COST RISK ASSESSMENT OF 13 KM LONG HEADRACE TUNNEL IN THE HIMALAYAS

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OUTLINE

- The Project
- The Problem
- The Solution
- The Result
- The Conclusions

THE PROJECT

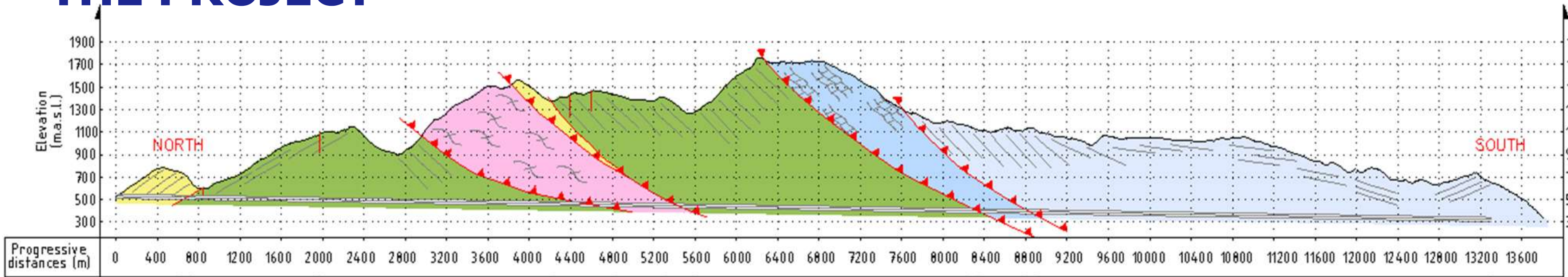
Hydropower Project located in the Himalayas

- Reservoir volume: 1,581 Mm^3; Dam: CFRD, 220 m high; Energy: 3,400 GWh/year
- Number of powerhouses: 2; Main powerhouse: 600 MW, located at 14 km from the reservoir; second powerhouse: 35 MW, located at the dam toe

Headrace tunnel to main PH

- 13.3 km length; alignment N-NE to S-SW
- Lithotypes are quartzites, phyllites, gneiss, mica-schists, marble-calcareous rocks
- Contact between lithotypes not well identified
- Maximum rock cover of 1,360 m
- Medium-weak strength of some rocks (i.e. phyllites)
- Squeezing problems anticipated considering the ratios between rock mass strength and in situ stresses

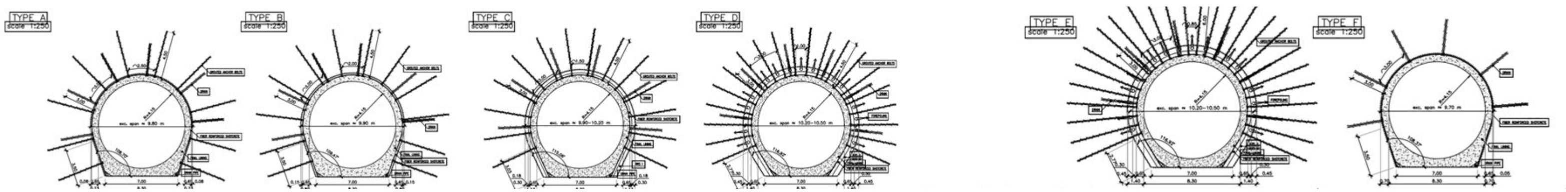
THE PROJECT



Extension (m)	611	132	1200	60	2204	593	491	309	2680	100	407	100	4414
Max Overb. (m)	260	227	570	602	1097	1012	981	963	1332	740	747	748	736
Geology (-)	Qz	Qz/Ph	Ph	Fault	Ph	Thrust	Gn	Thrust	Ph	Thrust	Mb-D	Thrust	Msh - Gn
UCS (MPa)	200	80	60	60	60	100	175	100	60	65	75	65	150
GSI (-)	55	35	50	20	50	25	45	25	50	25	45	25	50
mi (-)	20	15	7	7	7	15	25	15	7	15	9	15	25
D (m)	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2

Temporary Support System: rock Bolts (**B**), fiber reinforced Shotcrete (**Sfr**) and Reinforced Ribs of Shotcrete (**RRS**)

Permanent Support System: reinforced Concrete Lining



	Section Type					
	A	B	C	D	E	F
	USD/m	USD/m	USD/m	USD/m	USD/m	USD/m
Unit cost	11,200	13,100	22,100	28,000	29,000	9,000

THE PROBLEM

How to estimate a reasonable amount of contingency cost of the tunnel to be included in the project budget, due to uncertainties present in:

- Extent of geological formations
- Geo-mechanical conditions (rock mass strength / in situ stresses)
- Potential strike of events during construction:
  - → Rockfall and collapse
  - → Squeezing
  - → Flooding by underground water

THE SOLUTION

Cost Model & Monte Carlo Simulations

Including variables treated as random (with uniform distributions):

- Position of limits between the 14 geological stretches
- % length of each geological stretch (14) affected by each kind of event (3)
- % cost increase per unit length associated with each event

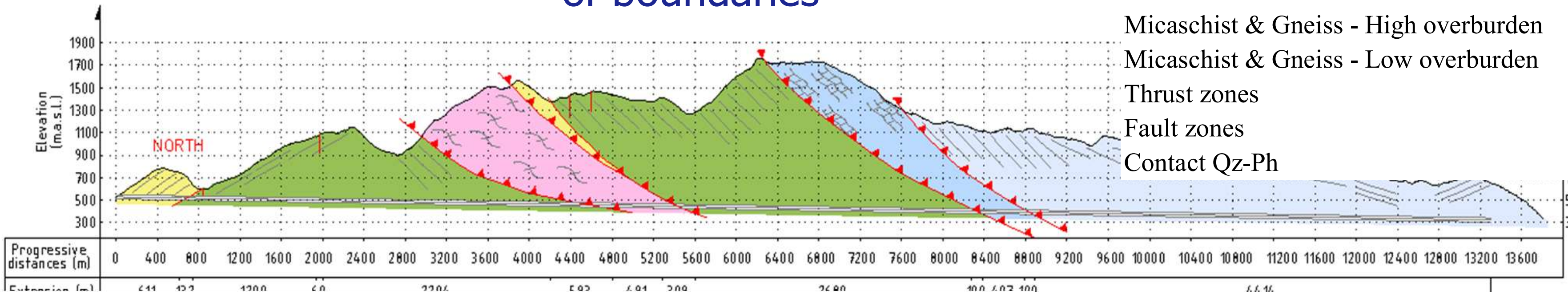
Including variables treated as deterministic:

- Position of initial and end points of the tunnel (i.e. tunnel length is fixed)
- % use of each cross section, A to F (6), on each geological stretch (14)
- Cost per unit length of different cross sections, A to F

THE SOLUTION

Uncertainty in the position of boundaries

Quartzite
Phyllite
Gneiss
Marble & Dolomite
Micaschist & Gneiss - High overburden
Micaschist & Gneiss - Low overburden
Thrust zones
Fault zones
Contact Qz-Ph



Headrace tunnel - Geological zones	Base case length m	Base case Progressive m	Uncertainty Range m
Initial point		0	0
Quartzites - Contact	611	611	130
Contact - Phyllite	132	743	130
Phyllite - Fault	1200	1943	60
Fault - Phyllite	60	2003	60
Phyllite - Thrust	2204	4207	500
Thrust - Gneiss	593	4800	480
Gneiss - Thrust	491	5291	300
Thrust - Phyllite	309	5600	300
Phyllite - Thrust	2680	8280	100
Thrust - Marbles and Dolomites	100	8380	100
Marbles and Dolomites -Thrust	407	8787	100
Thrust - Micaschists and Gneiss 1	100	8887	100
Micaschists and Gneiss 1 - Micaschists and Gneiss 2	2463	11350	1000
Micaschists and Gneiss 2 - Final point	1950	13300	0

130 → Uniform [-65; +65]

i-th simulation
Random = -23
Base Case Progressive = 611 m
Simulated Progressive = 588 m

THE SOLUTION

Uncertainty in geo-mechanical conditions

GRC and LDP have been adopted to analyze the dependency of rock-support pressure p_i to the tunnel radial convergence u_i (RocSupport v4) and the distance from excavation face. The main assumptions of this method are:

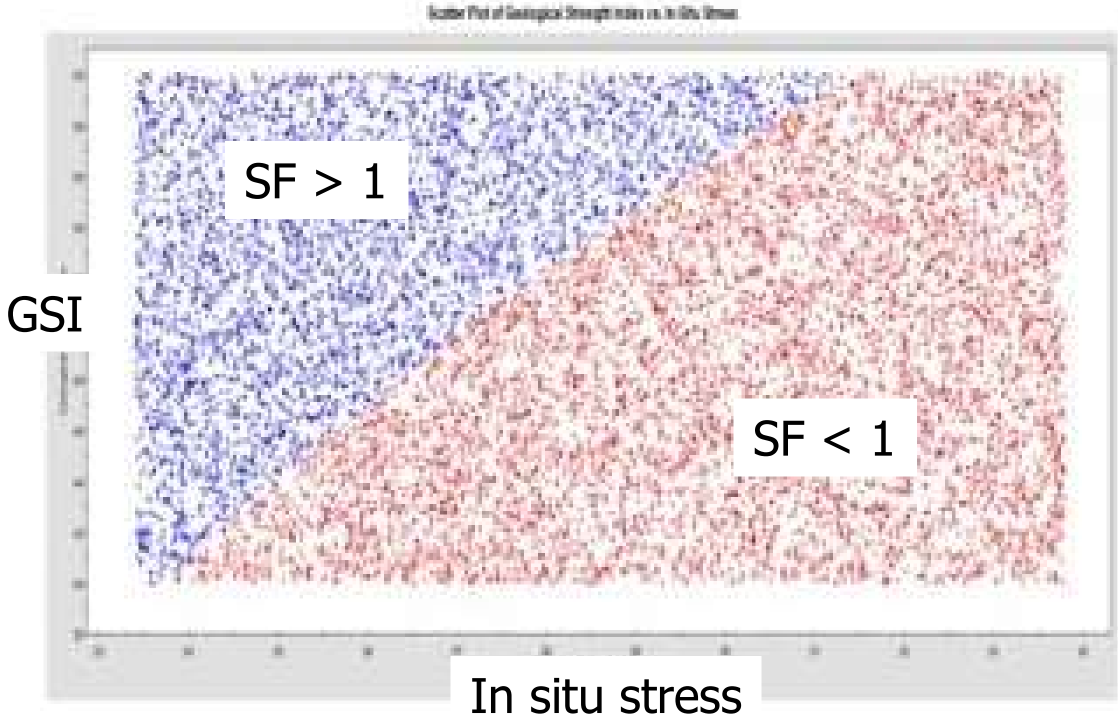
- a radial symmetry of the problem (i.e. circular tunnel, isotropic state of stress);
- an Hoek-Brown criterion with a peak and a post-peak behavior (Carranza-Torres, 2004);
- a rock modulus estimation based on Hoek, Carranza-Torres, Corkum (2002);
- a LDP based on Diederichs (2009).

Safety Factor, SF:

$$SF = \frac{Support\ Strength}{Support\ Stress}$$

THE SOLUTION

For each calculation (i.e. each geological stretch & each support section A-F) with the **GRC and LDP model,** to try to cover uncertainties on the rock quality and in-situ stress (the topographic profile, folding, faults), a Monte Carlo analysis with 1000 samples has been carried out considering uniform distributions for GSI and p0. The results have been expressed in terms of the variation of the Safety Factor (SF) against GSI and p0.

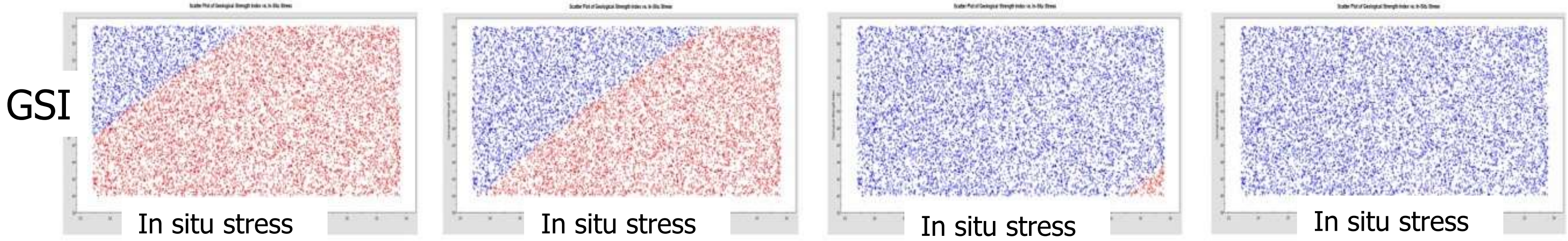


Safety Factor, SF:

$$SF = \frac{Support\ Strength}{Support\ Stress}$$

THE SOLUTION

Uncertainty in geo-mechanical characteristics



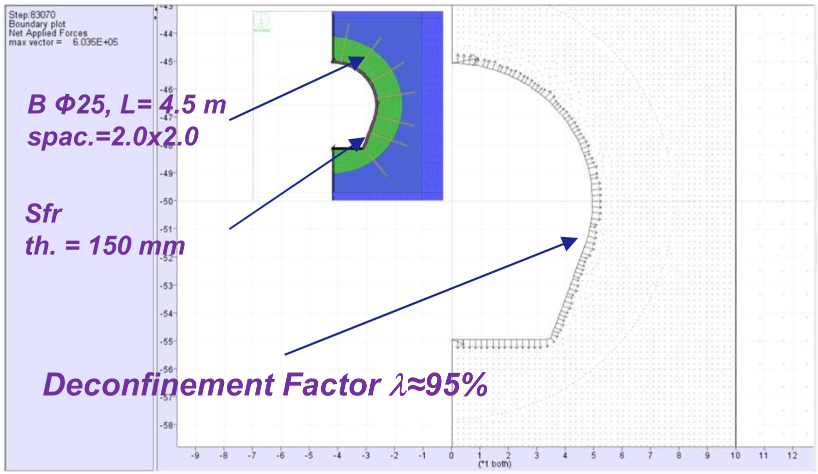
	Section B	Section C	Section D	Section E
Probability of Failure: $\frac{A_{red}}{A_{red}+A_{blue}} =$	$\approx 83\%$	$\approx 61\%$	$\approx 1\%$	$= 0$
Percentage of application:	$100\% - 83\% = 17\%$	$100\% - 61\% - 17\% = 22\%$	$100\% - 1\% - 17\% - 22\% = 60\%$	$100\% - 17\% - 22\% - 60\% = 1\%$

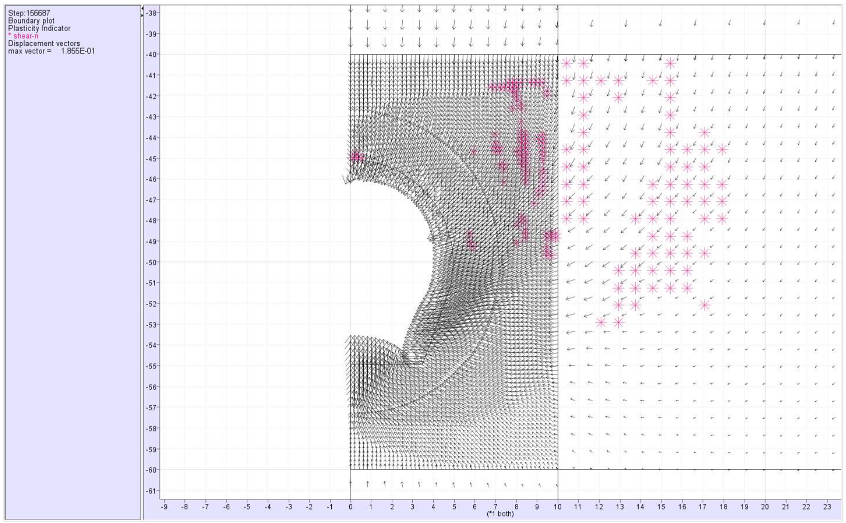
Start chainage (km)	End chainage (km)	Length (m)	A (%)	B (%)	C (%)	D (%)	E (%)	F (%)
0+000	0+611	611	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0+611	0+743	132	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0+743	1+943	1200	69.7%	26.2%	4.1%	0.0%	0.0%	0.0%
1+943	2+003	60	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
2+003	4+207	2204	5.7%	32.4%	39.7%	22.2%	0.0%	0.0%
4+207	4+800	593	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%
4+800	5+291	491	61.0%	38.6%	0.4%	0.0%	0.0%	0.0%
5+291	5+600	309	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%
5+600	8+280	2680	0.0%	0.0%	18.9%	66.5%	14.6%	0.0%
8+280	8+380	100	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%
8+380	8+787	407	0.0%	61.5%	38.5%	0.0%	0.0%	0.0%
8+787	8+887	100	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%
8+887	11+350	2463	93.0%	7.0%	0.0%	0.0%	0.0%	0.0%
11+350	13+300	1950	93.0%	7.0%	0.0%	0.0%	0.0%	0.0%

THE SOLUTION

Checking the results obtained with GRC – LDP simplified model with advanced numerical analysis (Finite Difference Method, FLAC v8)

Models are plane strain; deconfinement factor (λ) for each section obtained by the GRC-LDP analysis; rock mass characterized by a Hoek-Brown criterion with peak and post-peak; concrete lining characterized by the CEB-FIP Model Code 2010





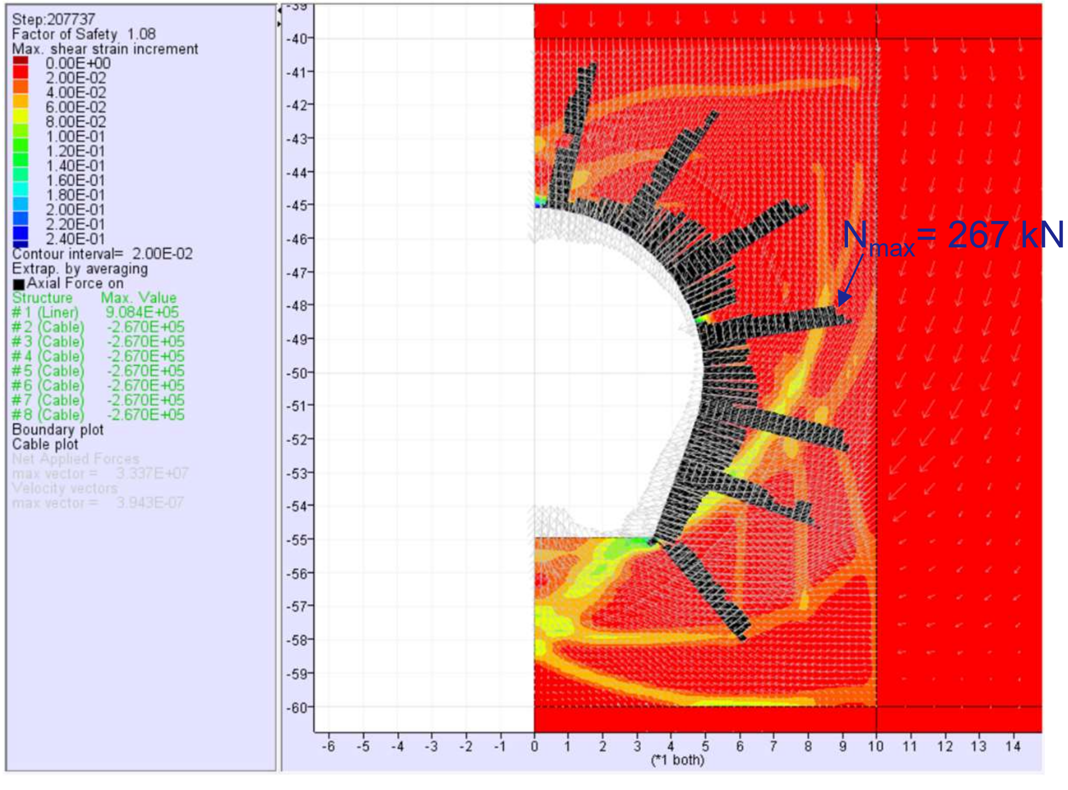
THE SOLUTION

Advanced Numerical Analyses with **FDM** (Finite Difference Method, FLAC v8)

The FD analyses allow to estimate the SF of temporary support system, the stresses in the permanent lining and the leakage out of the tunnel.

Safety Factor, SF:

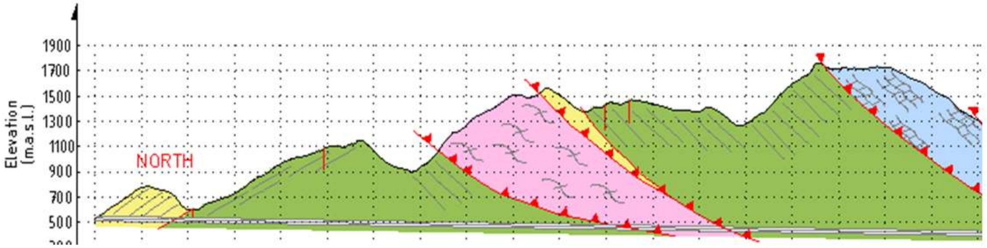
$$SF = \frac{Support\ Strength}{Support\ Stress}$$



*Section **B** – **Phyllite** –*
Safety Factor (SF=1.08)

THE SOLUTION

Uncertainty related to events and the associated cost



Event	Ratio of cost increase respect the base case cost	
	Min	Max
Collapse / Rockfall	0.00	1.00
Excessive deformation (Squeezing)	0.00	0.50
Flood	0.00	0.20

13600

Headrace tunnel Geological zones	Rockfall / Collapse		Excessive deformation (Squeezing)		Flood	
	Min	Max	Min	Max	Min	Max
Quartzites	0.00	0.10	0.00	0.05	0.00	0.20
Contact	0.00	0.20	0.00	0.10	0.00	0.20
Phyllite	0.00	0.15	0.00	0.20	0.00	0.10
Fault	0.00	0.20	0.00	0.20	0.00	0.20
Phyllite	0.00	0.15	0.00	0.20	0.00	0.10
Thrust	0.00	0.20	0.00	0.20	0.00	0.20
Gneiss	0.00	0.05	0.00	0.05	0.00	0.10
Thrust	0.00	0.20	0.00	0.20	0.00	0.20
Phyllite	0.00	0.15	0.00	0.20	0.00	0.10
Thrust	0.00	0.20	0.00	0.20	0.00	0.20
Marbles and Dolomites	0.00	0.05	0.00	0.05	0.00	0.20
Thrust	0.00	0.20	0.00	0.20	0.00	0.20
Micaschists and Gneiss 1	0.00	0.10	0.00	0.05	0.00	0.10
Micaschists and Gneiss 2	0.00	0.10	0.00	0.05	0.00	0.10

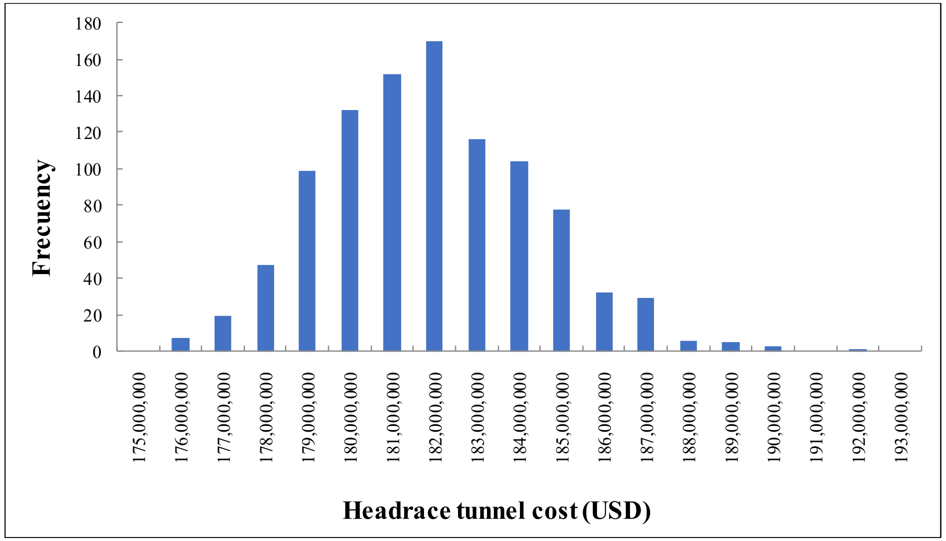
THE SOLUTION

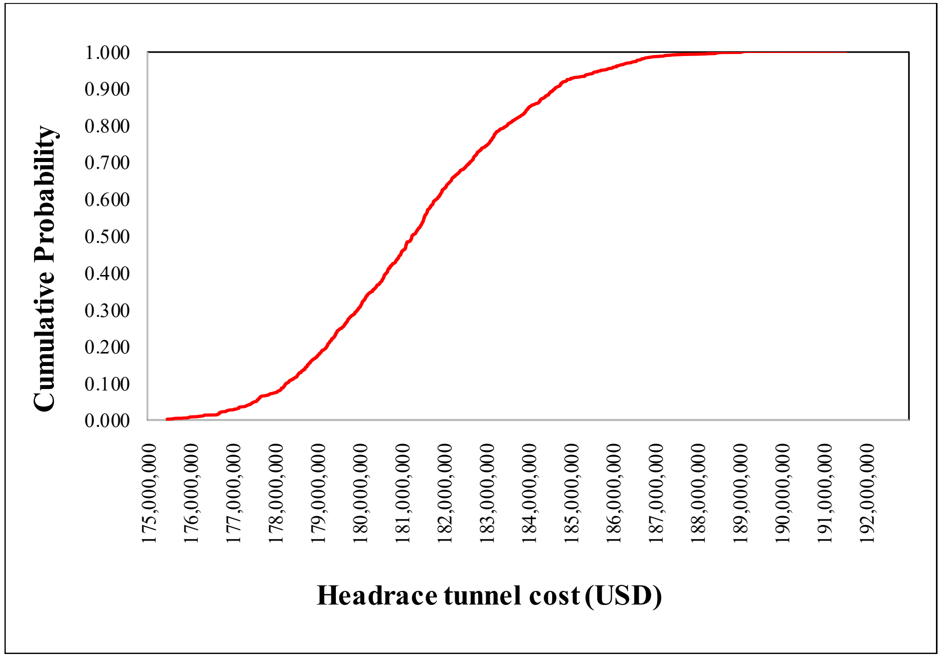
Monte Carlo simulations

- Number of simulations is selected
- Random length of each tunnel stretch is generated for each simulation
- Random length of tunnel affected by rockfall, squeezing and flood is generated for each simulation
- Overall cost estimate is calculated for each simulation
- Histogram of tunnel cost is obtained
- Probabilities associated with exceedance levels of cost are estimated

THE RESULT

Summary of Cost Risk Analysis		
Min Cost	USD	175,439,645
Max Cost	USD	191,521,796
Mean Cost	USD	181,395,162
50% Exceedance Probability Cost	USD	181,259,374
25% Exceedance Probability Cost	USD	183,068,364
10% Exceedance Probability Cost	USD	184,644,549
5% Exceedance Probability Cost	USD	185,862,176
1% Exceedance Probability Cost	USD	187,562,531



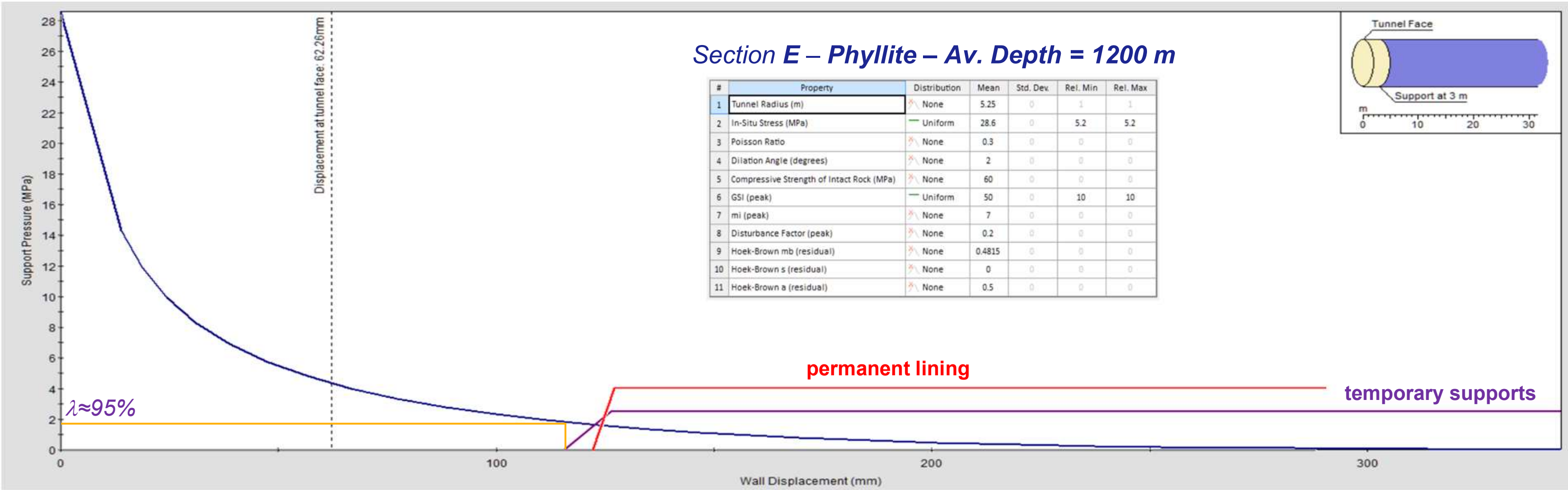


THE CONCLUSIONS

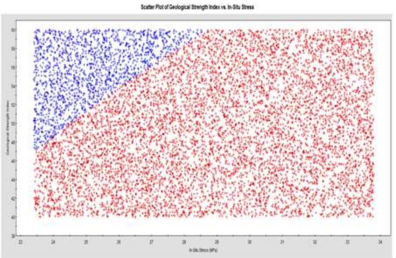
- Advantages of combining complex numerical models with simple approaches in probabilistic context
- Fast evaluation of safety factors with simplified models + checking results with numerical models (more time consuming, not suited for large number of simulations)
- Integration of results in a probabilistic model for cost estimate with Monte Carlo simulations
- Helpful to keep track of assumptions and hypothesis on ‘unknowns’
- Explicit the sources of uncertainty (what is included… and what is not included)
- Informative for decision making regarding the economic and financial feasibility of large projects with limited information

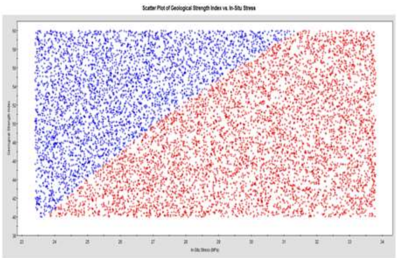
THANK YOU FOR YOUR ATTENTION

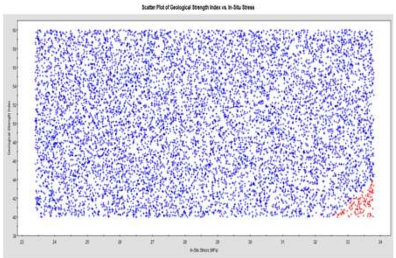
Uncertainties- Geomechanical properties

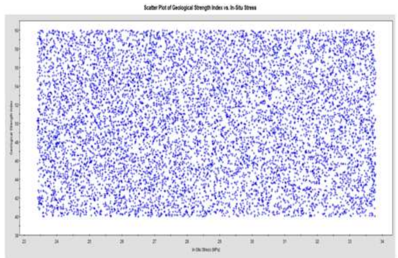


#	Property	Distribution	Mean	Std. Dev.	Rel. Min	Rel. Max
1	Tunnel Radius (m)	None	5.25	0	1	1
2	In-Situ Stress (MPa)	Uniform	28.6	0	5.2	5.2
3	Poisson Ratio	None	0.3	0	0	0
4	Dilation Angle (degrees)	None	2	0	0	0
5	Compressive Strength of Intact Rock (MPa)	None	60	0	0	0
6	GSI (peak)	Uniform	50	0	10	10
7	mi (peak)	None	7	0	0	0
8	Disturbance Factor (peak)	None	0.2	0	0	0
9	Hoek-Brown mb (residual)	None	0.4815	0	0	0
10	Hoek-Brown s (residual)	None	0	0	0	0
11	Hoek-Brown a (residual)	None	0.5	0	0	0









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Sunkoshi HRT – ***Monte Carlo Analysis***