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ANALYSIS & DESIGN OF A CUT & COVER TUNNEL

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ABSTRACT:
This paper discusses the analysis and design of an in-situ tunnel structures constructed of cast in-situ concrete without an external waterproofing membrane. The structures are cast within a temporary trench excavated in the land reclamation area. The tunnel cross section under consideration provides five tubes, one for road traffic in each direction, one for rail traffic in each direction and one for a service gallery. The internal dimensions of the road tubes, gallery structures are defined in accordance with the road alignment. The internal dimensions of the rail tubes are defined in accordance with the rail alignment. The CCT structures are reinforced concrete structures cast in-situ within an open dewatered construction pit. The segments are equipped with watertight movement joints, which allow the segments to move in the longitudinal direction and rotate about the vertical and horizontal axis (but not about the longitudinal axis). The segment joints resist by shear keys vertical and torsional movements. Each segment is constructed by through-going casting joints in the structure. The base slab will typically be cast first, followed by the walls and the roof slab. In the longitudinal direction loads are transferred across segment joints via shear connections. The preferred connection is via shear keys in the walls. The CCT structures are required to resist the loading effects of an accidental flood in terms of fulfilling requirements for clearance profiles, vertical deformations, and road drainage functionality. The structure has been verified for permanent loads, live loads, natural loads, accidental loads, loads during execution, SLS and ULS load combinations plus project specific load combinations. The segments are assumed to be cast at a minimum temperature of +5.0°C during winter and a maximum temperature of +25.0°C during summer. In this paper, considering all above project requirement the CCT structure is analyzed by Autodesk robot software & the complete design has been done which cover all aspects like SLS, ULS, extreme event design along with fire, fatigue, robustness check, STM at frame corners. Also automated excel sheet is developed for quick design of the structure considering all design checks.

1. INTRODUCTION

1.1. Description of structure

The Cut & cover Tunnel considered in the case study is having cross section of ~42 m wide and 9m high.

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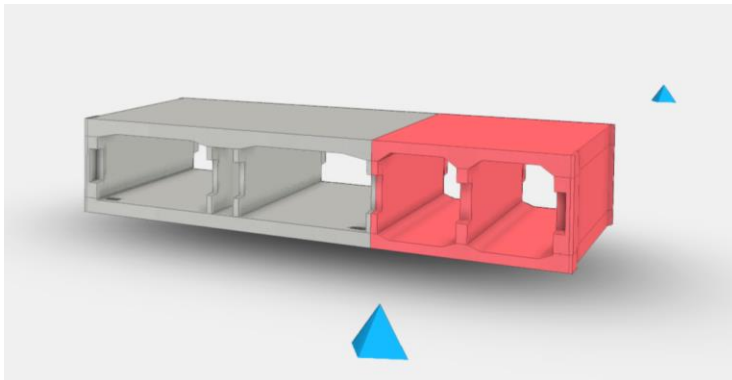

Fig. 1 – Typical Cross Section, CCT

The cross section is divided into the following structural parts. There is structural and reinforcement continuity between the adjoining structural parts.

- Base slab
- Roof slab
- External wall, roadside
- Central gallery walls (2 nos.)
- Internal wall between road tube and rail tube
- Internal wall between rail tubes
- External wall, rail side

1.2. Background

The CCT structure under consideration are reinforced concrete structures cast in-situ within an open dewatered construction pit. The structure is equipped with watertight movement joints, which allow the tunnel to move in the longitudinal direction and rotate about the vertical and horizontal axis (but not about the longitudinal axis). The joints resist by shear keys vertical and torsional movements. Each CCT structure is constructed by through-going casting joints in the structure. The base slab will typically be cast first, followed by the walls and the roof slab. In the longitudinal direction loads are transferred across joints via shear connections. The preferred connection is via shear keys in the walls.

Since the tunnel is near to the sea, following water levels are considered in the design.

(a) HHWL (10.000 years return) = + 3.45
(b) HWL (100 years return) = +2.11
(c) LLWL (10.000 years return) = -3.03
(d) LWL (100 years return) = -1.98
(e) MSL = + 0.0
(f) Global Warming water Level = MSL+1.5

The static structural systems of the CCT section have mostly a 2D behavior in the direction transversal to the alignment and for that reason the analysis can be carried out with 2D FEM analysis. The 2D FEM models have a length of 1.0 m to design the structures per running meter in the longitudinal direction. The CCT structures are

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designed for a design life of 120 years as a part of permanent works. The internal surfaces of the load bearing structure road and rail tubes are protected in CCT by passive fire protection materials. Remaining areas are unprotected. The fire resistance of all load bearing structures is verified in both cases. The design parameters are as mentioned below.

Structure	Structural members	Minimium (Nominal) concrete cover	Maximum crack width
Cut & Cover Tunnel	Outside	75 (85)	0.20
	Inside rail traffic tubes, roof inside road traffic tubes, inside gallery walls.	50 (60)	0.20
	Inside road traffic tubes: walls and bottom slab	75 (85)	0.20

The structure is subjected to cyclic loading from traffic loads on the railway tube and the roadway tubes. Both reinforcement and concrete are verified for fatigue condition.

2. Design Approach

The scope of the topic is to present the structural behavior of the CCT, under a selected set of conditions, that are expected to give a representation of the entire CCT. The following effects are analyzed:

- Transverse crack development under service limit states
- Concrete stresses under service limit states
- Watertightness
- Minimum reinforcement
- Shear and flexural strength under Ultimate limit states including accidental design situations.
- Structural deflection
- Fire – for unprotected area

The structure is required to be designed for a maximum concrete compression under SLS-characteristic loading, to not exceed a stress limit of $\sigma_c \leq k_1 f_{ck} = 24$MPa.

The deflection of the roof slab & walls must be limited to span/250.

In the below table a summary of different water & backfill levels considered in the design of the CCT structure is presented.

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Finished ground level (m)	Roof level (m)	Additional backfill above finished ground level (m)	Depth of backfill considered as SIDL (m)	Depth of backfill on top of roof slab excluding SIDL portion (m)	Total depth of backfill on top of roof (m)
4.5	-2.68	1	2	6.18	8.18

The traffic load and rail load are considered for CCT structure. Although the live loads will give favorable effects they also induce bottom face Bending moments in the slab. At rail sections rail traffic loads of LM71 and SW/2 are considered and for road sections Load Model 1 and Load Model 2 is applied as traffic loads. For accidental cases a vehicle impact load of 500kN at a height of 1.25m from road surface and a train impact load of 1000 kN at a height of 1.8m from rail level is considered.

The design of frame corners are verified with STM method. Strut-and-tie models (STM) are the chosen method used for the global design of these D-regions. STMs are suitable for design for load carrying capacity requirements (ULS), since it is based on the lower-bound theorem of Plasticity and yields lower-bound (conservative) solutions provided that sufficient ductility is assigned. However, it is noted that Eurocode clause 5.6.4(2) in 0 allows a STM to be used for SLS by ensuring that load path envisaged does not deviate significantly from that in accordance with linear elastic stress distribution.

2.1 Strength requirements applied for strut and tie analysis

The requirements applied for the analysis in this report has been summarized below.

Materials:

Concrete: C40/50

$$f_{cd} = \frac{40MPa}{1.45} = 27.6\ MPa$$

Reinforcement: K, 500, Class B.

$$f_{yd} = \frac{500MPa}{1.20} = 416.7MPa$$

ULS Strut-and-tie requirements:

Struts

For a strut which contributes to the shear capacity, in this report the inclined struts, the strut capacity is:

$$\sigma_{Rd,max} = \nu_v f_{cd} = \left(0.7 - \frac{40MPa}{200\ MPa}\right) \cdot 27.6MPa = 0.5 \cdot 27.6MPa = 13.8\ MPa$$

For other struts it is conservatively chosen to apply:

$$\sigma_{Rd,max} = \nu_n f_{cd} = 20.3MPa$$

Nodes

$$\sigma_{Rd,max} = \nu f_{cd} = 0.8 f_{cd} = 22.1MPa$$

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Thus, the strut strength in all cases is more severe than the strength of the nodes and thus governing the design.
Ties

$$\sigma_{Rd,max} = f_{yd} = 416.7MPa$$

SLS Strut-and-tie requirements: (cf. section 8.7.2 in **Error! Reference source not found.**)
This limitation of the reinforcement stress is set to $\sigma_{SLS,max} = 200MPa$.

2.2 Modelling considerations

The transverse behaviour is analysed using a frame model that represents the behaviour of a 1.00m section of the standard element. The analysis carried out is elastic, that is, uncracked properties were used. The base slab is supported in vertical direction as well as in the horizontal transverse direction. The base slab is supported in horizontal direction with the supports at wall locations. The support of the base slab in the transverse direction is mainly for model stability and a spring stiffness of 60000 kN/m2 is used.
To verify robustness of individual members, specifically the internal walls, a plastic hinge model is utilized to identify the required plastic moment capacity needed to maintain structural integrity and resist the development of a local mechanism. This is done from a virtual work principle.
The following loads are considered in the 2D model.

- Permanent loads:
- Self-weight of structural concrete
- Ballast concrete
- Rail Track Slab and Road pavement
- Water pressure (MSL and Global Warming)
- Vertical Friction
- Structural Backfill / Surrounding Soil
- Imposed deformation.
- water proofing, surfacing & other coating.
- Shear key loads
- Variable and transient loads:
- Rail traffic
- Road traffic
- Load on earth Surfaces
- Aerodynamic effect
- variable loads in service gallery
- Natural loads:
- Water level variation (HWL, LWL)
- Temperature gradient, summer
- Temperature gradient, winter
- Snow Load
- Ice Loads-Pile up
- Accidental loads:

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- Vehicle Impact
- Train Impact
- Extreme Water Level (HHWL)
- Explosion Load (Internal Walls)
- Explosion Load (Road / Rail Tube)
- Flooded Tunnel
- seismic load

Following types of load combinations are used in the analysis of the structure.

1. SLS Frequent
2. SLS Characteristic
3. SLS Quasi-permanent
4. ULS cases
5. ALS cases

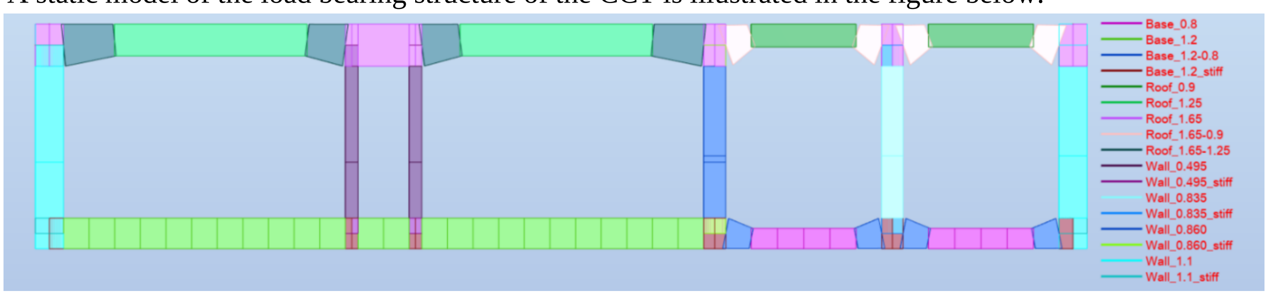
The design of the elements are carried out based on the criteria mentioned above.

2.3. Codes and Standards

1. EN-1992-1-1 "Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings"
1. EN-1992-1-1 "Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design"

3. Modelling Philosophy

A static model of the load bearing structure of the CCT is illustrated in the figure below.



2D FEM model, CCT

The FEM model is constituted by beam elements located at the centre of the slabs and walls with rigid connections between walls and slabs as highlighted in above Figure. The base slab is supported by vertical elastic springs. The thickness of the beams varies at the locations of the chamfers in the road and rail tubes. However, the chamfers at the base slab in the rail tubes are modelled with a constant thickness.

The vertical support is modelled as springs applied to the bars/shells of the base slab. Unidirectional horizontal spring supports on the walls are omitted, Since the loads at each side of the tunnel are close to balancing each other. Basically, only a different surcharge and an upper 1.0 m of backfill on one side of the tunnel can result in an unbalanced load. This would normally result in additional forces on the opposite external wall due to the reaction from the soil but due to the structure transversal stiffness and the relatively small value of the unbalanced loads this effect can be disregarded. The unbalanced load is transferred to the base slab as friction.

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The verifications of CCT are carried out based on the various loading conditions & geometry. The worst set of loadings is considered over each designed section. Various Loads & load combinations are applied on the model as mentioned above.

3.1. Material Properties

The material properties used in the 2D models are shown in the following figures.

	E (MPa)	G (MPa)	NI	LX (1/°C)	RO (kN/m3)	Re (MPa)
	35000.00	14583.33	0.2	0.00	25.0	40.00

Material properties – short term

	E (MPa)	RO (kN/m3)	Re (MPa)	G (MPa)	NI	LX (1/°C)
	15086	25	40	6286	0	0.00

Material properties – long term

Reinforcing steel is of grade 500 with minimum yield strength (fy) of 500 MPa. Modulus of elasticity of steel (Es) is 200 000 MPa.

3.2. Tunnel Analysis & Design – Step by step method

The design and analysis were done according to the following steps.

STEP 1: The uplift check is performed 1st to see whether the geometry of tunnel is adequate to resist the very high uplift force since the water level are at a very level near to the sea.

STEP 2: As mentioned in the above sections the geometry of robot model is prepared as per the clients requirement.

STEP 3: All the load cases are applied in the model considering different water levels, earth pressure are applied with respect to water levels, traffic loads are applied in all road & rail tubes along with impact & aerodynamic load, shear key loads are applied for the differential settlement between two segments & the ice pile up load. Total no. of load cases applied in the model is 98.

STEP 4: Load combinations are applied in the models considering the factor from EN-1992-1-1. Around 4000 load combinations are applied considering several worst set of load cases to get the worst possible result.

STEP 5: The soil along the length of tunnel is varying a lot. Hence 40 robot models are prepared for different soil properties & a sensitivity analysis is done to find out the critical cases.

STEP 6: For the envelope of all these load combinations the design of structure is performed by an automated excel sheet for both service cases & strength & accidental cases. The crack width has been checked for frequent load combinations. The deflection & water tightness (by keeping the neutral axis

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depth below 250mm) of the structure is checked for the quasi-permanent combinations & the stress in concrete & steel is verified for the characteristic combinations. For the reinforcement of all the elements the most governing case is the crack width check. All the elements are checked in ULS & accidental cases as well. Accidental cases considers the effect due to seismic as well. Shear check of all elements are done with the ULS & accidental load combinations.

STEP 7: The gallery walls are not coated with passive fire protection material. So the fire check has been done the gallery walls to see the reinforcement provided is sufficient. The fire check has been done with the provisions given in EN- 1992-1-1, part 1-2. ISO834 curve is used in the verification.

STEP 8: A separate model is prepared for the fatigue verification considering the provision of EN-1992-1-1. The fatigue verification is carried out for all possible traffic loading conditions.

STEP 9: For all the corners & T junction between walls & slab with the forces from robot model, strut & tie model is prepared in CAST software & checked. The development length of the bars are increased because of the check.

STEP 10: The utilization ratio is checked at all lap locations in the structure.

The design procedure followed for the reinforcement check is shown below.

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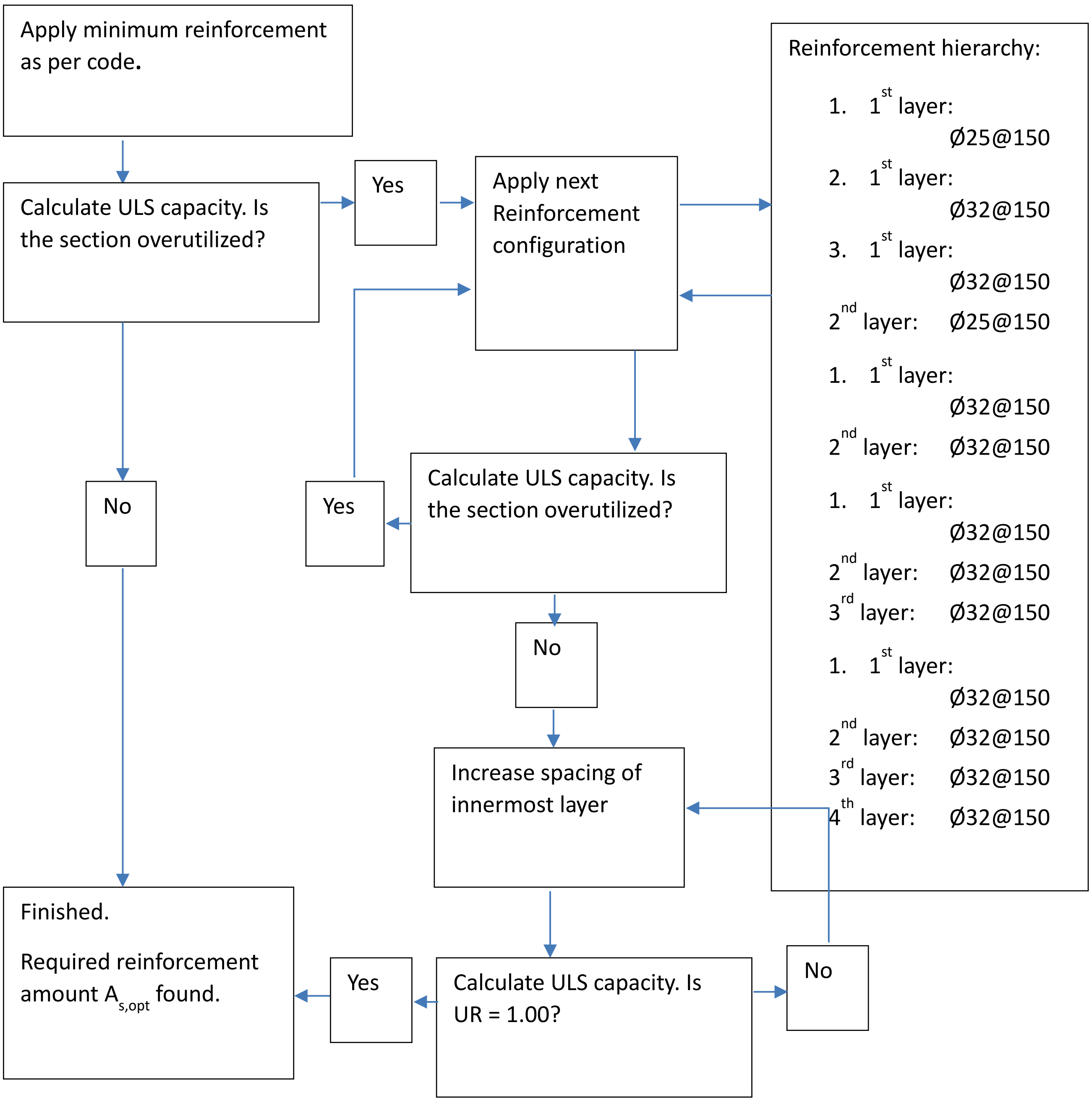

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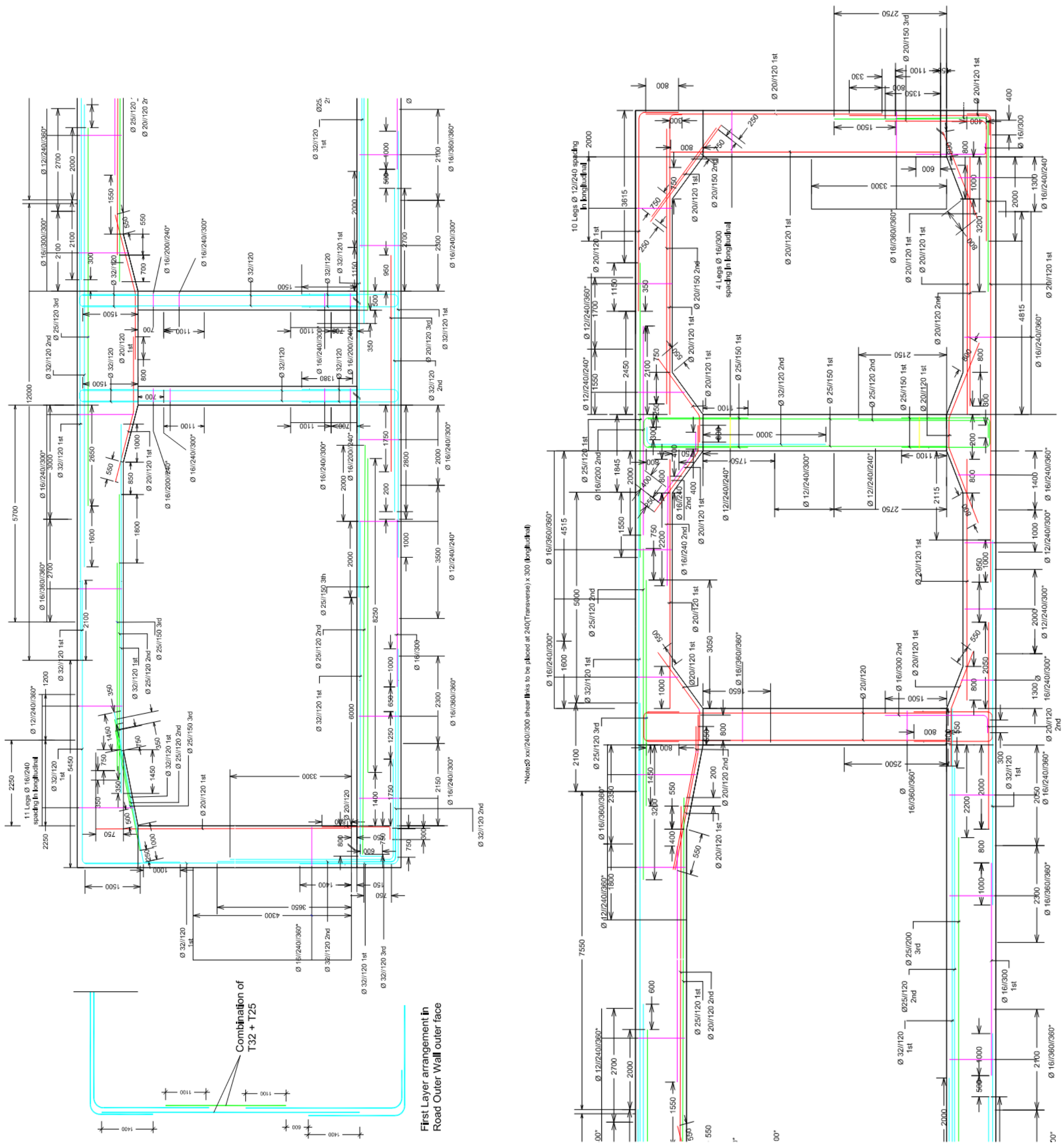

Cut-and-cover Tunnel Section reinforcement details

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4. Conclusion

The cut-and-cover tunnels is designed to meet the traffic requirement for 100- years. For the analysis of a tunnel near sea, as discussed above water levels should be considered very accurately based on the hydrological survey. The soil properties is to be considered very carefully for a site near to seashore. As discussed above 40 cases are analyzed to find out the critical case for design. Another important parameter is to check the structure for water tightness. Since there is no external water proofing membrane, all the segment joints need to be checked carefully for the compression zone depth. The water stopper should be placed within the compression zone of the section.

The governing load cases for finalizing the reinforcement of the cut & cover tunnel is the soil pressure & water pressure applied on the structure. Special attention required for finalizing the friction angle for calculating horizontal earth pressure & friction.

5. Acknowledgements

The authors would like to thank Professor Mirza Amir Baig, for his advice and guidance during the preparation of this paper.

6. References

EN-1992-1-1 "Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings“
EN-1992-1-1 "Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design“