Going Deep..

..Putting the Underground Dimension to Use

Chris Laughton, Fermilab
Definition of a Tunnel..

“A long hole in the ground with an optimistic engineer at one end and a lawyer at the other.”

(Source.. Chartered Institute of Claims Adjusters, UK)

it is a bit of a gamble..
A Punter’s Guide to the Underground

“I keep six honest serving-men
(They taught me all I knew);
Their names are What and Why and When
And How and Where and Who.” Rudyard Kipling

Aiming to provide a balanced perspective..

..honest answers..
Outline

**What** goes Underground?

**Why** go Underground?

**How** is the Underground built?

**Where** are problems encountered?

**When** do risks get mitigated?

**Who** can best mitigate the risks?

..simple to conceive

..not so easy to build (for most of us!)
“Success” is in the eye of the beholder?

An “Engineering Wonder”...

&

or

The Chunnel

..a “Financial Black Hole”
What Goes Underground?
What Goes Underground?
Shelters and Fully-Designed Homes..

Basic protection from enemies and elements..

As-found shelters to...

Partially-modified for added protection and comfort..

Built to drawings and specifications..

Klasies River Cave in Sth. Africa (Source: archaeology.about)

Cave sites in Croatia (Source: NIU)

Restaurant in Finland (Source: Rockplan)

...all modern conveniences
What Goes Underground?
Mining Operations..

Open Pits transitioning to Underground mines..
exploiting lodes to depth and
reducing environmental footprints

Kemi Mine, Source; Gridpoint
Henderson Mine, Colorado
Nchanga Open Pit, Zambia

Laughton 5/2/07
What Goes Underground?
Water Systems..

- Canal (Source: Chesapeake & Ohio)
- Potable (Source: NYC DEP)
- Storm/Wastewater (Source: Kenny Construction)
- Collection/Supply/Irrigation/Distribution (Source: USBR)
- Underground Sewage Treatment Plant, Bondi, Australia
- Qanats (Source: US Water News)

Over 1000km kilometers of transit tunnels in the United States (FHWA)

(Source: SWECO) (Source: Eurotunnel) (Source: Eurotunnel)
What Goes Underground? Road Traffic..

In the US over 400 tunnels in 35 states
(Source: FHWA)

Loma Larga Tunnel through a Limestone Anticline, Monterrey, Mexico.

(Source TIRSYS)
What Goes Underground?
Hydro-Electric Power Plants..

Surge Shaft

High Pressure Tunnel

Powerhouse

Dinorwig HEPSS

(Source; First Hydro)
What Goes Underground?
Fuel Storage..

- Solution-Mined Salt Domes
- Depleted “Reservoir Rocks” (CO₂)
- Lined Hard Rock Caverns (Compressed and Liquified Natural Gas, LNG)

Hard Rock Caverns for Underground Natural Gas Storage (Pilot Plants)

Unlined Rock Caverns.. Storing Oil
(Source: Geostock)

(Source: National Energy Technology Laboratory)
What Goes Underground?
Packaged and Bulk Materials..

- Silo/Bunker Storage..
  - Coal, Grains, Ore..

- Warehousing
  - often in converted mine space

(Source; Hunt Midwest)

(Source: Helsinki Energy)

(Source: K-Plus)

Year-round environmental stability (dark, cool, humid..)
– Mushroom cultivation
– Food aging..
  • Wines (100+ caves in California alone)
  • Cheeses…”

Sources; Messrs. Pelizza and Peila

Close to Diablo Canyon
Theta 13 Site
Baseline  
Design Input

Source: Justin Winery
Source: Karsten Heeger
Laughton 5/2/07
What Goes Underground?
Critical Infrastructure..

• Secure sites with network-wide access
  – Controlled exit/entry
  – Atmospheric control (temp., humidity, dust..)
  – Ready access for modification and maintenance

• Space and Cost Saving Opportunities (“Utilidors”).
  – Heating/Cooling
  – Communications
  – Data transfer
  – Wastewater
  – Freshwater
  – Transport
  – Power
  – etcetera..
What Goes Underground?
In Northern Illinois.. Aggregate Operations

• Underground sites at..
  – Bartlett
  – Elmhurst (water retention)
  – Fox River Stone
  – Joliet S&G
  – Lemont #360
  – North Aurora
    • Ground monitoring
    • Hydrogeologic studies
  – Increased exploitation expected..
    • Less road haulage
    • Less airborne dust
    • Less neighborhood disturbance
    • Smaller environmental footprint
What Goes Underground? Research Facilities

- Worldwide, many underground research laboratories and test sites (waste repository characterization, physics, geo-’bio-sciences, engineering research, education/training.)
  - Aberdeen, Amelie, Asse, Aspo, Baksan, Baradello, Bern, Bernburg, Boulby, Broken Hill, Bure, Canfranc, Cascades, CERN, DESY, Edgar Mine, Fairport Harbor, Fanay-Augeres, Fermilab, Frejus-Modane, Gorleben, Gotthard, Gran Sasso, Grimsel, Hagerbach, Haut-Marne, Homestake, Honronobe, Kaariainen, Kamaishi, Kamioka, Kimbalton, Kolar Gold Fields, Konrad, Lake Lynn, La Vue des Alpes, Lodz, LSBB, Meuse, Mizunami, Monaco, Mont Blanc, Mol, Mont Terri, Morsleben, Nevada Test Site, Nizhnekansky, Ogoya, Olkiluoto, Oto Cosmo, Peks, Pyhasalmi, Silver Fox, SLAC, Solotvina, Soudan, SNOLab, Stripa, Tono, Tournemire, Tumbling Creek, Tynwarnhale, Val D’Or, Walferdange, Whiteshell, WIPP, Yang-Yang, Yucca Mountain... to name but a few...

- Sites located in a range of soil and rock masses
- Access through mines, road tunnels or purpose-built...
What Goes Underground?
Public Facilities

In addition.. Museums, Art Galleries, Restaurants, Car Parks, Offices, Classrooms, Shopping Malls, Libraries, Civil Defense and Military Installations, Pedestrian Networks......

Olympic Arenas
(60m+ free span)

(Source, Rockplan)

Gyms..

(Source, Rockplan)

Pools..

State Parks..

(Source, Rockplan)

Laughton 5/2/07
What Goes Underground?
Pretty Much Anything You Want
..given enough time and money.

(Sources: Palmaz Winery, Koalie Net)
Why Go Underground?
Why Go Underground?
Urban Congestion..

• Go underground to avoid..
  – Road pavement
  – Buried infrastructure
  – Basements & foundations
  – Surface condemnations
  – Right of way interruptions
  – Minimize surface disruption

(Source; Gridpoint)
(Source; SWECO)
(Source; Hayward Baker)
Why Go Underground? Create Green Space..

• “The Central Artery/Tunnel Project will create more than 300 acres of landscaped and restored open space, including over 45 parks and major public plazas”. Source; MassPike
Why Go Underground?
Preserve Green Space..

Either..

Mineral Location

Or..

Source: Glebe Mines, Hope Valley, Derbyshire, UK

Laughton 5/2/07
Why Go Underground?
Protection..

• Separation from
  – Traffic (road, rail, aviation..)

• Shelter from
  – Rock Falls & Avalanches

(Source: Caltrans)

California Coastal Highway
(Devil’s Slide)

(Source: AUCA)

(Source: FHWA)

Laughton 5/2/07
Why Go Underground?

Isolation

• Stable, Quiet and Shielded
  – Waste Isolation
  – Experiments and Testing..

(Source; DOE Radiochemistry, Hagerbach)
Why Go Underground?  
Too Expensive.. & Too Risky..

### Metro Line Installed Costs, $/km

<table>
<thead>
<tr>
<th>Type</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>At Grade</td>
<td>$29M</td>
</tr>
<tr>
<td>Elevated</td>
<td>$42M</td>
</tr>
<tr>
<td>Cut &amp; Cover</td>
<td>$69M</td>
</tr>
<tr>
<td>Tunnel</td>
<td>$82M</td>
</tr>
</tbody>
</table>

Comparison of metro system costs worldwide..
- Construction Cost averages in Jan.’95
- LCC considerations excluded
- Land acquisition included
- Rolling stock excluded

Source: ITA, ‘04
How is the Underground Built?
How is the Underground Built?
Excavation In Soils

“Digger Shield”
Source; Traylor Brothers

“Brunel-Equivalence”

Earth Pressure Balance
–Source; Lovat
Job; Denny Way

Slurry Shield,
Source; Herrenknecht
Job: Hamburg

Laughton 5/2/07
How is the Underground Built?

Excavation in Rocks

Mechanical Systems

Explosives

Source: SSCL

Source: CERN-LEP

Source: Atlas Copco

Source: Atlantacleanwater

Source: SSCL

Source: IIEpE

Source: Continental Conveyors

Laughton 5/2/07
How is the Underground Built?
Some Ground Improvement Options..

Freezing.. to stabilize the ground and/or preserve the water table

Grouting.. to stabilize the ground and/or render it ~ watertight

Source; LEP

Source; CleanwaterAtlanta

Laughton 5/2/07
How is the Underground Built?
Some Ground Support Systems.

- Steel Arches
- Rock Bolts and Steel Channel
- Cast Iron Segments
- Shotcrete
- Cast-in-Place Concrete
- Pre-Cast Concrete Segments
- Integrated Waterproofing (Daya Bay Construction Option)

(Sources: LEP, NuMI, Solexperts, SSCL)
How is the Underground Built?
As Ground Conditions Change..

Same Rock Unit
- Different conditions
- Different behaviors

Same Excavation System
- Different treatments
- Different supports

Ground Varies!

Fractured...
Failed..
How is the Underground Built?

..With Good Teams

Understanding the conditions & impacts &..

..responding quickly, effectively and safely.
Where are Problems Encountered?

“The best laid schemes o' mice an' men Gang aft agley..” R. Burns
Where are Problems Encountered?

Ground Surprises..

- Geo-material properties vary in time/space (e.g. geo-statistics..)
  - Strengths
  - Loads/Stresses
  - Deformations (elastic and plastic)
- Ditto for groundwater
- Sometimes the engineering process fails to account for the impacts of geo-variability on..
  - Designed structures..
  - Surrounding structures/environment
Where are Problems Encountered?
Major Excavation Happen..
Where are Problems Encountered? Worldwide, Major Projects.. Major Losses

- 1999 Hull Yorkshire Tunnel, UK Collapse US$ 55 mio
- 1999 TAV Bologna - Florence, Italy Collapse US$ 9 mio
- 1999 Anatolia Motorway, Turkey Earthquake US$ 115 mio
- 2000 Metro Taegu, Korea Collapse US$ 24 mio
- 2000 TAV Bologna - Florence, Italy Collapse US$ 12 mio
- 2002 Taiwan High Speed Railway Collapse US$ 30 mio
- 2003 Shanghai Metro, PRC Collapse US$ 80 mio
- 2004 Singapore Metro, Singapore Collapse t.b.d.
- 2005 Barcelona Metro, Spain Collapse t.b.d.
- 2005 Lausanne Metro, Switzerland Collapse t.b.d.
- 2005 Lane Cove Tunnel, Sydney Collapse t.b.d.
- 2005 Kaohsiung Metro, Taiwan t.b.d.

………. etcetera..

Source; Munich Re

Laughton 5/2/07
Where are Problems Encountered? Daylight.. not always a good thing

Major Collapse in Barcelona..
- Buildings Destroyed
- 1000+ People Evacuated

Critics assert.. (common themes)
- Inadequate geologic study
- Unsound methods and means
- Poor management in design and construction..

(Source: geography field work)
Where are Problems Encountered?
Fractured Rock Subject to Stress & Gravity
(...potentially in any underground excavation)

Not
“Rock Solid”

Observed at the engineering scale
rock is rarely solid..
A “hard” rock mass may contain
weak clays or even voids..

Sources: AME-Geolab, Muller, Jacobs

Laughton 5/2/07
Where are Problems Encountered?
Changing Groundwater Conditions

“High Water Pressure Complicates Arrowhead Tunnels..” (Source; ENR 5/2005)

- Original design ~ Mid-90’s
- Contract 1 – terminated (water)
- Contract 2 - officials keeping fingers crossed (alleged DSCs on horizon..)

Changes in Water Table Can Cause Ground Subsidence, ENR 7/03
(Subway Construction Shanghai)
Where are Problems Encountered?
Contaminating Ground & Aquifers

• During Construction..
  – Hallandsas Tunnel, Sweden. Cattle poisoned! (Source BVA)
  – Project began ‘92.. scheduled for completion ‘12.

• During Operation..
  – Gran Sasso Laboratory, Italy. “..Lab's drainage system could contaminate local water supplies” (Source; Science 6/2003)
  – Milwaukee Deep Tunnel.. well closed when fecal coliform bacteria detected.. allegedly tunnel leak. (Source; Milwaukee Journal Sentinel).
When Do Risks Get Mitigated?

Three principal ways to lose money: wine, gambling, and engineers. While the first two are more pleasant, the third is by far the more certain. after Baron Rothschild, *circa* 1800.
When Do Risks Get Mitigated?
In Defining Project Needs

• There are no ground rules, codes or standards
  – Understand the demands placed on the ground
  – Projects may not be viable in some ground types

• Before drafting solutions...
  1) Define Key Project Needs
  2) Investigate the Ground
    identifying;
      a) showstoppers, and
      b) cost drivers

Can’t Pick & Choose!

Laughton 5/2/07
When Do Risks Get Mitigated?
In Studying the Regional Geology

Putting the Site in Context..

Benefit from the experience of others..
- Same/similar rock
- Same/similar needs
- Much of the early work can be done from behind the desk

Laughton 5/2/07
When Do Risks Get Mitigated?

In Scoping the Site Investigation (SI)

• Right/Reliable data = reliable design..
  – Key project needs defined..
    • e.g. stability, dryness, alignment, egress..
    • identify and prioritize the critical questions the investigating geo-engineer must answer
  – Adequate investigation
    • Diablo Canyon SI ~ $500k
    • Braidwood SI ~ $125k
      – 2 Vertical B/Hs
      – Tests
      – Geo Data Report
    ...Worth the $s

(Sources: UofChicago, Hublin et al.)
When Do Risks Get Mitigated?
In Analyzing the SI Data

- Mixed-scale data sets.. experience needed
- Field Investigation..
  - Exposures
  - Geophysics
  - Boreholes
  - Testing
    - D-T-H
    - Field
    - Lab

Source: U of C.. ISGS Braidwood DTH Logs, Advanced Geoscience

Source; Henderson Mine

Laughton 5/2/07
When Do Risks Get Mitigated?
Characterizing Subsurface Site(s)

- **3-D Geo-Models**
  - From cms to kms
  - Basis of Design..
    - **Conditions**: dry, damp, wet, massive, hard, stratified, seamy, schistose, jointed, blocky, crushed, soil-like..
    - **Behaviors**: raveling, running, flowing, squeezing, swelling, spalling, rockburst..
      (a new language to learn!)
  - Deciding between options..
    - Siting
    - Design
    - Construction

Homestake Mine Section
SSCL Fence Diagram
Henderson Mine Section

Laughton 5/2/07
When Do Risks Get Mitigated? Interdisciplinary Trade-Offs for Best Value

Early Optimization.. Avoidance is the best form of mitigation!!

1, 2, 3 Rotation + Reduction

LEP alignment adjusted to minimize Jura tunneling… (site investigation provides the rationale)

Laughton 5/2/07
When Do Risks Get Mitigated?
Design & Specify for Geo-Diversity

• Plan for Variation..
  – Geologic Uncertainties
  – Design & Construction Changes
    • Bid Flexibility
    • Instrumentation

• Design Mitigation?
  – Too little ~ adds risk
  – Too much ~ adds cost

Many Designs
..One Tunnel
When Do Risks Get Mitigated?  
Design for Construction Safety

Even the best-trained amongst us can make fatal errors..

Fatalgram

METAL/NONMETAL MINE FATALITY - On October 17, 2002, a 49-year-old mine rescue team trainer with 26 years mining experience and a 38-year-old co-trainer with 2 years mining experience were fatally injured, at an abandoned underground gold mine. Both were participating under oxygen in an exercise to evaluate conditions in this mine. As the team was walking up the steep decline to return to the surface, the victims experienced breathing difficulties and collapsed. The first victim was pronounced dead at the scene. The second victim was transported to a medical facility where he succumbed to his injuries on October 23, 2002.

(Source; USMRA)

Target Safety & Health During Construction..
(e.g. remote/automated operations)

Fewer hours underground with greater physical separation and protection..

(Source; Atlanta Clean Water)

Laughton 5/2/07
When Do Risks Get Mitigated?  
Design for Operational Safety

• Mont Blanc Fire Event, 6/99
  – Truck fire spread to 35 vehicles
  – Fire duration.. 53 hours
  – Fire Damage.. extensive
  – Tunnel closed for 2 years
  – **Intense heat and toxic fumes killed 39 people**

• 13 individuals/companies found guilty of manslaughter (Source: BBC News)

• One of several fatal fire events of the last few years

• Safe egress.. a key issue
When Do Risks Get Mitigated?

$-Reality Checks avoid Sticker Shocks

Design something “AFFORDABLE”..

- Run-of-Mine tunnels ~ few $K per m., BUT costs increase rapidly as user demands grow..
  - Sewer Tunnels ~ $6k/linear meter
  - Subway Tunnels ~ $42k/linear meter
  - NYC Road Tunnel > $1.5M/lin.m.

* Sources; Transalt, AUCA’04

(DUSEL/Theta 13 excavation costs between $12k and $50k/lin.m.)
Who Can Best Mitigate The Risks?

Risk is OK as Long as You Know You’re Taking It..
Who Can Best Mitigate the Risks?
So Many Experts So Little Consensus..

• Who was At Fault?..
  – “Singapore tunnel team may have cut corners.” ENR, 5/04.
  – “…engineers could face prison.” Foundation World, 5/05.
  – “Inquiry blasts lax site and design..” T&TI, 6/05.
  – “lack of practical expertise in the client organizations…
  – ..lack of engineering expertise and its continuity throughout the contract..” T&TI, 9/05.

• Depends what you read/who you talk to.. but, industry guidelines are available..

Litigation pending..
…Points of view differ
Who Can Best Mitigate the Risks?
Owners and Industry Working Together..

- US Best Practices courtesy of the Tigner-Sanford-Toohig (TST) Model..
  - SSC-CDG worked with US Industry Team to develop better contract practices..
    - Project-Wide Competence (Low-Bid Heart Surgeon?)
    - Streamlined Management
  - Still model of choice in US..
  - Currently being updated..
### Who Can Best Mitigate the Risks?

**TST Model & TBM Innovation**

<table>
<thead>
<tr>
<th>Diameter Range</th>
<th>Record</th>
<th>Make and Model</th>
<th>Project Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.01 - 4.00 m</td>
<td>172.4 m</td>
<td>Robbins Mk 12C</td>
<td>Katoomba Carrier, Australia.</td>
</tr>
<tr>
<td>4.01 - 5.00 m</td>
<td>128.0 m</td>
<td>Robbins MB 146-193-2</td>
<td>SSC No. 4, Texas.</td>
</tr>
<tr>
<td>5.01 - 6.00 m</td>
<td>99.1 m</td>
<td>Robbins MB 1410-251-2</td>
<td>Little Calumet, Illinois.</td>
</tr>
<tr>
<td>6.01 - 7.00 m</td>
<td>114.6 m</td>
<td>Robbins MB 222-183-2</td>
<td>Dallas Metro, Texas. (NuMI TBM)</td>
</tr>
</tbody>
</table>

- **Contractor-Led Innovation TBM** World Record (~$1,000/meter)
  - High Power TBM (TRC/FNAL)
  - Lach, Foster, Malamud, May et al.

- **Manufacturer-Led Innovation** World Record on TARP drive
  - Source: The Robbins Company, TRC

- **Contractor-Owner Collaboration (Fermi/Kenny) - Instrumentation**
  - TBM Performance/Health
  - Monitored on www. (TM-2141)
  - Lach, Fashimpour, Florian, Kucera, Lucas & Shea (Fermilab)
  - Budd & Johnson (Kenny Con.)

Source: Laughton 5/2/07
Who Can Best Mitigate the Risks?
TST Model & Drilled Shaft Innovation

• Contractor-Led Innovation..
  – SSCL worked with Association of Drilled Shaft Contractors
  – Established compatibility between project needs & drilled shaft options

• Oil Rig Converted, Used Extensively..
  – Safer
  – Faster
  – Cheaper
  – Better (less damage to rock)

Converted Oil Well Drill Rig (Beck Foundations)

Source: SSCL
Who Can Best Mitigate the Risks?
Industry & DUSEL Collaborators

DUSEL - The Deep Underground Science & Engineering Laboratory

Cascades Tunnel
Henderson Mine, Co
Soudan Mine, Mn
Homestake Mine, SD

Decision Pending
Coming soon to a site near Fermilab (between 700-2500 km) soon..

Laughton 5/2/07
Who Can Best Mitigate the Risks? Scientists, Engineers & Industry Together

- Research can add real value to the DUSEL Program and Industry at large...
  - Safer
  - Lower Cost/Risk
  - Faster Delivery
  - Higher Quality
  - Research can improve the viability of experiments such as the Long Baseline..

DUSEL “Metro-Map”
Who Can Best Mitigate the Risks?
DUSEL Geo-Investigators...

Larger Caverns = Larger Risk

Approximate Cavern Span, m

Approximate Depth, km

- LEP (CERN)
- LHC (CERN)
- Gjovik (Ice Rink)
- Korea Invisible Mass Search (Yang HEPPS)
- Super-Kamikande (Kamioka Mine)
- Gran Sasso (Road Tunnel)
- SNOLab (Creighton Mine)
- Western Deep (Crusher Room)
- Domed Cavern
- Prismatic Cavern

We really do need to know what goes on between the boreholes.. So we can pick the best sites and develop the most accurate engineering models..

Laughton 5/2/07
Who Can Best Mitigate the Risks?
DUSEL Geo-Engineers...

"Choosing a span greater than rock conditions can allow is the greatest error a designer can make." after Johansen, ‘79

Molasse Cavern Designs (CERN)
Who Can Best Mitigate the Risks?
Industry.. Storage of Cryogenic Fluids

“Holy Grail” for LNG storage.. (R&D $’s)
Pilot project..
  – Belt & braces approach
  – Multilayer containment
  – Freezing addresses the key issue of rock property variation..

ground masses are never really solid

(Source: Hydrocarbon Technology)
In Conclusion..

• **What** goes Underground?
  – Pretty **much anything** that could be placed on surface

• **Why** go Underground?
  – **Many advantages.** Cost and risk are the main drawbacks

• **How** is Underground Space Created?
  – Technology **exists** to build in pretty much any geo-material

• **Where** Problems are Encountered Underground?
  – **Same old problems.** no foolproof solutions

• **When** do risks get mitigated?
  – Opportunities for risk management are there.. they need to be seized

• **Who** can best mitigate the risks?
  – Practitioners and researchers collaborating together at sites like DUSEL.
End of the Tunnel..

Exciting Times ahead for the underground practitioners..

Thanks for the opportunity to work on such technically challenging projects..

Questions?

Source: AGS Students

NuMI Shaft Construction