Guldborgsund Tunnel. Operation of tunnel and drained ramps

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ABSTRACT
The tunnel at Guldborgsund is an immersed tunnel connecting the Danish islands Lolland and Falster. The tunnel is a twin tube road tunnel. The tunnel is approximately 500 m long including portal structures, and has approx. 400 m open ramp on each side of the tunnel. The tunnel is owned and administered by the Danish Road Directorate.
The tunnel was built mid 1980's and opened to traffic in 1988. The tunnel is part of the international European route E47 connecting Copenhagen to Fehmarn. The tunnel was originally built as a 2 lane main road with one carriageway lane and one emergency lane in each tunnel tube, and in 2007 upgraded to a 4 lane highway, where the original emergency lanes were converted to carriageway lanes.
On Falster, the ramp is established in clay till deposits above chalk and on Lolland the ramp is established in sandfill above chalk as this area was used as dry dock to level -10 m during construction works. The dry dock area was refilled with sand after casting and floating the tunnel elements out.
The main water aquifer in the area is the chalk. The original groundwater lowering in the open ramps is described in NGM article 1988 by Claes Thunbo Christensen and consisted originally of approximately 50 relief wells relieving groundwater pressure from the chalk. In the open ramps on both sides of the tunnel the system of relief wells are supplemented with horizontal and deep drains for securing acceptable water levels below the road.
The article focus on the operation and maintenance works done for the last 10-15 years in order to secure the open ramps against hydraulic failure and piping, but do also include work with permissions from Danish authorities. Regeneration with hydrochloric acid and sodium dithionite has been executed, but also additional wells have been supplemented to the system.

Keywords: Immersed tunnel, groundwater lowering, chalk, uplift safety, operation.

1 PROJECT

Structure
The tunnel was designed by CNT CONSULT and built by Christiani & Nielsen in the period from mid-1980's to 1988. The tunnel consists of 2 immersed tunnel elements cast together into one monolithic structure with a total length of 470 m. In both ends dikes are established to shorten the tunnel lengths in the 1200 meter "coast to coast crossing". The dimensions of the tunnel section is approx. 9 m high and 21 m wide with 0,8 m thick concrete. In both ends portal structures are established connecting the tunnel elements to the open ramps. The portal structures consists of a 12 m high concrete structure with portal reservoir and access tunnel to relief wells in the substructure to level -10 m and with top of structure in + 2.5 m. Road entrance from the open ramp is in level - 6 m. Rambøll has been consultant in O&M activities since start of 00'ies and Per Aarsleff has delivered maintenance services to the system since 2010.

Figure 1.1. Guldborgsundtunnel. Aerial view.

An aerial view is seen in Figure 1.1.

Figure 1.2 Photo from Falster site of tunnel entrance.

Establishment of ramps

The ramps were established dry by use of pumping wells and groundwater lowering in the chalk. The system of pumping wells were in end of the construction period partly converted to relief wells and supplemented by new wells to a relief system to take care of the permanent groundwater lowering system for securing uplift safety in the open ramps.

Open ramp and Relief system

On both sides the ramps are placed in natural soil meaning that on Falster its foundation is in the natural clay till with chalk below in level -10m, and on Lolland the previous dry dock excavated to -10 m is refilled with sand and the ramp is here founded in this fill with the chalk in level -10 m below.

The chalk is the local regional water bearing aquifer with an interpreted permeability of 1 * 10^{-4} m/sec and a water level at rest a little above the water level in Guldborgsund at +0.0 m. The site investigations from GEO (former DGI) at the time of construction emphasizes that permeability might increase by depth estimated by sectional pumping tests.

In the open ramps a relief system is established in order to lower the groundwater level in the chalk and on Lolland also in the sandfill. The system is supplemented by longitudinal drains, but it is only on Lolland in the sandfill this system contributes with relevant drainage. The relief system consisted in 1988 of 7 relief wells on each side of the ramp and 10 relief wells in the bottom of the portal structure for each ramp. The wells on each side of the ramp relieved water to a longitudinal collector pipe and the wells in bottom of the portal structure relieved water directly into the portal reservoir. In total 24 wells in each ramp secured the ramp from piping and hydraulic failure. The relief system was placed in the deep part with surface between -6 and -4 m and was and are still able to secure the entire ramp. The system of wells is shown in Figure 1.3.

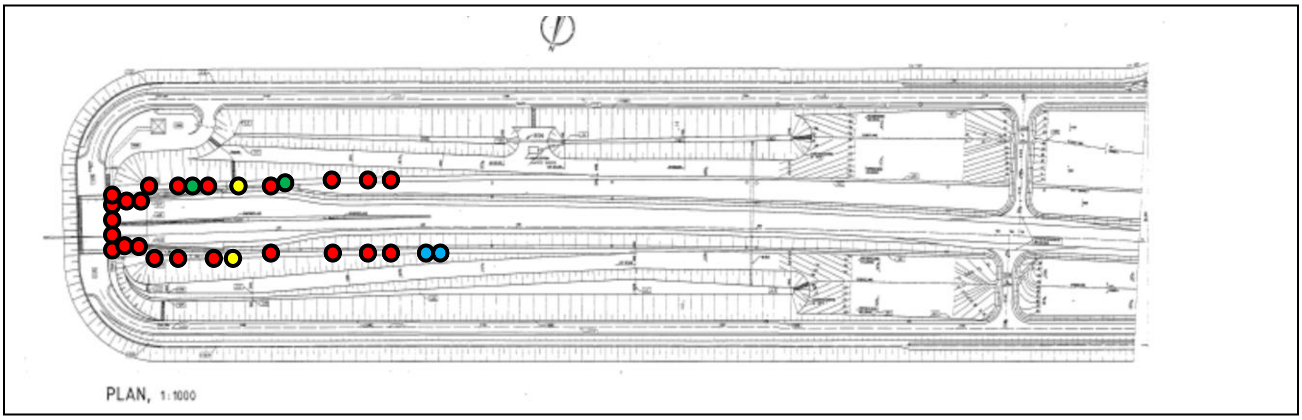

Figure 1.3 System of relief wells. Overview.

2 MAINTENANCE

Maintenance early 90s
The relief system was reconditioned early in the 90s with the conditioner Herli Rapid, but results of this is not well documented. In that process supplementary observation wells were established in order to improve monitoring of water level.

Maintenance early 00s
4 new relief wells (marked with yellow in Figure 1.3) were established in the middle of the ramps on both sides.

Extraordinary maintenance 2009
In 2009 piping was observed in a small local area in the north side of ramp on Lolland and 2 additional relief wells (marked with blue in Figure 1.3) were established.

Maintenance 2009
The monitoring results showed the need for supplementary relief wells as it was agreed with the owner that the project should be treated after EC 7 standards and corresponding partial coefficients and in high consequence class.
From 2009 maintenance also included regular reconditioning of the relief wells, which was executed with hydrochloric acid. The plan was to treat 8-10 relief wells /year in order to treat all wells within 7-10 years. The obvious risk is that wells not handled with regular intervals cannot gain effect by acid treatment.

Maintenance 2010-2014
The relief wells have been under regular treatment as 8-10 wells are being reconditioned each year. The results from capacity tests have shown significant improvements on the majority of the treated wells.
In 2010 reconditioning with sodium dithionite was also implemented as a trial to see if the effect of reconditioning could be extended.

3 RESULTS FROM MONITORING AND MAINTENANCE

Sodium dithionite treatment
Laboratory tests showed a significant improvement of added solubility of ochre in water compared to hydrochloric acid meaning that it might be possible to remove ochre sediments in the filter to a point where repeated sediments in the filters were delayed. The process from free iron Fe^{++} to Fe^{+++} is a process which improves if Fe^{+++} is already present and is delayed if Fe^{+++} is not present. The hope was, that if this treatment was introduced, the time between reconditioning could be increased and thereby keeping the relief system in good operation conditions for longer periods between reconditioning. The focus point was to reduce maintenance costs. 8 treatments were executed but after following the development of these 8 treatments over 3 years it was not possible to see a clear effect allowing for increased periods between reconditioning.

The final solvents from the treatment was sodium and SO_4, which from a discharge point was non problematic after dilution in the portal reservoir in portal structure.

Hydrochloric acid treatment
The treatment was performed and followed normal practice in Denmark after the main part of ochre was removed by capacity pumping followed by adding hydrochloric acid in a dilution of 1:20 with 24 hours of reaction time and ended with a capacity pumping, where the solvents created by the acid treatment was removed.

Very different improvements were identified, but in general improvement above 100-200 % was seen. Improvements in an selected amount of wells are shown in figure 1.4, where “specific capacity” after treatment are shown vs. “specific capacity” before treatment.

Few treatments have shown only little improvements measured in relief yields but the general effect is seen in lowering of water level in the ramp.

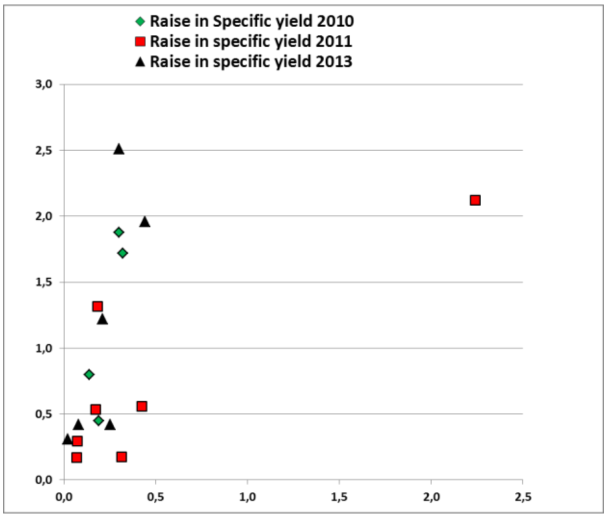

Figure 1.4 Results of acid treatment. Specific capacity after treatment vs. specific capacity before treatment. Units are m^3/hour/m lowering.

Water levels 2001-2015

Water levels in the 12 monitoring wells in the ramps are measured on a monthly basis, giving the water level in top of chalk as well as in a deeper layer of the chalk. The results from the monitoring wells in between the relief wells are used to determine the periods between acid treatments as water level after treatment are lowered around 1 m below target level and in the period up to next treatment water level rises to approximately target level.

On Lolland in the old sand filled dry dock the target level is defined as the bottom of road foundation as water level in the road bearing layer will reduce bearing capacity and reduce the lifetime for road and pavement. On Falster the target level is defined as level with uplift safety approaching 1.0 (incl. γ-values and K_{FI} value) against hydraulic failure and with upwards gradient equal to 0.6.

The spread of monitoring wells are also used to determine, which relief wells are chosen for next treatment in maintenance program.

Typical variations of water level in 2 of these wells are shown for the last 14 years in

Figure 1.5. The typical variation is a raise of water level of 3-5 cm per month. Each year 8-10 wells are chosen for acid treatment and bringing the water level down corresponding to the degeneration. Last shown drop on figure 1.4 is related to acid treatment of all 5 wells in the portal reservoir close to L1 and L2 and the drop in water level here is higher than the previous drops in water level.

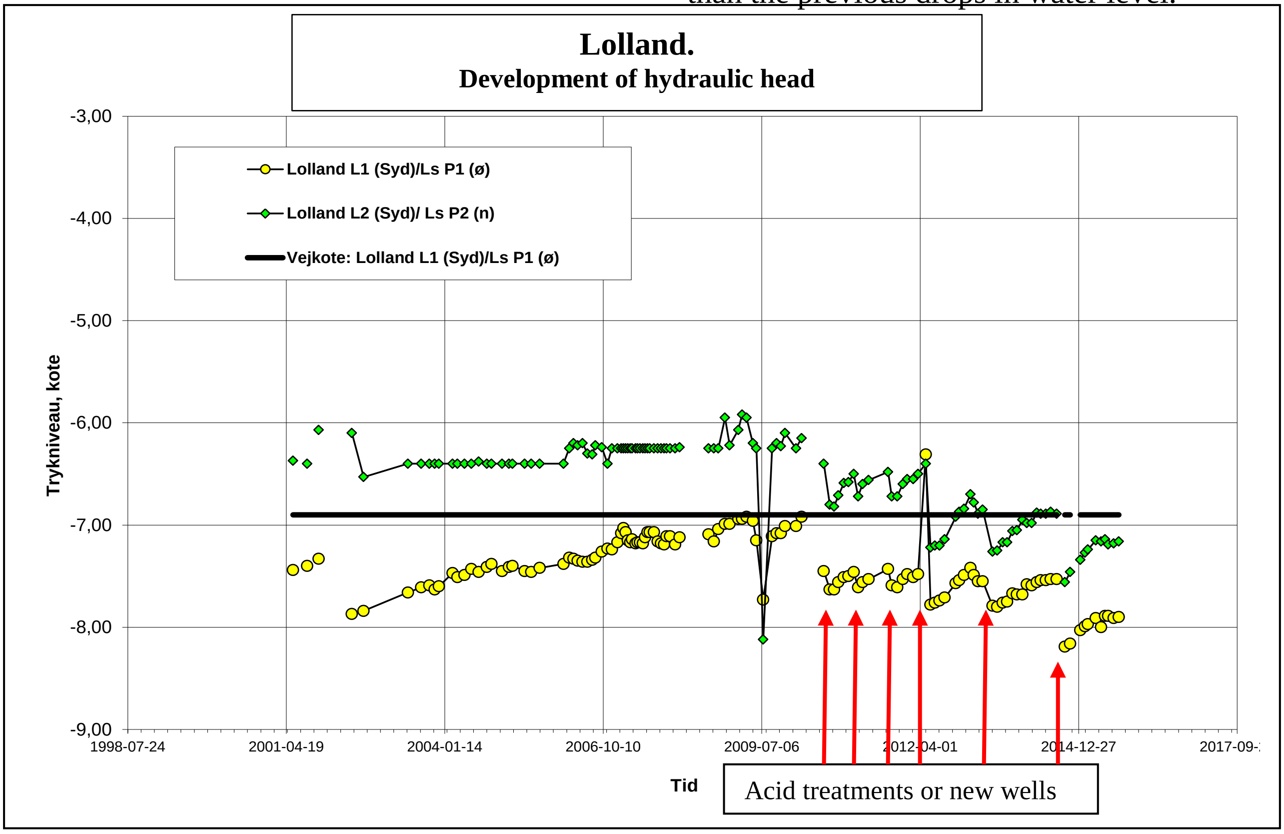

Figure 1.5 Lolland. Overview of water levels in 2 monitoring wells.

Access challenges to these wells gives reasons to take them all in one sequence instead of 1-2 each year. The yellow dots in Figure 1.5 represent water level in upper part of chalk and the green dots represent waterlevels in the chalk 5 m lower. It might not verify the presence of increasing permeability by depth, but it verifies the presents of several flow zones in the chalk. On Falster the clay till layer is present from top chalk to base of road foundation. Here it is accepted that the water level around the deepest part at the entrance to the portal structure is above surface and observation wells here are closed to avoid relief of water. The wells are sealed and are being monitored by manometer. The water level here is monitored and managed in order to have a reasonable uplift safety against uplift, but also to avoid upwards gradients above 0.6.

Relieved water yields

The groundwater relieved from the relief wells are measured manually twice a year, but only measured data on the single wells are available 6-7 years back.

There are only few data available from the initial operation phase and summarized yields from Lolland ramp are shown in Figure 1.6. It is seen that initial relief of groundwater from the wells and drains was approximately 50 m^3/hours and dropped in the period up to 2007 to a little below 15 m^3 /hour. From 2007 a more regular maintenance of the relief wells started.
As seen on Figure 1.6, the initial relief of groundwater from the wells and drains were 50 m^3/hours but are now stabilized on 25 m^3/hours. The initial yield on Falster side is not available but today this yield is also around 20-25 m^3/hour.
This relief yield achieves acceptable relief of upwards groundwater pressure on Falster side. The groundwater level on Lolland side is by the system lowered to below the bearing layers in the highway.

The increase in yields is in general related to the ongoing acid treatment of the wells, but in 2009 it was related to additional 2 wells established to handle the piping area.

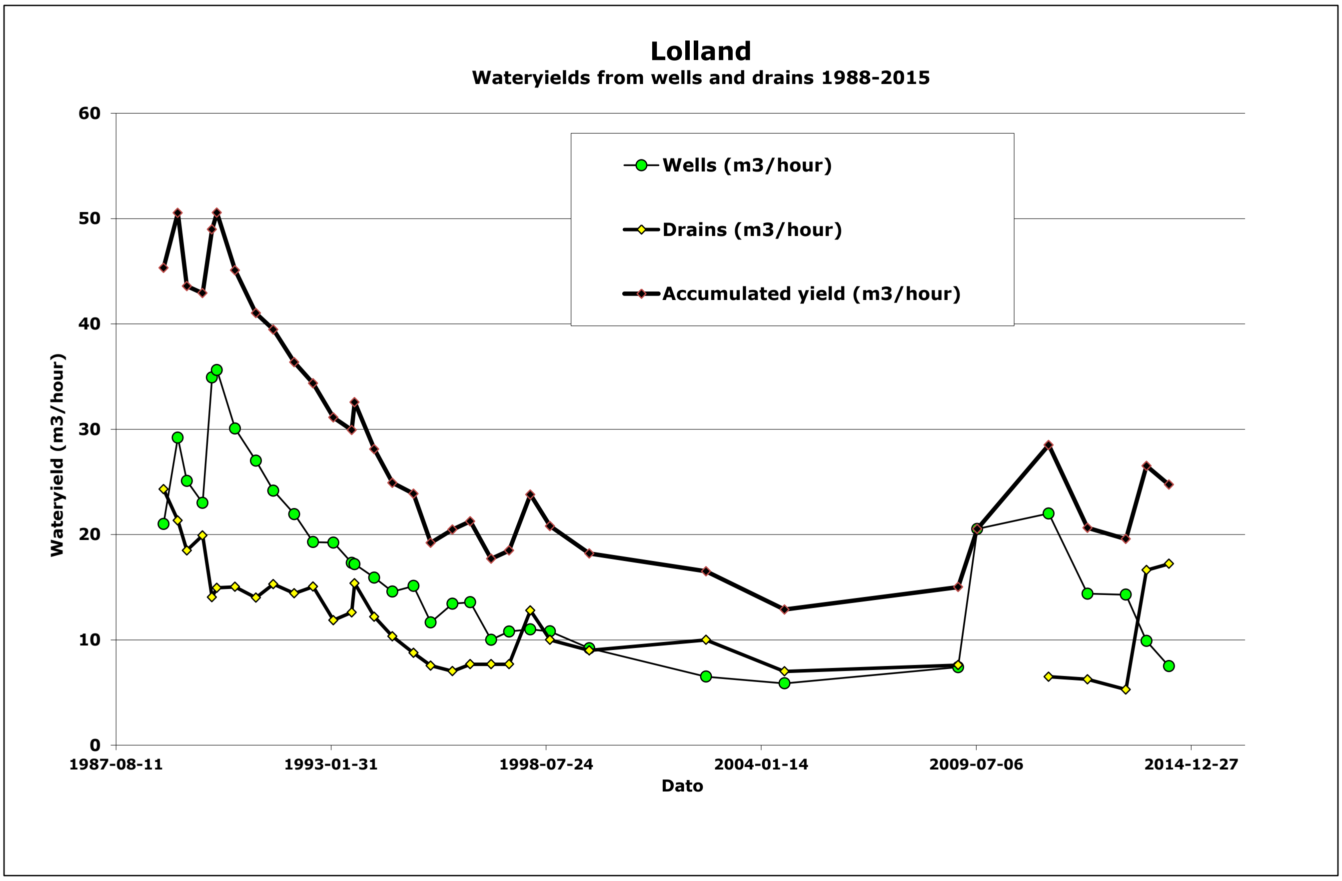

Figure 1.6 Yield measurements1988-2014

Section 4 comprises an explanation to understand, why we in 2016 can maintain acceptable water level for 25 m^3/hours relief, which required 50 m^3/hours in 1988.
Yield monitoring in single wells are ongoing twice a year and used for selecting relevant wells for reconditioning. Measurements for the period 2009 to 2015 are shown in Figure 1.7 for the relief wells on Falster North ramp.

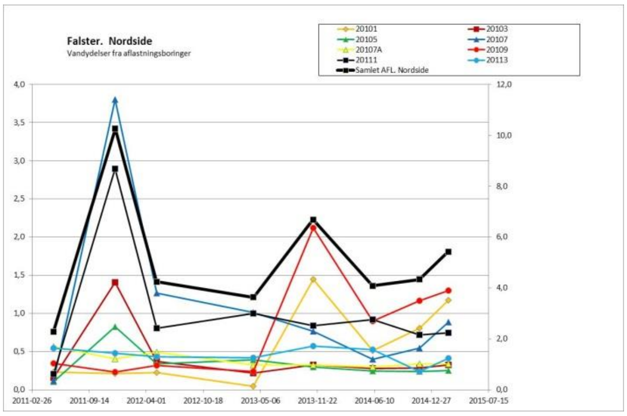

Figure 1.7 Yield measurements Falster North.

Groundwater quality
The groundwater quality at Guldborgsund chalk aquifer differs from Lolland to Falster. On Falster it is a “normal” Danish coast near groundwater quality defined as a groundwater with high salinity and an iron content of 1-2 mg/liter.
On Lolland the groundwater has a significant content of sulfur, which has led to a chemical attack on parts of the concrete structure (portal reservoir) and the relief wells (installations and concrete protective structures). To prevent concrete deteoriation ventilation has been installed in the portal reservoir on Lolland and concrete structures for relief wells have been repaired/ exchanged. On the concrete protection of the relief wells the corrosion is very visible as can be seen on the photo in Figure 1.8.

Permission
A review of all legal basis for the tunnel in 2011 made it clear that this basis had to be updated.

Figure 1.8 Installation of relief well in concrete ring on ramp at Lolland. Photo T.N. Petri.

The process ended with 3 updated permissions adapted to present operation and maintenance including

- Groundwater lowering (500.000 m^3/year)
- Establishment of new wells
- Discharge of relieved groundwater to Guldborgsund.

Well installations
During the maintenance and supervision works on site the following observations have been made related to non-satisfactory construction works.

Damage in filter screen: In one well on Lolland filtersand and blue PVC screen parts with slots were airlifted/pumped up from the well during capacity testing of the well before acid treatment. A following video inspection of the well identified a damaged screen, where a significant "handball size" big hole could be seen in bottom. Se Figure 1.9

Figure 1.9 Still picture from well video.

The well has not been mechanically treated since commissioning and it is likely that the hole has been present since establishment. So far no remedial actions have been taken as the situation seems stable in the chalk.

In one of the wells it was identified that the concrete bottom was not able to resist the pressure from the acid treatment and it was found that only a poor thin blinding layer was present in bottom of the concrete protective structure. In the bottom plate of the concrete structure a recess was made by wood allowing the well to be drilled from surface and the recess could afterwards be sealed. Apparently this was not done. Se photo in Figure 1.10.

Figure 1.10 "Bottom" of well "protection"

4 EVALUATIONS

Relief system

The relief system is well functioning, but requires monitoring as well as maintenance on a regular basis.

Groundwater quality

The presence of sulfur in the groundwater increases maintenance costs as structural parts and installations are worn down faster on Lolland than on Falster.

Monitoring

The level of monitoring seems reliable and adequate in order to plan maintenance activities consisting of acid treatments, new relief wells, monitoring wells and general refurbishment.

Relief yield from the system

The system today can be operated with acceptable water pressure below the ramps for 50% of the initial yield from 1988. It is considered that settlements have caused a reduction in the fractures in the ongoing consolidation process of the chalk.

In Figure 1.11 an overview of the increase in effective stresses are established based on groundwater lowering, dike-establishment and gravity structures. Areas marked with brown indicates stress increases above 100 kN/m2, red is 50-100 kN/m^2, orange is 25-50 kN/m^2 and yellow is below 25 kN/m^2. The figure is not 3-dimensional correct as effective stresses from dike load and gravity structures will decrease by depth due to spreading and increased stresses from the groundwater relief will maintain the full additional effective stress in the whole aquifer to an unknown depth.

Commissioning

Thorough final supervision of all works before commissioning is recommendable as significant deficiencies are registered 28 years after commissioning.

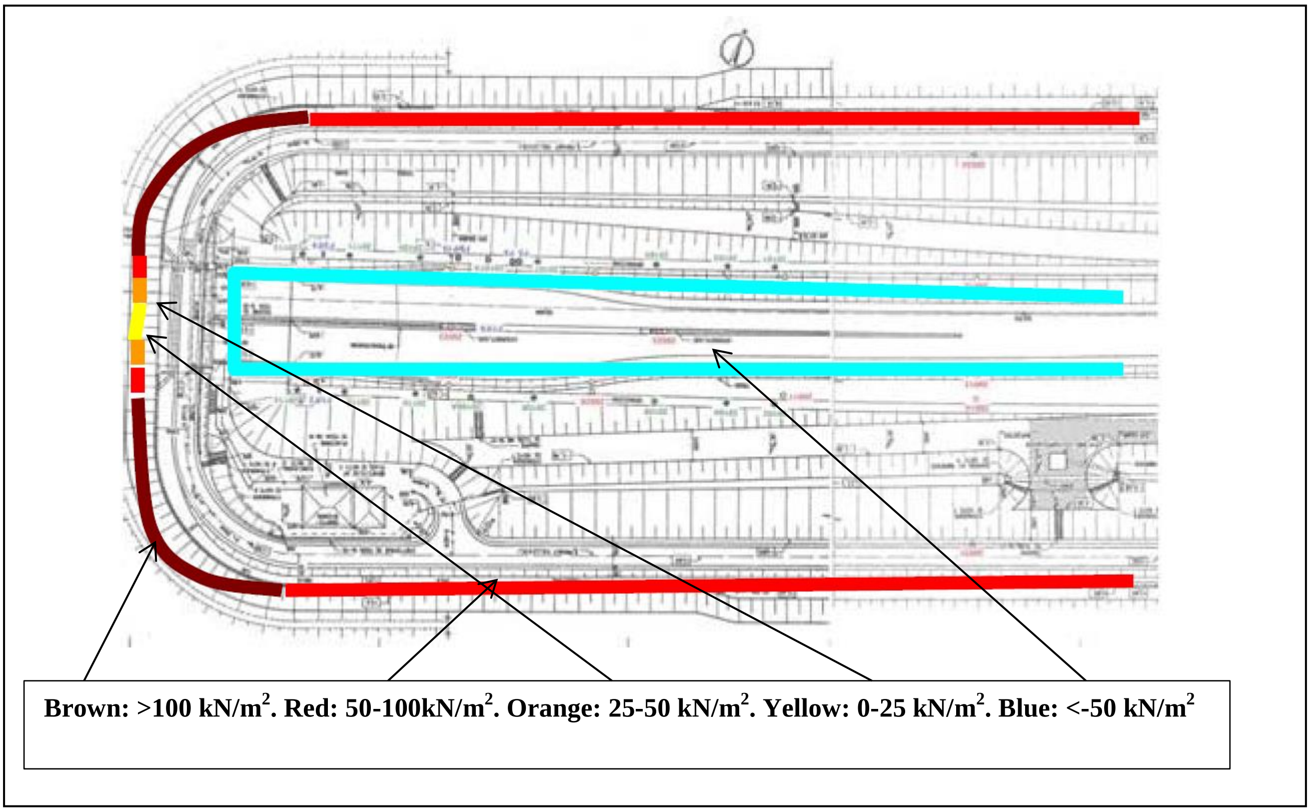

Figure 1.11 Falster overview. Estimated changes in effective stresses.