EOSC547: Tunnelling & Underground Design

Topic 1: Introduction – Tunnelling Past & Present

Tunnelling Challenges: Bertha

Seattle is undertaking the replacement of the Alaskan Way Viaduct with a 3.2 km tunnel. The project is estimated to cost US$3.14 billion. The $80 million TBM - Bertha - created for this project by Hitachi Zosen Corporation is a record-breaking 17.5 m diameter.

The TBM is about 80% of the way through after being stuck for three years after tunnelling only 300 m of the roughly 2.8 km tunnel. Investigators believe that Bertha was overheating — that grime and gunk had gotten past bearing seals, entered the machine, and muddied the operation. Engineers decided they needed to replace not only the seals but also the $5 million main bearing, as well as reinforcing the steel on it's cutter head. The added costs for these delays and repairs are projected to be in excess of $220 million.

Tunnelling Challenges: Bertha

The contractor is now asking for an additional $480 million to cover the unexpected expenses.

The contractor blames an abandoned steel pipe for triggering damage to the TBM in the form of the machine overheating.

The state maintains that under the design-build contract, the contractors are generally responsible for damage and delays, except for unforeseen soil conditions that weren't flagged in the state's geotechnical study.

The state could also wind up paying $223 million for its own oversight costs, because the project is three years late and now trending for a spring 2019 opening.

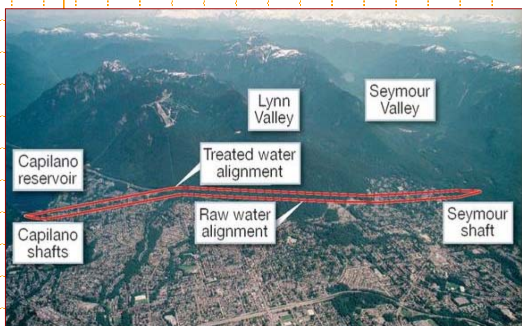
B.C. Tunnelling Projects – Water Conveyance

Seymour-Capilano Twin Tunnels

- 7.1 km long, 3.8 m diameter twin tunnels.
- Tunnel excavation was completed in Nov. 2010, with lining installation completed in Aug. 2014.
- The tunnels were originally expected to make up $200 million of the project's total $800 million budget, but that number doubled to $400-million.

Tunnelling Challenges: Seymour-Capilano

The $200 million claims case was settled in a closed agreement. The dispute had arose regarding the safety of the design because of unexpected rock mass conditions. The contractor stopped work half way through, and Metro Vancouver cancelled the contract and sued for breach of contract. A new contractor was brought in to complete the tunnels – using the same design; the estimated cost overrun was 100%.



Tunnelling Challenges

The Boston "Big Dig" rerouted a major highway that passed through the city centre underground. This freed up an unprecedented 30 acres in downtown Boston, giving planners a historic opportunity to shape the future of the city.

At US$14.6 billion, this was the most costly highway project in the U.S., but it was plagued by escalating costs, scheduling overruns, leaks, design flaws, charges of poor execution and use of substandard materials, criminal arrests, and one death. The project was completed 9 years late and about 190% over budget.

Tunnelling Challenges

The Gotthard Base Tunnel is a rail tunnel that passes through the base of the Swiss Alps. With a length of 57 km, it is the world's longest and deepest traffic tunnel. It has virtually no gradients, enabling trains to travel more quickly through the Alps. It is expected to open in December 2016.

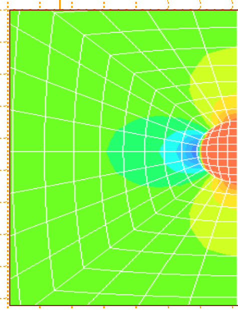
The initial cost in 1998 was projected to be US$7.2 billion with completion in 2012. However, unexpected ground conditions together with scheduling delays has increased this cost to over US$12 billion. The project will be completed 4 years late and about 170% over budget.

Tunnelling Successes – Canada Line

The $2 billion Canada Line was completed 15 weeks ahead of schedule and on budget. Although Cambie Street merchants protested over lost business incurred during construction, property values along the line have increased and ridership has steadily grown and exceeded projections. In terms of environmental benefits, Canada Line's transportation capacity represents a reduction of 14,000 tons of CO_2 emission over its first 5 years.

Course Overview

In this course, we'll examine the different principles, approaches, and tools used in tunnel excavation and underground design. The examples and case histories reviewed will focus on tunnel excavations in both soft soil and hard rock.



The topics we'll examine will step through the tunnel design process, from the writing and review of geotechnical baseline reports, to tunnelling methods for different ground conditions, to support design.

Content

Introduction
- state of tunnelling, tunnelling in Canada.

Geological Uncertainty
- "The Known Knowns, Known Unknowns, & Unknown Unknowns".

Geotechnical Baseline Reports
- contract types; baseline reports; site investigation; risk.

Soft Ground Tunnelling Methods
- cut and cover; compressed air; earth pressure balance machines.

Hard Rock Tunnelling Methods
- drill and blast; open tunnel boring machines, ground support types.

Tunnelling in Weak Rock
- Terzaghi's rock load; sequential excavation; observational approach.

Support of Tunnels
- ground response & support interaction curves.
→ **Rock Support & Excavation**
- NATM.

Tunnelling in Burst-Prone Rock
- stress as a boundary condition; in situ stress determination.

General Information

Lectures: Monday, 11:00 to 14:00 (EOS-M 101)

Grades:	Tunnel design team project	
	Part 1 – Baseline Report	15%
	Part 2 – Squeezing Ground	25%
	Part 3 – Spalling & Bursting	25%
	student prepared lecture	25%
	peer review participation	10%

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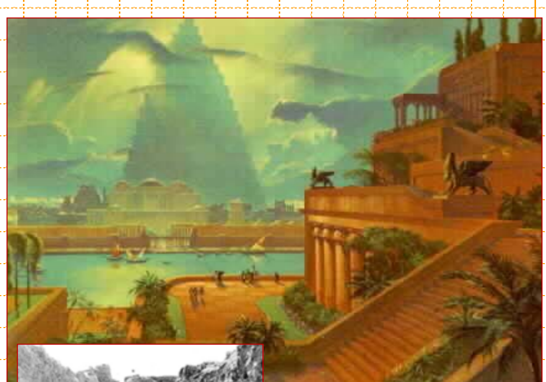
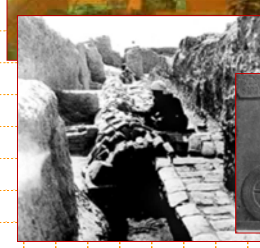
Tunnel Construction: In the Beginning

All major ancient civilizations developed tunneling methods. In Babylonia, tunnels were used extensively for irrigation; and a brick-lined pedestrian passage some 900 m long was built around 2180 BC under the Euphrates River to connect the royal palace with the temple. Construction was accomplished by diverting the river during the dry season.

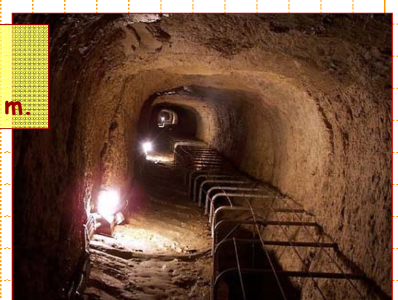




Tunnel Construction: In the Beginning

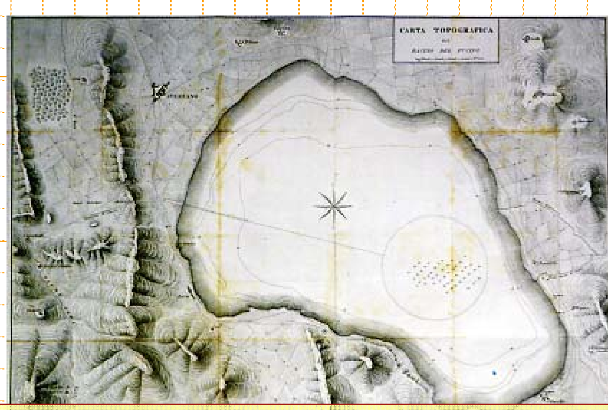
The Greeks and Romans both made extensive use of tunnels to reclaim land by drainage and for water aqueducts.

6th-century-BC Greek water tunnel on the isle of Samos driven some 1100 m through limestone with a cross section about 2 x 2 m.



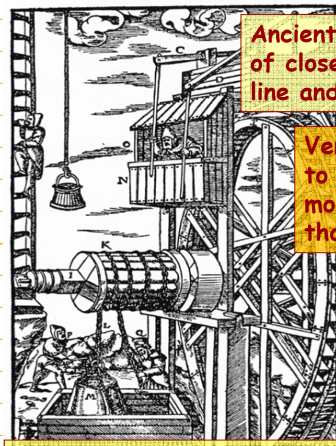
Perhaps the largest tunnel in ancient times was a 1600 m long, 8 m wide, 10 m high road tunnel (the Pausilippo) between Naples and Pozzuoli, built in 36 BC.

Tunnel Construction: In the Beginning



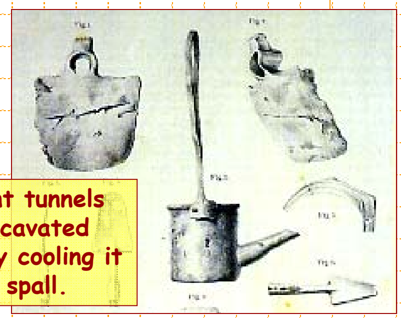
In the AD 41, Romans used some 30,000 men to push a 6 km tunnel over 10 years to drain Lacus Fucinus. They worked from shafts 40 m apart and up to 125 m deep. Far more attention was paid to ventilation and safety measures when workers were freemen, compared to those who were slaves.

Tunnel Construction: In the Beginning



Ancient construction was carried out using a succession of closely spaced shafts to provide ventilation. String line and plumb bobs were used for surveying.

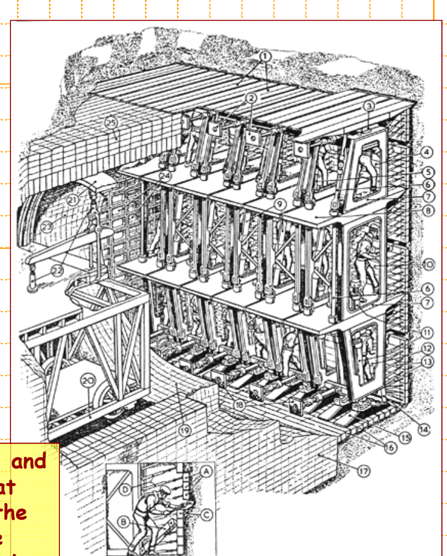
Ventilation methods were primitive, often limited to waving a canvas at the mouth of the shaft, and most tunnels claimed the lives of hundreds or even thousands of the slaves used as workers.



To save the need for a lining, most ancient tunnels were located in strong rock, which was excavated by heating the rock with fire and suddenly cooling it by dousing with water causing the rock to spall.

Modern Beginnings: The Thames

Tunnelling in soft, water saturated ground began with Marc Brunel when he invented the principle of shield tunnelling and undertook a contract to tunnel under the Thames between 1825 and 1841. His shield consisted of 12 independent cells in which workers hand excavated the ground behind a secure wall of 'poling boards'. One board would be removed to provide access for digging, after which it would be replaced and pushed forward by hydraulic jacks to re-engage the face support.

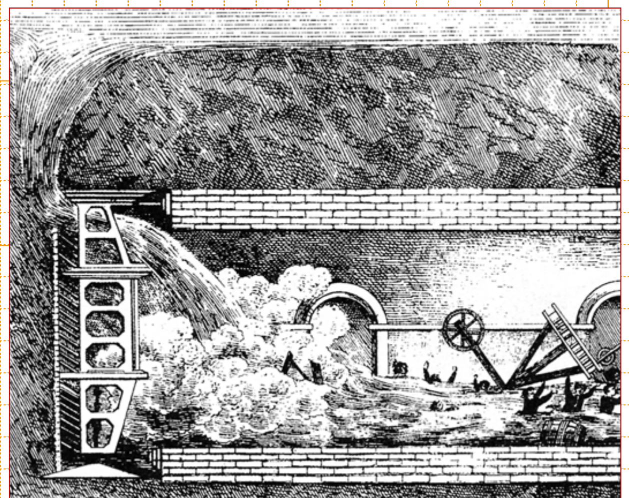


Brunel's shield was 7 m high and 12 m wide, and enabled 36 miners to work the tunnel face at one time. The brickwork built right behind the 'shield' served as an abutment for the whole frame. On average, progress was 3-5 m/week.

Harding (1981)

Modern Beginnings: The Thames

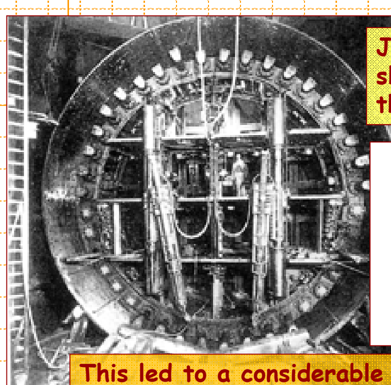
Flooding was a constant problem for Brunel in tunnelling under the Thames. In one such flood 6 men drowned. Brunel's complaint to those offering advice on tunnelling in such difficult conditions, "In every case they make the ground to suit the plan and not the plan to suit the ground".



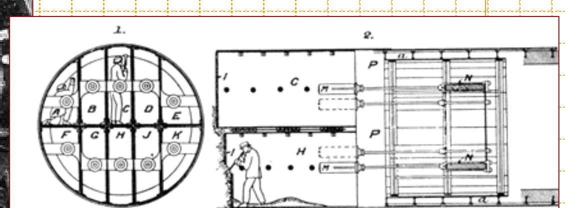
Completed in 1843, Brunel's tunnel is still in full use as part of London's Underground railway system, exactly as built!

Modern Beginnings: The Thames

James Greathead solved the problem of containing groundwater during the construction of subaqueous tunnels in loose soil, by combining shield tunnelling with the use of compressed air during his construction of the London Underground.



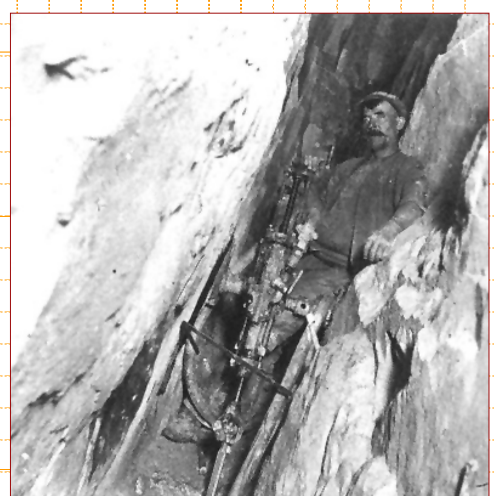
James Greathead's 2.5 m diameter circular shield, propelled by screw jacks, employed the first use of cast iron lining segments.



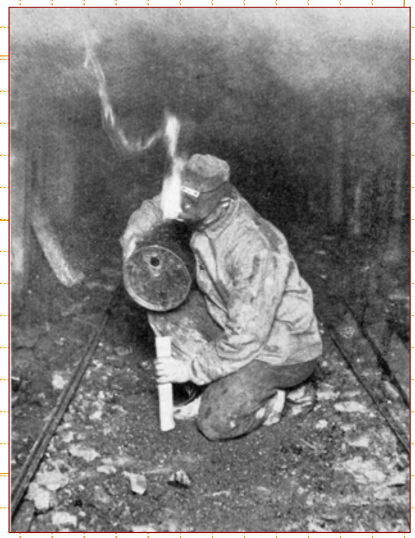
This led to a considerable increase in the number of shield driven tunnels world-wide. At the beginning of the 20th century, the majority of the tunnels were built with Greathead shields.

State of Tunnelling in Canada

Canada, Mining & Tunnelling

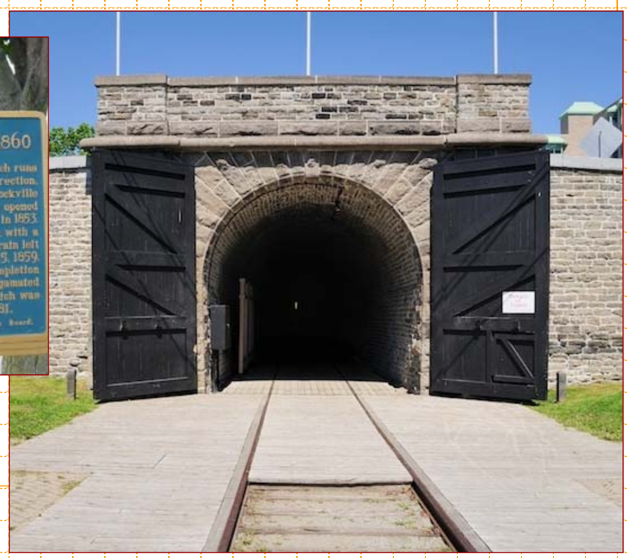


Canada, Mining & Tunnelling

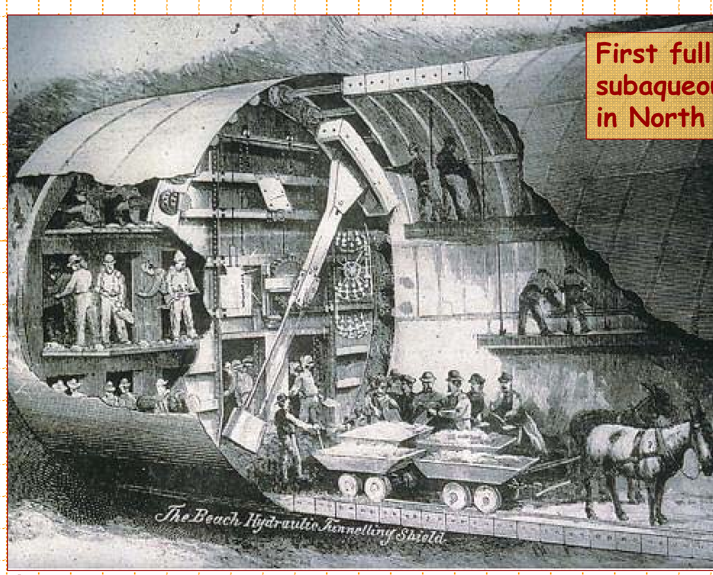


Canada, Mining & Tunnelling

Canada's First Tunnel



1890 St. Clair Tunnel



First full-size subaqueous tunnel built in North America.

1909 Spiral Tunnel

1930 Windsor-Detroit Tunnel

First to Link Two Nations

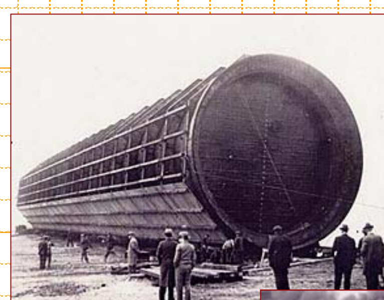
Windsor-Detroit Tunnel Is Unique; Cost Is $25,000,000

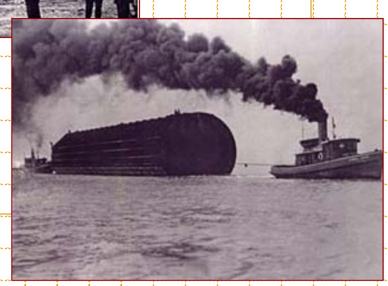
Nov 1 - 1930

1,000 Cars Hourly

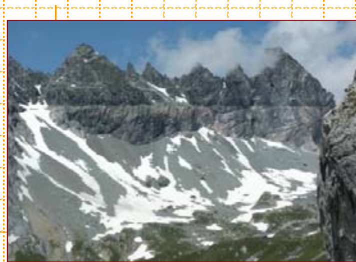
Capacity Of 22-Foot Roadway Is Large; Saves Time For Commuters

The Windsor and Detroit tunnel is the first vehicular subway ever built between two nations. Two others are in use in the United States—the Holland tunnel in New York and the George A. Posey tunnel, connecting Oakland and Alameda, California.





Perspectives – Value of Tunnels



World's Longest Rail Tunnels

Tunnel	Length (km)	Completion Date
Gotthard Base (CH)	57.1	2018
Brenner Base (Au-It)	55	2025
Sei-kan (Japan)	53.9	1988
Mont d'Ambin (Fr-It)	52	2023
Chunnel (ENG-FR)	50.5	1994
Loetschberg (CH)	34.6	2007

#30 Mount MacDonald (CAN) @ *14.6 km*
#43 New Cascade (USA) @ *12.5 km*

Canada = 5 rail tunnels > 2 km
USA = 4 rail tunnels > 2 km
Switzerland = 42 rail tunnels > 2 km

Perspectives – Value of Tunnels

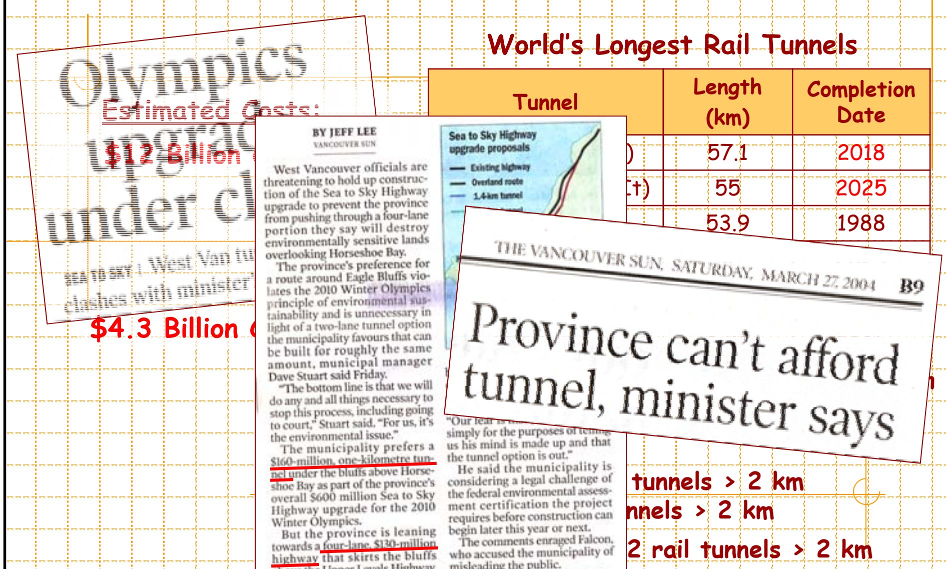
World's Longest Rail Tunnels

Tunnel	Length (km)	Completion Date
)	57.1	2018
t)	55	2025
	53.9	1988

Estimated Costs:

$12 Billion

$4.3 Billion



Olympics upgrad under cl

SEA TO SKY | West Van tu clashes with minister

BY JEFF LEE
VANCOUVER SUN

West Vancouver officials are threatening to hold up construction of the Sea to Sky Highway upgrade to prevent the province from pushing through a four-lane portion they say will destroy environmentally sensitive lands overlooking Horseshoe Bay.

The province's preference for a route around Eagle Bluffs violates the 2010 Winter Olympics principle of environmental sustainability and is unnecessary in light of a two-lane tunnel option the municipality favours that can be built for roughly the same amount, municipal manager Dave Stuart said Friday.

"The bottom line is that we will do any and all things necessary to stop this process, including going to court," Stuart said. "For us, it's the environmental issue."

The municipality prefers a $160-million, one-kilometre tunnel under the bluffs above Horseshoe Bay as part of the province's overall $600 million Sea to Sky Highway upgrade for the 2010 Winter Olympics.

But the province is leaning towards a four-lane, $130-million highway that skirts the bluffs above the Upper Levels Highway.

"Our fear ... simply for the purposes of ... us his mind is made up and that the tunnel option is out."

He said the municipality is considering a legal challenge of the federal environmental assessment certification the project requires before construction can begin later this year or next.

The comments enraged Falcon, who accused the municipality of misleading the public.

THE VANCOUVER SUN, SATURDAY, MARCH 27, 2004 B9

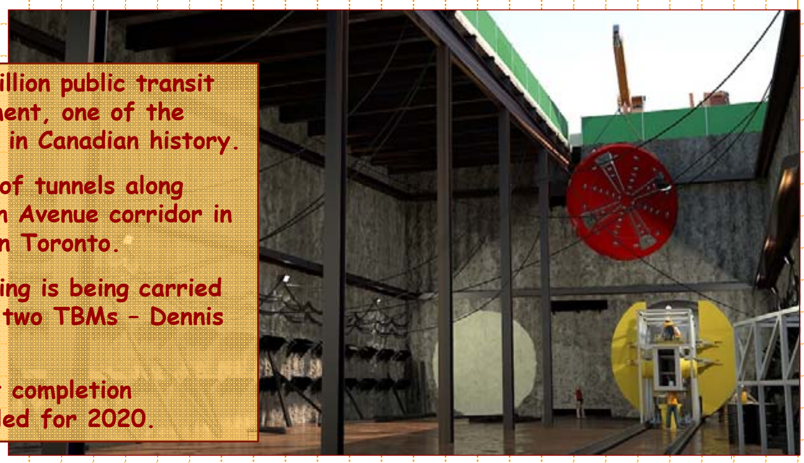
Province can't afford tunnel, minister says

tunnels > 2 km
nnels > 2 km
2 rail tunnels > 2 km

Top Canadian Infrastructure Projects

Eglinton-Scarborough Crosstown Light Rail Transit

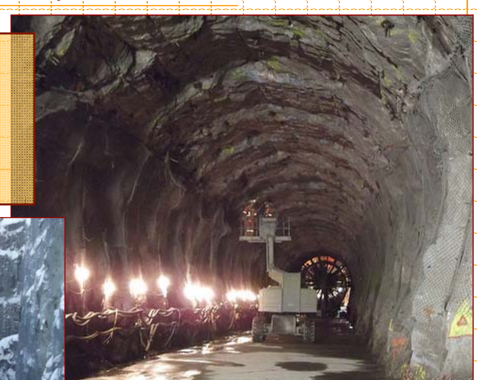
- $8.2 billion public transit investment, one of the largest in Canadian history.
- 10 km of tunnels along Eglinton Avenue corridor in midtown Toronto.
- Tunnelling is being carried out by two TBMs – Dennis & Lea.
- Project completion scheduled for 2020.



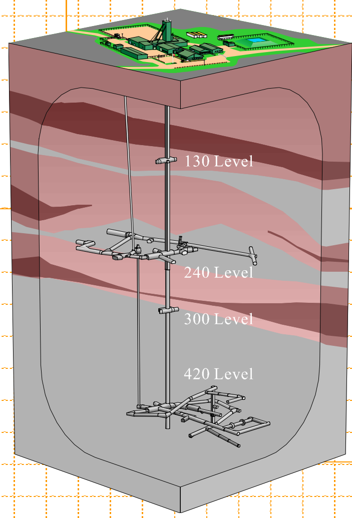
Top Canadian Infrastructure Projects

La Romaine Hydroelectric Complex

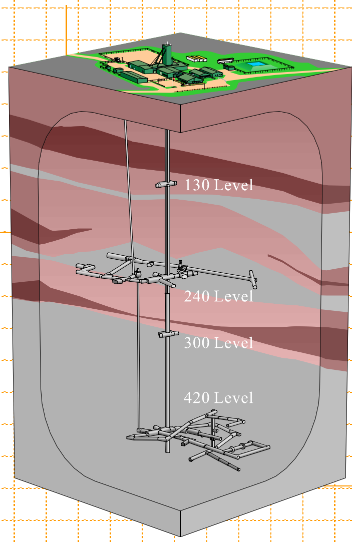
- $6.5 billion, 1550 MW hydroelectric complex , to be completed in 2020.
- Four rockfill dams , with multiple bypass and pressure tunnels.

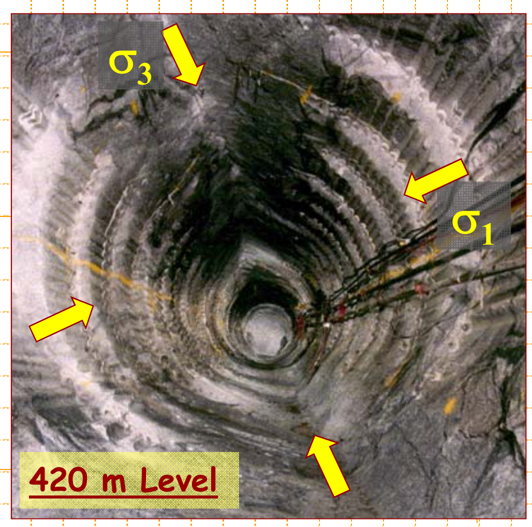


A Canadian Export – High Stress Expertise



A Canadian Export – High Stress Expertise

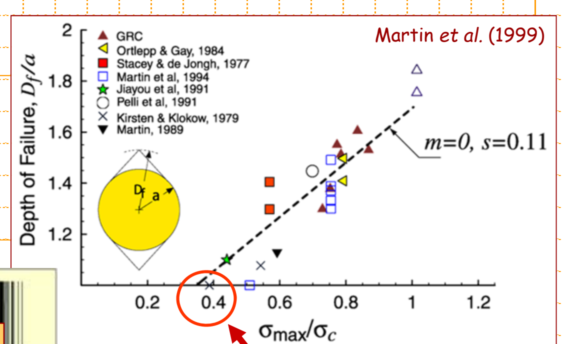




Martin (1997)

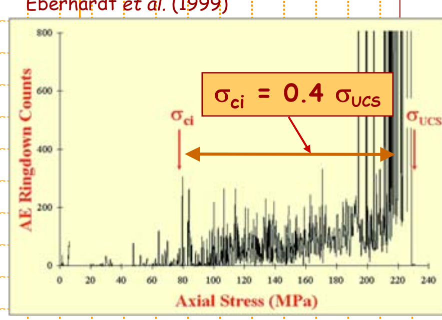
A Canadian Export – High Stress Expertise

A Canadian Export – High Stress Expertise



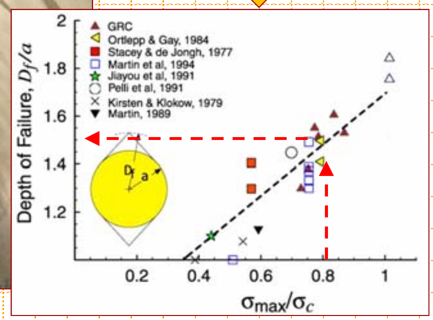
$\sigma_{max} = 0.4\ \sigma_{UCS}$

Eberhardt et al. (1999)

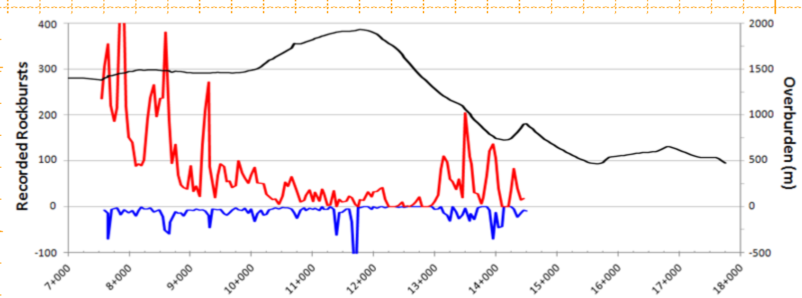


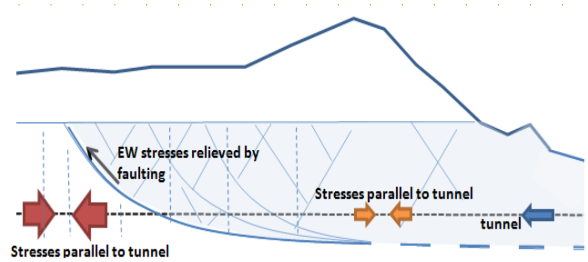
A Canadian Export – High Stress Expertise

Using Martin et al. (1999)'s empirical relationship



A Canadian Export – High Stress Expertise





B.C. Tunnelling Projects – Water Conveyance

Port Mann Water Supply Tunnel

- Approximately 1km long, 3.5 m diameter, 40 m under the Fraser River.
- Excavation is being carried out using a CAT EPB TBM; construction is being undertaken by the McNally-Aecon Joint Venture.
- Expected completion in late 2014.

B.C. Tunnelling Projects - Transportation

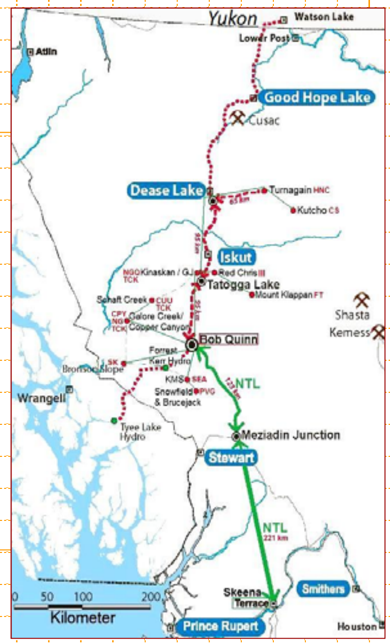
Evergreen Line

- 11 km extension to GVRD's rapid transit system, which includes a 2 km long 10 m diameter bored tunnel.
- Design-build-finance contract with tunnelling work being conducted by SNC-SELI JV.
- The tunnel is being excavated with a CAT EPB TBM and is expected to finish in early 2015.

B.C. Tunnelling Projects

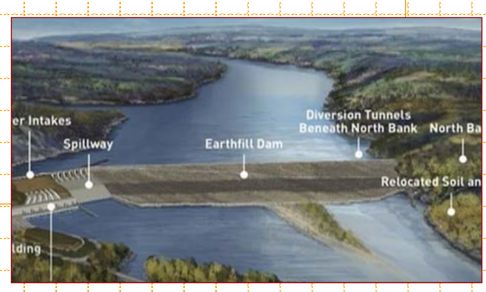
B.C. is also currently experiencing an increase in activity in hydroelectric project development.

- AltaGas has completed their 195 MW Forrest Kerr Hydro Project in northern B.C. The project included over 5000 m of access, tailrace and power tunnels. Tunnel construction was carried out by Procon. The project is now in service.
- AltaGas is also constructing the 66 MW McLymont Creek Hydro Project downstream of Forrest Kerr. This project includes an intake, surface powerhouse and a 2.7 km long power tunnel. Tunnel excavation commenced in Q2 2013, with tunnel excavation being carried out by Procon Mining and Tunnelling. The project is scheduled for completion in mid 2015.



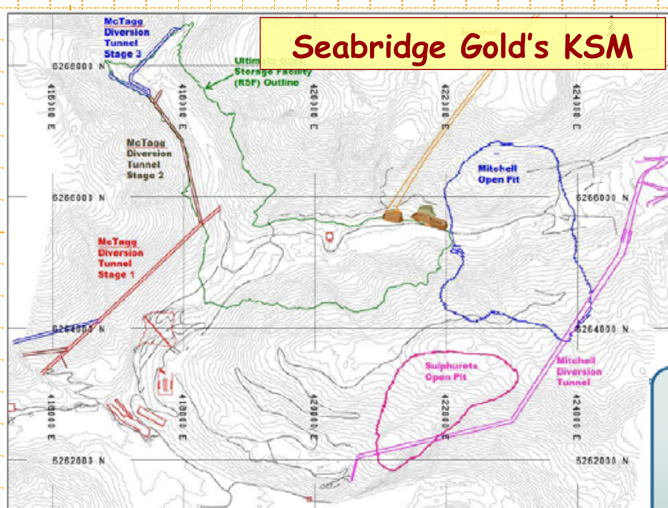
B.C. Tunnelling Projects - Hydroelectric

- BC Hydro's $1B John Hart Generating Station Replacement Project, located near Campbell River on Vancouver Island, includes a 2.1 km long tunnel, underground powerhouse, and associated shafts and access tunnels. Underground construction is scheduled to start in Fall 2014.
- Innergex Renewable Energy is constructing the Upper Lillooet Hydroelectric Project 70 km northwest of Pemberton. The project includes two facilities, the Upper Lillooet and Boulder Creek, with 2500 m and 2900 m long drill and blast power tunnels, to be completed in mid 2016.
- The province has approved the $8.8 billion Site C hydroelectric dam, the third generating station on the Peace River. Site C will provide enough energy to power the equivalent of about 450,000 homes per year.



B.C. Tunnelling Projects – Mining & Energy

Seabridge Gold's KSM



Ore Transport Tunnels

- Parallel pair of tunnels.
- Required to access the plant and tailing management facility from mine sites.
- Each tunnel consists of two sections, 16 km and 7 km, with a short section of road in between.
- Parallel tunnels with cross connections provide an escape route in case of emergency, and enable ventilation during construction.
- Tunnels include two slurry pipelines, return water pipeline, diesel pipeline and transmission line.
- Return water pipeline fitted with a turbine to generate electricity.

Diversion Tunnels

- Two tunnels (Mitchell and McTagg) divert streams away from the Mitchell pit and rock storage facilities.
- Keep fresh water away from surface disturbances, maintaining water quality.
- Water discharging through tunnels directed through turbines to generate electricity that supplements power from the provincial grid.
- Will remain in operation after mining ceases and will supply power to water treatment facilities.

Tunnelling Association of Canada – B.C. Chapter

The Tunnelling Association of Canada and its B.C. Chapter are highly active, organizing monthly talks at the Steamworks Pub in downtown Vancouver. These have been highly successful in allowing graduate students and junior engineers to network with locally-based tunnelling professionals.

Student Membership $15 !!

http://www.tunnelcanada.ca/

Future Perspectives

- The level of tunnelling expertise within Canada is extensive, honed through the large number of tunnels that have been completed in a variety of challenging geological settings, in major cities and remote locations.

- Our collective experiences with EPB in glacial deposits and hard rock tunnelling in high stresses are only two examples where Canada has positioned itself as an international leader.

- The tunnelling industry is active in B.C., with a number of transportation, water and sewer, hydroelectric, mining and pipeline projects planned, ongoing and completed in Greater Vancouver and other regions of the province.