Structural Design Criteria & Design Loads on Delhi Metro Rail and Checking of Safety of Radial Joints in Tunnel Lining Segments

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Abstract- The authors have checked the Design Criteria & Design Loads being adopted in Delhi Metro Rail and have also checked the safety of Radial Bolts used in tunnel lining segment by DMRC. The research paper thus shall help in detailing the design criteria & design loads in the most successful and time bound Metro Rail work being executed by DMRC in NCR Region comprising of New Delhi/Old Delhi and surrounding areas of UP & Haryana states. The Delhi Metro Rail network is a masterpiece and a landmark civil work in India and matches with all International standards and practices adopted to suit local conditions. All other Metro Rail networks in India are following the knowledge and experience of Delhi Metro Rail as the main guiding factor. Further, in this research paper the safety of most important Radial Bolts being used in Reinforced Cement Concrete segments is checked in both radial and circumferential directions against the moment and axial shear force at the two critical points, i.e. at the Crown and at the Springing, in the Circular tunnel lining segments. In detailed calculations, the design of radial bolts is found to be safe from International Standards and thus through this paper, the authors emphasize the importance of checking of safe bolt design in tunnel lining segment along with the design criteria and design loads.

Index Terms- — Bursting Check of Radial Joints in Tunnel, Design Criteria for Tunnel, Design Loads for Tunnel, Design of Radial Joints in Tunnel, , Joints in Tunnel Lining Segments.

1. INTRODUCTION

The Delhi Metro Rail Corporation(DMRC) has successfully completed Phase I and Phase II of Metro Rail network and presently Phase III works are in advanced stage of execution in New Delhi/Old Delhi/Gurgaon/Ghaziabad/Faridabad in NCR Region in India. Delhi Metro Rail Corporation has followed standard design parameters given below:

2. Design Parameters

Following are the major Design parameters while proceeding to plan, analyze and design the Metro Rail Underground Tunnels:

i) Characteristics of rock/soil mass and collection of engineering geological data-base from surface exposures and boreholes.
ii) Rock mass/soil classification and identification of potential failure modes.
iii) Structurally controlled and gravity driven failures and Stress induced, gravity assisted failures.
iv)Evaluation of static and dynamic possible failure modes.
v) Determination of in situ stress field in surrounding rock/soil mass.
vi) Checking of shear strength to potential failure surface.
vii) Calculation of factor of safety or risk of potential failures.
viii) Analysis of size of overstress zones around excavations
ix) Determination of support requirements.
x) Non-linear support-interaction analysis to design support.
xi) Design of support, taking into account excavation sequences availability of materials and cost effectiveness of the design.
xii) Installation of support with strict quality control to ensure correct bolt and cable lengths, anchoring, tensioning and grouting, and effective Shotcreting as required.
xiii) Monitoring of excavation and support behaviour to validate design and to permit modifications of future designs

3. Design Methods

There are three main categories of Design methods of Metro Rail Tunnel Linings

3.1 Direct Loading Method

In this method, the load is calculated based on the rock/soil depth on the tunnel using the finite element method. This load is independent of rock/soil-structure proportional stiffness. In this method, restrain effects of the rock/soil around the structure can be modelled by Winkler springs (compression only).
In cut and cover parts, considering the whole rock/soil weight on the tunnel crest – this is a realistic method to determine the internal forces on the tunnel.

3.2 Rock/Soil-Structure Interaction Method

In this method, the effect of rock/soil-structure proportional stiffness is taken into account to determine the internal forces of the structure. In order to determine the erection loads of the structural components, it is necessary to consider the rock/soil structure proportional stiffness plus the order and succession of the construction. To achieve, Convergence Confinement Method (CCM) or Numerical Methods (NM) or Finite Element Method (FEM) is used, with the limitations, advantages and applicability of each method is taken into account.

3.3 Fundamentals of Seismic Analysis

Effects of Ground motion on the tunnel during the earthquake is generally categorized into the following three classes:
a) Longitudinal Bending
b) Compression-Extension
c) Warping (In-Plane deformation of the structure section - Ovaling)

The mobilized strains in the structure due to longitudinal bending and compression extension are usually analyzed on the model of Beam on Elastic Bed at which the equivalent linear or non-linear springs must be considered. However, it is easy to decrease the longitudinal strains by using structural joints along the tunnel. In order to calculate the structural internal forces due to the ground shear displacements which cause ovaling in the structure, Seismic Intensity Method or Rock/Soil-Structure Interaction Method by using time history or displacement methods such as Response Displacement Method can be employed. The effects of Rock/soil-structure proportional stiffness around the tunnel must be taken into account anyway.

4. Design Load Conditions

Design load conditions considered while constructing Metro Rail Tunnels drilled by using NATM (New Austrian Tunnelling Methods) or TBM (Tunnel Boring Machine).
It is worth mentioning that in underground tunnels which are drilled using NATM method, the retaining system to control the tunnel stability comprises two stages of primary covering and final covering. The load distribution assumption between these two parts is highly effective in the design procedure.
Considering the special constructional conditions in this country plus the inaccuracies, it must be tried to make the primary covering that bear the erection loads alone as much as possible and avoid using the final covering capacity for that, otherwise it would be necessary to construct the final covering with a little distance from the primary covering to make sure that the primary covering is not supposed to bear the external loads singly for a long time. Thus, the primary covering will be designed for the erection loads and the final covering will be designed for the other loads on the tunnel.

4.1 Design loads considered in Metro Tunnels Lining

i) Dynamic forces due to earthquake
ii) Loads due to strength loss of the primary covering after a long term loads due to the probable saturation of the soil mass in NATM method
iii) Live loads due to the on ground traffic
iv) Live load due to the train movement, if applicable.
v) Dead load on Tunnels
vi) Ground pressure (soil/rock) surrounding tunnel
vii) Water pressure

4.2 Tunnel Structure Dead Load

Dead Load on Tunnel comprises the vertical load due to the tunnel weight which is distributed along the structure middle axis.

4.3 Ground Pressure (Soil or rock surrounding Tunnel)

Considering the soil/rock mass geo-mechanical properties along with the path, any method of direct loading or rock/soil-structure interaction can be employed to calculate the soil pressure. In cut and cover parts, all the soil/rock weight is applied to the structure in which lateral pressure will be calculated based son the tunnel walls displacements toward the side soil/rock mass and with respect to the lateral reaction coefficient of the soil. In other parts, which are constructed in underground methods, loading for primary structure must be determined considering the order of construction stages by taking the rock/soil-structure interaction into account.

4.4 Water Pressure

In case the underground water table is high with respect to the tunnel floor, the hydrostatic water pressure contribution must be considered to see the effect of water load on tunnel

4.5 Traffic/Vehicle Loads/ Train Loads

On ground vehicle loads/ train loads must be considered along with the grade level according to Indian Code of Practice for Bridge Loading. Besides the mentioned load, tunnels must be designed for a uniform load of 24 kN/m² on the road level separately. This uniform load should include the impact coefficient.

4.6 Seismic Loads

Considering the seismic danger in the project area as Delhi falls under Seismic Zone IV, the tunnel needs to be designed in a way such that both primary cover and the final cover are able to bear static and seismic loads simultaneously with the proper safety factors. In order to determine the seismic loads, soil-structure interaction must be considered along with the stiffness proportions between the structure and soil/rock.

5 Design of Radial Joints in Underground Tunnel Segments of Metro Rail

5.1 Safety Check of Radial Joints

The safety of Radial joints (flat type) being used in Delhi Metro Rail is required to be checked. At the joints of tunnel segments, bolts are treated as reinforcement to check whether they are safe against the moments and shear forces. Safety of joints is done in the same method as checking of safety of segments is done. Thus the points where maximum positive (Crown, say point A) or negative (Springing say point B) moments are generated, both the points are to be checked.

As per below Table in the segmental ring of tunnel lining, Joint A (Crown) has positive moment and Joint B (Springing) has negative moment respectively. The value of moments and axial and internal shear forces at critical points A and B calculated using computer software are tabulated as follows

TABLE 1

	MOMENT KN.M/M	AXIAL FORCE KN/M	SHEAR FORCE KN/M
JOINT A, CROWN	121.6	1039	51.3
JOINT B, SPRINGING	-88.1	1317	32

Tunnel lining Segment is considered as a ring when calculating internal forces. Bending moment distribution co-efficient, ζ =0.30 is used. Bending moment distribution can be worked out by equation,

$M_j = (1- \zeta). M$. Hoop force caused by the weight of metro tunnel track slab is 7 kN/m and the Hoop force caused by the weight of trains 26 kN/m is as per given design data.

Thus Axial Force at Joint A
= 1039+ 1.4x (7+26) = 1085.20kN/m
Axial Force at Joint B = 1317 + 1.4(7+26) = 1363.20 kN/m.

Thus, design moment and internal forces at Joint A and Joint B are as tabulated below:

TABLE 2

Joint Details	Moment kN.m/m	Axial force kN/m	Shear force kN/m
Joint A, Crown	85.1	1085.2	51.3
Joint B Springing	-61.7	1363.2	32

5.2 Check of Radial Joint A (Crown)
Ultimate Capacity

Joint A (Crown) can be simplified as tensile reinforcement. Given design data:
Concrete Compressive Strength,
$f_{cu} = 50\ N/mm^2$
Width of section b = 1500mm, Height of section h = 280mm
Tensile Strength of Bolt f_y= 400 N/mm^2
Shear Strength of Bolt f_s =260 N/mm^2
Thus moment M = 85.1 x 1.5= 127.7 kN.m
Axial force N = 1085.2 x 1.5= 1627.8 kN
Axial shear force at Joint A =0
Area of Bolt (considering 2 bolts),
As= 2x3.14x 152 =1413 mm^2
According to BS 8110-3-1985(As per basic design formula)

$N_u = k_1 b.e - f_y.A_s$ eqn (1)

$M_u = N_u.\ e_c$
$= k_1 b.e.\ (h/2-k_2.e) - f_y.A_s(h/2-d)$ eqn (2)

Eccentricity e_0 =2.4 x 104(f_{cu}/γ_m) 0.5
= 2.4 x 104(50/1.5) 0.5 = 0 .0014.
$= (0.45\ fcu\ /\ 0.0035).(\ 0.0035 - e_o/3)$
$= (0.45\ x\ 50/0.0035).\ (0.0035 - 0.0014/3)$
= 19.50 eqn (3)
$((2 - eo/0.0035).^2 + 2)/(4(3 - eo/0.0035))$
= 0.438 eqn(4)

Initial Eccentricity e_0 = M/N
= (127.7/1627.8) x 1000 =78.4mm
Additional Eccentricity e_a = maximum of (h/20, or 20) =20mm
Thus Eccentricity $e = e_0 + e_a$ = 78.4 + 20
=98.40mm eqn (5)

Substituting Equations 3, 4 & 5 into equation 1 & 2 above
(19.5 x 1500 x e - (400/1.15) x1413) x 98.40
$= k_1 b.e\ (h/2\text{-}k_2.e) - f_y.A_s(h/2\text{-}d)$

= 19.50 x 1500 x e (140- 0.438. e) –
(400/1.15) x 1413 x (140-160) eqn (6)

Solving Equation 6 , we get the value of
e= 130mm.
Now substituting the value of e into equations 1 & 2 we get
$N_u = k_1 b.e - f_y.A_s$
= (19.5 x 1500 x 130 /1000 - (400/1.15)x 1413/1000 = 3311kN
Thus N_u (3311) >N (1627.8) kN. Hence OK
$M_u = N_u.e_c$ = (3311). 130/1000 =430.4kN.m which is > M =127.7 kN.m . Hence O.K.

Thus Ultimate Capacity of Radial Bolts at Joint A (Point of max. Positive Moment i.e. at Crown)) is > requirement Thus OK. Hence Radial Bolt at Joint A(Crown) is safe against Axial force and Moment .

5.3 Joint B(Springing) Bolts Check (at the point of Maximum negative moment)
Assuming Bolts do not bear tension,
Moment M= 61.7 x 1.5=92.6 kN.m
Axial force, N= 1363.2x 1.5= 2044.8 kN
According to BS 8110-3-1985 , as per Basic formula ,
$N_u = k_1 b.e + \sigma_s.A_s$ eqn (7)
$M_u = Nu.e_c = k_1 b.e\ (h/2\text{-}k_2.e) + \sigma_s\ f_y\ (h/2\text{-}\ d)$ eqn (8)
Initial eccentricity e_0 = M/N
= (61.7 x1000) /1363.2 = 45.3 mm
Additional eccentricity e_a = maximum of
(h/20, or 20) = 20mm
Eccentricity e = $e_0 + e_a$ = 45.3+20= 65.3mm
Thus 19.5 x 1500 x e. 65.3
= 19.5 x 1500 x e (140 -0.438.e) eqn (9)
From equation (9) we get e =170.5mm > 120 Thus bolts don't have tension. Hence O.K. Substituting the value of e into equation 7 & 8 we get:
$N_u = k_1 b.e$ (No tension)
= (19.5 x 1500 x 170.5)/1000 = 4987.1kN > N=2044.8kN. Hence O.K.
$M_u = N_u.\ e_c$ = (4987.1 x 65.3)/1000 =326kN.m > M=92.6kN.m Hence O.K.

Thus Ultimate Capacity of Radial Bolts at Joint B which is point of max. Negative Moment (i.e. Springing) is > requirement Hence OK. Hence Radial Bolt at Joint B(Springing) is safe against axial force and moment .

5.4 Shear Stress

The maximum shear force per meter is
F= 97.5kN/m

The maximum shear force per segment is F_s= 97.5 x 1.5 =146.3 kN
The shear stress
$\sigma_s = F_s/A$=146300/1413=104 N/mm^2
$\sigma_s < f_s/\gamma_m$ = 208 N/mm^2 is < Bolts shear stress capacity, 260 N/sqmm Thus OK.

6 Bursting Check of Radial Bolts

Radial joints are checked against bursting Tensile Force in both directions.
6.1 Bursting Check of radial bolts in longitudinal direction
P_0 = 1627.8 kN.(refer Joint A details above)
Yp_0 =b/2=130/2 = 65mm.
Y_0= 280/2= 140 mm. Thus Yp_0/Y_0 =0.46

TABLE 3
(According to BS 8110 Part I,Table 4.7)

Y_{p0}/Y_0	0.2	0.3	0.4	0.5	0.6	0.7
F_{bst}/P_0	0.23	0.23	0.20	0.17	0.14	0.11

From above table, F_{bst}/P_0 = 0.182
Bursting force F_{bst} ,= 296.3 kN
Required area of Bursting reinforcement,
$A_{s,bst} = F_{bst}/(0.95f_y)$ = 624 mm^2
Provide 6 nos. 12 dia steel bars.
Area= 678mm^2
Provided reinforcement, area > required steel area. Hence OK.

6.1 Bursting check of Radial bolts in Radial direction

P_0= 2044.8 kN (refer Joint B details as above)
Yp_0 = b/2= (1500 – 200)/2 =650 mm
Y_0 = 1500/2 = 750 mm
Yp_0/Y_0 =650/750 = 0.88
According to BS 8110 ,Part I , table 4.7
F_{bst}/P_0 = 0.052
Bursting force F_{bst} ,= 106.3 kN
Required area of Bursting reinforcement
$A_{s,bst} = F_{bst}/(0.95f_y)$= 224 mm^2
Thus provide 2 nos. 12 dia steel bars.,
Area = 226 mm^2
Provided steel reinforcement, area > required steel area. Hence OK.

7 Conclusion

In this research paper ,the authors have mentioned detailed design loading as adopted for planning of Metro Tunnels by Delhi Metro Rail and it can be worked out either by considering direct loading method

or by considering soil/rock mass structure interaction method. Seismic analysis of underground tunnels has also become important in India in areas which are in high seismic zones.
Finally, in this paper, the authors have worked out the design criteria for the safe design checking of radial joints in tunnel segment as adopted in Delhi Metro Rail with detailed calculations.

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