Energy storage
in artificial subsurface openings - construction, operation, risk and decision making

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Energy storage in artificial subsurface openings - construction, operation, risk and decision making

Energy Storage Caverns (in rock)

- Examples
- How are they built – how to present this in models
- Risk and decision making

Energy Storage Caverns

Examples – Different Operations

- CAES
- Magnetic
- Pumped Hydro
- Oil/Gas
- CO_2 -plus

Compressed Air Energy Storage

Source: RWE AG

Cavern/Surrounding Ground
→ *Subjected to*
High and Cyclic Pressure/Temperature

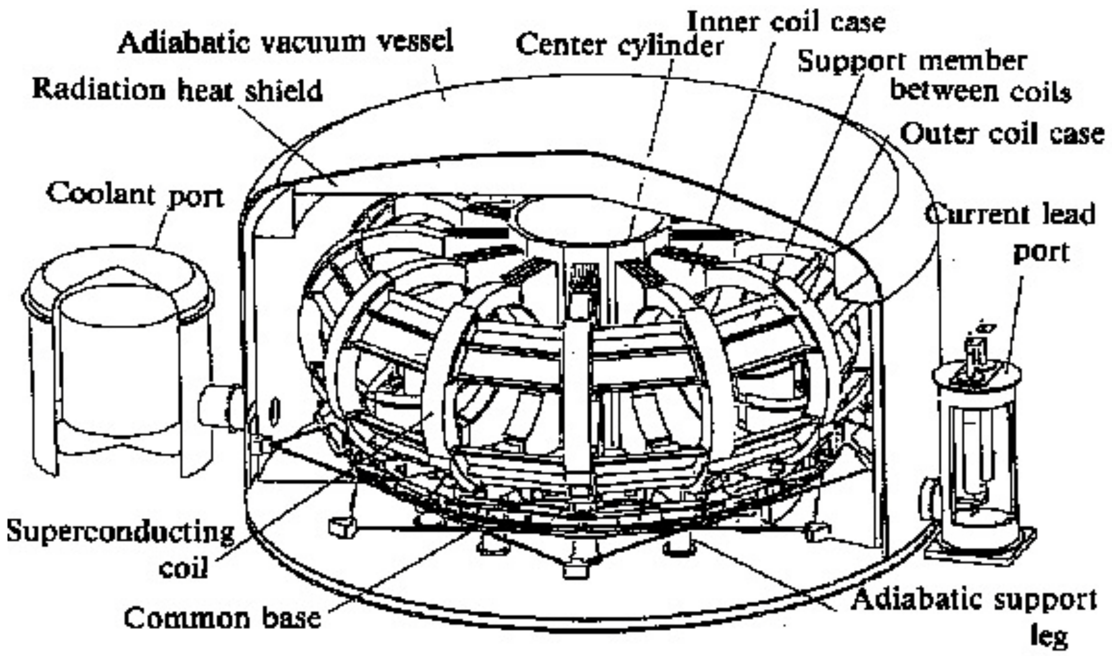
Air is compressed and stored in natural formations, natural or artificial caverns

Compression causes heating
- Heat can be removed and stored separately
- Hot air can be stored

Compressed air
- Flows through turbine while expanding
- Expansion process can be combined with gas turbine
- Heat can be extracted

to **produce energy**

Superconducting Magnetic Energy Storage



: Conceptual design of a superconducting coil
Source: http://www.wtec.org/loyola/scpa/02_06.htm

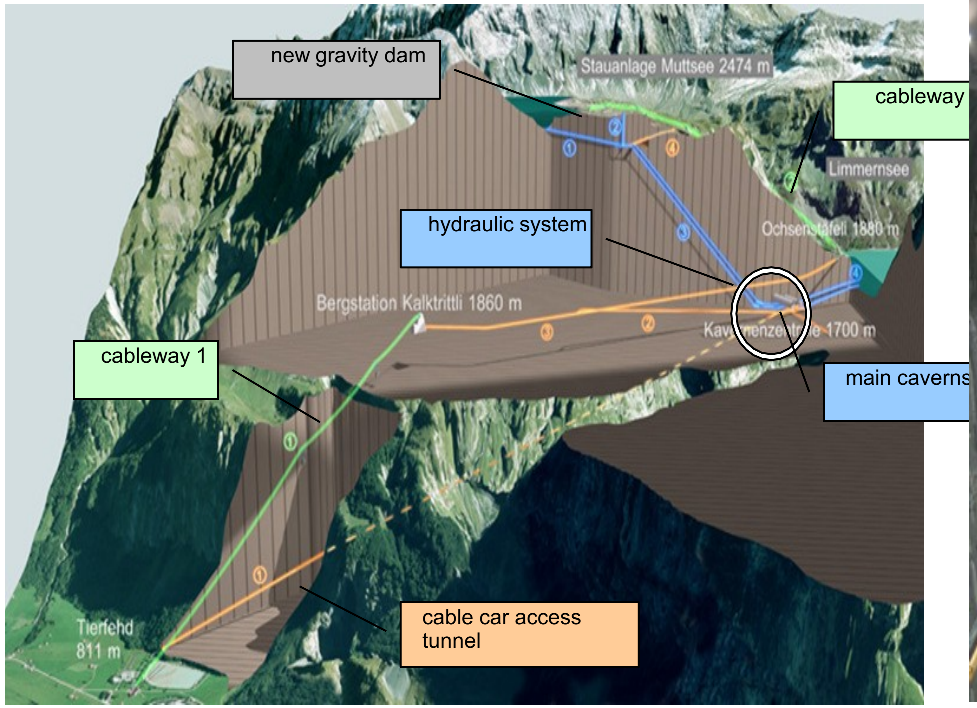
Cavern instead of "vessel" for containment
Subjected to
High and Cyclic Pressure/ Low Temperature

Short-term Energy Storage
Fast respond times
But
Requires Cooling (Reduces efficiency)

Magnetic field acts on containment

Pumped Hydroelectric Storage

Example Linth-Limmern 1500 MW Plant -Switzerland



General Layout

Machine Cavern 150x31x54m

From Müller et al WTC 2013

Classic energy storage using gravity

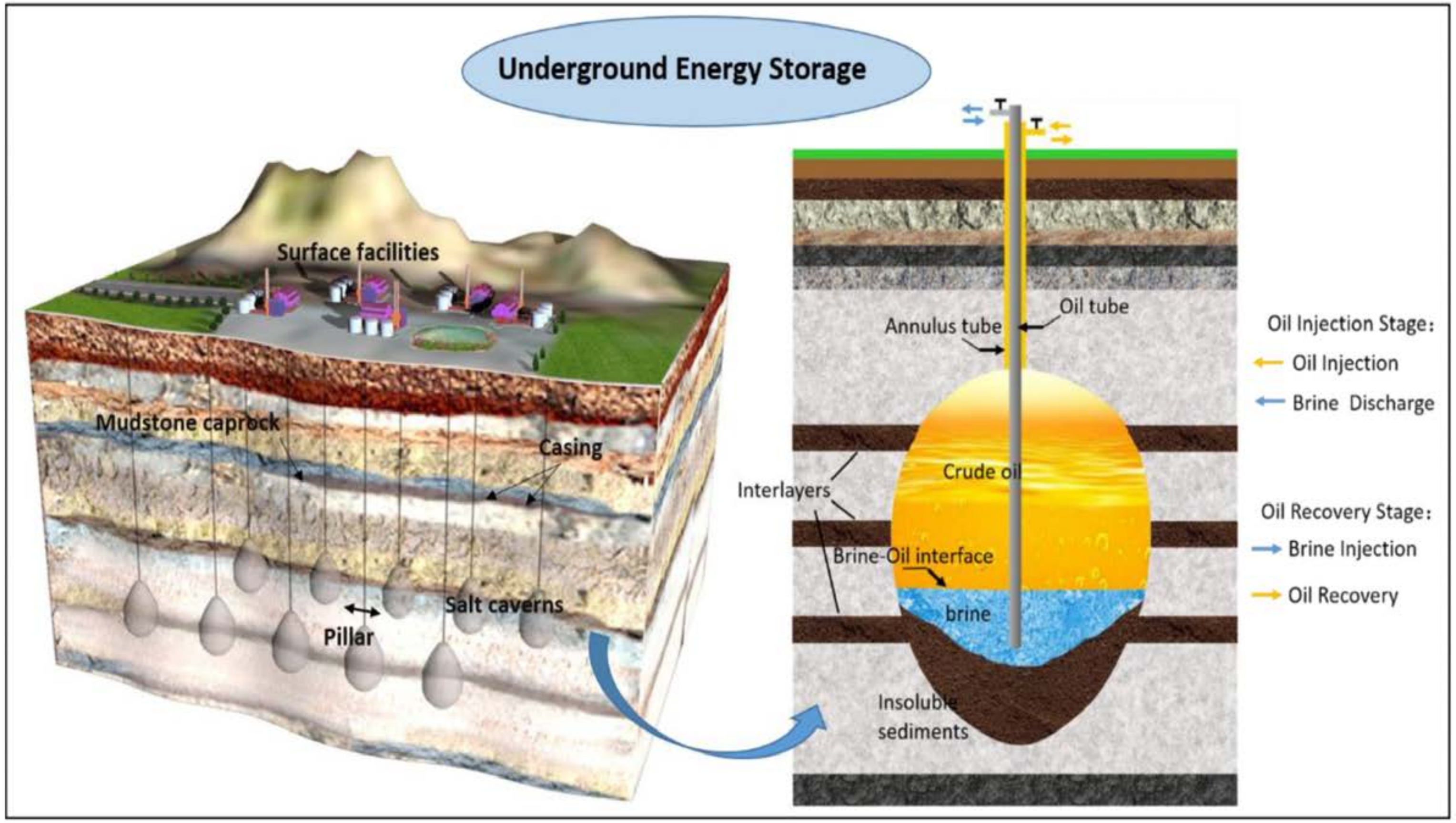
Reversible Turbine/Pump -Generator/Motor System

Pump water when excess energy available

Use water when energy needed

→ *Cavern to accommodate large machinery or transformers – no groundwater inflow where electric equipment*

Oil/Gas Storage in Salt Caverns



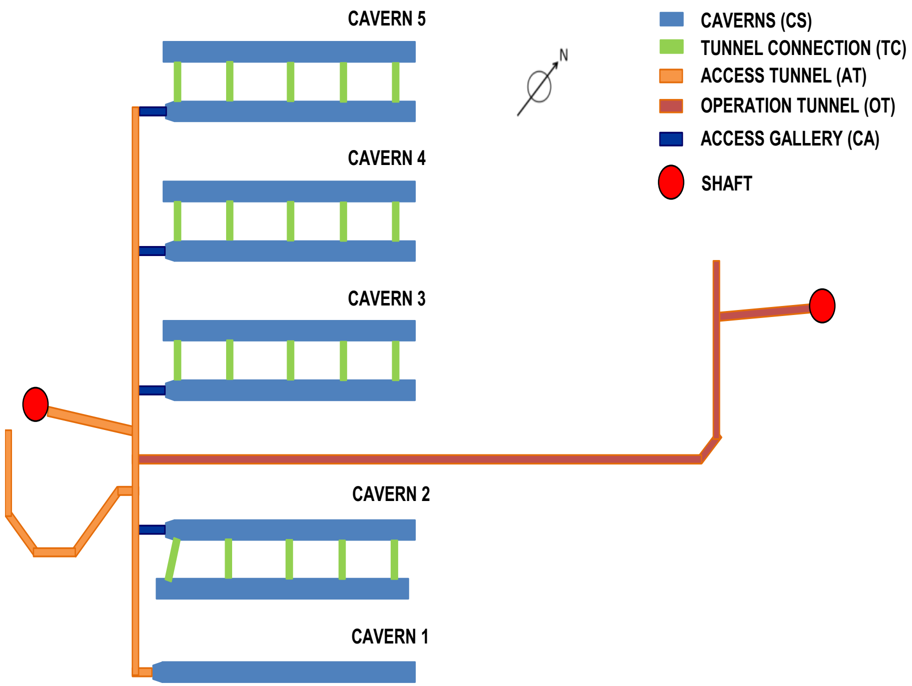
From: Zang et al. **Microscopic Pore Structure of Surrounding Rock for Underground Strategic Petroleum Reserve (SPR) Caverns in Bedded Rock Salt** Energiies 2020

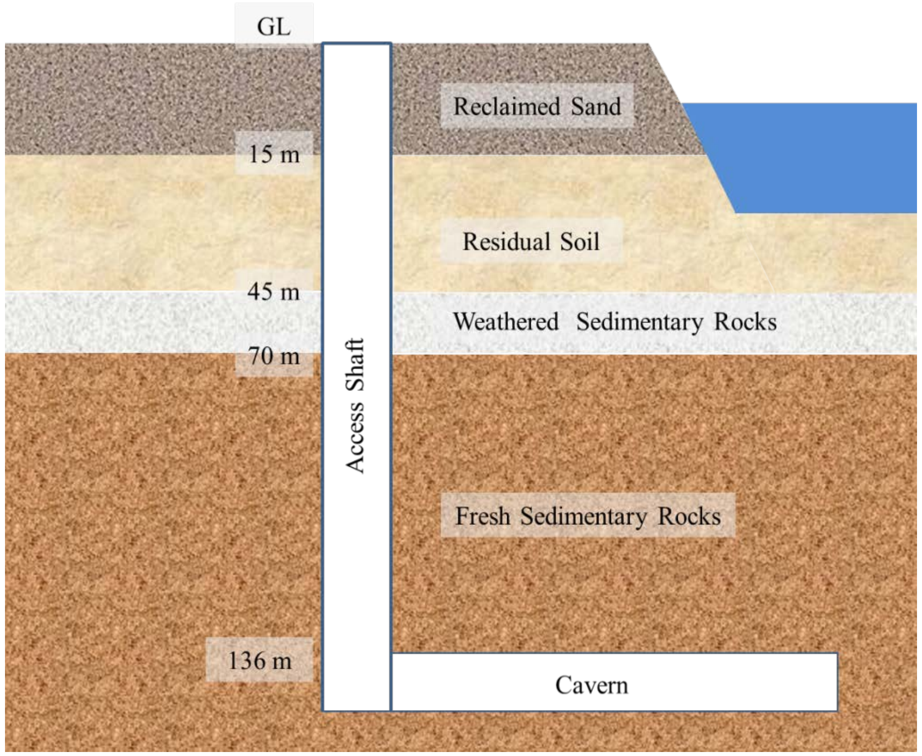
Caverns created through leaching of salt

Typical volumes are ~ 10 million barrels ~ 1.6 million m^3 per cavern

→ *Caverns in salt are "by definition" watertight*
However, subsidence with damage on the surface possible
Cyclic pressurization particularly if gas

Oil/Gas Storage in Rock Caverns





Jurong Oil Storage Caverns Singapore

System of Tunnels and Caverns

Cavern Size
20 x 27 x 340 m

→ *Rock around caverns must have low permeability*

NEW IDEA Underground CO_2 Storage for Energy Storage and Production

Concept

- Capture CO_2 and store it as Supercritical CO_2 in caverns
- Use Supercritical CO_2 for power production preferably but not exclusively in a closed (Allam) cycle

Pluses

- Contribute to CCUS
- Very efficient power production
- Advantageous compressibility of Supercritical CO_2

Minuses

- Temperature increase caused by compression
- Limited total volume
- Cavern and surrounding ground subjected to high and cyclic pressure and temperature

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Energy Storage Caverns

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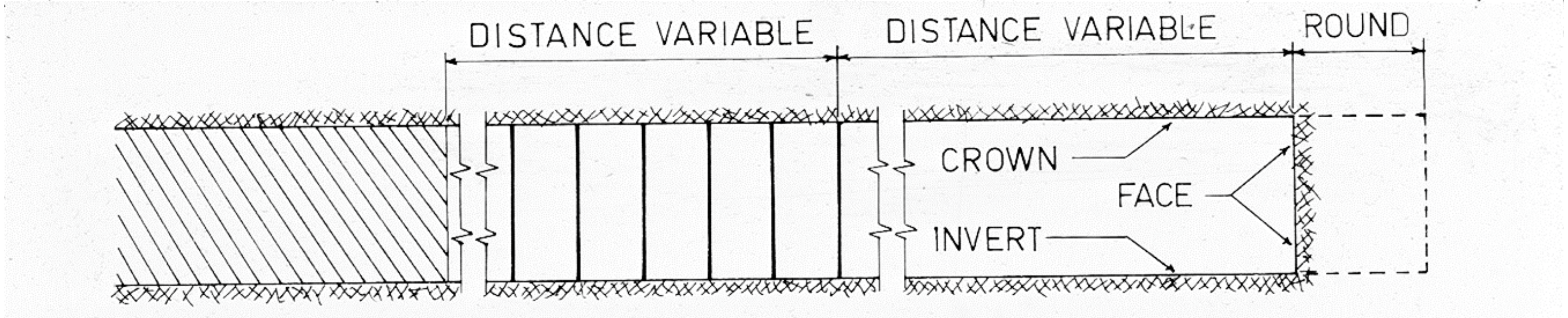
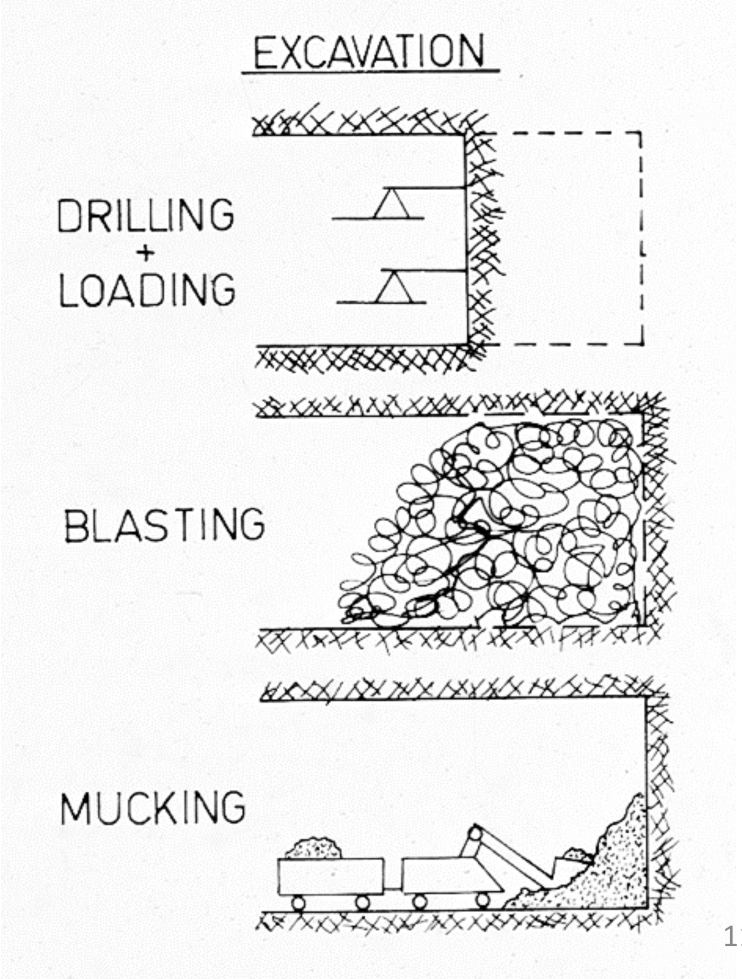




PERMANENT SUPPORT (LINER)

CAST IN PLACE CONCRETE

SHOTCRETE

SEGMENTED ELEMENTS

INITIAL SUPPORT

STEEL SETS

BOLTS

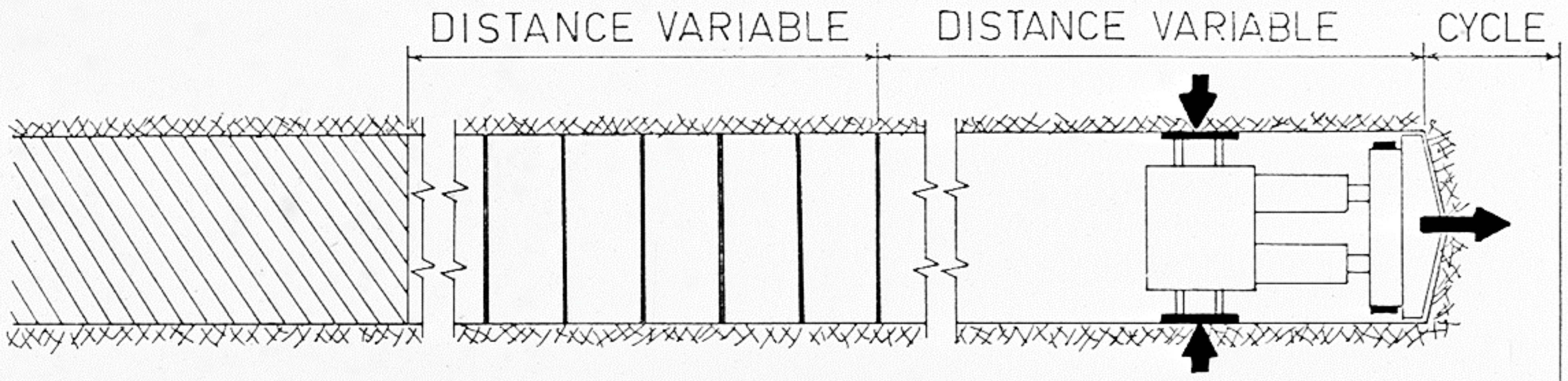
SHOTCRETE

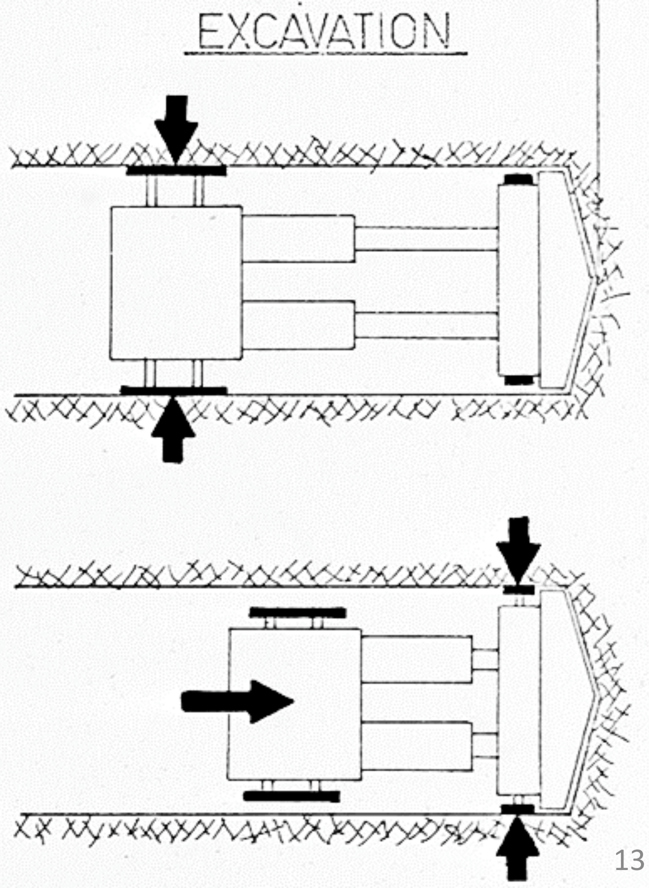
SEGMENTED ELEMENTS

COMBINATIONS

TUNNEL IN ROCK DRILLING AND BLASTING

Drill Rig





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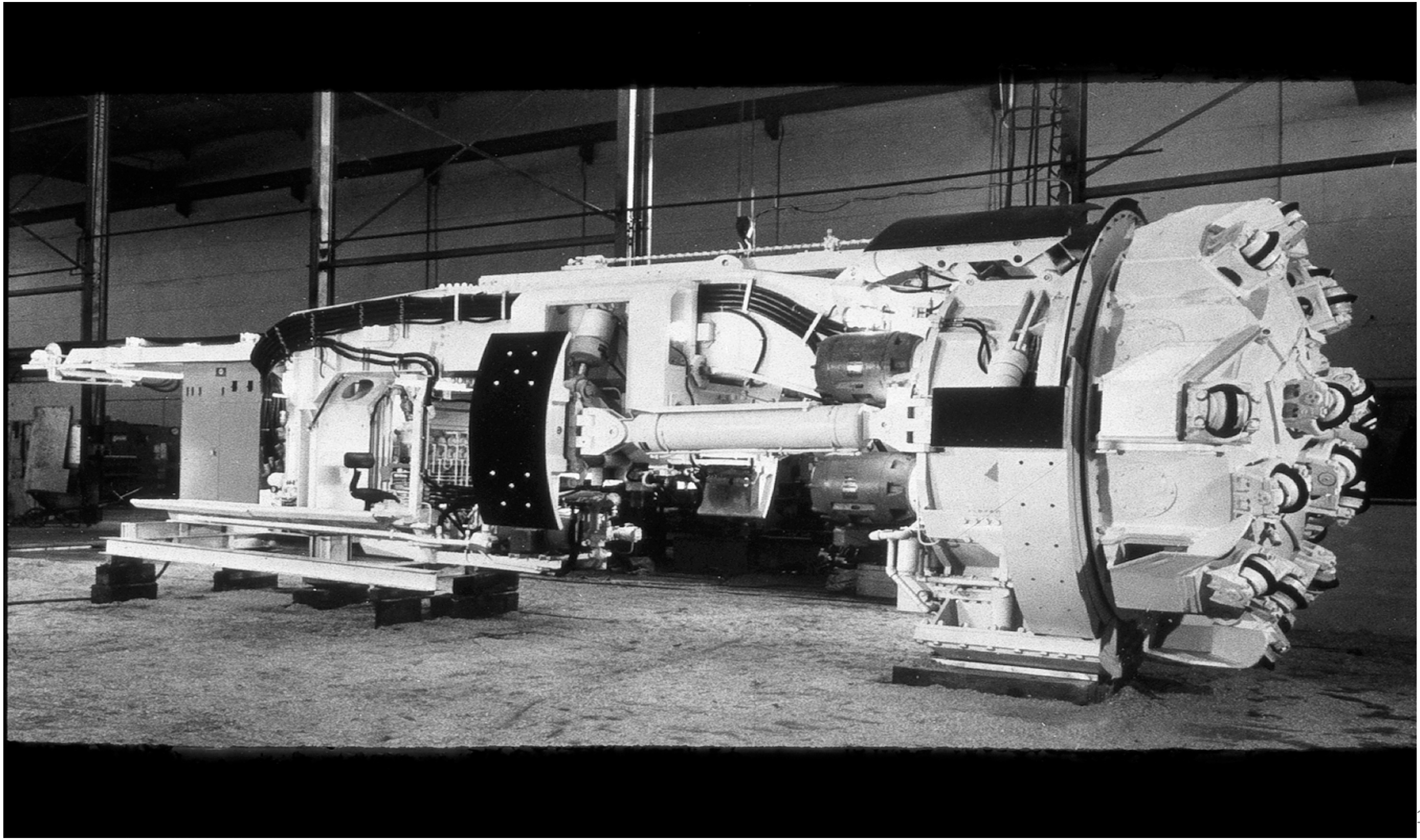
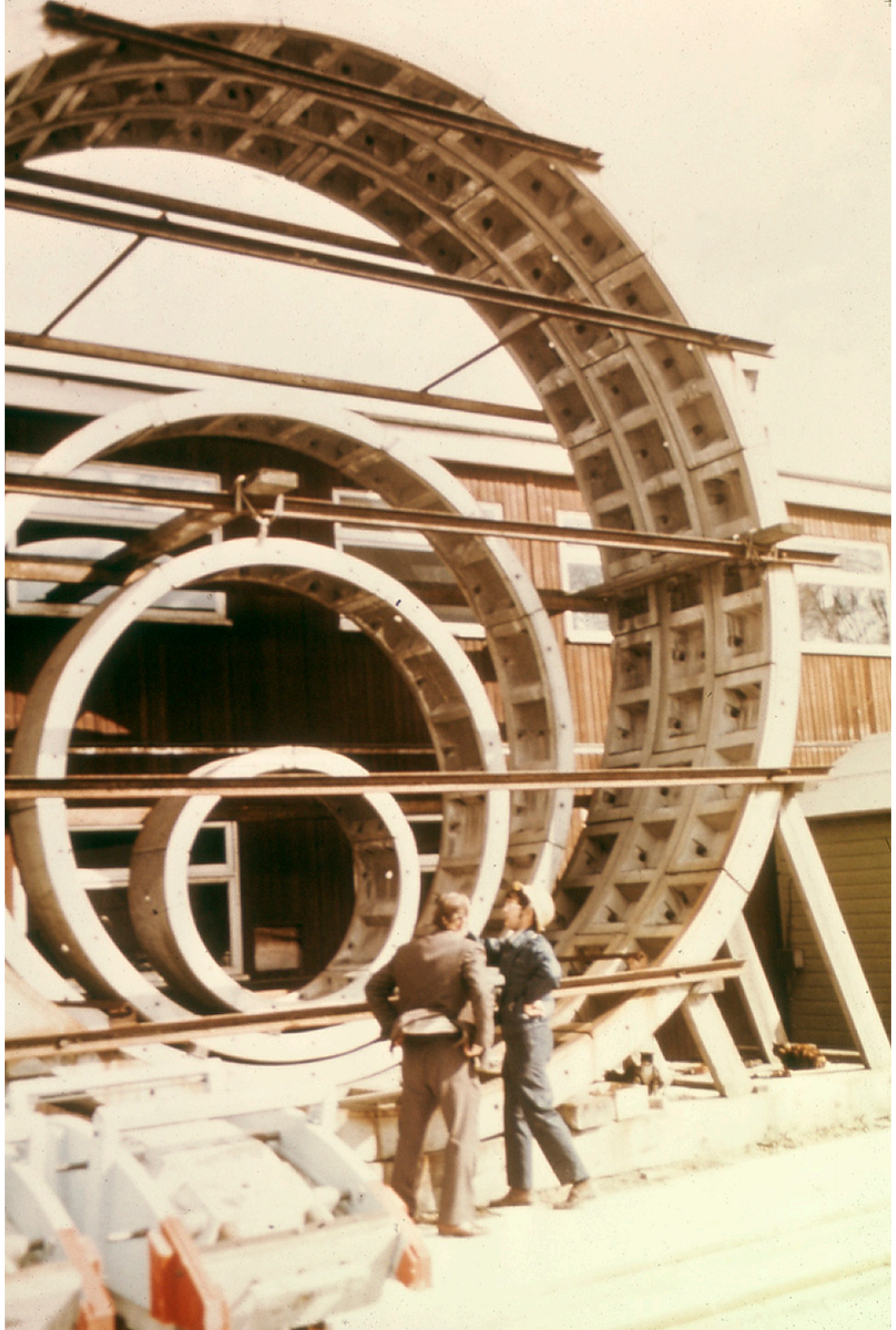
COMBINATIONS

TUNNEL IN ROCK
TBM - Tunnel Boring Machine

Robbins Rock Tunnel Boring Machine



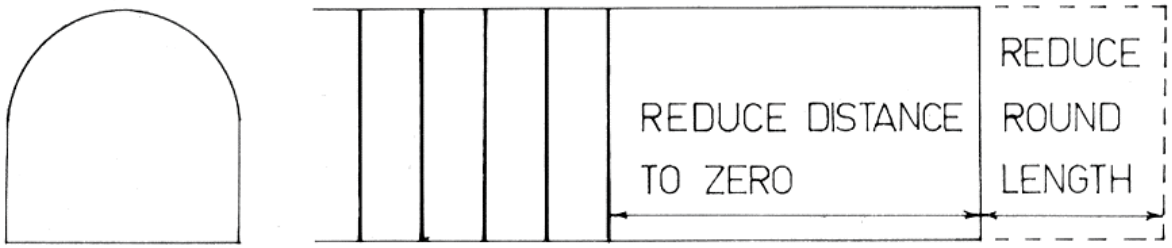
Segmented
Tunnel
Liners



STABILITY OF UNDERGROUND OPENING

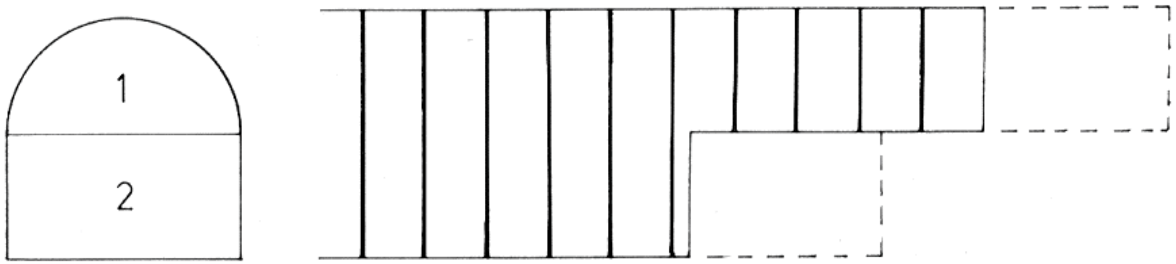
Quality of Rock and Size of Opening Affect Excavation – Support – Process

REDUCE UNSUPPORTED TIME

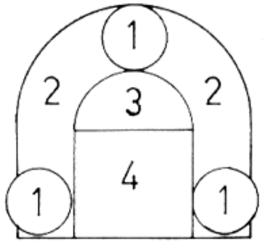


INITIAL
SUPPORT

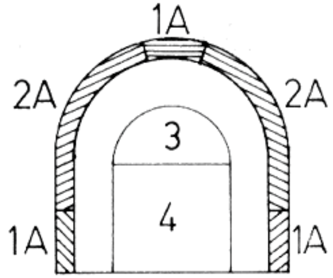
REDUCE CROSS-SECTIONAL AREA



HEADING AND BENCH$_H$



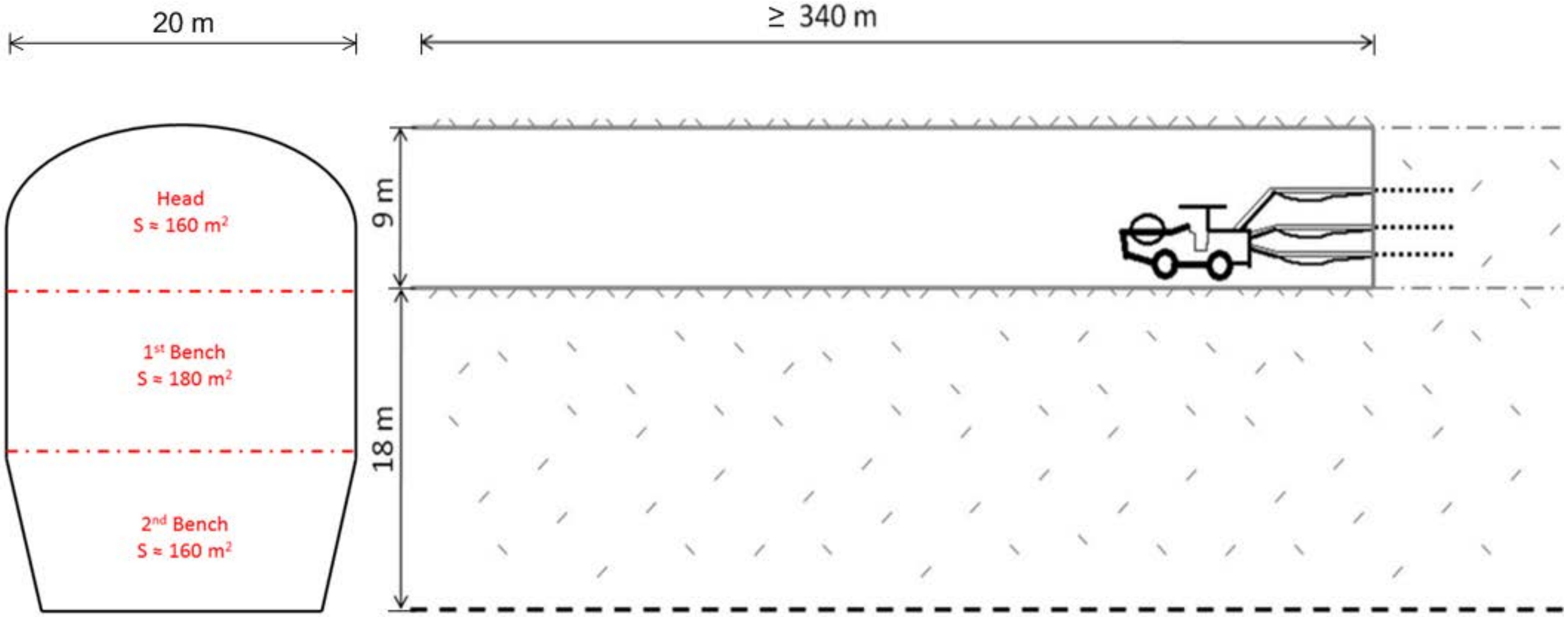
MULTIPLE



DRIFT

JURONG, Oil Storage Caverns, Singapore

Cavern construction with drilling and blasting, multiple headings and benches



Washington DC Metro
Dupont Station Cavern

Monte Ceneri Base Railroad Tunnel Switzerland -

Energy storage in artificial subsurface openings - construction, operation, risk and decision making

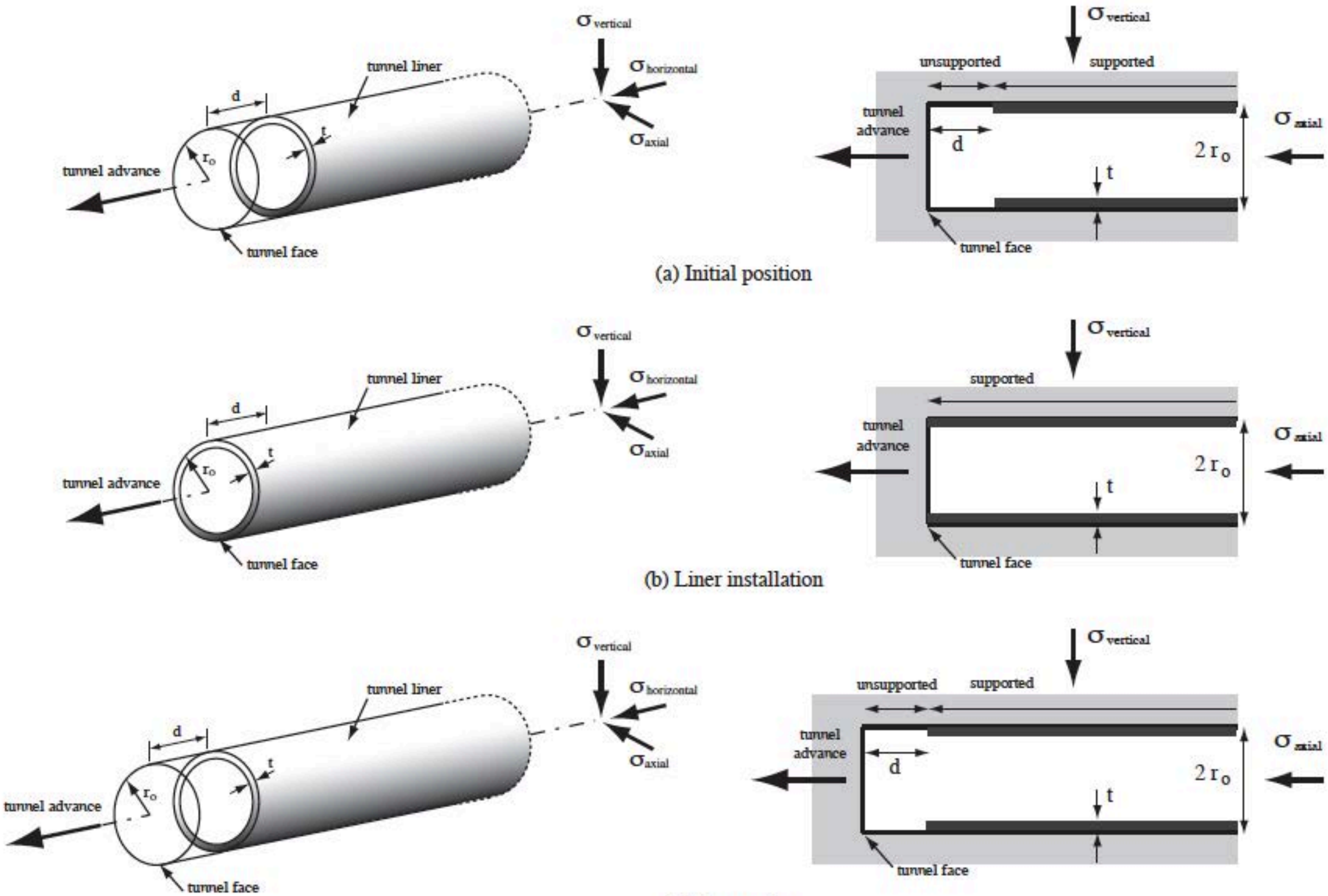
Energy Storage Caverns

Examples

How are they built **– how to present this in models**

Risk and decision making

Excavation and Support of a Lined Tunnel



(a) Initial position

(b) Liner installation

(c) Excavation

Deformable Supports Gotthard Base Tunnel

Open
Slot

Deformable Supports Gotthard Base Tunnel

Closed Slot

We have seen that

Construction of caverns involves:

Complex excavation support processes
Complex stability issues

Operation of energy storage caverns may involve:

Complex load cycles and possibly high loads
Complex temperature cycles and possibly high/low temperatures

This requires models
That can represent the physical processes
That can represent assess and optimize the interaction of all these processes
all of which are **uncertain**

Models representing physical conditions and processes

3-D Finite Element Model
representing stresses/pore pressures

Discrete Fracture Network Model
representing geometry, flow, temperature

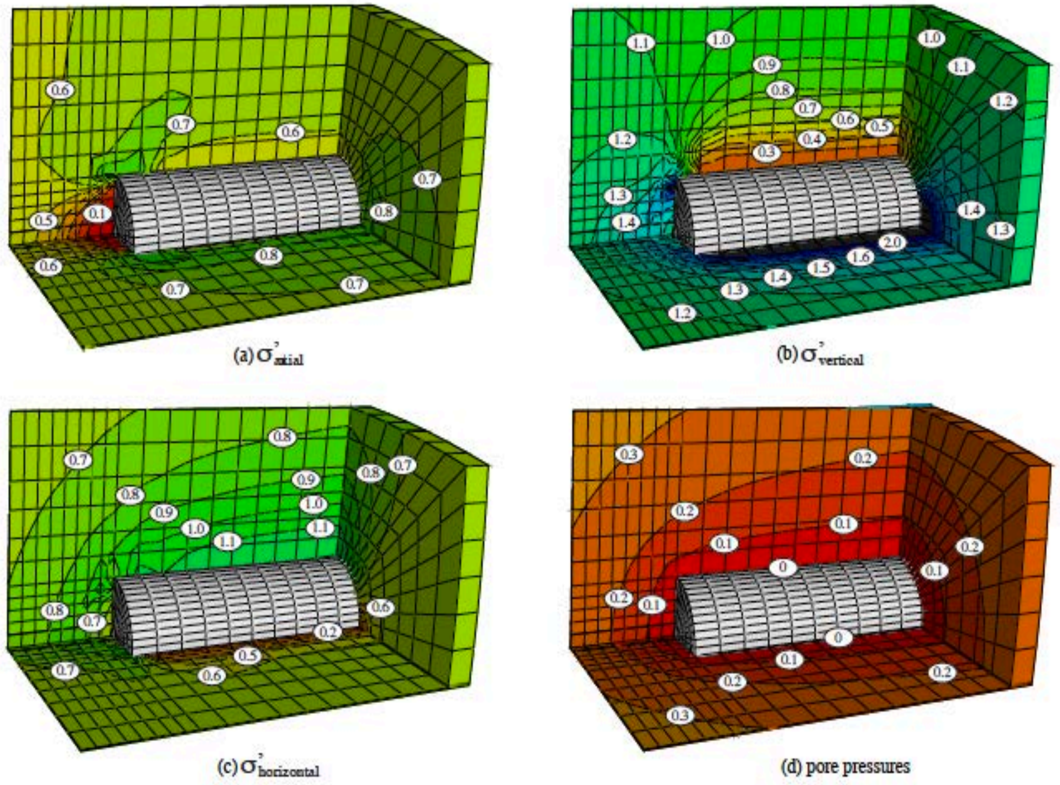
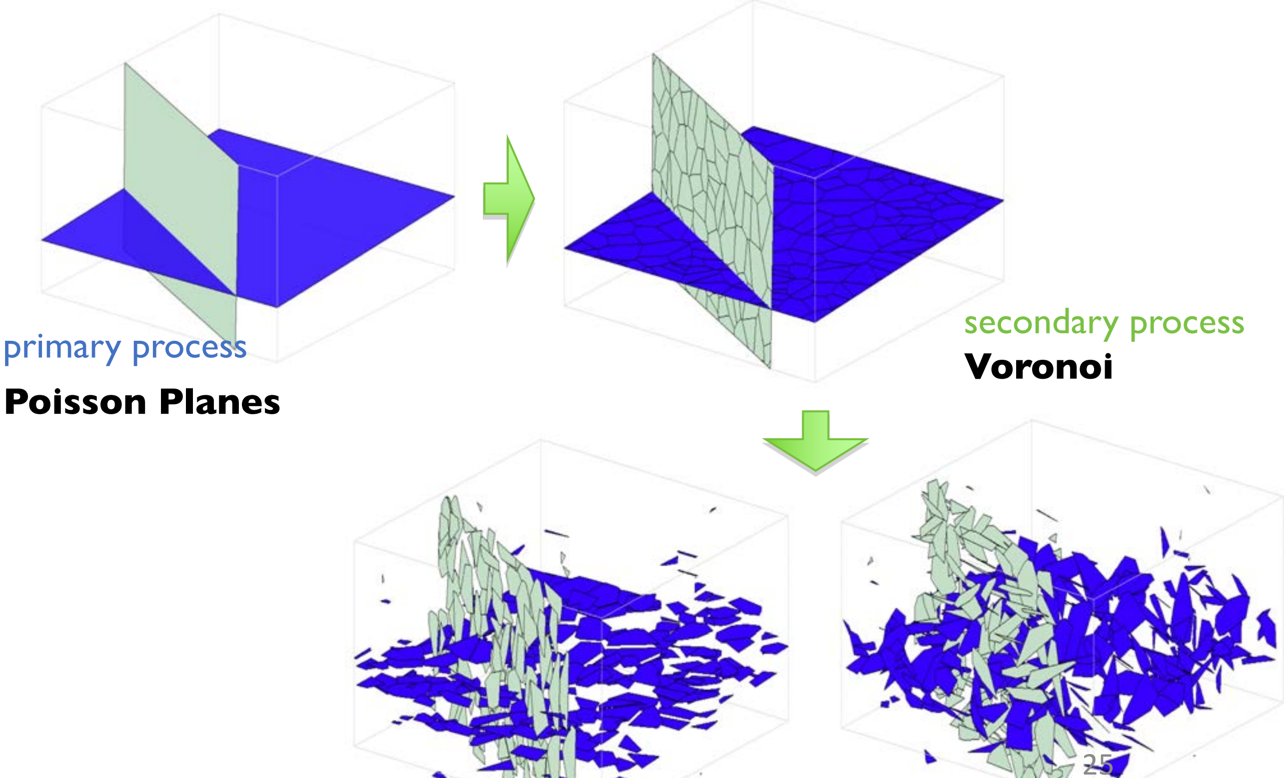


Figure 4.14 Three-dimensional View of Stresses and Pore Pressures for an Unsupported Deep Tunnel with $r_o = 2m$, $\sigma'_v = 1.0$ MPa, $K_o = 0.5$, $u = 0.5$ MPa. Long Term Analysis

GEOFRAC – Stochastic Fracture Pattern Model

GEOFRAC's stochastic processes are implemented and optimized in MATLAB.



Sousa et al. 2010

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Energy Storage Caverns

Examples

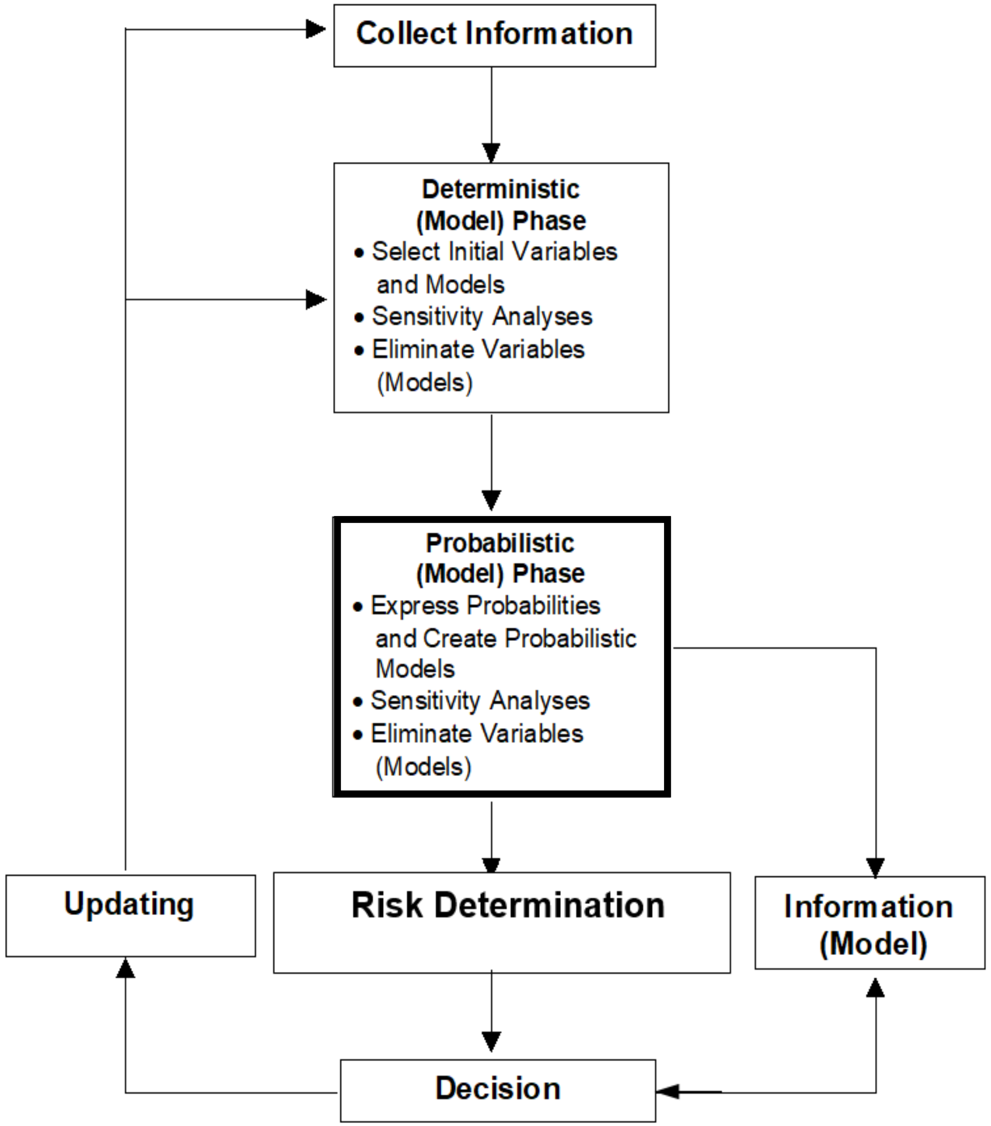
How are they built **–** how to present this in models

All the above are affected by many uncertainties

↓

Risk based on decision making under uncertainty

Decision Making under Uncertainty



Decision Aids for Tunnelling (DAT)

Developed by H.H. Einstein and Group at MIT together with EPFL (Switzerland)

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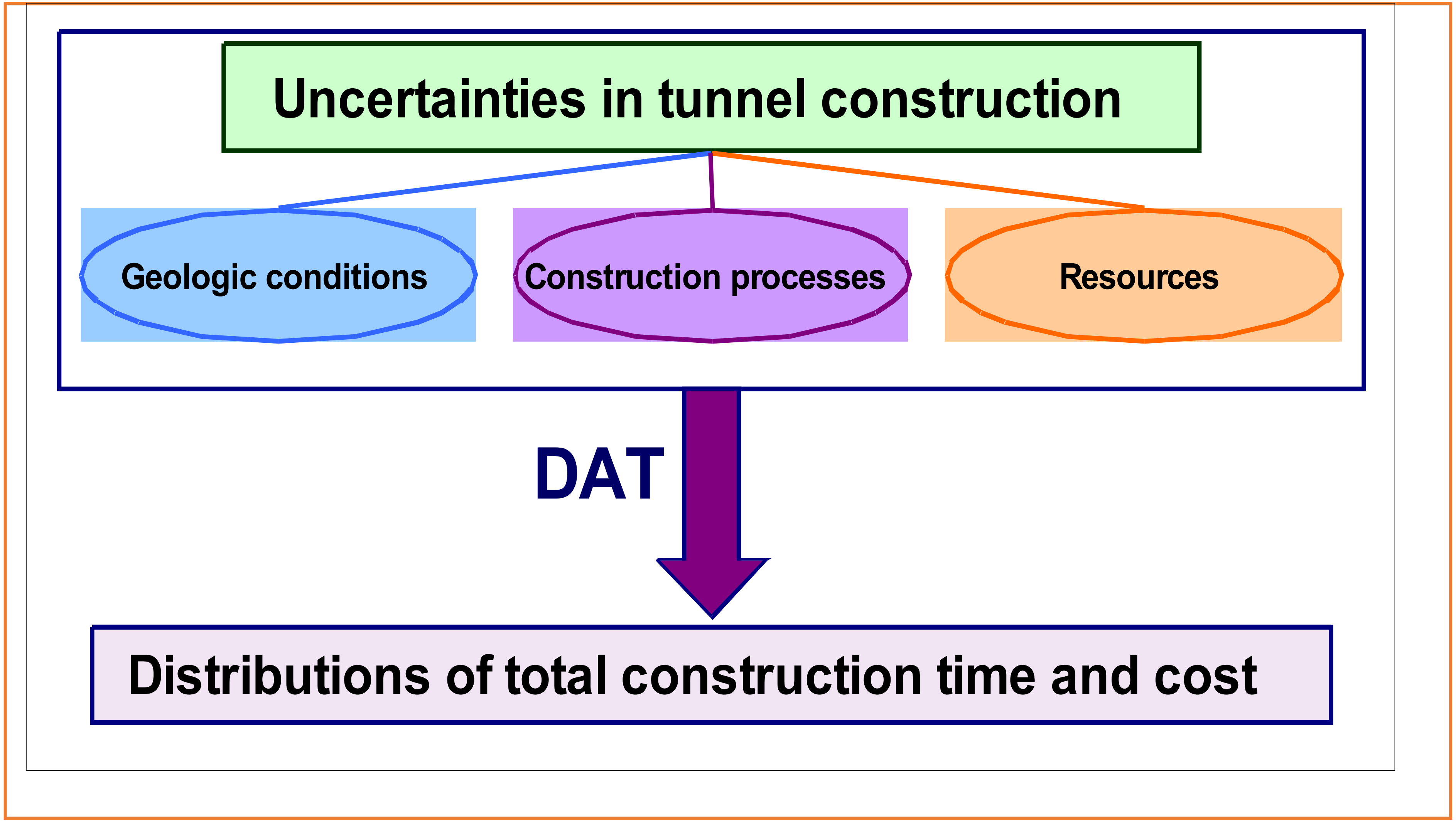
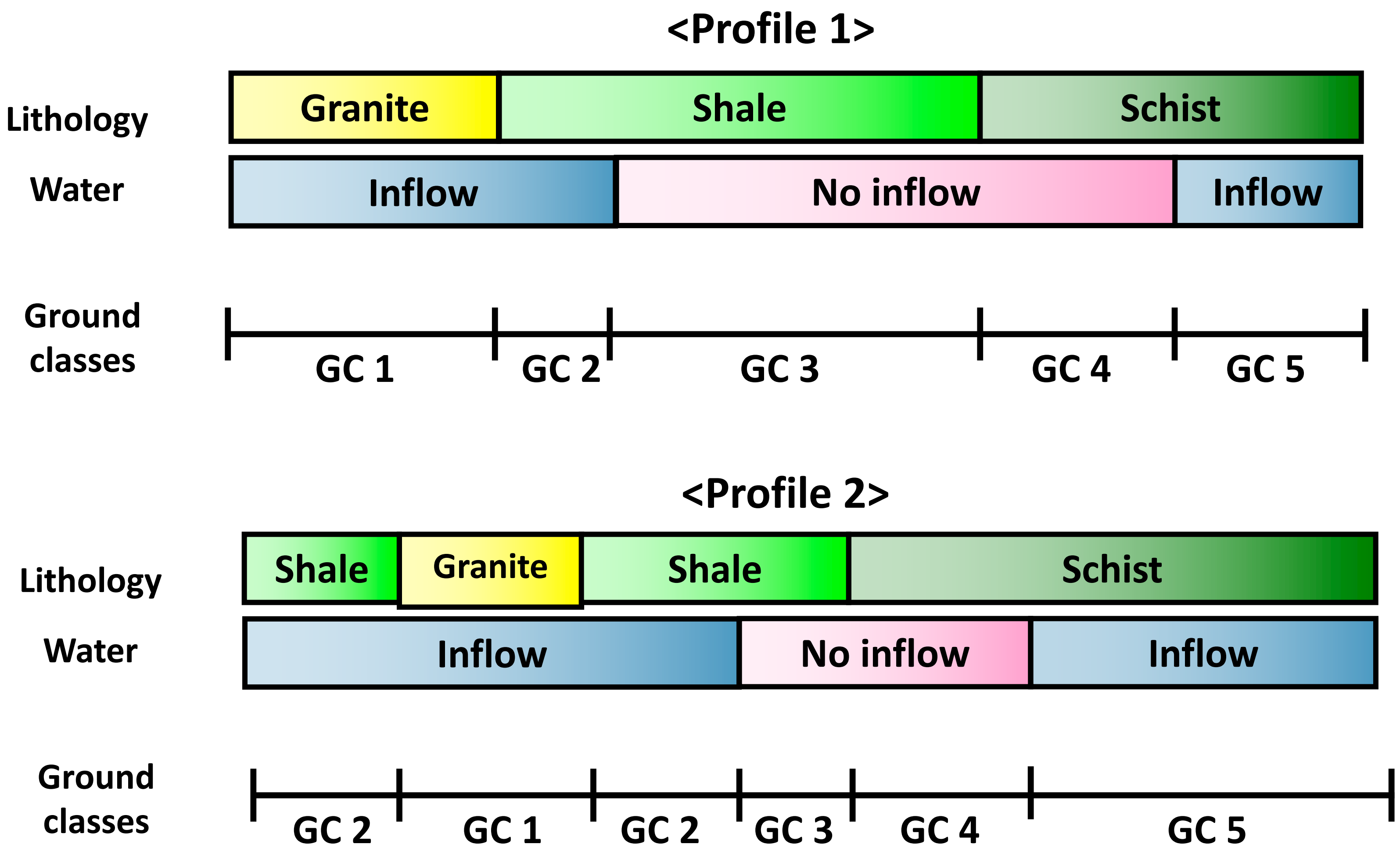
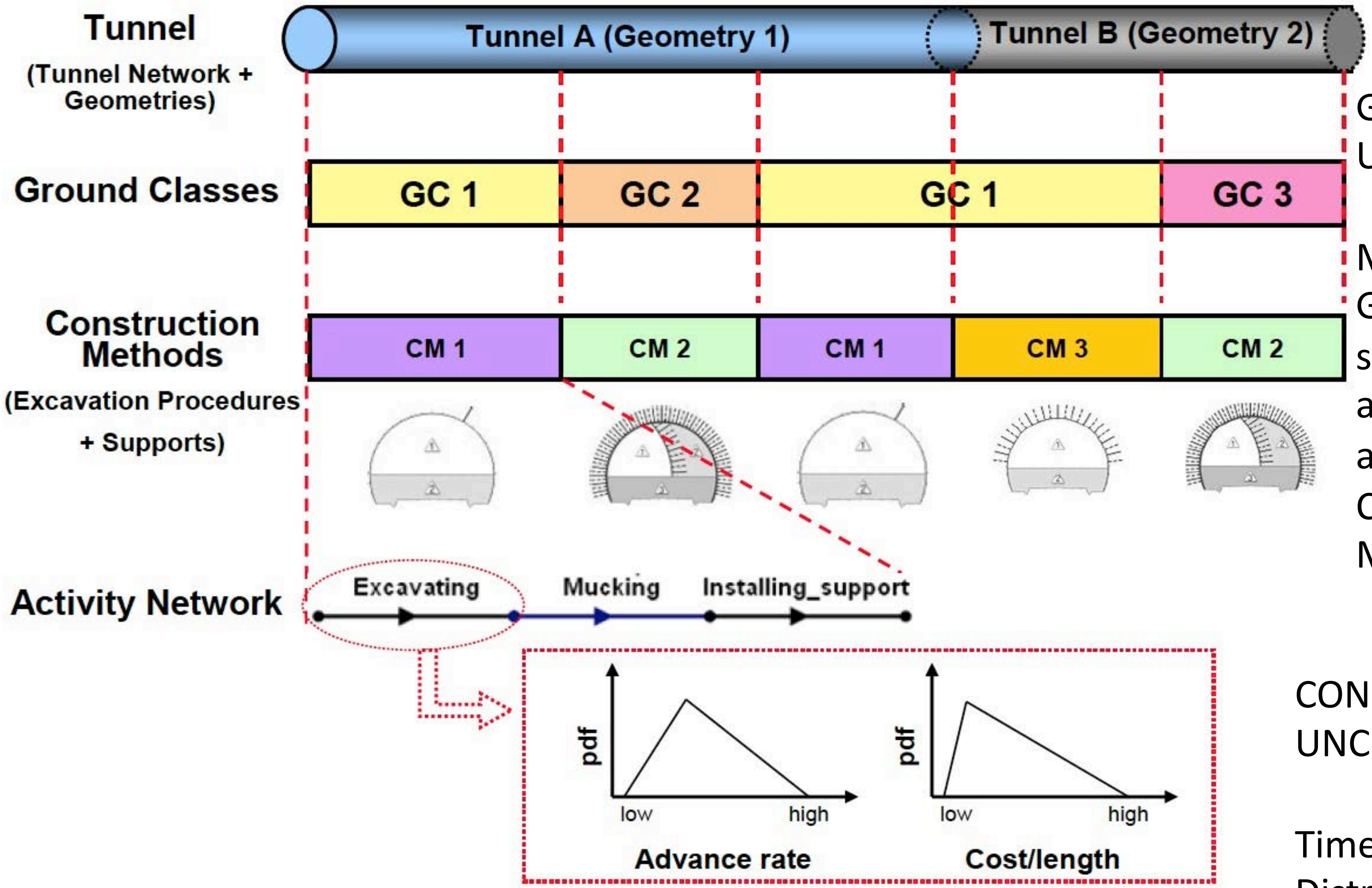


Descripton of Geology with Uncertainties

- **Ground Class Profile**



Decision Aids for Tunneling - Principles



GEOLOGIC UNCERTAINTY

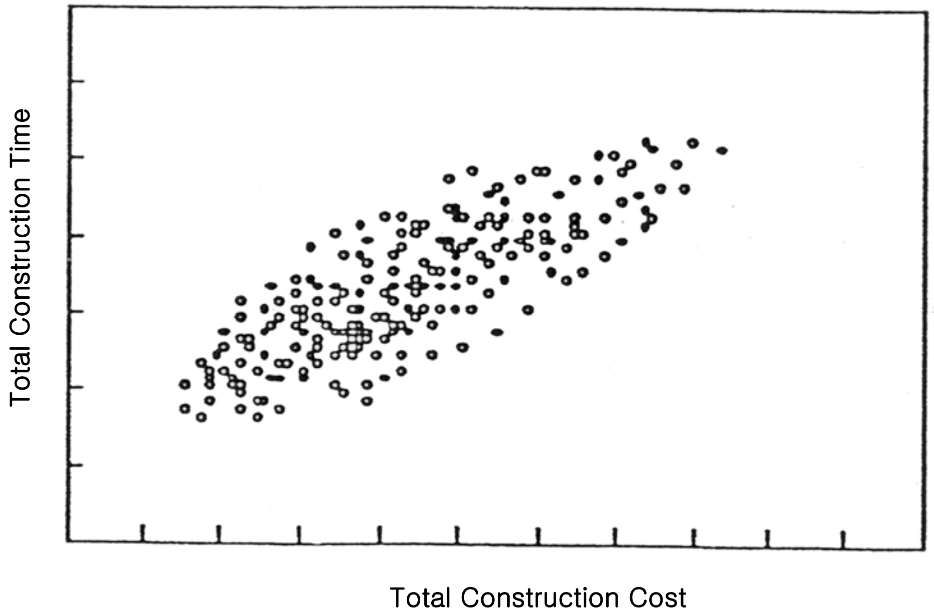
Multiple Groundclasse s and associated Construction Methods

CONSTRUCTION UNCERTAINTY

Time- and Cost-Distributions

RESULT

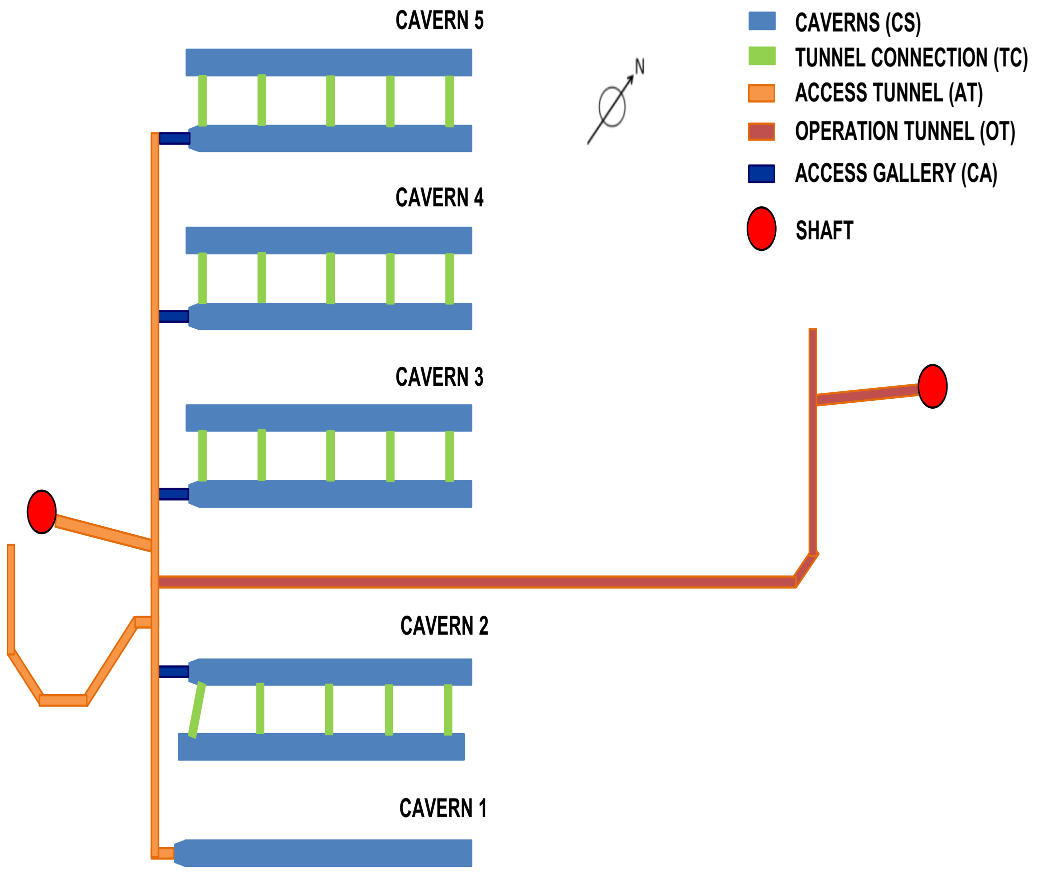
TIME-COST SCATTERGRAM



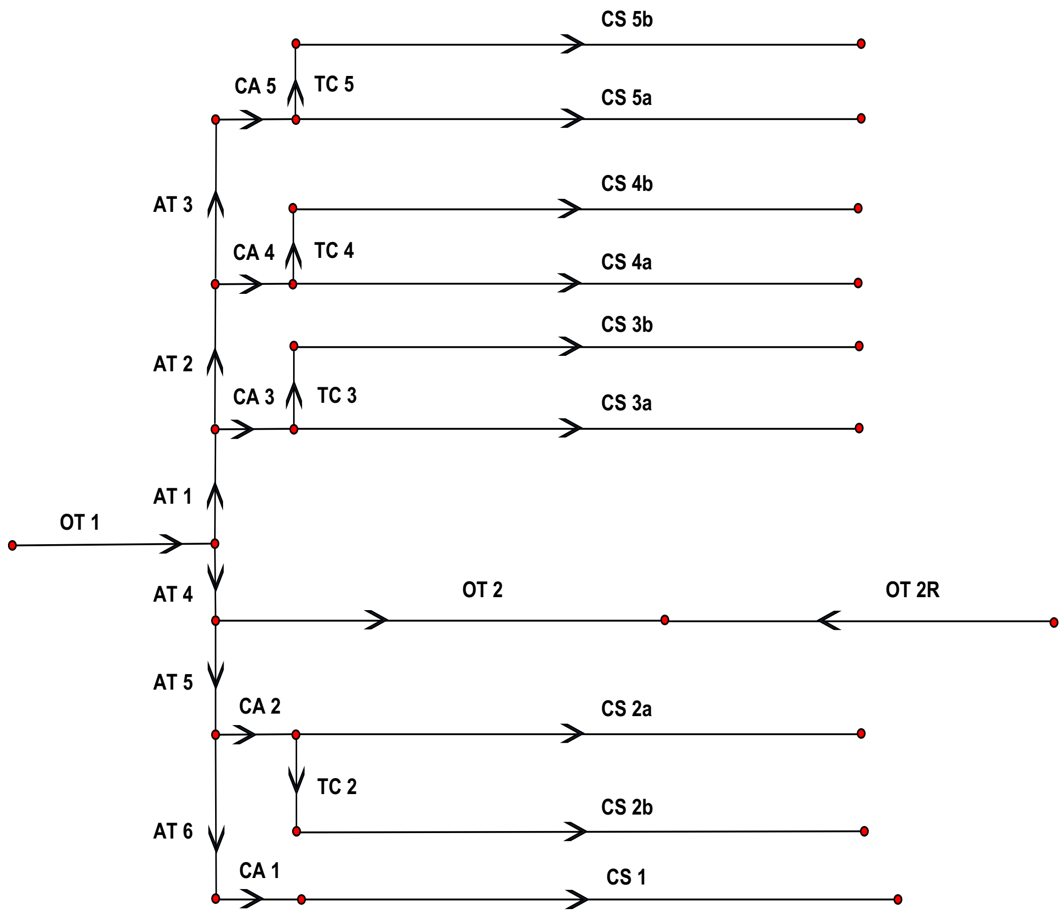
Used to assess risk e.g probability to exceed a limit cost or time

DAT Application: JURONG, Oil Storage Caverns, Singapore

Layout



Tunnel/Cavern Networks" for the DAT



JURONG, Oil Storage Caverns, Singapore

Comparison of Construction Time DAT and Actual   Boxplot

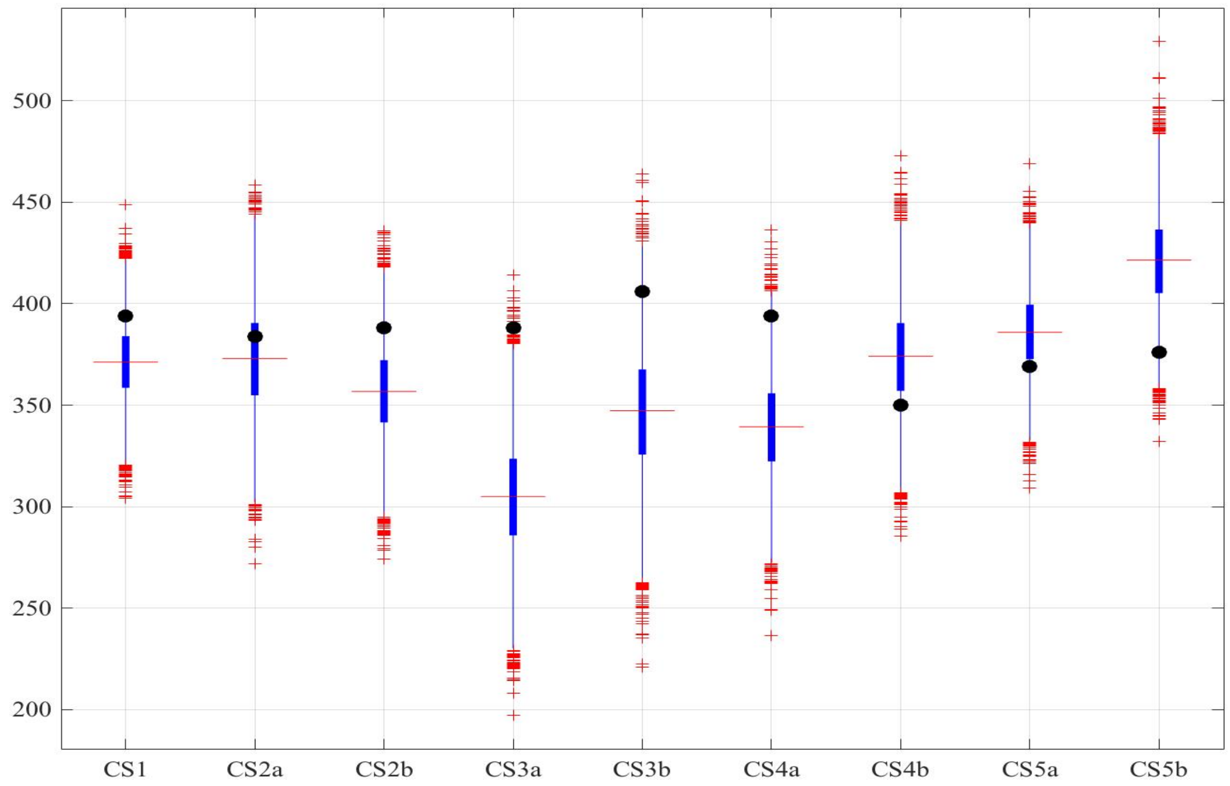
Construction
Time in Days

Black Dots – actual

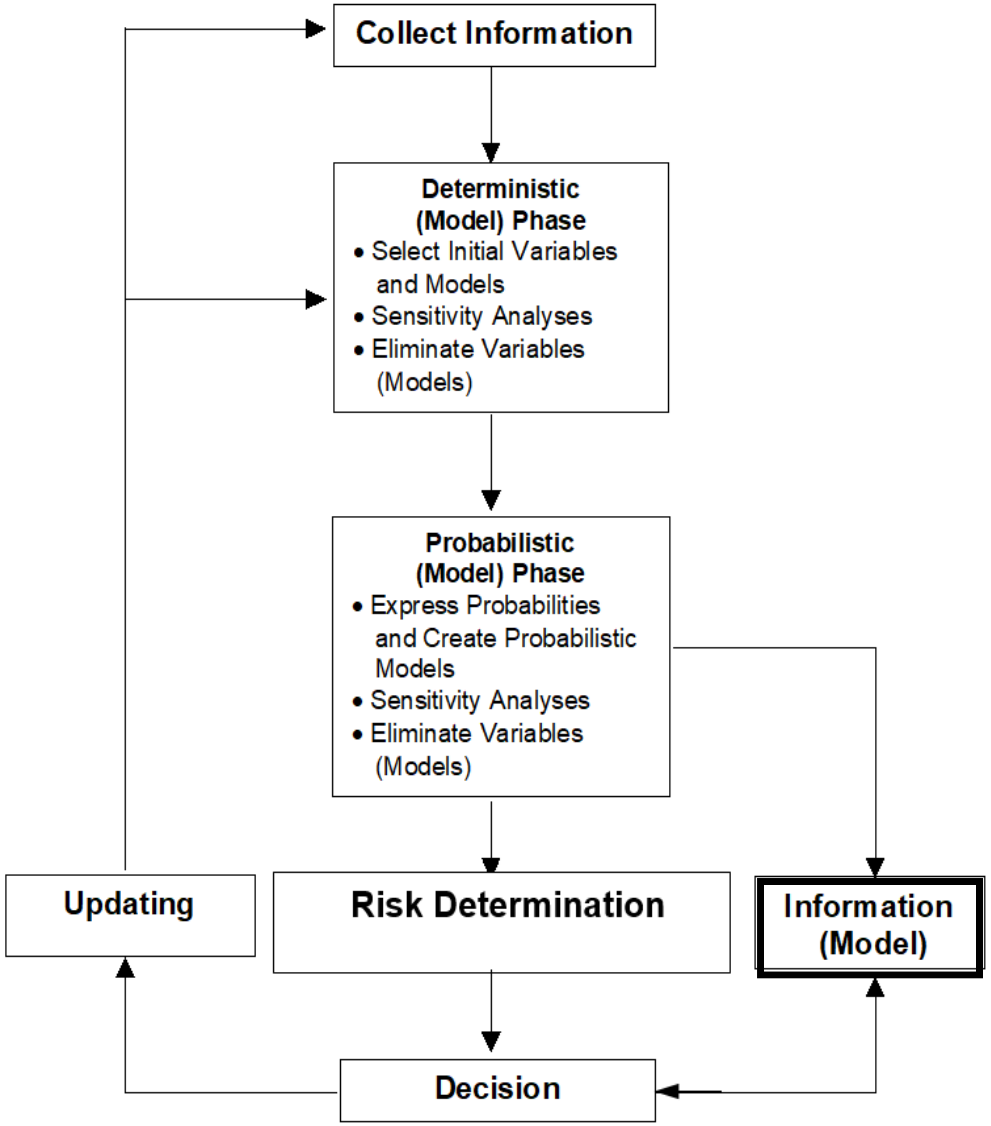
Horiz. Line – Median DAT

Blue Section- +/- 25% DAT

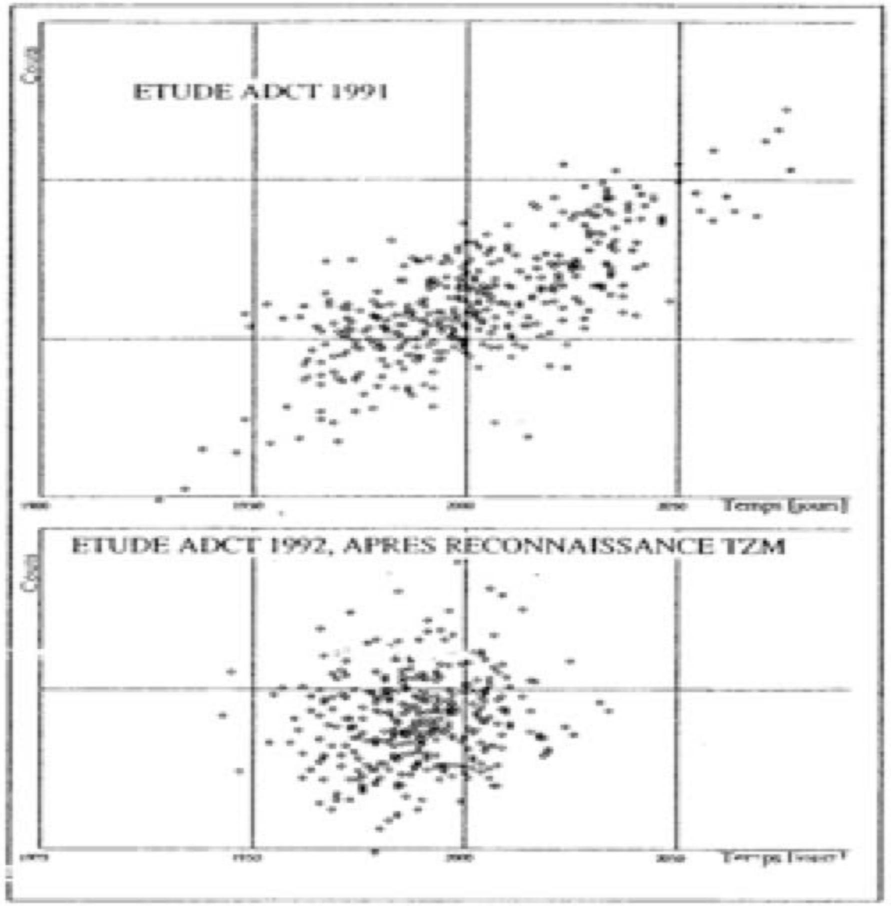
Orange Rectangles 95/5% DAT



Different Caverns


Collect Information
Deterministic
(Model) Phase
• Select Initial Variables and Models
• Sensitivity Analyses
• Eliminate Variables (Models)
Probabilistic
(Model) Phase
• Express Probabilities and Create Probabilistic Models
• Sensitivity Analyses
• Eliminate Variables (Models)
Updating
Risk Determination
Information
(Model)
Decision

Effect of Exploration on Construction Time Cost Scattergram.



Top Scattergram Before Exploration; Bottom Scattergram After Exploration. (From Descoeudres and Dudt, 1994).

Is Exploration worthwhile?
Estimate with Preposterior Analysis using Bayes Theorem

$$P[B_j|A] = \frac{P[A|B_j] \cdot P^{o}[Bj]}{\sum_{j=1}^{n} P[A|B_j]P[B_j]}$$

where

where	Po	=	prior probability
	P'	=	posterior probability
	P[A|B]	=	likelihood function
	Bj	=	state of nature
	A	=	new information

i.e.

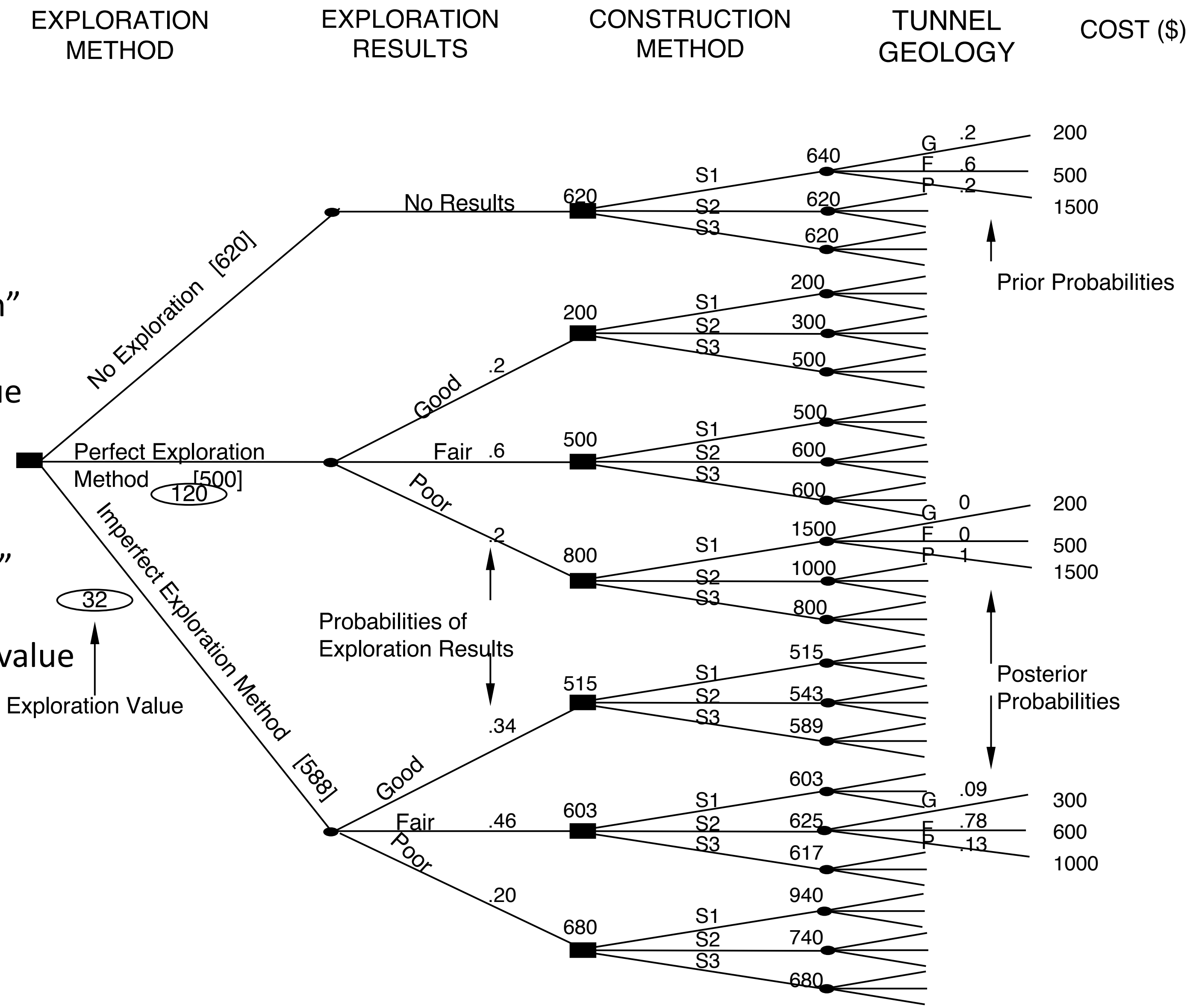
[Posterior Probability of Bj given new information A] = [Likelihood of the new information A, given Bj] × [Prior Probability of Bj] × [Normalizing Factor]

Updated Estimated Probability of Geology = Reliability of Exploration x Initially Estimated Probability of Geology

Difference between “no exploration” and” perfect exploration” = expected value of perfect information –EPI

Difference between “no exploration” and “imperfect exploration” = expected value of information –EVI

If EVI (EPI) > Cost of Exploration
Then DO exploration



“Virtual Exploration” - Exploration Decision Tree

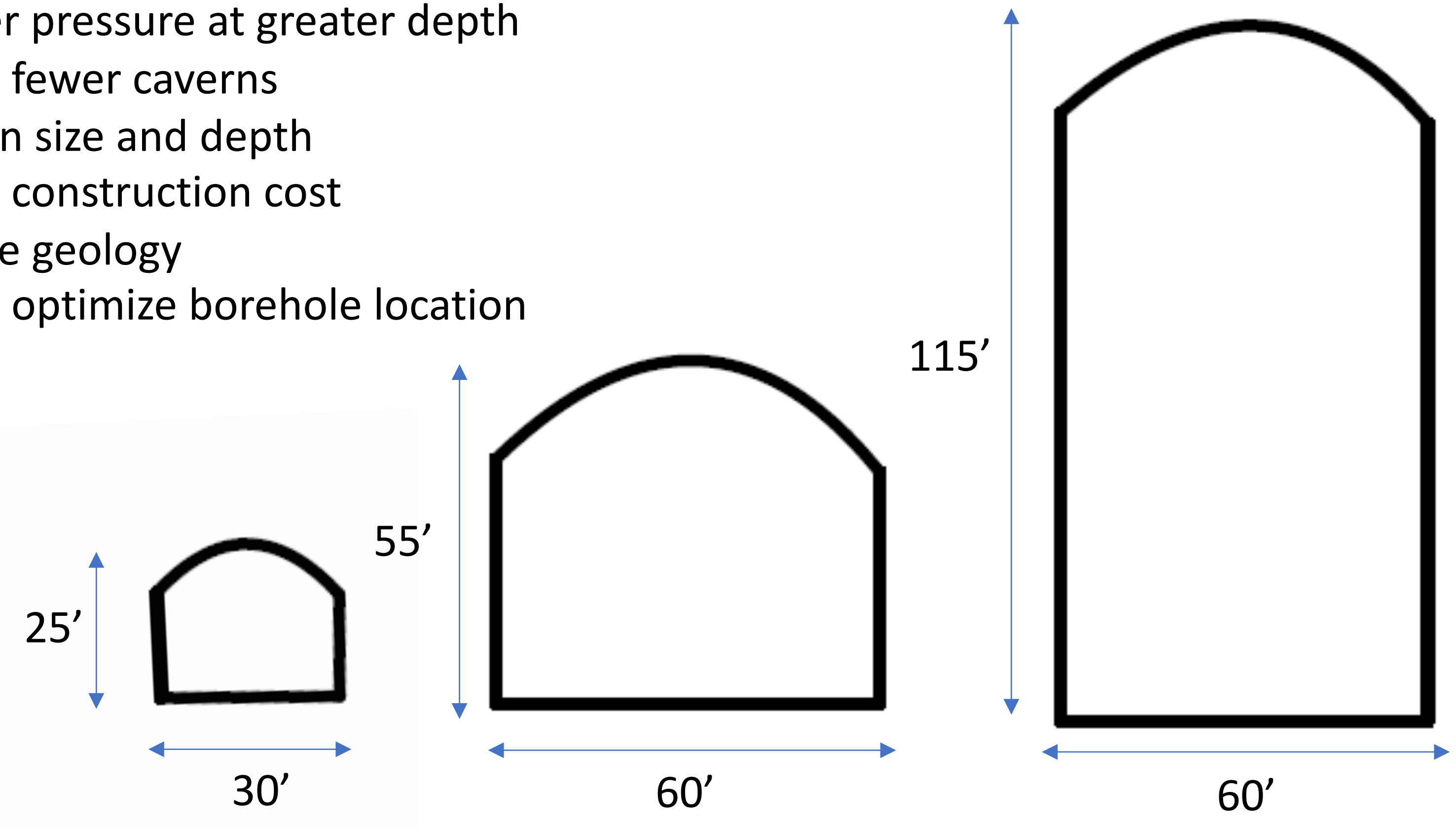
Columbia Gas Storage Caverns-Multiple Caverns to Store 2000 MMCF
Different Combinations of Cavern Sizes and
Depths (2000 or 5000 feet below surface)

PUTTING EVERYTHING TOGETHER

Operation – Higher pressure at greater depth
> fewer caverns

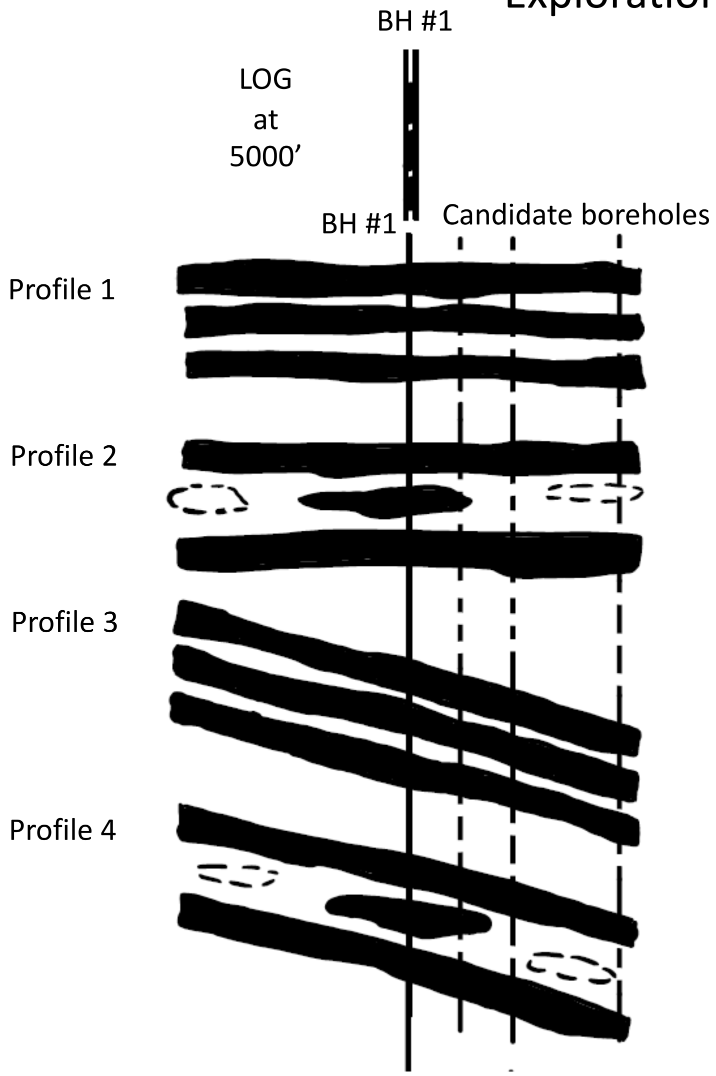
Construction – Cavern size and depth
> construction cost

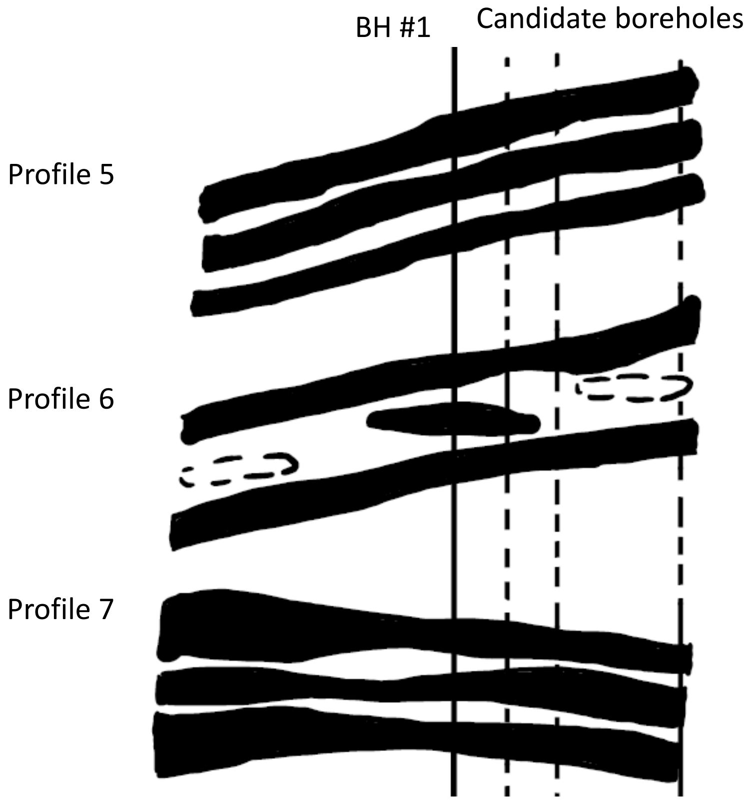
Exploration – Define geology
> optimize borehole location



				Construction Costs for Different Geologies (in Million $)				
Actions	Caverns Size	Capacity	Cavern Volume	Excellent	Good	Fair	Poor	Very Poor
a_1 Build 25’ @ 2000’	42 caverns 2420’ x 2370’	2000 MMCF	66.806 MMCF	**87.4**	131.1	174.8	218.5	**262.2**
a_2 Build 55’ @ 2000’	15 caverns 1530’ x 1500’	2000 MMCF	66.806 MMCF	62.64	93.96	156.6	219.24	281.88
a_3 Build 115’ @ 2000’	11 caverns 1010’ x 1020’	2000 MMCF	66.806 MMCF	**53.66**	107.32	187.81	241.47	**321.96**
a_4 Build 25’ @ 5000’	19 caverns 1030’ x 590’	2000 MMCF	12.464 MMCF	49.11	98.22	147.33	196.44	245.55
a_5 Build 55’ @ 5000’	7 caverns 690’ x 540’	2000 MMCF	12.464 MMCF	39.89	79.78	139.62	219.40	279.23
a_6 Build 115’ @ 5000’	5 caverns 535’ x 300’	2000 MMCF	12.464 MMCF	36.53	91.33	64.39	237.45	238.77

Exploration Borehole 1 shows alternating layers of shale (black) and sandstone (white)
Can be interpreted as seven different profiles



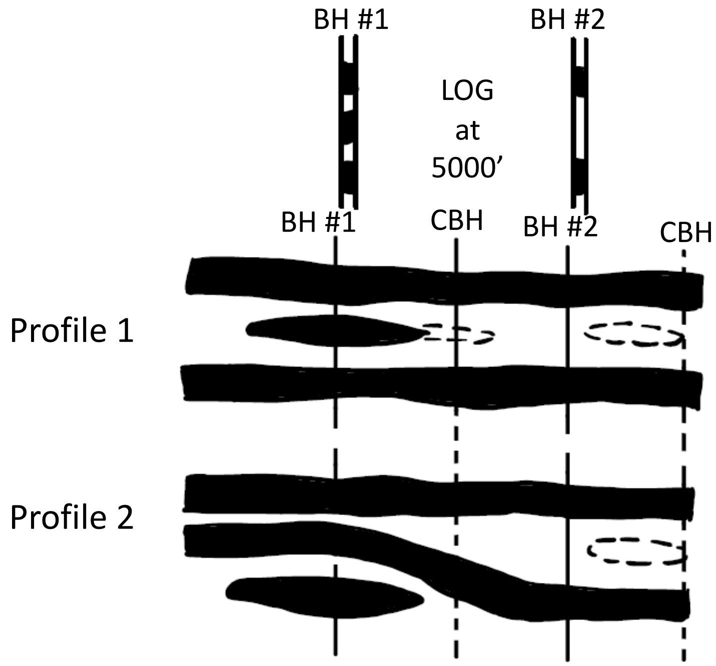


Use Preposterior Analyis to assess best location of second borehole

200 ft right	EVI = 0
500 ft right	EVI = $ 0.7 million
1000 ft right	EVI = $ 3.1 million

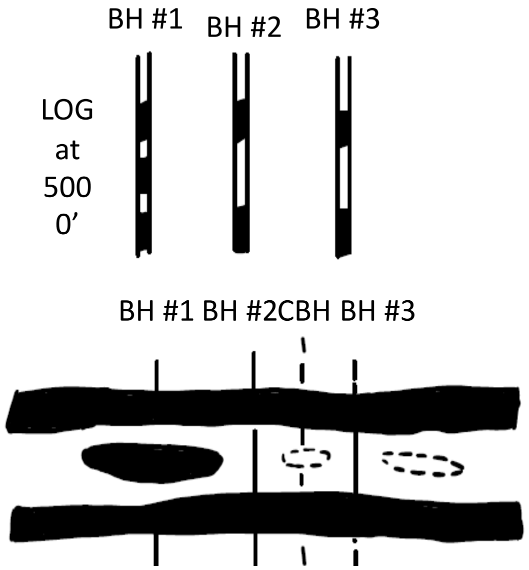
Preposterior Analysis for

Third Boring



500 ft right of boring 2 EVI = 0
500 ft left of boring 2 EVI = $ 1.4 million

Fourth Boring



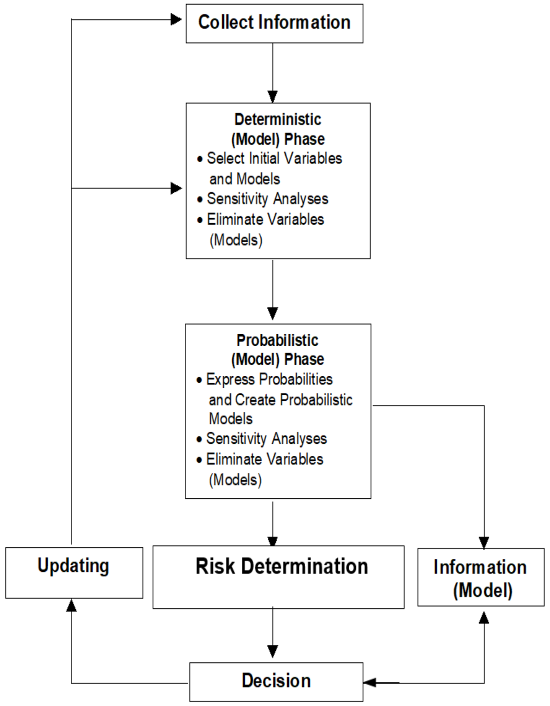
Between boring 2 and 3 EVI =0

Then:

Do Borings

Use Information to reduce Uncertainty

Repeat:



To conclude

- Caverns in rock are and will be important for energy storage

- Operation and construction are complex
- Models have to reflect this complexity

- Operation and construction take place in uncertain conditions
- Models have to reflect uncertainty

- Decision making under uncertainty can be used to
  - Assess risk
  - Assess approaches to reduce uncertainty