FLAT BOTTOM TANKS
ENDANGERED BY ICE LENSES

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ABSTRACT

This paper reports on a study, which has been conducted for a German court.
The foundation for a series of above ground cylindrical flat bottom tanks according to DIN 4119 has been prepared in a way that, under very special circumstances, formation of ice lenses could not be neglected.
The stress-distribution in the shell wall due to a possible ice lens was investigated by FEM. It showed, that the tank wall is likely to buckle due to the size of the locally imposed deviations of the foot-ring.

NOTATION

φ	Circumferential coordinate of the tank. $\varphi = 0^{o}$ denotes the meridian, under which the ice lens is acting

Other symbols are explained in the relevant sections.

SITUATION

Somewhere in the new federal states of Germany a group of some fifteen flat bottom tanks according to DIN 4119 had been built for the storage of petro-chemical products. The owner suspected, that the foundation of the tanks had not been built according to the relevant technical rules and put the consultant office and the builder before court. The court asked for an expertise to answer questions such as

- had the foundation of the tanks been planned and executed according to the relevant technical rules
- is it possible, that ice lenses will form in the local situation
- is it possible, that the tanks will be damaged by ice lenses
- which technical measures could be taken to prevent damages by ice lenses

It was obvious that the answers had to be given out of two different fields of engineering. A colleague was asked for cooperation, who runs a consultants office in soil mechanics. The authors of the present paper prepared the answers for the tank shell under local load, which we will present in this paper.

ANSWERS FROM SOIL MECHANICS

The very complex interaction of particle size distribution, humidity and temperature cycles will not be discussed due to the length of the paper. We will just summarize the major features, which we used as boundary conditions when investigating the risk for the shells.

- The present soil is likely to produce ice lenses
- The possibility of critical frost conditions is not small
  (after 30 days with a 24-hour-mean-temperature of –10°C the soil is frozen up to a depth of 85 cm)
- Single ice lenses can stack up to one meter height
- Pressures from ice lenses can be
  15 kN/m^2 – 50 kN/m^2 in silt ('Schluff')
  50 kN/m^2 – 200 kN/m^2 in silty clay
  > 200 kN/m^2 in clay
  For the specific particle size distribution on site the ice can produce pressures of approx. 50 kN/m^2
- The lift of the ice lenses can be in the order of "some cm"

GEOMETRY OF THE TANK

Radius 17000 mm
Height of eve 16400 mm
Footplate 500 mm x 8 mm
Bottom membrane (no value given, assumed 5 mm – 7 mm)
Spherical roof
Roof-radius = 51000 mm, height of roof top 19300 mm, plate thickness 5 mm, 42 rafters IPE 220
Nominal volume: 15000m^3
Approx. weight of steel structure (without foot and bottom membrane): 1860 kN
Approx. snow load 680 kN

TABLE 1. Strakes of the tank wall (overall effective wall thickness: 8.48 mm)

No	bottom [mm]	top [mm]	thickness [mm]	steel grade	$\sigma_{x,k}$ (selfweight) [N/mm^2]	$\sigma_{x,k}$ (snow) [N/mm^2]
1	0	2000	12.2	S 355	1.43	0.52
2	2000	4500	9.6	S 355	< 1.81	0.66
3 – 8	4500	16400	8	S355 / S 235	< 2.18	0.80

(2 Ring stiffeners)

Half wave lenth for the elastic chessboard pattern (strake no 1):

$$L_{,el} = 2\pi\sqrt{(R*T)} / \sqrt{\sqrt{[12*(1-\mu^2)]}} \qquad L_{,el} = 1.57 \text{ m} \qquad (4.1)$$

MODEL A

The features of the problem were seen as:

- thin walled cylindrical shell with meridional local edge load
- the presence of the annular foot plate of the tank is beneficial for the distribution of the concentrated meridional compression stresses
- It was decided, that FEM should not be used to evaluate the stability behaviour of the tank, but to give a rough approximation about the stress distribution in the tank wall.
- the stability of the tank wall can be checked e.g. according to the suggestion of Knödel/Ummenhofer [3], [4]

As a safe side assumption it was taken, that the compression forces of the ice lens go vertically upward towards the tank foot, without spreading to the sides. Further it was assumed, that if the ice lens would develop more than one meter along the circumference of the tank, a load of 50 kN could be transferred into the tank.

Special attention was paid to the foundation of the tank.

- Since the tank has a roof structure (cladding plates on roof trusses), strainless deformations of the shell will not be possible due to vertical deflections, which are locally imposed on the lower edge. The tank structure will be very stiff, it will show rigid body translations.
- If the foundation is also very stiff the tank will - under a concentrated load - completely lift of the foundation until its lower edge will be doubly point loaded above the ice lens and at the opposite side.
- For moderate stiffness of the foundation the tank will sink uniformly into the foundation due to its self weight (eventually with additional snow loads). A concentrated load from an ice lens will partially release this deformation.

Following simplifications were made:

- The stepped wall thickness of the tank was neglected, 12.2 mm were used throughout.
- The roof was modelled flat instead of spherical. In order to reduce the overestimated in-plane-stiffness the wall thicknes of the roof was taken as one millimeter (instead of five).

The properties of the different layers of the foundation were (from top to bottom)
a) asphalt (neglected); b) broken stone layer, 0.30 m depth, 120 MN/m^2 ; c) natural soil, silty clay, 1.0 m effective depth, 45 MN/m^2

The moduli given are for the secondary loading. The relation between primary and secondary loading was taken to be 2.4. The interaction between the ready built tank and the foundation is like a primary loading, therefore the above moduli have been divided by 2.4: b) 120 MN/m^2 / 2.4 = 50 MN/m^2 ; c) 45 MN/m^2 / 2.4 = 19 MN/m^2 .

Allowing for a foot with a width of 0.50 m, the resultant line-spring-stiffness for the foundation of the edge of the tank is c = 8.4 N/mm^2 (8.4 N/mm line-load to produce a deformation of 1 mm). The uniform settlement for the empty tank under dead load is

$$uz = 18 \text{ N/mm} / (8.4 \text{ N/mm}^2) = 2.14 \text{ mm} \qquad (5.1)$$

For the FE calculations ANSYS 5.3 was used (SHELL63). The mesh size was chosen to have circumferential lengths of 2.5º or 740 mm from $-10° \leq \varphi \leq +10°$ and four times that size for the rest of the tank.
Some data sets were calculated allowing for geometrical nonlinearities. No significant differences were found, compared to the linear calculations.

Under a load of 50 kN, which is applied to the bottom node at $\varphi = 0$, the bottom edge of the tank lifts to 1,90 mm at $\varphi = 0°$ and settles to 2.19 mm at $\varphi = 180°$, which are differential settlements of –0.24 mm / +0,05 mm. The maximum inward deflection of the wall above the local load is 0.6 mm. The distribution of the membrane-meridional stresses is given in fig 1. The maximum local compressive stress is 6.0 N/mm^2 .

TABLE 2 Stability check for meridional membrane stresses according to DIN 18800 Teil 4

item	eqn.	formula	present tank strake no. 1	present tank strake no. 2
radius		R [mm]	17000	17000
wall thickness		T [mm]	12.2	9.6
length		L [mm]	16400	16400
Young's modulus		E [N/mm^2]	$2.1*10^5$	$2.1*10^5$

yield limit		fy [N/mm^2]	360	360
geometry parameter		R/T	1393	1771
geometry parameter		L/R	0.965	0.965
parameter	(28)	C_x	1.00	1.00
ideal critical stress	(26)	$\sigma_{xSi} = 0.605 * C_x * E * T/R$	91.3 N/mm^2	71.8 N/mm^2
normalised slenderness	(1)	$\lambda_{Sx} = \sqrt{(fy/\sigma_{xSi})}$	1.99	2.24
norm. real buckl. stress	(8d)	$\kappa_2 = 0.2 / \lambda_{Sx}^2$	0.0507	0.040
real buckling stress	(4)	$\sigma_{xS,R,k} = \kappa_2 * fy$	18.3 N/mm^2	14.4 N/mm^2
partial safety factor	(13)	γ_M	1.447	1.450
buckling limit stress	(9)	$\sigma_{xS,R,d} = \sigma_{xS,R,k} / \gamma_M$	12.6 N/mm^2	9.90 N/mm^2

According to a suggestion of Knödel/Ummenhofer (1998) the buckling limit stress may be increased by a factor of 1.67, if local loads have been accounted for when evaluating the meridional membrane stress distribution. This is to compensate the effect, that the knock-down-factors in the buckling codes do already contain a part for uneven edge load distribution due to building tolerances. With this, the buckling limit stresses for the bottom strakes read as follows:

strake no. 1: $\sigma_{xS,R,d}$ = 1.67 * 12.6 N/mm^2 = 21.0 N/mm^2

strake no. 2: $\sigma_{xS,R,d}$ = 1.67 * 9.90 N/mm^2 = 16.5 N/mm^2

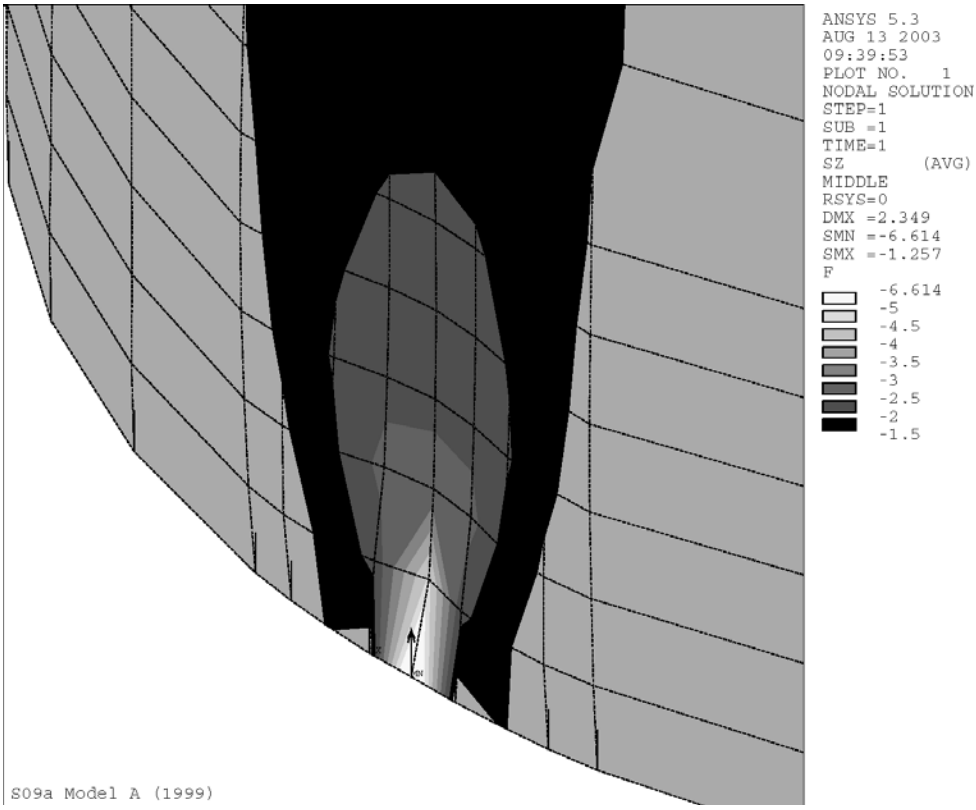

Fig. 1 Distribution of meridional membrane stresses due to a 50 kN point load

MODEL B

In Model B we improved the tracing of the load situation. We modelled the tank's foot plate (SHELL181), the asphalt-layer, the broken stone layer and the silty-clay layer (SOLID45). The ice lens was modelled by imposing some lift to the bottom nodes of the lowest layer.

TABLE 3 Properties of the soil layers

		layer depth [cm]		modulus [MN/m^2]		
layer no	item	min	max	min	median	max
0	tank foot	–	–	–	–	–
1	asphalt-concrete	8	8		10000	
2	frost resistant layer (broken stone)	40	55	30	50	80
3	limed silty-clay	0	30	15	30	55
4	untreated silty-clay, ICE LENS	–	–	–	–	–

The mesh for the steel structure was modified in a way, that we had much smaller elements at the concentrated load and a coarser mesh at the back of the tank. The smallest elements have a circumferential length of 0.5º or 150 mm with a height of 200 mm, the biggest elements have 15º or 4500 mm. The width of the footplate elements as well as the elements of the soil layers beneath were chosen to be 83 mm (6 elements on 500 mm).

In order to keep element size rectangular and regular as wide as possible, we accepted some elements to have aspect ratios of 1:45. Since those are far off the concentrated load, we assume that the results will not significantly be affected with respect to the desired accuracy.

The soil pressure underneath the tank foot caused the edges of the foot plate to lift, which in turn produced tensile contact pressures between the surface of the top soil layer and the foot plate. In order to omit time consuming calculations with contact elements, we disconnected the outer nodes of the footplate. The footplate remains coupled to the top soil layer under the tank wall and at the next nodes at each side, which are situated in a distance of 83 mm each. This was considered to be sufficient to model the transfer of loads into the shell.

The loads caused by the ice lens were modelled by imposing a displacement f to the nodes around the center of the ice lens, which is determined according to the function

$$f = f0 * (1 – (r / (REL))**8) \qquad (6.1)$$

where

f0 maximum lift in the center of the ice lens

r distance of the respective node to the center of the ice lens

REL radius of the ice lens

The chosen shape of the ice lens' surface is arbitrary. It should be flat to account for plasticity of the ice lens and it should be zero along the edge of the ice lens to minimize peak shear deformations in the soil. The maximum lift f0 was chosen in a way, that the vertical pressures on the surface of the ice lens were close to 50 kN/m^2 = 0.050 N/mm^2.

Following steps were taken to minimize vertical tensile stresses in the soil layers and as well to abandon contact elements:

- the soil layers were set under gravity load:
  this generates compression forces in the soil, which compensate tensile forces from continuity
- it was checked, which nodes near the ice lens have vertical tensile forces:
  these were disconnected from the boundary conditions - in the subsequent calculations it was verified, that these nodes have upward deviations. Typically these nodes were covering a distance of 1.2*REL.

We looked at two extreme configurations:

- stiff foundation
  the soil layers have their minimum depths and their maximum moduli, the ice lens develops relatively close to the tank foot – this configuration is expected to give higher peak stresses in the tank

- soft foundation
  the soil layers have their maximum depths and their minium moduli, the ice lens develops relatively far from the tank foot – this configuration is expected to give lower peak stresses in the tank

TABLE 3 Comparison of the results of Model B

item	stiff foundation	soft foundation
uniform settlement under 18 N/mm [mm]	0.13	0.72
max lift of ice lens [mm]	0.15	0.60
differential settlement due to ice lens [mm]	-0.014 / +0.00	–0.013 / 0.00
soil pressure above ice lens [kN/m^2] (see fig 2)	50 – 60	50
soil pressure under tank foot [kN/m^2]	400	340
max meridional compression in tank [N/mm^2] (see fig 3)	2.4	1.9
max inward deflection of the tank [mm]	0.2	0.1

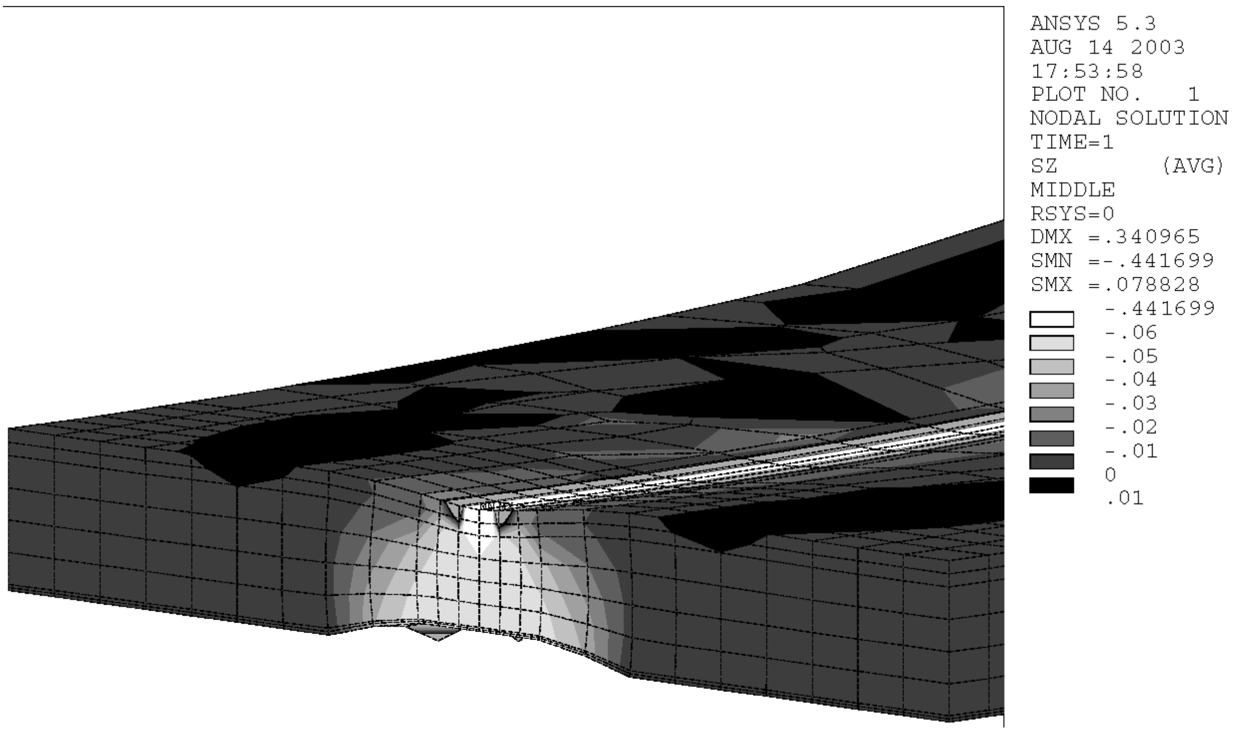

Fig. 2 Soil pressures – stiff foundation – maximum lift due to ice lens 0.15 mm

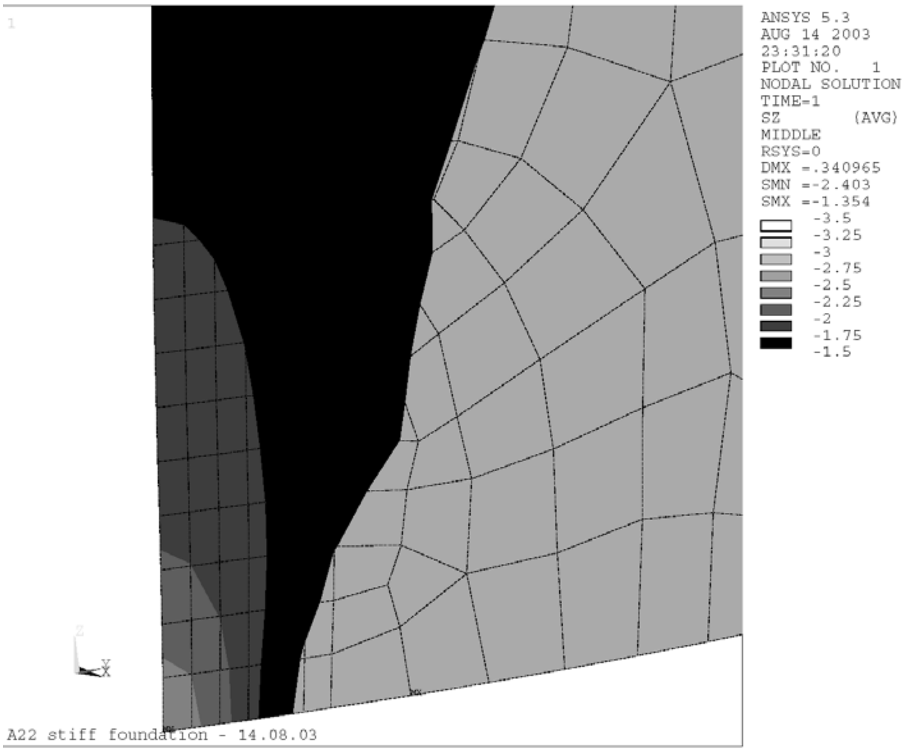

Fig. 3 Meridional membrane stresses – stiff foundation – maximum lift due to ice lens 0.15 mm

CONCLUSIONS

- A local load of 50 kN caused by an ice lens seems to be much for a tank with R/T = 1400. But this load corresponds to the self weight of the tank gathered along 2.8 m of circumference (or 9.4º)
- The tank filled to a height of 15.4 m produces compressive stresses of approx. 150 kN/m^2 under it's bottom. This is by a factor of 3 higher than the pressures to be produced by an ice lens. The ice lens can develop under such conditions, but cannot produce any lift.
- The critical state is when the tank is empty without snow load.
- On the site under consideration ice lenses might develop, but they will not affect the stability of the tank.
- Tanks founded on very fine clay may be critical.

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