Revolutionary iso-static structural design of hinged double-decked tunnels in Antwerp Belgium

Oosterweel Link

To improve the traffic flow in the Antwerp region, it was decided to complete the R1 Ring road by building the Oosterweel Link. The initial solutions were considered either non-sustainable or were out of budget. The final solution, explained further in this project presentation, resulted in a pioneering iso-static 2×2 lane Double Decked Cut & Cover (DD C&C) tunnel. This solution satisfies political, financial and geotechnical boundary conditions, creating a sustainable solution within the targeted budget. The final design stage is nearly completed and the anticipated construction start is by early 2019.

In 1969 the Ring road (R1) of Antwerp was opened to the public in its current state. However, since then, and for more than 50 years now, the 10 km north-western quadrant of the R1 is still missing (fig. 2, box 2,3 and 4). With increasing traffic passing the Antwerp region every day and the disability to divert traffic in case of an accident, the R1 is extremely vulnerable to congestion. Nowadays, the Antwerp R1 is ranked fourth of Europe's most congested highways.

To improve the traffic flow in the Antwerp region in the year 2000 the decision was made to complete the R1 with the realisation of the Oosterweel Link (Masterplan 2020). The Oosterweel Link closes the R1, improves the access to the port of Antwerp (Europe's second largest harbour) and creates a second main road connection between the banks of the tidal river Schelde (fig. 2, box 2). Originally, the €3.2 billion Masterplan for the Oosterweel Link consisted of a 2x2 lane, 1500 m long, 25 m high, double decked cable stayed bridge over the harbour (fig. 2, box 4) and a 2×3 lane 900 m long immersed tunnel (fig. 2, box 2) underneath the river Schelde. However, by late 2009 the residents of Antwerp blocked the realisation of the bridge via a referendum. The environmental impact of the bridge on the (future) expanding residential areas in the old Docklands of Antwerp was considered to be non-sustainable.

Immersed tunnel versus Cut & Cover Tunnel

By replacing the bridge with two aligned, 2×2 lane immersed tunnels on almost the same location an alternative solution with less environmental impact was suggested in 2010 (fig. 3 and 4). This alternative design addressed most referendum

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1 Oosterweel Link cross over junction from a birds-eye view
credits: Zwarts & Jansma Architects
2 Location of Scheldetunnel (box 2), Kanaaltunnel (box 4) and OKA tunnel (red intersection of box 5 & 6)
3 Immersed tunnel alignment
4 Cross section of the immersed tunnel
5 Double Decked Cut & Cover tunnel alignment

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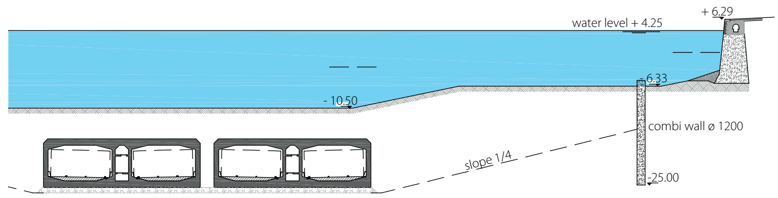

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objections but it appeared to be €500 million costlier and thus the politicians aimed for substantial cost reductions.

Hence, in 2011 employer BAM NV appointed THV RoTS to review the immersed tunnel design with the aim to get the design within the original budget, but still meeting the same functional requirements. THV RoTS initiated a brain storm session which eventually resulted in an alternative 2x2 lane Double Decked Cut & Cover (DD C&C) tunnel design in the Canal Zone (fig. 2 box 4, fig. 5 and fig. 6). This DD C&C tunnel is supposed to be built by means of a top-down method tunnel with 45 m deep Diaphragm walls. This is definitely an out of the box solution as the deep walls (D-walls) of this DD C&C tunnel can only be realised after creating a long (but narrow) man-made island through the Antwerp Harbour by means of a 25 m wide cofferdam of sheet piles filled with sand (fig. 7). For comparison, an immer-sion trench for two aligned immersed tunnels is 120-150 m wide and requires the replacement of more than 1000 m of deep quay walls as well as the replace-ment of an intersecting bridge. The immersion procedure would also block the Harbour for 10 weekends, whereas the DD C&C tunnel saves the existing adjacent objects and keeps the harbour accessible at any time.

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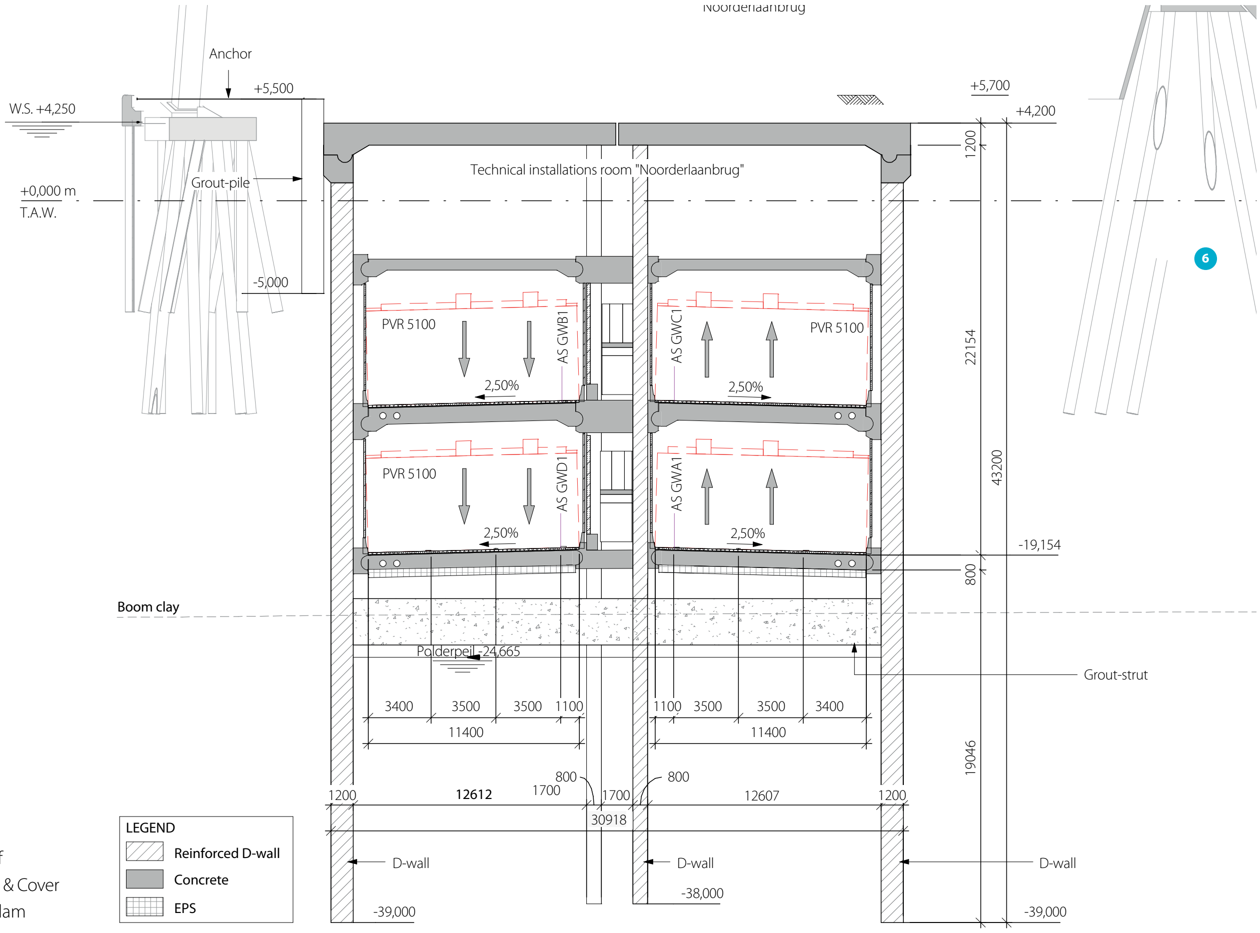
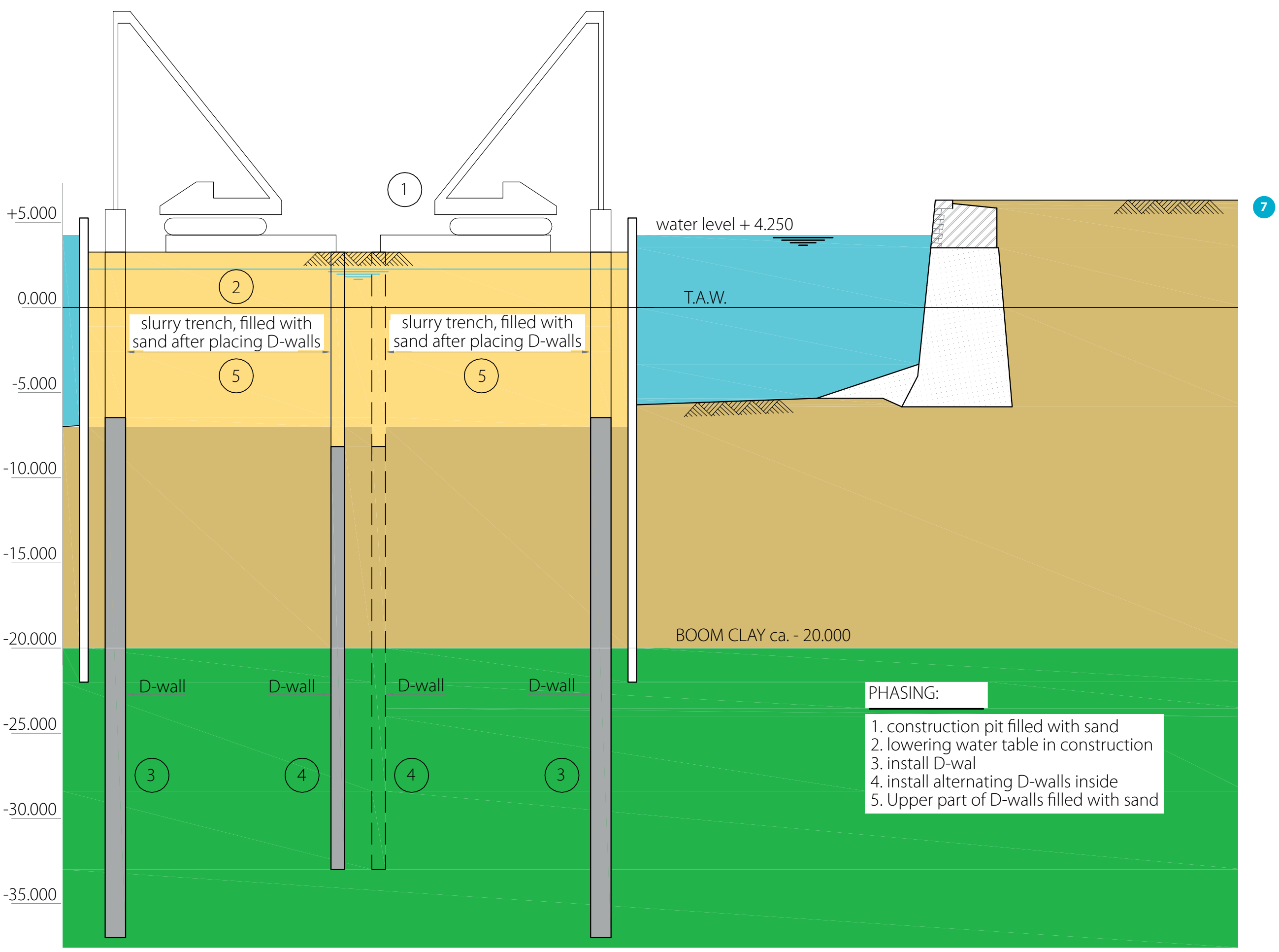
Double deck Cut & Cover tunnel

The approximately 25 m deep DD C&C tunnel proved to be a cost-effective design as the double deck configuration econo-mically uses the same D-walls for both road deck levels. This solution also generates cost reductions by eliminating six viaducts up to 25 m deep in the sub terrain Oosterweelknoop-punt (fig. 2, box 3 and fig. 1) as it allows an easier cross-over junction between the remaining 2×3 lane immersed Schelde-tunnel and the 2×2×2 lane DD C&C tunnel in the Canal Zone. The specific Antwerp geological conditions are particularly favourable for a DD C&C tunnel as at a depth between 20-30 m below the surface an up to 80 m thick impermeable clay layer is present, the Boom Clay. This Boom Clay layer ensures the long-term absence of high ground water pressures against the bottom slab of the tunnel by simple drainage, which provides optimal conditions for an efficient structural design. This ‘polder concept’ was also adopted for the very wide open C&C sections of the Oosterweel Link (fig 2, box 3, 5 and 6) thus in total delivering the unlikely cost reduction of more than €400 million compared to the original double immersed tunnels. As most of these costs reductions originate from reduced amounts of concrete and earth works, the DD C&C tunnel design reduces many tons of CO_2 and is thus providing a more sustai-nable solution. It was politically decided to invest a part of these savings again by replacing the remaining bridge intersecting the Albert canal with the OKA tunnel (fig. 8) as it provides an even more sustainable solution. This underground tunnel junc-tion is to be built with the same DD C&C construction method.



6 Cross section



7 Installing D-walls of Double Decked Cut & Cover tunnel from cofferdam

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Soil-Structure interaction: Design by Testing

The Boom Clay not only provides advantageously dry excavation conditions, but also initiates several structural challenges. When excavating a deep construction pit in the overlaying Pleistocene sand layers, the Boom Clay has the tendency to swell. This not only happens at short notice but will continue over a long period of time. This will generate a substantial long term swelling pressure against the deep concrete bottom slab. As the swelling behaviour of the Boom Clay is supposed to be rather substantial but very hard to quantify, a 20 m deep full scale 20 × 20 m^2 trial pit (fig. 9) was initiated based on a 'Design by Testing' design philosophy [1]. In order to assess the driveability of sheet piles through the hard glauconite sands also a full-scale sheet pile driveability field test was initiated [2].

The results of the full-scale trial pit provided a lot of valuable information about the short term swelling behaviour and pore pressure development in the Boom Clay during excavation. This is very important input for the advanced FE modelling (PLAXIS) which is widely adopted for the pioneering soil-structure interaction design of these tunnels. Despite the optimisation of the horizontal stability of the (shorter) D-walls originating from the trial pit results, the absolute value for the long-term swelling remained hard to quantify as it can continue for decades, although its significance will reduce in time. Based on a literature study, the trial pit results and long term monitoring results at other locations, a long term (100 years) swelling of 190 mm is predicted. To counteract this issue a 400 mm Expanded Polystyrene (EPS) layer is implemented below the base slab, specifically designed to absorb the predicted ongoing swelling of the subsoil (fig. 10).

8 Projection of underground tunnel junction of Kanaaltunnel and OKA tunnel (in red box)
9 Full scale trial pit
10 Differential heave in FE model results
11 Detail of concrete hinge design at the base slab

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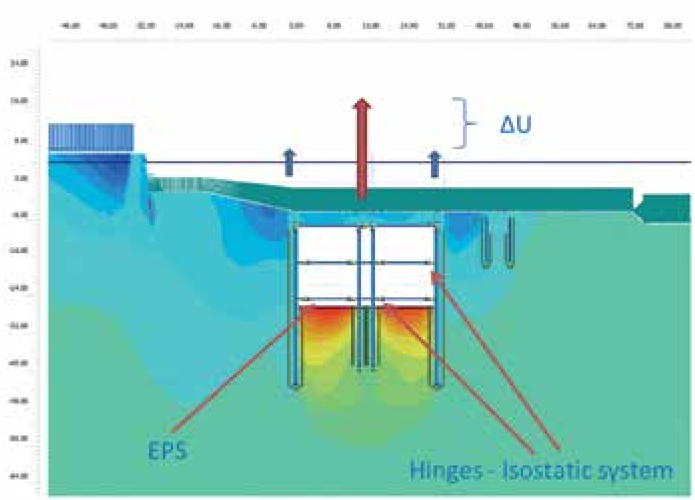

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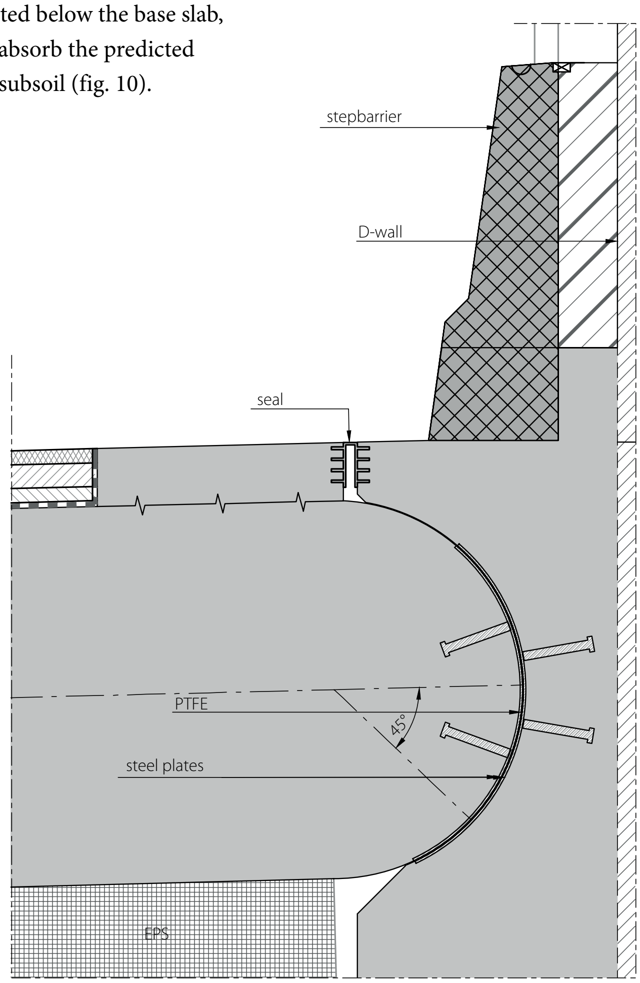
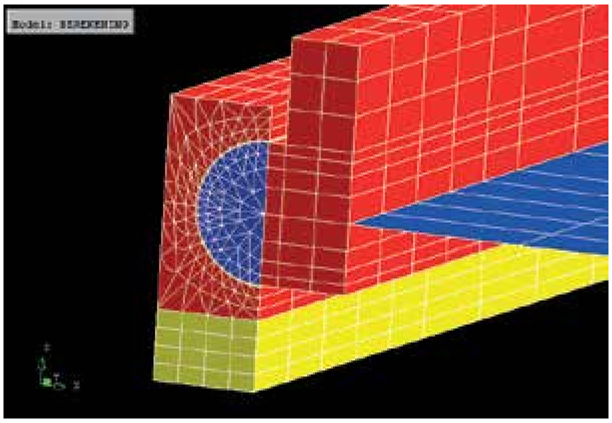


12 DIANA model of the hinge (floor modelled as a plate)
13 OKA tunnel in BIM view (looking in northern direction)
14 Cross section OKA tunnel (see fig. 13)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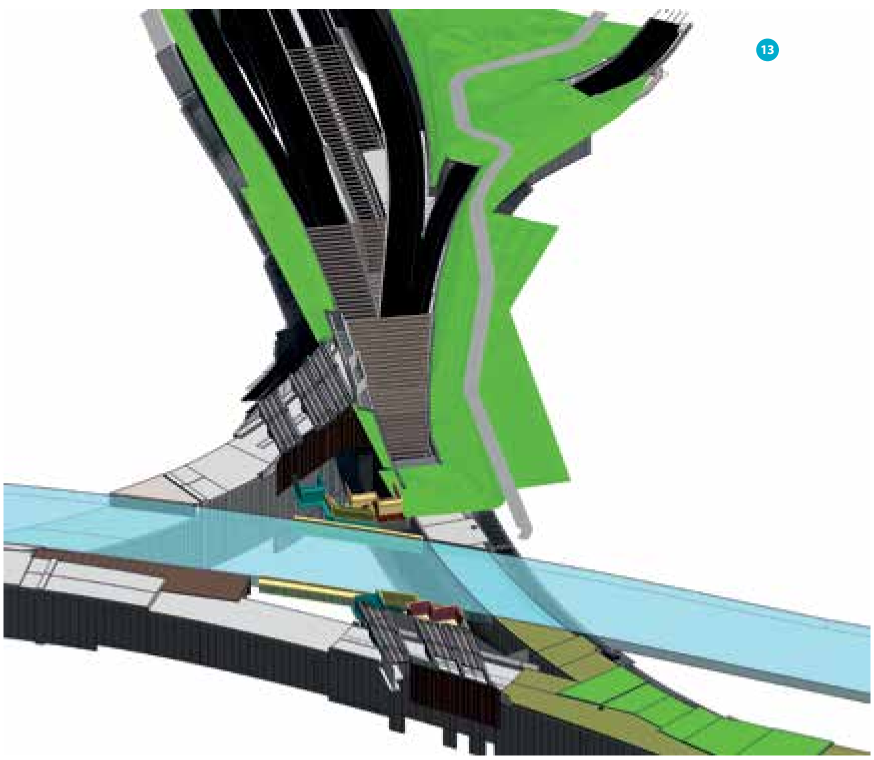
Iso-static double decked structural tunnel section

As the effects of long term swelling are strongly related to soil-structure interaction, significant differential heave rates between the external D-walls and the middle D-walls were acknowledged with extensive FE modelling (fig. 10). As this will eventually initiate unacceptable stresses in the usually adopted heavy monolithic concrete tunnel structures, a possibly unprecedented structural design is implemented by THV RoTS. Based on a risk driven design approach it was decided to use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hinges between the concrete decks and the D-walls, in order to create an iso-static tunnel structure which allows for differential heave.

Because of the application of hinges in each joint the horizontal stability of the double deck tunnel section has to be guaranteed by horizontal soil- and water pressures as well as the deep fixation of the D-walls in the Boom clay. The long-term behaviour of the Boom clay (from undrained towards drained) affects this fixation. Hence a large number variations of FE calculations were made; variations in ground conditions on the short and long term behaviour (based on the trial pit), variation in stiffness of the D-walls, asymmetric soil loadings, load combinations etc.

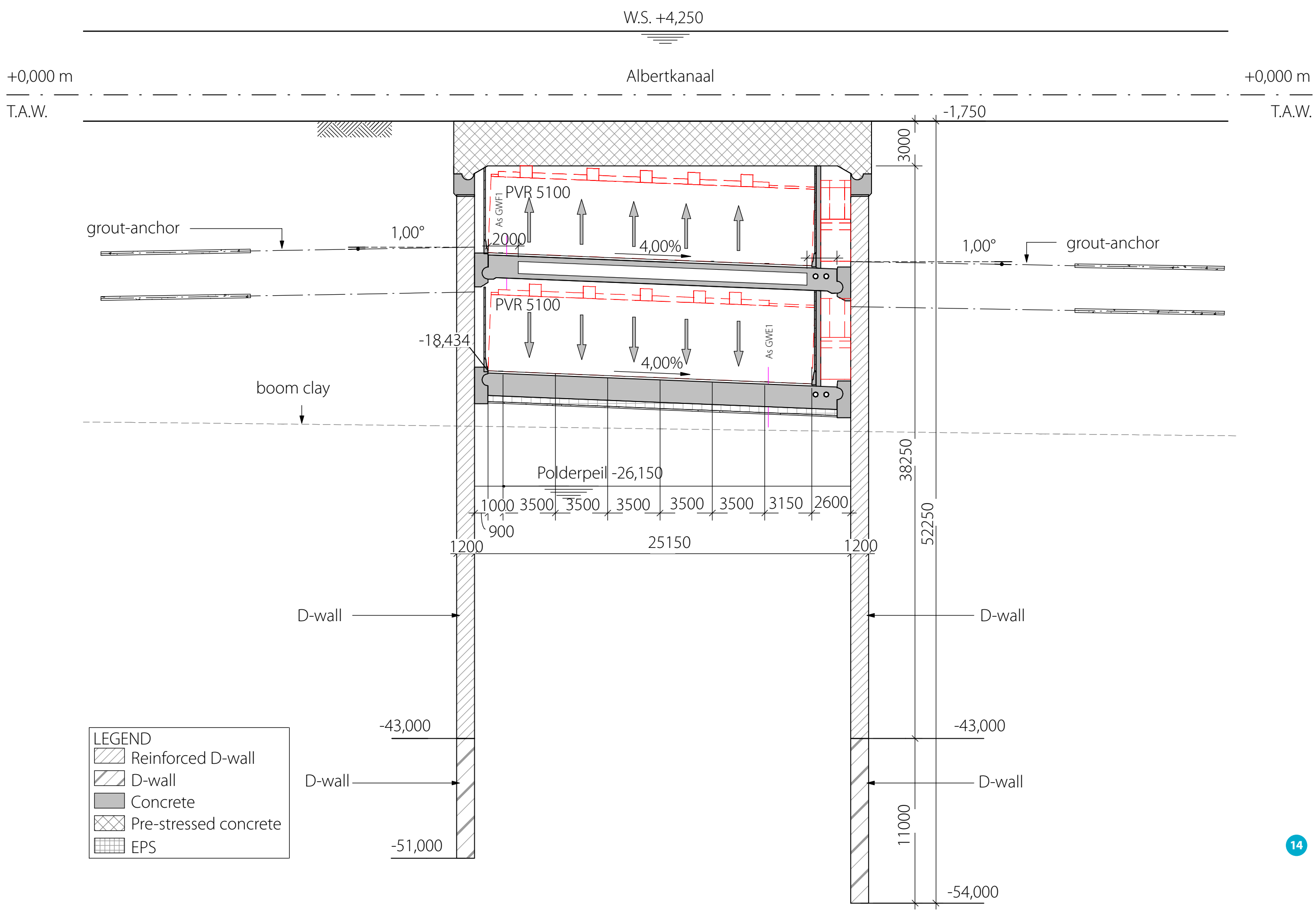
Hinge design

Based on the iso-static tunnel section, the boundary conditions for the concrete hinge design require to account for:
- Rotation due to: differential heave, deflections of the D-walls during excavation of the tunnel section, deflection of the decks due to creep and traffic loads resulting in a total, absolute rotation from 10 mrad up to 40 mrad;
- Strut forces: the normal forces in the decks vary from 1500 kN up to 7000 kN per running meter (ULS);
- Impact of geometrical imperfections during construction should be minimized;
- Functionality under extreme conditions as explosions and inundation should be guaranteed;
- Need for long term maintenance should be minimized;
- Water tightness of the hinges between the roof deck and D-walls should be assured.

Several known concrete hinge designs were considered but none of them could meet all the above requirements. Hence a customized circular cam-pocket design was developed (fig. 11). This concrete hinge design was extensively researched with 3D FE models (DIANA) (fig. 12). Although initially a full concrete hinge contact seemed feasible, in order to simulate microcracking and verify this design full-scale trial testing was needed. Finally, it was decided not to pursue this pioneering route but to introduce two steel plates with an intermediate PTFE layer in the circular cam-pocket in order to obtain a non-disputable behaviour of the hinges.

OKA tunnel

This newly developed DD C&C iso-static tunnel design is also adopted for the even more challenging OKA tunnel in the Oosterweel Link which is intersecting the Albert Canal (fig. 8 red box). This OKA tunnel will consist of an unprecedented 800 m long 5-lane double-decked tunnel, which is designed to



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accommodate all transport of dangerous goods (EU-TEN Tunnel, category A). The safety level of this tunnel and the risks involving dangerous goods transport has been extensively analysed, by means of Quantitative Risk Analyses (QRA), Computational Fluid Dynamics (CFD) and by studying structural blast loads [3]. As it was decided that the OKA tunnel should remain in a state of 'not beyond repair' in case of an extreme (LPG) explosion it was decided to adopt the concrete hinges here as well, allowing the intermediate decks to fail without damaging the water tightness of the outer D-walls. In case of such a calamity the D-walls remain supported by means of additional implemented grout anchors.

Conclusions

Challenging political, financial and geotechnical boundary conditions have led to a pioneering DD C&C iso-static hinged tunnel design to complete the Ring road R1 of Antwerp, creating a sustainable solution with estimated construction costs within the targeted budget. The final design stage is nearly completed and the contractual inception stage is entered. Meanwhile, public debate is slowly converging to a widely-supported integral transport covenant in which also the remaining 2×7 lane open cut section (fig. 2, box 6) is supposed to be covered with a tunnel roof. In anticipation of the outcome of this process this open cut section is already structurally and geometrically prepared for tunneling. The anticipated construction start of the Oosterweel Link is by early 2019. ☒

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