

COMPARATIVE ANALYSIS OF PRECAST SEGMENTAL LINING FOR METRO TUNNELS

**A Thesis Submitted
In Partial Fulfillment of the Requirements for the
Degree of**

**MASTER OF TECHNOLOGY
in
STRUCTURAL ENGINEERING
by**

RAJEEV KUMAR

(23/STE/504)

Under the Supervision of

Dr. (Prof.) PRADEEP K. GOYAL



**Department of Civil Engineering
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Bawana Road, Delhi-110042, India**

MAY, 2026



DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Shahbad Daulatpur, Main Bawana Road, Delhi-110042

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Shahbad Daultapur, Main Bawana Road, Delhi-110042

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Dr. (Prof.) Pradeep K. Goyal
(SUPERVISOR)

Professor, Department of Civil Engineering,
Delhi Technological University, Delhi

Date: 26-05-2026

ABSTRACT

This thesis covers the analysis of precast tunnel segments for the Metro tunnels. Maximum overburden cases have been considered for analysis in this study. Precast concrete segments are permanent structural lining of a circular tunnel ring formed by TBM. They resist permanent structural loads from the surrounding soil, rock, and groundwater pressure.

The segments function as a reaction frame for advancing the TBM by pushing its hydraulic thrust jacks directly against the front face of the most recently installed segmental ring.

There are various technical papers and literature available pertaining precast segmental lining of tunnels. Some of the most relevant literatures are reviewed during this project work.

The principal objective is to verify one single precast segmental lining ring for circular tunnel. The segmental lining is verified for the maximum overburden height and with a uniformly distributed surcharge load of 50 kPa applied at the ground level. Tunnel case considered for this study is 5.8 m internal diameter circular tunnel and this is to be constructed using precast segmental lining.

The results obtained in this analysis can only be used for the segment lining design. No conclusions can be drawn regarding the ground surface settlements. The model indicated can be used to obtain normal effective stresses around the tunnel lining to define ground loads acting on the segmental lining of tunnel.

The bending moments obtained from FEM analysis are higher than those from Analytical calculations using Muir-Wood and Curtis approach, except for the Case-4 (i.e. without Surcharge). Shear forces in FEM analysis are generally on higher in all four cases. The axial forces in FEM analysis are also higher than those from Analytical calculations, except for Case-4 as presented in this thesis.

It can be concluded that the values obtained from FEM analysis are generally on conservative side, however, it is recommended that these values should be verified through independent analytical calculations to arrive at maximum governing forces to be used for design. The higher one obtained from FEM analysis and Analytical calculations shall be used judiciously for the structural design of precast segmental lining to ensure safe and optimum design of Metro tunnels.

Despite the recent advances in structural designs of tunnels, more research is necessary for analysis of precast segmental lining for metro tunnels due to its complex behavior.

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I am deeply grateful to my mentor & supervisor, **Dr. (Prof.) Pradeep K. Goyal**, Professor in Civil Engineering Department (CED), whose expert guidance and unwavering support have been instrumental throughout this research journey. His profound knowledge and insightful advice have significantly enriched my work, and I sincerely appreciate the time and effort he invested in mentoring me.

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Sincerely,

Rajeev Kumar

Roll No. - 23/STE/504

M.Tech. (Structural Engineering)

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LIST OF ABBREVIATIONS / ACRONYMS

TBM : Tunnel Boring Machine
NATM : New Austrian Tunneling Method
FEM : Finite Element Method
ITA : International Tunneling Association
2D : Two Dimensional
3D : Three Dimensional
SLS : Serviceability Limit State
ULS : Ultimate Limit State
GWT : Ground Water Table
HRL : Highest Recorded Level
BM : Bending Moment
SF : Shear Force

LIST OF SYMBOLS

I_e : Effective moment of inertia of the segmental ring

I_0 : Moment of inertia of a completely continuous, jointless ring

I_j : Residual joint stiffness (often taken as zero for a conservative approach if joints transmit no bending moment).

N : Number of segments forming the ring

E_r, ν_r : Young's Modulus and Poisson's ratio of the precast concrete ring.

E_g, ν_g : Young's Modulus and Poisson's ratio of the surrounding ground

I_e : Effective moment of inertia adjusted for the segments.

R_0 : Radius of the segmental lining of tunnel

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Metro tunnels are underground structures designed for Mass Rapid Transport Systems (MRTS) in urban areas. These tunnels can be constructed by various methods like Tunnel Boring Machines (TBM), Cut & Cover or New Austrian Tunneling Method (NATM) depending upon ground conditions, land availability, and construction feasibility. TBM tunnels are preferred for urban metro projects because they minimize disruption on the surface while safely excavating deep underground tunnels, lower dust emissions, protect urban air quality and automated precast concrete lining saves significant time.

The diameter of circular tunnel is decided by considering the internal space requirements, selection of TBM and intended use. For metro tunnels the internal diameter is generally governed by kinematic envelope (structural gauge) of train.

Precast concrete segments are permanent structural lining of a circular tunnel ring formed by TBM. They resist permanent structural loads from the surrounding soil, rock, and groundwater pressure. The segments function as a reaction frame for advancing the TBM by pushing its hydraulic thrust jacks directly against the front face of the most recently installed segmental ring.

Selecting the right design, materials and construction method for tunnel determines structural efficiency, long term durability, cost and safety during construction. The choice of reinforcement type in precast concrete segments plays a vital role in structural capacity, crack control, and corrosion resistance.

Joint configuration of precast segmental is important for the overall performance of the tunnel lining during earthquakes.

Design Engineers mostly use Finite Element Methods (FEM) to model soil-structure interaction and design the segmental lining. FEM models simulate both the surrounding ground and segment lining using non-linear fracture mechanics. Continuum analysis considers the complex cross-ring plastic behavior, TBM thrust force and localized stresses induced by segment splitting phenomenon.

Empirical solutions given by Muir Wood (1975) & Curtis (1976) provide classical method for the analysis. This method considers the tunnel as a continuous elastic ring with reduced bending stiffness.

This dissertation covers a comparative analysis of precast concrete segments for metro tunnel lining using both FEM analysis and the Analytical solution based on Muir-Wood & Curtis approach.

1.2 PRECAST CONCRETE SEGMENTS

Precast concrete segments are high-accuracy, manufactured in casting yard, pre-engineered reinforced concrete elements to form a continuous, load-bearing segment rings in a tunnel. The segmental lining is used in mechanized tunneling with Tunnel Boring Machine (TBM). This tunneling system provides continuous structural lining which provides both temporary excavation support as well as permanent tunnel structure.

1.3 SEGMENTAL LINING COMPOSITION

Tunnel ring is made of segments to allow installation and assembly by a mechanical segment erector inside the TBM:

- **Ordinary Segments:** Ordinal segments form the major portion of the ring with parallel edges.
- **Adjacent Segments:** These are placed on either side of the final segment having one tapered edge.
- **Key Segment:** Key segment or keystone is a small wedge-shaped part installed longitudinally or radially to complete and interlock the final ring.

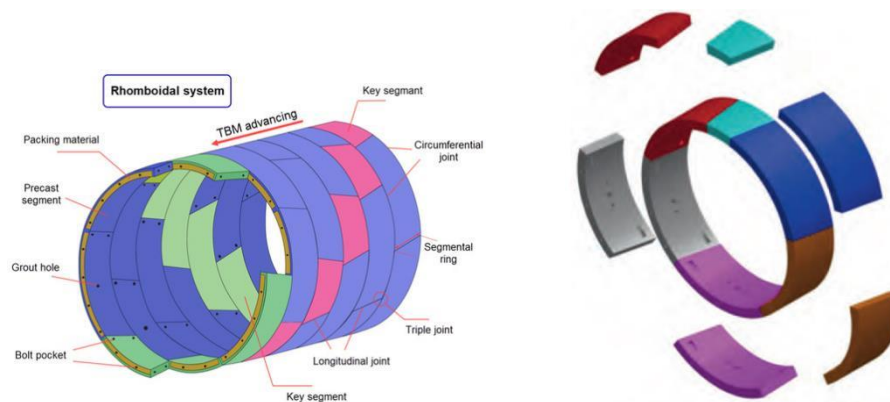


Figure 1.1: Typical Segment Rings



Figure 1.2: Photograph of Stacking of Precast Segments
(Courtesy SPC Industries)

1.4 MAIN COMPONENTS AND JOINTS

The precast segments are interconnected through specialized joints at interfaces:

- **Longitudinal Joints:** These are the joints between adjacent segments within the ring and carry the bending moments and compressive forces in the segment ring.
- **Circumferential Joints:** Circumferential joints are the continuous joints formed between two adjacent rings of segmental lining.
- **Gaskets:** The elastomeric or hydrophilic rubber gaskets are fixed into grooves around each segment perimeter to prevent water ingress and ensure sealing of joints.
- **Grout Holes:** These holes in precast segments are used to inject pressurized grout material to fill the annular gap between outer surface of segmental lining and the surrounding soil.

1.5 LOADS FOR STRUCTURAL DESIGN

Precast Segmental lining is designed utilizing technical papers & specialized literature or following the procedure as specified ITA Working Group 2 Publications. The segments shall carry following two main loads:

1.5.1 Temporary Loads During Construction Stage:

- a) **Demoulding, Stacking & Lifting:** These forces are induced during stripping during de-molding, stacking in the casting yard and lifting during transportation to site.
- b) **TBM Thrust Forces:** This force is exerted by hydraulic jacks which directly push the precast segments for forward moving of the TBM.

1.5.2 Permanent Loads:

- a) **Soil & Water Pressure:** Soil & water forces are long-term forces during service stage of segmental lining, and these forces are primarily generated by soil/rock overburden and hydrostatic pressure.
- b) **Distortion Restraints:** Structural analysis checks are conducted to ensure joint rotation to be within permissible range generally limited to around 1% of the radius of segment ring.

1.6 DETAILS OF TUNNEL BORING MACHINE

Tunnel Boring Machine, which are commonly called TBM is a massive engineering machine used to excavate tunnels with a circular cross-section. TBMs serve as a safer, faster, and more precise alternative to traditional drill-and-blast methods, minimizing ground settlement and surface disruption in sensitive or urban areas.

1.6.1 Key Components of TBM:

- 1) **Cutterhead:** It is a massive rotating wheel equipped with heavy-duty disc cutters, rollers, and teeth at the front of TBM. It pushes against the rock or soil with huge hydraulic pressure and continue boring the ground to form a tunnel.
- 2) **Shield & Erector:** It is a protective steel cylinder in the middle of TBM that prevents the surrounding ground from collapsing while the TBM advances.

Inside this shield, a mechanical erector arm lifts and installs precast concrete segments to form segmental lining for tunnel.

- 3) **Trailing Gear:** Trailing gear is a long train of support structures at rear stretching around 150 m or more. It houses the power supplies, ventilation, control systems, and conveyor belts or slurry pipelines needed to transport the excavated soil / rock or muck from the tunnel.

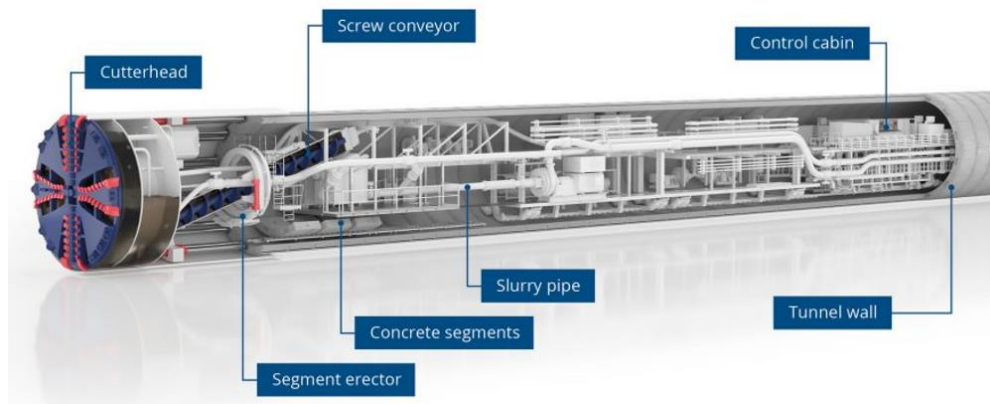


Figure 1.3 : Schematic Diagram with Components of TBM
(Courtesy HS2 Ltd.)

1.6.2 Advantages of TBM over Traditional Tunneling:

- a. **Continuous Operations:** TBM allows continuous boring, removal of soil, and simultaneous installation of precast segments.
- b. **Structural Precision:** It operates within a margin of error of just a few millimeters using laser guidance systems.
- c. **Safety:** In TBM tunneling, the workers are protected inside the steel shield rather than facing open, unlined rock faces.
- d. **Environmental Control:** TBM significantly reduces vibrations, structural damage risk, noise, and dust as compared to other tunneling methods.

CHAPTER 2

LITERATURE REVIEW

2.0 LITERATURE STUDY AND RESEARCH GAP

There are various technical papers and literature available pertaining precast segmental lining of tunnels. Some of the most relevant literature reviewed during this project study are summarized below;

2.1 “The circular tunnel in elastic ground” by Muir Wood, 1975

The paper detailed a method for analyzing stresses and bending moments in tunnel linings. This work is highly influential in tunnel design, particularly regarding the interaction between the tunnel lining and the surrounding ground. The core contribution of this paper is a simplified elastic analysis that considers the "elliptical" deformation mode of the tunnel lining and relates bending moments to stiffness factors.

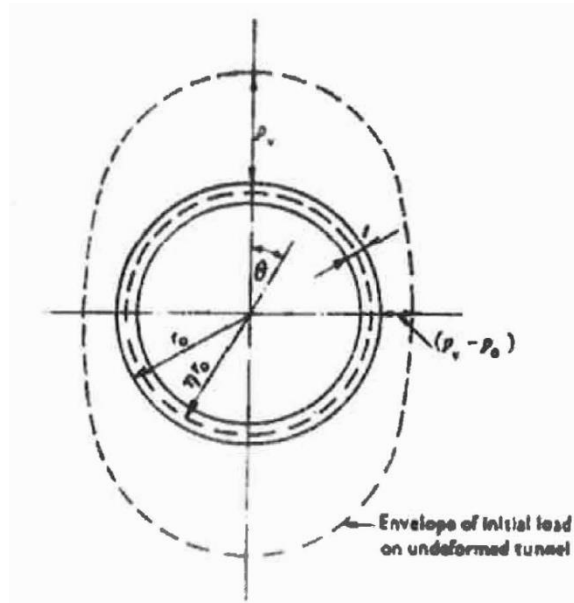


Fig. Reference Diagram for initial loading on tunnel prior to deformation

Key aspects of this paper and its impact:

Focus on Elastic Ground:

The paper focuses on analyzing tunnels in elastic ground, providing a foundational understanding of how linings behave under stress.

Elliptical Deformation Mode:

It simplifies the analysis by considering the tunnel lining to deform elliptically, which allows for easier calculation of bending moments.

Stiffness Factors:

The paper establishes a relationship between bending moments in the lining and stiffness factors, which are crucial for understanding the tunnel lining flexibility relative to the ground.

Ground-Lining Interaction:

A key aspect is the analysis of how the tunnel lining interacts with the surrounding ground, considering factors like ground stresses and the presence of joints in the lining.

Foundation for Further Research:

The paper also served as a basis for further research into tunnel design, including the impact of twin tunnels and other complex scenarios.

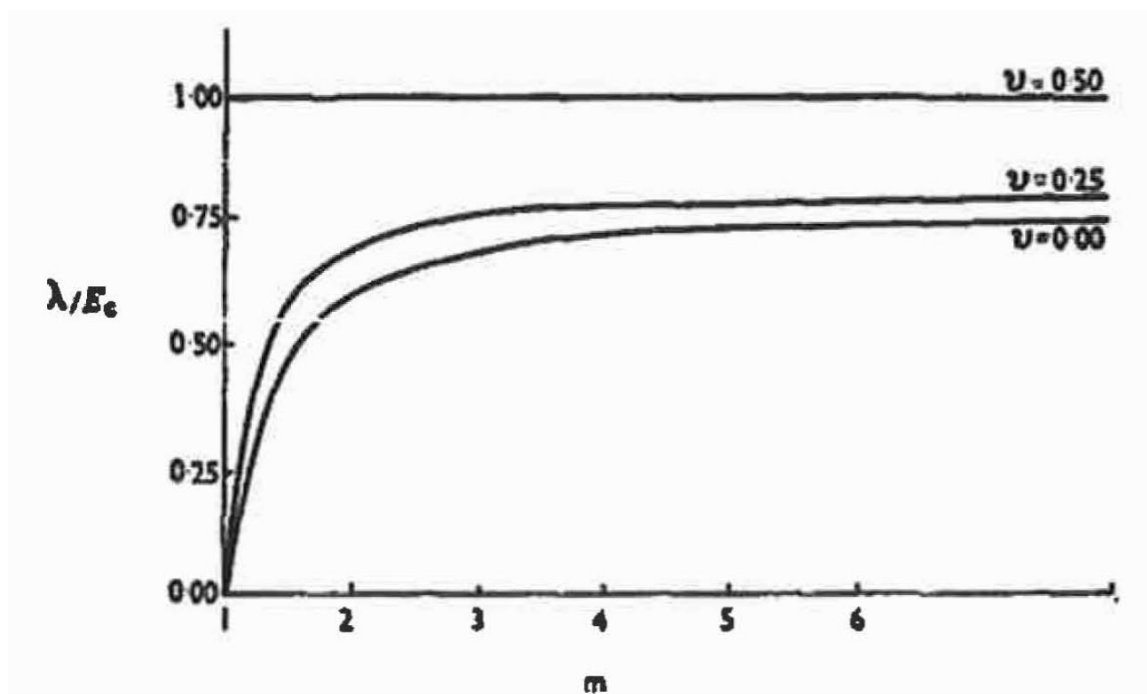


Fig. Relationship between coefficient λ of ground reaction and mode of deformation 'm' for different values of Poisson's ratio ' ν '

Influence on Design:

The concepts presented in the paper are essential for understanding how to design tunnel linings that can withstand the stresses imposed by the surrounding ground and how to account for the flexibility of the lining and the ground properties.

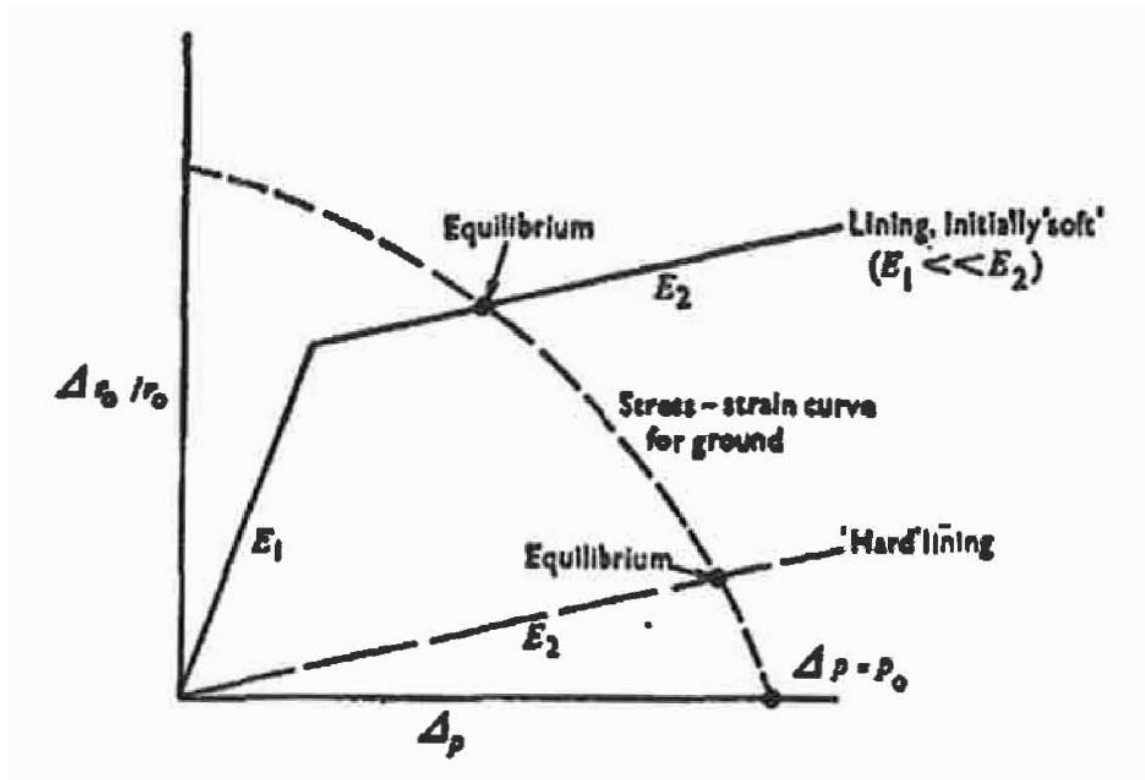


Fig. Diagrammatic representation of the benefit of an initial phase of high compressibility of a lining in relation to its ultimate condition of loading, p - Δp

2.2 “Discussion on the Circular Tunnel in Elastic Ground” by D. J. Curtis, 1976

Curtis (1976) published an important paper elaborating and extending the Muir-Wood's approach. Curtis rectified mathematical inconsistencies regarding shear forces at the soil-lining interface and amplified the equations to properly accommodate tangential pressures and structural slip variables.

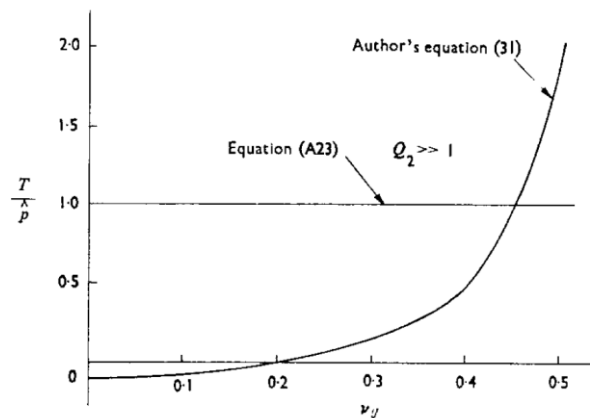
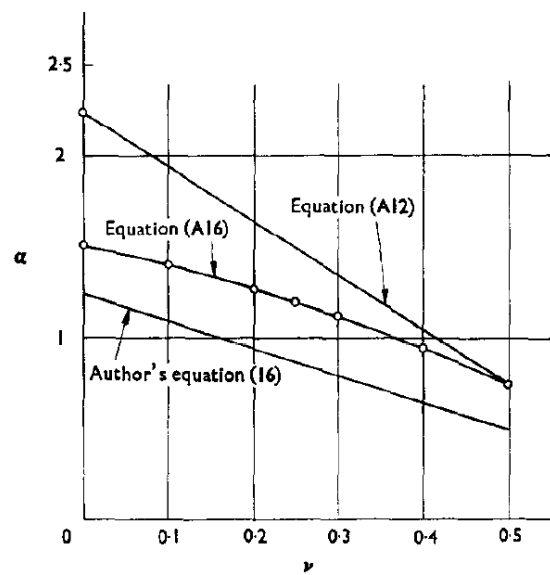
In this paper, Curtis provided critical corrections and updates to previous structural design models proposed by H.D. Morgan (1961) and Sir Alan Muir Wood (1975) regarding how circular tunnel linings interact with surrounding elastic ground.

Equation 16, originally given by Muir Wood for maximum bending moment;

$$M_{\max} = \pm \frac{p_0 r_0^3 \eta^2 EI (1 + \nu) (5 - 6\nu)}{6EI(1 + \nu)(5 - 6\nu) + 2\eta^3 r_0^3 E_c}$$

This was modified by Curtis as Equation 16A as below;

$$M_{\max} = \frac{\pm P_0 r_0}{4} / \left\{ 1 + Q_2 \left[\frac{3 - 2\nu}{3 - 4\nu} \right] \right\}$$



The resulting framework, widely known as the Muir Wood & Curtis method, remains one of the most frequently used closed-form analytical solutions for calculating bending moments, shear forces, axial forces, and deformations in segmental linings of tunnels.

2.3 “Tunnel Lining Design-Do the Theories Work?, B. Schmidt, 1984

The interaction between segmental lining and surrounding soil has been the subject of many recent literatures and it is now possible to deal precisely with complex interactions. This literature, however, has not much contributed to the thorough understanding of soil-structure interaction around a tunnel. Although we have continuum mechanics solutions, it is still not sure that if they provide an improvement in accuracy with which linings are designed.

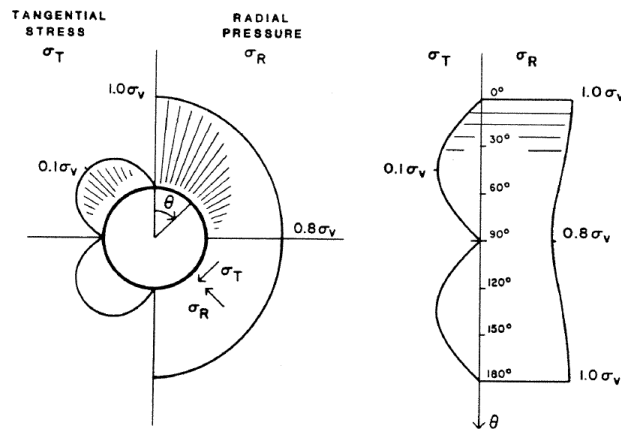


Fig. Pressure at Soil-Lining Boundary, assuming no slip, for continuum mechanics approach shown with ($K_0=0.8$)

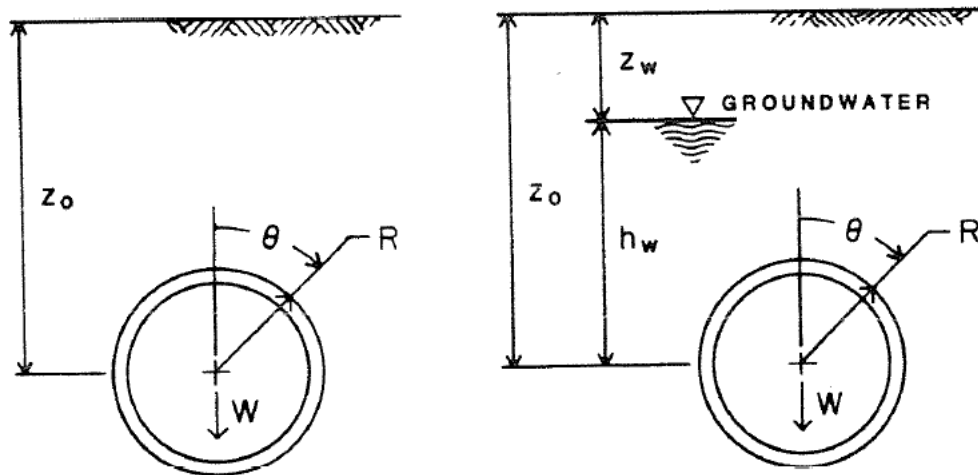


Figure 2.5: Tunnel Geometry for Analysis

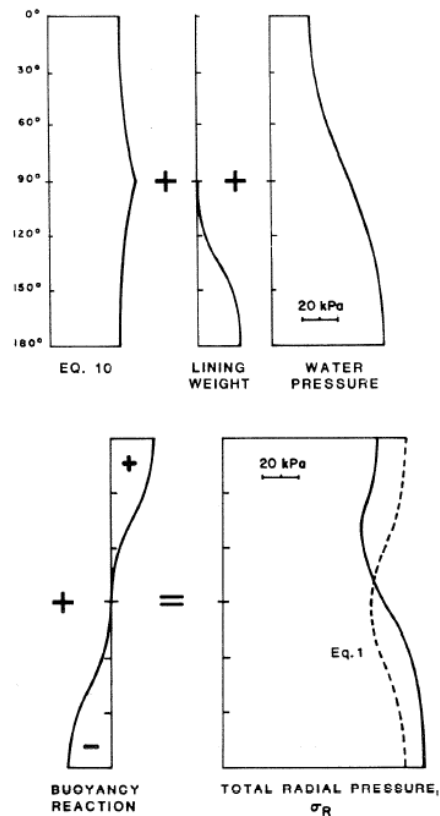


Fig. Contribution to radial lining pressures, compared to continuum mechanics assumption

Continuum mechanics models using closed solutions are good tools for parametric studies and when properly calibrated, can be an aid in detailed design of tunnel lining. Using Finite Element Method (FEM) goes one step ahead, allowing soil to be analyzed in layers and taking the vertical in-situ stress gradient into consideration.

However, these methods require the use of data input that is ambiguous to much extent, including the equivalent soil modulus and presumed initial load on the tunnel lining.

2.4 “Stresses in Lining of Bored Tunnels” by Joseph Penzien & Ching L. Wu, 1998

In this paper, an analytical method is given for determining the stresses in segmental linings of tunnels induced by kinematic soil-structure interaction. Three scenarios of plane strain cases are considered as follows;

- (1) Relaxation of in-situ soil stresses at segmental lining after installation

- (2) Overburden pressure at the soil surface, and
- (3) Two-dimensional free-field soil response perpendicular to the lining axis as developed by an earthquake

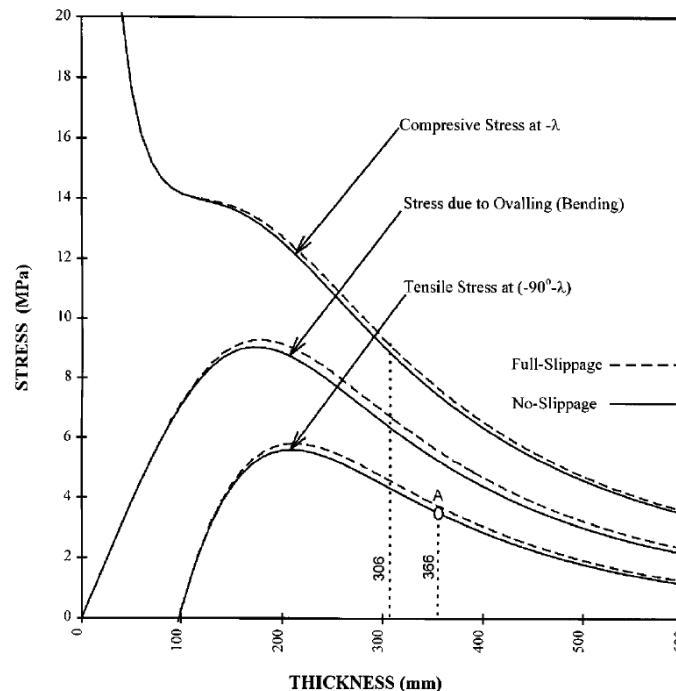


Fig. Stresses at inner fibers of concrete lining

The different solutions obtained for the cases of full slip and no slip at the soil-lining structure interface during the occurrence of shear deformations shown that the full slip case has only a small effect on the shear and bending moments in segmental lining, however, it reduced the maximum axial force by approximately 50%. Since the axial force produced by the dilatational type of deformation is much higher than the maximum axial force produced by the shear type deformation, this 50 % reduction has less effect on the combined axial force due to both types of deformation. Consistent with this observation, slippage has little effect on the maximum combined normal stresses in the segmental lining as produced by in-situ stress relaxation and seismic free-field soil response.

2.5 “Segmental Ring Design-New Challenges with High Tunnel Diameters” ITA Muir Wood Lecture by Fritz Gruebl, 2012

The segmental ring usually is calculated as a coupled double ring. In a FEM program, only a single ring can be calculated, as coupling of two rings is not possible or very time consuming for most of all calculation programs.

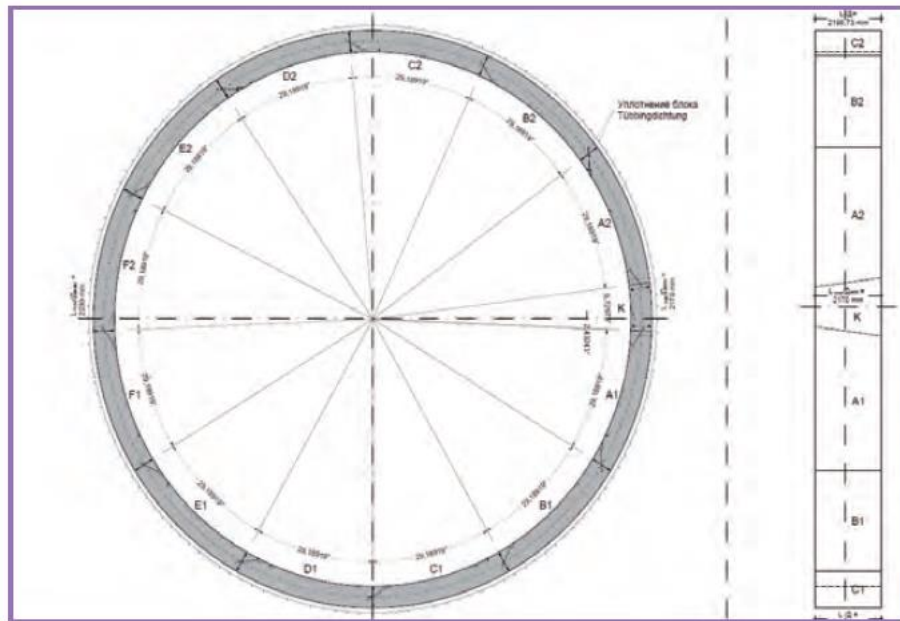


Fig. Segmental Ring for the Orlovski-Tunnel

To check extremes, a single ring with articulations and a single rigid ring is calculated, as well as rigid ring with a reduced area-wise moment according to Sir Allen Muir Wood's formula.

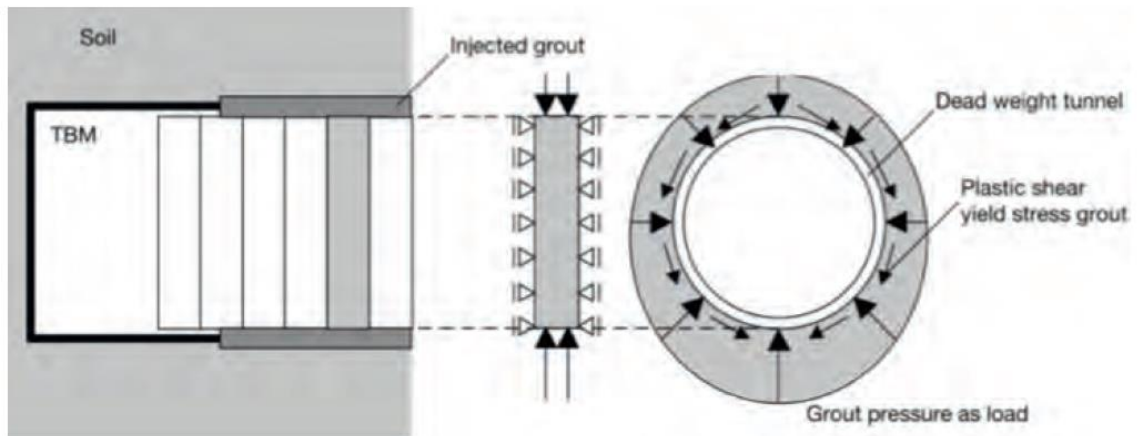


Fig. Forces & definitions for load case of tail void back-grouting (Groeneweg, 2007)

Other methods for analysis include Duddeck and Erdmann's (1982) model and an empirical method based on tunnel distortion ratios (Sinha 1989; Deere et.al. 1969) which was originally developed by Peck (1969).

The elastic equation is a simple approach for calculating the internal forces in segmental lining for circular tunnels. For this method, the segmental lining is modeled using a uniform bending rigidity that considers the effect of longitudinal joints between the segments. To consider for the reduced flexural rigidity in the lining due to the presence of segment joints, the moment of inertia of segmental lining should be reduced in accordance with Muir Wood's (1975).

CHAPTER 3

METHODOLOGY FOR ANALYSIS

In this study, the analysis of segmental lining is done using two approaches, i.e. by analytical method and by Finite Element Method (FEM). The results obtained from the two methods have been compared for assessment.

The philosophy given by Muir-Wood & Curtis has been used for analytical calculations. The FEM analysis of the tunnel segmental lining has been conducted using the FEM software Praxis 2D.

3.1 MUIR-WOOD & CURTIS METHOD

The Muir Wood & Curtis method is a widely used analytical method for calculating the bending moments, shear forces, and axial forces in circular tunnel linings. Initially developed by Muir Wood in 1975 and later corrected and expanded by Curtis in 1976, this method provides a reliable approach for structural analysis. It is particularly highly effective for evaluating interaction between segmental lining and surrounding elastic ground around the tunnel.

3.1.1 Key Assumptions

This method simplifies the complex physical environment into a solvable mathematical equation with following assumptions:

- **Plane Strain:** The tunnel cross-section is analyzed in two-dimensional plane strain conditions.
- **Linear Elastic Continuum:** Both the surrounding ground and the tunnel lining act as homogeneous and linear elastic materials.
- **Deep Tunnel Condition:** The tunnel is assumed to be deep enough so that the primary stress state before excavation is uniform across the diameter.
- **Continuum Bonding:** Full contact is maintained between the ground and the segmental lining. Soil-structure interaction is limited to radial and tangential reactions.

3.1.2 Approach for Solution

Segmental linings of tunnel are not continuous rings and consist of multiple precast concrete segments joined together. These joints reduce the overall bending stiffness of the segment ring.

To take care of this, Muir Wood introduced an effective bending stiffness (I_e). If a tunnel ring has N segments (where $N > 4$), the actual moment of inertia of the lining cross-section (I_0) is reduced using the following equation;

$$I_e = I_j + I_0 \left(\frac{4}{N} \right)^2$$

.....Equation 3.1

Where:

I_e : Effective moment of inertia of the segmental ring

I_0 : Moment of inertia of a completely continuous, jointless ring

I_j : Residual joint stiffness (often taken as zero for a conservative approach if joints transmit no bending moment).

N : Number of segments forming the ring

3.1.3 Equations for Structural Analysis

The method calculates structural forces based on the elliptical deformation mode, driven by the active vertical stress (σ_v) and horizontal stress ($\sigma_h = K_0 \cdot \sigma_v$, where K_0 is the coefficient of earth pressure at rest).

a) Bending Moment (M)

The bending moment is induced due to the differences between vertical and horizontal ground pressures which cause the ovaling deformation of ring. The maximum bending moment occurs at the ring top (crown), bottom (invert), or spring-line (the widest horizontal axis).

$$M = \pm \frac{\sigma_v(1 - K_0)R_0^2}{4} \cdot \left(\frac{1}{1 + \eta} \right) \quad \text{.....Equation 3.2}$$

Where η is stiffness ratio introduced by Curtis. It measures the relative bending stiffness of the segmental lining against the distortion stiffness of the ground.

$$\eta = \frac{3E_r I_e (1 + \nu_g)}{E_g R_0^3 (1 - \nu_r^2)} \quad \text{.....Equation 3.3}$$

where;

E_r, ν_r : Young's Modulus and Poisson's ratio of the precast concrete ring.

E_g, ν_g : Young's Modulus and Poisson's ratio of the surrounding ground

I_e : Effective moment of inertia adjusted for the segments.

R_0 : Radius of the segmental lining of tunnel

b) Axial Force (N)

The maximum thrust generally occurs at the spring-line and is mainly driven by the average ground pressure.

$$N = \frac{\sigma_v(1 + K_0)R_0}{2} \quad \text{.....Equation 3.3}$$

3.2 FINITE ELEMENT METHOD

Finite Element Method (FEM) is vital tool for analyzing precast segmental linings in TBM tunnels. It simulates the complex soil-structure interactions, non-linear material behaviors, and the staggered, multi-ring structural mechanics of bolted or un-bolted precast segments in tunnels.

3.2.1 Approaches for Modelling

- **2D FEM Model:** It is used for long, straight tunnels where the longitudinal behavior can be simplified as plane strain. This assumes the tunnel is infinitely long and analyzes the section under full overburden and hydrostatic pressure.

- **3D FEM Model:** 3D model is required for complex geometry, highly variable geotechnical profile, tunnel intersections, modeling the specific TBM thrust loads. It also captures the staggering effect between adjacent segment rings.
- **Beam-Spring Model:** Beam-Spring model is a simplified, cost-effective 1D modeling method where the lining is represented by beam elements, and the surrounding ground is modeled using radial and tangential springs.

The joints between segments and rings are modeled using rotational and translational springs.

3.2.2 Modeling of Precast Segmental Lining

- **Material Properties:** Precast Segments are subjected to high magnitude localized stresses, especially during TBM thrusting. FEM models use non-linear constitutive models to precisely capture cracking and deformation.
- **Simulation of Joints:** Joints are the weakest locations in a precast segmental lining and govern the overall stiffness of the segment ring. In 3D FEM, they are typically modeled in three following ways:
 - a) **Contact Surfaces:** Interfaces using Coulomb friction and normal stiffness to permit gap opening and shear sliding between adjacent segments of tunnel lining.
 - b) **Equivalent Stiffness Reduction Method:** It is a simplified 2D/3D method where the overall bending stiffness (EI) of the continuous segmental ring is reduced by a predefined coefficient to take care of joint flexibility.
 - c) **Spring Elements:** Discrete zero-thickness spring elements assigned with nonlinear moment-rotation ($M-\theta$) and axial force-displacement relationships.

3.2.3 Critical Cases

FEM analysis evaluates the various cases during construction and service stage:

- **Construction & TBM Thrust:** High localized stress concentrations are induced by TBM hydraulic jacks which directly push the installed segment rings.
- **Tail Void Grouting:** It simulates the hardening and pressure of grout injected behind the TBM as the shield moves ahead.

- **Long-Term Serviceability Limit State & Ultimate Limit State:** Serviceability Limit State (SLS) & Ultimate Limit State (ULS) analysis of the lining under maximum long-term groundwater pressure, soil settling, settlement and probable earthquakes.

The principal objective is to verify one single precast segmental lining ring for circular tunnel. The segmental lining is verified for the maximum overburden height and with a uniformly distributed surcharge load of 50 kPa applied at the ground level.

3.3 TUNNEL GEOMETRY AND PARAMETERS OF SEGMENTAL LINING

The tunnel case considered for this study is of 5.8 m internal diameter circular tunnel and this to be constructed using precast segmental lining. The parameters used for this tunnel are listed on the table below:

Table 3.1: Details of Precast Segmental Lining

S.No.	Description / Parameter	Dimension / Detail
1.	Internal Diameter of Tunnel	5800 mm
2.	Thickness of Segments	275 mm
3.	Outer Diameter of Tunnel	6350 mm
4.	Number of Segments in a Ring	5 + 1 Key
5.	Width of Segments	1400 mm
6.	Weight to Segments	Normal Segments = 3.0 T each Key Segment = 1 T
7.	Total Weight of Complete Ring	16 T
8.	Grade of Concrete	M 45



Figure 3.1: Arrangement of Segmental Lining

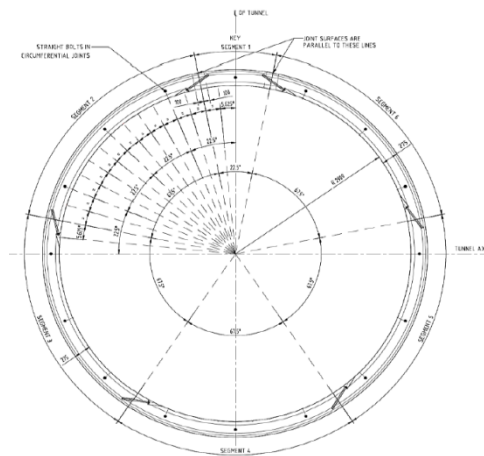


Figure 3.2 : Typical Segment Ring Configuration

Four different cases have been analyzed as part of this study for each condition as follows:

Case 1: Short Term : Ground Water Table (GWT@HRL*) with uniform surcharge of 50 kPa

Case 2: Long Term : Dry Condition with uniform surcharge of 50 kPa

Case 3: Long term for GWT@GL with uniform surcharge of 50 kPa

Case 4: Long term for GWT@GL without surcharge

Maximum Overburden above tunnel Crown = **13.917m**

(Reference date is taken from Agra Metro tunnel stretch between Taj Mahal to Agra Fort, Agra, India), 2025-26.

*HRL : Highest Recorded Level

CHAPTER 4

RESULTS AND DISCUSSION

4.1 ANALYTICAL CALCULATIONS BASED ON MUIR-WOOD AND CURTIS

4.1.1 Case-1: Short Term : GWT@ HRL with Uniform Surcharge of 50 kPa

Table 4.1: Analytical Calculations for Case-1

GEOMETRY OF TUNNEL:	
External diameter of tunnel (d_e)	6.350 m
Thickness of lining (h)	0.275 m
Compression area (h_c)	0.000 m
Radius to extrados of lining (r_e)	3.175 m
Centroid radius of lining (r_0)	3.038 m
Overburden above tunnel roof (z)	13.917 m
Overburden above tunnel axis (z_0)	17.092 m
Water level above tunnel axis (h_w)	4.342 m

LOADINGS:	
Surcharge (q_z)	50.00 kN/m^2
Factor of safety SF(u)	1.00 kN/m^2
Factor of safety SF(s')	1.00 kN/m^2
Hydrostatic pressure (u)	43.42 kN/m^2
Unfactored effective vertical stress (q_1)	194.93 kN/m^2
Factored effective vertical stress (s'_v)	194.93 kN/m^2
Effective horizontal stress (s'_h) = $k \cdot s'_v$	97.46 kN/m^2
Distortional pressure (p_0) = $s'_v - s'_h$	97.46 kN/m^2
Uniform pressure (p_u) = $(\sigma'_v + \sigma'_h) / 2$	146.20 kN/m^2
Shear strength (t) = $c' + p_u \cdot \tan j'$	84.41 kN/m^2

PROPERTIES OF SOIL & WATER	
Effective unit weight of soil (g'_k)	8.91 kN/m^3
Average unit weight of soil (g_k)	18.91 kN/m^3
Lateral pressure ratio (k)	0.500
Effective cohesion of ground (c'_d)	0.0 kN/m^2
Effective friction angle of ground (j'_d)	30.0 °
Unit weight of water (g_w)	10.0 kN/m^3
Deformation modulus of ground (E_g)	40,500 kPa
Poisson's ratio of ground (n_g)	0.45

SEGMENTAL LINING PROPERTIES	
Concrete grade (C)	40/50
Mean concrete strength (f_{cm})	50 MPa
Plain strain elastic Modulus of lining (E_l^*)	36,169 MPa
Elastic Modulus of lining (E_l)	35,355 MPa
Poisson's ratio of lining (n_l)	0.15
Area of lining per meter (A)	0.275 m^2
Total number of regular segments (N)	5
Second moment of area of lining (I_l)	1.73E-03 m^4
Effective Second moment of area of lining ($I_{l,eff}$)	1.109E-03 m^4

No Slip Condition

Calculations (As per Curtis, 1976)	
N_0	460.25 kN/m
Q_2	1.8570
(if $S_t < t$): S_n	-9.83 kN/m
(if $S_t > t$): S_n	-25.47 kN/m
S_n	-9.83 kN/m
S_t	54.06 kN/m

	Q (°)	u_r (mm)	N (kN/m)	M (kNm/m)	V (kN/m)
Crown	0	-4.14	498.60	-55.30	0.00
	10	-3.88	504.60	-51.96	-7.65
	20	-3.15	521.88	-42.36	-14.38
	30	-2.02	548.35	-27.65	-19.38
	40	-0.64	580.83	-9.60	-22.04
	45	0.10	598.11	0.00	-22.38
	50	0.83	615.39	9.60	-22.04
	60	2.22	647.87	27.65	-19.38
Axis	70	3.35	674.34	42.36	-14.38
	80	4.08	691.62	51.96	-7.65
	90	4.34	697.62	55.30	0.00

Full Slip Condition

Calculations (As per Curtis, 1976)	
N_0	464.18 kN/m
Q_2	1.8570
S_n	18.03 kN/m
S_t	0.00 kN/m

	Q (°)	u_r (mm)	N (kN/m)	M (kNm/m)	V (kN/m)
Crown	0	-5.08	582.95	-60.60	0.0
	10	-4.77	584.10	-56.95	-8.4
	20	-3.89	587.41	-46.42	-15.8
	30	-2.54	592.49	-30.30	-21.2
	40	-0.88	598.72	-10.52	-24.2
	45	0.00	602.04	0.00	-24.5
	50	0.88	605.35	10.52	-24.2
	60	2.54	611.58	30.30	-21.2
Axis	70	3.89	616.66	46.42	-15.8
	80	4.77	619.97	56.95	-8.4
	90	5.08	621.12	60.60	0.0

50% Slip Condition

Q (°)	u_r (mm)	N (kN/m)	M (kNm/m)	V (kN/m)	
0	-4.61	540.77	-57.95	0.00	Crown
10	-4.33	544.35	-54.45	-7.65	
20	-3.52	554.65	-44.39	-14.38	
30	-2.28	570.42	-28.97	-19.38	
40	-0.76	589.77	-10.06	-22.04	
45	0.05	600.07	0.00	-22.38	
50	0.86	610.37	10.06	-22.04	
60	2.38	629.72	28.97	-19.38	
70	3.62	645.50	44.39	-14.38	Axis
80	4.43	655.80	54.45	-7.65	
90	4.71	659.37	57.95	0.00	

4.1.2 Case-2: Long Term : GWT (Dry Case) with Uniform Surcharge of 50 kPa

Table 4.2: Analytical Calculations for Case-2

GEOMETRY OF TUNNEL:		LOADINGS:	
External diameter of tunnel (d_e)	6.350 m	Surcharge (q_z)	50.00 kN/m ²
Thickness of lining (h)	0.275 m	Factor of safety SF(u)	1.00 kN/m ²
Compression area (h_c)	0.000 m	Factor of safety SF(s')	1.00 kN/m ²
Radius to extrados of lining (r_e)	3.175 m	Hydrostatic pressure (u)	0.00 kN/m ²
Centroid radius of lining (r_o)	3.038 m	Unfactored effective vertical stress (q_1)	233.76 kN/m ²
Overburden above tunnel roof (z)	13.917 m	Factored effective vertical stress (s'_v)	233.76 kN/m ²
Overburden above tunnel axis (z_o)	17.092 m	Effective horizontal stress (s'_h) = $k \cdot s'_v$	116.88 kN/m ²
Water level above tunnel axis (h_w)	0.000 m	Distortional pressure (p_o) = $s'_v - s'_h$	116.88 kN/m ²
		Uniform pressure (p_u) = $(\sigma'_v + \sigma'_h) / 2$	175.32 kN/m ²
		Shear strength (t) = $c' + p_u \cdot \tan j'$	101.22 kN/m ²

PROPERTIES OF SOIL & WATER		SEGMENTAL LINING PROPERTIES	
Effective unit weight of soil (g'_k)	8.91 kN/m ³	Concrete grade (C)	40/50
Average unit weight of soil (g_k)	18.91 kN/m ³	Mean concrete strength (f_{cm})	50 MPa
Lateral pressure ratio (k)	0.500	Plain strain elastic Modulus of lining (E_l^*)	18,085 MPa
Effective cohesion of ground (c'_d)	0.0 kN/m ²	Elastic Modulus of lining (E_l)	17,678 MPa
Effective friction angle of ground (j'_d)	30.0 °	Poisson's ratio of lining (n_l)	0.15
Unit weight of water (g_w)	10.0 kN/m ³	Area of lining per meter (A)	0.275 m ²
Deformation modulus of ground (E_g)	40,500 kPa	Total number of regular segments (N)	5
Poisson's ratio of ground (n_g)	0.25	Second moment of area of lining (I_l)	1.73E-03 m ⁴
		Effective Second moment of area of lining ($I_{l,eff}$)	1.109E-03 m ⁴

No Slip Condition

Calculations (As per Curtis, 1976)	
N_0	545.83 kN/m
Q_2	4.3081
(if $S_t < t$): S_n	-30.28 kN/m
(if $S_t > t$): S_n	-37.36 kN/m
S_n	-30.28 kN/m
S_t	88.01 kN/m

	Q	u_r	N	M	V
	(°)	(mm)	(kN/m)	(kNm/m)	(kN/m)
Crown	0	-6.43	398.26	-44.13	0.00
	10	-6.03	407.16	-41.47	-6.11
	20	-4.85	432.79	-33.81	-11.48
	30	-3.05	472.05	-22.07	-15.47
	40	-0.84	520.21	-7.66	-17.59
	45	0.33	545.83	0.00	-17.86
	50	1.51	571.46	7.66	-17.59
	60	3.72	619.62	22.07	-15.47
	70	5.52	658.88	33.81	-11.48
	80	6.69	684.50	41.47	-6.11
Axis	90	7.10	693.40	44.13	0.00

Full Slip Condition

Calculations (As per Curtis, 1976)	
N_0	556.63 kN/m
Q_2	4.3081
S_n	16.91 kN/m
S_t	0.00 kN/m

	Q (°)	u_r (mm)	N (kN/m)	M (kNm/m)	V (kN/m)
Crown	0	-9.52	538.73	-56.83	0.0
	10	-8.95	539.81	-53.40	-7.9
	20	-7.29	542.92	-43.53	-14.8
	30	-4.76	547.68	-28.41	-19.9
	40	-1.65	553.53	-9.87	-22.6
	45	0.00	556.63	0.00	-23.0
	50	1.65	559.74	9.87	-22.6
	60	4.76	565.58	28.41	-19.9
Axis	70	7.29	570.35	43.53	-14.8
	80	8.95	573.45	53.40	-7.9
	90	9.52	574.53	56.83	0.0

50% Slip Condition

Q (°)	u_r (mm)	N (kN/m)	M (kNm/m)	V (kN/m)	
0	-7.98	468.50	-50.48	0.00	Crown
10	-7.49	473.49	-47.44	-6.11	
20	-6.07	487.86	-38.67	-11.48	
30	-3.90	509.87	-25.24	-15.47	
40	-1.25	536.87	-8.77	-17.59	
45	0.17	551.23	0.00	-17.86	
50	1.58	565.60	8.77	-17.59	
60	4.24	592.60	25.24	-15.47	
70	6.40	614.61	38.67	-11.48	Axis
80	7.82	628.98	47.44	-6.11	
90	8.31	633.97	50.48	0.00	

4.1.3 Case-3: Long Term : GWT (@GL) with Uniform Surcharge of 50 kPa

Table 4.3: Analytical Calculations for Case-3

GEOMETRY OF TUNNEL:		LOADINGS:	
External diameter of tunnel (d_e)	6.350 m	Surcharge (q_z)	50.00 kN/m^2
Thickness of lining (h)	0.275 m	Factor of safety SF(u)	1.00 kN/m^2
Compression area (h_c)	0.000 m	Factor of safety SF(s')	1.00 kN/m^2
Radius to extrados of lining (r_e)	3.175 m	Hydrostatic pressure (u)	170.92 kN/m^2
Centroid radius of lining (r_0)	3.038 m	Unfactored effective vertical stress (q_1)	136.74 kN/m^2
Overburden above tunnel roof (z)	13.917 m	Factored effective vertical stress (s'_v)	136.74 kN/m^2
Overburden above tunnel axis (z_0)	17.092 m	Effective horizontal stress (s'_h) = $k \cdot s'_v$	68.37 kN/m^2
Water level above tunnel axis (h_w)	17.092 m	Distortional pressure (p_0) = $s'_v - s'_h$	68.37 kN/m^2
		Uniform pressure (p_u) = $(\sigma'_v + \sigma'_h) / 2$	102.56 kN/m^2
		Shear strength (t) = $c' + p_u \cdot \tan j'$	59.21 kN/m^2

PROPERTIES OF SOIL & WATER		SEGMENTAL LINING PROPERTIES	
Effective unit weight of soil (g'_k)	10.31 kN/m^3	Concrete grade (C)	40/50
Average unit weight of soil (g_k)	20.31 kN/m^3	Mean concrete strength (f_{cm})	50 MPa
Lateral pressure ratio (k)	0.500	Plain strain elastic Modulus of lining (E_l^*)	18,085 MPa
Effective cohesion of ground (c'_d)	0.0 kN/m^2	Elastic Modulus of lining (E_l)	17,678 MPa
Effective friction angle of ground (j'_d)	30.0 °	Poisson's ratio of lining (n_l)	0.15
Unit weight of water (g_w)	10.0 kN/m^3	Area of lining per meter (A)	0.275 m^2
Deformation modulus of ground (E_g)	40,500 kPa	Total number of regular segments (N)	5
Poisson's ratio of ground (n_g)	0.25	Second moment of area of lining (I_l)	1.73E-03 m^4
		Effective Second moment of area of lining ($I_{l,eff}$)	1.109E-03 m^4

No Slip Condition

Calculations (As per Curtis, 1976)	
N_0	319.30 kN/m
Q_2	4.3081
(if $S_t < t$): S_n	-17.71 kN/m
(if $S_t > t$): S_n	-21.85 kN/m
S_n	-17.71 kN/m
S_t	51.49 kN/m

	Q (°)	u_r (mm)	N (kN/m)	M (kNm/m)	V (kN/m)
Crown	0	-4.09	775.65	-25.82	0.00
	10	-3.86	780.86	-24.26	-3.57
	20	-3.17	795.85	-19.78	-6.72
	30	-2.12	818.81	-12.91	-9.05
	40	-0.82	846.98	-4.48	-10.29
	45	-0.14	861.97	0.00	-10.45
	50	0.55	876.96	4.48	-10.29
	60	1.84	905.14	12.91	-9.05
	70	2.90	928.10	19.78	-6.72
	80	3.58	943.09	24.26	-3.57
Axis	90	3.82	948.30	25.82	0.00

Full Slip Condition

Calculations (As per Curtis, 1976)	
N_0	325.62 kN/m
Q_2	4.3081
S_n	9.89 kN/m
S_t	0.00 kN/m

	Q (°)	u_r (mm)	N (kN/m)	M (kNm/m)	V (kN/m)
Crown	0	-5.57	857.82	-33.24	0.0
	10	-5.23	858.45	-31.24	-4.6
	20	-4.27	860.27	-25.47	-8.6
	30	-2.78	863.06	-16.62	-11.7
	40	-0.97	866.47	-5.77	-13.2
	45	0.00	868.29	0.00	-13.5
	50	0.97	870.11	5.77	-13.2
	60	2.78	873.53	16.62	-11.7
Axis	70	4.27	876.31	25.47	-8.6
	80	5.23	878.13	31.24	-4.6
	90	5.57	878.76	33.24	0.0

50% Slip Condition

Q (°)	u_r (mm)	N (kN/m)	M (kNm/m)	V (kN/m)	
0	-4.83	816.74	-29.53	0.00	Crown
10	-4.54	819.65	-27.75	-3.57	
20	-3.72	828.06	-22.62	-6.72	
30	-2.45	840.93	-14.77	-9.05	
40	-0.90	856.73	-5.13	-10.29	
45	-0.07	865.13	0.00	-10.45	
50	0.76	873.54	5.13	-10.29	
60	2.31	889.33	14.77	-9.05	
70	3.58	902.21	22.62	-6.72	Axis
80	4.41	910.61	27.75	-3.57	
90	4.70	913.53	29.53	0.00	

4.1.4 Case-4: Long Term : GWT (@GL) without Surcharge

Table 4.4: Analytical Calculations for Case-4

GEOMETRY OF TUNNEL:		LOADINGS:	
External diameter of tunnel (d_e)	6.350 m	Surcharge (q_z)	0.00 kN/m ²
Thickness of lining (h)	0.275 m	Factor of safety SF(u)	1.00 kN/m ²
Compression area (h_c)	0.000 m	Factor of safety SF(s')	1.00 kN/m ²
Radius to extrados of lining (r_e)	3.175 m	Hydrostatic pressure (u)	170.92 kN/m ²
Centroid radius of lining (r_o)	3.038 m	Unfactored effective vertical stress (q_1)	116.36 kN/m ²
Overburden above tunnel roof (z)	13.917 m	Factored effective vertical stress (s'_v)	116.36 kN/m ²
Overburden above tunnel axis (z_o)	17.092 m	Effective horizontal stress (s'_h) = $k \cdot s'_v$	58.18 kN/m ²
Water level above tunnel axis (h_w)	17.092 m	Distortional pressure (p_0) = $s'_v - s'_h$	58.18 kN/m ²
		Uniform pressure (p_u) = $(\sigma'_v + \sigma'_h) / 2$	87.27 kN/m ²
		Shear strength (t) = $c' + p_u \cdot \tan j'$	50.38 kN/m ²

PROPERTIES OF SOIL & WATER		SEGMENTAL LINING PROPERTIES	
Effective unit weight of soil (g'_k)	10.31 kN/m ³	Concrete grade (C)	40/50
Average unit weight of soil (g_k)	20.31 kN/m ³	Mean concrete strength (f_{cm})	50 MPa
Lateral pressure ratio (k)	0.500	Plain strain elastic Modulus of lining (E_t^*)	18,085 MPa
Effective cohesion of ground (c'_d)	0.0 kN/m ²	Elastic Modulus of lining (E_l)	17,678 MPa
Effective friction angle of ground (j'_d)	30.0 °	Poisson's ratio of lining (n_l)	0.15
Unit weight of water (g_w)	10.0 kN/m ³	Area of lining per meter (A)	0.275 m ²
Deformation modulus of ground (E_g)	40,500 kPa	Total number of regular segments (N)	5
Poisson's ratio of ground (n_g)	0.25	Second moment of area of lining (I_l)	1.73E-03 m ⁴
		Effective Second moment of area of lining ($I_{l,eff}$)	1.109E-03 m ⁴

No Slip Condition

Calculations (As per Curtis,1976)			Q	u _r	N	M	V
			(°)	(mm)	(kN/m)	(kNm/m)	(kN/m)
N ₀	271.70 kN/m	Crown	0	-3.53	740.92	-21.97	0.00
Q ₂	4.3081		10	-3.33	745.35	-20.64	-3.04
(if S _t < t): S _n	-15.07 kN/m		20	-2.75	758.10	-16.83	-5.71
(if S _t > t): S _n	-18.60 kN/m		30	-1.85	777.65	-10.98	-7.70
S _n	-15.07 kN/m		40	-0.75	801.62	-3.81	-8.76
S _t	43.81 kN/m		45	-0.17	814.37	0.00	-8.89
			50	0.42	827.13	3.81	-8.76
			60	1.52	851.10	10.98	-7.70
			70	2.41	870.64	16.83	-5.71
			80	3.00	883.40	20.64	-3.04
		Axis	90	3.20	887.83	21.97	0.00

Full Slip Condition

Calculations (As per Curtis,1976)	
N_0	277.08 kN/m
Q_2	4.3081
S_n	8.42 kN/m
S_t	0.00 kN/m

	Q (°)	u_r (mm)	N (kN/m)	M (kNm/m)	V (kN/m)
Crown	0	-4.74	810.84	-28.29	0.0
	10	-4.45	811.38	-26.58	-3.9
	20	-3.63	812.93	-21.67	-7.4
	30	-2.37	815.30	-14.14	-9.9
	40	-0.82	818.20	-4.91	-11.3
	45	0.00	819.75	0.00	-11.4
	50	0.82	821.30	4.91	-11.3
	60	2.37	824.21	14.14	-9.9
Axis	70	3.63	826.58	21.67	-7.4
	80	4.45	828.12	26.58	-3.9
	90	4.74	828.66	28.29	0.0

50% Slip Condition

Q (°)	u_r (mm)	N (kN/m)	M (kNm/m)	V (kN/m)	
0	-4.14	775.88	-25.13	0.00	Crown
10	-3.89	778.36	-23.61	-3.04	
20	-3.19	785.51	-19.25	-5.71	
30	-2.11	796.47	-12.56	-7.70	
40	-0.79	809.91	-4.36	-8.76	
45	-0.08	817.06	0.00	-8.89	
50	0.62	824.21	4.36	-8.76	
60	1.94	837.65	12.56	-7.70	
70	3.02	848.61	19.25	-5.71	Axis
80	3.73	855.76	23.61	-3.04	
90	3.97	858.24	25.13	0.00	

4.2 FEM ANALYSIS USING PLAXIS SOFTWARE

Numerical analysis is used to define the ground load to be applied at tunnel segmental lining. Thus, PLAXIS 2D is used modelling staged construction to analyze stress distribution.

The coordinate system is set up with the Y-axis coinciding with the vertical axis in the model center. The model is 100 meters long and 50 meters high. The model is meshed with 15-noded quadratic elements. The ground level is located at +0.00m. The standard boundary conditions are applied in the model meaning that no horizontal deformations are allowed in the vertical boundaries and no vertical deformations are possible at the bottom edge of the model. The most decisive situation is modelling two tubes with the minimum distance between each other is chosen.

Hardening soil model is applied as constitutive model. Thus, the geotechnical input parameters for both the granular and cohesive soil are used as per APPENDIX I & II.

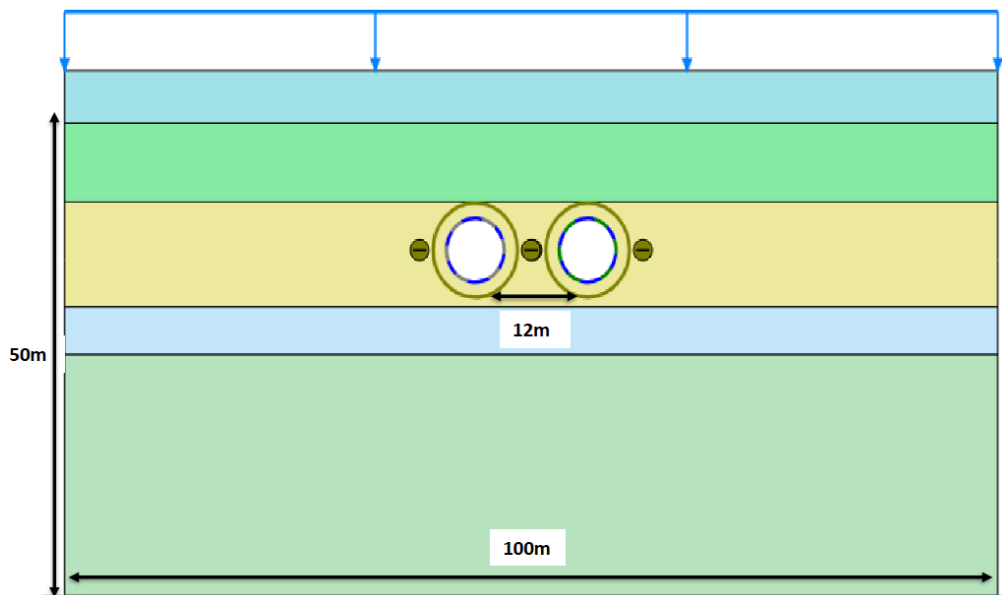


Figure 4.1 : Plaxis Calculation Model

The segmental lining is modelled by means of plate structural elements with elastic properties considering a reduced moment of inertia of the complete segment ring due to the presence of segment joints leading to increased flexibility of the ring.

In this regard, equivalent lining stiffness is used according to Muir Wood (1975) & Curtis (1976) as per APPENDIX-IV.

Excavation stages are modelled for different phases in PLAXIS as presented below;

Table 4.5: Stages for PLAXIS Analysis

Stage	Calculation procedure	Start from stage	Description
0	K_0 Procedure	-	Initial stress state
1	Plastic	0	Surcharge of 24kPa and reset of displacements
2	Plastic	1	Left tunnel excavation and installing segmental lining
3	Plastic	2	Right tunnel excavation and installing segmental lining
4	Plastic	3	Future Building Surcharge Case - 50 kPa - Long Term

The following results can only be used for the segment lining design. No conclusions can be drawn regarding the ground surface settlements from this analysis.

The model indicated above can be used to obtain normal effective stresses around the tunnel lining to define ground loads acting on the segmental lining of tunnel.

Detailed calculations and analysis have been presented in the subsequent sections.

4.2.1 Case-1: Short Term : GWT@ HRL with Uniform Surcharge of 50 kPa
 PLAXIS analysis and force contours for this case are presented below;

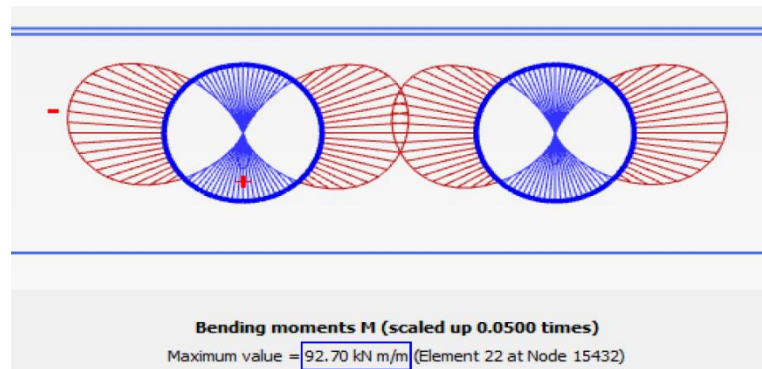


Figure 4.2 : Bending Moment from PLAXIS for Case-1

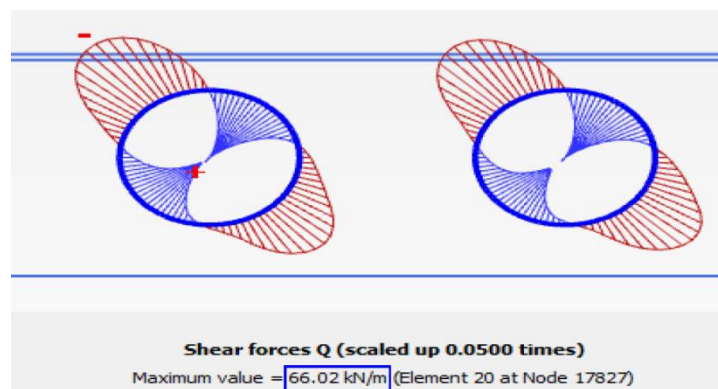


Figure 4.3 : Shear Force from PLAXIS for Case-1

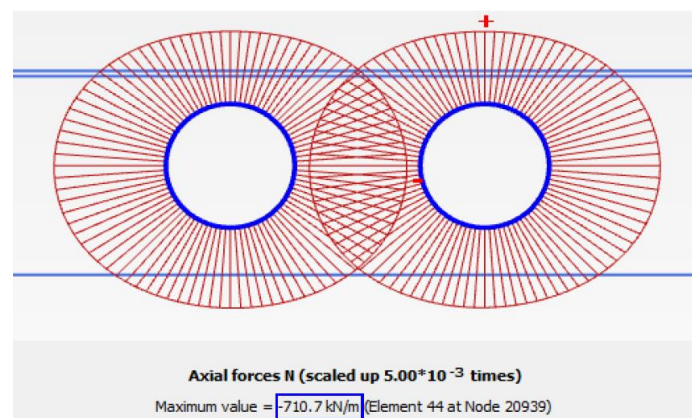


Figure 4.4 : Shear Force from PLAXIS for Case-1

4.2.2 Case-2: Long Term : GWT (Dry Case) with Uniform Surcharge of 50 kPa
PLAXIS analysis and force contours for this case are presented below;

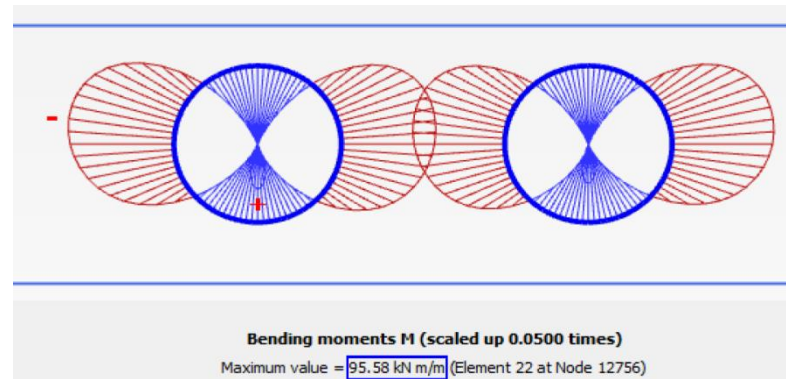


Figure 4.5 : Bending Moments from PLAXIS for Case-2

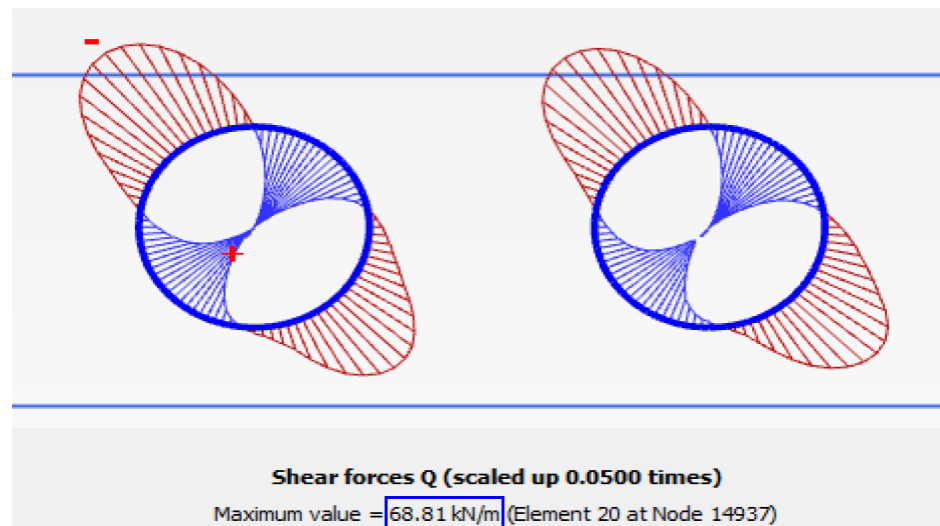


Figure 4.6 : Shear Force from PLAXIS for Case-2

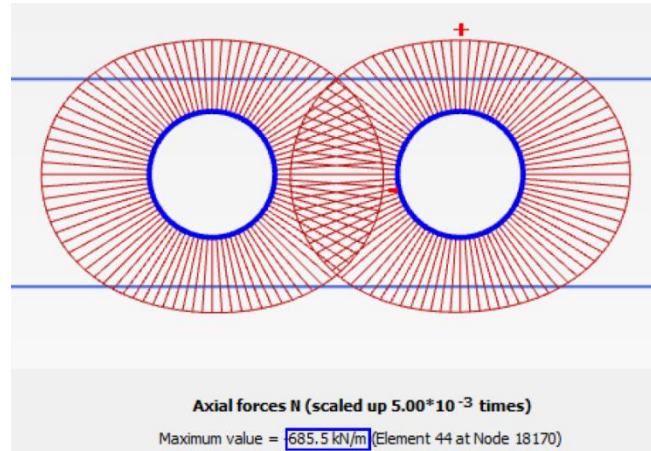


Figure 4.7 : Axial Force from PLAXIS for Case-2

4.2.3 Case-3: Long Term : GWT (@GL) with Uniform Surcharge of 50 kPa

PLAXIS analysis and force contours for Case-3 case are presented below;

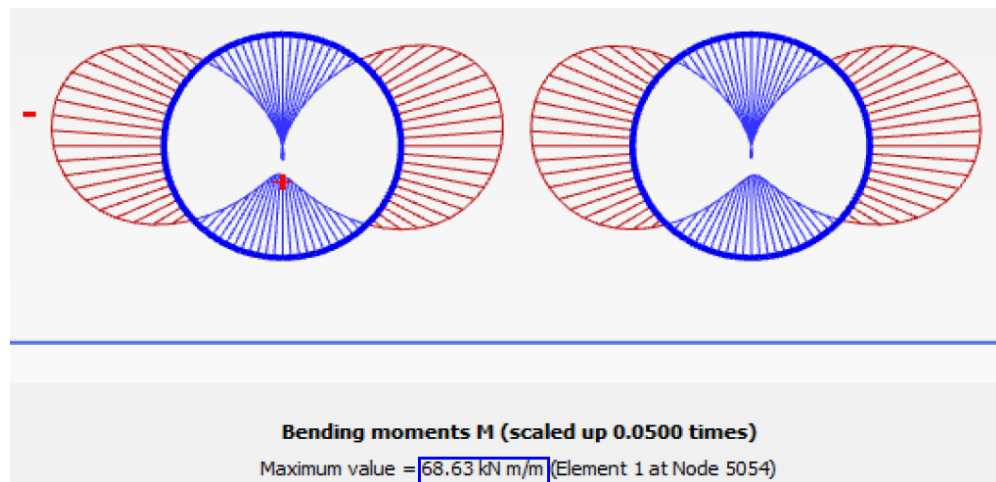


Figure 4.8 : Bending Moment from PLAXIS for Case-3

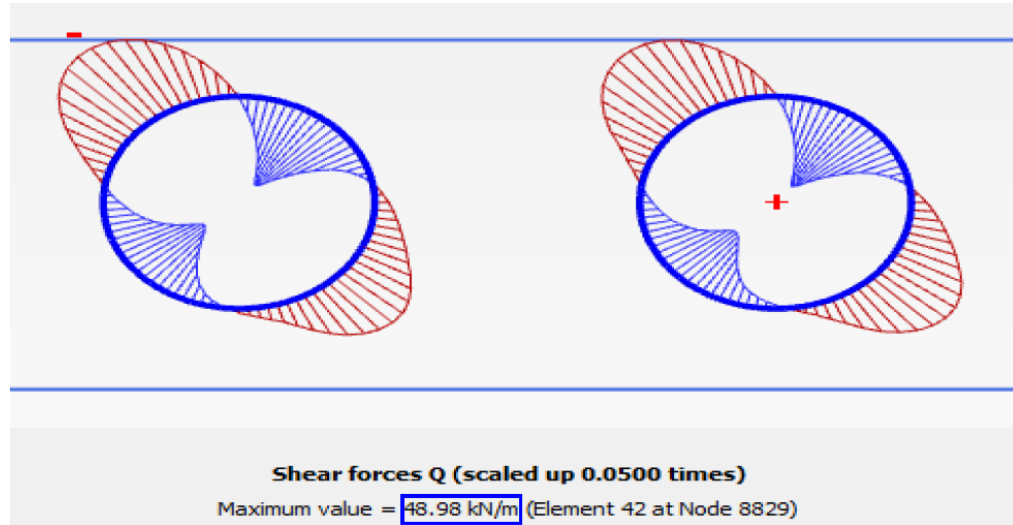


Figure 4.9 : Shear Force from PLAXIS for Case-3

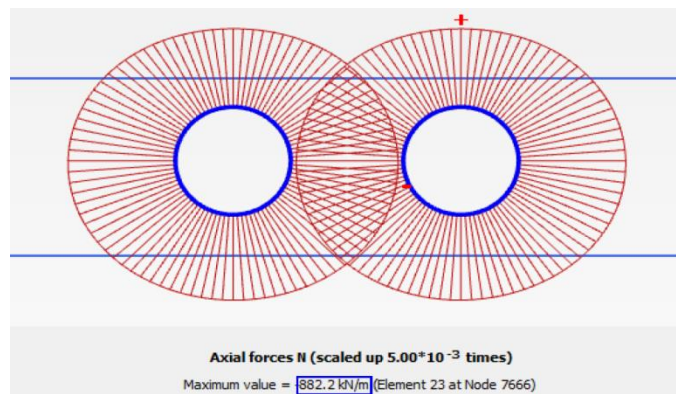
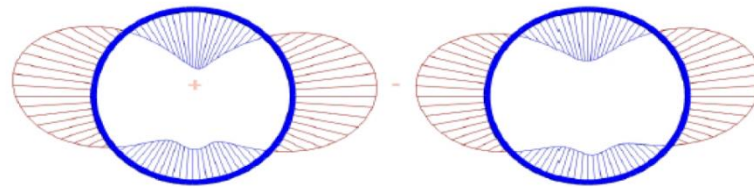


Figure 4.10 : Axial Force from PLAXIS for Case-3

4.2.4 Case-4: Long Term : GWT (@GL) without Surcharge

PLAXIS analysis and force contours for Case-4 case are presented below;



Bending moments M (scaled up 0.100 times)

Maximum value = 20.69 kN m/m (Element 22 at Node 5056)

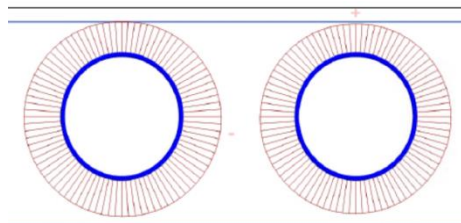
Figure 4.11 : Bending Moment from PLAXIS for Case-4



Shear forces Q (scaled up 0.0400 times)

Maximum value = 19.52 kN/m (Element 19 at Node 5903)

Figure 4.12 : Shear Force from PLAXIS for Case-4



Axial forces N (scaled up 2.50×10^{-3} times)

Maximum value = 604.1 kN/m (Element 44 at Node 7666)

Figure 4.13 : Axial Force from PLAXIS for Case-4

4.3 SUMMARY OF RESULTS

Based on the analytical calculation using Muir-Wood & Curtis approach and FEM analysis, the results of Bending Moments, Shear Forces and Axial Forces in segmental lining are summarized as follows;

4.3.1 Bending Moments: The values of maximum bending moments are given below in Tabular as well as Graphical form.

Table 4.6: Results of Maximum Bending Moment (M) [in kNm/m]

CASES	Analytical Calculations (Based on Muir-Wood & Curtis) (Mmax in kNm/m)			FEM Analysis (Plaxis)
	No Slip	Full Slip	50% Slip	
Case-1	55.30	60.60	57.95	92.70
Case-2	44.13	56.83	50.48	95.58
Case-3	25.82	33.24	29.53	68.63
Case-4	21.97	28.29	25.13	20.69

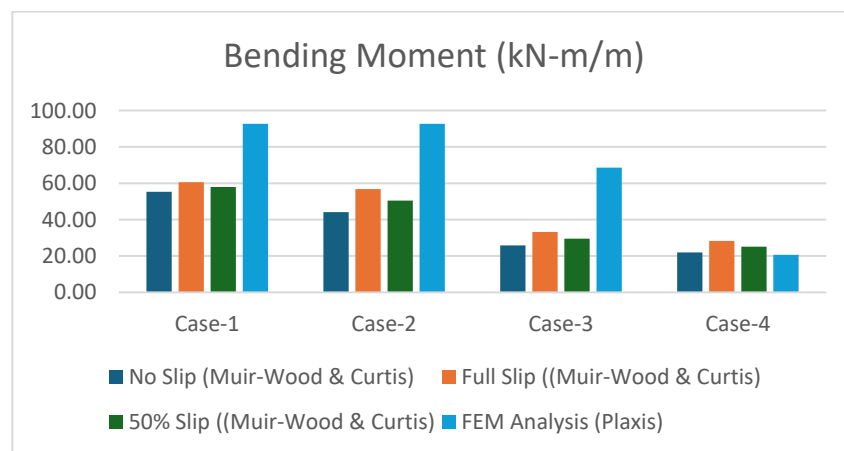


Figure 4.14 : Graph showing Bending Moments for both Methods

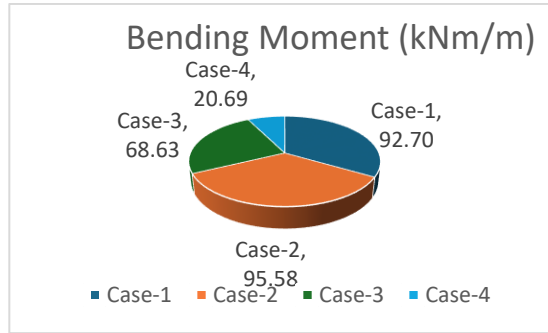


Figure 4.15 : Bending Moments from FEM Analysis

4.3.2 Shear Force: The values of maximum shear forces are given below in Tabular as well as Graphical form.

Table 4.7: Results of Maximum Shear Force (V) [in ken/m]

CASES	Analytical Calculations (Based on Muir-Wood & Curtis) (Vmax in kN/m)			FEM Analysis (Plaxis)
	No Slip	Full Slip	50% Slip	
Case-1	22.38	24.50	22.38	66.02
Case-2	17.86	23.00	17.86	68.81
Case-3	10.45	13.50	10.45	68.63
Case-4	8.89	11.40	8.89	19.52

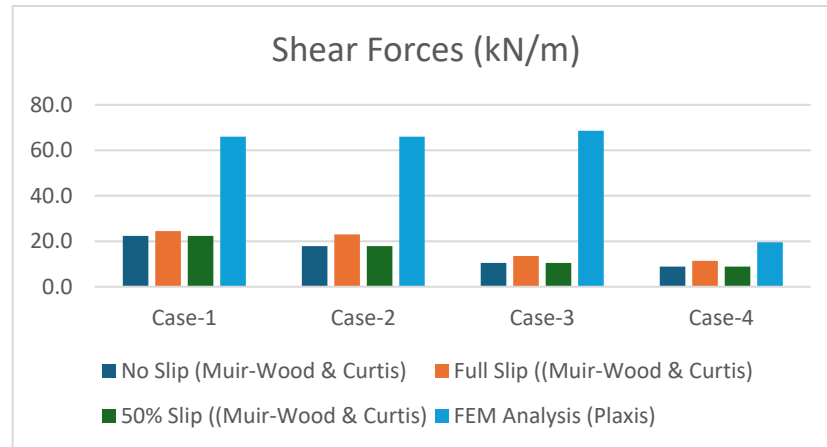


Figure 4.16 : Graph showing Shear Forces for both Methods

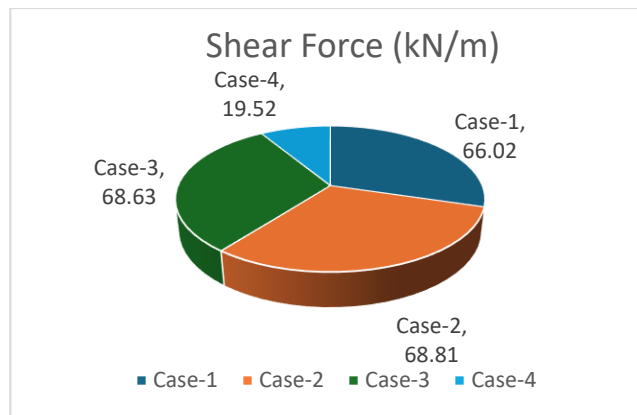


Figure 4.17 : Shear Forces from FEM Analysis

4.3.3 Axial Force: The values of maximum axial forces are given below in Tabular as well as Graphical form.

Table 4.8: Results of Maximum Axial Force (N) [in kN/m]

CASES	Analytical Calculations (Based on Muir-Wood & Curtis) (Nmax in kN/m)			FEM Analysis (Plaxis)
	No Slip	Full Slip	50% Slip	
Case-1	697.62	621.12	659.37	710.70
Case-2	693.40	574.53	633.97	685.50
Case-3	948.30	878.76	913.53	882.20
Case-4	887.83	828.66	858.24	604.10

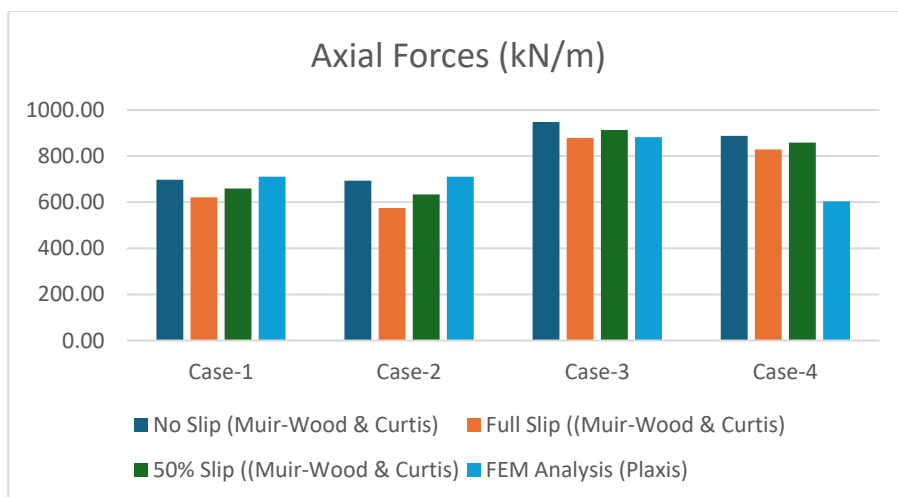


Figure 4.18 : Graph showing Axial Forces for both Methods

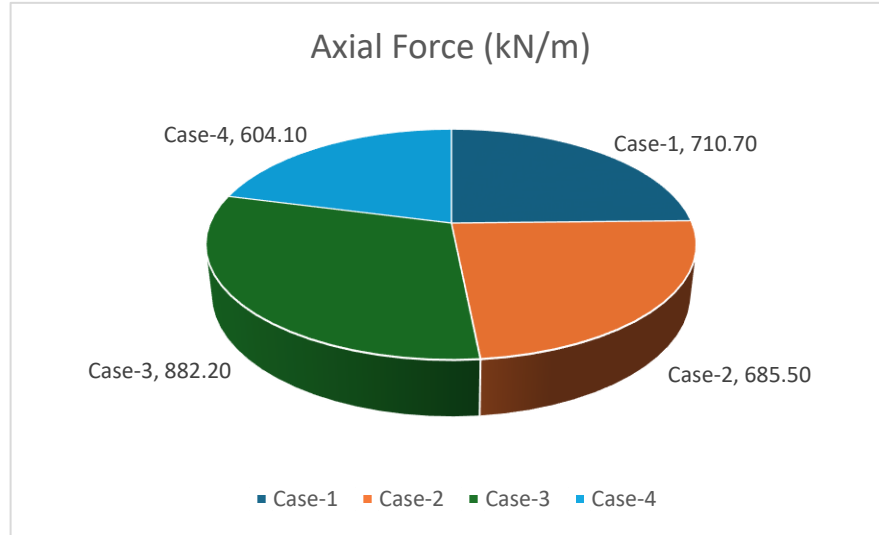


Figure 4.19 : Axial Forces from FEM Analysis

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

The bending moments obtained from FEM analysis are higher than those from Analytical calculations using Muir-Wood and Curtis approach, except for the Case-4 (i.e. without Surcharge).

CASES	Analytical Calculations (Based on Muir-Wood & Curtis) (Mmax in kNm/m)			FEM Analysis (Plaxis)
	No Slip	Full Slip	50% Slip	
Case-1	55.30	60.60	57.95	92.70
Case-2	44.13	56.83	50.48	95.58
Case-3	25.82	33.24	29.53	68.63
Case-4	21.97	28.29	25.13	20.69

CASES	Analytical Calculations (Based on Muir-Wood & Curtis) (Vmax in kN/m)			FEM Analysis (Plaxis)
	No Slip	Full Slip	50% Slip	
Case-1	22.38	24.50	22.38	66.02
Case-2	17.86	23.00	17.86	68.81
Case-3	10.45	13.50	10.45	68.63
Case-4	8.89	11.40	8.89	19.52

Shear forces in FEM analysis are generally on higher side in all four cases.

The axial forces in FEM analysis are also higher than those from Analytical calculations, except for Case-4.

CASES	Analytical Calculations (Based on Muir-Wood & Curtis) (Nmax in kN/m)			FEM Analysis (Plaxis)
	No Slip	Full Slip	50% Slip	
Case-1	697.62	621.12	659.37	710.70
Case-2	693.40	574.53	633.97	685.50
Case-3	948.30	878.76	913.53	882.20
Case-4	887.83	828.66	858.24	604.10

From this study, it can be concluded that the value obtained through FEM analysis are generally on conservative side, however, it is recommended that these values should be verified through independent analytical calculations to arrive at maximum forces to be used for design as worst case scenario. The higher one obtained from FEM analysis and Analytical calculations shall be used judiciously for the structural design of Precast segmental lining to ensure safe and optimum design of Metro tunnels.

Despite the recent advances in structural designs of tunnels, more research is necessary for analysis of precast segmental lining for metro tunnels due to its highly complex behavior. This research will contribute towards more accurate and precise analysis of metro tunnels for different loadings and ground conditions in future.

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APPENDIX-I

I.1 Geotechnical Parameters

Depth (m)	Soil Layer	SPT N_{60}	Dry Density (kN/m^3)	Bulk Density (kN/m^3)	Saturated Density (kN/m^3)	Design Shear Strength Parameters				E_u (MPa)	E' (MPa)	Poisson's Ratio [#] μ		Permeability k (m/s)	Coeff. of Earth Pressure at rest K_0	Coeff. of Earth Pressure at Active state K_a	Coeff. of Earth Pressure at Passive state K_p
						Undrained Condition		Drained Condition				Undrained Condition	Drained Condition				
						C_u (kPa)	Φ_u (deg)	C' (kPa)	Φ' (deg)								
0.0-5.0	CL/CI-1	8	15.5	17.5	20.4	45	0	0	26	9.0	7.0	0.45	0.25	2.34×10^{-7}	0.56	0.39	2.56
5.0-12.5	CL/CI-2	25	16.1	19.0	20.2	140	0	0	27	25.0	20.0	0.45	0.25	1.45×10^{-7}	0.55	0.38	2.66
12.5-22.5	CL	45	16.7	20.3	20.4	250	0	0	30	45.0	40.0	0.45	0.25	1.77×10^{-7}	0.53	0.36	2.77
22.5-27.0	SM	70	16.7	20.3	20.4	0	0	0	33	-	70.0	-	0.30	3.03×10^{-7}	0.47	0.31	3.25
> 27.0	CI	90	16.7	20.3	20.4	300	0	0	30	95.0	75.0	0.45	0.25	2.28×10^{-7}	0.53	0.36	2.77

I.2 Hardening Soil Parameters for Tunnel

Layer Name	Depth_min	Depth_max	total depth	depth_mid	Bulk Unit Wt	C'	Φ'		K_0	μ'	E_i (at mid of each layer)	Pref	m	σ_3'	σ_1'	$(E_{oed})_{ref}$	$(E_{50})_{ref}$	$(E_u)_{ref}$	R_f
	m	m	m	m	kN/m3	kPa	Degree	Radian			kPa	(Kpa)		kPa	kPa	kPa	kPa	kPa	
CL/CI-1	0	5	5	2.5	17.5	0	26	0.454	0.56	0.25	7000.000	100.00	0.5	24.57	43.75	12699.61	15874.51	38098.8	0.9
CL/CI-2	5	12.5	7.5	8.75	19	0	27	0.471	0.55	0.25	20000.000	100.00	0.5	86.68	158.75	19048.22	23810.27	57144.7	0.9
CL	12.5	22.5	10	17.5	20.3	0	30	0.524	0.53	0.25	40000.000	100.00	0.5	175.70	331.5	26363.28	32954.1	79089.8	0.9
SM	22.5	27	4.5	24.75	20.9	0	33	0.576	0.47	0.25	70000.000	100.00	0.5	225.61	480.025	55924.03	69905.03	167772.1	0.9

APPENDIX-II

Materials: Soil and Interfaces - Hardening Soil

Identification number	1	2	3	4	5
Identification	CL/CI 1	CL/CI 2	CL	SM	CI
Soil model	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil
Drainage type	Drained	Drained	Drained	Drained	Drained
Colour					
Comments					
y _{unsat}	17.50	19.00	20.30	20.30	20.30
y _{sat}	20.40	20.20	20.40	20.40	20.40
e _{init}	0.5000	0.5000	0.5000	0.5000	0.5000
n _{init}	0.3333	0.3333	0.3333	0.3333	0.3333
Input method	Direct	Direct	Direct	Direct	Direct
Rayleigh α	0.000	0.000	0.000	0.000	0.000
Rayleigh β	0.000	0.000	0.000	0.000	0.000
Identification number	1	2	3	4	5
Identification	CL/CI 1	CL/CI 2	CL	SM	CI
Soil model	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil
Drainage type	Drained	Drained	Drained	Drained	Drained
Colour					
Comments					
E ₅₀ ^{^ref}	12.69E3	19.04E3	26.36E3	55.90E3	75.00E3
E _{oed} ^{^ref}	12.69E3	19.04E3	26.36E3	55.90E3	75.00E3

Identification number	1	2	3	4	5
E _{ur} ^{^ref}	38.09E3	57.14E3	79.09E3	167.8E3	225.0E3
v _{ur}	0.2500	0.2500	0.2500	0.3000	0.2500
Use defaults	True	True	True	True	True
K ₀ ^{^nc}	0.5616	0.5460	0.5305	0.4701	0.5305
R _f	0.9000	0.9000	0.9000	0.9000	0.9000
Determination	v-undrained definition	v-undrained definition	v-undrained definition	v-undrained definition	v-undrained definition
v _u definition method	Direct	Direct	Direct	Direct	Direct
v _u ,equivalent (nu)	0.4950	0.4950	0.4950	0.4950	0.4950
Skempton B	0.9833	0.9833	0.9833	0.9783	0.9833
K _{w,ref} /n	1.493E6	2.240E6	3.100E6	6.292E6	8.820E6
Identification number	1	2	3	4	5
Identification	CL/CI 1	CL/CI 2	CL	SM	CI
Soil model	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil
Drainage type	Drained	Drained	Drained	Drained	Drained
Colour					
Comments					
Classification type	USDA	USDA	USDA	USDA	USDA
SWCC fitting method	Van Genuchten	Van Genuchten	Van Genuchten	Van Genuchten	Van Genuchten
Permeability fitting method	Van Genuchten	Van Genuchten	Van Genuchten	Van Genuchten	Van Genuchten
Soil class (USDA)	Silty clay	Silty clay	Silty clay	Loamy sand	Silty clay
< 2 μ m	48.00	48.00	48.00	6.000	48.00
2 μ m - 50 μ m	45.00	45.00	45.00	11.00	45.00
50 μ m - 2 mm	7.000	7.000	7.000	83.00	7.000
Identification number	1	2	3	4	5

APPENDIX-II Continues.....

Identification number	1	2	3	4	5
Cross permeability	Impermeable	Impermeable	Impermeable	Impermeable	Impermeable
Drainage conductivity, dk	m ³ /day/m	0.000	0.000	0.000	0.000
R_thermal	m ² K/kW	0.000	0.000	0.000	0.000
Identification number	1	2	3	4	5
Identification	CL/CI 1	CL/CI 2	CL	SM	CI
Soil model	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil
Drainage type	Drained	Drained	Drained	Drained	Drained
Colour					
Comments					
K_0 determination	Manual	Manual	Manual	Manual	Manual
K_0,x	0.5616	0.5500	0.5300	0.4700	0.5300
K_0,z	0.5616	0.5500	0.5300	0.4700	0.5300
K_0,x = K_0,z	True	True	True	True	True
P.O.P	kN/m ²	0.000	0.000	0.000	0.000
O.C.R	1.000	1.000	1.000	1.000	1.000

Identification number	1	2	3	4	5
Identification	CL/CI 1	CL/CI 2	CL	SM	CI
Soil model	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil
Drainage type	Drained	Drained	Drained	Drained	Drained
Colour					
Comments					
c_s	kJ/t/K	0.000	0.000	0.000	0.000
λ_s	kW/m/K	0.000	0.000	0.000	0.000
ρ_s	t/m ³	0.000	0.000	0.000	0.000
Thermal expansion type	Isotropic	Isotropic	Isotropic	Isotropic	Isotropic
α_sv	1/K	0.000	0.000	0.000	0.000
Phase change	False	False	False	False	False
D_v	m ² /day	0.000	0.000	0.000	0.000
f_Tv	0.000	0.000	0.000	0.000	0.000
Identification number	1	2	3	4	5
Identification	CL/CI 1	CL/CI 2	CL	SM	CI
Soil model	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil
Drainage type	Drained	Drained	Drained	Drained	Drained
Colour					
Comments					
Stiffness determination	Derived	Derived	Derived	Derived	Derived
Strength determination	Manual	Manual	Manual	Manual	Manual
R_inter	0.6700	0.6700	0.6700	0.6700	0.6700
Consider gap closure	True	True	True	True	True
δ_inter	m	0.000	0.000	0.000	0.000

APPENDIX-III

Materials: Plates

Identification number		1	2
Identification		LINING_Long Term	LINING Short Term
Material type		Elastic	Elastic
Colour			
Comments			
w	kN/m/m	6.850	6.850
Input method		Direct	Direct
Rayleigh α		0.000	0.000
Rayleigh β		0.000	0.000
Prevent punching		False	False
Identification number		1	2
Identification		LINING_Long Term	LINING Short Term
Material type		Elastic	Elastic
Colour			
Comments			
Isotropic		True	True
Identification number		1	2
Identification number		1	2
Identification		LINING_Long Term	LINING Short Term
Material type		Elastic	Elastic
Colour			
Comments			
c	kJ/t/K	0.000	0.000
λ	kW/m/K	0.000	0.000
ρ	t/m ³	0.000	0.000
α	1/K	0.000	0.000
A_eff,T	m ²	0.000	0.000

APPENDIX-IV

Lining Properties Considered in Analysis

			$I_{ring} = I_{joint} + I_{full} \cdot (4 / m^*)^2$						
			where $I_{ring} < I_{full}$ and $I_{full} = b \cdot d^3 / 12$						
			Note: * - no. of regular segments excluding the key segment.						
			Thickness	I	E-modulus	A	Weight	EA	EI
			[m]	[m ⁴]	[GPa]	[m ²]	[kN/m/m]	[kN/m]	[kNm ² /m]
			Segmental lining	0.275	0.00173				
			Ring (Short Term)	0.275	0.00111	35,355	0.275	6.875	9.72E+09
			Ring (Long Term)	0.275	0.00111	17,678	0.275	6.875	4.86E+09
			** I_{joint} has been ignored since $I_{joint} \ll I_{full}$						

APPENDIX-V

Relevant Codes

CODE	INSTITUTION	TITLE
ACI 544.7R (2016)	American Concrete Institute (ACI)	Report on Design and Construction of Fiber Reinforced Precast Concrete Tunnel Segments
AFTES (2005)	French Tunneling and Underground Engineering Association (AFTES)	Recommendation for the design, sizing and construction of precast concrete segments installed at the rear of a tunnel boring machine (TBM)
BSI PAS 8810 (2016)	British Standards Institute (BSI)	Tunnel design. Design of concrete segmental tunnel linings. Code of practice.
DAUB (2013)	German Tunnelling Committee (DAUB)	Lining Segment Design: Recommendations for the Design, Production, and Installation of Segmental Rings
JSCE (2007)	Japan Society of Civil Engineers (JSCE)	Standard Specifications for Tunneling-2006: Shield Tunnels
LTA (2008)	Singapore Land Transport Authority (LTA)	Civil Design Criteria for Road and Rail Transit Systems
ÖVBB (2011)	Austrian Society for Concrete and Construction Technology (ÖVBB)	Guideline for Concrete Segmental Lining Systems
STUVAtec (2005)	German Research Association for Underground Transportation Facilities	STUVA Recommendations for Testing and Application of Sealing Gaskets in Segmental Linings, Tunnel, 8 (2005)

(Reference: ITA Working Group 2-Research, 2019)

APPENDIX - VI

Example of Load Factors for various Governing Load Cases (ACI 544.7R, 2016)

LOAD CASE	LOAD FACTORS
Load case 1: stripping (demolding)	$1.4w$
Load case 2 : storage	$1.4 (w + F)$
Load case 3 : transportation	$1.4 (w + F)$
Load case 4 : handling	$1.4w$
Load case 5 : thrust jack forces	$1.2J$ (1.0 if max machine thrust available)
Load case 6 : tail skin grouting	$1.25 (w + G)$
Load case 7 : secondary grouting	$1.25 (w + G)$
Load case 8 : earth pressure and groundwater load	$1.25 (w + WA_p) + 1.35 (EH + EV) + 1.5 ES$
Load case 9 : longitudinal joint bursting	$1.25(w + WA_p) + 1.35 (EH + EV) + 1.5 ES$
Load case 10 : additional distortion	$1.4M_{distortion}$
Note: w = self-weight; F = self-weight of segments positioned above; J = TBM jacking force; G = grout pressure; WA_p = groundwater pressure; EV = vertical ground pressure; EH = horizontal ground pressure; ES = surcharge load; and $M_{distortion}$ = Additional distortion effect	

Load Factors for Design Parameters (Final Service Stage) (AASHTO DCRT-1-2020)

	W, WA _p		EH, EV		ES	
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
ULS	1.25	0.90	1.35	0.90	1.50	0.75
SLS	1.0		1.0		1.0	
Note: w = self-weight; WA _p = groundwater pressure; EV = vertical ground pressure; EH = horizontal ground pressure; and ES = surcharge load.						

(Reference: ITA Working Group 2-Research, 2019)

APPENDIX – VII

Design Checks and Critical Design Parameters for SLS of Tunnels Segments

SLS States	Location	Items to Check	Critical Design Parameter
Stress	Segment section	Stress in concrete	Allowable compressive stress of concrete
		Stress in reinforcement	Allowable tensile stress of steel bars
	Segment joints	Stress in concrete	Allowable compressive stress of concrete
		Stress in connectors	Allowable stress of connecting bolts
Deformation	Segmental ring	Ring deformation	Allowable deformation
	Segment joints	Joint opening	Allowable gap between segments joints
		Joint offset	Allowable offset between segments joints
Cracking	Segment section	Flexural crack width	Allowable concrete crack width
			Shear crack capacity

APPENDIX – VIII

Serviceability Limit State Design

Allowable Crack Widths:

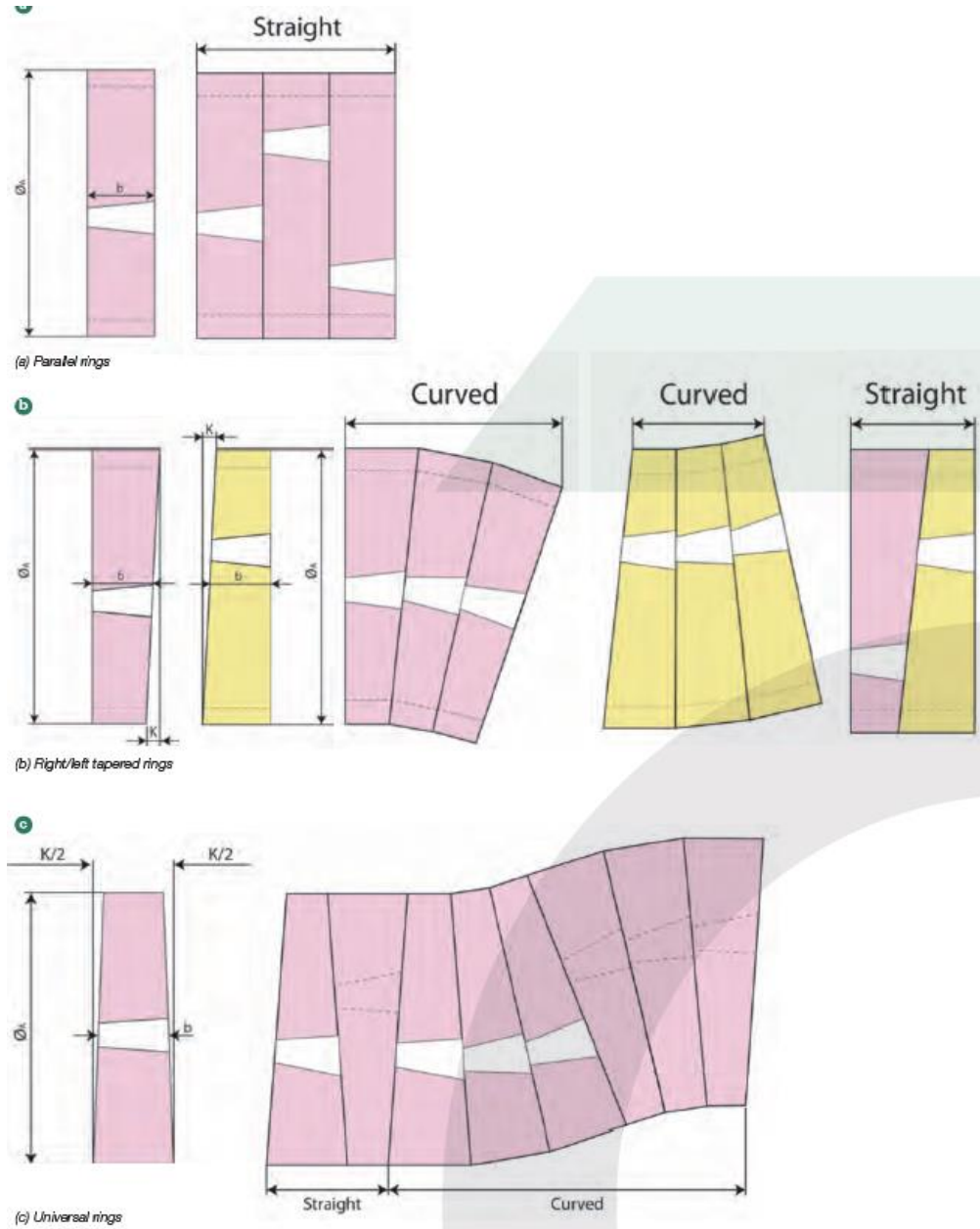
AUTHORITY	ALLOWABLE CRACK WIDTH	COMMENT
ACI 224 (2007)	0.30 mm	Structures exposed to soil
EN 1992-1-1 (2004)	0.30 mm	RC members
fib Model Code 2010 (2013)	0.20 mm	Leakage to be limited with some surface staining
Singapore Land Transport Authority design criteria (2010)	0.30 mm	-
(DAUB, 2013)	0.20 mm	0.15 mm when below groundwater table
JSCE standard (2007)	$0.004d_c$	d_c is the concrete cover over the rebar
RILEMTC 162-TDF (2003)	0.30 mm	Fiber-reinforced concrete

Allowable Crack Widths for Tunnels Segments (OVBB 2011):

REQUIREMENT CLASS	DESIGNATION	APPLICATION	REQUIREMENT	ALLOWABLE CRACK WIDTH
AT1	Largely dry	One-pass lining with very tight waterproofing requirements	Impermeable	0.20 mm (0.008 in)
AT2	Slightly moist	One-pass lining for road and railway tunnels with normal waterproofing requirements (excluding portals)	Moist, no running water in tunnel	0.25 mm (0.010 in)
AT3	Moist	One-pass lining without waterproofing requirements	Water dripping from individual	0.30 mm (0.012 in)
AT4	Wet	One-pass lining without waterproofing requirements	Water running in some places	0.30 mm (0.012 in)

APPENDIX – IX

Segment Ring Geometry & Systems (A)



(Reference: ITA Working Group 2-Research, 2019)

APPENDIX – X

Segment Ring Geometry & Systems (B)

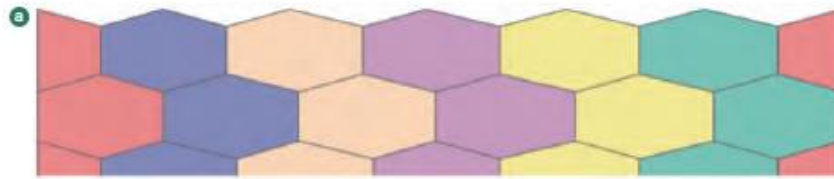


Figure 4a : Hexagonal system

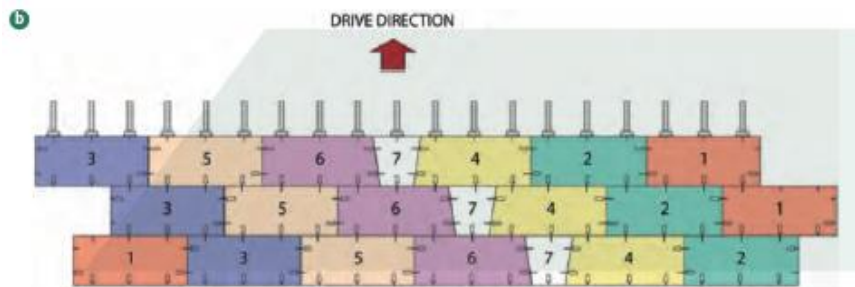


Figure 4b : Rectangular system

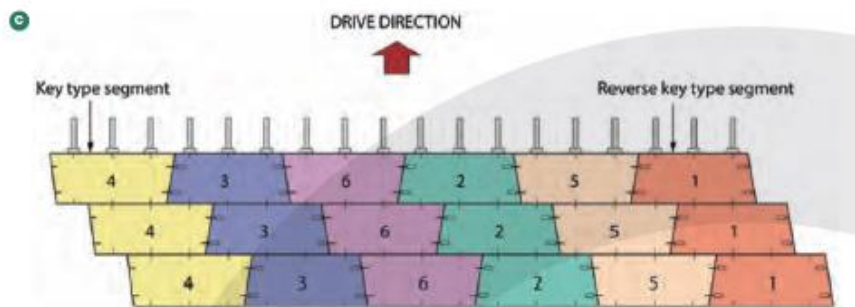


Figure 4c : Trapezoidal system

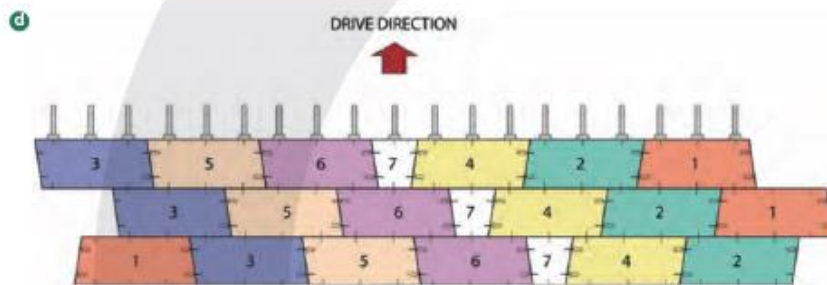


Figure 4d : Rhomboidal system

(Reference: ITA Working Group 2-Research, 2019)

APPENDIX – XI

Segment Demolding, Lifting & Storage

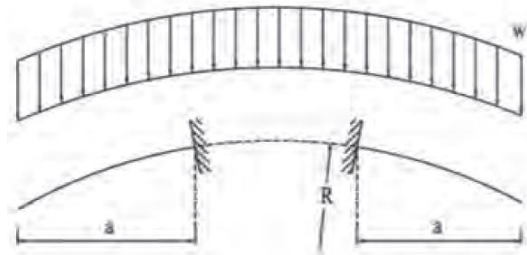
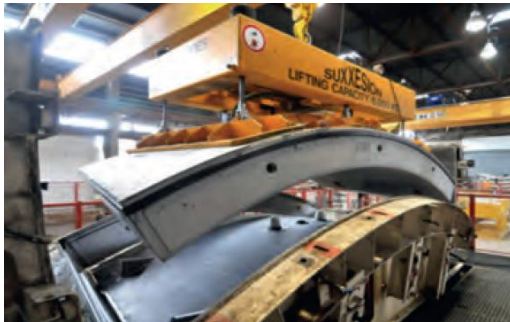


Fig. Segment Stripping (Demolding) from forms & Forces acting on segment



Fig. Segment Stacking for Storage & Transportation

APPENDIX – XII Segment Storage

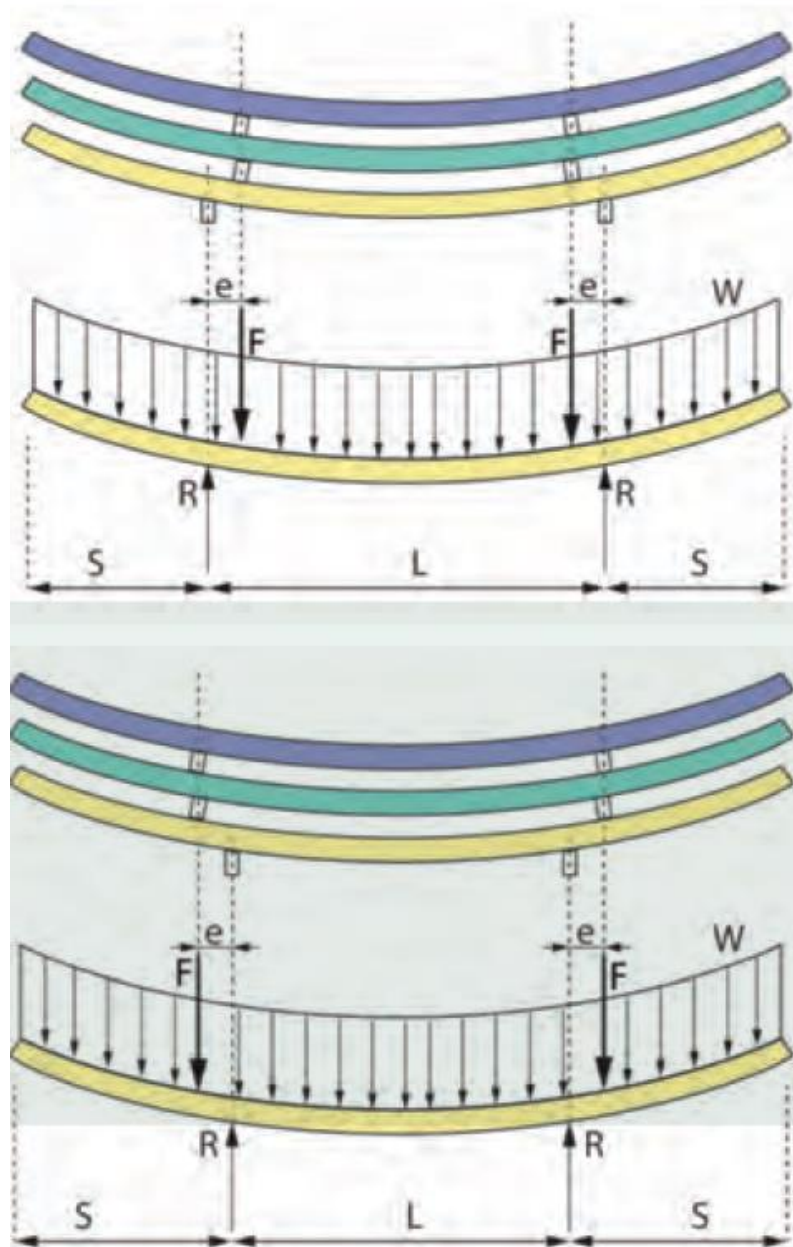


Fig. Forces acting on segment during stacking

APPENDIX – XIII

Seismic Loading

The approach used to examine the effect of seismic actions on tunnel stability is the free-field shear deformation method, which represents the most conservative condition. This method assumes that the deformation of the structure should conform to the deformation of the soil in the free field under the design earthquakes.

According IS1893:2002, for underground structures and foundations at depths of 30 m or below, the design horizontal acceleration spectrum value shall be taken as half the value obtained in previous formula, and for structures and foundations placed between the ground level and 30 m depth, the design horizontal acceleration spectrum value shall be linearly interpolated between A_h and $0.5 A_h$.

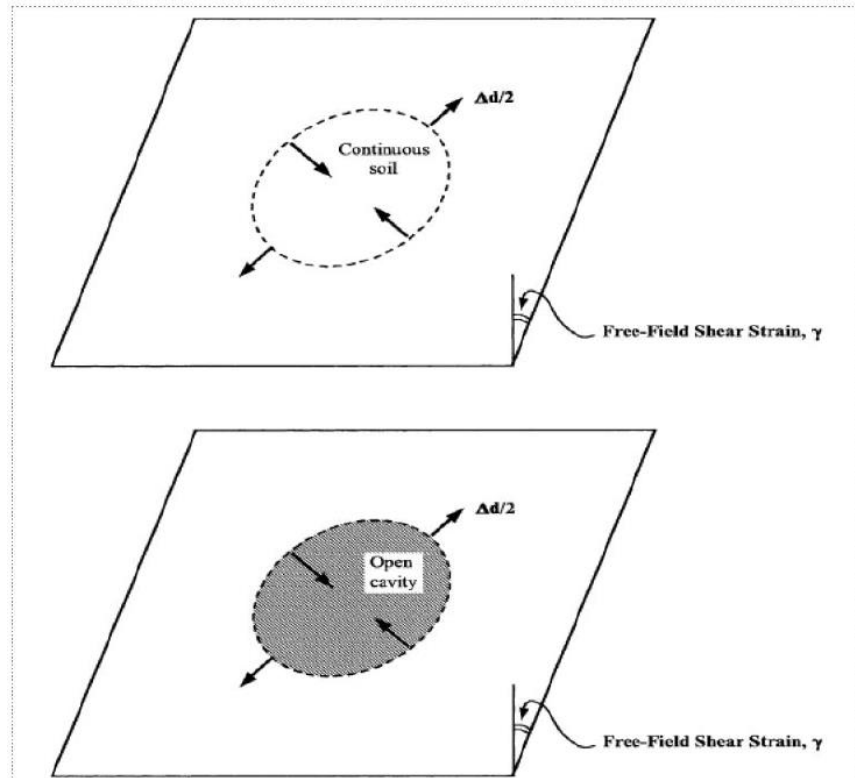


Fig. Free-field shear distortion of perforated and non-perforated ground of circular shape

APPENDIX – XIV

NOTATIONS USED BY MUIR WOOD (1975)

a, b, c, d, A, B , constants	m	mode of distortion of lining
c' cohesion (in effective stress terms)	n	number of segments in a ring of lining
E Young's modulus for lining (replaced by $E/(1-\nu_1^2)$ where lining continuous along tunnel)	p	normal pressure between ground and lining
E_g Young's modulus for ground	$\bar{p}$	mean value of p
F stress function	$\hat{p}$	maximum value of $\pm (p-\bar{p})$
F_c competence factor	p_0	excess of p on vertical axis over p on horizontal axis
G_c modulus of rigidity of the ground	p_v	value of p on vertical axis of tunnel
I second moment of area of lining per unit length of tunnel	q	discharge of water per unit area of ground in unit time
I_n effective value of I for a jointed lining	r	radius (and as suffix in radial direction)
I_j effective value of I at a joint in a lining	r_0	radius to extrados of tunnel lining
K constant	R_c	compressibility factor
k coefficient of permeability for water	R_s	stiffness factor
K_0 coefficient of earth pressure at rest	T	shear stress between ground and lining
l (as suffix) longitudinal direction	t	effective thickness of lining
M bending moment in lining per unit length of tunnel	u	radial movement of ground
N ratio of horizontal to vertical pressures in the undisturbed ground	u_0	value of u at $r=r_0$
u_{00} circumferential movement of ground at $r=r_0$	$\dot{u}_0$	maximum value of $\pm u_0$
u_w piezometric pressure at steady state of flow of ground water	θ	angle (and as suffix in circumferential direction)
Δr_0 uniform radial deflexion of lining	λ	coefficient of ground reaction
Δp uniform variation in p	ν	Poisson's ratio for ground
ϵ strain in ground	ν_1	Poisson's ratio for lining
η ratio of radius of lining centroid to that of extrados	σ	ground pressure
	$\tau_{r\theta}$	shear stress in ground in r, θ plane
	ϕ	Airy stress function
	ϕ'	angle of friction (in effective stress terms)

APPENDIX – XV

NOTATIONS USED BY CURTIS (1976)

g	gravitational acceleration	u_1	deformation of lining
H_3	water head at radius r_3	u_0	deformation of ground in absence of a lining
N	circumferential (hoop) thrust per unit length of lining	$\bar{u}$	deformation of ground inhibited by presence of a lining
P_w	pressure on lining due to water	γ	rate of creep
Q	Author's compressibility factor R_c	ϵ	strain
Q_2	analogous to the inverse of Author's stiffness factor R_s , expressed thus as for a solid lining $Q_2 = Qr_0^2/t^2$	ρ	density of water
Q_k	seepage factor	σ_v, σ_h	pre-existing vertical and horizontal stress in undisturbed ground ($\sigma_v - \sigma_h = P_0$)
S_n, S_t	normal and shear stresses	ϕ	ratio of uniaxial creep strain to immediate (elastic) strain
T_0	time interval between excavation and installation of lining		

Rishabh Tyagi

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