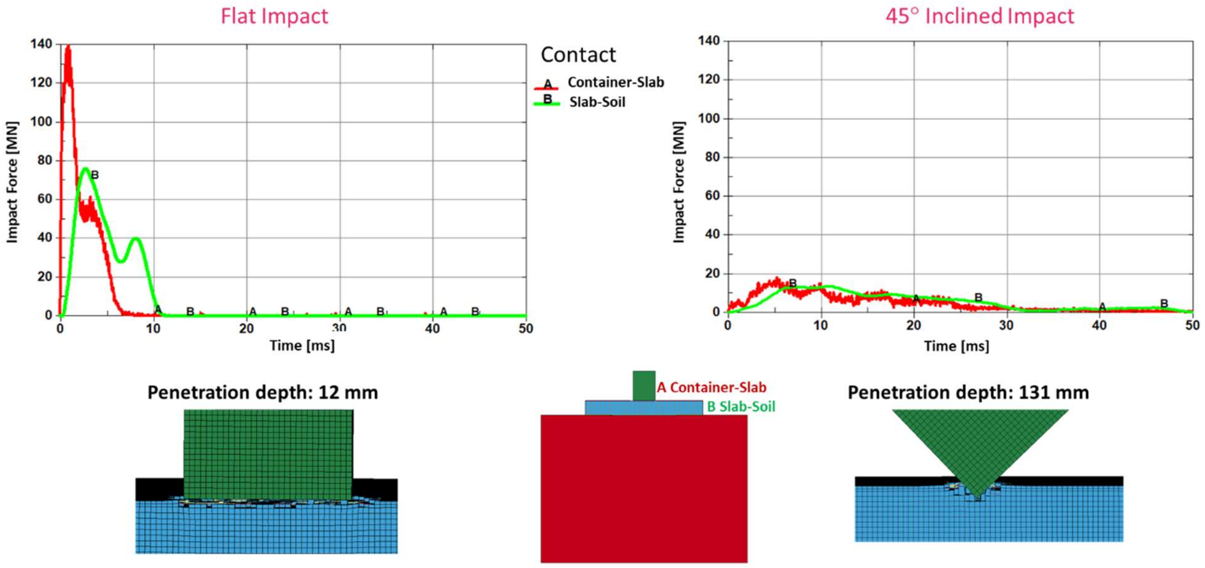


Figure 5. Time histories of the impact forces

RC Floor Slab Displacements and Strains

Figure 6 shows the time histories of the maximum vertical bending deflection at the center of the concrete floor slab. The calculations show that for the case of flat impact a maximum slab deflection of up to 29 mm can be expected at the bottom surface of the slab. The maximum calculated residual displacement of the slab is about 15 mm. For the inclined impact where the energy is mainly absorbed locally through the container penetration at the upper surface of the slab, the bending deflection of the slab is low (6 mm).

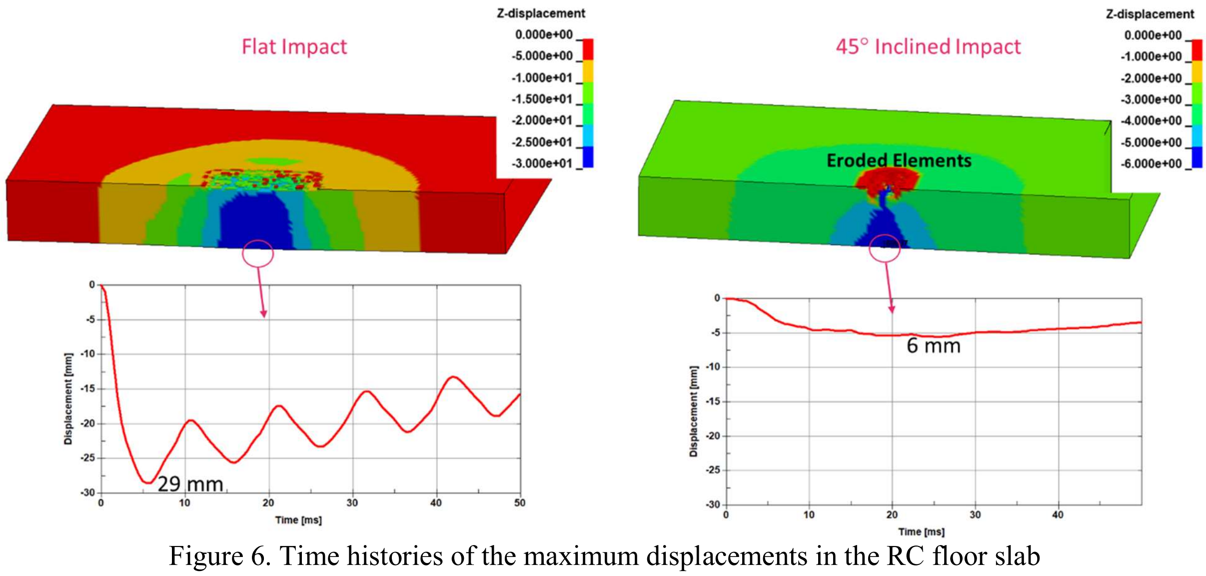


Figure 6. Time histories of the maximum displacements in the RC floor slab

Bending reinforcement strains of the RC floor slab are compared for the flat and inclined container impacts in Figure 7. In the case of the flat impact, the top reinforcements are partially damaged and the strain values up to 5% are reached. However, the bottom reinforcement suffered plastic strain values of up to 0.5 %, which corresponds to a total axial reinforcement strain of 0.75%.

The top reinforcement suffered local tears in case of the impact with 45° inclination. However, the strains in the bottom reinforcements stayed in elastic range.

The shear stirrups of the floor slab in the punching area suffered axial strains of up to 3% in case of the flat impact. For the inclined impact, the upper shear reinforcement in the vicinity of the impact area were torn.

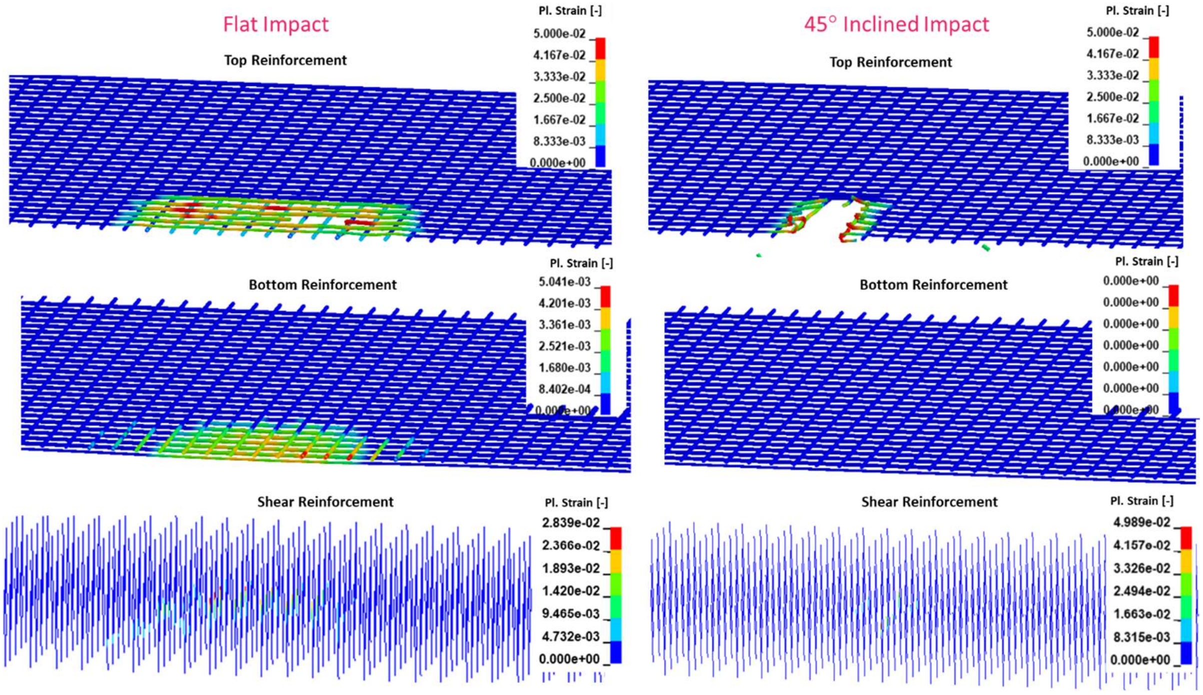


Figure 7. Maximum calculated strains of the bending reinforcement

Displacement in Soil

The displacements in soil are shown in Figure 8. It can be seen that the maximum displacement in the soil layer is reached during the impact of the flat container. In case of the inclined container the displacements were small.

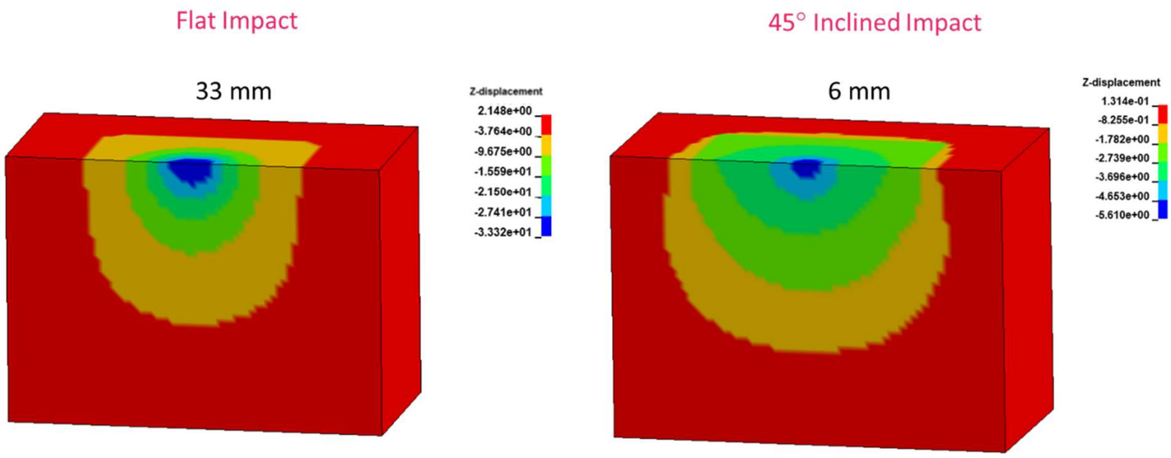


Figure 8. Maximum displacement in the subground soil

Simplified Method

The described simplified method is used to compare the deformation energy of the punching cone with the impact energy of the system. The contribution of the soil to the energy dissipation is neglected conservatively.

The conservative deformation energy obtained based on the equation 1 for the RC floor slab used in the current study was 2600 kJ, which is twice the impact energy of 1300 kJ. However, in order to absorb this impact energy only through the membrane effect, a large deflection (sag of the membrane) up to 50 cm may be expected. Since the leak tightness of the floor slabs of the storage facilities have to be assured, such large slab deformations may not be allowed.

The RC floor slab studied here, however, contains shear stirrups in order to control such large deformations, and thus in order to avoid reaching the crack width that breaches the capacity of the seal sheet below the floor slab. In this case, applying the simplified method, the energy in the punching cone is mainly absorbed by plastifying stirrups. If the impact energy were solely absorbed by the stirrups, this leads to a deformation of the punching cone of about 32 mm according to Figure 9. The maximum slab deflection obtained from finite element analysis for flat impact was about 29 mm with a residual deflection of about 15 mm (Figure 6). Even though this value is local and does not represent the displacement of the entire punching cone for correlating to the simplified method, it helps to confirm the plausibility of the finite element results.

In the case of a real impact, the energy will be dissipated by: local damages in the container, spalling and cracking of concrete, bending and shear reinforcement, as well as the local energy absorption in soil. Therefore, dimensioning the slab using an energy check only in the stirrups can be considered as conservative.

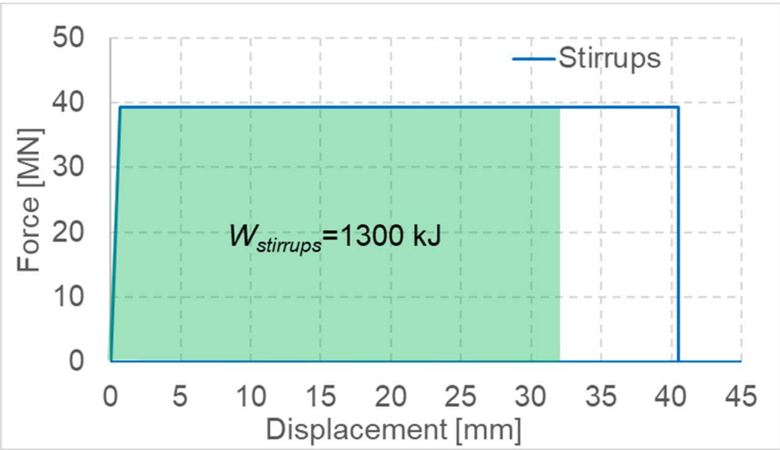


Figure 9. Deformation energy of the shear reinforcement

CONCLUSION

Numerical analyses are conducted to predict the nonlinear dynamic response of a RC ground floor slab subjected to accidental drop-weight impact of a waste container, where nonlinear material models are used for concrete, reinforcement, and soil.

The calculations show that contact forces between the waste container and the floor slab, as well as between the slab and the soil are the highest in case of a flat impact. In this case, both longitudinal and shear reinforcement can plastify. The maximum reinforcement strains remain, however, below the allowable ultimate steel strain. In this case, the concrete and the reinforcement on the upper side of the floor slab can partially be repaired. Despite the expected local damages and cracking of the floor slab, the leak tightness of the structure after an accident can still be assured thanks to the seal membrane applied under the slab, letting the operator of the facility more time for repair works.

In the case of inclined impact (45° angle), the impact energy is mostly absorbed locally due to the concrete and reinforcement damage on the upper slab surface. After inclined impact, the damaged concrete and reinforcement at the upper surface can locally be repaired.

Simplified conservative methods using energy balance check are useful to compare the deformation energy of the punching cone with the impact energy of the drop-weight in order to validate the numerical results.

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