ITA-Working Group Research

Guidelines for Design of Shield Tunnel Lining

Preface

These guidelines present the basic concepts of shield tunnel lining and do not supersede relevant specifications of each country or each project. The aim of these guidelines is to promote advances in the design of shield tunnels in accordance with the objectives of ITA prescribed in SECTIONⅡof the Statutes of ITA.

The working to make these guidelines was started at the Working Group Research meeting in Amsterdam in 1993. After much study, discussion and investigation, they were completed on December,1999. These guidelines consists of three parts. Part I describes the outline of procedure of design. Part II presents the detailed design methods. Part III provides the references including examples of design. There are various methods to design shield tunnel lining and these guidelines gives no priority to a specified method. They introduce design methods generally and widely. Usually, shield tunnel is excavated in soft ground, compared to rock tunnel. The parameters of lining such as dimension and strength of materials are subject to not only ground condition but also construction condition. When actually designing tunnel lining, it is needed much experience and practice. It is not expected that these guidelines would cover everything to design tunnel lining, but it may be very helpful to design it. It is hoped that they will be continuously improved with the progress of tunnelling technology.

I highly appreciate Monsieur Yann Leblais who led our study as Animateur, Professor Andre Assis and Professor Z Eisenstein who guided our study as Tuteur and Former Tuteur respectively, Herr Dr.Harald Wagner, Professor Teodor Iftimie, Dr.Birger Schmidt, Signor Piergiogio Grasso who greatly contributed to this study, and members of Research and Development Committees of Japan Tunnelling Association chaired by Professor Toru Konda who made the draft of these guidelines.

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PART I

OUTLINE TO DESIGN LINING

After planning works of tunnel, the lining of shield tunnel is designed with the following sequence, as a rule.

1. Decisiopn of specification, code or standard for design works
Tunnel to be constructed should be designed with appropriate specification standard, code or standard, which are indicated by persons in charge of project or decided by discussion between designers and them.

2. Decision of inner dimension of tunnel
Inner diameter of tunnel to be designed should be decided in consideration of the space which is demanded to tunnel. This space is decided by;
Construction gauge and car gauge in case of railway tunnel,
Traffic volume and number of lanes in case of road tunnel,
Discharge incase of water tunnel and sewer tunnel,
Kind of facilities and their dimension in case of common duct.

3. Decision of load conditions
The loads acting on lining are ground pressure such as earth pressure and water pressure, dead load, reaction, surcharge and thrust force of shield jacks, e.t.c.. Designer should select the critical cases to design lining.

4. Decision of lining conditions
Designer should decide the lining condition such as dimension of lining (thickness), strength and characteristics of materials and arrangement of reinforcement, e.t.c..

5. Computation of member forces
Designer should compute member forces such as bending moment, axial force and shear force of lining with appropriate models and design methods.

6. Check of safety
Designer should check the safety of lining against the computed member forces in consideration of critical conditions of them.

7. Review
If designed lining is not safe against design loads, designer should change lining

condition and design lining again. And, if designed lining is safe but not economical, designer should change lining condition and design lining again.

8. Approval of design

If designer judges that designed lining is safe, economical and optimum, documents of design should be approved by persons in charge of project.

Figure 1 shows the flow chart to design tunnel lining.

The annex is a summarized schematic example of step by step design procedure.

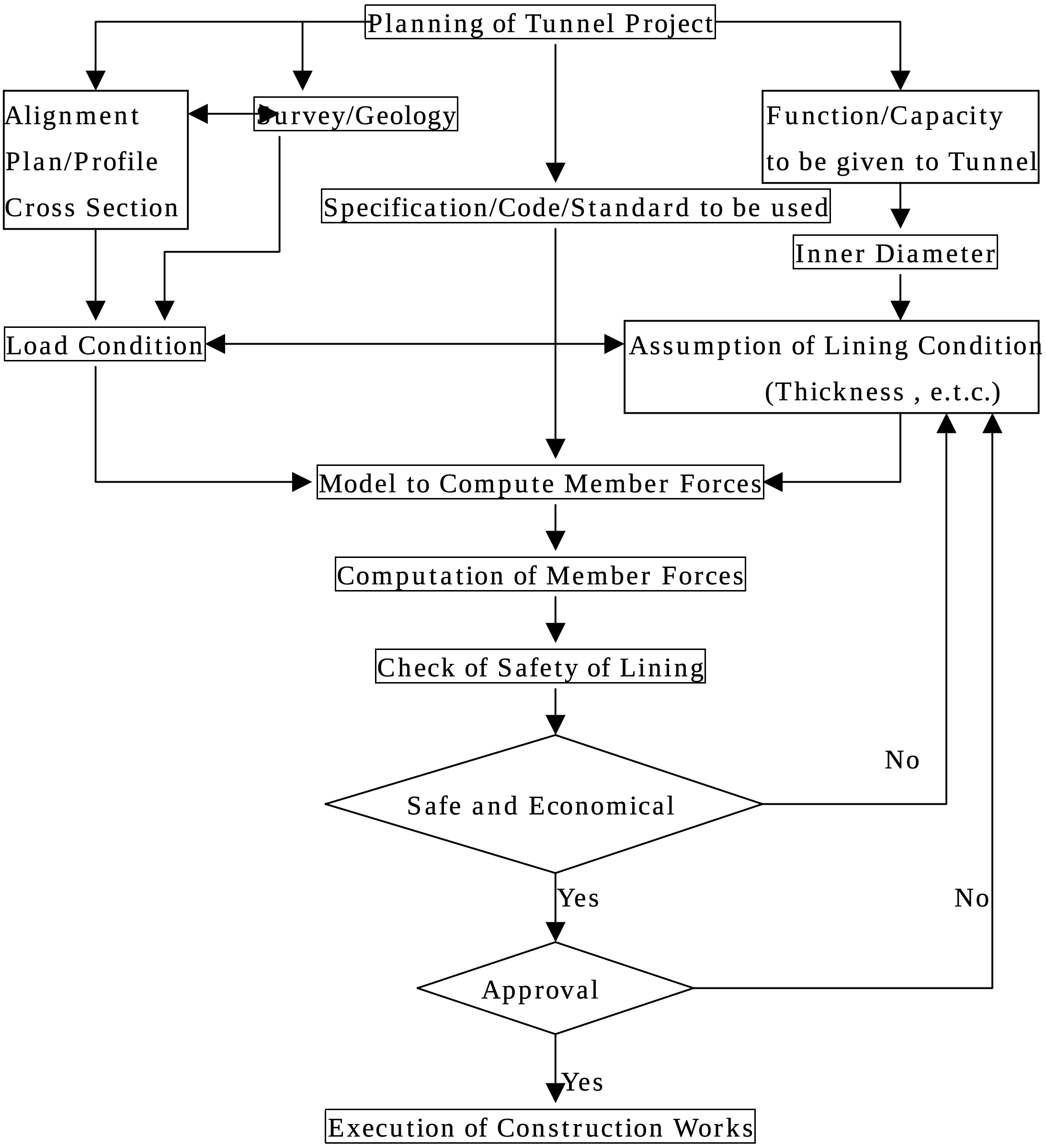


Figure 1 Flow Chart to design Tunnel Lining

ANNEX

Schematic Example of Step by Step Design Procedure

WORKING GROUP 2 "RESEARCH"

Recommended guidelines for design of shield tunnel lining.

Summarized schematic example of step by step design procedure.

STEP 1 **DEFINE GEOMETRIC PARAMETERS**

Alignment, excavation diameter, lining diameter, lining thickness, average width of ring, segment system, joint connections.

STEP 2 **DETERMINE GEOTECHNICAL DATA**

Specific gravity, cohesion (unconfined and effective), friction angle (unconfined and effective), modulus of elasticity, modulus of deformation, K_o-Value.

STEP 3 **SELECT CRITICAL SECTIONS**

Influence of overburden, surface loads, water, adjacent structures.

STEP 4 **DETERMINE MECHANICAL DATA OF TBM**

Total thrust pressure, number of thrusts, number of pads, pad geometry, grouting pressure, space for installation.

STEP 5 **DEFINE MATERIAL PROPERTIES**

Concrete class, compressive strength, modulus of elasticity, steel type, tensile strength, gasket type, gasket width, elastic capacity, allowable gap.

STEP 6 **DESIGN LOADS**

6.1 Geostatical loads

Analyse load effects on lining segments and ground.

LOADING 1: Initial state of stress

LOADING 2: Initial stress relief

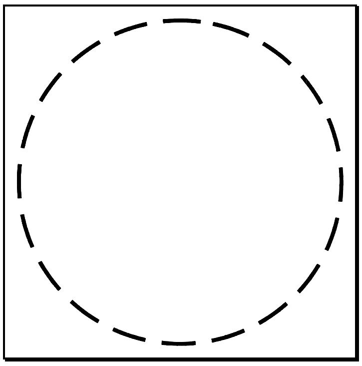


Fig. 1: Loading Case 1

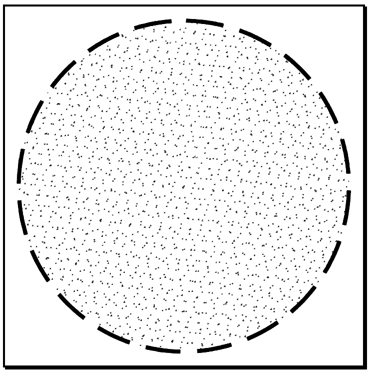


Fig. 2: Loading Case 2

LOADING 3:Excavation supported by shield

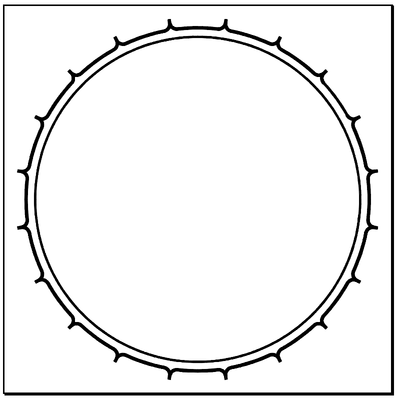


Fig. 3: Loading Case 3

LOADING 4: Excavation supported by grouted segment

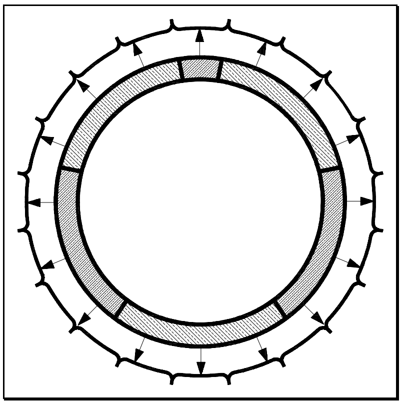


Fig. 4: Loading Case 4

LOADING 5: Long term deformation

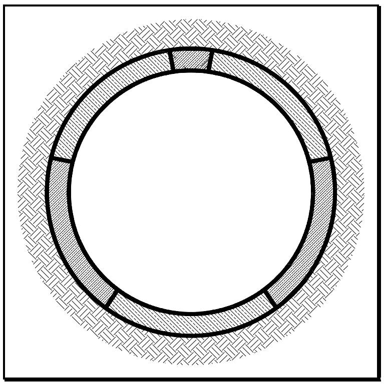


Fig. 5: Loading Case 5

6.2 Thrust Jacking loads

Analyse load effects distributed on segment types by thruster pads.

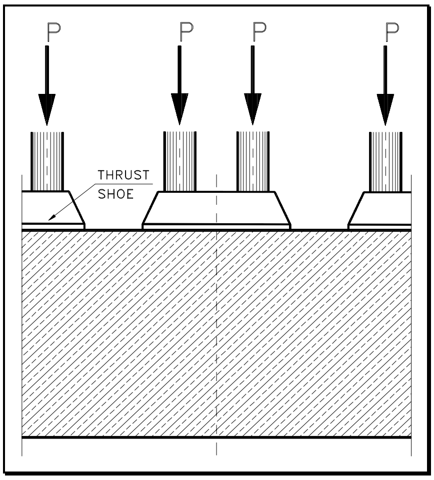


Fig. 6: Thruster pads distribution

6.3 Trailer and other service loads

Including main bearing loads, divided by number of wheels.

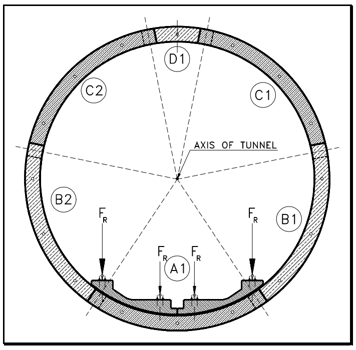


Fig. 7: Trailer load distribution

6.4 Secondary grouting loads

Extending regular grout pressure.

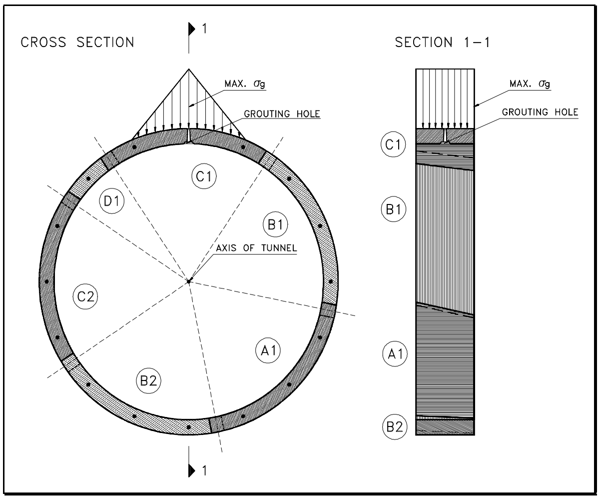


Fig. 8: regular grout pressure

6.5 Dead load, storage and erection loads

Bending moment influence.

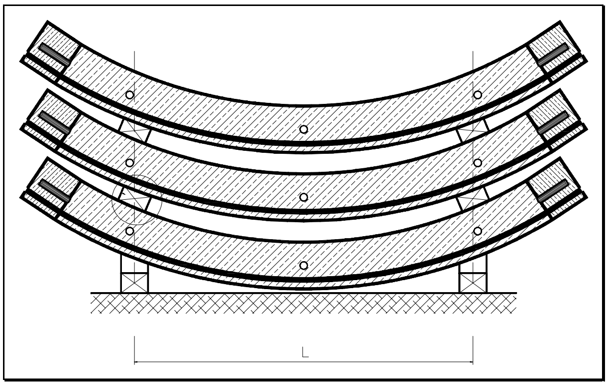


Fig. 9: Self weight of segments on stock

STEP 7 DESIGN MODEL

The three- dimensional condition has to be simulated by symbolic computation into two dimensional conditions.

7.1 Analytical model

Using formulas in accordance with national standards and with superposition of selected design loads.

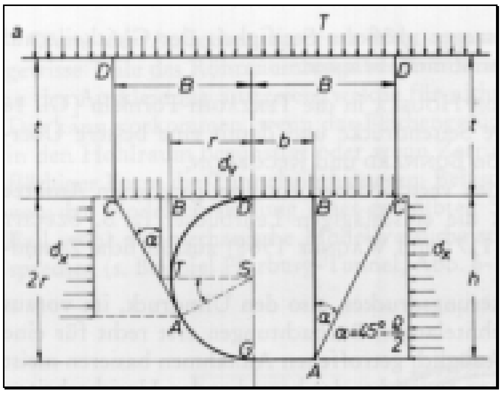


Fig. 13: Design load - Assumption of TERZAGHI

7.2 Numerical model

Using Finite-Element programs with constitutive laws in accordance with national standards to achieve stresses and strains under elasto-plastic conditions, allowing simulation of detailed construction stages.

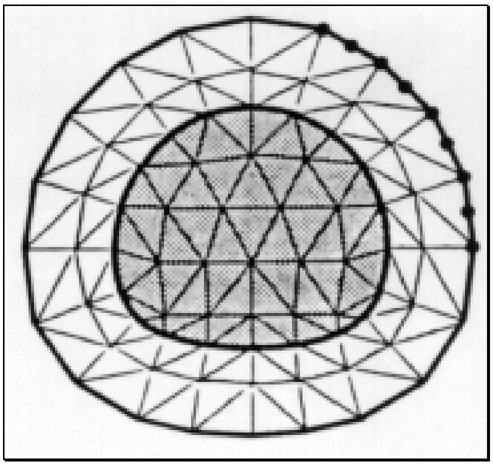


Fig. 14: FEM network configuration

STEP 8 COMPUTATIONAL RESULTS

Are represented in table format as normal and shear forces, bending moments and deflections, defining the design loads and subsequently reinforcement of the segments.

PART II

DESIGN METHOD OF SHIELD TUNNEL LINING

CONTENTS

1. General

1.1 Scope of Application

These guidelines provide general requirements for the design of segmental linings made of reinforced concrete, and the secondary lining of shield tunnel constructed in very soft ground such as alluvial or diluvial layers. They can be applied to the segmental lining of rock tunnel which is excavated in earth or soft rock by Tunnel Boring Machine (TBM). The physical characteristics on soft ground are as follows, in general.

$N \leqq 50$

$E \quad 2.5 \times N \leqq 125 \quad \mathrm{MN/m^2}$

$q_u \quad N/80 \leqq 0.6 \quad \mathrm{MN/m^2}$ Equ.1.1.1

Where, N:N value given by the standard penetration test,

E: E elastic modulus of soil. and

qu:Unconfined compressive strength of soil

1.2 Design Principle

It is a design principle to examine the safety of lining of shield tunnel for its purpose of usage. The calculation processes including the prerequisite of design, the assumption and the conception of design, and the design lifetime should be expressed in the report, in which the tunnel lining is examined in terms of its safety.

1.3 Definition of Terms

The following terms are defined for general use in this recommendation.

Segment: Arc-shaped structural member for initial lining of shield tunnel; These guideline is intended for precast concrete segment. (See Fig.1.3.1.)

Segmental lining: Tunnel lining constructed with segments; 1 ring of lining comprises some pieces of segments.

Segmental lining completed in shield: The segmental lining system that all of segments are assembled inside shield and lining is completed inside shield

Enlarged segmental lining: The segmental lining system that all segments except key segment are assembled inside shield and ,right after shield, key segment is inserted and lining is completed

Thickness: Thickness of lining of the cross section of tunnel

Width: Length of segment in longitudinal direction

Joint: Discontinuity in the lining and contact surface betweeen segments

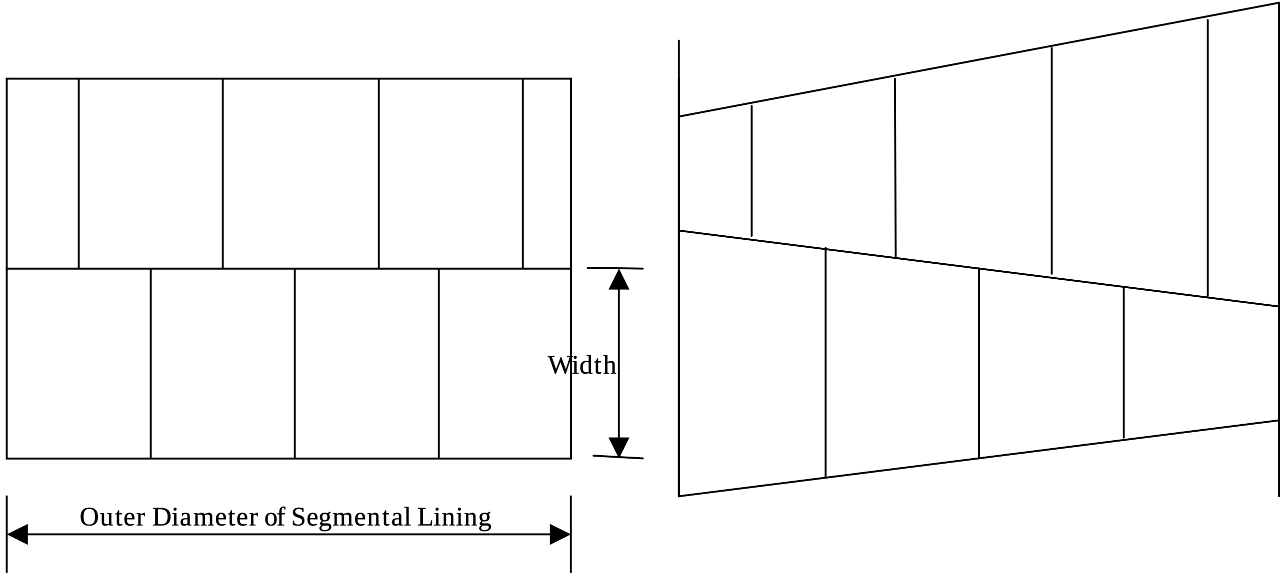
Types of joints: Plain joints:
- with connecting elements
  - straight steel bolts
  - curved steel bolts
  - reusable inclined steel bolts
  - plastic or steel connector
- without connecting elements
- with guiding bars

Tongue and groove joints

Hinge joints:
- with convex - concave faces
- with convex - convex faces
- with centering elements
  - steel rod link
- without centering elements

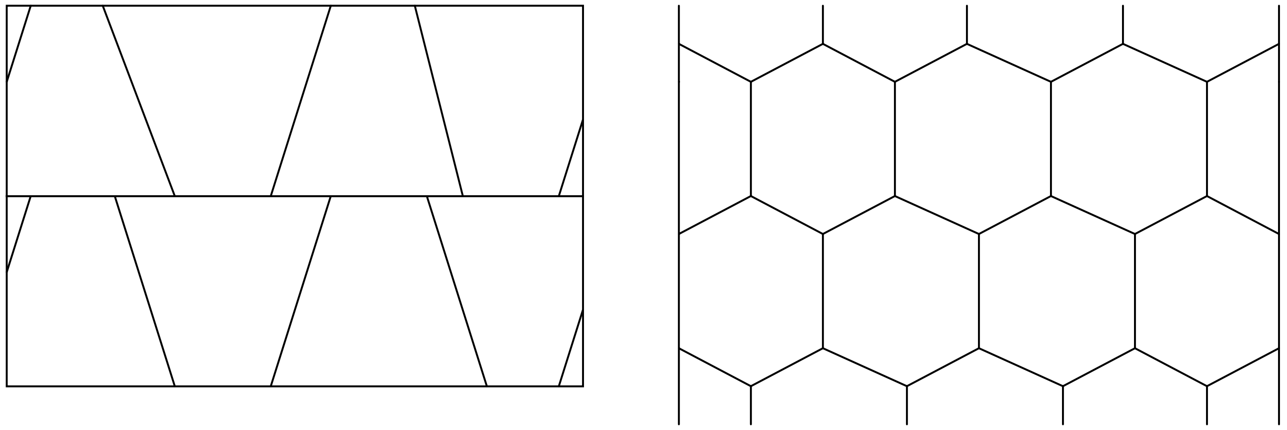
Pin joints

Circumferential joint: joint between rings
Radial joint: joint between segments in longitudinal direction
Bolt for joints: Steel bolt to joint segments



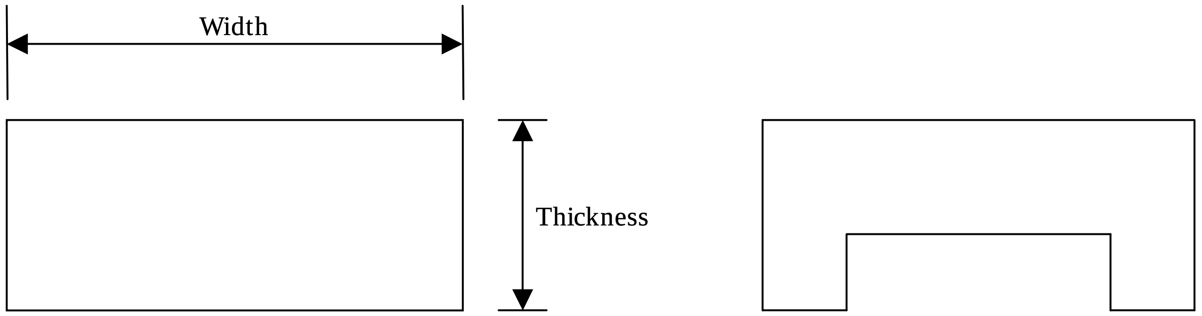
Rectangular Segment

Tapered Segment



Trapezoid Segment

Hexagon Segment



Flat Type Segment

Box Type Segment

Fig.1.3.1 Type of Segment

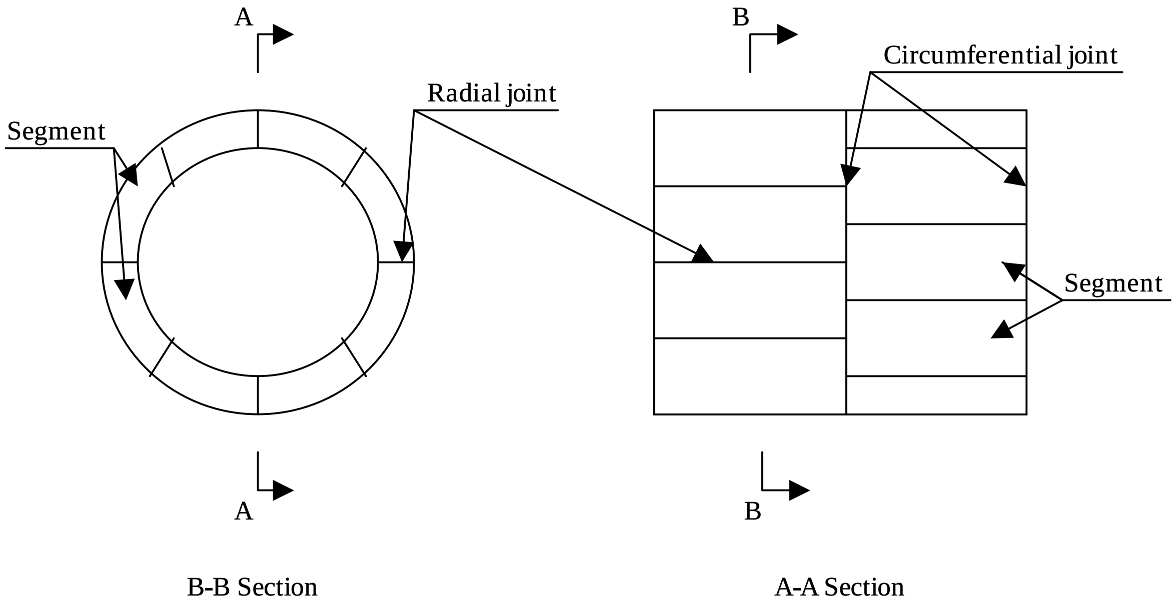


Fig.1.3.2 Segmental Lining

In actual design and construction, lining makeup, segment shapes, joint and waterproofing details, and tolerances should be selected for effective, reliable and rapid erection, considering the following.

1) Method and details of erection and erection equipment
2) Functional requirements of the tunnel, including lifetime and watertightness requirements
3) Ground and groundwater conditions, including seismic conditions
4) Usual construction practice in the location of the tunnel

1.4 Notation

The following notations are used in these guidelines.

t: Thickness
A: Area
E: Modulus of elasticity
I: Moment of inertia of area
EI: Flexural rigidity
M: Moment
N: Axial force
S: Shearing force
ζ: Ratio between the increment of moment transmitted through the adjacent segment at the joint and M
$(1+\zeta)$M is transmitted through the segment. $(1-\zeta)$M is transmitted through the joint.
D: Diameter of lining Dc: Diameter of centroid
Ro,Rc,Ri: Outer radius, radius of centroid and inner radius of the lining
γ, γ', γw, γc: weight of soil, submerged unit weight of soil, unit weight of water and unit weight of concrete

H: Overburden
$\gamma_W \times H_W$: Groundwater pressure at crown of lining
p_o: Surcharge
W: Weight of lining per meter in longitudinal direction
p_g: Dead Load
p_{e1}: Vertical earth pressure at crown of lining
p_{w1}: Vertical water pressure at crown of lining applied to the elastic equation method (See 5.2.)

q_{e1}: Horizontal earth pressure at crown of lining
q_{w1}: Horizontal water pressure at crown of lining applied to the elastic equation method (See 5.2.)
p_{e2}: Vertical earth pressure at bottom of lining
p_{w2}: Vertical water pressure at bottom of lining applied to the elastic equation method (See 5.2.)
q_{e2}: Horizontal earth pressure at bottom of lining
q_{w2}: Horizontal water pressure at bottom of lining applied to the elastic equation method (See 5.2.)
p_W: Water pressure
F_W: buoyancy
λ: Coefficient of lateral earth pressure
k: Coefficient of subgrade reaction
δ: Displacement of lining
p_k: Subgrade reaction/ la reaction/ Bettung
C: Cohesion of soil / La cohesion du sol / Kohaesion vom Boden
ϕ: Angle of internal friction of soil
f'ck: Nominal strength of Concrete (Characteristic Compressive Strength of Concrete)
fy: Yield Strength of steel
Es: Modulus of elasticity of steel

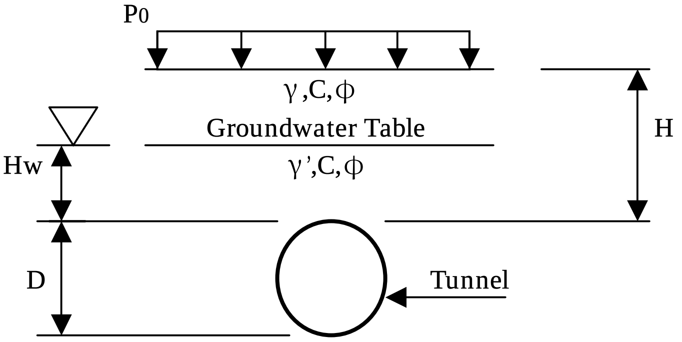


Fig.1.5.1 Notation

2. Loads

2.1 Kinds of Loads

The following loads should be considered in the design of lining.

The following loads must always be considered.

(1) Ground pressure
(2) Water pressure
(3) Dead Load
(4) Surcharge
(5) Subgrade Reaction

If necessary, the following loads should be considered.

(6) Loads from inside
(7) Loads during construction stage
(8) Effects of earthquake
Special loads
(9) Effects of adjacent tunnels
(10) Effects of settlement
(11) Other loads

2.2 Ground pressure

The ground pressure should be determined in accordance with appropriate analysis. For example, the ground pressure should act radially on lining or be divided into the vertical ground pressure and the horizontal ground pressure. In the latter case, the vertical ground pressure at the tunnel crown should be a uniform load and ,as a rule, should be equal to the overburden pressure, if the designed tunnel is a shouldow tunnel. If it is a deep tunnel, the reduced earth pressure can be adopted in accordance with Terzaghi's formula (See Formula 2.2.1.), Protodiaconov'formula or other formulae. The horizontal ground pressure should be the uniformly varying load acting on the centroid of lining from the crown to the bottom. Its magnitude is defined as the vertical earth pressure multiplied by the coefficient of lateral earth pressure. (See Fig.2.2.3(1).) It can be evaluated as the uniform load or the uniformly varying load with the pentagon model. (See Fig.2.2.3(2) .) The value of coefficient of lateral earth pressure to be used in the design calculation should be between the value of coefficient of lateral earth pressure at rest and the one of coefficient of active lateral earth pressure. Designer should decide it in consideration of relaxation and construction conditions.

Concerning the unit weight of soil for the calculation of earth pressure, the wet unit weight should be used for soil above groundwater table and the submerged unit weight should be used for one below groundwater table.

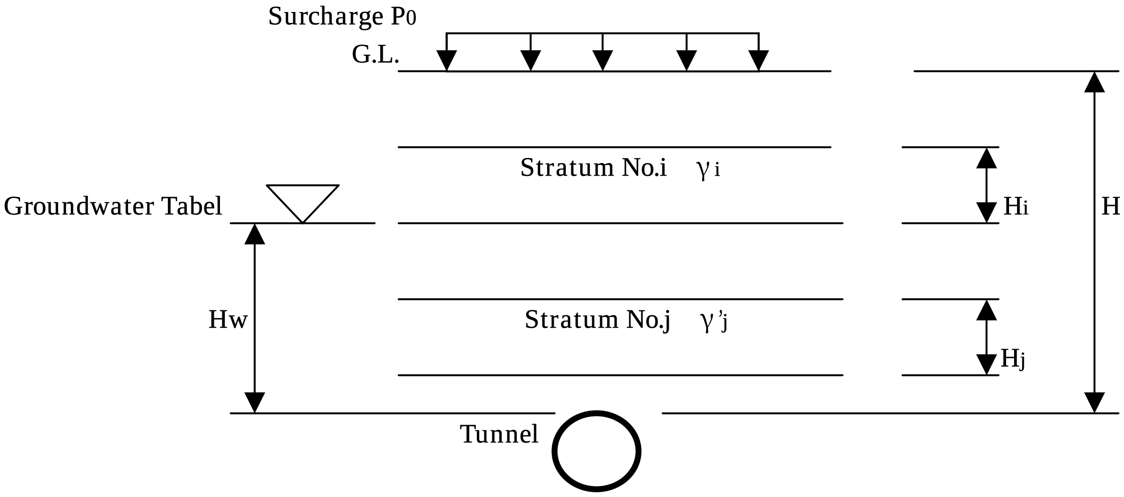


Fig.2.2.1 Section of Tunnel and surrounding Ground

$P_{e1}=P_0+\Sigma\gamma_i H_i+\Sigma\gamma'_j H_j$ Equ.2.2.1

Where,

P_o=Surcharge

γ_i=Unit weight of soil of Stratum No.i which is located above groundwater table

H_i=Thickness of Stratum No.i which is located above groundwater table

γ'_j=Unit weight of soil of Stratum No.j which is located under groundwater table

H_j= Thickness of Stratum No.j which is located under groundwater table

$H=\Sigma H_i+\Sigma H_j$

$h0=B1[1-C/B1\gamma)\}\{1-\exp(-k0\tan(\phi)H/B1)]/K0\tan(\phi)+P0\exp\{-K0\tan(\phi)H/B1\}/\gamma$

$B1=R0\cot(\pi/8+\phi/4)$

$P_{e1}=\gamma h0$ (if tunnel is located above groundwater table.)

$P_{e1}=\gamma' h0$ (if $h0 \leqq Hw$)

Terzaghi's formula Formula 2.2.1

Where,

h0=Reduced earth pressure divided by unit weight of soil

K0=Ratio between lateral earth pressure and vertical earth pressure=1

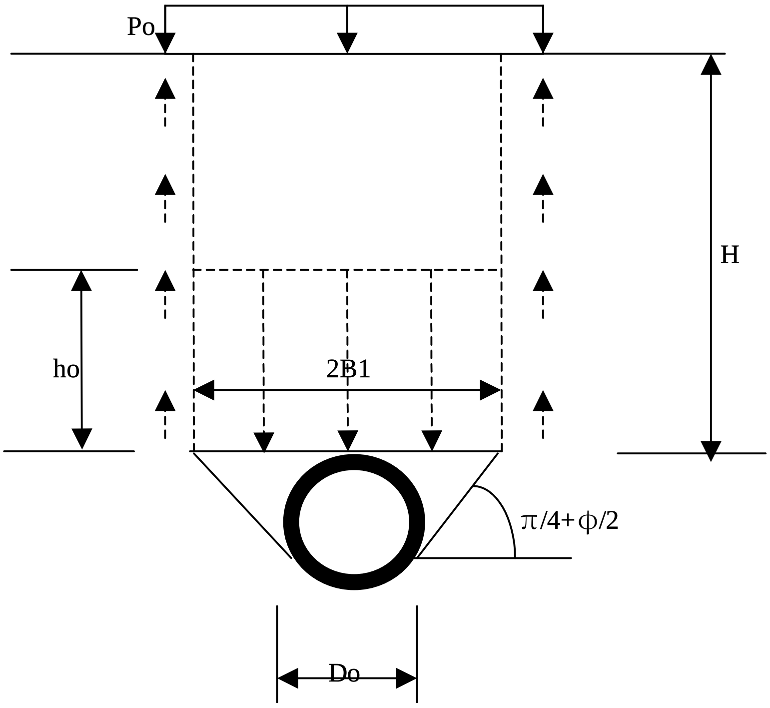
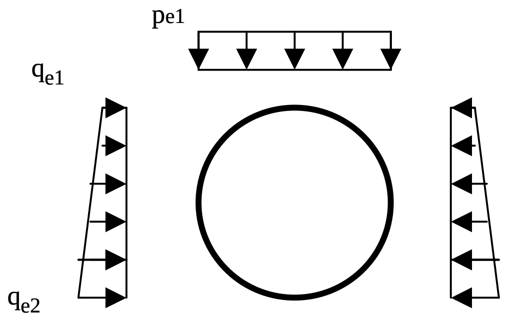


Fig.2.2.2 Reduced Earth Pressure calculated by Terzaghi's formula



Where;

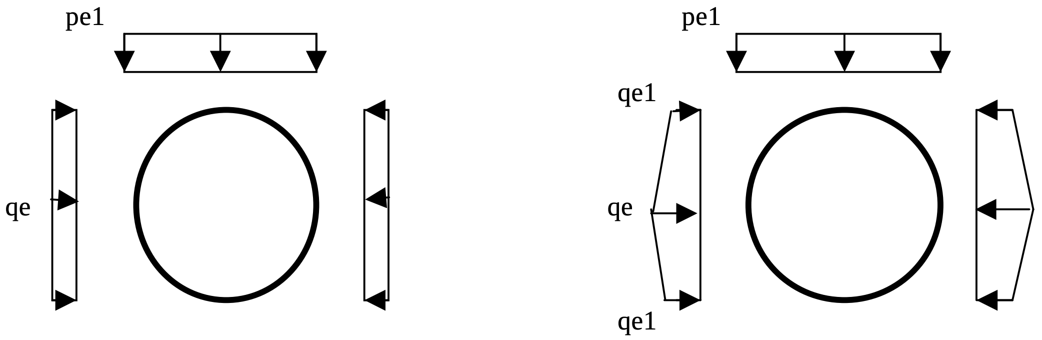
$qe1=\lambda(pe1+\gamma\times t/2)$ (if tunnel is located above groundwater table.)

$qe1=\lambda(pe1+\gamma'\times t/2)$ (if tunnel is located under groundwater table.)

$qe2=\lambda\{pe1+\gamma\times(2Ro-t/2)\}$ (if tunnel is located above groundwater table.)

$qe2=\lambda\{pe1+\gamma'\times(2Ro-t/2)\}$ (if tunnel is located under groundwater table.)

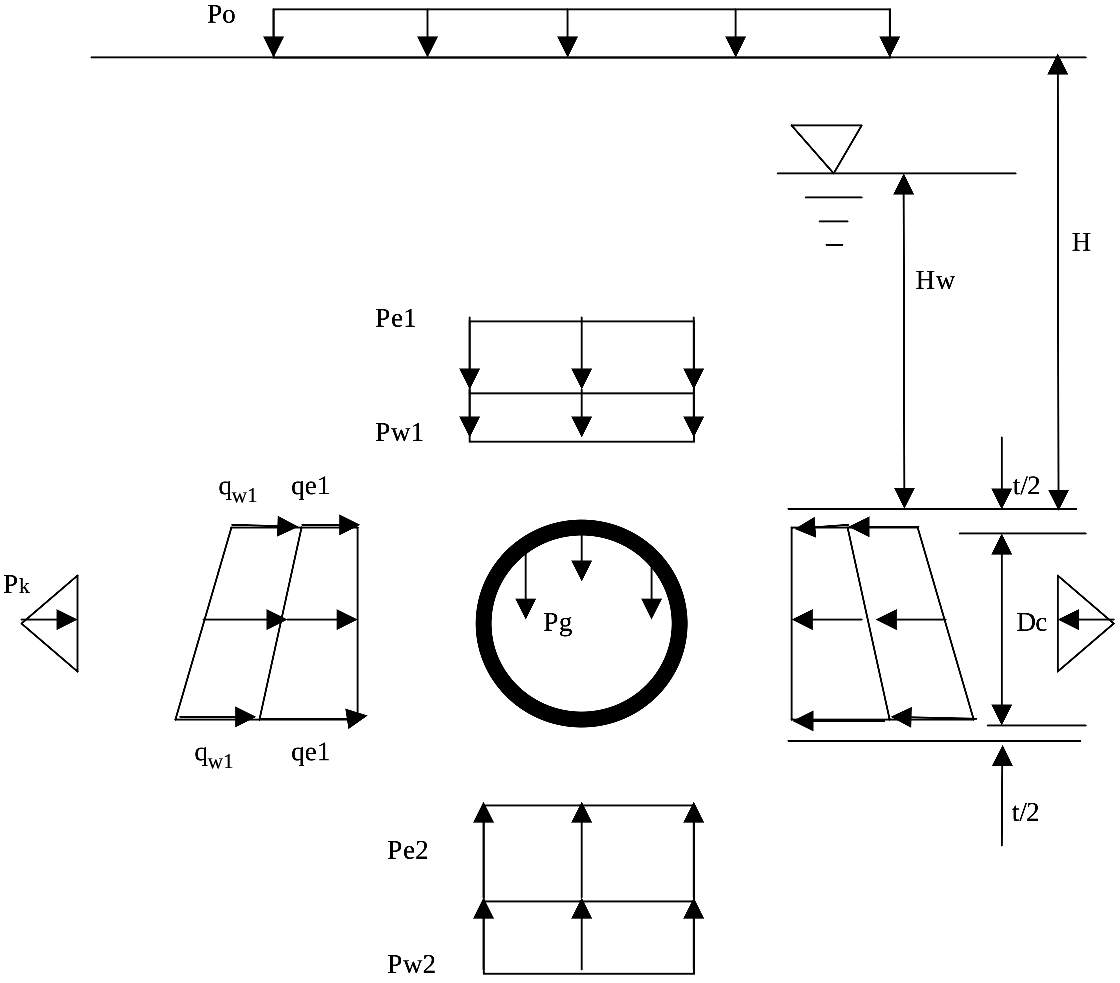
Fig.2.2.3 Ground Pressure acting on Lining (1)



Where,

$qe=(qe1+qe2)/2$

Fig.2.2.3 Ground Pressure acting on Lining (2)

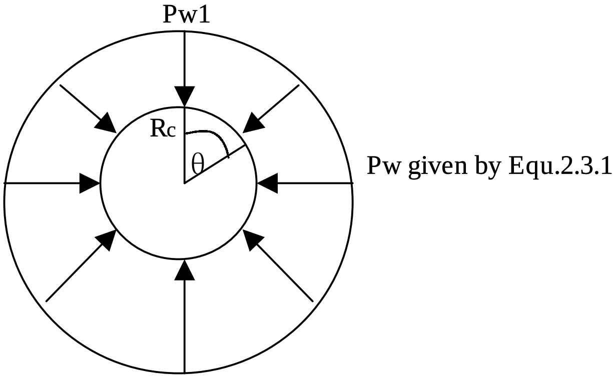


Pe2=Pe1+Pw1+πPg-Pw2

Fig.2.2.4 Load Condition of Elastic Equation Method

2.3 Water pressure

As a rule, the water pressure acting on lining should be the hydrostatic pressure. The resultant of water pressure acting on lining is the buoyancy. If the resultant of the vertical earth pressure at crown and the dead load is greater than the buoyancy the difference betueen them acts as the vortical earth pressure at bottom (subgrade reaction). If the buoyancy is greater than the resultant of the vertical earth pressure at crown and the dead load, the tunnel would float.



$P_{w1} = \gamma_w H_w$ (Water pressure at tunnel crown)

$P_w = P_{w1} + \gamma_w R_c (1 - \cos\theta)$ Equ. 2.3.1

Fig.2.3.1 Hydrostatic Pressure

2.4 Dead Load

Dead load is vertical load acting along the centroid of the cross-section of tunnel and is calculated in accordance with Equ.2.4.1

$p_g = W/(2\pi R_c)$

$p_g = \gamma_c \times t$ (If the section is rectangular,)

Equ.2.4.1

2.5 Surcharge

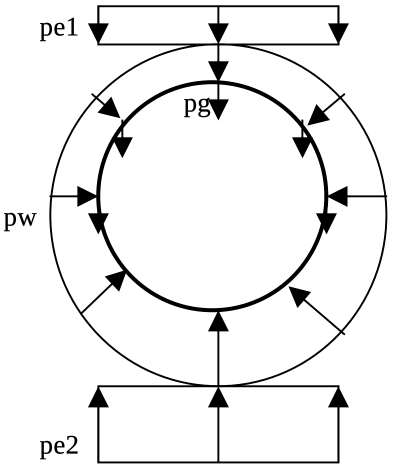
The followings act on lining as the surcharge. They increase earth pressure actiong on lining.

Road trafic load,Railway trafic load,Weight of buildings

2.6 Subgrade Reaction

When we compute the member forces in the lining, we must determine the acting range, the magnitude and the direction of the subgrade reaction. The subgrade reaction is divided into the reaction independent of the displacement of ground such as pe2 (See Fig.2.6.1.) and the reaction dependent on the displacement of ground. It is assumed that the latter subgrade reaction is proportional to the displacement of ground and its factor of proportionality is defined as the coefficient of subgrade reaction. The value of this factor depends on the ground stiffness and the dimension of lining (radius of lining), and the subgrade reaction is the product of the coefficient of subgrade reaction and the displacement of lining which is decided by the ground stiffness and the rigidity of segmental lining. The rigidity of segmental lining depends on the rigidly of segment, the number and type of joint. . The bedded rigid frame model can evaluate the subgrade reaction as the spring force. (See Fig.2.2.3, Fig.2.6.2 and Fig.5.2.3.)

In case the member forces are computed with the FEM, plain strain elements simulating ground are evaluated as spring for subgrade reaction.



$2rpe2 + \pi r^2 \gamma w = 2rpe1 + 2\pi rpg$

$pe2 = pe1 + \pi pg - \pi r \gamma w/2$

Fig.2.6.1 Subgrade Reaction independent of the Displacement of Ground (pe2)

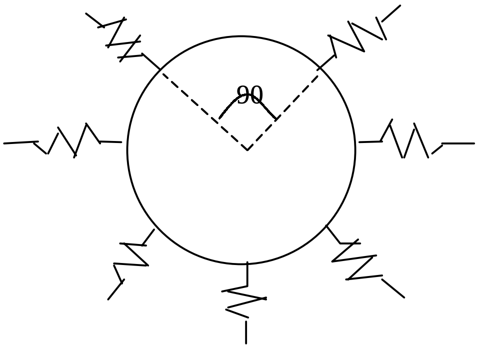


Fig.2.6.2 A Model of Subgrade Reaction

2.7 Loads from Inside

Load caused by facilities suspended from the ceiling of tunnel or inner water pressure should be investigated.

2.8 Loads during Construction Stage

The following loads acts on the lining during construction stage.

① Thrust force of shield jacks

When segments are produced, the strength of segment against the thrust force of shield jacks should be tested. For the analysis of influence of shield jack forces to segments, designer should examine shear and bending forces resulting from credible eccentricity, including cases of placement at the limit of tolerance.

② Loads during transportation and handling of segments

③ Pressure of backfill grouting

④ Load by operation of erector

⑤ Others

Dead load of backup carriages, jack force of segment reformer, torque of cutterhead

2.9 Effects of Earthquake

The static analysis such as the seismic deformation method or the seismic coefficient method, or the dynamic analysis should be used for the seismic design. The seismic deformation method is usually adopted to investigate the effect of earthquake to tunnels. Details should be presented apart from these guidelines.

2.10 Other Loads

If necessary, the effect of adjacent tunnels or effect of unequal settlement should be investigated.

3. Materials

These guidelines are intended for the reinforced concrete segment as the material of initial lining and cast-in-place concrete as the material of secondary lining. Japan Industrial Standard (JIS), Deutsche Industrie-Norm (DIN) and American Concrete Institute (ACI) Standard specify the test methods of materials.

There may not be a cast-in-place inner lining. If the outer segmental lining is designed and constructed to meet lifetime tunnel lining demands, then a one –pass lining is certainly permitted.

3.1 Modulus of Elasticity

Tab.3.1.1 shows the moduli of elasticity of concrete and steel, as a reference.

Tab.3.3.1 Modulus of Elasticity of Concrete and Steel

Nominal Strength f'_{ck}(MN/m^2)	18	24	30	40	50	60
Modulus of Elasticity of concrete E_c (×10^4MN/m^2)	2.2	2.5	2.8	3.1	3.3	3.5
Modulus of Elasticity of Steel	E_S =210,000(MN/m^2)					

Quotation from Standard Specification for Design and Construction of Concrete Structures issued by Japan Society of Civil Engineers (JSCE)

3.2 Stress-Strain Curve

Fig.3.2.1 and 3.2.2 show the stress-strain curves of concrete and steel respectively.

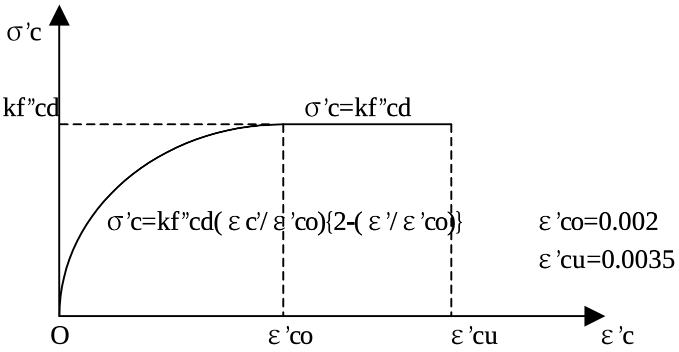


Fig.3.2.1 Stress-Strain Curve of Concrete

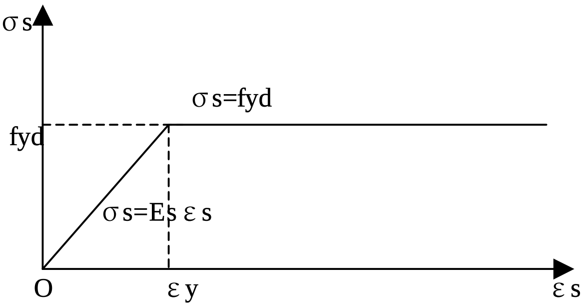


Fig.3.2.2 stress-Strain Curve of Steel

4. Safety Factors

The safety factors should be based on the ground loading and should be defined in accordance with the structural requirements and codes, for example, national Standard Specification for Design and Construction of Concrete Structures for each project. Construction procedure and performance should be linked with the safety factors. On their application to the design computation, refer to “5.3 How to check the safety of section”. If tunnel is designed as temporary structure, the safety factors can be modified.

5. Structural Calculation

SI unit should be used in the structural calculation of lining.

5.1 Design Principles

The design calculation of cross section of tunnel should be done for the following critical sections. (See Fig.5.1.1.)

① Section with the deepest overburden
② Section with the shouldowest overburden
③ Section with the highest groundwater table
④ Section with the lowest groundwater table
⑤ Section with large surcharge
⑥ Section with eccentric loads
⑦ Section with unlevel surface
⑧ Section with adjacent tunnel at present or planned one in the future

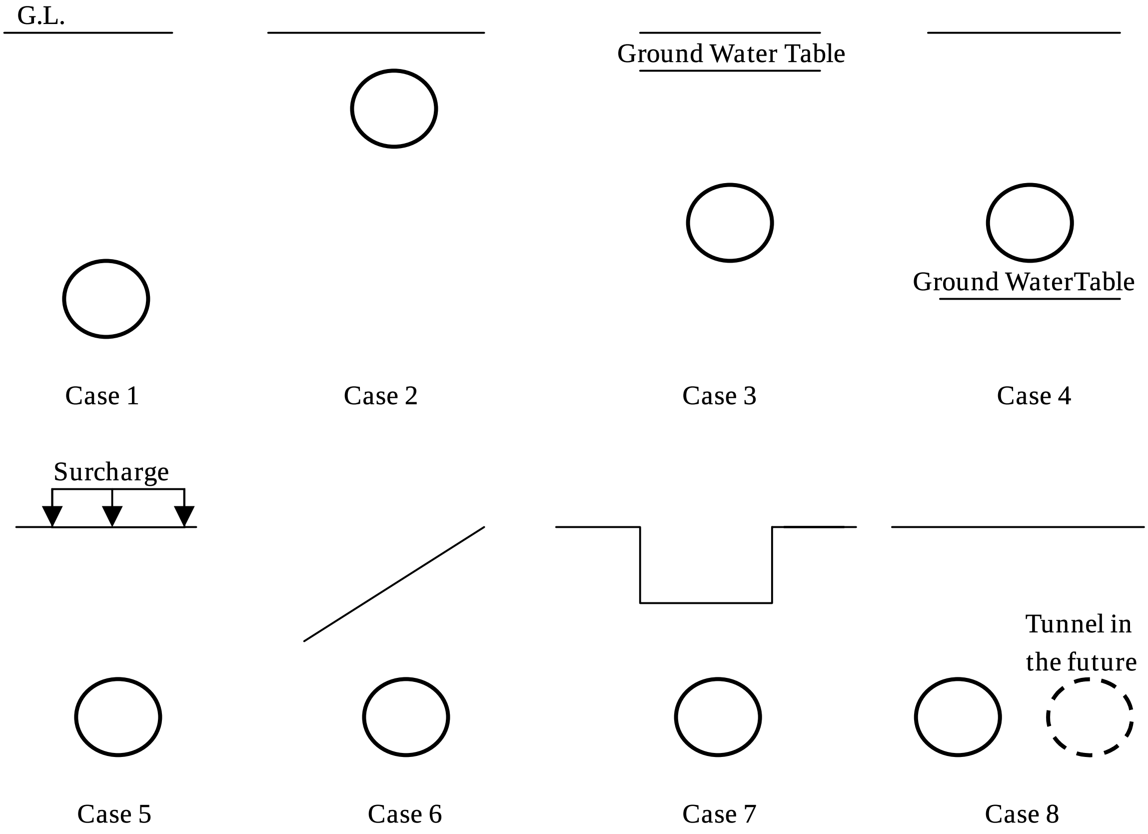


Fig.5.1.1 Critical Sections to be checked

5.2 Computation of Member Forces

The Member Forces (M,N,S) are calculated using various structural models.

5.2.1 Model for computation

The member forces should be computed with the following methods.

① Bedded frame model method (See Fig.s 5.2.1,2,3.)

② Finite Element Method (FEM) (Fig.5.2.4.)
③ Elastic equation method (See Fig.5.2.5. and Tab.5.2.1.)
④ Schultze and Duddeck Model
⑤ Muir Wood Model

Refer to Fig.5.2.6.

The bedded frame model method is a method to compute member forces with matrix method using a computer because this model is mutiple statically indeterminate. This method can evaluate the following conditions.
1) ununiformly varying load due to change of soil condition (See Fig.5.2.2(b).)
2) eccentric loads (See Fig.5.2.2(c).)
3) hydrostatic pressure (See "2.3 Water Pressure".)
4) spring force to simulate subgrade reaction (See "2.6 Subgrade Reaction".)
5) effect of joint by simulating joints as hinges or rotation springs (semi-hinge) (See “5.2.2 Evaluation of Joints”)

If the subgrade reaction against displacement due to dead load cannot be expected, the member forces caused by dead load must be independently calculated and superposed with member forces caused by the other loads. In this case, the member forces caused by dead load can be computed by the elastic equation method.

This method can adopt not only the subgrade reaction in normal direction but also the one in tangential direction. The options on the range of the subgrade reaction are as follows.
① Full round-bedded model
② Bedded model without subgrade reaction at crown
③ Full round-non-tension bedded model

See Fig.5.2.3.

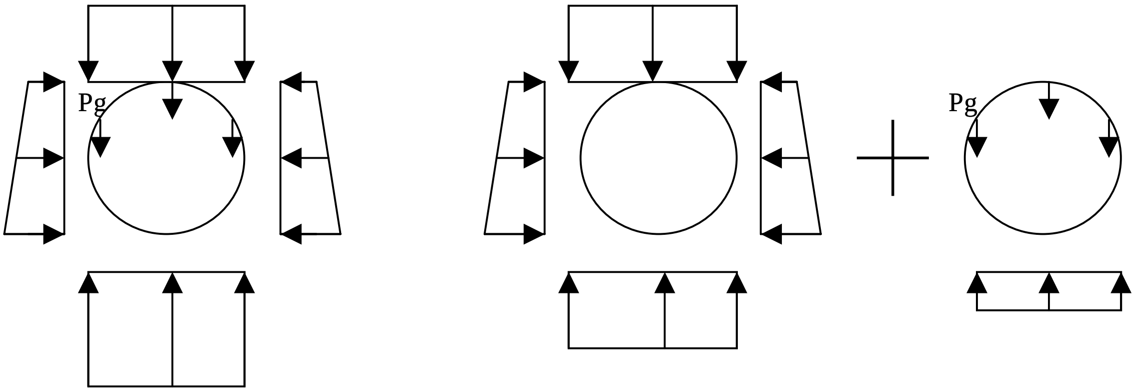
The FEM is based on the theory of continuous body and has been adopted with the developement of computer. In the FEM, Young modulus and the Poisson's ratio of soil must be parameters. In the design by the FEM, segmental lining is evaluated as beam element. The FEM can compute not only the member forces of tunnel lining but also the displacement and stress-starin state of surrounding ground and the influence to overlying or adjacent structures induced by tunnel construction.

The FEM model can reproduce the behavior of interaction of lining and massive ground realistically with the following merits.

1) The behavior of massive ground can be evaluated in consideration of the initial state of stress of ground, the parameters of ground such as Unit weight of soil, Young modulus and the Poisson’s ratio, the shape and size of tunnel section and the execution method including its procedure.
2) The behavior of lining which resists the loads depends on the lining structure (number of segments, their configuration and joint type, the characteristics of backfill grouting and their efficiency, and the loading given by the ground. These factors can be evaluated.
3) The degree of relaxation which depends on the ground condition, the construction method such as the type of shield method and backfill grouting method including the size of tail void can be evaluated.

The elastic equation method is a simple method to calculate member forces without a computer. But it cannot evaluate the conditions of above-mentioned 1) to 5). (See Fig.5.2.5.)

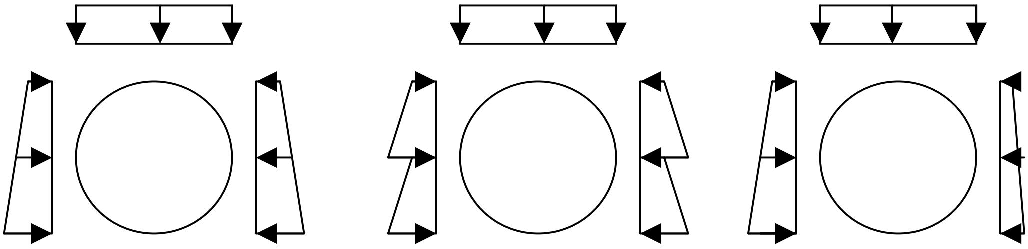
In this method, water pressure should be evaluated as the combination of vertical uniform load and horizontally uniformly varying load and horizontal subgrade reaction should be simplified as triangularly varying load. (See Fig.2.2.4.)



Model (a) Model (b)

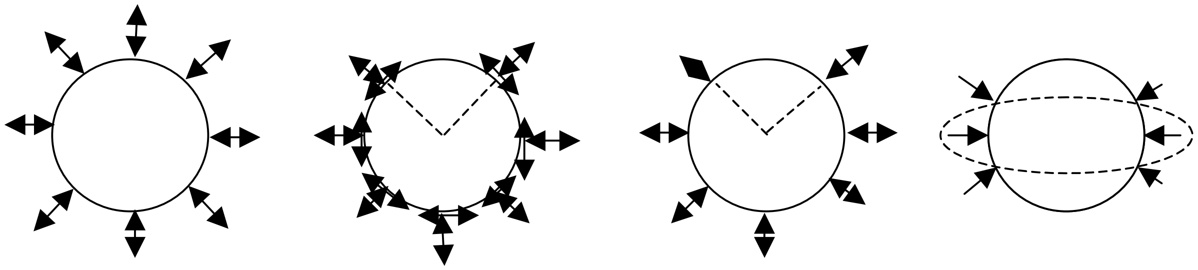
The subgrade reaction against displacement due to dead load can be evaluated in Model (a) and not evaluated in Model (b).

Fig.5.2.1 Models for Bedded Frame Method to calculate Member Forces



Model (a) Adaptable Model (b) Adaptable Model (c) Adaptable

Fig.5.2.2 Adaptable Loading Models for Bedded Frame Method



Model (a) Model (b) Model (c) Model (d)

Model	Range of Bedding	Direction of Bedding	Bedding Compression/Tension
a	Full round	Normal	Compression and tension
b	Without crown	Normal and tangential	Compression and tension
c	Without crown	Normal	Compression and tension
d	Dependent on displacement	Normal	Compression only

Fig.5.2.3 Range and Direction of Subgrade Reaction of Calculation Model of Bedded Frame method

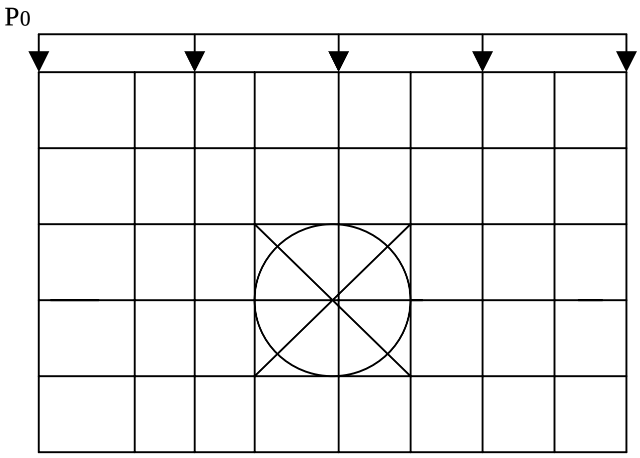
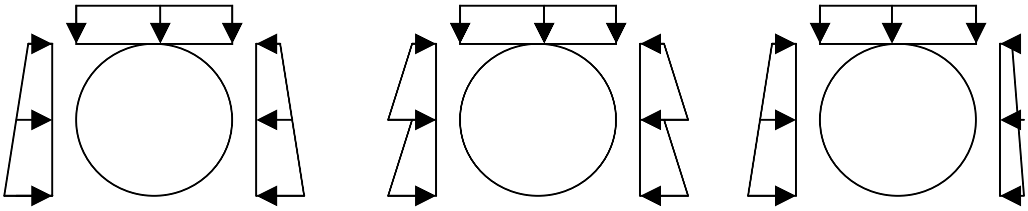


Fig.5.2.4 FEM Mesh Layout



Model (a) Adaptable

Model (b) Unadaptable

Model (c) Unadaptable

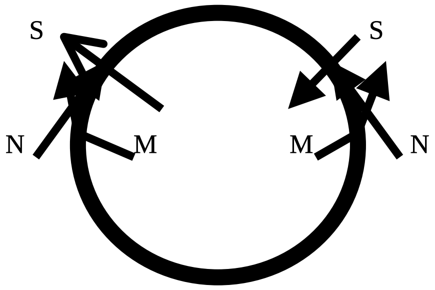
Fig.5.2.5 Loading Models for Elastic Equation Method to calculate Member Forces

Table 5.2.1 Elastic Equations to compute Member Forces

Load	Moment (M) (@Rc^2)	Axial Force (N) (@Rc)	Shear Force (S) (`Rc)
Uniform load in vertical direction ($P=p_{e1}+p_{w1}$)	$(1-2S2)@P/4$	$S2@P$	$-SC@P$
Uniform load in lateral direction ($Q=q_{e1}+q_{w1}$)	$(1-2C2)@Q/4$	$C2@Q$	$-SC@Q$
Triangular lyvarying load in lateral direction ($Q'=q_{e2}+q_{w2}$) ($Q-Q'$)	$(6-3C-12C2+4C3)@(Q-Q')/48$	$(C+8C2-4C3)@(Q-Q')/16$	$(S+8SC-4SC2)@(Q-Q')/16$
Subgrade reaction in lateral direction ($k\delta$)	$0 \leqq \theta \leqq \pi/4$ $(0.2346-0.3536C)@k\delta$ $\pi/4 \leqq \theta \leqq \pi/2$ $(-0.3487+0.5S2+0.2357C3)@k\delta$	$0 \leqq \theta \leqq \pi/4$ $0.3536C@k\delta$ $\pi/4 \leqq \theta \leqq \pi/2$ $(-0.7071C+C2+0.7071S2C)@k\delta$	$0 \leqq \theta \leqq \pi/4$ $0.3536S@k\delta$ $\pi/4 \leqq \theta \leqq \pi/2$ $(SC-0.7071C2S)@k\delta$
Dead load (g)	$0 \leqq \theta \leqq \pi/2$ $\{(3/8)\ \pi-\theta S-(5/6)C\}@g$ $\pi/2 \leqq \theta \leqq \pi$ $\{-\pi/8+(\pi-\theta)S-(5/6)C-(1/2)\pi S2\}@g$	$0 \leqq \theta \leqq \pi/2$ $\{\theta S-(1/6)C\}@g$ $\pi/2 \leqq \theta \leqq \pi$ $\{-\pi S+\theta S+\pi S2-(1/6)C\}@g$	$0 \leqq \theta \leqq \pi/2$ $\{\theta C-(1/6)S\}@g$ $\pi/2 \leqq \theta \leqq \pi$ $\{-(\pi-\theta)C+\theta S+\pi SC-(1/6)S\}@g$
Lateral displacement at spring (δ)	$\delta=\{(2P-Q-Q')+\pi g\}@Rc^4/\{24(\eta EI/h+0.045k\ c^4)$		

θ=Angle from crown

$S=\sin\theta$ $S2=\sin^2\theta$ $S3=\sin^3\theta$ $C=\cos\theta$ $C2=\cos^2\theta$ $C3=\cos^3\theta$



Refer to “Gudelines-Fig. 5.2.6.pdf”.

Fig.5.2.6 Models to compute Member Forces

5.2.2 Evaluation of Joints

If the segmental lining is jointed with or without bolts, its actual flexural rigidity at joint is smaller than the flexural rigidity of segment. (Structurally, segmental ring can be modeled as multiple hinged ring or lining having the rigidity between perfectly uniform rigidity ring and multiple hinged ring.) If segments are staggered, the moment at joint is smaller than the moment of the adjacent segment. The actual effect of joint should be evaluated in the design.

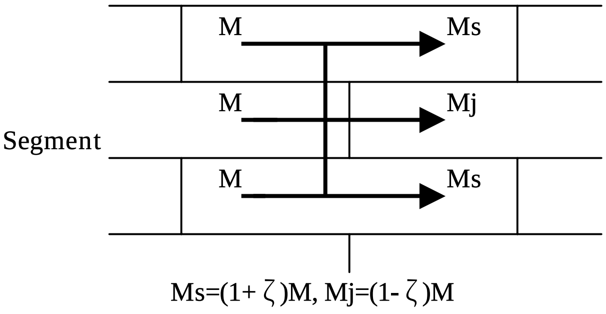


Fig.5.2.6 Distribution of Moment at Joint

5.3 How to check the safety of section

According to the calculation result of member forces, the safety of the most critical sections must be checked with the limit state design method or the allowable stress design method. They are shown, as follows.

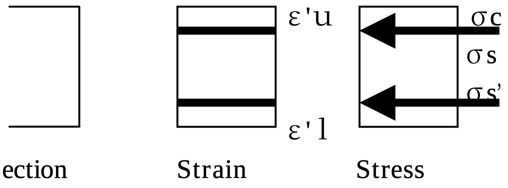
① Section with the Maximum positive moment
② Section with the Maximum negative moment
③ Section with the maximum axial force

The safety of lining against the thrust force of shield jacks should be checked.

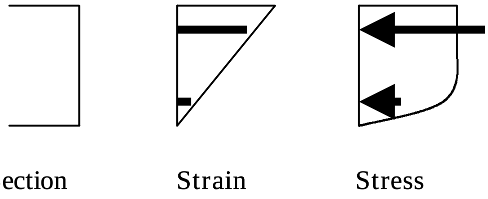
5.3.1 Limit state design method

The relationship between the design axial capacity and the design flexural capacity of member cross sections subjected to axial load and flexural moment is described by the curve as shown in Fig.5.3.1. Therefore, as a rule, the safety for combined axial load and flexural moment is examined by confirming that the point (Md, Nd) is located inside of the (Mud, Nud) curve, that is, at the side of the origin as shown in Fig.5.3.1. (Mud, Nud) are calculated by Equ.5.3.1 and Equ.5.3.2 respectively. On the stress-strain curve of cincrete and steel, refer to “3.4 Stress-Strain Curve”. In the Fig.5.3.1 and the equations 5.3.1 and 5.3.2, γ_b and γ_s are the safety factors of concrete and steel.

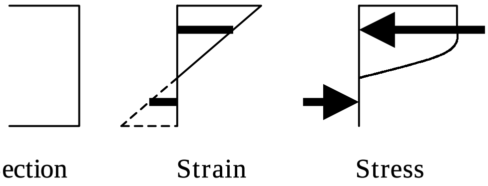
① Ultimate Limit State Ⅰ
$\varepsilon'u=\varepsilon'l=\varepsilon'cu$
Nud=Nmax, M=0



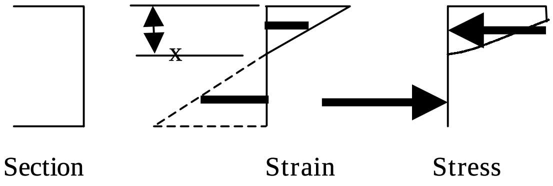
② Ultimate Limit State Ⅱ
$\varepsilon'u=\varepsilon'cu$, $\varepsilon'l=0$, x=t



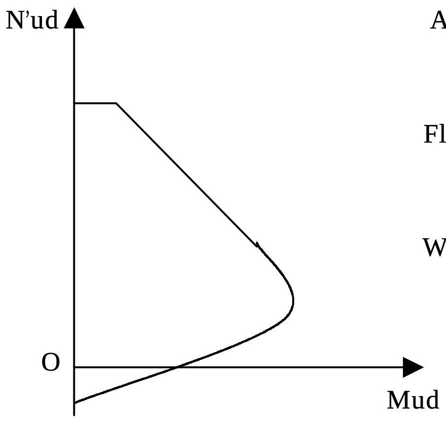
③ Ultimate Limit State Ⅲ
$\varepsilon'u=\varepsilon'cu$, $\varepsilon'l<0$, $x_O<x<t$



④ Ultimate Limit State Ⅳ
$\varepsilon'u=\varepsilon'cu$, $\varepsilon'1<0$, $x=x_O$
Nud=0



Where, $\varepsilon'u$=Upper extreme fiber strain
$\varepsilon'l$=Lower extreme fiber strain
x=Distance between upper extreme fiber and neutral axis



Axial Capacity

$$N'ud=\int \sigma(y)bdy/\gamma b+(Ts+T's)/\gamma s \qquad \text{Equation 5.3.1}$$

Integrate between –h/2 and h/2

Flexural Capacity

$$Mud=\int \sigma(y)ybdy/\gamma b+\{Ts(h/2-t)-T's(h/2-t')\}/\gamma s \qquad \text{Equation 5.3.2}$$

Integrate between –h/2 and h/2

Where, $Ts=As\sigma s$; $Ts'=As'\sigma s'$

Fig.5.3.1 Transition of Ultimate Limit States and Mud-N'ud Diagram

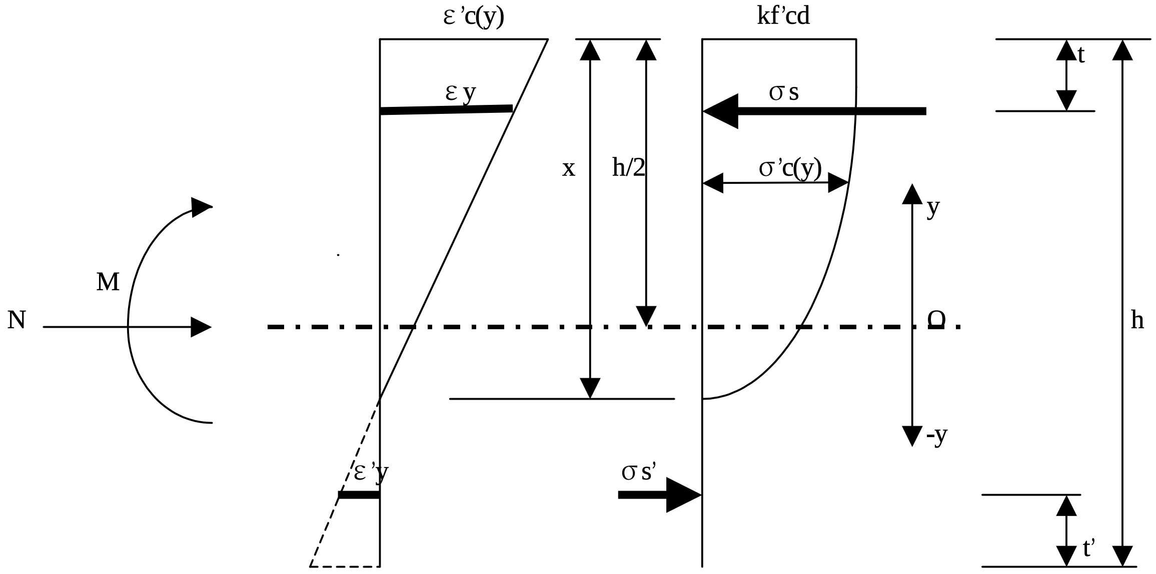


Fig.5.3.2 State of Stress and Strain Distribution

5.3.2 Allowable stress design method

If the extreme fiber stress of concrete and the stress of reinforcement are not more than the their allowable stresses, the segmental lining should be safe against the design loads. (See Equations 5.3.3 and 5.3.4.)

$\sigma_c \leqq \sigma_{ca} = f'_{ck}/F_c$ Equation 5.3.3

$\sigma_s \leqq \sigma_{sa} = f_{yd}/F_s$ Equation 5.3.4

Where,

σ_c : Extreme fiber stress of concrete

σ_{ca} : Allowable stress of concrete

f'_{ck} : Characteristic compressive strength (Nominal strength) of concrete

F_c : Safety factor of concrete

σ_s : Stress of reinforcement

σ_{sa} : Allowable stress of reinforcement

f_{yd} : Yield stress of steel

F_s : Safety facror of steel

5.4 Structural Calculation of Joints

At joints, bolts are evaluated as reinforcement. The safety of joint should be checked by the same method as the one to check the safety of segment described in "5.3 How to check the safety of section". As the locations of joints are indefinite before the assembling of segments, the design calculation should be done for the three most critical sections described in "5.3 How to check the safety of section".

If bolts are used for erection only and removed after erection, the joint should transmit a moment limited by the normal force across the joint. Between rings, the force to be transferred from one ring to another is governed by geometric interlock and the residual longitudinal force.

5.5 Check of safety against thrust force of shield jacks

The safety of lining against the thrust force of shield jacks should be checked with the following equation, in the minimum.

$$f'_{ck}/F_c \geqq F_s/A$$

Where,

f'_{ck} : Characteristic compressive strength (Nominal strength) of concrete
F_c : Safety factor of concrete
F_s : Total thrust force of shield jacks
A : Area of cross section area of lining

If more critical conditions are expected by the selection of used jacks, such cases should be checked because bending moment is caused by it.

Microcracks of segment are propagated by the thrust force of shield jacks. They influence the longevity of segmental lining. The quality control of tensile strength of concrete of segment should be considered to prevent the increase of microcracks when segments are produced._

6. Structural Details

6.1 Dimension & Shape of Segment

The less the number of pieces of one segmental ring is, the better the efficiency to manufacture and assemble segments. But, in consideration of their transportation and handling, the length of arc and the weight of one segment should be determined.

6.2 Measures against Leakage

If the allowable leakage dischaege is designed, the drainage system can be instaled in the tunnel. If not, the measures against leakage should be necessary. Watertightness requirements should be determined based on the ultimate use and the functional requirements of the finished tunnel. An initial lining that is followed by a cast-in-place inner lining (whether or not a waterproofing membrane is applied) should be sufficiently tight to permit the placement of inner lining without compromise to its quality. Then, sealing strips should be applied as necessary. One-pass lining segments below the groundwater table should be furnished with one or two gaskets to seal the tunnel. If only one gasket is used, then provisions should be made to place caulking in the event that excessive leakage is expected.

(See Fig.6.2.1.)

The sealing method is divided into the gasket sealing and the paint sealing and the former is usually adopted. The gasket sealing is to stick gasket on surface of joint of segment. The materials of gasket are butyl non-sulfide rubber, deformation butyl rubber, solid rubber, special synthesis rubber and/or water- expansive material. Water-expansive gasket is a compound of polymer which reacts with water and, natural rubber or urethane. If tunnel is excavated in ground with high ground water pressure, two-line gasket should be stuck on joints of segments. In some cases, butyl rubber is not sufficiently resilient to provide an adequate seal under significant external water pressure. Then, it can be used as sealing strips in an initial segmental lining (which is followed by an inner lining.)

The caulking is the method that the groove which is made on inside-surface of segment is filed with the materials of causing. The main chemicals of them are epoxy resin, thiokol and urea resin. The caulking should be executed after rebolting of segment, cleanup of groove and painting of primer.

If leakage can not be stopped with the gasket sealing and the caulking, the urethane injection would be effective, which is executed through holes to be made in segment, as urethane reacts with groundwater and is expanded.

If the quality of selected waterproofing system is not proven through the previous tests or construction records, its system should be tested in the laboratory under the expected maximum pressure (with a suitable safety factor) and with joint geometry incorporating maximum permitted out-of-tolerance placement of segment at the joint. Where groundwater is aggressive to components of the lining or components installed in the tunnel, full waterproofing should be applied, including the use of waterproof concrete or external waterproofing of segments, or both. (For example, salt groundwater or groundwater high chloride or sulphate content is aggressive to these components.)

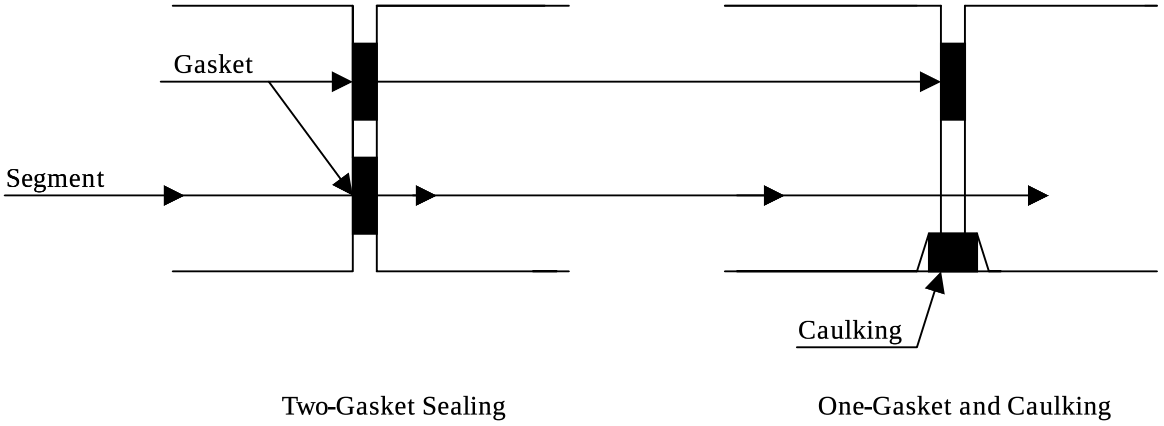


Fig.6.2.1 Gasket Sealing and Caulking

6.3 Structural Details to handle segments and grout

When segments are assembled with an erector, segment should have an equipment to handle and hang segment. The lately developed vacuum type erector can handle segments without the above-mentioned equipment hanging a segment.

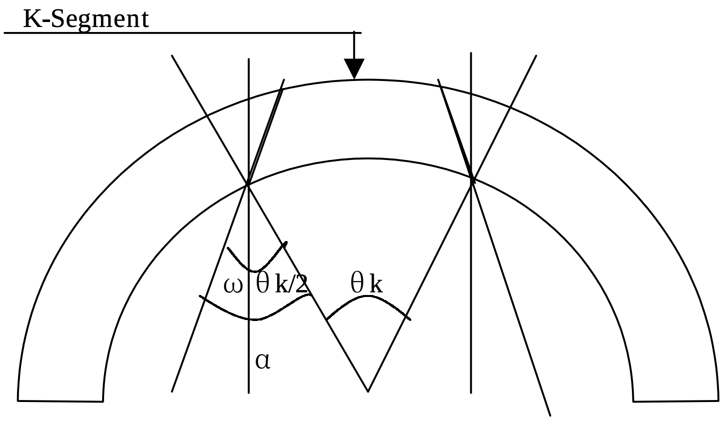
If the backfill grouting is performed through segments, each segment should have a grout hole with the inner diameter of about 50 mm to inject grout uniformly. A grout hole can be used for the equipment hanging a segment.

6.4 Angle of Joint of Key-Segment

The type of K-segment is divided into K-segment inserted in radial direction (Kr-Segment) and K-segment inserted in longitudinal direction (Kl-segment). If this angle is too large, axial force acting on segment works as force to slide joint..(See fig.6.4.1.)

Kl-segment can prevent the influence of axial force because its angle of joint is very small.

The design of the K-segment, if used, should consider the geometry of the erection system in the shield (and vice versa).



$\alpha=\theta k/2+\omega$ (Both side-tapered K-segment)

$\alpha=\theta k+\omega$ (One side-tapered K-segment) Equ.6.6.1

Where, α=Angle of joint of K-segment

θk=Central angle of K-segment

ω=Spare angle to insert K-segment(Usually, $2° \leqq \omega \leqq 5°$)

Fig.6.4.1 Angle of Joint of K-Segment

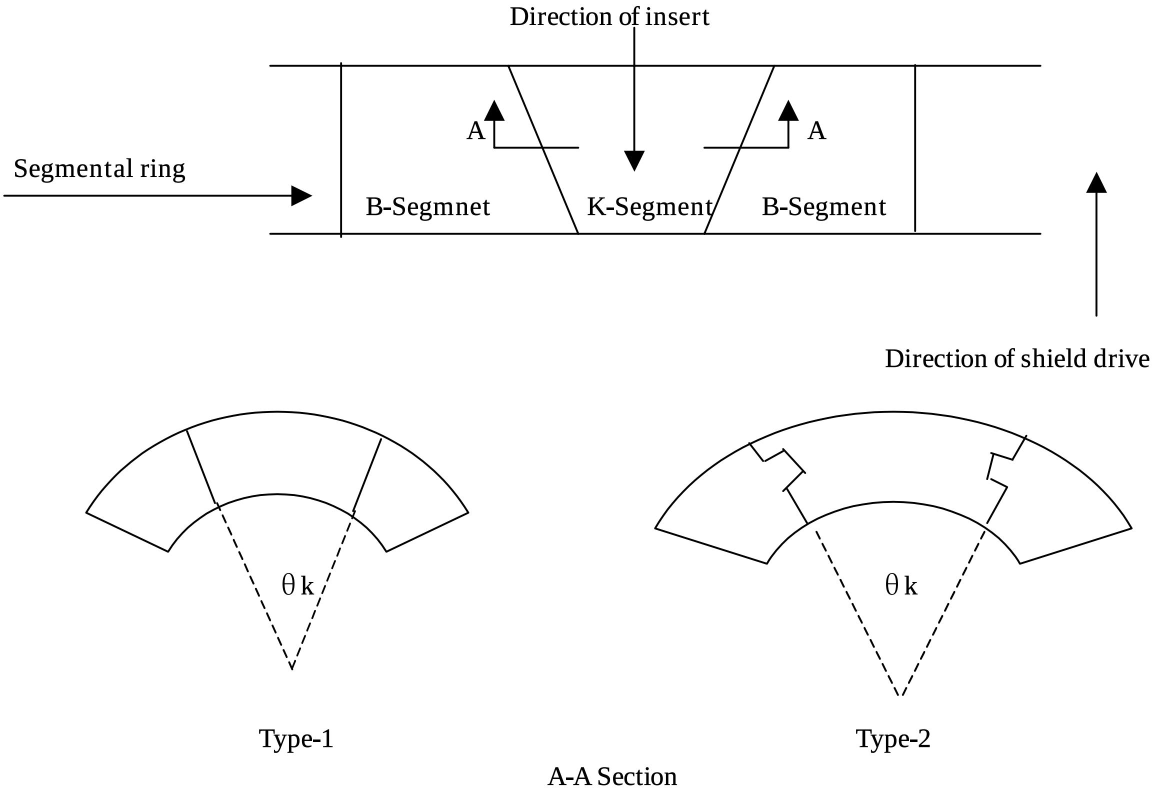


Fig.6.4.2 Joint of K-Segment inserted in Longitudinal Direction

6.5 Tapered Segment

Tapered segments are used for the construction of curved alignment or the direction control of shield. The difference between the maximum width and the minimum width can be calculated with Equ.6.7.1.

$$\delta = \{(m/n)S + S'\}D/(R + D/2) \qquad \text{Equ.6.7.1}$$

Where, δ=difference between max.width and min.width of tapered segmental ring
S=Width of standard segmental ring
S'=Max.width of tapered segmental ring
m=Number of standard segmental rings in curved section
n=Number of tapered segmental rings in curved section
D=Outer diameter of tunnel
R=Radius of alignment at the center of tunnel

7. Production of Segments

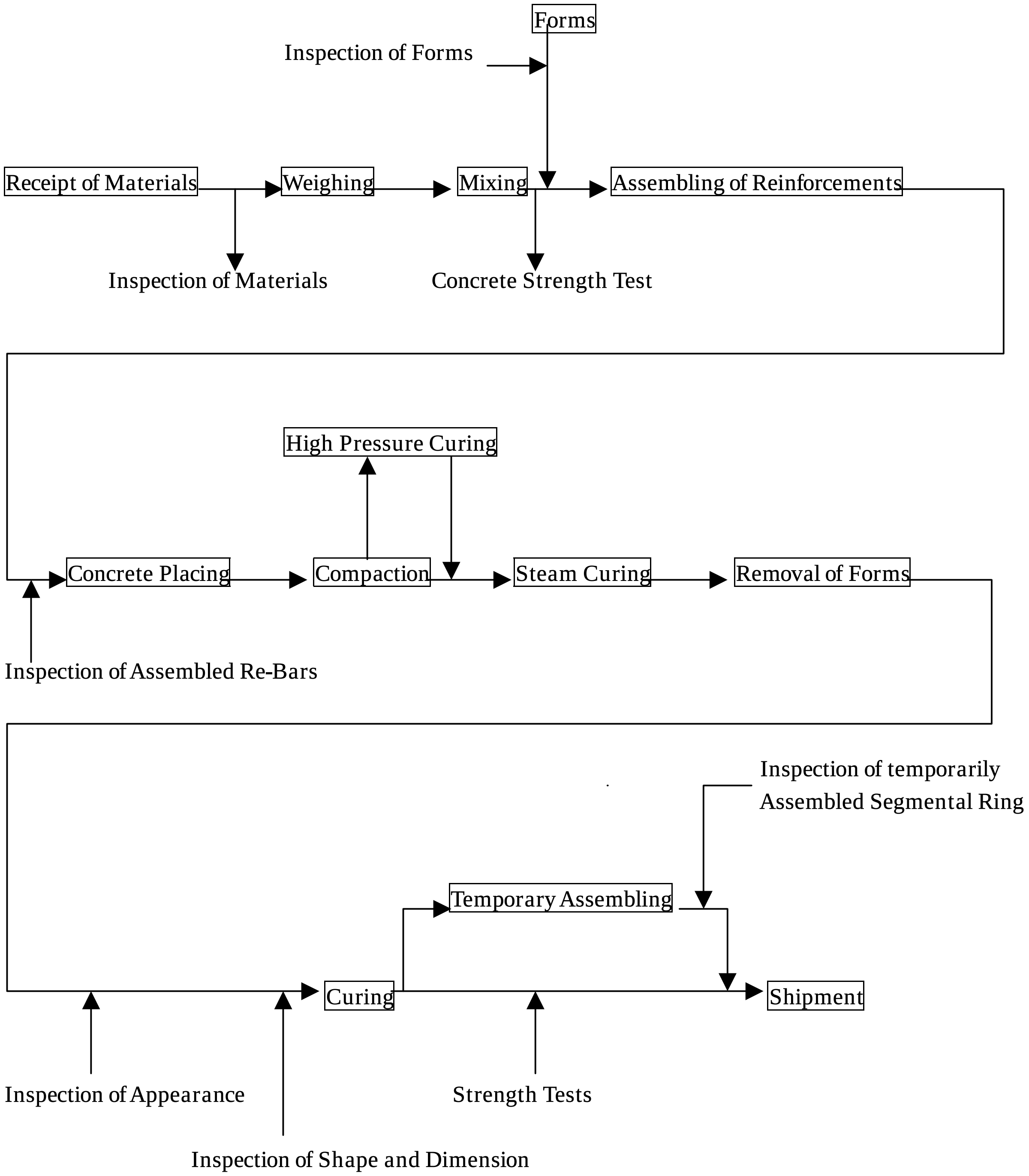
7.1 Tolerance of dimension

The errors of dimension of produced segments should not be more than the tolerance. They should be minimize to prevent lealkage and to assemble segments easily and accurately.

7.2 Inspection

The following inspections should be made for segment for the quality control of it. Fig.7.2.1 shows the sequence of production of segment.

① Inspection of materials
② Inspection of appearance
③ Inspection of shape and dimension
④ Temporary assembly inspection of temporarily assembled segmental ring
⑤ Performance tests (Strength tests)
⑥ Other tests



Extract form Standard Specification for Design and Construction of Tunnelling issued by JSCE

Fig.7.2.1 Sequence of Manufacture of Segments

8. Secondary Lining

8.1 General

Secondary lining is constructed with cast-in-place concrete. It is divided into non-structural member and structural member. The former is executed to reinforce segments, to prevent corrosion and vibration, to improve appearance of lining and to correct alignment. In the latter case, secondary lining is constructed as a structural member combined with segmental lining.

8.2 Thichness

The thickness of secondary lining as a non-structural member usually ranges form 15 cm to 30 cm. The thickness of secondary lining as a structural member is decided in accordance with the result of design calculation.

8.3 Computation of Member Forces

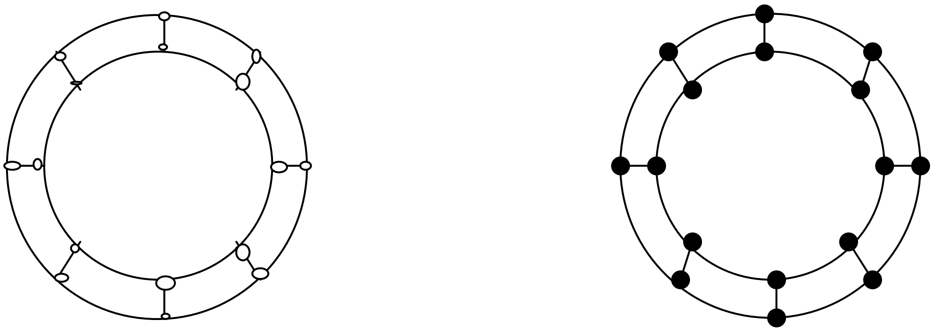
If secondary lining is constructed as a structural member, member forces of secondary lining should be computed by using loads which act on lining after the completion of secondary lining. In this case, the tunnel lining combined by the segmental lining and the secondary lining is divided into the double shell structure and the composite structure in accordance with the smoothness of border between both linings. In case of the double shell structure, only axial force must be transmitted through the border of both lining and shear force need not to be transmitted through it. In case of the composite structure, both of axial force and shear force must be transmitted through the border of both lining by dowelledly jointing both lining or making the surface of border uneven. As a rule, tunnel lining combined by segmental lining and secondary lining should be treated as the double shell structure.

If secondary lining is a non-structural member, the design calculation of it can be omitted but, for safety, it might be made by using dead load as load condition. If a waterproofing membrane without the drainage system is placed before casting the secondary lining, the secondary lining should be designed for the full water pressure, as maximum.

Assuming that tunnel lining combined by segmental lining and secondary lining is a double shell structure, the member forces of secondary lining should be computed by any rational method that properly considers the interaction between the initial lining and the secondary lining and is compatible with the design of the initial lining. Examples of methods how to compute member forces are as follows.

8.3.1 Bedded Frame Model Method

When the member forces of secondary lining are computed with the bedded frame model, the double ring frame model should be used. In this model, the outer ring simulates the segmental lining and the inner ring simulates the secondary lining. Fig.8.3.1 shows how to compute member forces of secondary lining with the bedded frame model.



○ : Hinged Joint

● :Rigid Joint

Double Shell Structure

Composite Structure

Fig.8.3.1 Bedded Frame Model

8.3.2 Elastic Equation Method

Assuming that loads acting on lining are sustained by segmental lining and secondary lining in proportion to the magnitude of the flexural rigidity. Equ.9.3.1 calculates the ratio between loads sustained by secondary lining and total loads. When member forces of secondary lining are calculated, loads multiplied by μ replace corresponding loads and EI１+EI２ replace EI in Tab.5.2.1.

$$\mu=(E_2 I_2/Rc_2^{4})/(E_1 I_1/Rc_1^{4}+E_2 I_2/Rc_2^{4}) \qquad \ldots\ldots\ldots\ldots\ldots\ldots \text{ Equ.9.3.1}$$

8.4 How to check the safety of section

The safety of section should be checked with the limit state design method or the allowable stress design method , wchich are the same methods as used for the segmental lining.

PART III

REFERENCES

1. Design Example (1)

Refer to “Guidelines-Design Example-1.pdf”.

2. Design Example (2)

Refer to “Guidelines-Design Example-2.pdf”

3. References

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