Steel – Concrete – Steel Sandwich Immersed Tunnels For Large Spans

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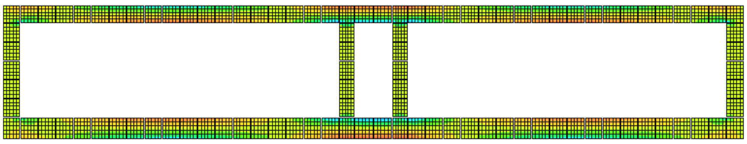
6-12-2016



Graduation committee

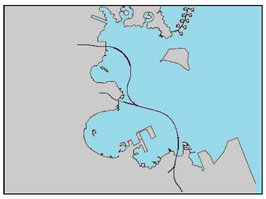
Chair	Dr. ir. K.J. Bakker	(TU Delft)
Supervisor	Prof. dr. ir. S.N. Jonkman	(TU Delft)
Supervisor	Dr. ir. drs. C.R. Braam	(TU Delft)
Supervisor	Ir. C.M.P 't Hart	(Royal HaskoningDHV)

Content

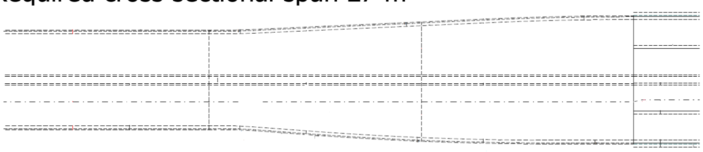
- Introduction
- Base case design
- FEA model
- Analysis of the model results
- Design optimization
- Design of tunnel variants
- Cost comparison of tunnel variants
- Conclusion and recommendations

Reference project: Sharq Crossing

- 2x2 tunnel northern connection
- 2x2 tunnel middle connection
- 2x3 tunnel southern connection



- Transition zone 2x4 + safety lanes on both sides
- Required cross sectional span 27 m



Problem description

- No throughghoing research regarding max span for reinforced concrete tunnel and SCS tunnel in transverse direction
- Structural respons of a SCS tunnel for a long span in the transverse direction
- No throughgoing research which type of tunnel is the most ideal solution for tunnels with a large span

Research objectives

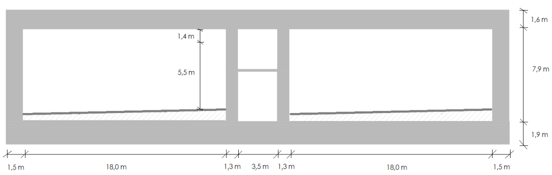
- Determining the max span for a SCS and a Reinforced concrete tunnel
- Insight in stress/strain distribution for a SCS tunnel for long span (structural respons)
- Determining the most ideal tunnel type for a tunnel with a large span in the transverse direction

Base case: Reinforced concrete tunnel (1)

- Cross-section and layout reinforcement
- Capacity calculations
- M, V, N and crack width checks
- Roof element, floor element and walls

Base case: Reinforced concrete tunnel (2)

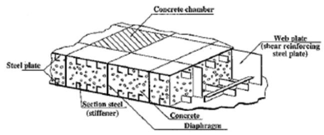
- Maximum reinforcement ratio applied
- Limiting span roof element 18 / 19 m
- Limiting span floor element 21 m



- Uplift / immersion condition fulfilled
- Span of 27 m, not feasible

Base case: SCS tunnel (1)

- What is a SCS tunnel?

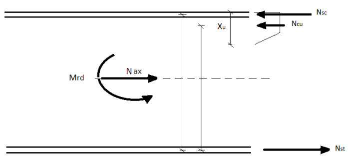


- Ideal configuration tensile and compressive elements
- No limit on, % of steel to be applied
- Double water tight
- Possibility to finish while afloat

Introduction | Base Case | FEA Model | Model Analysis | Design Optimization | Design Tunnel Variants | Conclusion

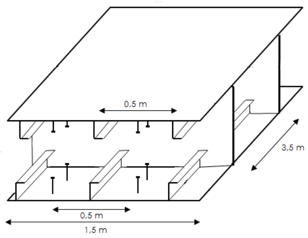
Base case: SCS tunnel (2)

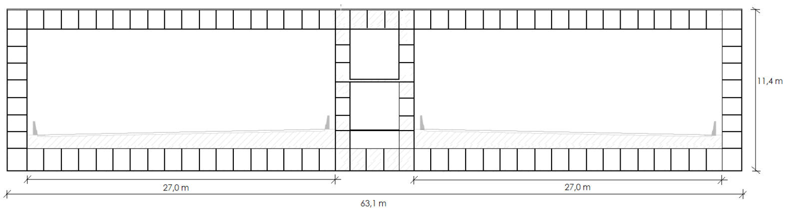
- Global dimensions
- Determining design loads
- Moment capacity and shear force capacity



Base case: SCS tunnel (3)

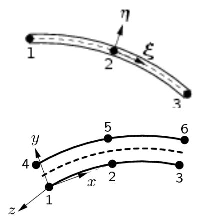
- Span of 27 m feasible for SCS tunnel
- Studs 25 Ø – h 100 mm
- Stiffener 150 x 150 x 15 mm
- Uplift / immersion condition fulfilled





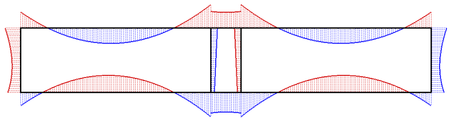
FEA simplified model (1)

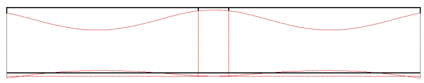
- Linear elastic 2-D analysis
- SCS element – modeled with CL9PE
- Bedding with CL12I
- c.t.c. dimensions



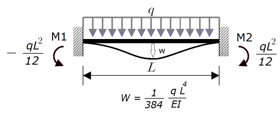
FEA simplified model (2)

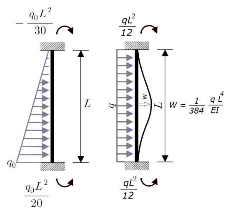
- FEA simplified model vs hand calculation





- Minor differences due to schematization

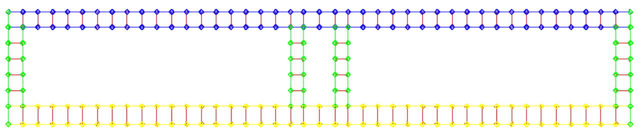




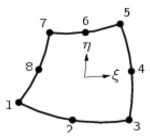
- Simplified FEA model validated

FEA detailed model (1)

- All elements modeled as built
- Except studs / stiffeners



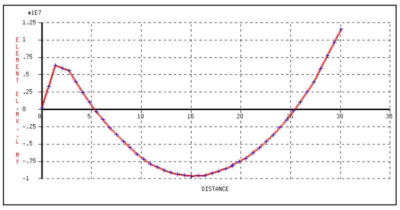
- Steel plates and diaphragm – CL9PE
- Concrete core – CQ16E
- Studs / stiffeners – CL12I

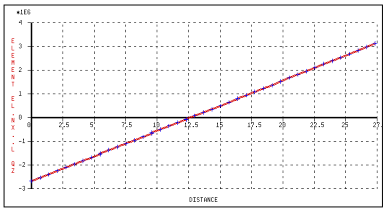


- Linear elastic analysis

FEA detailed model (2)

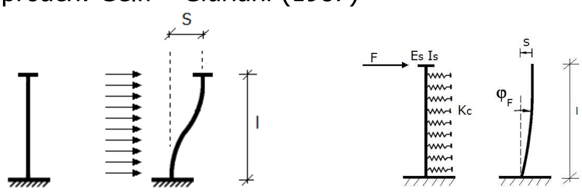
- Validation model: Simplified vs Detailed FEA model
- Minor differences
- Detailed model validated
- Design loads





Determination shear stiffness 2 approaches

- Approach: Gelfi – Giuriani (1987)

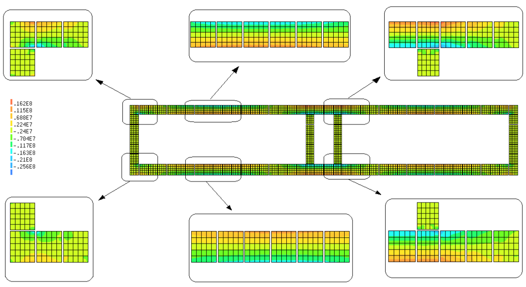


- Approach: Oehlers – Bradford (1995)

$$K = \frac{F_{max}}{d\ (\propto\ - 0{,}0017\ \times f_c)}$$

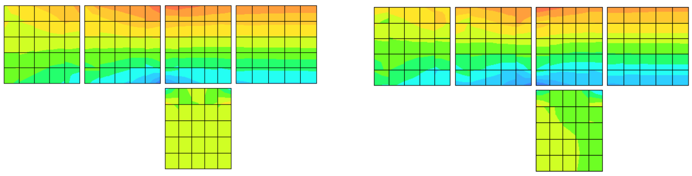
FEA detailed model stress analysis (1)

- Critical high stress / strain positions

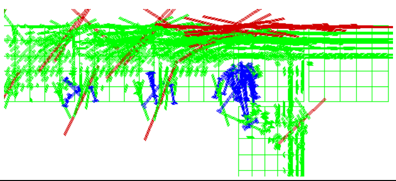


FEA detailed model stress analysis (2)

- Structural respons: concrete core (roof - inner wall)
- Stress Strain

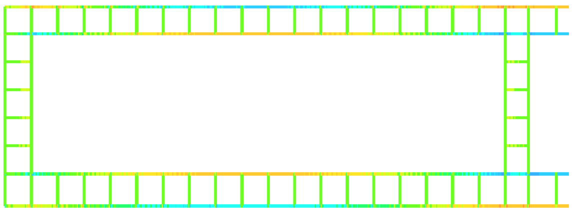


- Principal stress



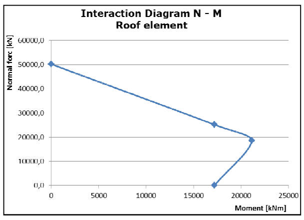
FEA detailed model stress analysis (3)

- Structural respons: steel plates



Design optimization: Interaction diagram

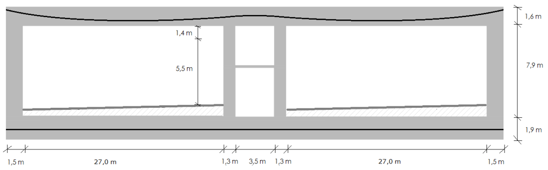
- Detailed design moment
- New moment capacity from interaction diagram



- Design optimized
- Steel reduction 21%, compared with previous design
- Concrete not reduced

Design tunnel variants: Prestressed tunnel

- Prestressed post tensioned tunnel element

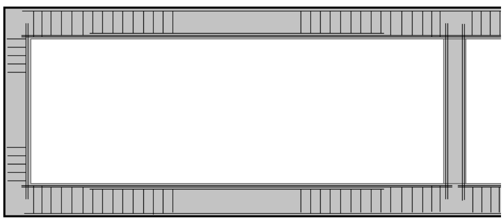


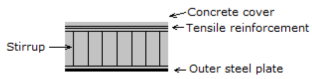
- No cracks in concrete
- Tendon anchors too large to fit
- High strength concrete required

- Transversally prestressed R.C. tunnel not feasible

Design tunnel variants: Steel shell tunnel variant 1

- Max reinforcement applied
- No concrete surface exposed to water

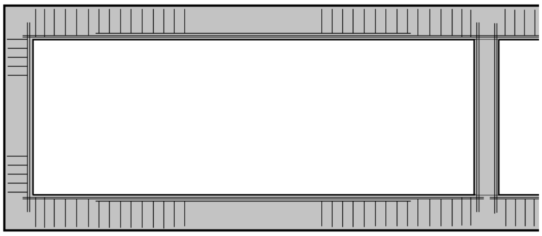


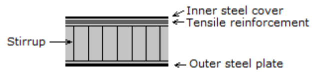


- Transverse span of 27 m feasible

Design tunnel variants: Steel shell tunnel variant 2

- Steel cover plate on the inside





- Crack width not relevant
- Reduction of reinforcement quantity

- Span 27 m feasible

Cost comparison of tunnel variants

Prestressed R.C. Tunnel	Steel Shell Tunnel variant 1	Steel Shell Tunnel variant 2	SCS Sandwich Tunnel
Not feasible	315 000 euro per m^1	351 000 euro per m^1	421 000 euro per m^1

Prices, february 2016

Conclusion (1)

- *Is a SCS sandwich immersed tunnel the most ideal solution for a tunnel with a large span in the cross direction?*

- Span up to 18 / 19 m R.C. tunnel most ideal

- Span from 19 – 28 m, steel shell tunnel ideal
  - more cost-efficient

- Span from 19 - 28 m, SCS tunnel also ideal
  - higher rest capacity M and V
  - more resistant against accidental loading (earthquake, explosion, sunken ship, erosion, sedimentation, more ductile)

- Span larger than 28 m, SCS tunnel only feasible solution

Length of span	Reinforced Concrete Tunnel	Steel Shell Tunnel	Steel Concrete Steel Sandwich Tunnel
< 19 m	**Most ideal solution**	Not ideal	Not ideal
19 – 28 m	Not feasible	**Ideal solution**	**Ideal solution**
>28 m	Not feasible	Not feasible	**Only feasible solution**

Conclusion (2)

- Structural response of SCS tunnel for large span
  - Tensile cracks
  - Only local concrete crushing and plastic state

- No effect on durability
- Reduction of shear stiffness
- Reduction of overall stiffness tunnel
- Moment redistribution

Recommendations

- Effect uneven soil settlement on SCS design
- Non-linear analysis, failure mechanisms of SCS tunnel
- Detailed analysis of structural repons of SCS tunnel on explosion / fire
- Detailed FEM analysis of steel shell tunnel for large span

Questions?

Extra Slides

Steel – Concrete – Steel Sandwich Immersed Tunnels For Large Spans

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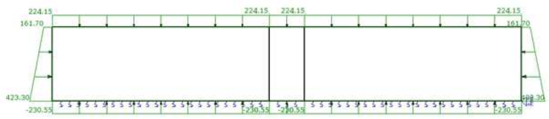
30-8-2016

Base case: Reinforced concrete tunnel

- Global dimensions
- Loading on the structure



- Determining the design loads M, V and N-force