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Collision Slope

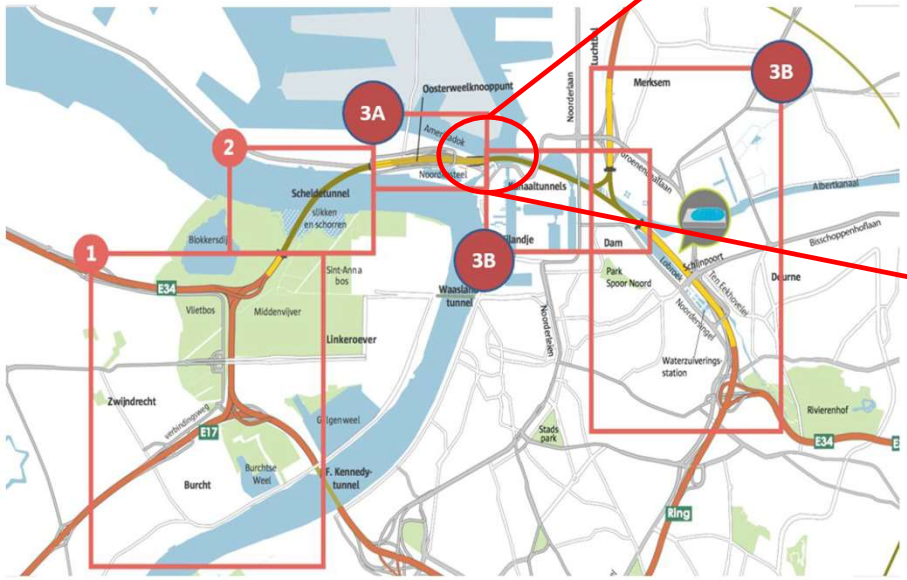
Amerikadock-Albertdock

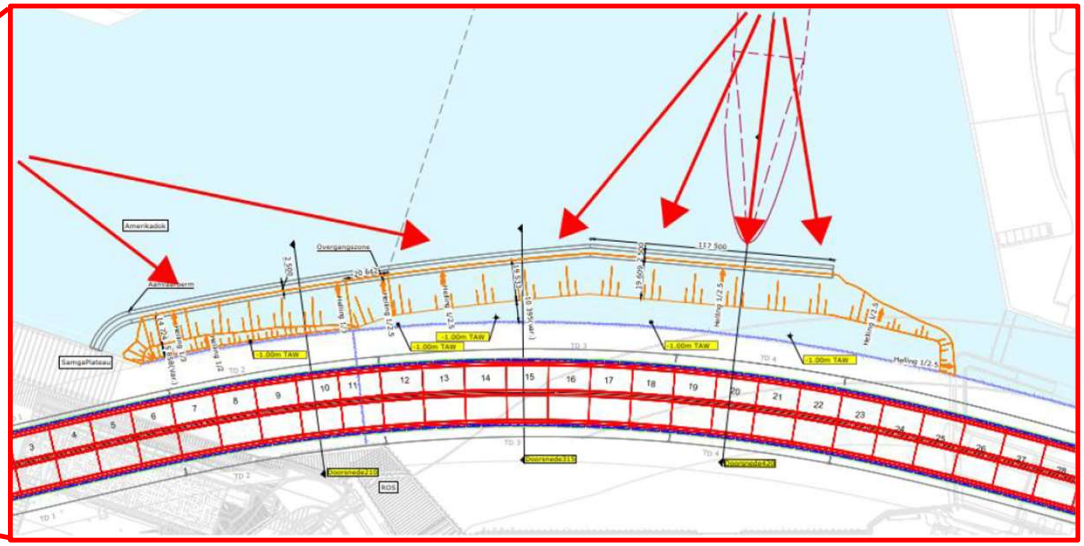
ir.lic. Bart Van Zegbroeck (Lantis/Sweco)

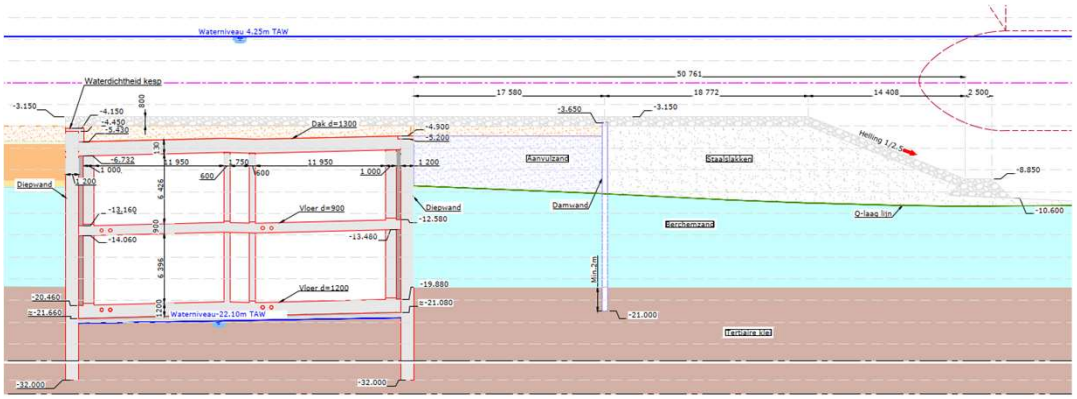
Ir. Louis Lesage (Sweco)

Ir. Jarne Croene (Sweco)

Problem Statement







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Problem Statement

- First decision => perpendicular impact on the slope will govern the design => logic

- Goals of the project
  - Calculate the path of a ship colliding with the collision slope
  - Calculate the forces of the ship on the tunnel
    - Forces of ship ending on top of the tunnel
    - Forces of ship ending in front of the tunnel

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Literature

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Pedersen

- Ship “running” on infite stiff slope => math formulation of Physics “easy” since path is known

Marine Structures 7 (1994) 1–29

Ship Grounding and Hull-Girder Strength*

Preben Terndrup Pedersen

Department of Ocean Engineering, The Technical University of Denmark, Building 101 E, DK-2800 Lyngby, Denmark

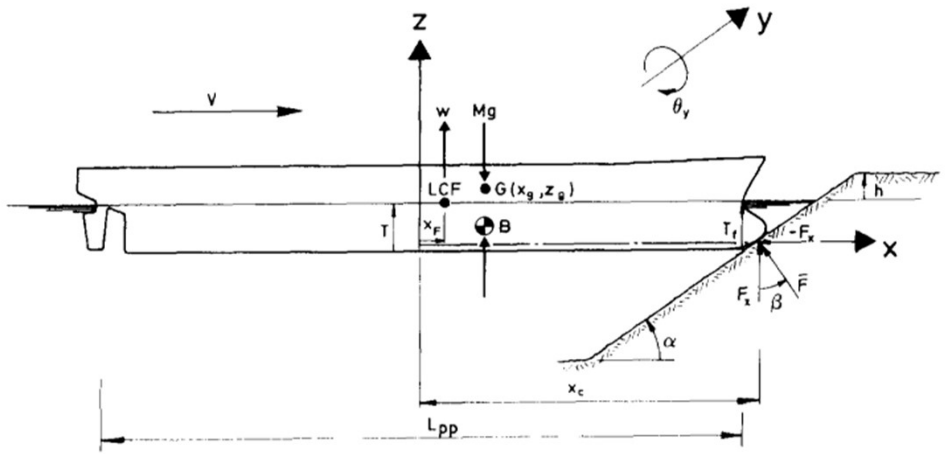


Fig. 1. Initial contact with the ground.

Pedersen

- Energy loss in time due to friction, loss of potential energy (rise of ship), and initial collision loss

$$E_k(t) = E_k^I - \int_0^{u(t)} F_f \, \mathrm{d}u - \int_0^{z(t)} F_z \, \mathrm{d}z$$

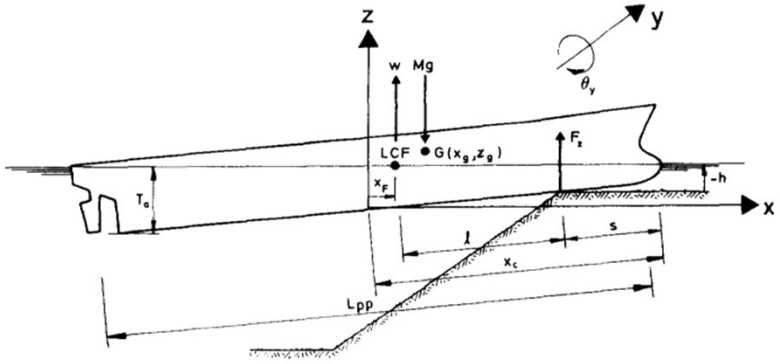


Fig. 4. Sliding on a subsea island.



Figure 3.6: *Grounding of the Else Terkol in the Bristol Channel. The tide is 8 m.*

Bo Cerup Simonsen

- Ship “running” on sandy slopes (seabed)”.
- Difficult mathematics since path is unknown
- Undrained behavior “estimated”
- Comparison with scale models

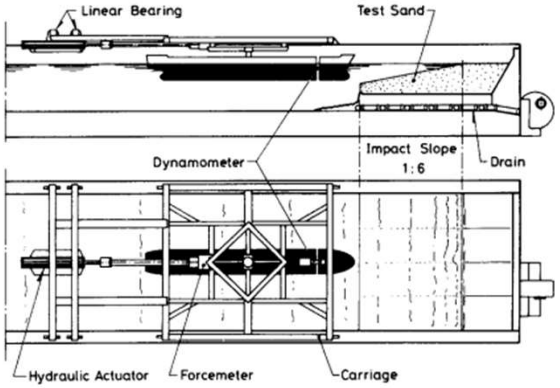


Figure 4.1: *Experimental setup for model testing of soft grounding.*

Table 4.1: *Main data for model scale grounding experiments.*

Length, L	2.57 m
Beam, B	0.378 m
Initial Draft, T	0.117 m
Ship mass, M_s	78.4 kg
Impact velocity, V	0.265 - 0.664 m/s
Slope inclination	1 : 6
Mean grain size, d_m	0.125 mm

Mechanics of Ship Grounding

Bo Cerup Simonsen
February 1997

DTU

DEPARTMENT OF
NAVAL ARCHITECTURE
AND OFFSHORE ENGINEERING

4.1. *Model Tests* 47

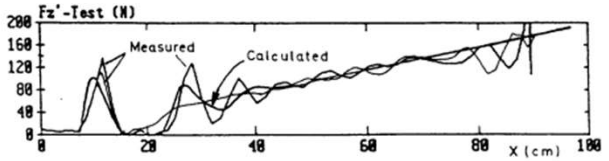


Figure 4.2: *Vertical ground reaction vs. horizontal position of ship. Theoretical prediction and results of two tests where the impact velocity*

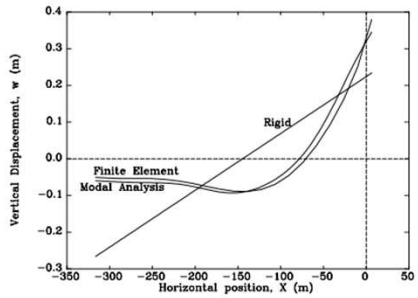


Figure 4.10: *Position of ship base line at $t = 0.95\,s$. The structural response for the flexible case is calculated both by modal analysis and by the finite element method.*

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General

- Literature of collison path in sand is scarce – models even scarcer. Most of literature is based on collision forces on stiff constructions (bridge piers) and on damage due to collision in the ships hull.
- European standard for collision force on “stiff” objects: EC1-7: Attachment C
- From real life examples one observes that in seabed sand the path tends to act like the Pedersen path => namely bedding reacts very stiff due to “undrained” behavior of seabed sands => ship runs up quickly,
- Applying this would lead to stopping distances which are small (“the smalles”) => what is the risk if the sands reacts drained and the ship begins to plow and stopping distance is bigger than based on Pedersen/Simonsen formulations?

General

- Lantis / Roco => decision is made to apply drained material => gravel – open structure => avoid complex “undrained” calculations
- Problem => no literature / no analytical models / no software available to solve problem with “click on the button”
- Need to develop a method which complies with the situation of Antwerp (fe. Stoerebaelt made their own models to estimate stopping distances on the “islands” around the structure)
- Analytical “spread sheet” whit solution based on “known” path–determination by use of an interative Plaxis 3D simulation

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Assumptions

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Geometry and charateristics slope

- Steel slags for collision slope
  - High φ (48°) => confirmed by Triax
    - Steep slope possible (1/2,5)
    - High bearing capacity
    - High passive resistance
  - High permeability (k > 10^{-3}m/s)
    - drained behaviour
  - Cheap
    - Waste product of steel industry
- Filler sand, Berchem sand, Boom clay
- Slope protection layer

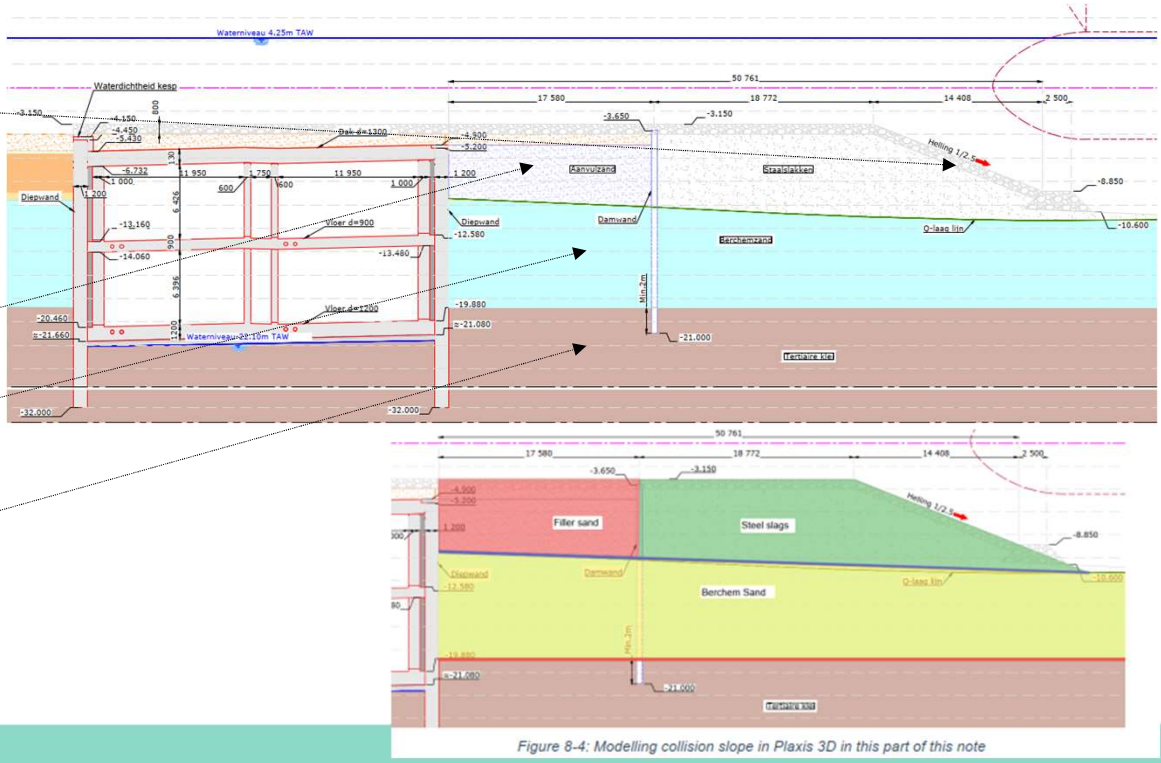
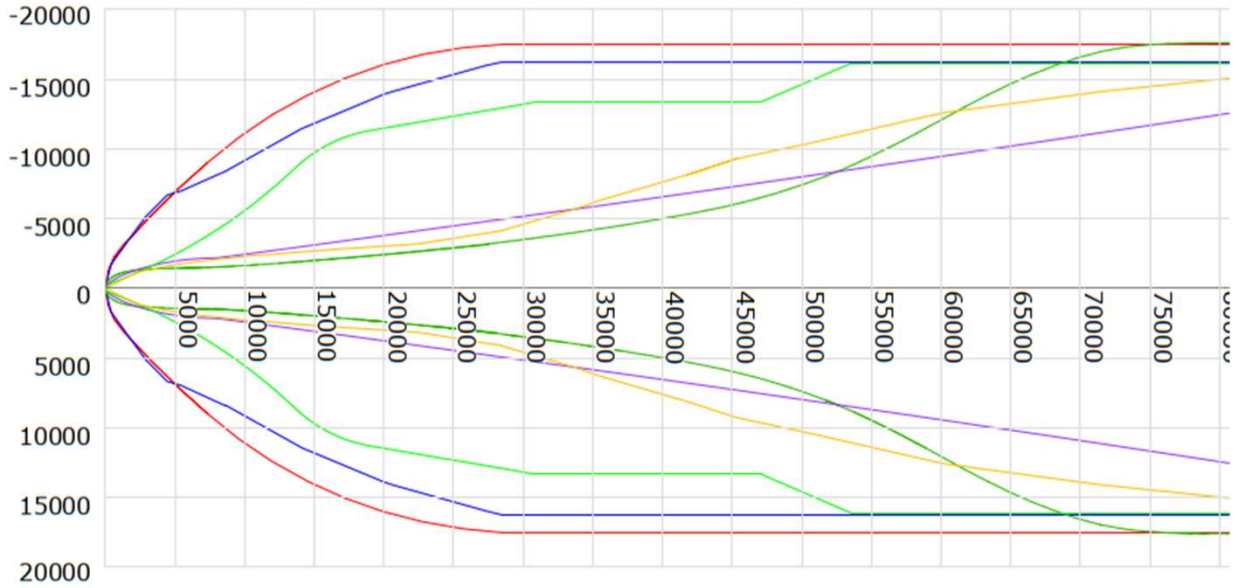


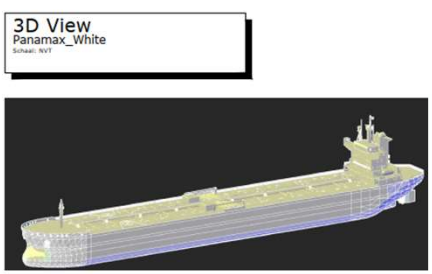
Figure 8-4: Modelling collision slope in Plaxis 3D in this part of this note

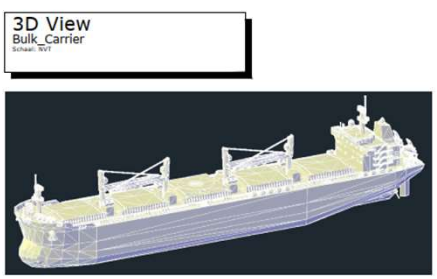
Vessels

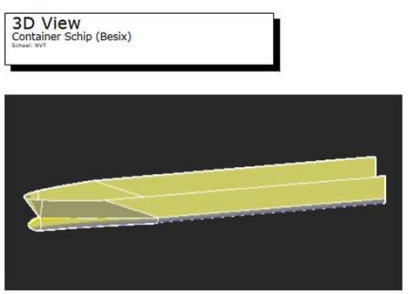
- List of passing vessels => Different shapes ! => challenging
  - Container ships
  - Bulk carriers
  - General cargo ships
  - …

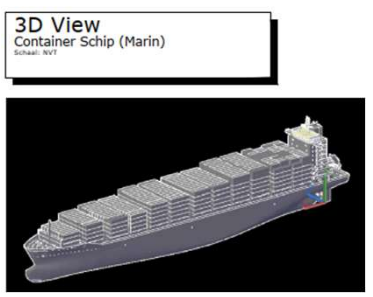


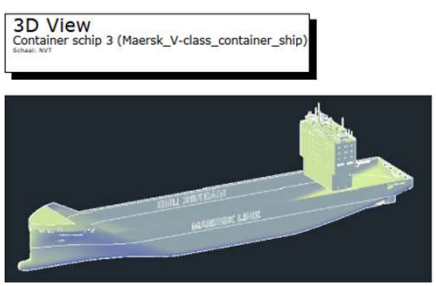
Panamax (Bulk Carrier), Average bulk carrier, Container ship Besix, Container ship Marin, Maersk-V-Class container ship





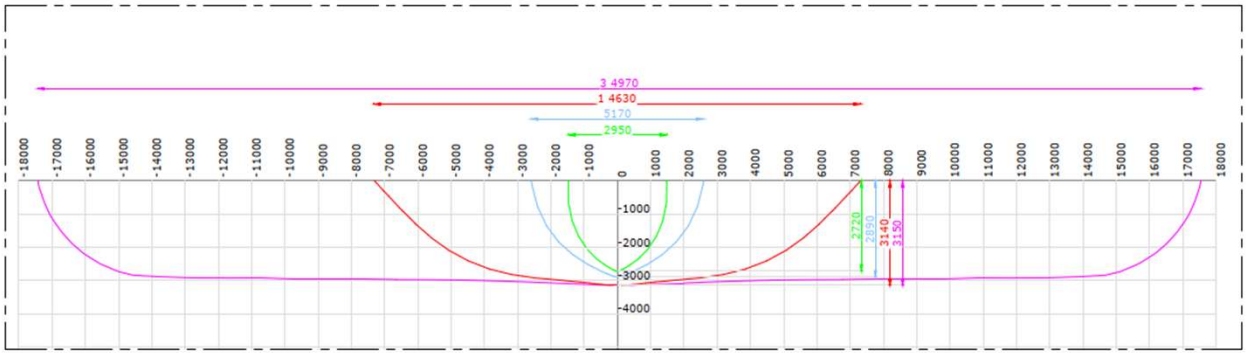


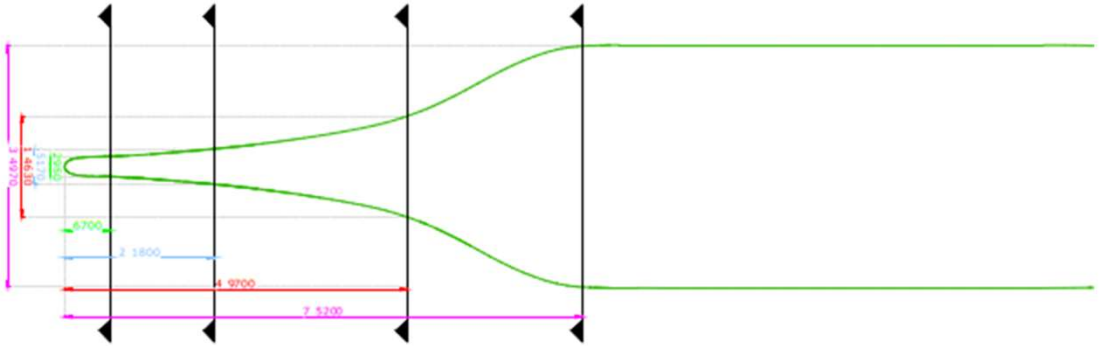




Design Vessel

- Maersk-V-Class Container Ship
  - Icebreaker type
  - Very sharp bulb!! => longest path logic since this shape gives lowest contact surface => highest pressure on soil during plowing!

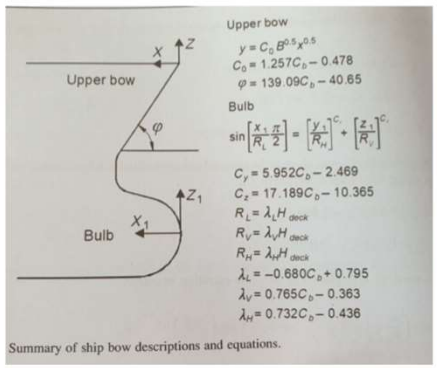






Parametrisation of the design vessel

- Parameterization of the bulb



Summary of ship bow descriptions and equations.

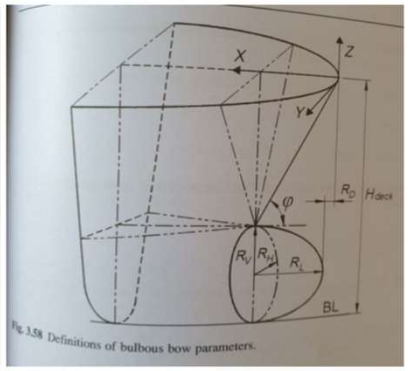
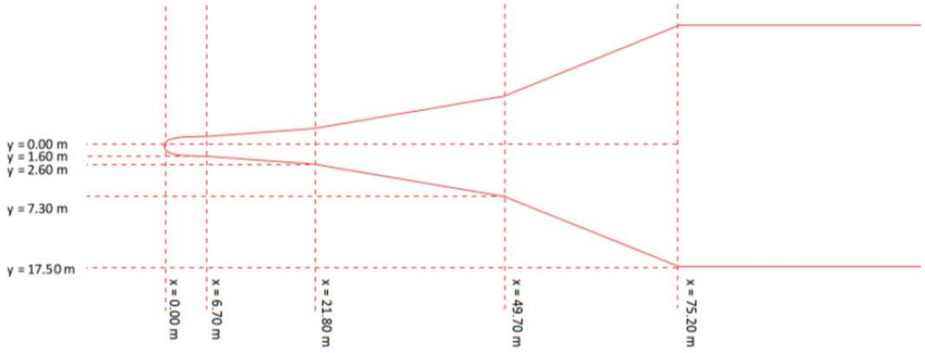


Fig. 3.58 Definitions of bulbous bow parameters.

Table 3-3: MAERSK-V-Class dimensions

	Symbol	Value [m]
Length of the ship	L	200
Width of the ship	B	35
Length of the bulb	R_L	6.70
Half height of the bulb	R_V	3.00
Radius of the bulb	R_H	1.60

- Parameterization of the bow
  - Elliptical shape with depth = R_V at changes in direction
  - Linear increase of the width in three parts

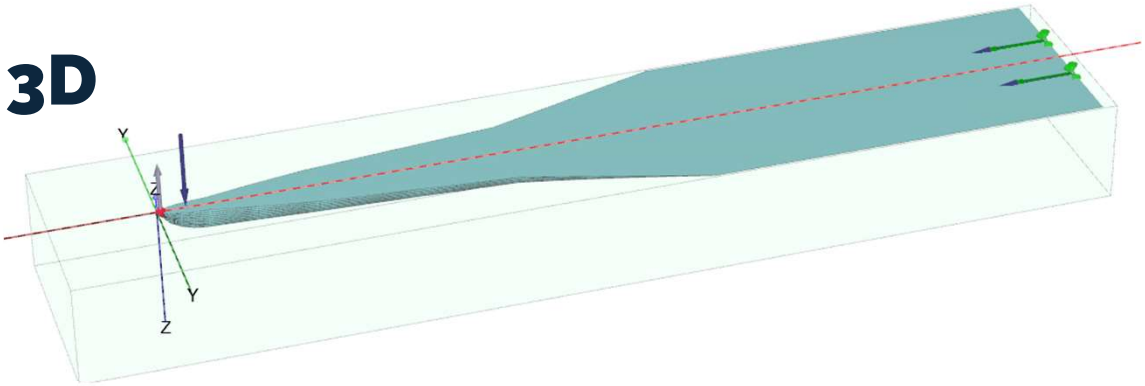


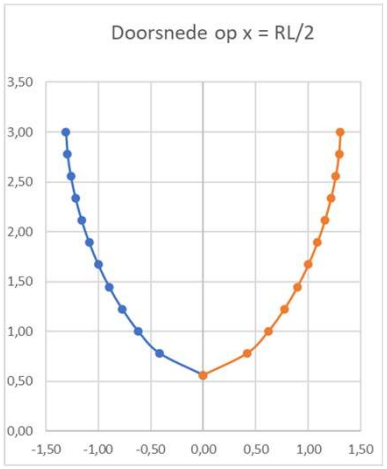
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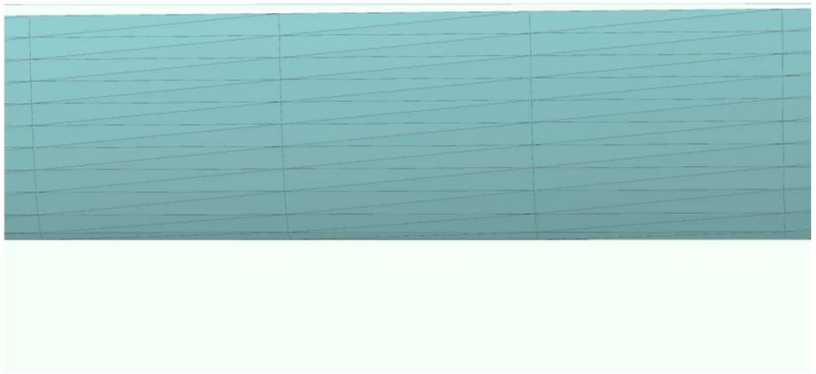
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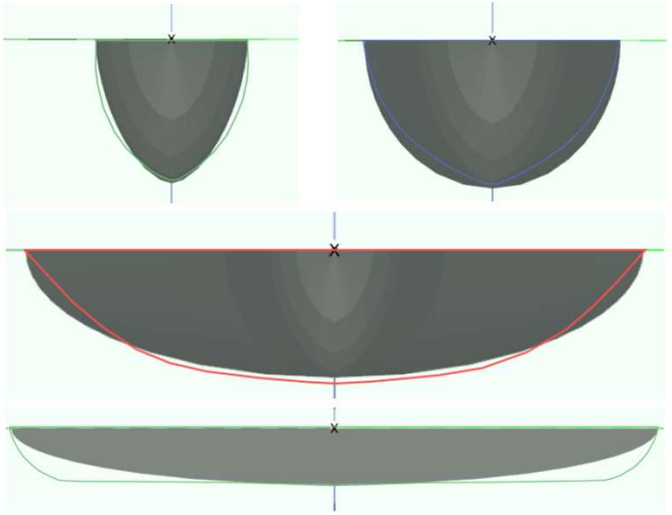
Implementation in Plaxis 3D

- Parameterized section of ship each 0,5 m
  - Coordinates of the points on the section
  - Connect 3 points → small elements
  - Create volume









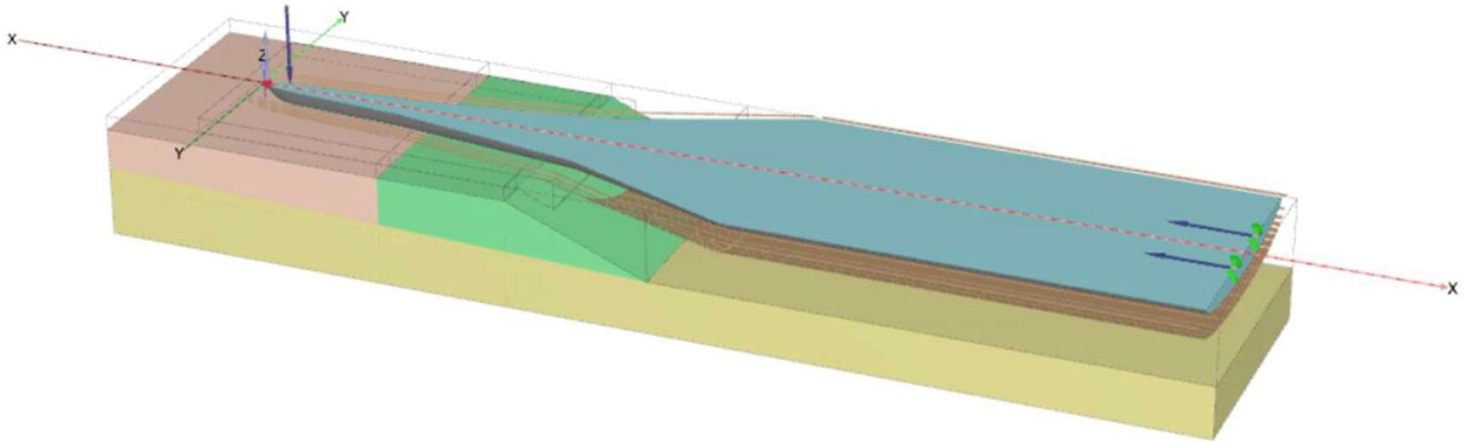
Implementation in Plaxis 3D

- Collision slope geometry
  - Moving of the ship in the collision slope
    - Ship is kept at same place
    - Collision slope is moved forward

Results of labo test

tan(δ)/tan(ϕ)

Material	Soil model	γ_d [kN/m³]	γ_n [kN/m³]	φ' [°]	Ψ [°]	δ [°]	c' [kN/m²]	E [MPa]	ν [-]	R_{inter} [-]
Steel slag	Mohr-Coulomb	20	22	48	18	20	0	25	0.3	0.328
Filler sand	Mohr-Coulomb	18	20	30	0	20	0	30**	0.3	0.630
Vessel	Linear Elastic	9.81*	9.81*	-	-	-	-	$30 \cdot 10^{12}$	0.3	-
Material	**Soil model**	**γd [kN/m³]**	**γn [kN/m³]**	**φ' [°]**	**Ψ [°]**	**δ [°]**	**c' [kN/m²]**	**ν [-]**	**Rinter [-]**	**p_{ref} [kN/m²]**
Berchem sand	HS small	16.8	19.7	35.5	3.5	20	0	0.3	0.510	137

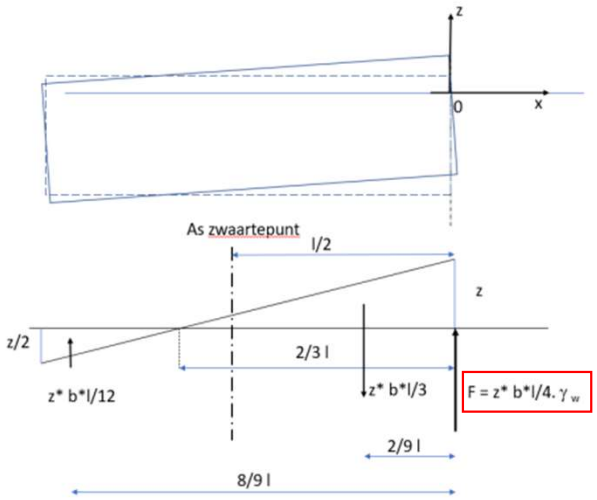


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Rotation point of the vessel

- Rotation point at 2/3 L of the front of the vessel
  - Lifting force $F = B \cdot L \cdot \Delta z \cdot \gamma_w / 4$ => this acts as a resistance on lifting => modelled as a spring



Moment:
8/9l*z.b.l/12 – 2/9 l . z.b.l/3 = 0

Force:
F = z.b.l/3-z.b.l/12

Heave center: 1/6.z

$$F_{front} = (z \cdot b \cdot 2/3\ l \cdot \gamma_w) / 2 = F_z = \frac{B \cdot L \cdot \gamma_w \cdot \Delta z}{3}$$

$$F_{back} = z/2 \cdot b \cdot 1/3\ l \cdot \gamma_w) / 2 = F_z = \frac{B \cdot L \cdot \gamma_w \cdot \Delta z}{12}$$

$$M_{tip} = F_{front} \cdot 1/3 \cdot 2/3\ l - F_{back} \cdot (2/3\ l + 2/3 \cdot 1/3\ l) = 0$$

$$F_z = F_{front} - F_{back} = F_z = \frac{B \cdot L \cdot \gamma_w \cdot \Delta z}{4}$$

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Path simulation

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Energy balance

- Energy of the ship at collision: $E_{kin} = \frac{mv^2}{2}$
  - Initial energy loss of 5% due to impact with collision slope
    Conservative for slope 1/2,5

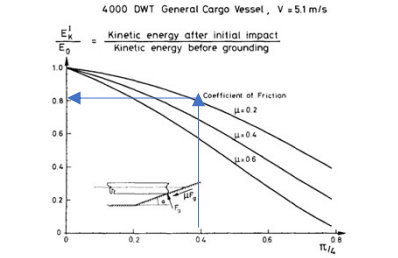


Fig. 3. Energy after initial impact as function of slope α. Added mass ratio $a_1 = a_2 = 1{\cdot}82$.

- Energy loss in three ways
  - Loss of potential energy due to the rise of the ship: $E_p = F_z \cdot \Delta z$
  - Loss of energy due to friction with the soil: $E_{x,friction} = \mu \cdot F_z \cdot \Delta x$
  - Loss of energy due to passive resistance : $E_{x,passive} = F_x \cdot \Delta x$

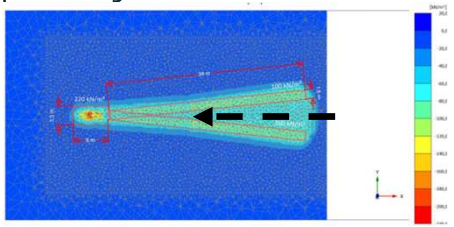
- Ship stops when $E_{kin} - E_p - E_{x,friction} - E_{x,passive} = 0$

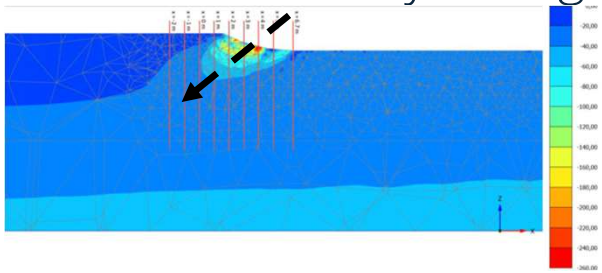
Draught [mTAW]	d [m]	m [ton]	v [m/s²]	Einitial [MNm]	Ecalc [MNm]
8,4	1	59107	2,5	187	177
9,4	2	66144	2,5	209	198
10,4	3	73181	2,5	231	219
11,4	4	80216	2,5	253	241
12,4	5	87253	2,5	275	262

d = depth under top collision slope

Simulation path of the ship

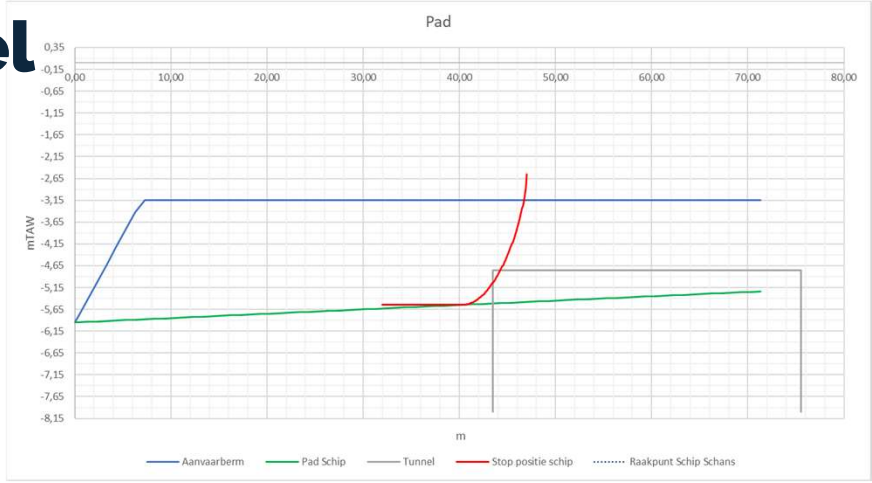
- Conservative Excel calculation
  - With prescribed slope of the ship
  - Need of a calculation to determine the slope of the ship
  - Attempt to predict slope very complex given that contact surface of the ship during plowing changes constantly => hard to put settlement and bearing capacity in math functions which constantly changing contact surface





- Plaxis 3D calculation
  - Determination of the slope of the ship by introducing geometrically the correct shape of the ship during the plowing motion

Simulation path of the ship - Excel



- Conservative Excel calculation
  - With prescribed slope of the ship

- Energy balance calculated every 1 m
  - Each step: $\Delta x = 1$ m, Δz calculated from prescribed slope
  - E_{kin} = known in function of depth
  - $E_p = F_z \cdot \Delta z = (B \cdot L \cdot \Delta z \cdot \gamma_w / 4) \cdot \Delta z$ → Calculated each step
  - $E_{x,friction} = \mu \cdot F_z \cdot \Delta x = \tan(\delta)/\tan(\varphi) \cdot (B \cdot L \cdot \Delta z \cdot \gamma_w / 4) \cdot \Delta x$ → Calculated each step
  - $E_{x,passive} = F_{x,passive} \cdot \Delta x$ → Calculated each step

- Ship stops when $E_{kin} - E_p - E_{x,friction} - E_{x,passive} = 0$

Simulation path of the ship - Excel

- Calculation of $F_{x,passive}$
  - Passive resistance coefficient K_p = 12,5 for φ = 45°
  - Taking into account shell factor = 1,5
    - Gives good fit between Plaxis and hand calculation

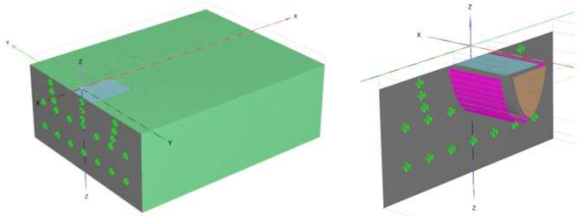


Figure 4-14: Plaxis 3D model - Hull - 3D effects (left), visualization interfaces (right)

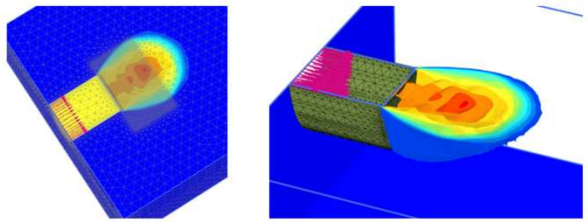


Figure 4-15: Visualization of the failure pattern

φ' = 35° → K_p = 6.5
φ' = 40° → K_p = 8.5
φ' = 45° → K_p = 12.5

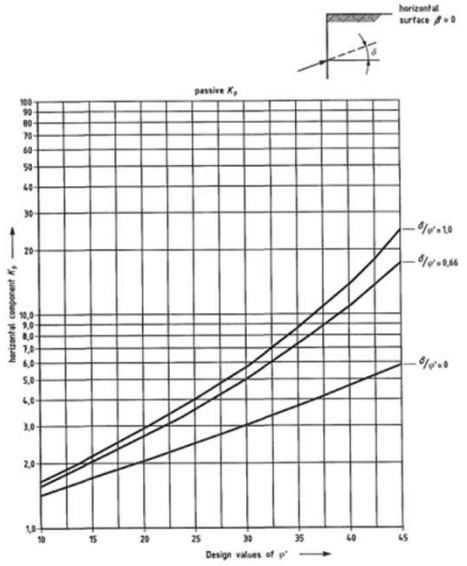
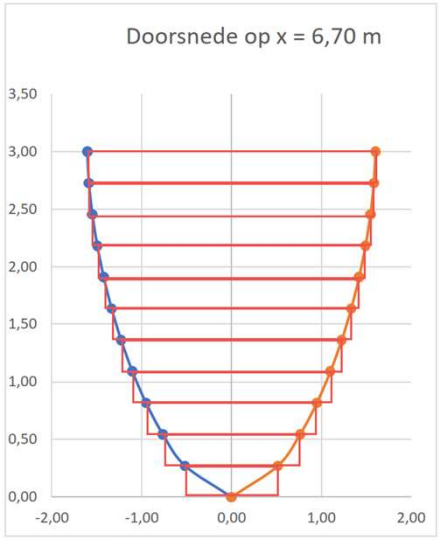


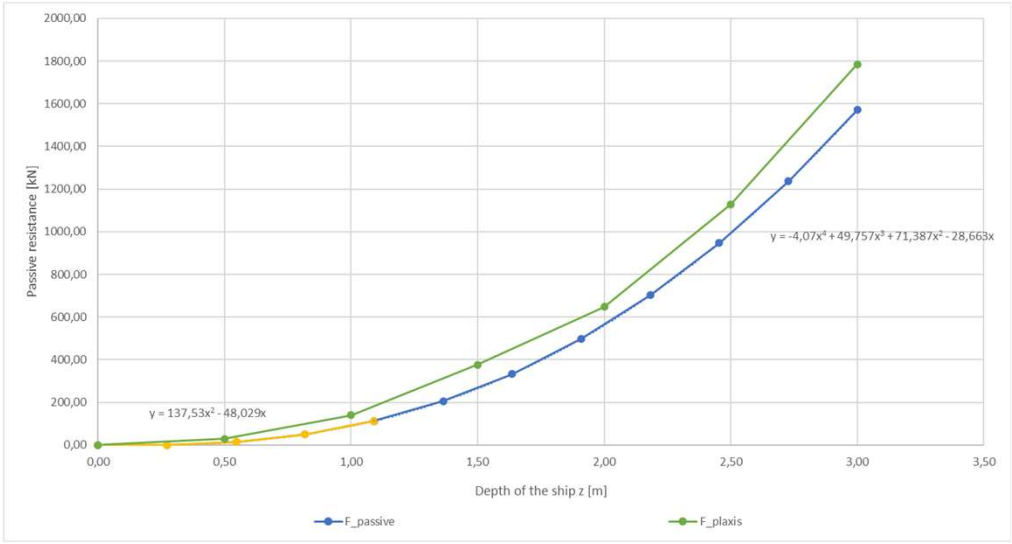
Figure 4-1: Passive resistance coefficient K_p for a horizontal surface level (β = 0)

Simulation path of the ship - Excel

- Calculation of $F_{x,passive}$
  - Parameterized sections of the ship at different positions
  - Calculate the passive resistance at each of the following sections in function of the depth of the ship invluding DIN factor to take account arching effects
    - At certain x in the path: Interpolation between previous section and next section
    - Calibration with plaxis 3D lead to an extra "shape factor" of 1,5 => dependend on hull schape 1,5 valid for Maersk..

Positie snedes	
1	6,70
2	10,48
3	14,25
4	18,03
5	21,80
6	30,17
7	39,94
8	49,70
9	57,35
10	66,28
11	75,20





Simulation path of the ship - Excel

- Slope of the ship is prescribed → Plaxis 3D calculation needed to determine slope of the ship
- Most conservative situation is that slope remains horizontal => energy loss only due to passive resistance since no development of F_z
- Ships with bottom level > -4,3m TAW can geometrically not collide with tunnel – the will run over the tunnel and might impose a vertical statical load on tunnel when stopped.
- First conclusion that can be drawn based on horizontal path in excel => Bulk carriers with all possible depths/draughts stop before tunnel => no need for more detailed path investigation

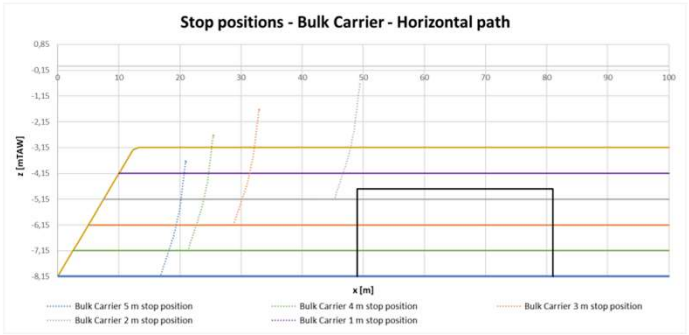


Figure 5-5: Stop positions - Bulk carrier - Horizontal path

Simulation path of the ship - Excel

- Second conclusion is that ships with bottom/draught < -7,5m TAW stop before tunnel
- Thirdly => Maersk-V-Class governs the design – longest stopping distance cfr. Horizontal path in excel. => realistic path prediction using Plaxis 3D will be based upon V-Maersk

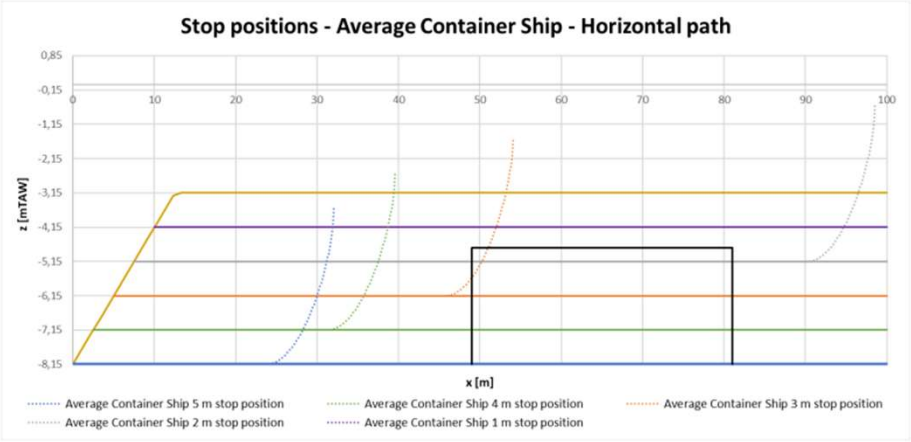


Figure 5-3: Stop positions - Average container ship - Horizontal path

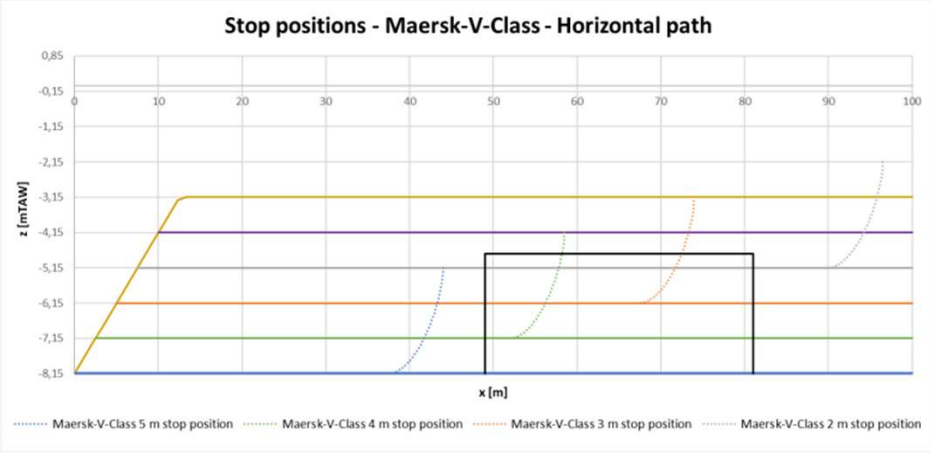


Figure 5-4: Stop positions - Maersk-V-Class - Horizontal path

Simulation path of the ship – Plaxis 3D

0

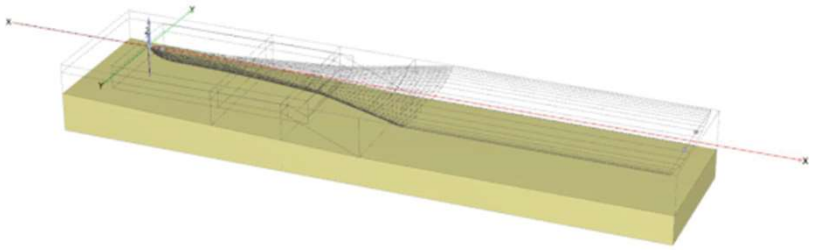


Figure 8-6: Initial phase

1

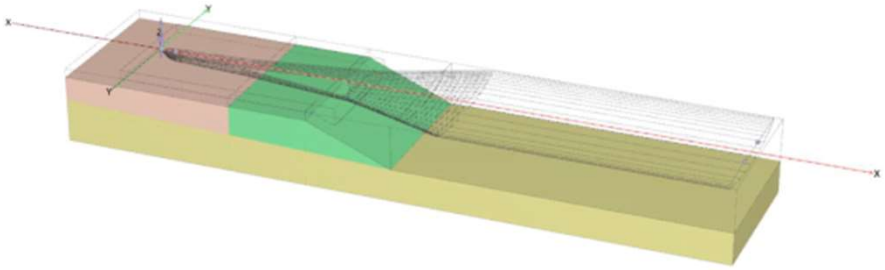


Figure 8-7: Phase 1 - Creating collision slope

2

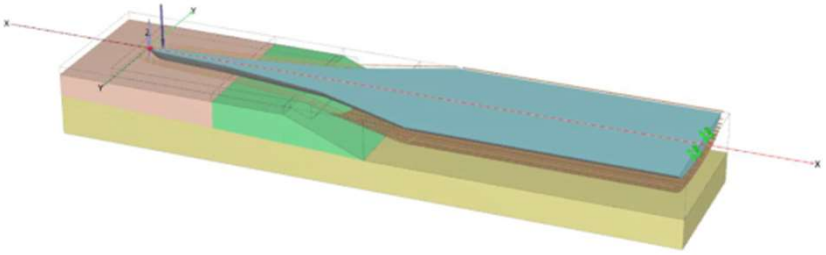
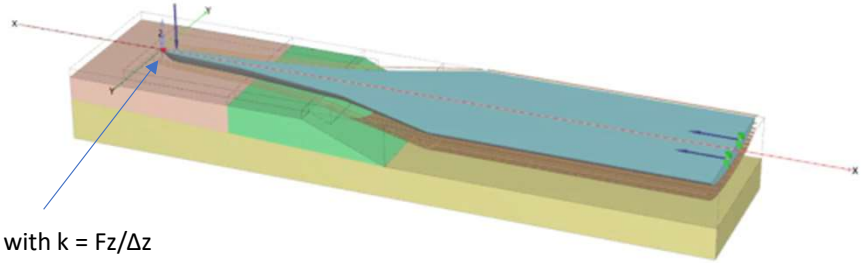


Figure 8-8: Phase 2 - Applying load F_z

Apply Fz to bring soil back in previous conditions

3

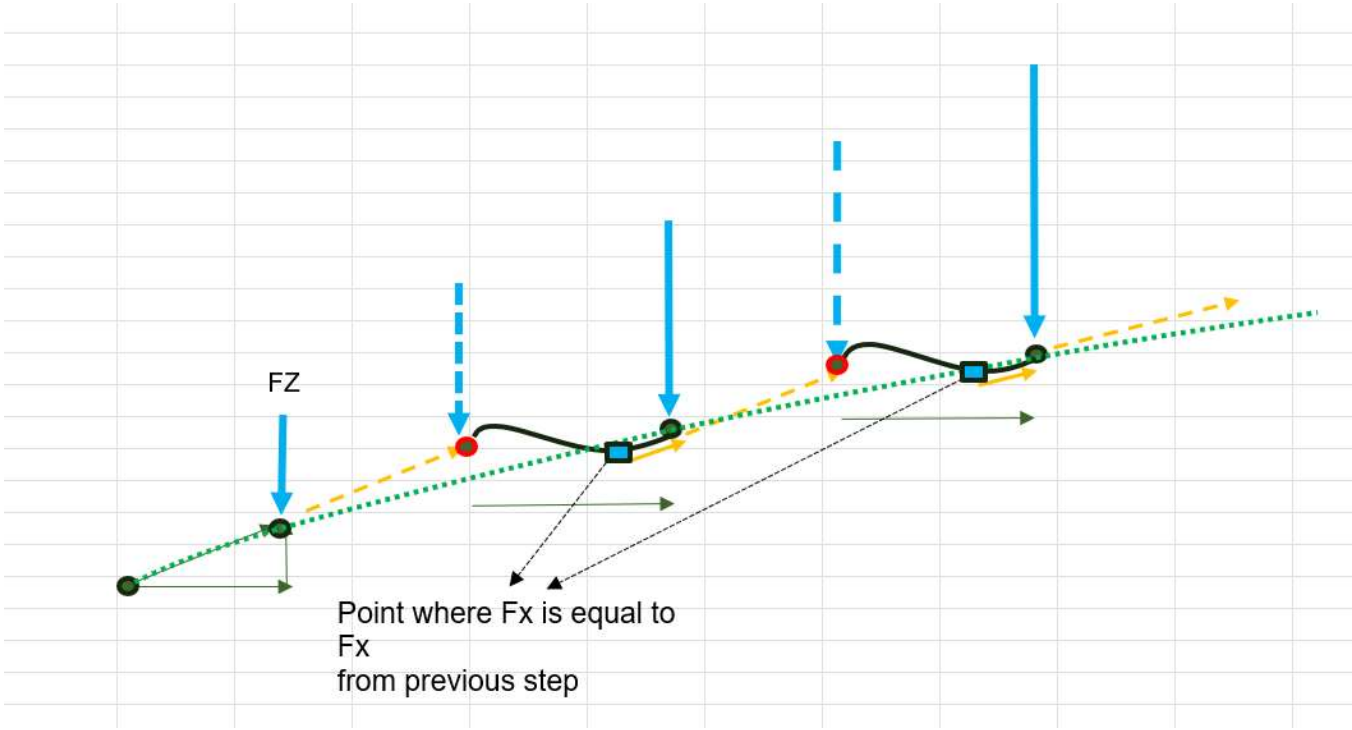


Spring with k = Fz/Δz

Figure 8-9: Phase 3 - Impose displacement Δx

Simulation path of the ship – Plaxis 3D

- Iterative calculation



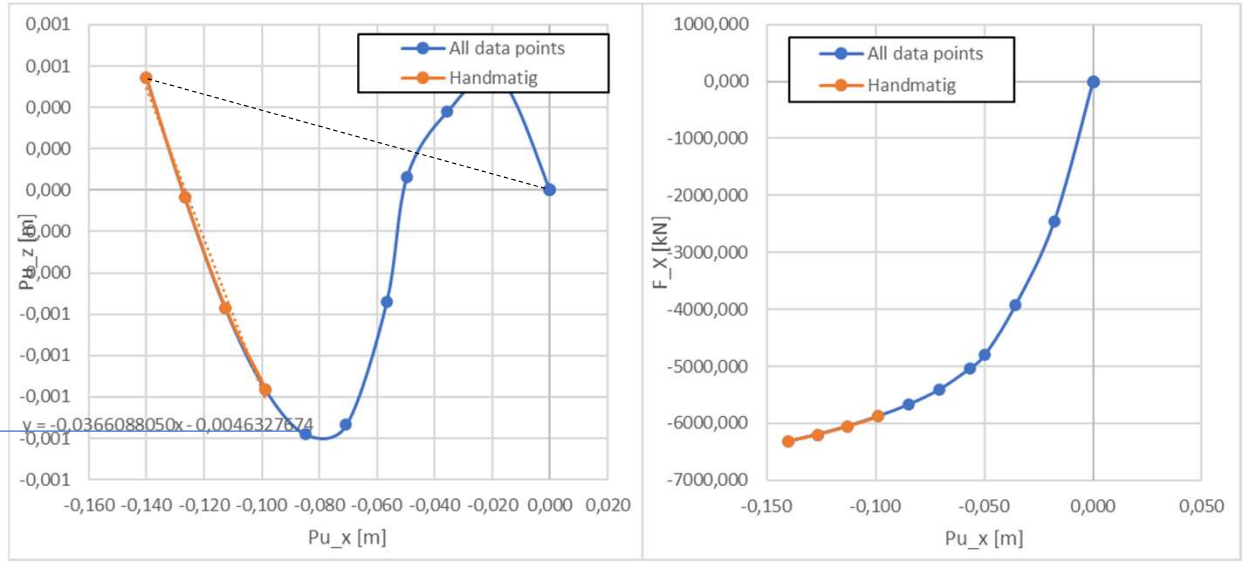
Simulation path of the ship – Plaxis 3D

- Iterative calculation

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
Iteratie	STEP 1: INPUT PLAXIS					STEP 2: COLLECT DATA FROM PLAXIS MODEL + CALCULATION HORIZONTAL AND VERTICAL DISPLACEMENT									STEP 3: CONTACT SURFACE + STRESS				STEP 4: ENERGY DISSIPATION				
						2.1		2.2				2.3	2.4											
	Δx [m]	Δx_{cumul} [m]	Δz_{cumul} [m]	F_z [kN]	ΔF_z [kN]	F_{veer} [kN]	Δz rise [m]	Δz,Fz [m]	kgrond MN/m	Δz,ΔFz [m]	verschil Δz [m]	F_x [kN]	slope	$\Delta x_{_actual}$ [m]	A [m²]	L [m]	Bgem[m]	σz [kN/m²]	E_x [MNm]	Ex_{cumul} [MNm]	E_z [MNm]	Ez_{cumul} [MNm]	$Etot_{cumul}$ [MNm]
1a-inter	1,00	1,000	0,0000	0								0											
1b-plaxis	0,05	1,051	0,0154	270		270	1,54E-02	0,00E+00	0,00	0,00E+00	1,54E-02	366	3,33	0,0514	3,73	3,56	1,05	72,48	0,01	0,01	0,00	0,00	0,01
2a-inter	0,05	1,101	0,0305	533	263		1,50E-02					366	3,33						0,02	0,03	0,01	0,01	0,04
2b-plaxis	0,05	1,150	0,0378	661		151	8,61E-03	-2,65E-03	-200,93	-1,31E-03	7,30E-03	712	5,65	0,0486	3,78	3,63	1,04	174,84	0,03	0,05	0,01	0,01	0,07
3a-inter	0,05	1,200	0,0466	816	155		8,85E-03					712	5,65						0,04	0,09	0,01	0,02	0,11
3b-plaxis	0,05	1,245	0,0522	913		112	6,41E-03	-4,45E-03	-183,36	-8,45E-04	5,56E-03	891	7,04	0,0451	3,85	3,70	1,04	237,40	0,04	0,13	0,01	0,03	0,16
4a-inter	0,05	1,295	0,0593	1.037	124		7,10E-03					891	7,04						0,04	0,17	0,01	0,03	0,21
4b-plaxis	0,05	1,341	0,0636	1.114		89	5,07E-03	-5,92E-03	-175,38	-7,09E-04	4,36E-03	1.017	8,99	0,0455	3,92	3,79	1,04	284,15	0,05	0,22	0,01	0,04	0,26
5a-inter	0,05	1,391	0,0692	1.211	97		5,56E-03					1.017	8,99						0,05	0,27	0,01	0,04	0,32
5b-plaxis	0,05	1,429	0,0727	1.272		71	4,06E-03	-7,09E-03	-170,88	-5,70E-04	3,49E-03	1.112	9,57	0,0389	3,99	3,86	1,03	318,77	0,05	0,33	0,01	0,05	0,38
6a-inter	0,05	1,479	0,0779	1.363	91		5,22E-03					1.112	9,57						0,06	0,38	0,01	0,06	0,44
6b-plaxis	0,05	1,515	0,0808	1.415		61	3,47E-03	-8,11E-03	-168,06	-5,44E-04	2,92E-03	1.216	10,28	0,0356	4,06	3,94	1,03	348,42	0,06	0,44	0,00	0,06	0,50
7a-inter	0,05	1,565	0,0857	1.500	85		4,87E-03					1.216	10,28						0,06	0,50	0,01	0,07	0,57
7b-plaxis	0,05	1,596	0,0880	1.541		50	2,86E-03	-9,06E-03	-165,55	-5,14E-04	2,34E-03	1.286	10,78	0,0308	4,13	4,01	1,03	373,37	0,06	0,56	0,00	0,07	0,64

Simulation path of the ship – Plaxis 3D

- Step 3: Applying imposed displacement



Point where Fx is equal to Fx from previous step

Simulation path of the ship – Plaxis 3D

- Interpolation step
  - Small at the start of the path (varying slope)
  - Increase step towards the end of the path (constant slope)

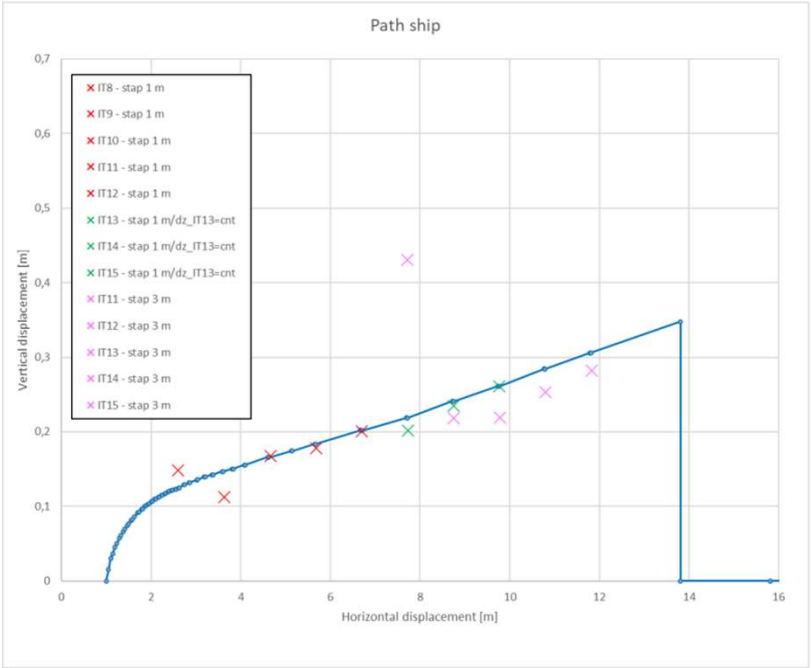


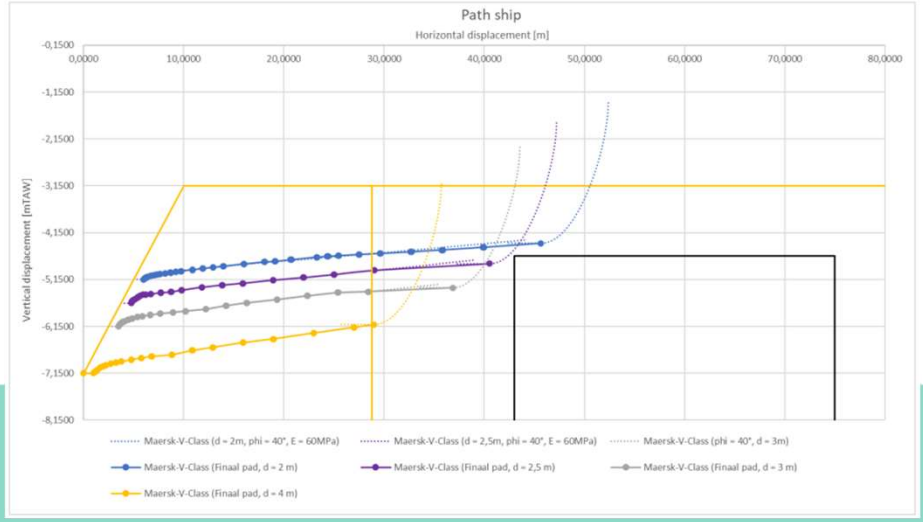
Figure 4-31: Influence of the interpolation step

Results

Table 8-4: Path simulations – Final paths

Ship type	Depth [m]	Average slope	Stopping length [m]	Distance bow-tunnel [m]	Distance tip-tunnel [m]	Rise Δz ship [m]
Maersk-V-Class	2	1/53	40.7	-2.7	-9.4	0.773
	2.5	1/44	36.8	2.5	-4.2	0.838
	3	1/42	34.4	6.1	-0.6	0.821
	4	1/28	29.0	14.0	7.3	1.036

- Final Results for Maersk-V-Class with $\varphi_{steel\ slags} = 48°$, $E_{oed} = 25MN/m^2$ (based on lab test) and correct position Sand fill in coffer dam with $\varphi_{sand} = 30°$, $E_{oed} = 30MN/m^2$
- No direct collision predicted – path is mainly "stiffness" driven (means at each point UC on bearing capicity UC << 1 – position ship comes from settlement…
- With $E_{oed} \cong 25$ à $30MN/m^2$ for good fill /slags results are still conservative + no considerations given on $E_{dyn!} = 3$ à $10\ E_{stat}$…



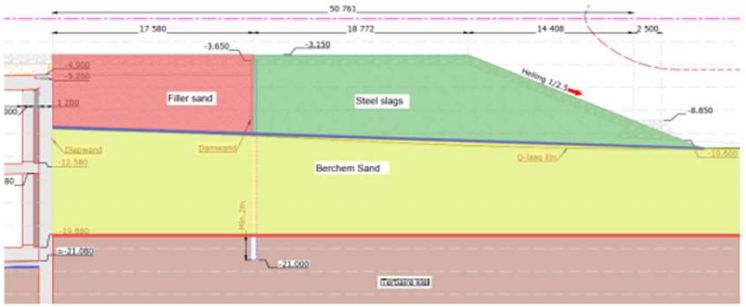
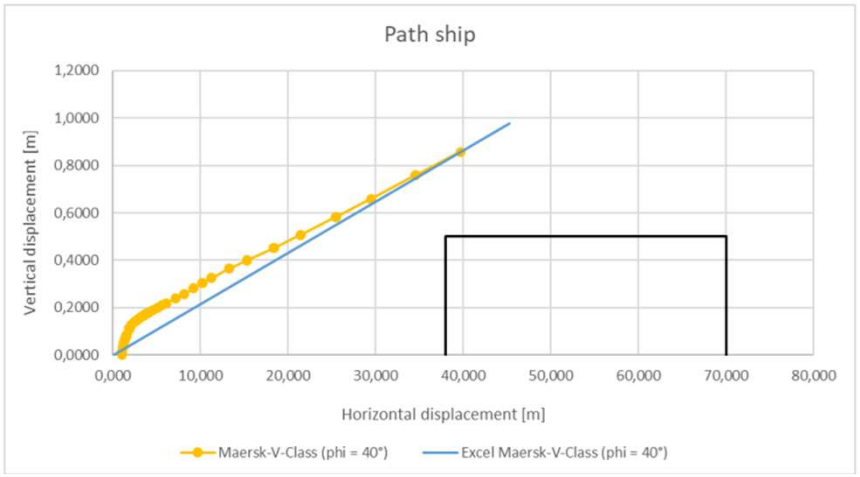
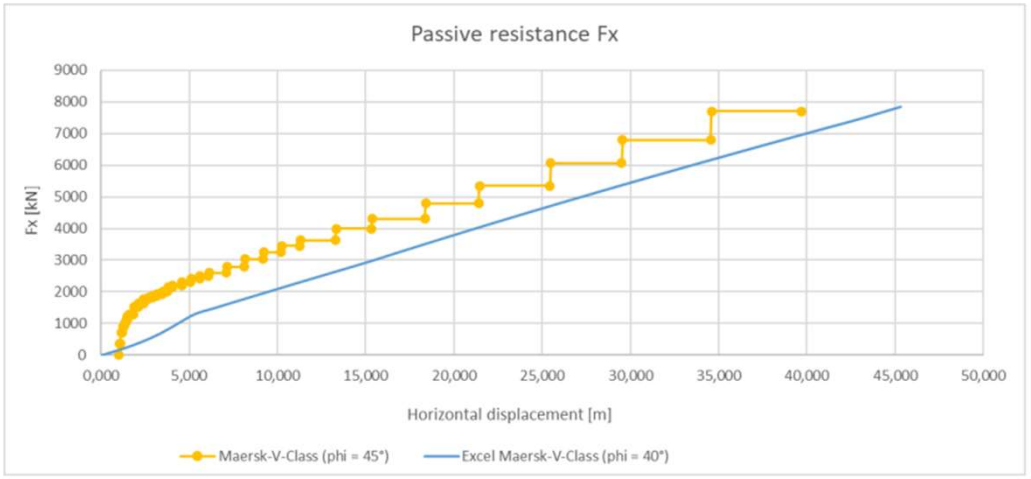


Figure 8-4: Modelling collision slope in Plaxis 3D in this part of this note

Comparison Excel-Plaxis 3D

With same path Excel predicts ca 5% longer stopping distance mainly due to difference in “passive” resistance



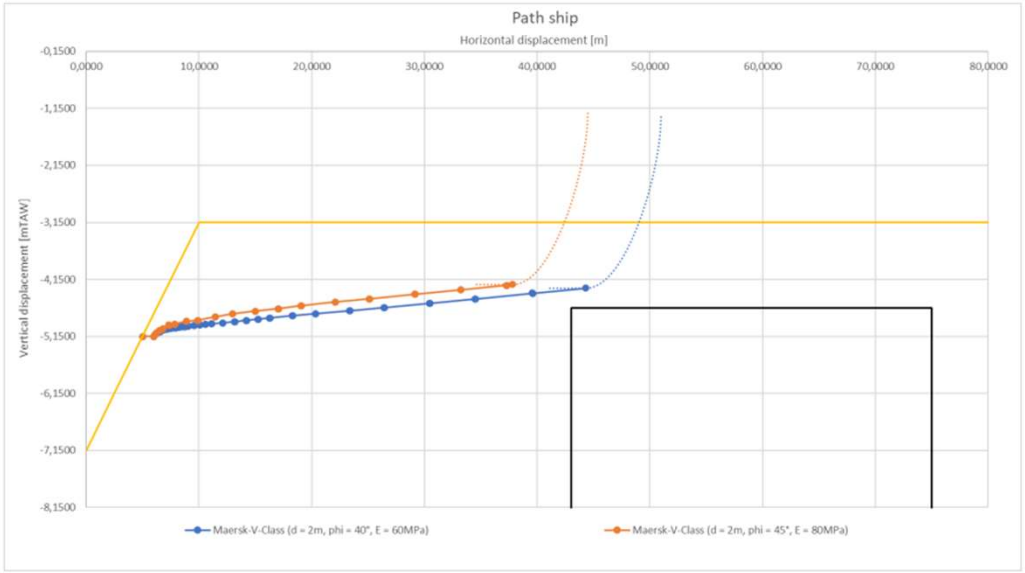


SWECO

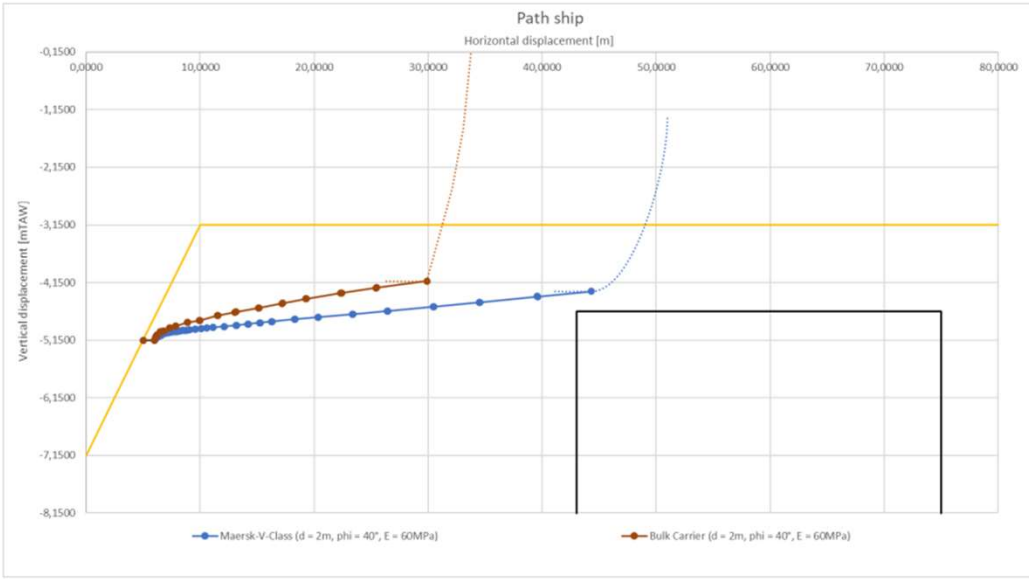
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Parameter study

Influence of ϕ and E_{oed}

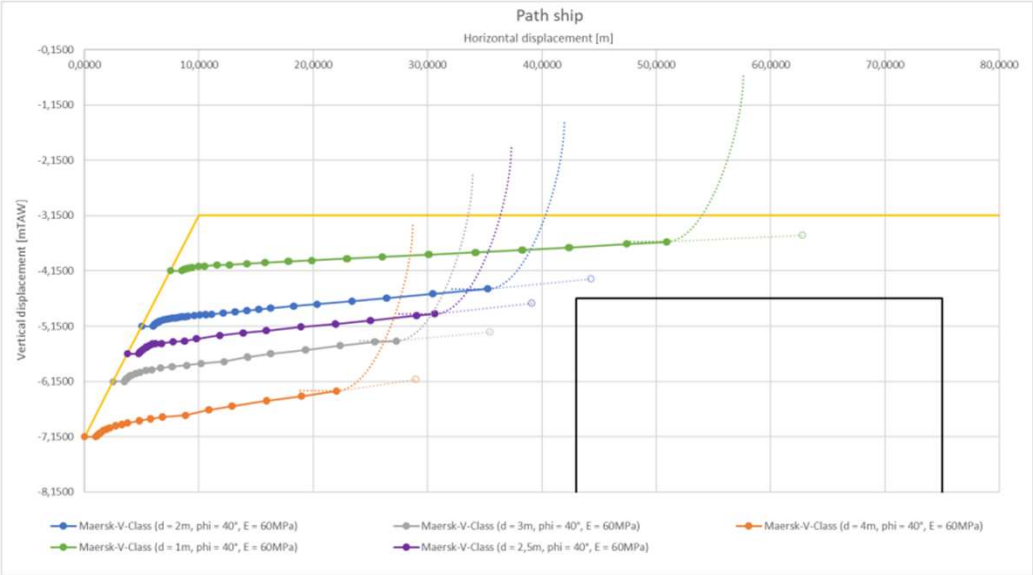


Influence of vessel type



Parameter study

Influence of speed of the ship



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Statistical analysis

SWECO

Statistical analysis

- Lantis wants to put extra safety in concept => what if path is not ca 1/50 but 1/100 => direct collision of ship on “roof” tunnels possible?
- Probability of ship collision $P = P_1 \cdot P_2 \cdot P_{Marin}$
  - P_1 = Chance that ship is container ship = 34,64 %
  - P_2 = Chance that ship has enough energy to go until the tunnel for a slope 1/100 = 6,35% => based on excel calculation
  - P_{Marin} = Chance that shipper loses control over the ship (calculated by Marin) = 0,014 % and collision occurs
- Treshold Lantis probability of collision $P_{tresshold} < 5 \cdot 10^{-6}$
- $P_{cal} = 4{,}99 \cdot 10^{-6} < p_{tresshold} = 5 \cdot 10^{-6}$
- So in essence no need to take account of a direct collision force on tunnel => still Lantis goes further and takes account of a direct collision force on the tunnel following a path of 1/100

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Forces on the tunnel

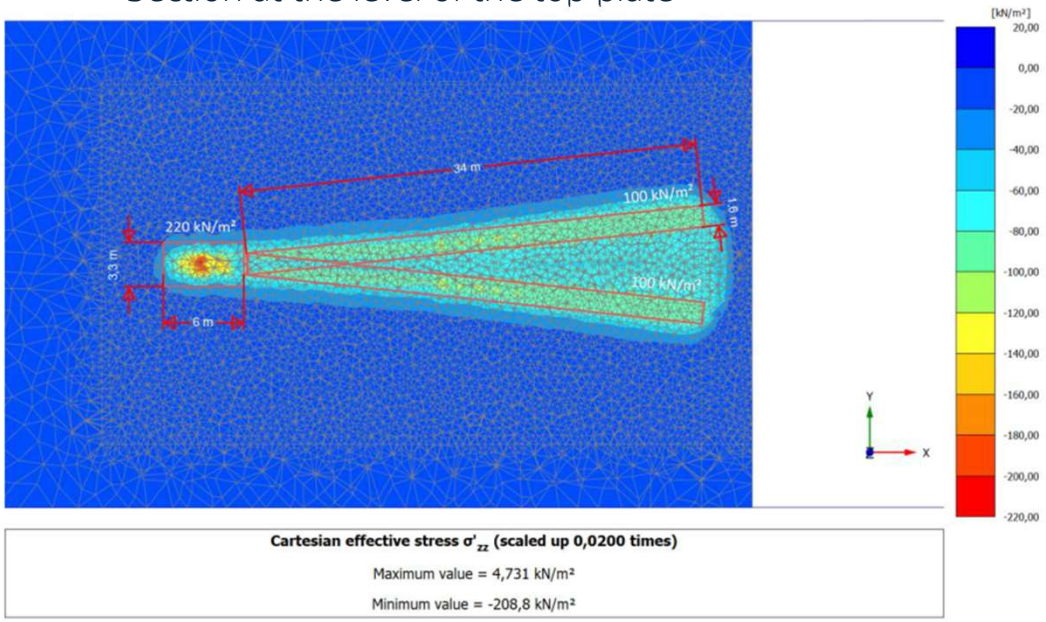
SWECO

Forces on the tunnel

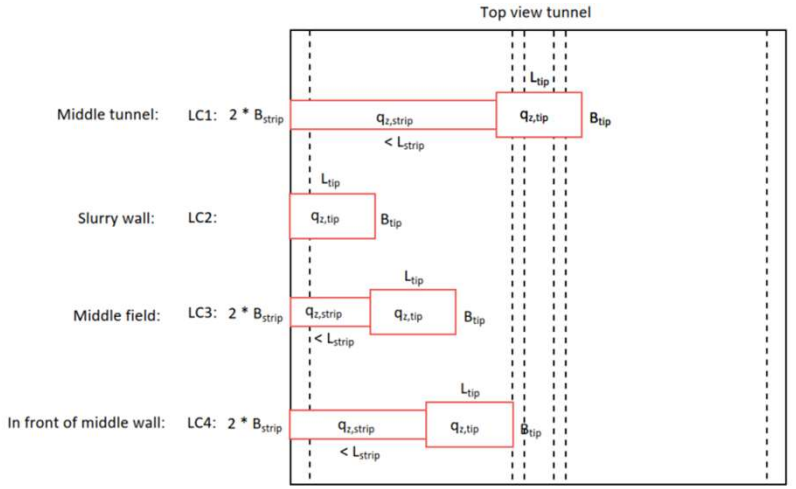
- Drained reaction of steel slags
  - Forces on the top plate of ships ending on top of the tunnel
  - Forces on the slurry walls of ships ending in front of the tunnel
  - In case path 1/100 for ship with d = 2 m → Direct Collision force on the tunnel
- Undrained reaction of steel slags
  - Shock wave/water load on the slurry walls of the tunnel

Forces on the tunnel - Drained

- Ships ending on top of the tunnel
  - Section at the level of the top plate



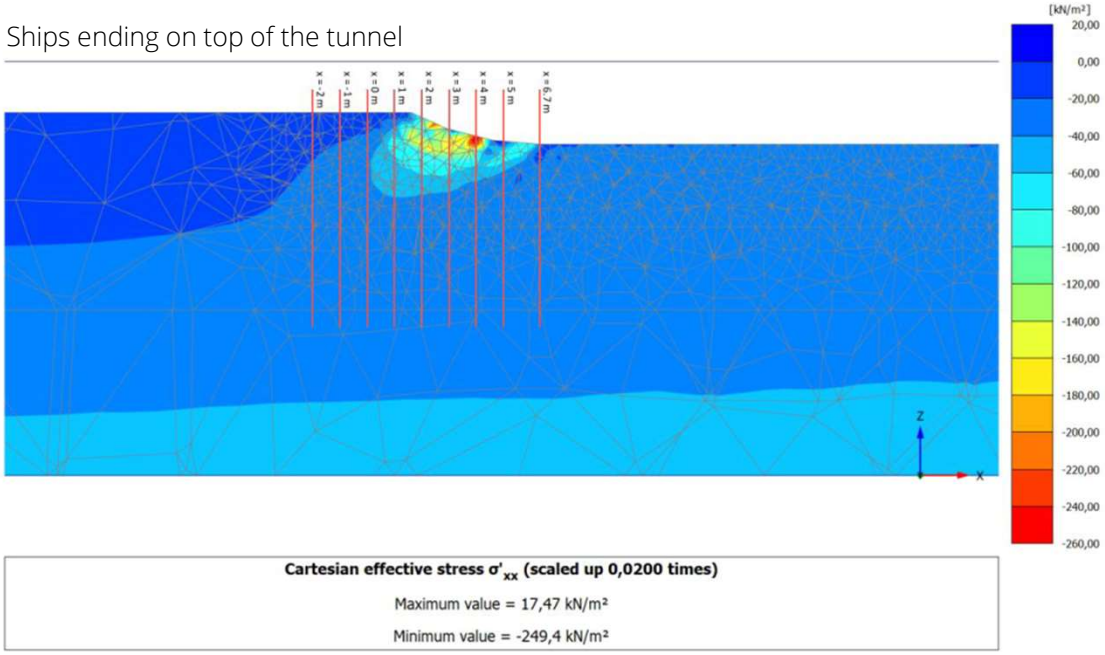
Ship type	d [m]	Surface at tip L [m]	B [m]	q_z [kN/m²]	q_x [kN/m²]	Surface at bow L [m]	B [m]	q_z [kN/m²]	q_x [kN/m²]	H/V
Maersk-V-Class	1	6.5	2.6	85	47	47.5	1.3	85	17	0.55
	2	6.0	3.3	220	132	34.0	1.6	100	60	0.60
	2.5	5.5	2.5	370	226	-	-	-	-	0.61



Forces on the tunnel - Drained

- Force on the slurry wall

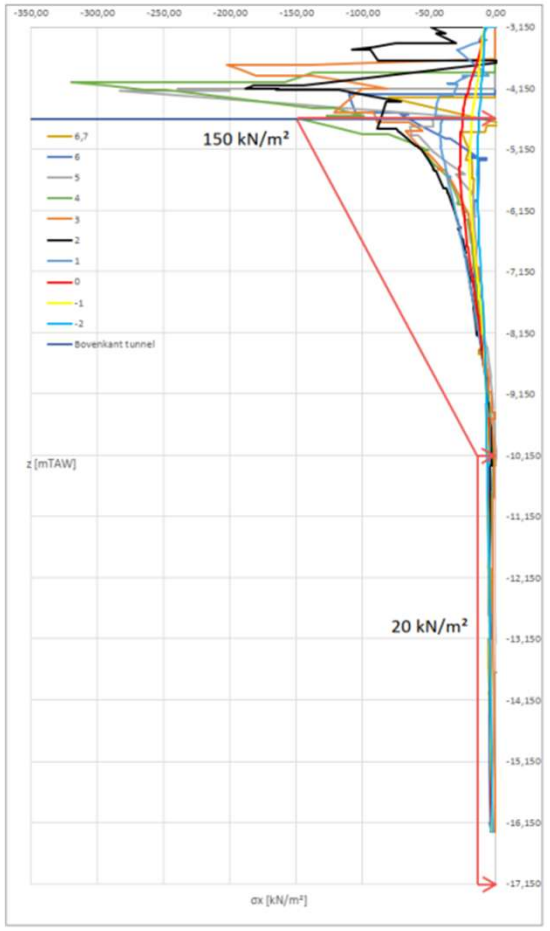
Ships ending on top of the tunnel



Cartesian effective stress σ'_{xx} (scaled up 0,0200 times)

Maximum value = 17,47 kN/m²

Minimum value = -249,4 kN/m²



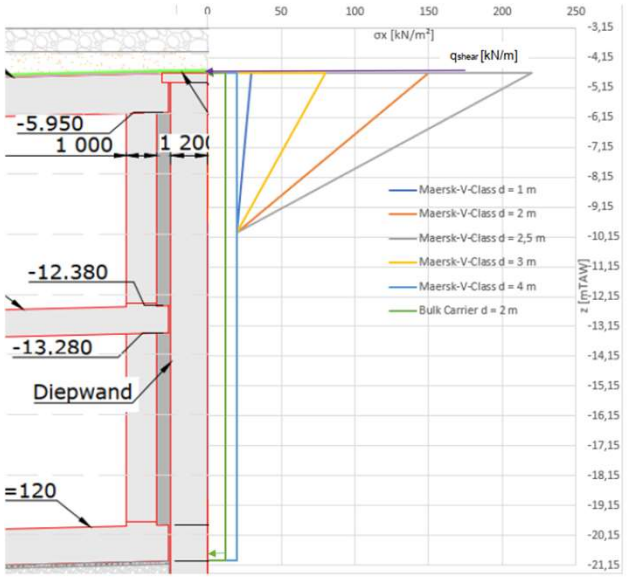
SWECO

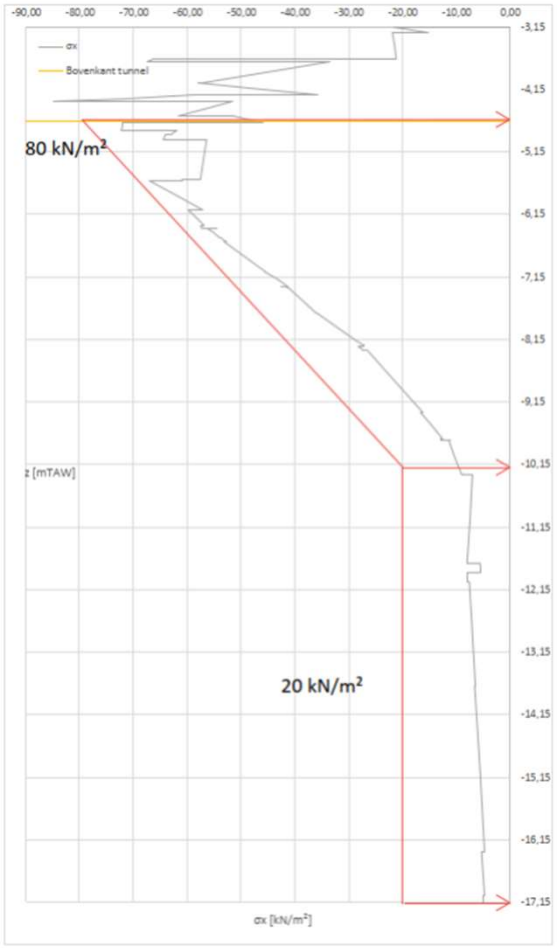
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Forces on the tunnel - Drained

- Force on the slurry wall
  - Ships ending in front of the tunnel – Only 1 section at exact ending position

Ship type	d [M]	q_{top} [kN/m²]	q_{shear} [kN/m]
Maersk-V-Class	1	30	165
	2	150	175
	2.5	220	162
	3	80	45
	4	20	11
Bulk Carrier	2	12	10





Forces on the tunnel - Drained

- Collision force for conservative path with slope 1/100
  - Remaining energy of ship with depth 2,2 m = 100 MNm
  - Collision force: EC1-7: Attachment C → F_{bow} = 116 MN

Ship type	d [m]	$E_{initial}$ [MNm]	$E_{dissipated}$ [MNm]	E_{rest}[MNm]
Maersk-V-Class	2.2	202	102	100
	2.4	207	116	91
	2.6	211	133	78
	2.8	216	151	65
	3.0	219	169	50
	3.2	224	190	34
	3.4	228	212	16
	3.6	230	225	5

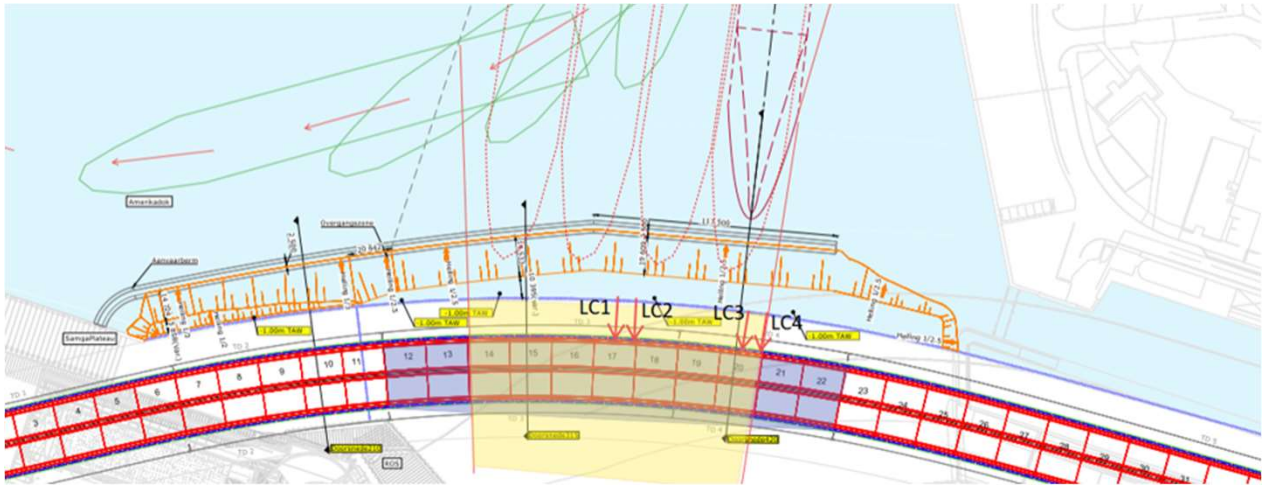
$$F_{bow} = \begin{cases} F_0 \cdot \bar{L} \cdot \left[\bar{E}_{imp} + (5 - \bar{L}) \cdot \bar{L}^{1.6}\right] & if\ \bar{E}_{imp} \geq \bar{L}^{2.6} \\ 2.24 \cdot F_0 \cdot \left[\bar{E}_{imp} \cdot \bar{L}\right]^{0.5} & if\ \bar{E}_{imp} < \bar{L}^{2.6} \end{cases}$$

In which:

- $\bar{L}$ = L_{ship}/275 = 240m/275 = 0.87 m
- F_0 = reference collision force = 210 MN
- $\bar{E}_{imp}$ = E_{rest}/1425 = 100MNm/1425 = 0.07 MNm

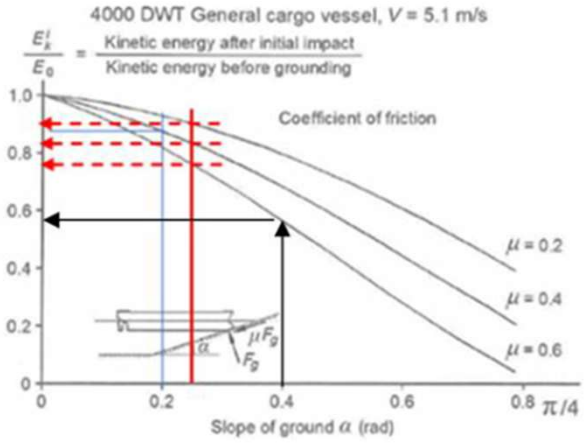
Forces on the tunnel - Drained

- Collision force for conservative path with slope 1/100
  - Remaining energy of ship with depth 2,2 m = 100 MNm
  - Collision force: EC1-7: Attachment C → F_{bow} = 116 MN
  - Monolithic roof plate over zone with possible ship collision to take this force



Forces on the tunnel - Undrained

- Undrained reaction of the steel slags → shockwave through the collision slope
  - Energy loss at impact ≈ 50%



$$v_2 = \sqrt{\frac{E_2}{E_1}} \cdot v_1 = 1.77 \text{ m/s} \quad \rightarrow \quad \Delta v = 0.73 \text{ m/s}$$

$$a = \frac{\Delta v}{\Delta t} = \frac{0.73 \text{ m/s}}{0.5 \text{ s}} = 1.46 \text{ m/s}^2$$

$$F_x = m \cdot a = 79000 \text{ ton} \cdot 1.46 \text{ m/s}^2 = 116 \text{ MN}$$

$$F_y = 0.6 \cdot 116 \text{ MN} = 72 \text{ MN}$$

$$F_{tot} = \sqrt{116^2 + 72^2} = 136.5 \text{ MN}$$

$$P = 136.5 \text{ MN} / 15 \text{ m}^2 = 9095 \text{ kN/m}^2$$

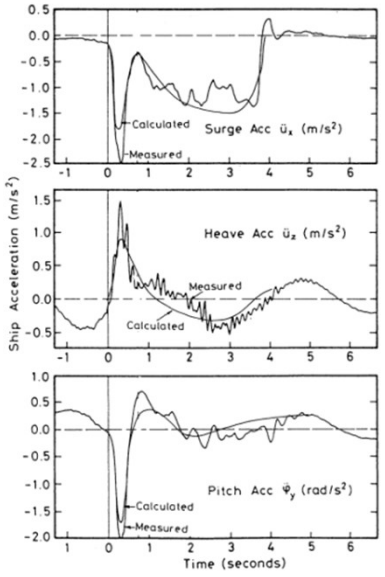
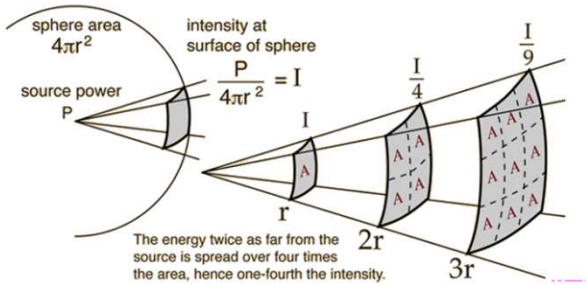
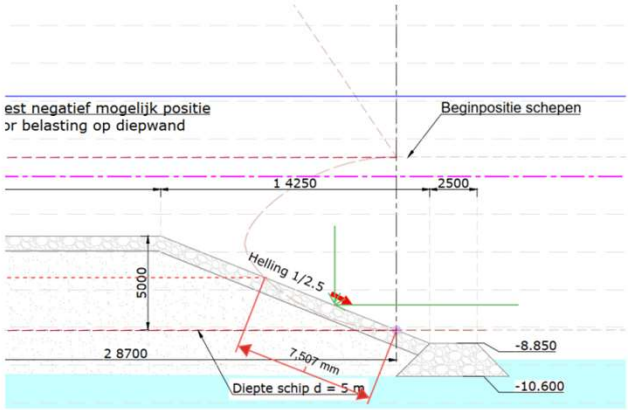


Figure 4.6: *Measured and calculated rigid body surge, heave and surge accelerations in test no. 4.*

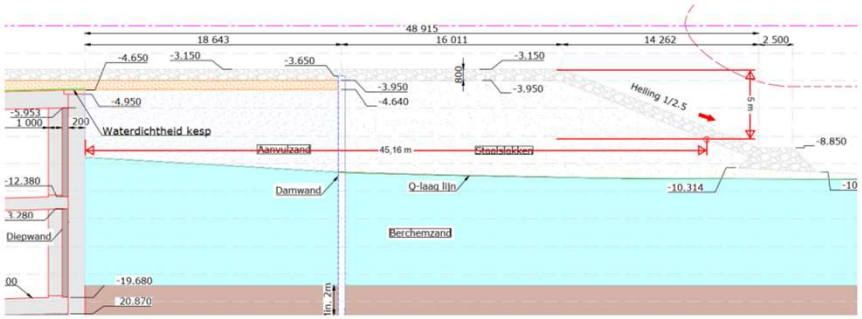
Forces on the tunnel - Undrained

- Undrained reaction of the steel slags
  - Shock wave propagation





$r_1^2 \cdot \pi = 7.5 \cdot 2 \rightarrow r_1 = 2.2\ m$

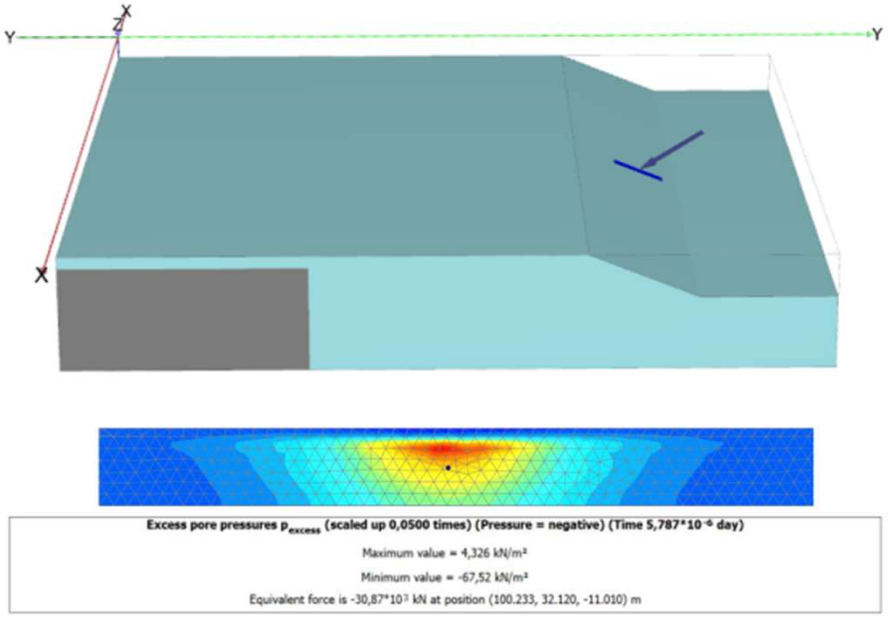


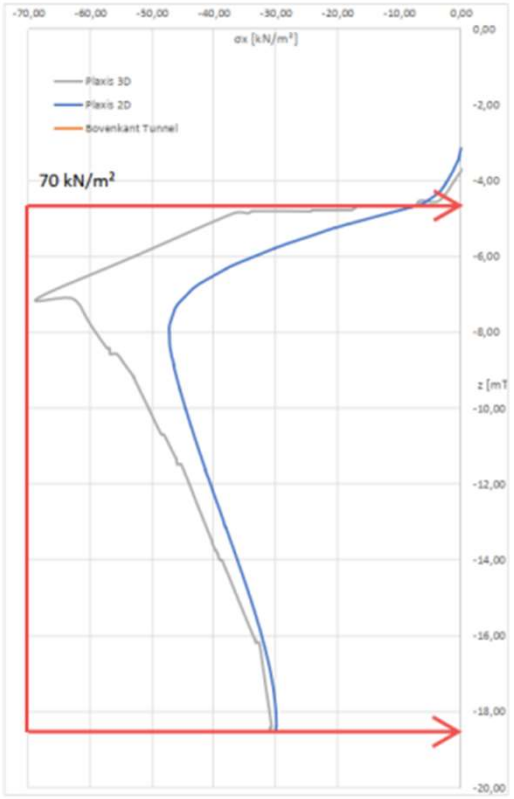
$r_2 = 44\ m - r_1 = 41.8\ m$

$$P_2 = P_1 \cdot \frac{r_1^2}{r_2^2} = 25\ kN/m^2$$

Forces on the tunnel - Undrained

- Undrained reaction of the steel slags - Plaxis





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Questions ?

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