Precast segmental liner design and construction for some of the world's most challenging tunnels

Jon Hurt

Colorado School of Mines

9/14/2016

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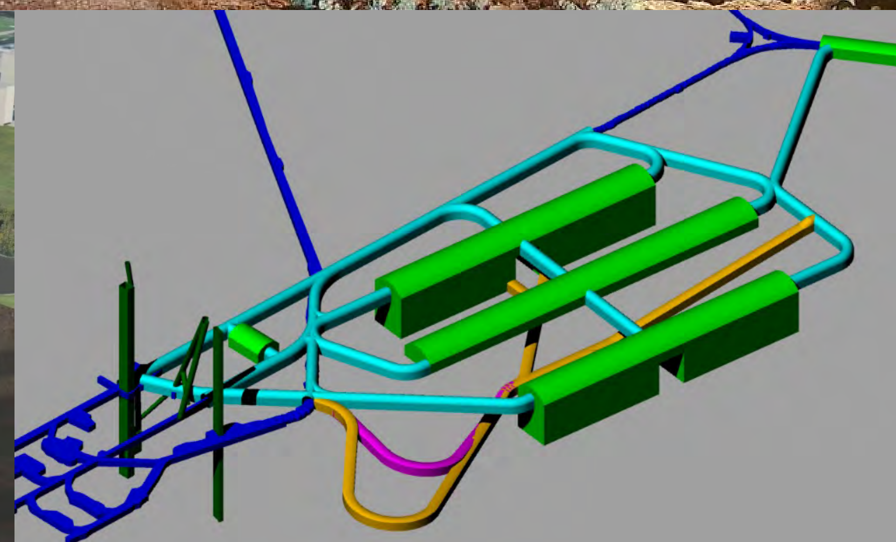
Jon Hurt PE, CEng, MICE
Principal
Tunnels Skills Leader

- leader of Arup's Tunnel Practice in the Americas
- global leader for the Tunnel Skills Network
- a project manager and tunnel engineer, wide range experience in management, design and construction of major tunneling projects
- experience includes underground construction projects on five continents including High Speed 1 in UK and NYC's 2nd Ave Subway
- currently PM for DOE's Long Baseline Neutrino Facility Far Site project
- Coordinator for Arup's philanthropic program in the Americas


normet



Arup has come a long way since the firm was founded, yet we stay true to Ove Arup's original values. Our unique trust ownership structure means our people are free to pursue the firm's vision rather than chase short-term shareholder returns. This is how we maintain our distinctive culture and intellectual independence.

Straight and honorable dealings ■ Humane organization

Total architecture ■ Social usefulness

Reasonable prosperity of members ■ Quality of work

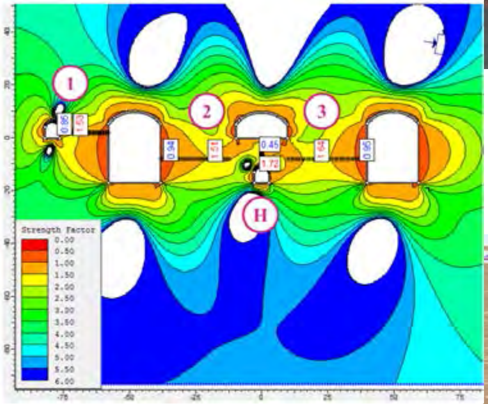
John Kuyt

Graduate Tunneling

Engineer

Full Time:

Miami – Norris Cut Tunnel,
Design Engineer on Site

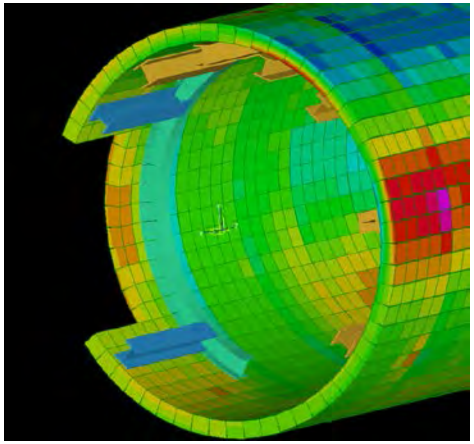


Lead, SD – LBNF, Cavern Separation Design

Colorado School of Mines:

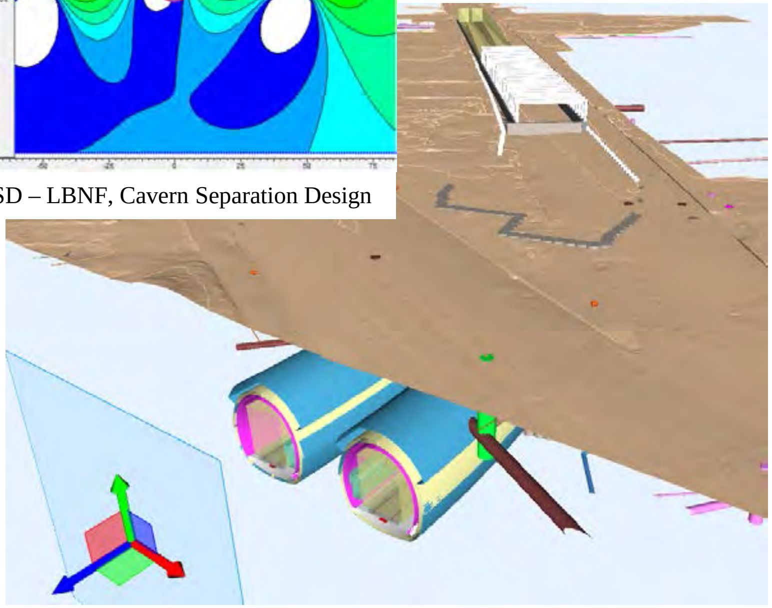
- BS Civil Engineering (2013)
- MS Underground Construction & Tunneling (2015)

Internships:



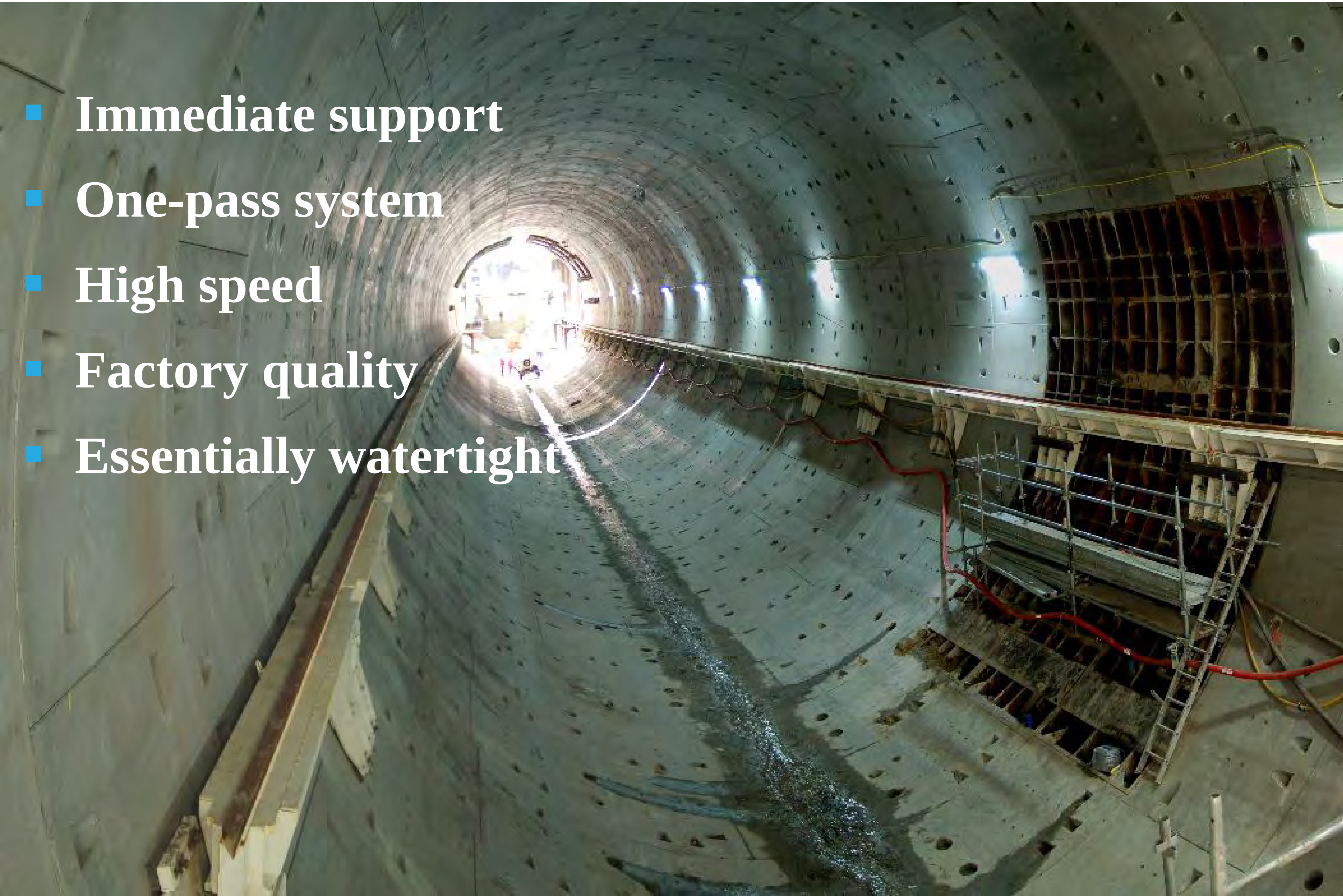
Los Angeles – Crenshaw/LAX Line
Cross Passage Design

San Francisco – Central Subway, Field
Engineering Intern



Edmonton, AB – Valley Line LRT, Project Engineer

Introduction to Segmental Linings



- Immediate support
- One-pass system
- High speed
- Factory quality
- Essentially watertight

airportlink in 2012

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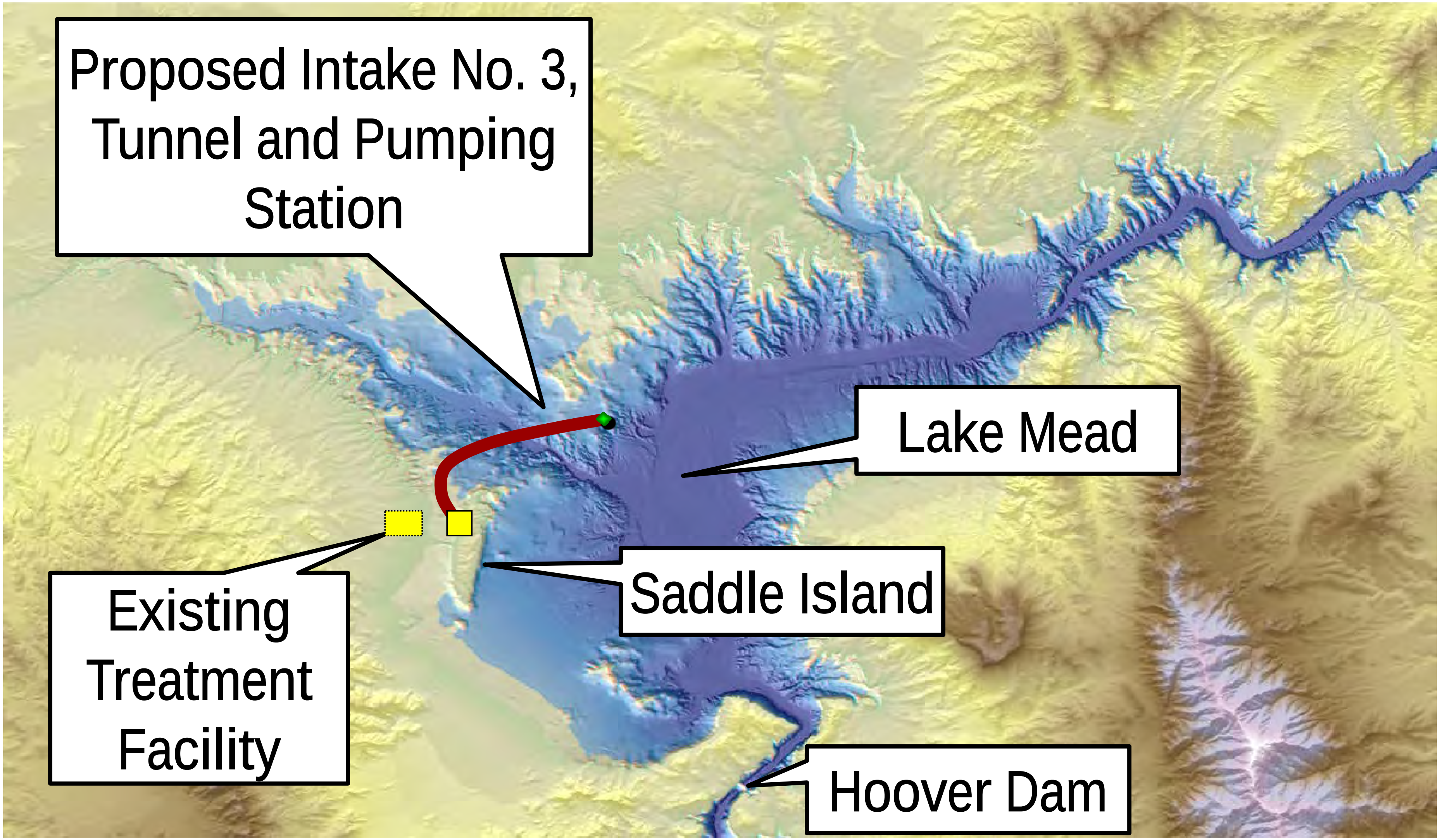
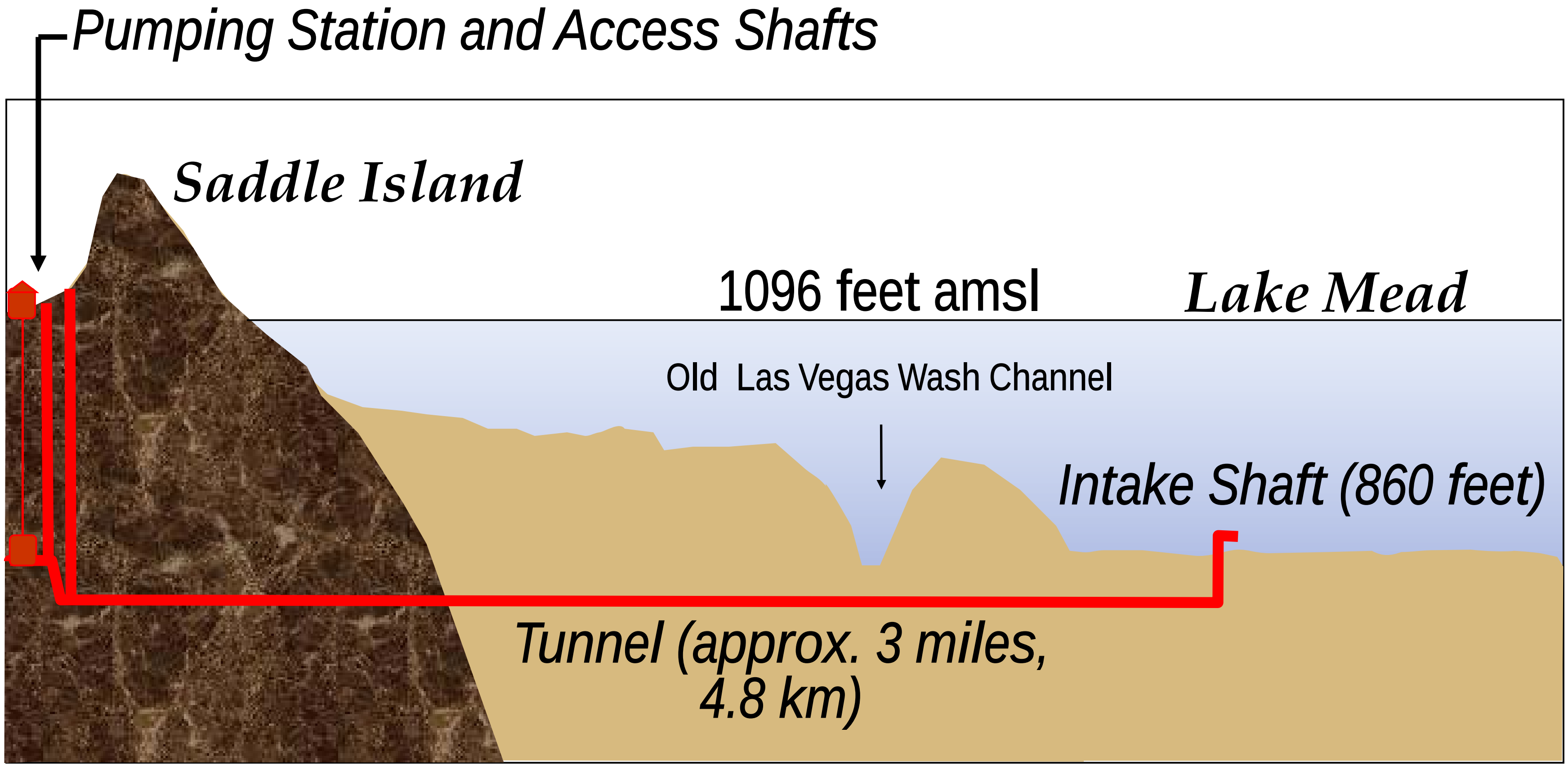
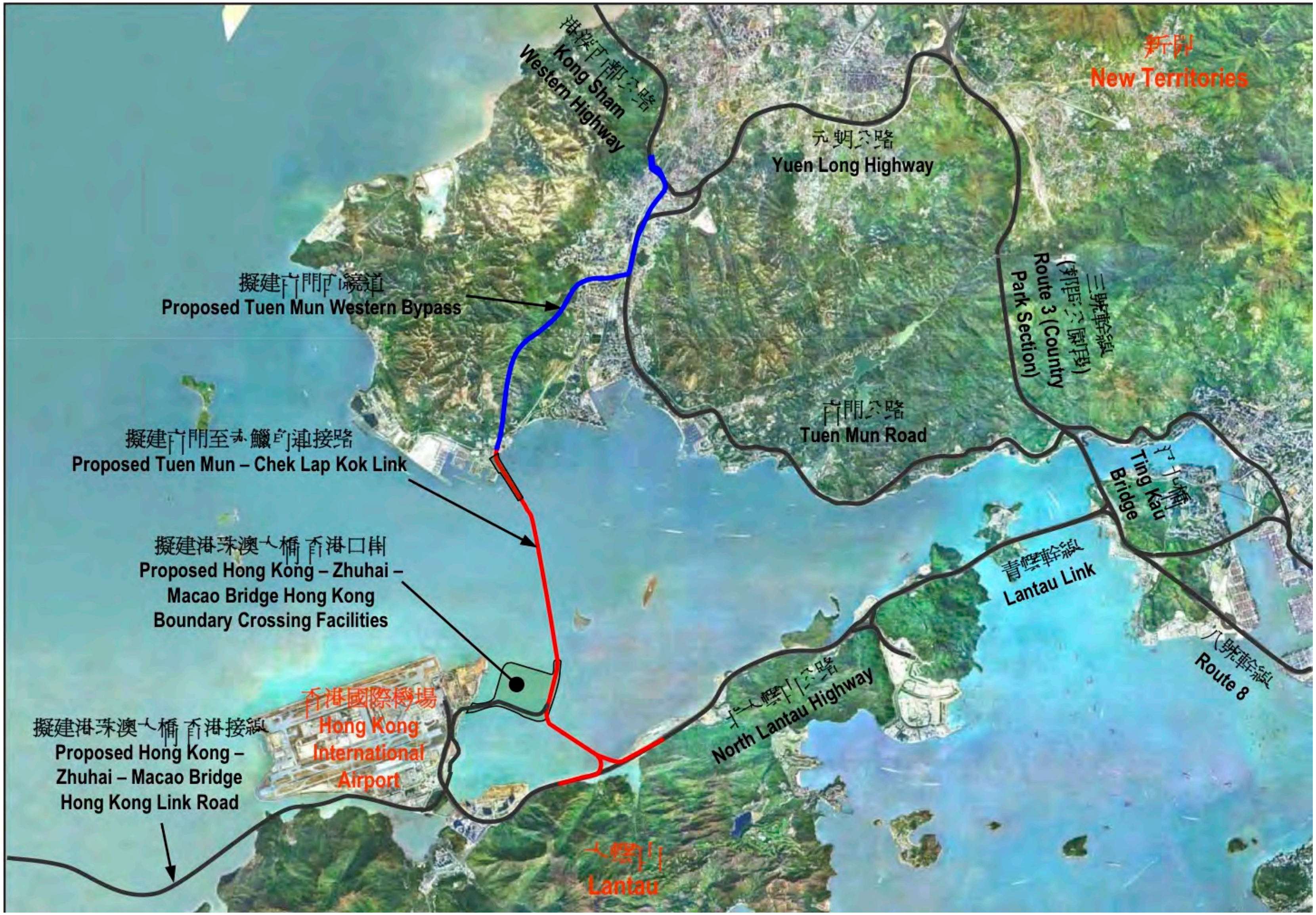
Intake No.3 Project Overview



Profile of Proposed Intake System



Tuen Mun to Chek Lap Kok



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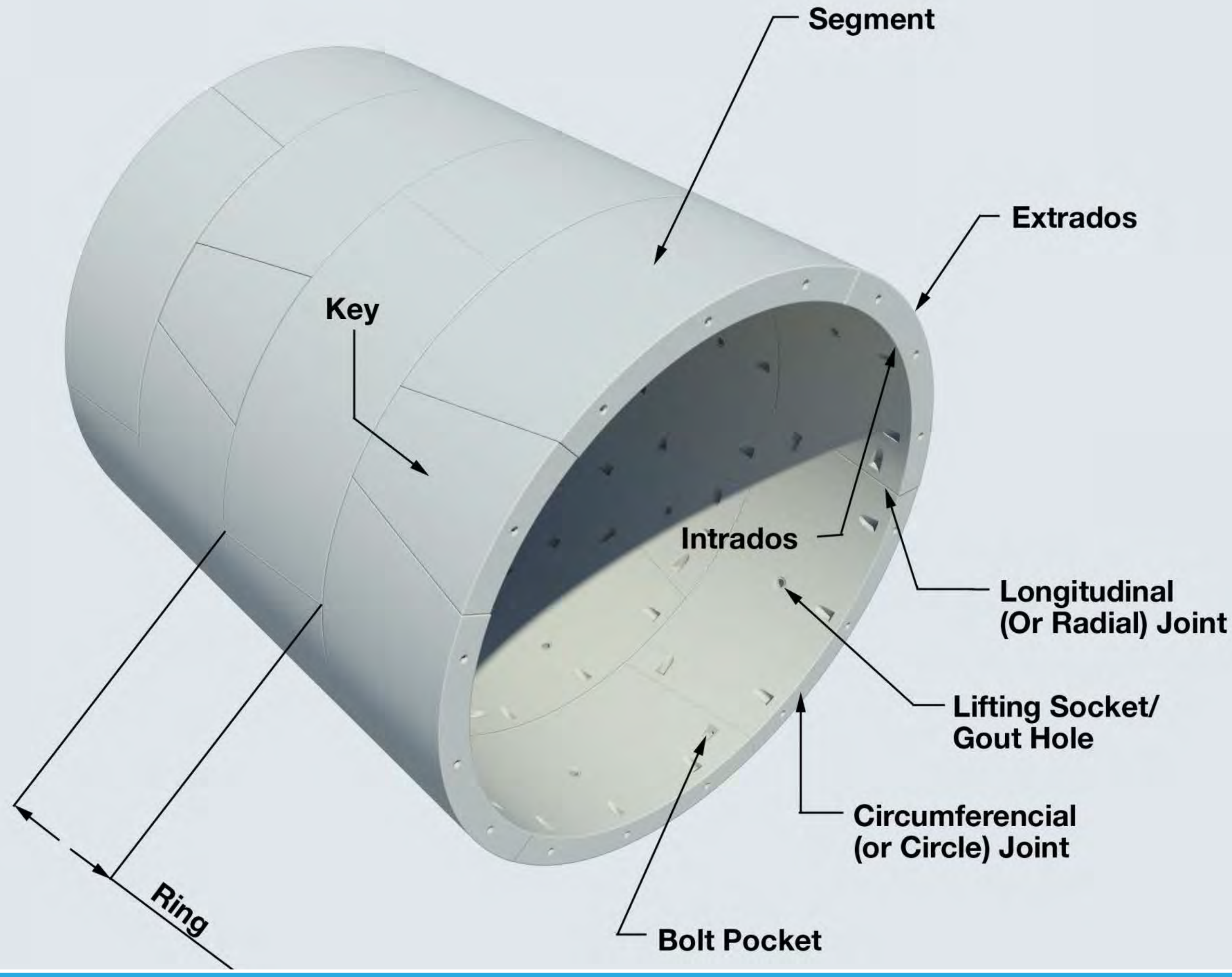
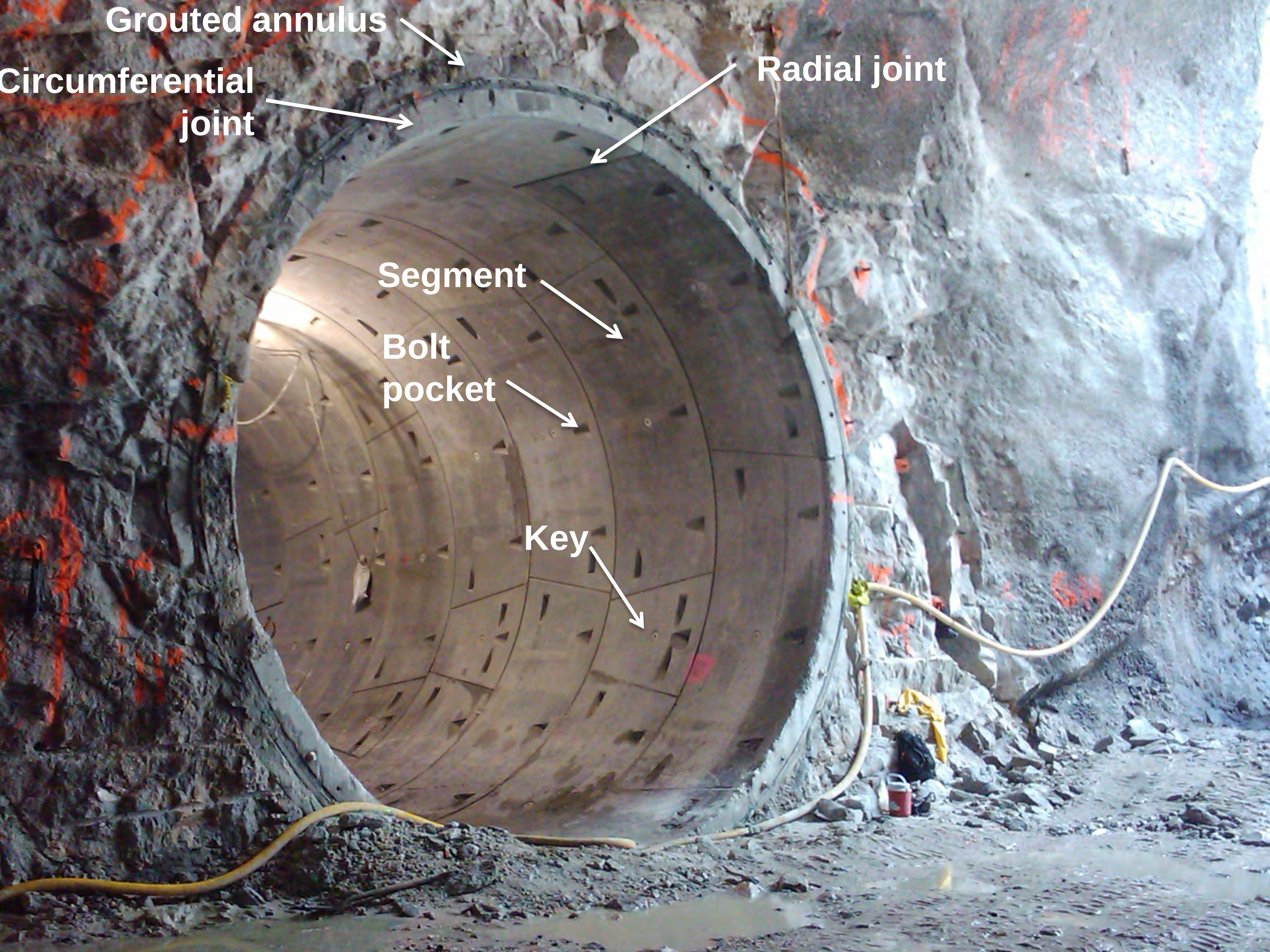
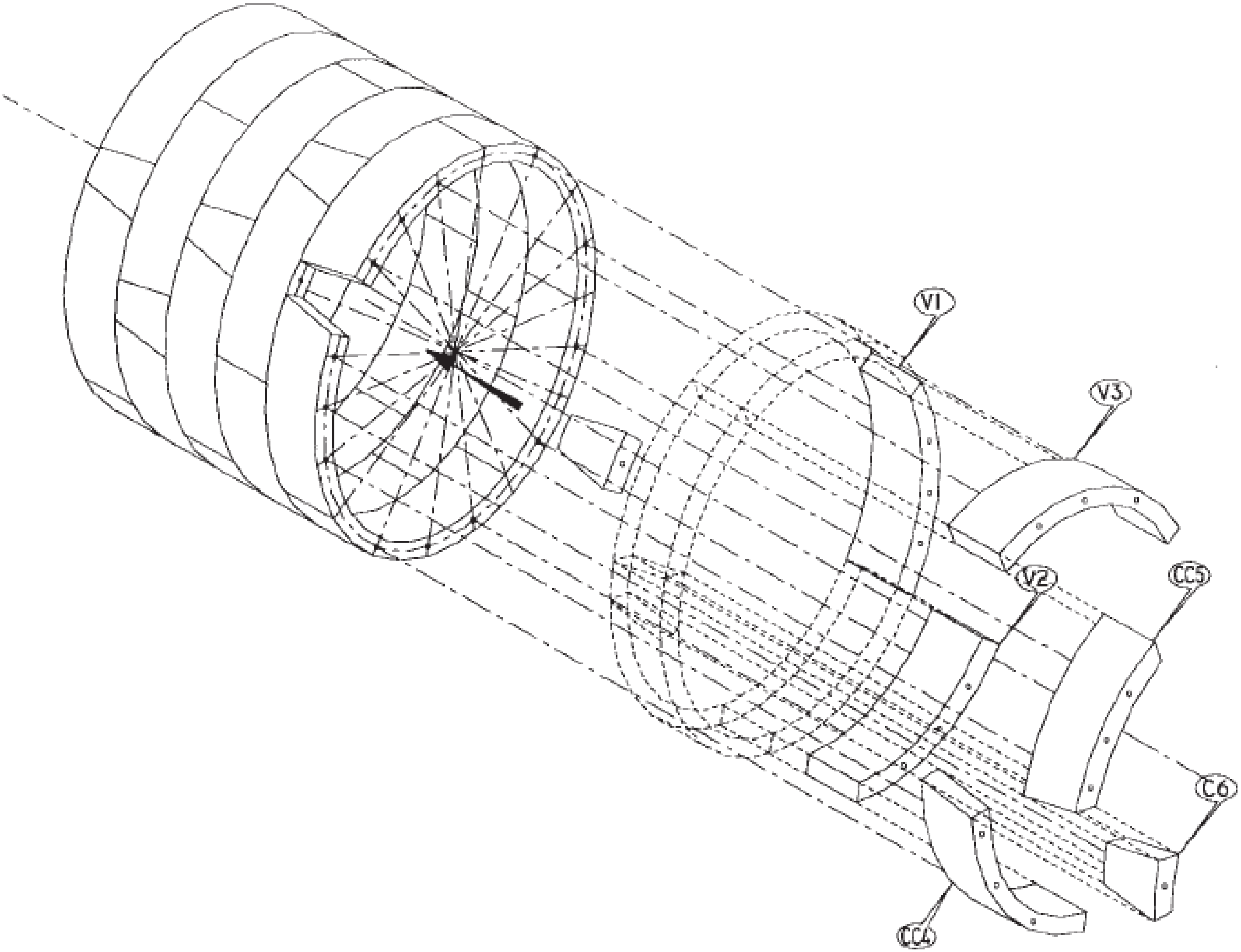
香港寶嘉
Dragages HongKong
Bouygues Construction group
BOUYGUES TRAVAUX PUBLICS
Dragages - Bouygues Joint Venture 寶嘉 - 布依格聯營
2015/12/15 00:13


Segment
Extrados
Key
Intrados
Longitudinal
(Or Radial) Joint
Lifting Socket/
Gout Hole
Circumferencial
(or Circle) Joint
Bolt Pocket
Ring


Grouted annulus
Circumferential joint
Radial joint
Segment
Bolt pocket
Key

Rectangular Lining



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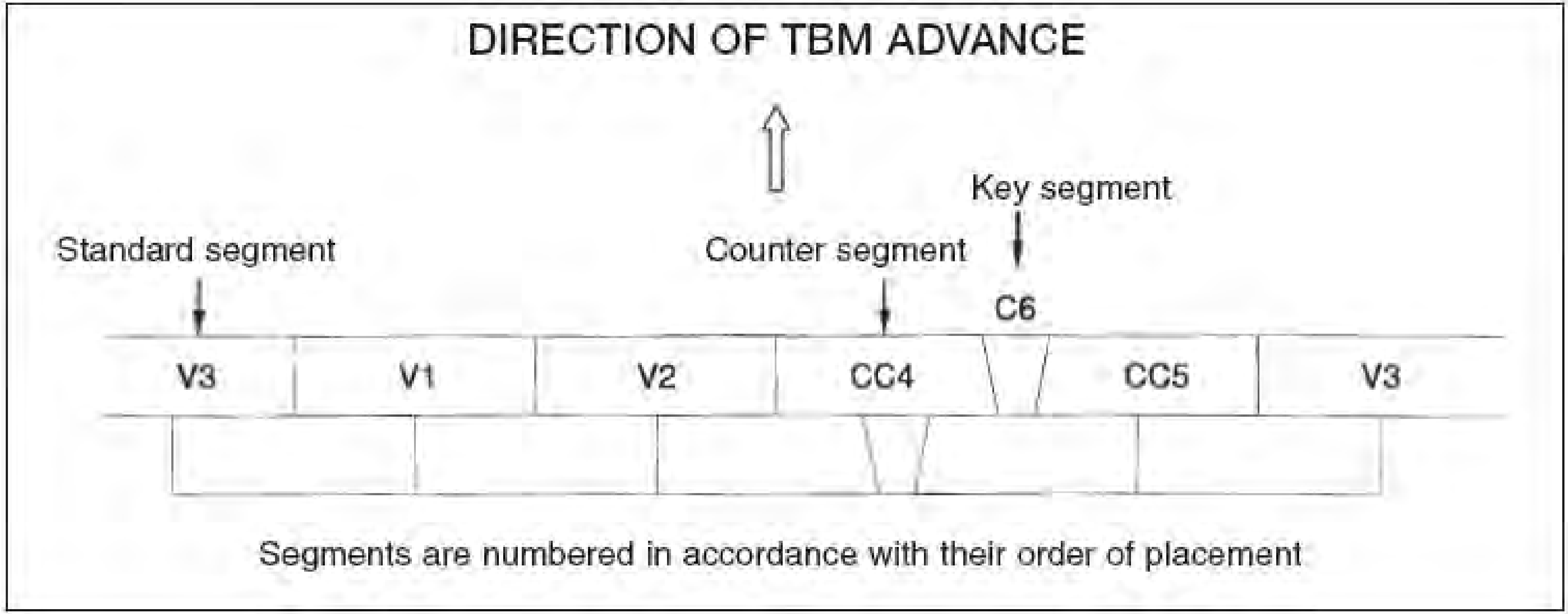
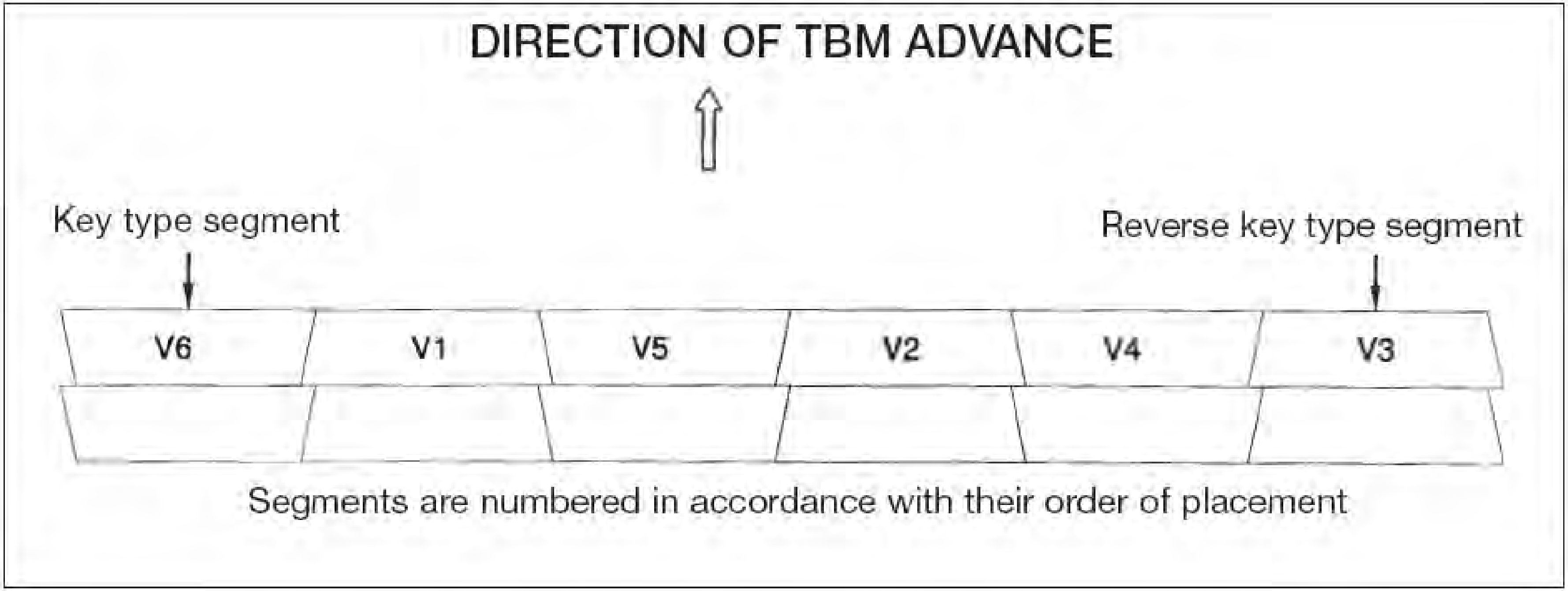
Rectangular Lining



Trapezoidal Lining



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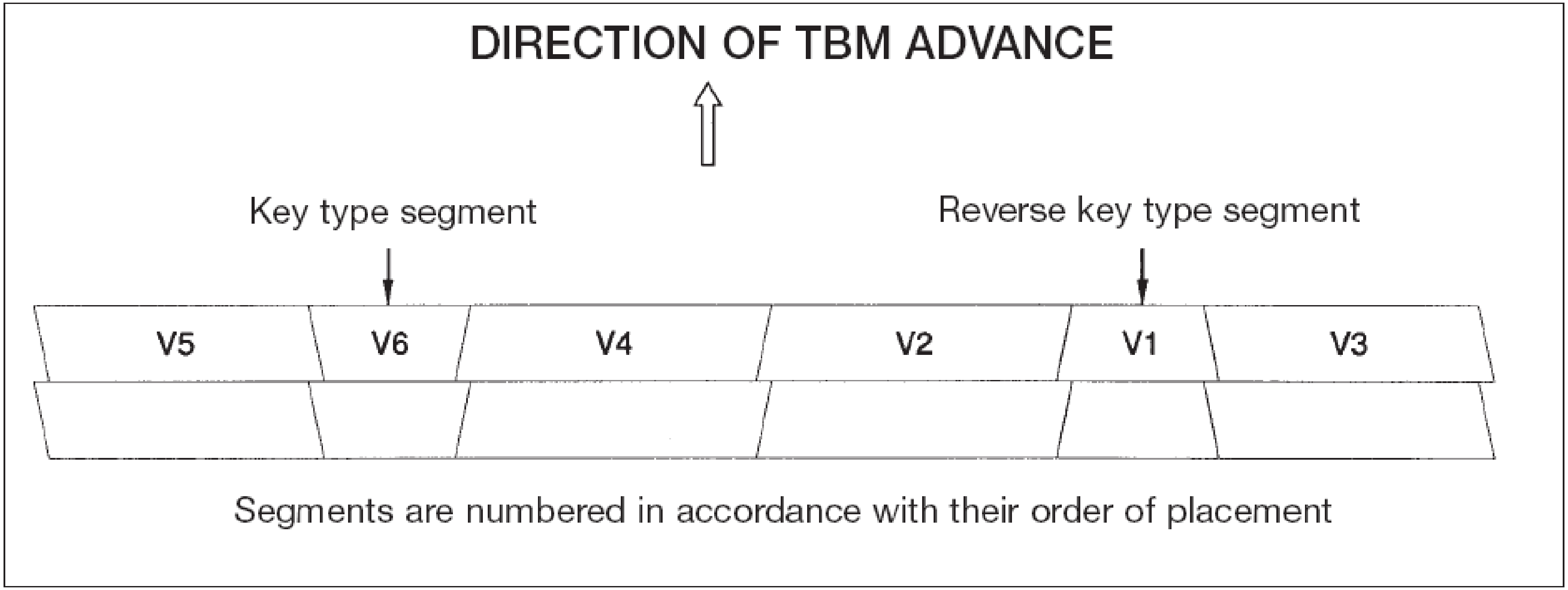
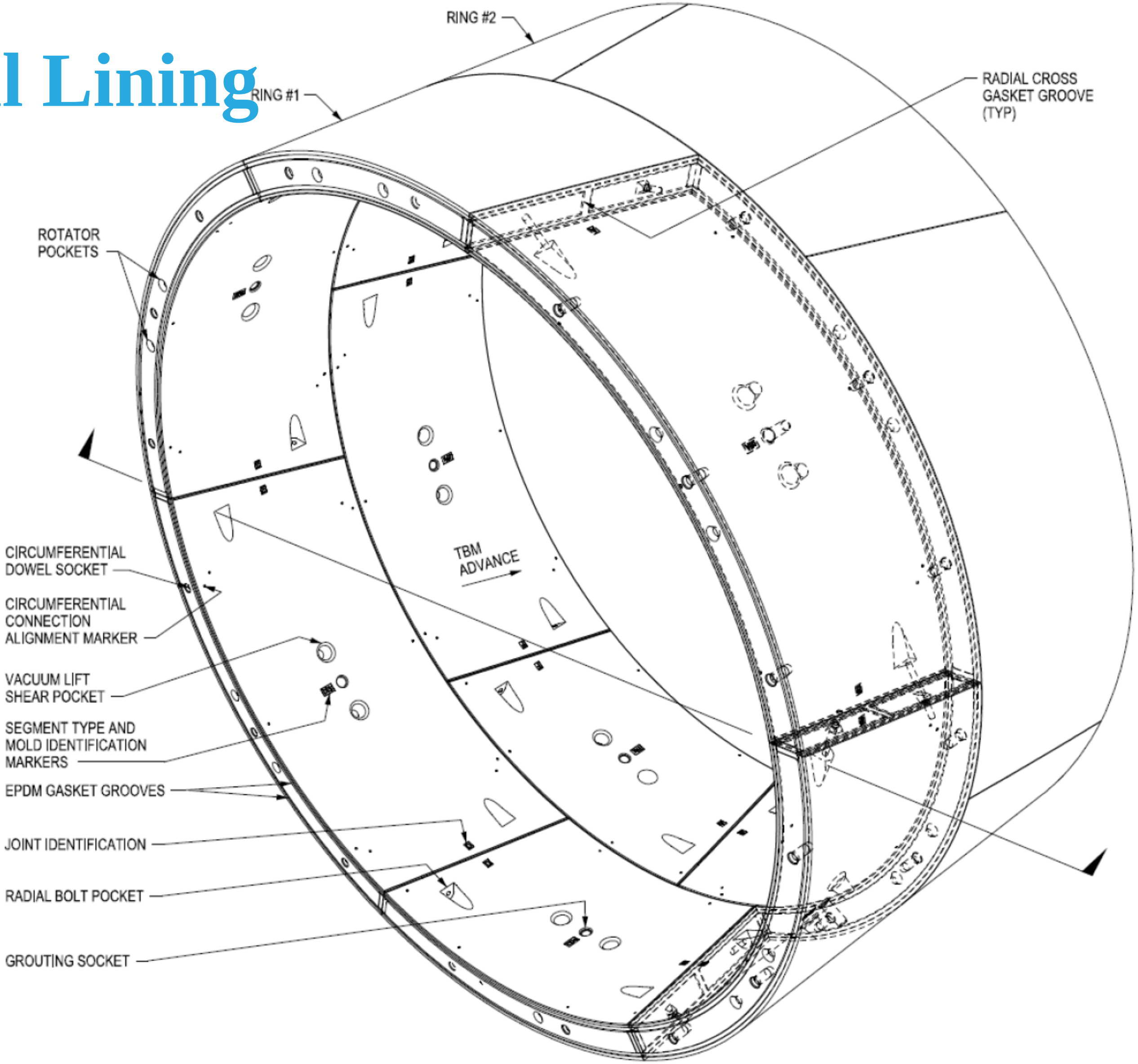
Rhomboidal Lining



Rhomboidal Lining



TUNNEL RING ASSEMBLY - ISO. VIEW

NO SCALE

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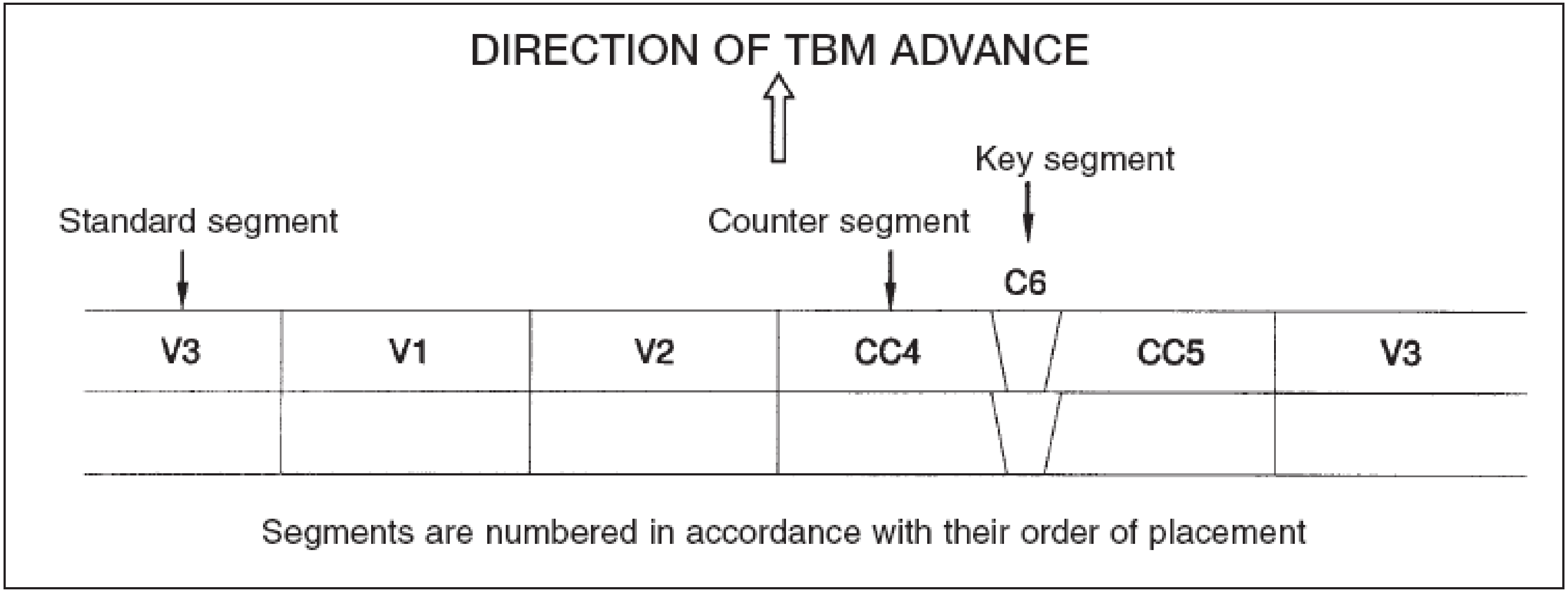
Expanded Lining



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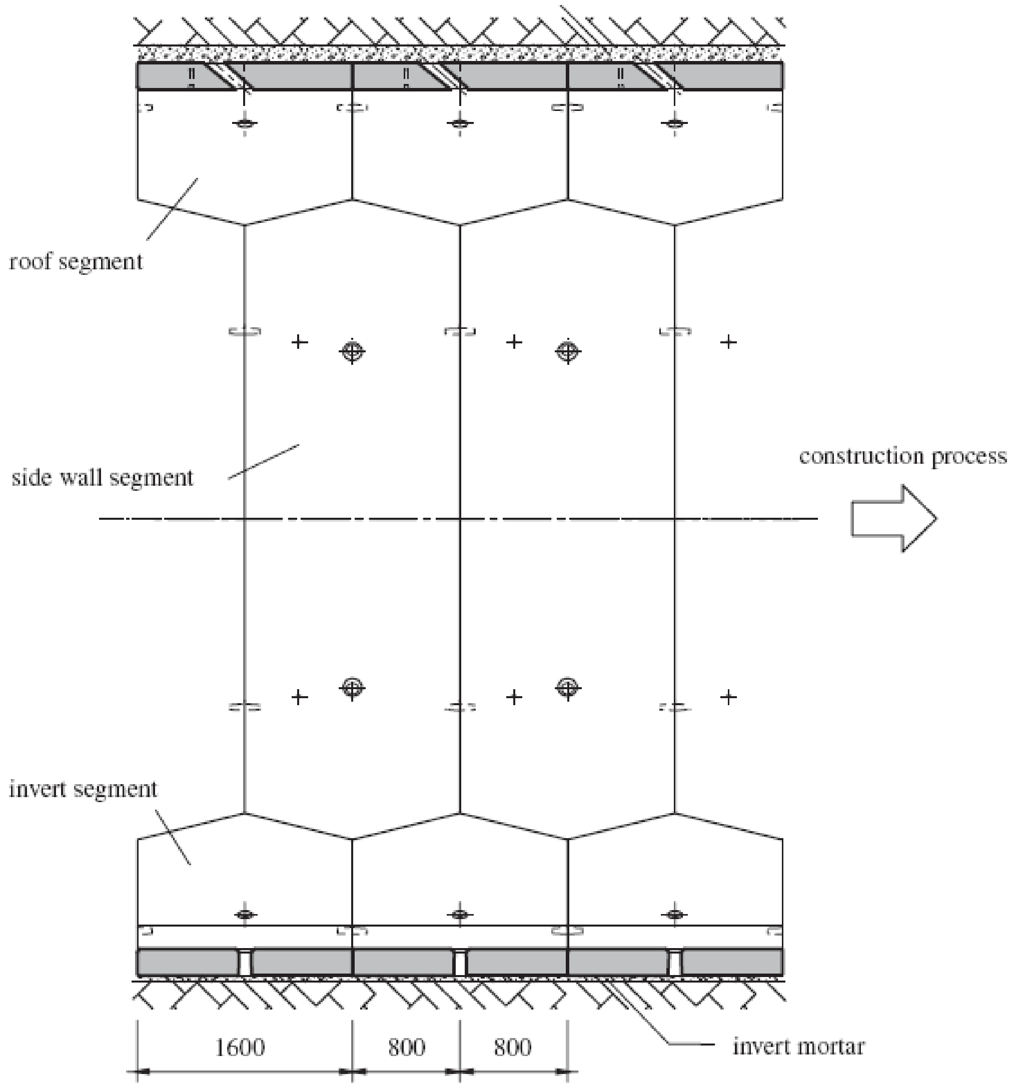
Expanded (Wedgeblock) Lining

Hexagonal (Honeycomb) Lining



Hexagonal (Honeycomb) Lining

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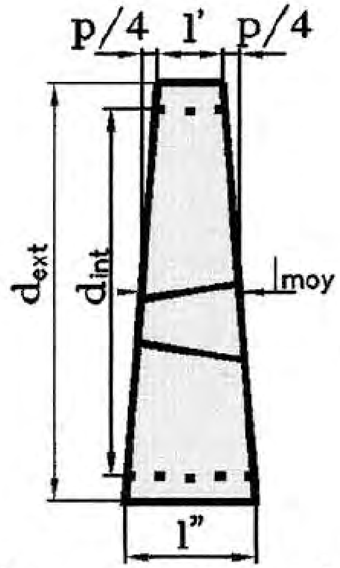
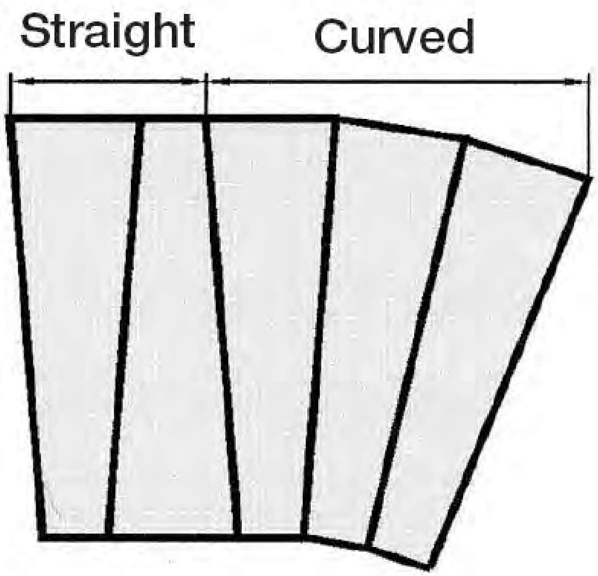
Tapered Linings

- **Taper can be applied to any lining geometry that allows rotation of rings**
- **Limits need for packing between segments on curves**



Universal tapered ring



Plan view

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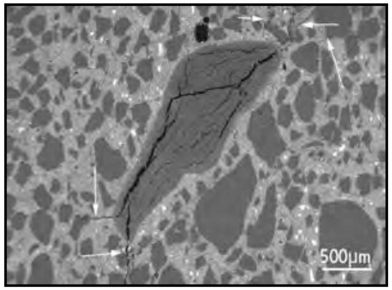
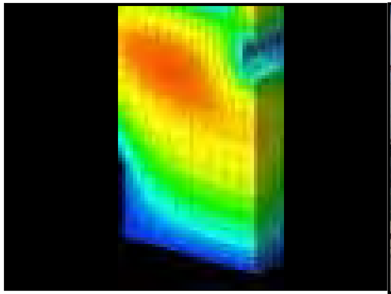
Joint Geometries

Concrete

Typically require:

- dense, impermeable, durable mix
- high early strength





Reinforced Concrete

- **Typically prefabricated welded cages**
- **Durability**

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Steel Fiber Reinforced Concrete

- **SFRC provides increased durability, simpler manufacturing and cost savings**
- **Surface Finish – Smooth, no exposed fibers**
- **Repairs – no corrosion protection required**

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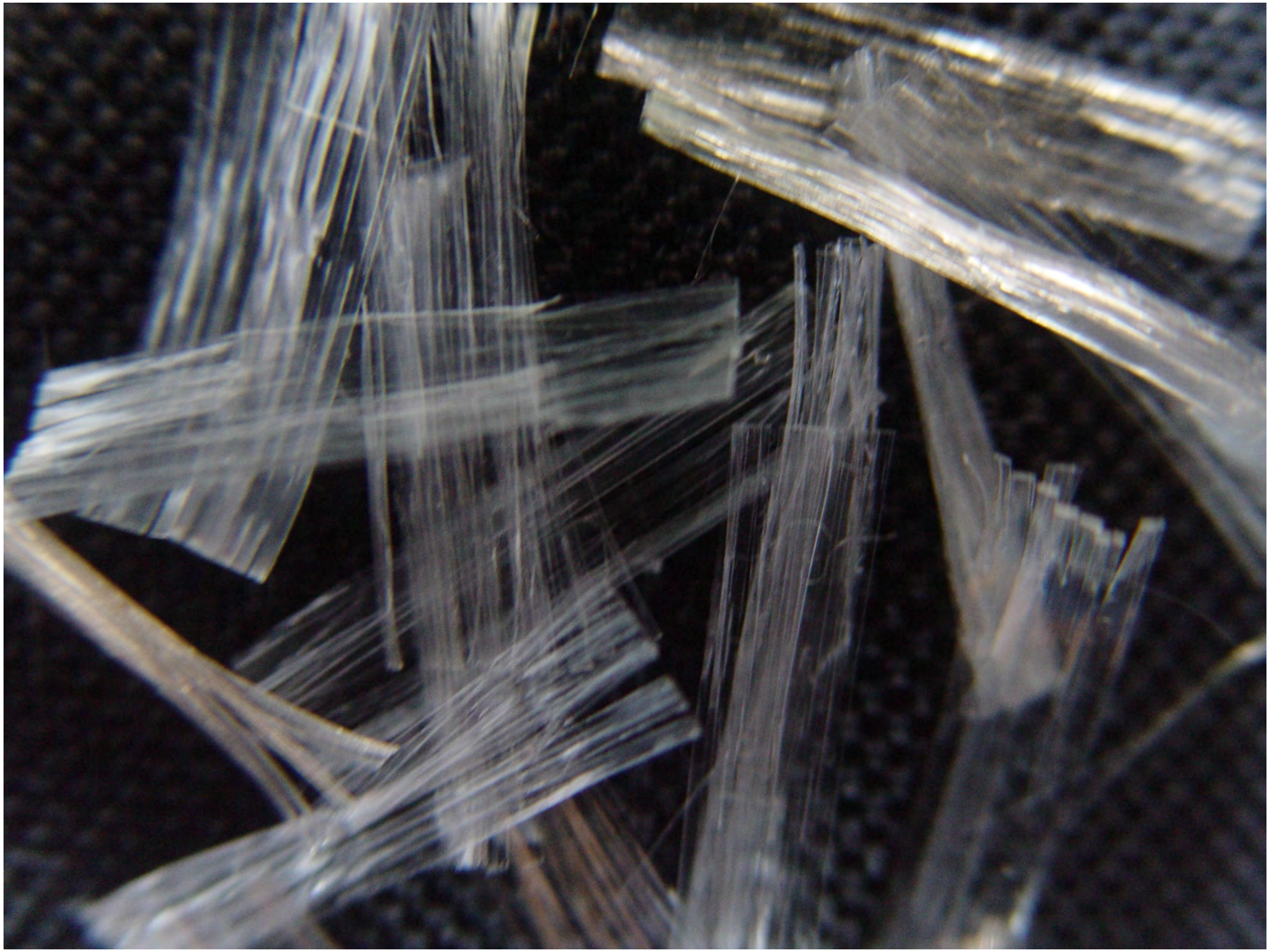
Polypropylene Fibers



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Fire Damage

Channel Tunnel

Storebelt

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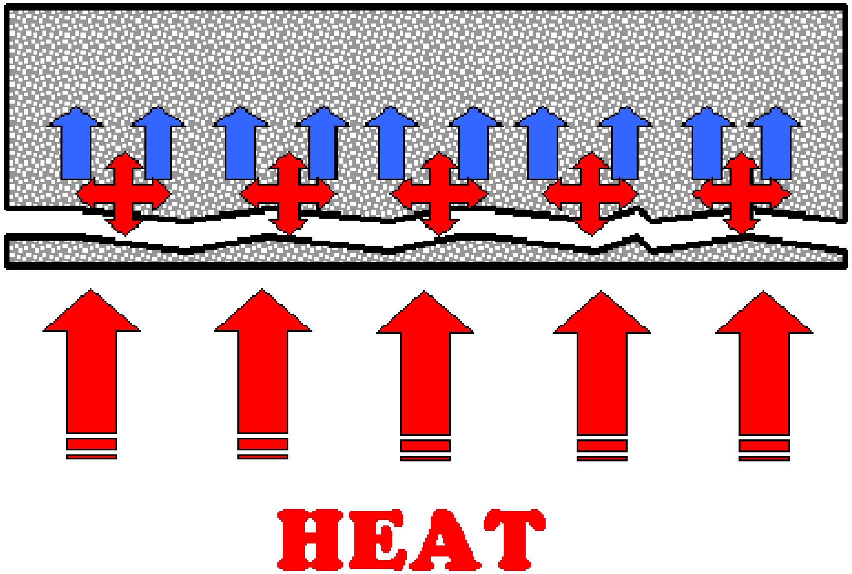
‘Normal’ Concrete

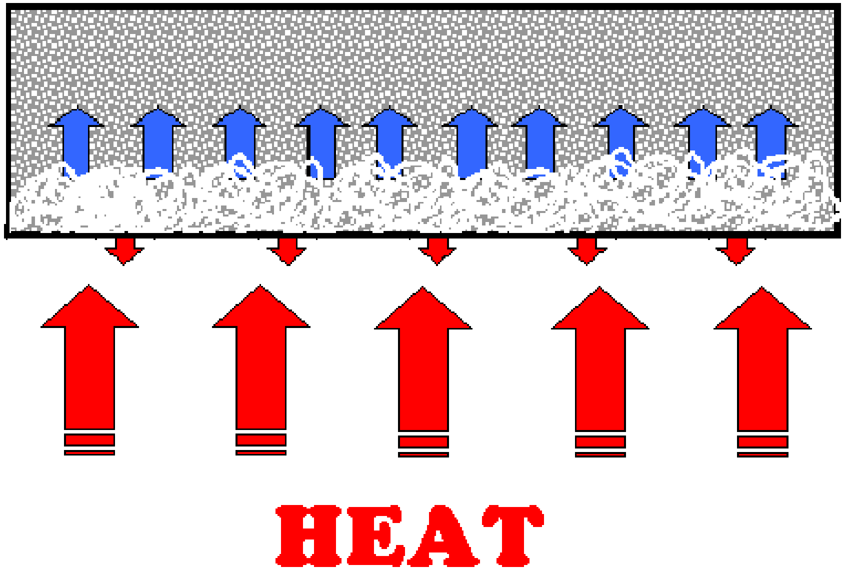


1. Moisture moves away from heat front

2. Vapour pressure increases as heat front advances

3. Vapour pressure > tensile strength of concrete and explosive spalling occurs

With Polypropylene Fibers

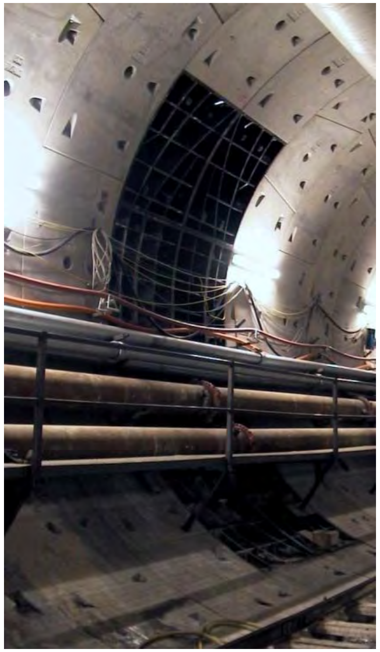


2. Fibres melt at 160° C form interconnecting passages for vapour pressure to escape


5
3

Steel/SGI Linings

- **Suitable for high load locations – eg openings.**
- **Steel – fabricated; Spheroidal Graphite Iron - cast**



Fixings and Appurtenances

EPDM/ Hydrophilic Gaskets

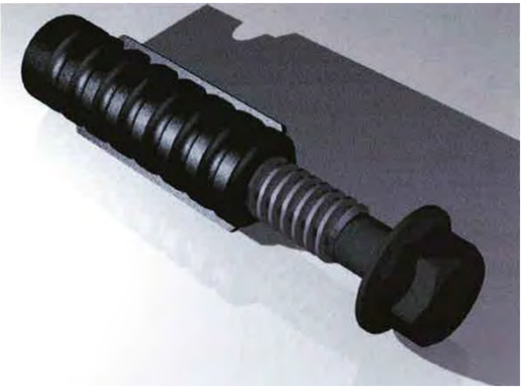
Bolts and Bolt Inserts

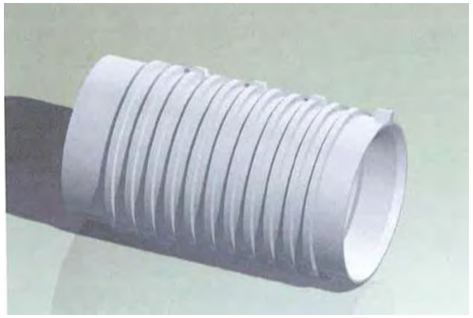
Alignment Dowels

Alignment Balls

Guide Rods

Lifting Sockets





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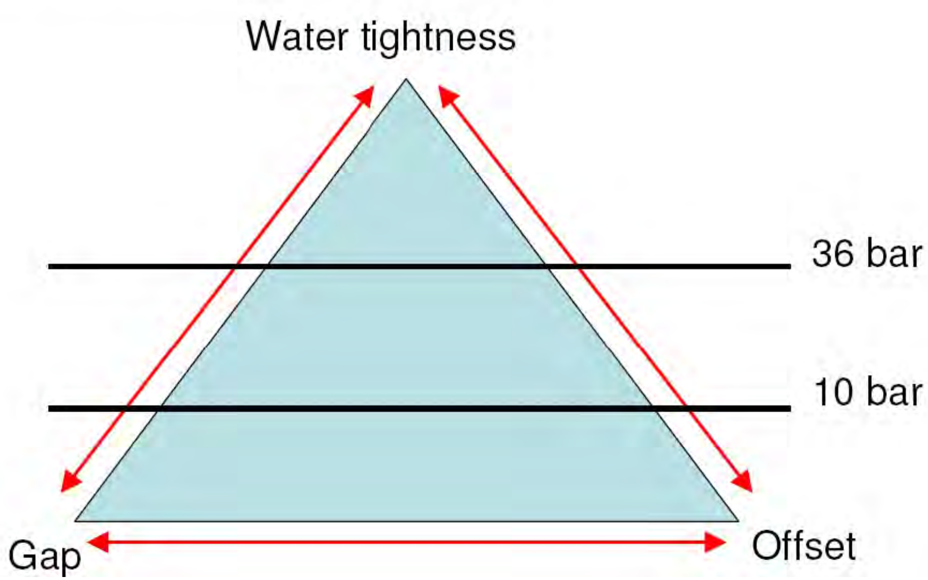
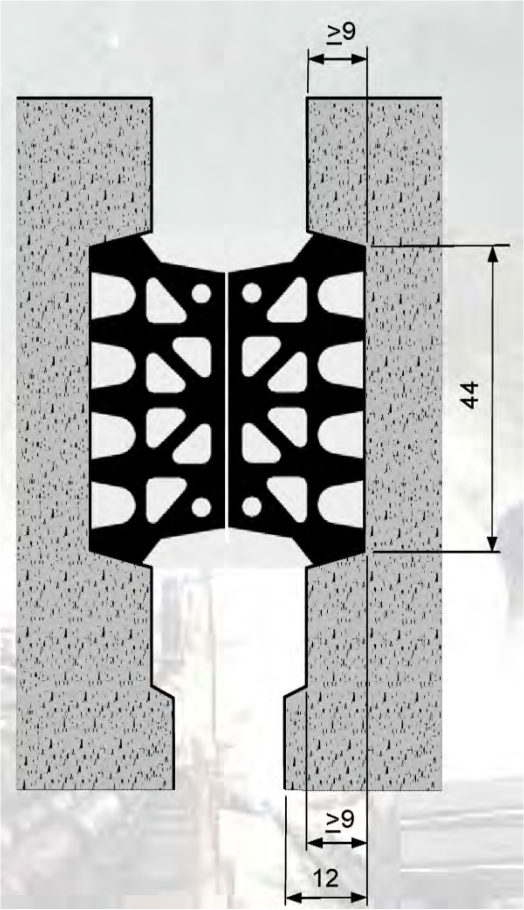
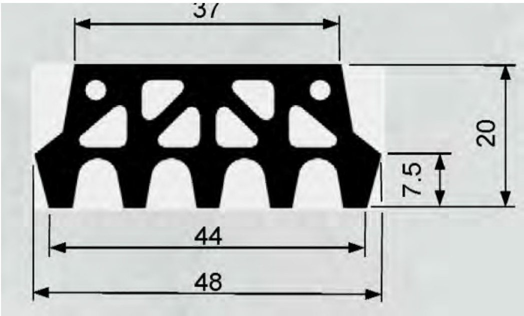
EPDM Gasket

- **Gaskets compressed against each other when lining is erected and provide sealing against water ingress**
- **Design for range of segment offsets and gaps**

Triangle of gasket performance:

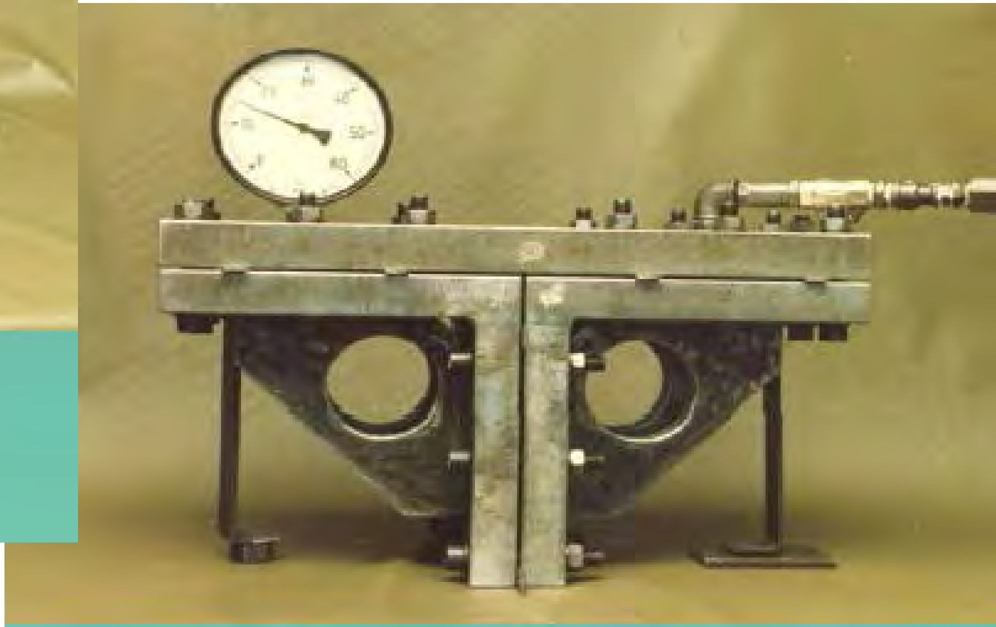






EPDM Gasket Testing

T-Joint Test Rig
open

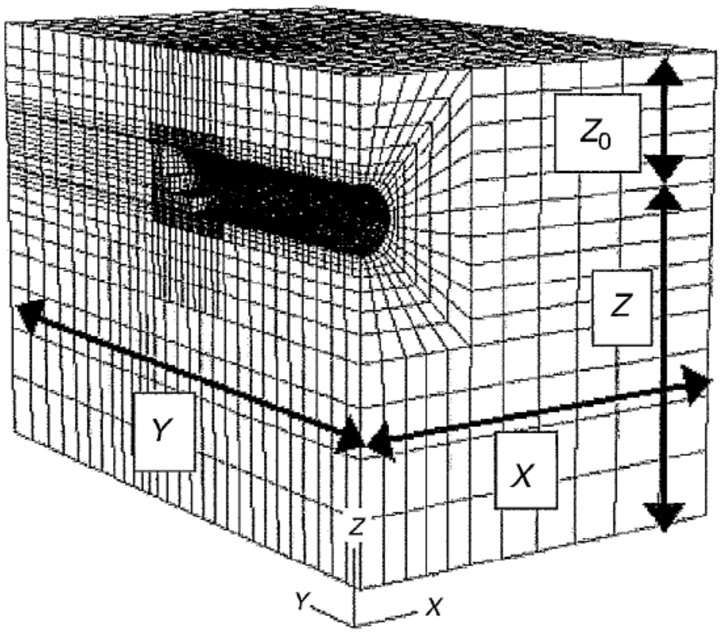


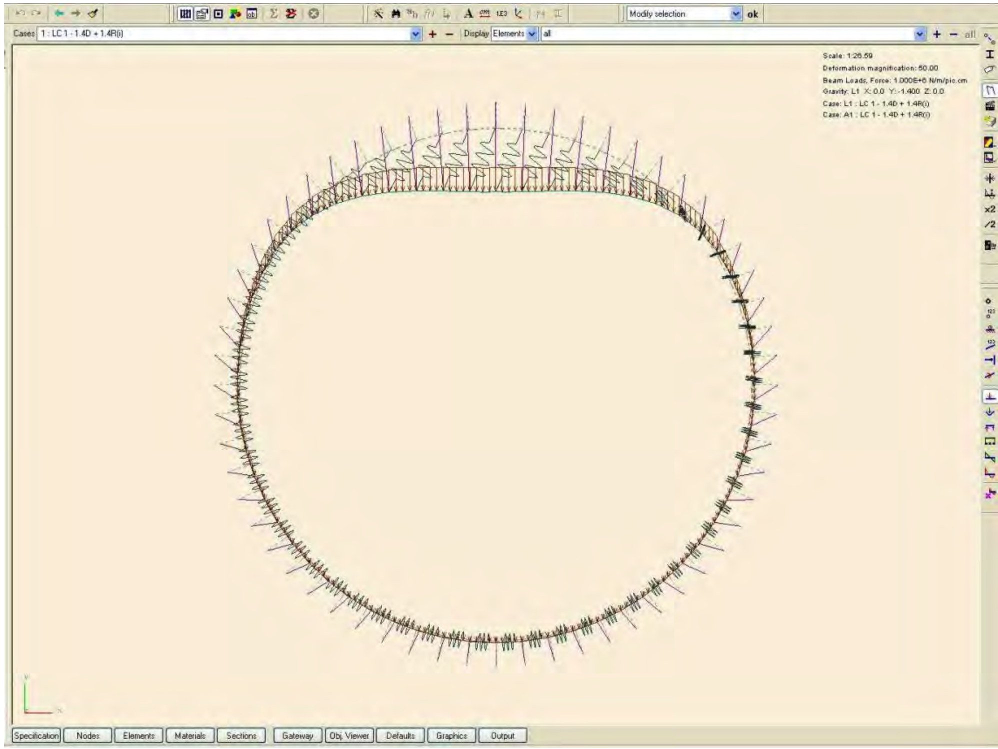
T-Joint Test Rig
closed

Ring Design

- **Continuum Analysis Models**
- **Bedded beam-spring**
- **Distortion Ratio**
- **Numerical Analysis**

From Einstein & Schwartz (1979)	**Full Slip** (no shear stress transmission)	**No Slip** (no relative shear displacement)
Compressibility ratio, **C*** / Flexibility ratio, **F***	$C^* = \frac{E_c R(1-\nu_s^2)}{EA(1-\nu^2)}$ / $F^* = \frac{E_c R^3(1-\nu_s^2)}{EI(1-\nu^2)}$	
Internal support forces, **M & N**	$\frac{M}{P_v R^2} = \frac{1}{2}(1-k_0)(1-2a_2^*)\cos 2\theta$	$\frac{M}{P_v R^2} = \frac{1}{4}(1-k_0)(1-2a_2^* + 2b_2^*)\cos 2\theta$
	$\frac{N}{P_v R} = \frac{1}{2}(1+k_0)(1-a_0^*) + \frac{1}{2}(1+k_0)(1-2a_2^*)\cos 2\theta$	$\frac{N}{P_v R} = \frac{1}{2}(1+k_0)(1-a_0^*) + \frac{1}{2}(1-k_0)(1+2a_2^*)\cos 2\theta$
where:	$a_0^* = \frac{C^* F^*(1-\nu)}{C^* + F^* + C^* F^*(1-\nu)}$ $a_2^* = \frac{(F^*+6)(1-\nu)}{2F^*(1-\nu)+6(5-6\nu)}$	$a_0^* = \frac{C^* F^*(1-\nu)}{C^* + F^* + C^* F^*(1-\nu)}$ / $a_2^* = \beta.b_2^*$ $\beta = \frac{(6+F^*)C^*(1-\nu)+2F^*\nu}{3F^* + 3C^* + 2C^* F^*(1-\nu)}$ $b_2^* = \frac{C^*(1-\nu)}{2[C^*(1-\nu)+4\nu-6\beta-3\beta C^*(1-\nu)]}$





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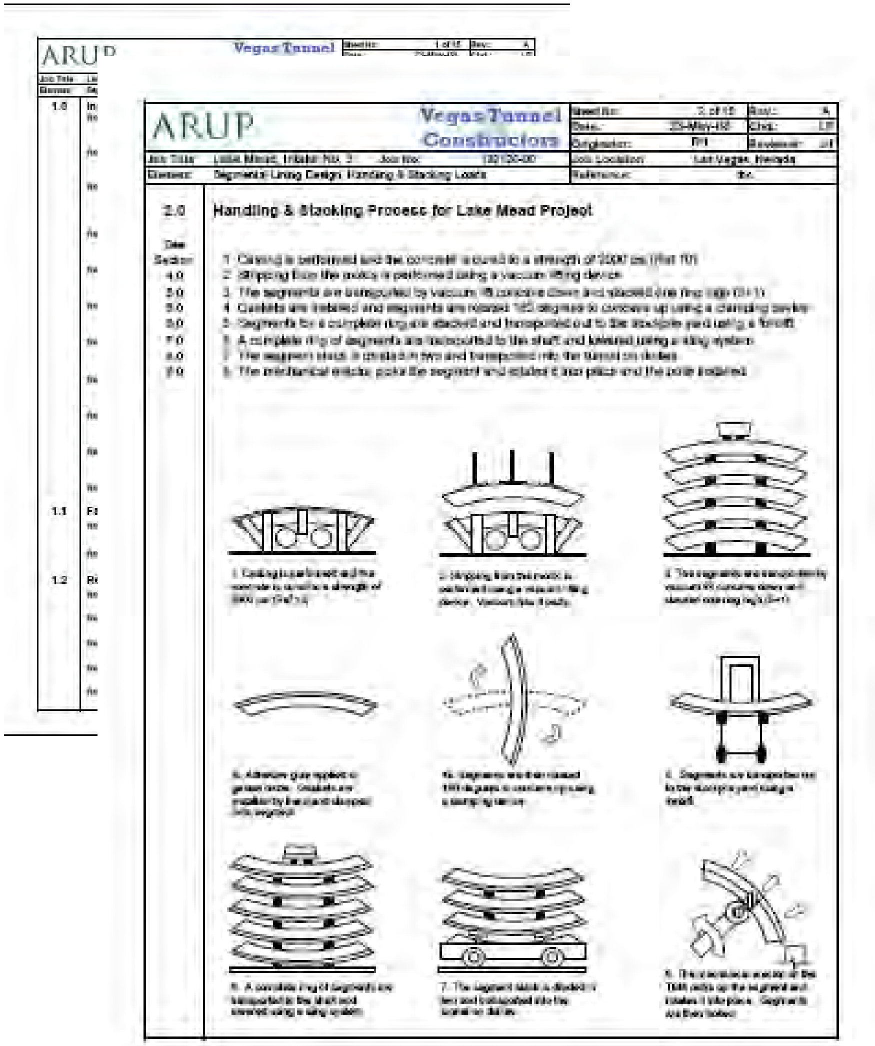
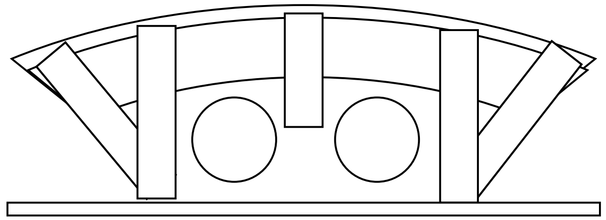
Segment Design – Manufacture and Handling

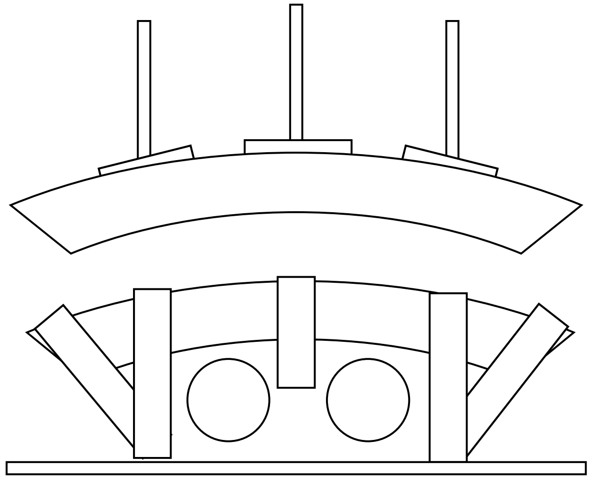


- **Consider all load cases from initial stripping of the concrete form to erection in the tunnel**

Segment Design – Manufacture and Handling



1. Segment is cast, and left in the form until the specified stripping strength is reached



2. Segment stripped from mold – design condition depends on strength and lifting device

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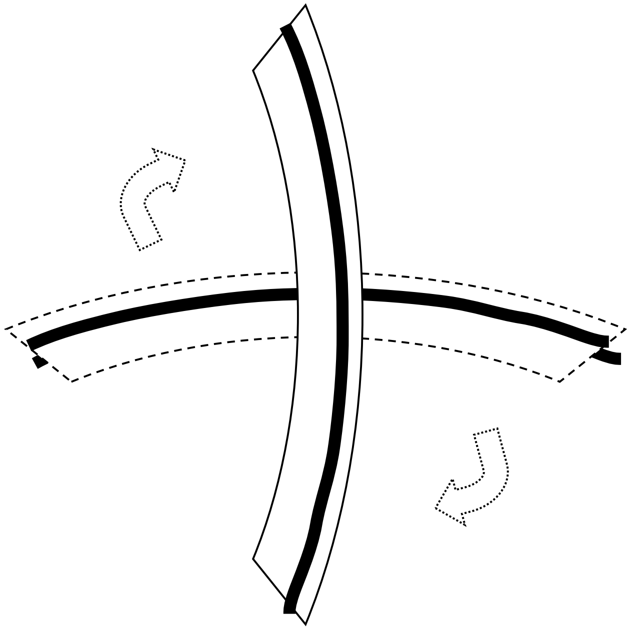
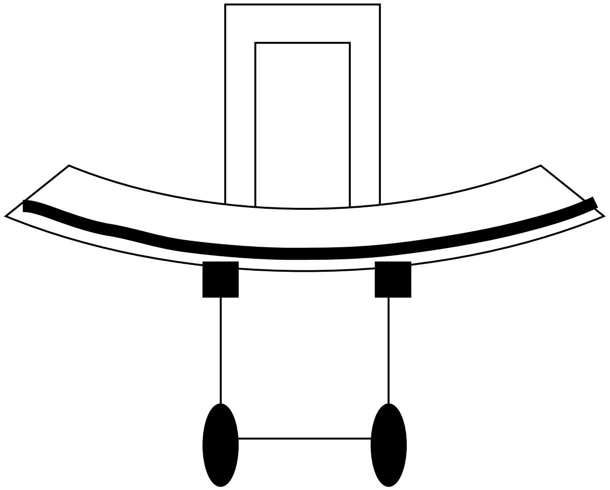
Segment Design – Manufacture and Handling



3. Segments are then rotated 180 degrees



4. Segments are transported out to the stockpile yard using a forklift or gantry crane.

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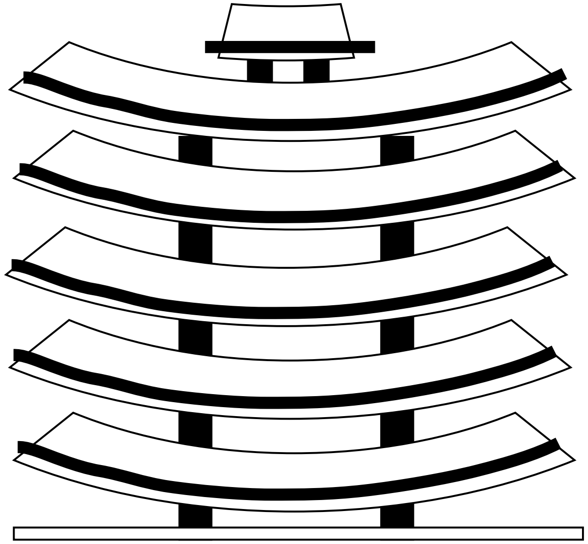
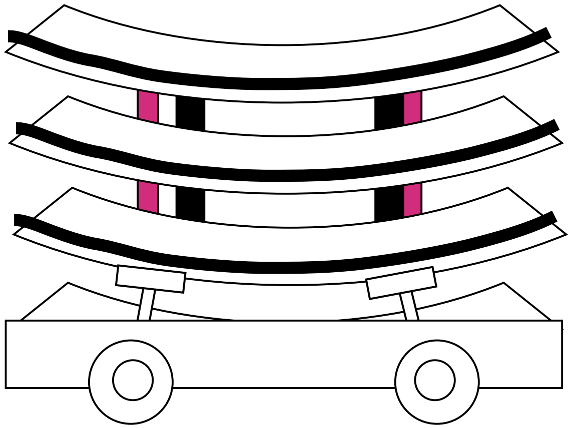
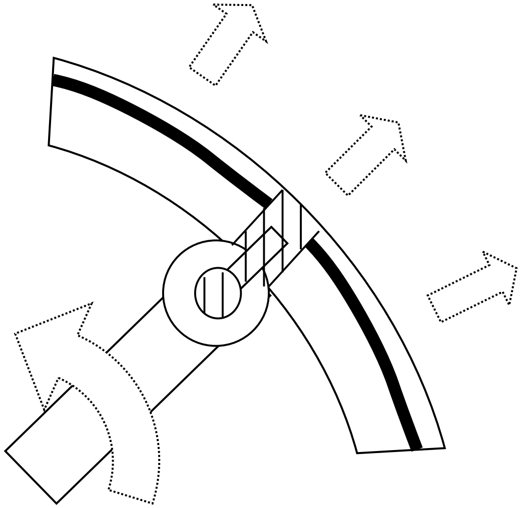
Segment Design – Manufacture and Handling



5. Segments are stacked



6. The segments are lifted onto the train and transported into the tunnel



7. The erector on the TBM picks up the segment & rotates it into place.

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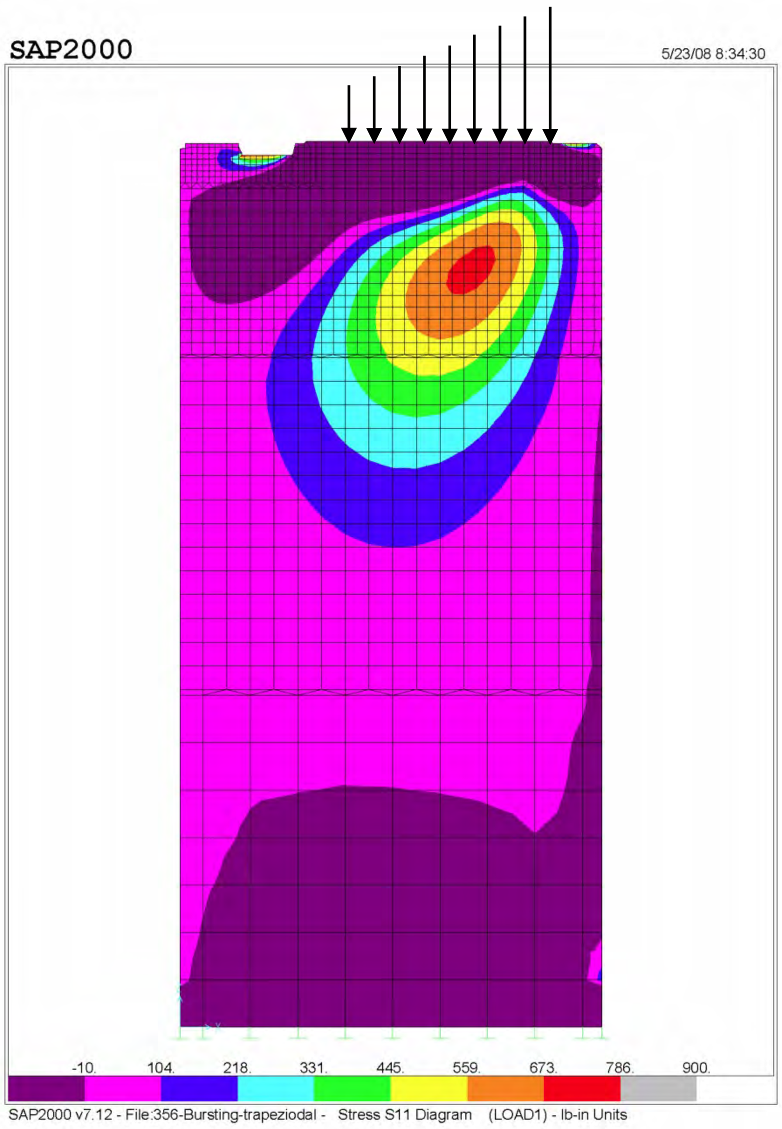
Joint Design

- **Consider the impacts of poor build – not all joint surface may be in contact**
- **Design for bursting stresses (arrangement similar to a tensioned anchorage)**
- **Consider hoop loads and thrust loads from the shove rams**



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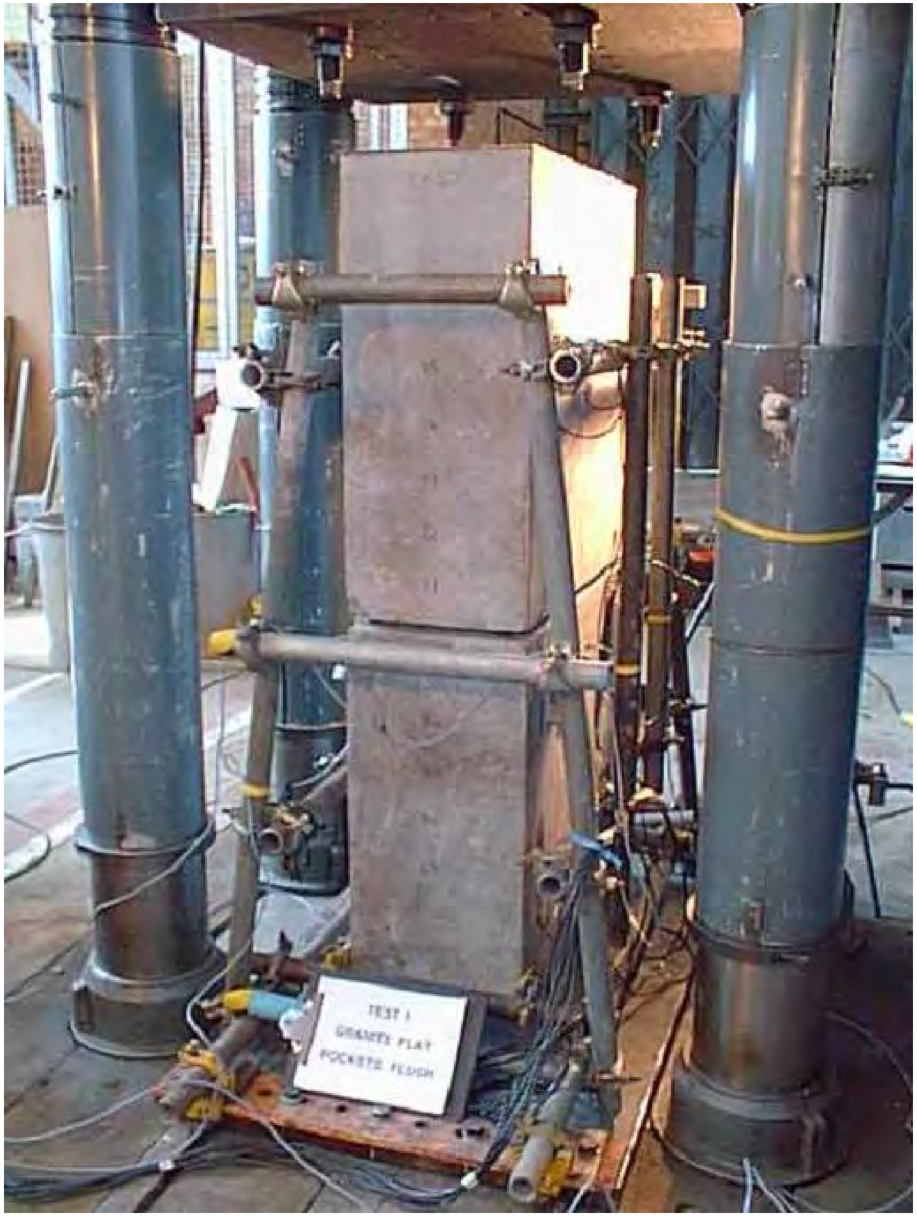
TEST 1


8000-3-4
8-22-02
8000-3-4
South Top

Manufacture

- **Plant Types**
  - Stationary
  - Carousel

- **Plant Location**
  - Jobsite
  - Precast factory

- **Molds**
  - Horizontal
  - Vertical

Stationary Plant

Carousel Plant

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Concrete

- **Vibration**
  - Internal pneumatic
  - External pneumatic/electric

- **Curing**
  - Steam
  - Insulation
  - Cloth


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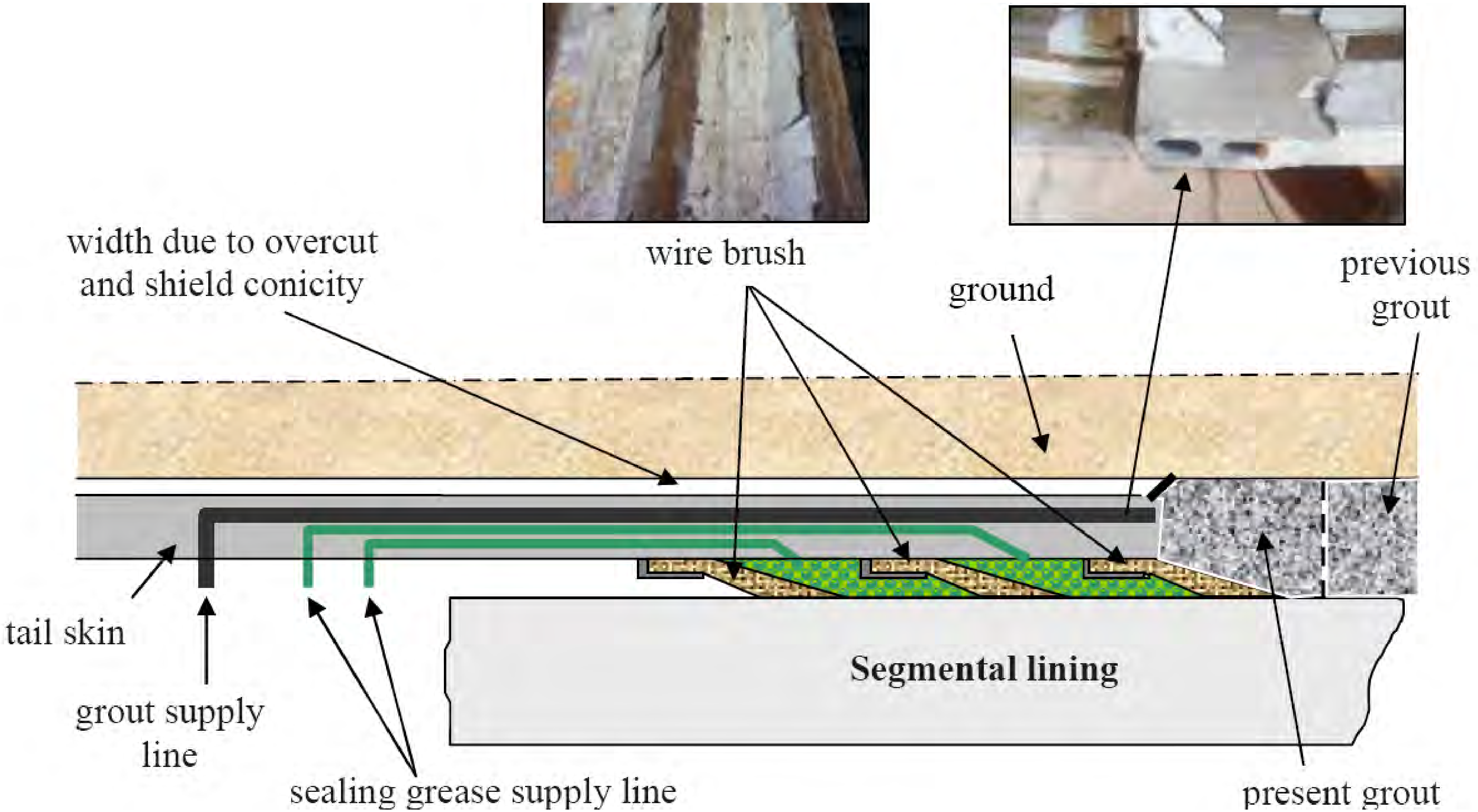
Annular Grouting

- **As TBM is advanced, void behind segment needs to be filled (overcut plus TBM skin thickness)**
- **In soft ground, essential to fill void quickly and completely to minimize settlement, and support segments**
- **In rock, need to support segments – but more difficult to grout**
- **If shunt flows are present, need to pay attention to avoid wash out.**
- **Secondary grouting to ensure all voids are full**


width due to overcut
and shield conicity
wire brush
ground
previous
grout
tail skin
grout supply
line
sealing grease supply line
Segmental lining
present grout

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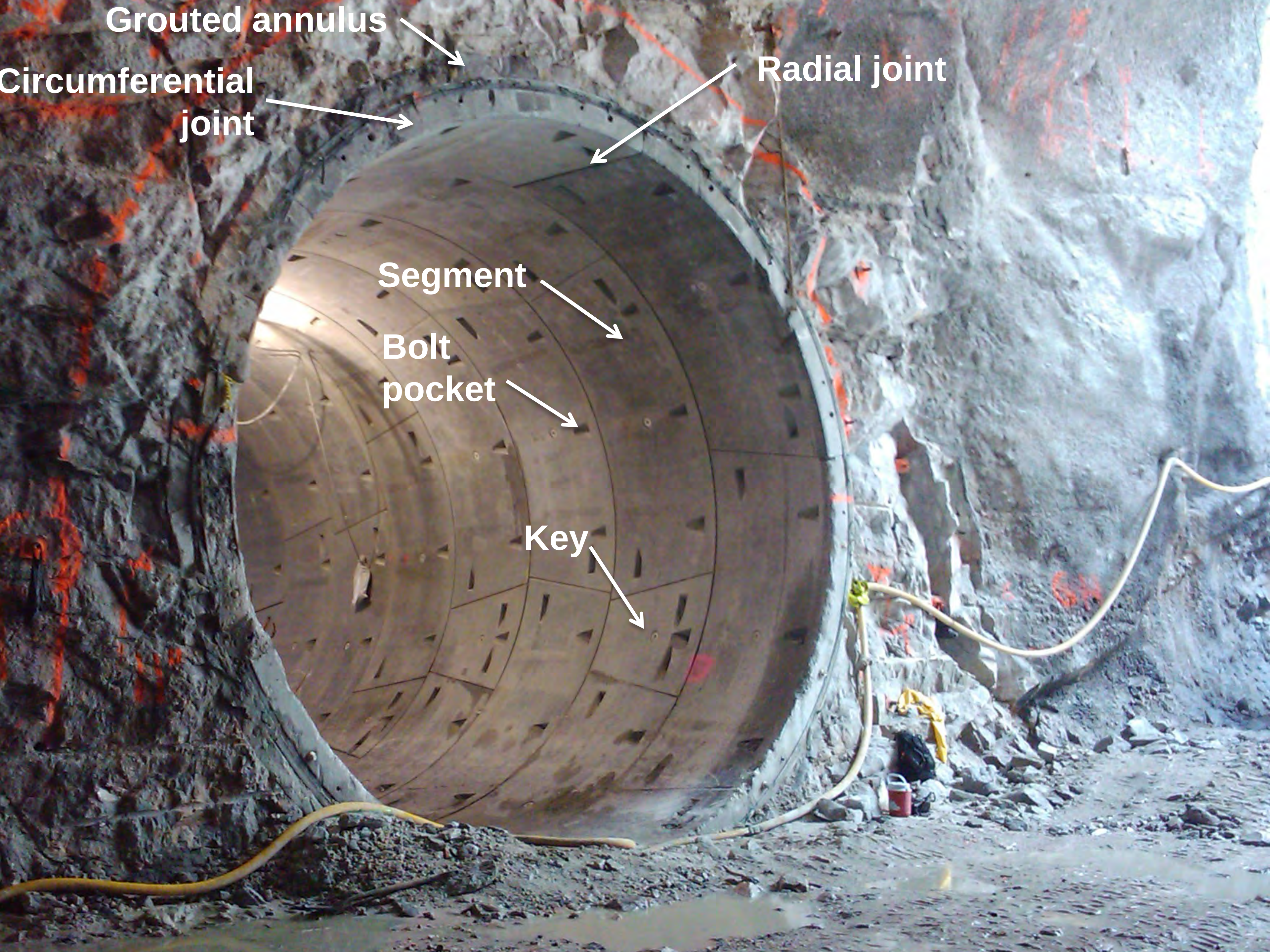
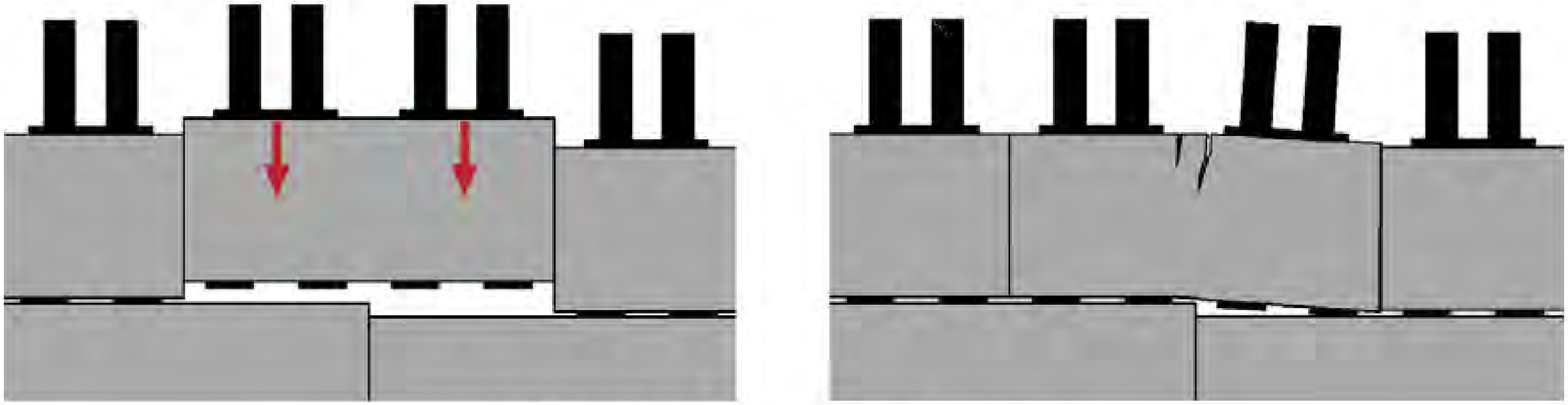


Grouted annulus
Circumferential joint
Radial joint
Segment
Bolt pocket
Key

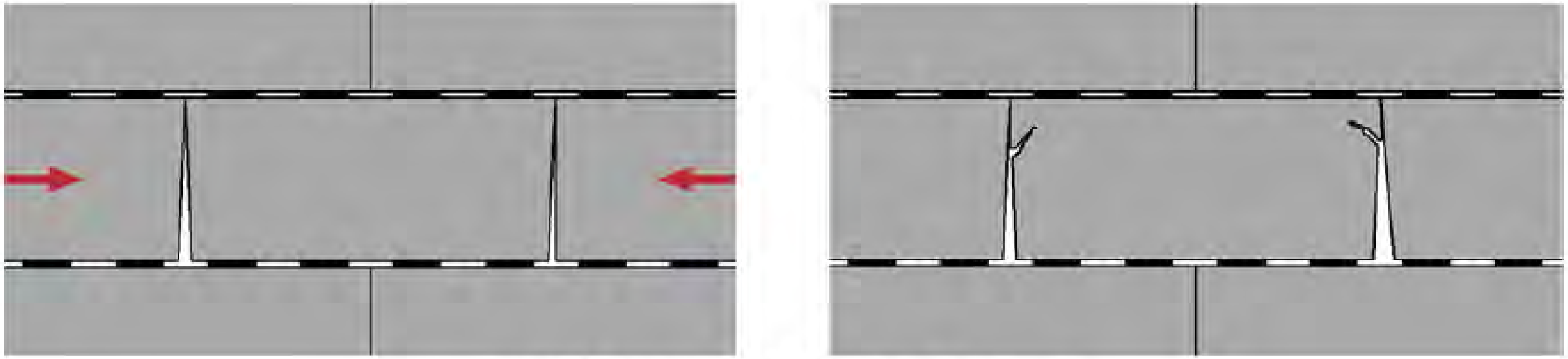

Grouted annulus

Segment Damage

S.H.P. Cavalaro et al. / Tunnelling and Underground Space Technology xxx (2011) xxx–xxx



(a) Longitudinal cracks formation



(b) Chipping of segment corner

Fig. 1. Formation of longitudinal cracks and chipping of segment corner.

Segment Damage

Table 2. Classification of segment damage during construction (JSCE, 2005, p.17)

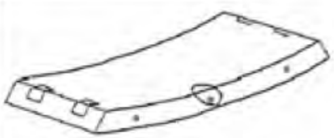
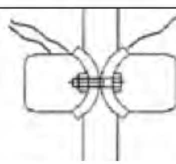
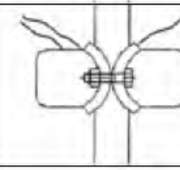
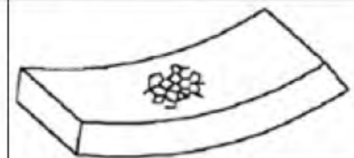
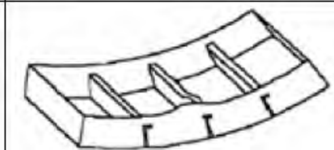
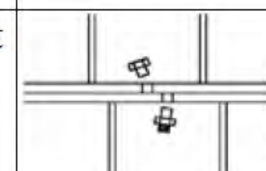
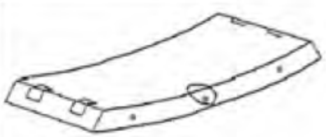
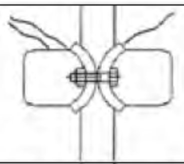
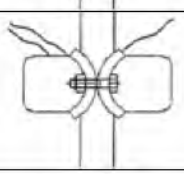
No.	Shield segment damage	Figure
1	Crack in axial dir.	
2	Crack in circumferential dir.	
3	Chipping at segment corner	
4	Stripping around segment joint	
5	Stripping around ring joint	
6	Crack/ Stripping around ring joint box	
7	Crack/ Stripping around segment joint box	
8	Stripping at outer surface	
9	Hair crack at inner surface	
10	Appearance of non-visible crack	
11	Buckling of longitudinal rib (steel segment)	
12	Deformation of rib (steel segment)	
13	Break of joint bolt	
14	Others	

Table 2. Classification of segment damage during construction (JSCE, 2005, p.17)

No.	Shield segment damage	Figure
1	Crack in axial dir.	
2	Crack in circumferential dir.	
3	Chipping at segment corner	
4	Stripping around segment joint	
5	Stripping around ring joint	
6	Crack/ Stripping around ring joint box	
7	Crack/ Stripping around segment joint box	

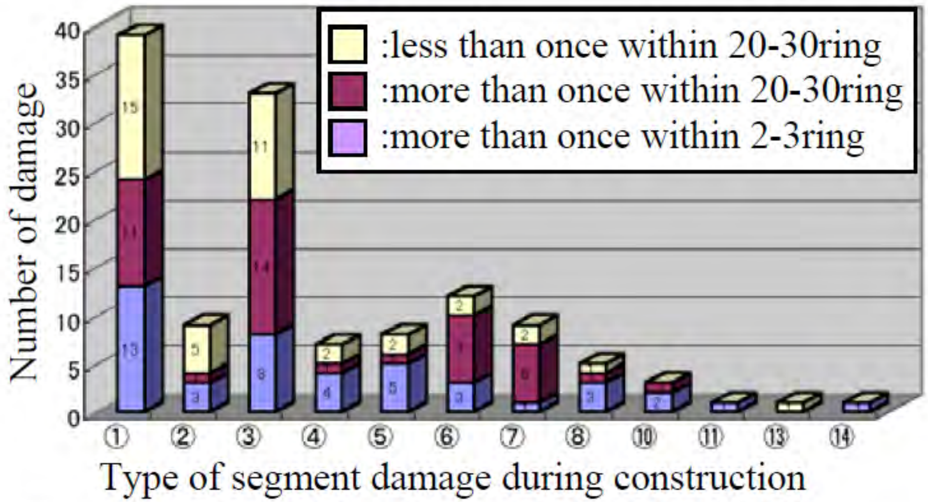


Figure 1. Frequency of segment damage during construction (JSCE, 2005, p.17)

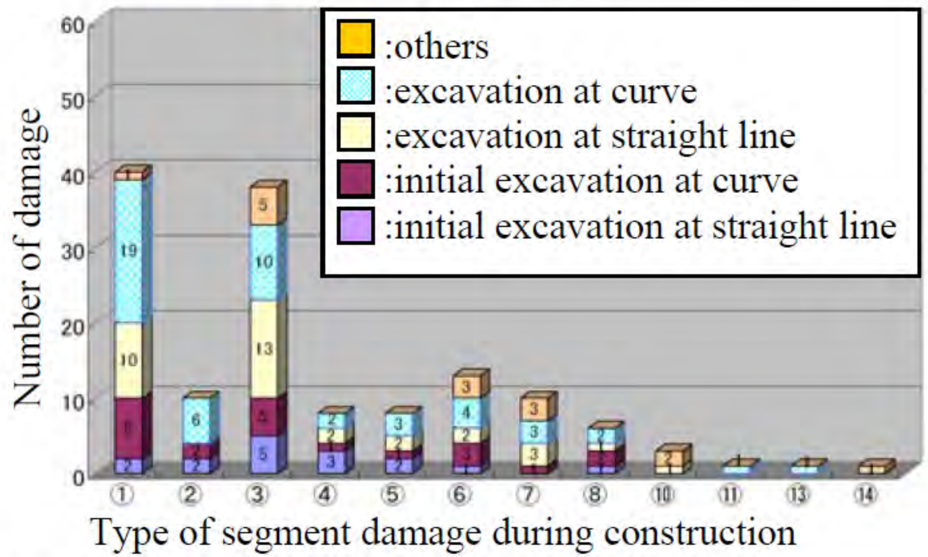
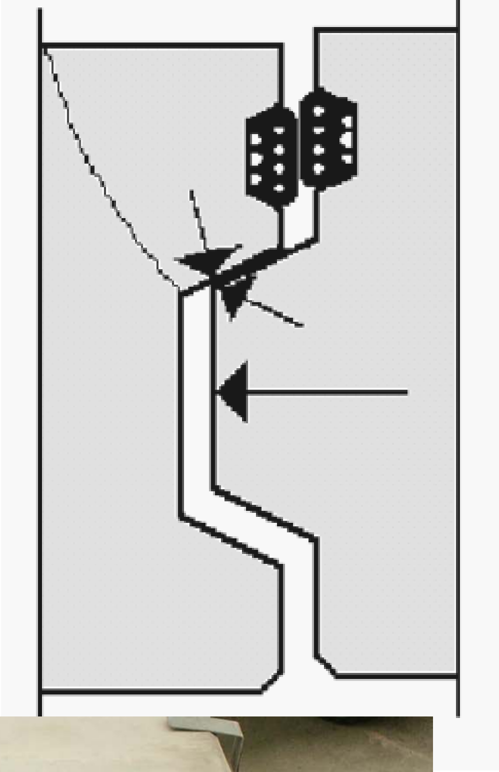


Figure 2. Construction stage at segment damage appearance (JSCE, 2005, p.19)

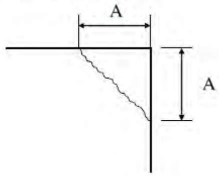
Damage Repair



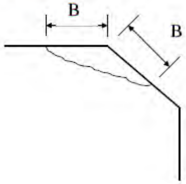
Guidelines For Precast Segment Repair (Prior To Erection)

- **Edge Repair**

a. Sharp Edge



b. Chamfered Edge



c. At Corners

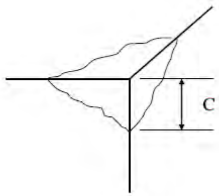


Table 1 - Guideline for Edge Repair

Action	A (mm)	B (mm)	C (mm)
No repair	< 5	< 5	< 5
Repair with Cementitious Mortar	5 - 50	5 - 50	5 - 70
Reject	> 50 or rebar exposed	> 50 or rebar exposed	> 70 or rebar exposed

- **Recesses**

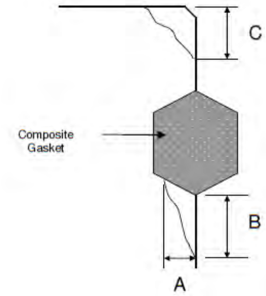


Table 2 - Guideline for Recesses Repair

Action	A (mm)	B (mm)	C (mm) (where applicable)
No repair	< 2	<5	-
Repair with Cementitious Mortar	2 - 10	5 - 30	0 - 10
Reject	> 10	> 30	> 10

Note: All visible blowholes on glued surfaces to be filled with Cementitious Mortar

- **Blowholes**

Table 3 - Guideline for Blowholes Repair

Action	Gasket Surface (mm)	Epoxy Surface (mm)	Intrados (mm)
No repair	-	-	< 2 wide
Repair with Cementitious Mortar	All	All	> 2

CHAPTER 3

Precast Concrete Segmental Linings

Jon Hurt and John Hart

segments as the excavation is advanced. The linings provide the immediate initial ground support required in soft ground or broken rock and also serve as high-quality, watertight final support.

When a precast lining provides initial and final support, it is referred to as a one-pass lining system. Sometimes, additional support is provided after the segments are erected, in the form of a welded steel pipeline or internal concrete lining. These are referred to as two-pass lining systems.

This chapter describes the unique requirements for precast concrete segments, the required material characteristics, design and manufacturing requirements, and waterproofing and construction considerations. Special requirements for wastewater tunnels and temporary linings are also included.

INTRODUCTION

Segments have been used in tunneling since 1869. Early segments were manufactured with cast iron, but in the 1960s precast concrete began to be used for segmental linings (Skelhorn and McNally 2009). Initially, these segments were sized so they could be lifted and bolted into place by hand, but over the years sophisticated segmental lining systems have been developed that can be mechanically installed by TBMs and provide an efficient, durable, and watertight tunnel lining.

Precast concrete segments are manufactured at a segment manufacturing plant, and the segments are erected by the TBM to form a completed ring during excavation. The various components of segmental linings are illustrated in Figure 3.1.

Precast concrete segmental linings provide several advantages. The manufacturing of the segments at a precast yard allows casting to be carried out in a controlled environment, with high quality control. The high degree of mechanization offered by modern TBMs allows rapid and accurate installation of the segments. And the need for an initial temporary support system is avoided, as are the challenges of providing a waterproof membrane and placing concrete in the tunnel environment.

Along with these advantages, however, the use of segments also presents challenges, which need to be addressed in the project specifications. The fabrication process needs to be able to repetitively deliver segments to high tolerances cast with high-quality, durable concrete. Segments need to be demolded, stored, transported, and erected without suffering damage. The segments and the various fittings need to be designed and specified to work as a complete system that allows the required tunnel alignment and lining tolerances to be achieved.

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