

# **Determination of specific rockmass failure envelope via PFC and its subsequent application using FLAC**

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# Presentation Outline

- Reason for the paper
- Model development
- PFC simulation and results
- FLAC simulation and results
- Conclusion

# Reason for the paper

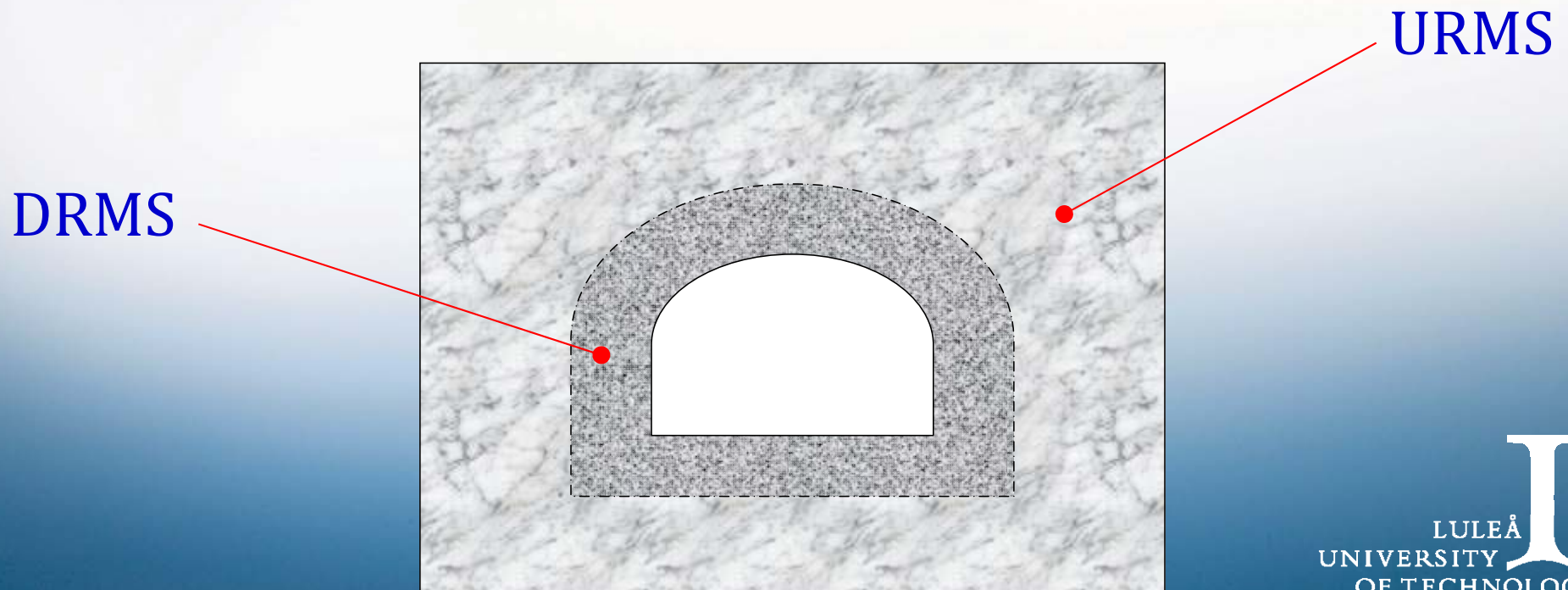
- Inputs obtained using HB-GSI criteria did not capture well the failure behaviour observed in brittle hard rock mass (Saiang & Nordlund, 2007)
- Hence, question..”Could we use PFC to obtain input values for the rock mass?”

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# Model development

- Two Itasca codes were used, PFC and FLAC
- The rockmass around the tunnel is divided into 2 notable regions: (i) Damaged - DRMS and (ii) Undamaged - URMS

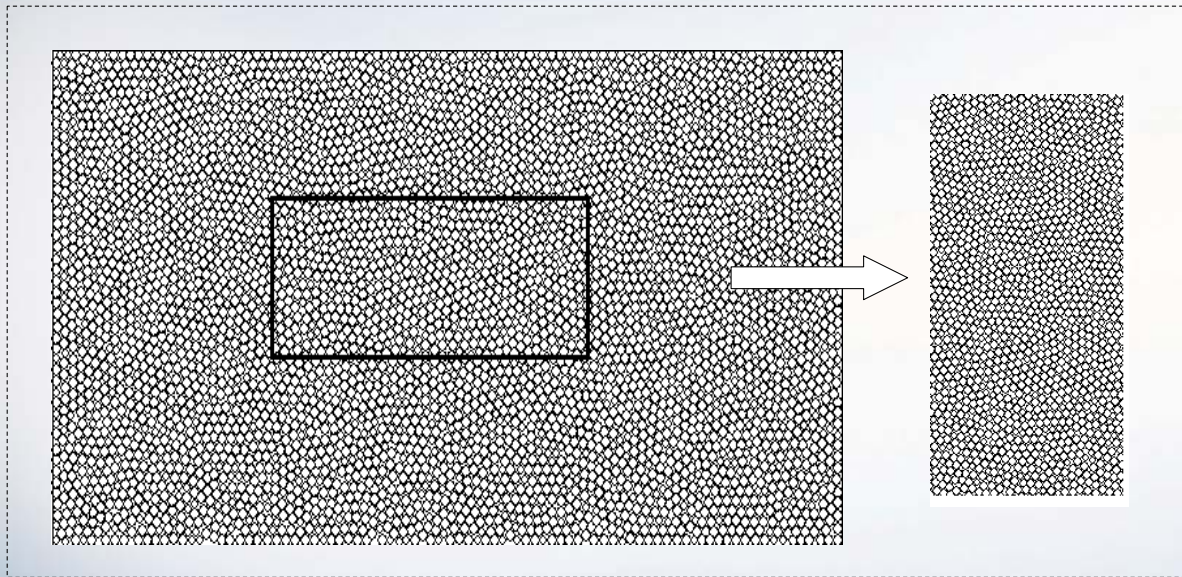


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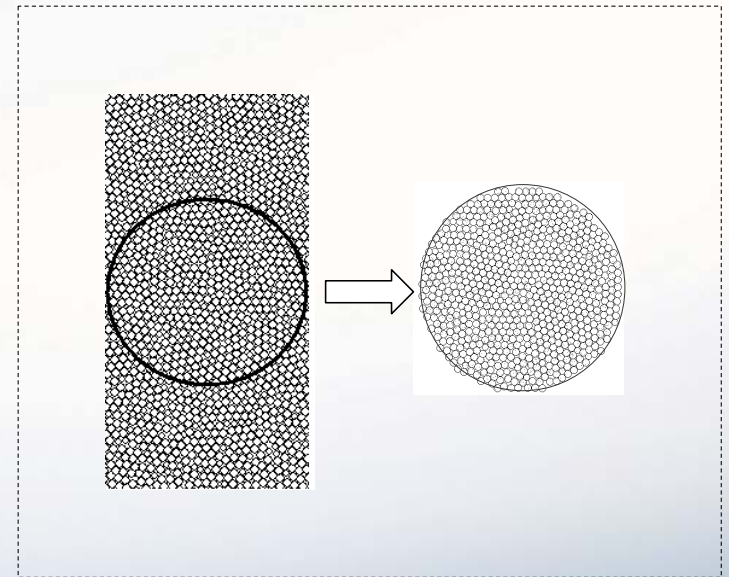
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# PFC simulation and Results

## PFC sampling procedure



Extraction of compression test specimen

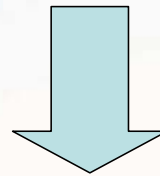


Extraction of tensile test specimen

# Rockmass parameters

## In-situ rock mass parameters

Parameters	Value
Intact compressive strength, $\sigma_{ci}$	180 MPa
Geological strength index, $GSI$	60
Hoek-Brown constant, $m_i$	33



*Roclab*

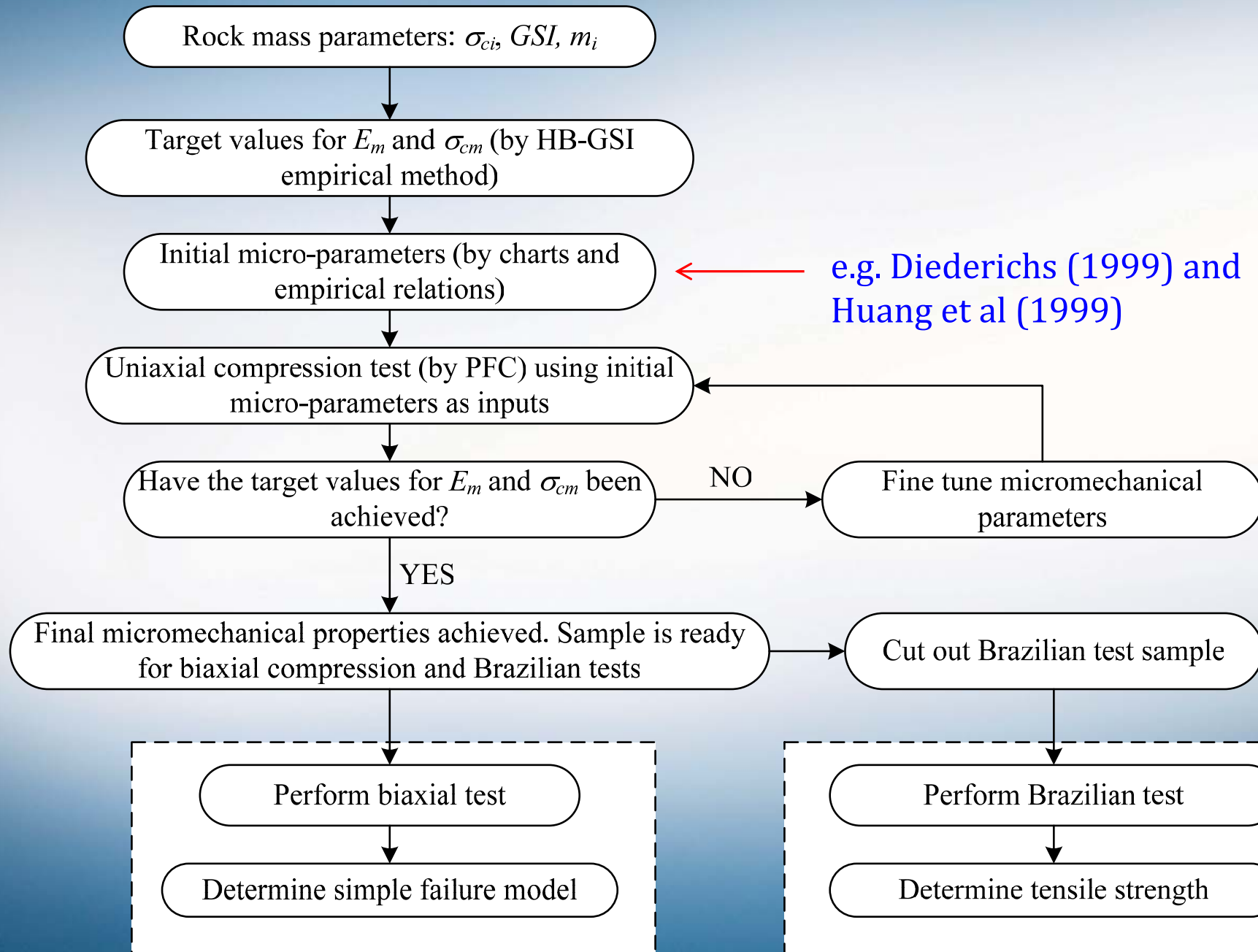
## Calculated target parameters (for PFC)

$D = 0$

$D = 0.75$

Parameters	Value	
	URMS	DRMS
Rockmass modulus, $E_m$	18 GPa	12 GPa
Rockmass compressive strength, $\sigma_{cm}$	19 MPa	10 MPa

# PFC model calibration procedure

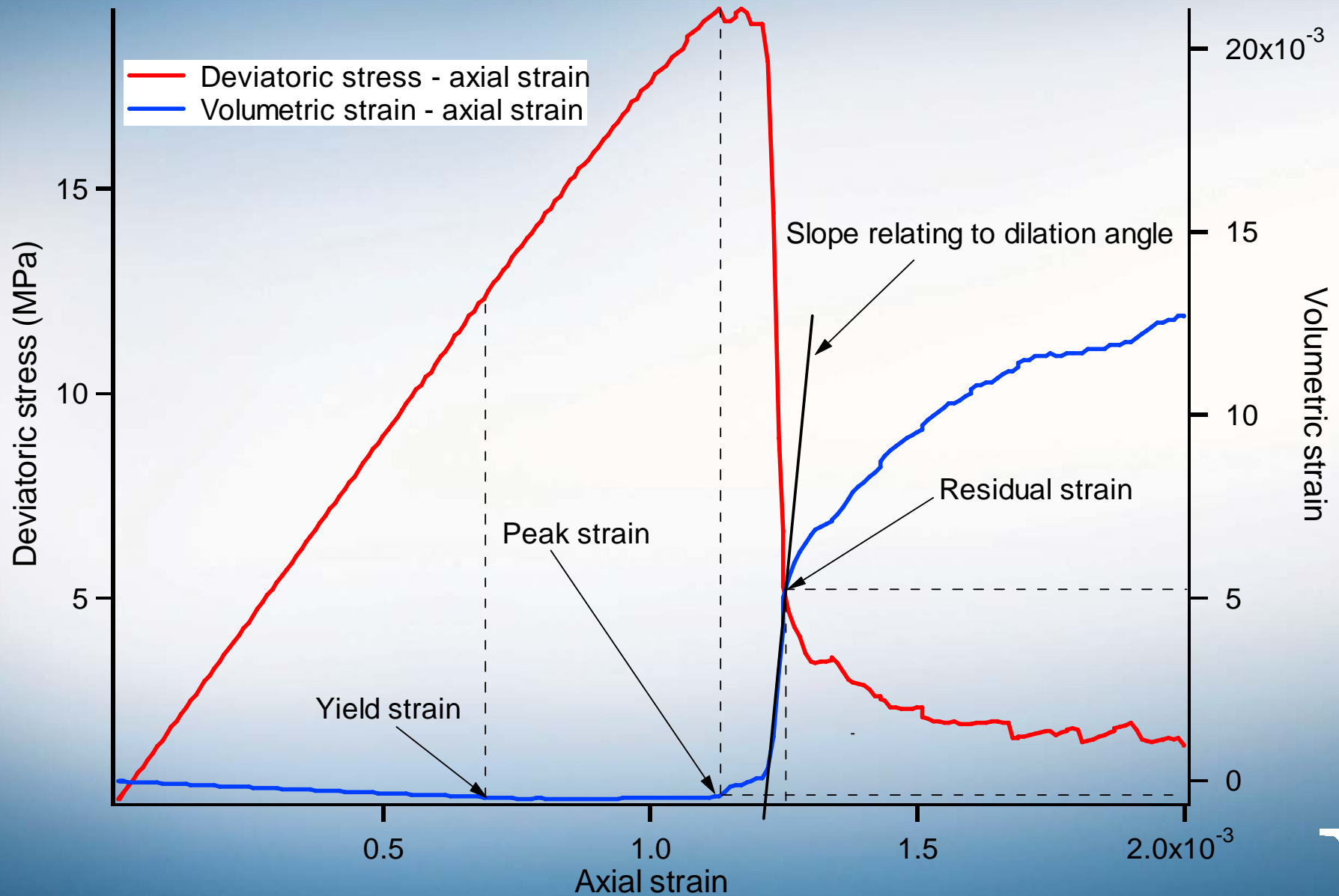


# Synthetic rockmass parameters

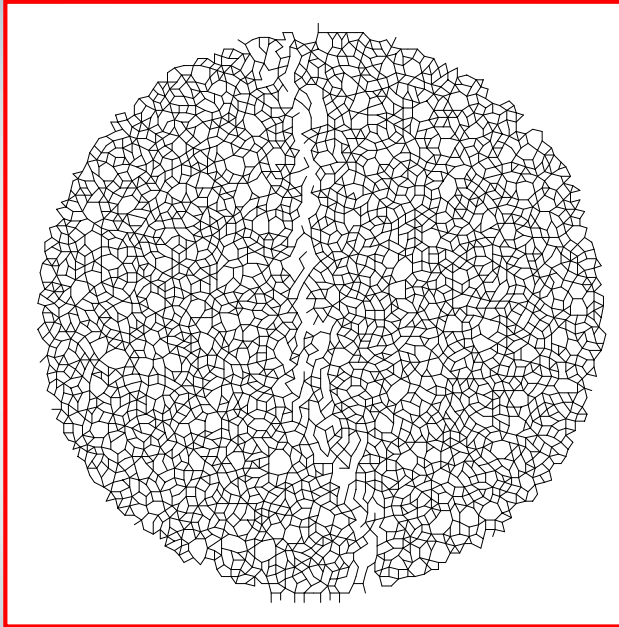
## PFC calibrated synthetic rockmass mechanical parameters

Parameters	Value	
	URMS	DRMS
Normal stiffness, $k_n$	58 GN/m	40 GN/m
Shear stiffness, $k_s$	23 GN/m	15 GN/m
Normal bond, $n_b$	2 MN	1 MN
Shear bond, $s_b$	10 MN	6 MN
Friction coefficient	1.0	1.0

# Stress-strain plot from compression test



# Tensile Test (Brazilian)



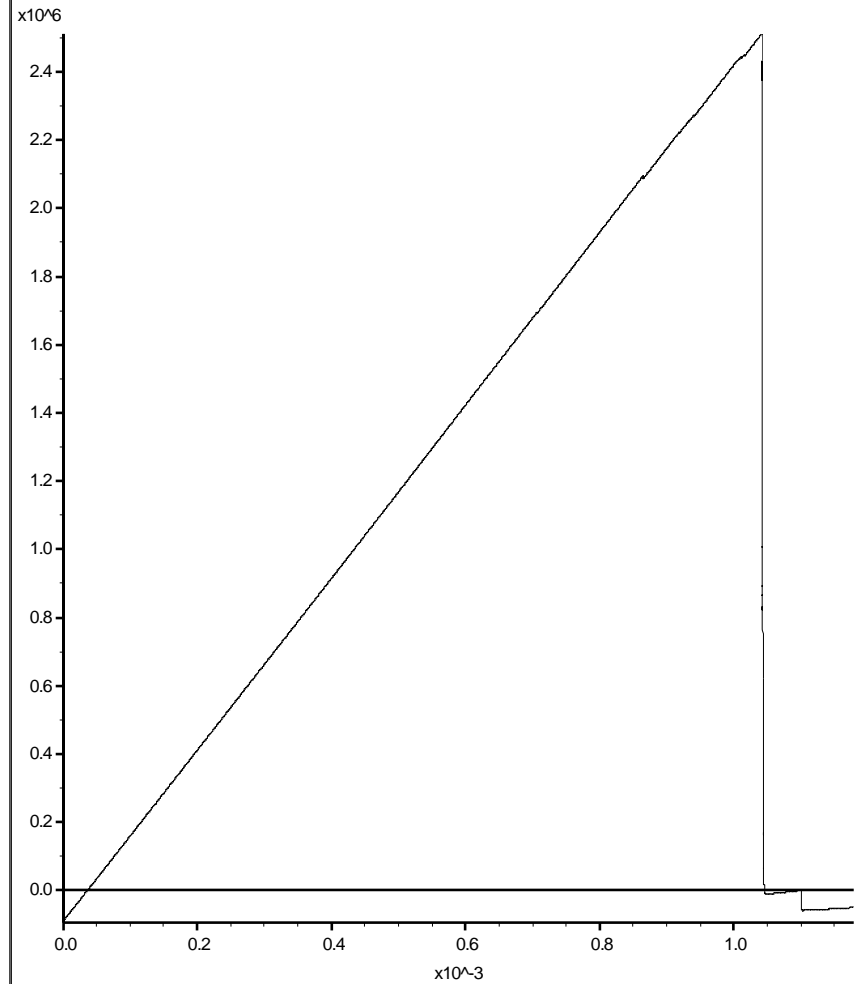
**PFC2D 3.10**  
Step 8721254 12:16:20 Wed Aug 20 2008

## History

Rev 200 devi (FISH Symbol)  
Linestyle  
-9.259e+004 <-> 2.513e+006

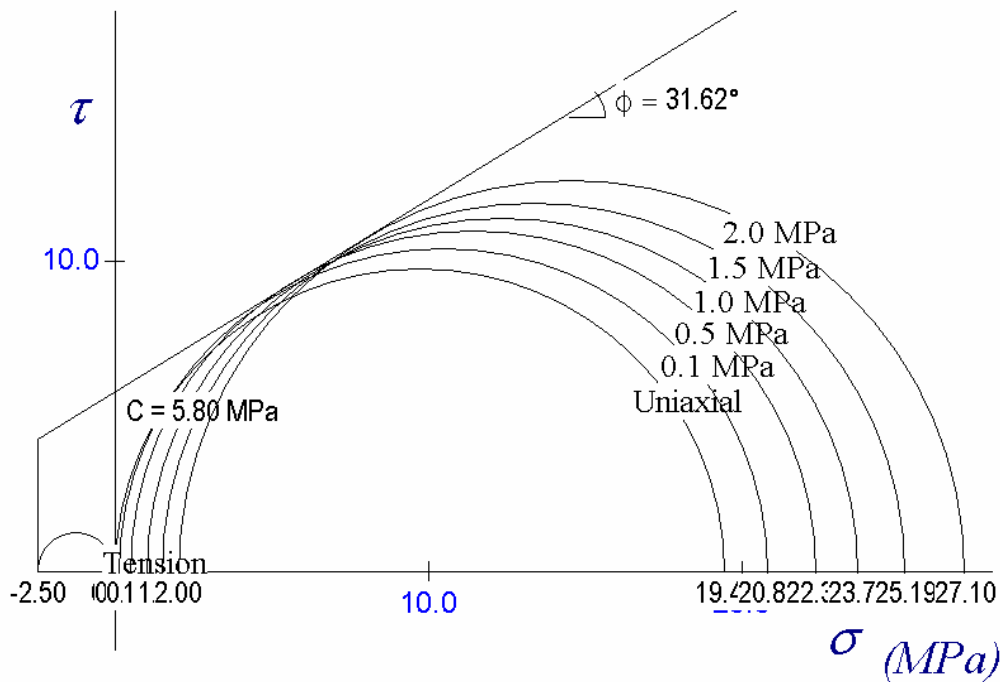
## Vs.

Rev 300 deax (FISH Symbol)  
-1.603e-010 <-> 1.178e-003



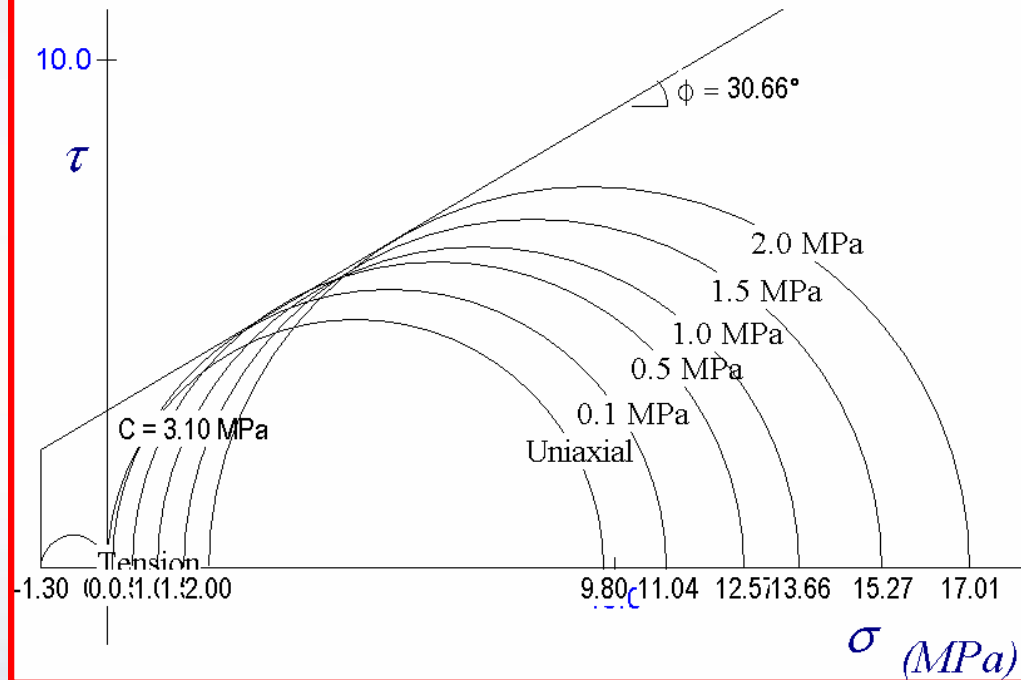
# M-C peak strength envelopes

Mohr-Coulomb Strength Envelope for URMS



URMS

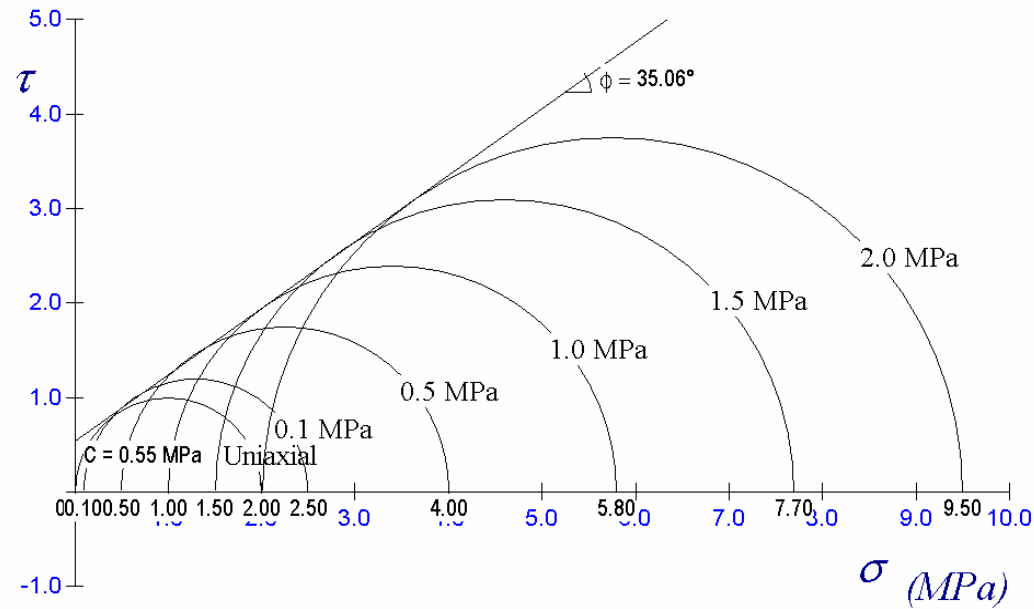
Mohr-Coulomb Strength Envelope for DRMS



DRMS

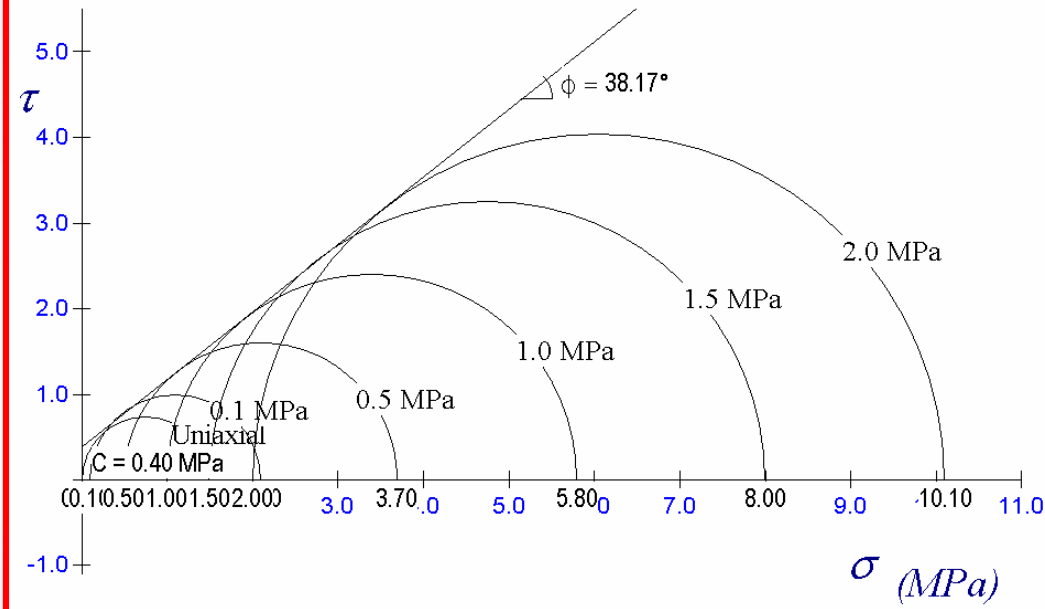
# M-C residual strength envelopes

Mohr-Coulomb Residual Strength Envelope for URMS



URMS

Mohr-Coulomb Residual Strength Envelope for DRMS



DRMS

# PFC derived strength parameters

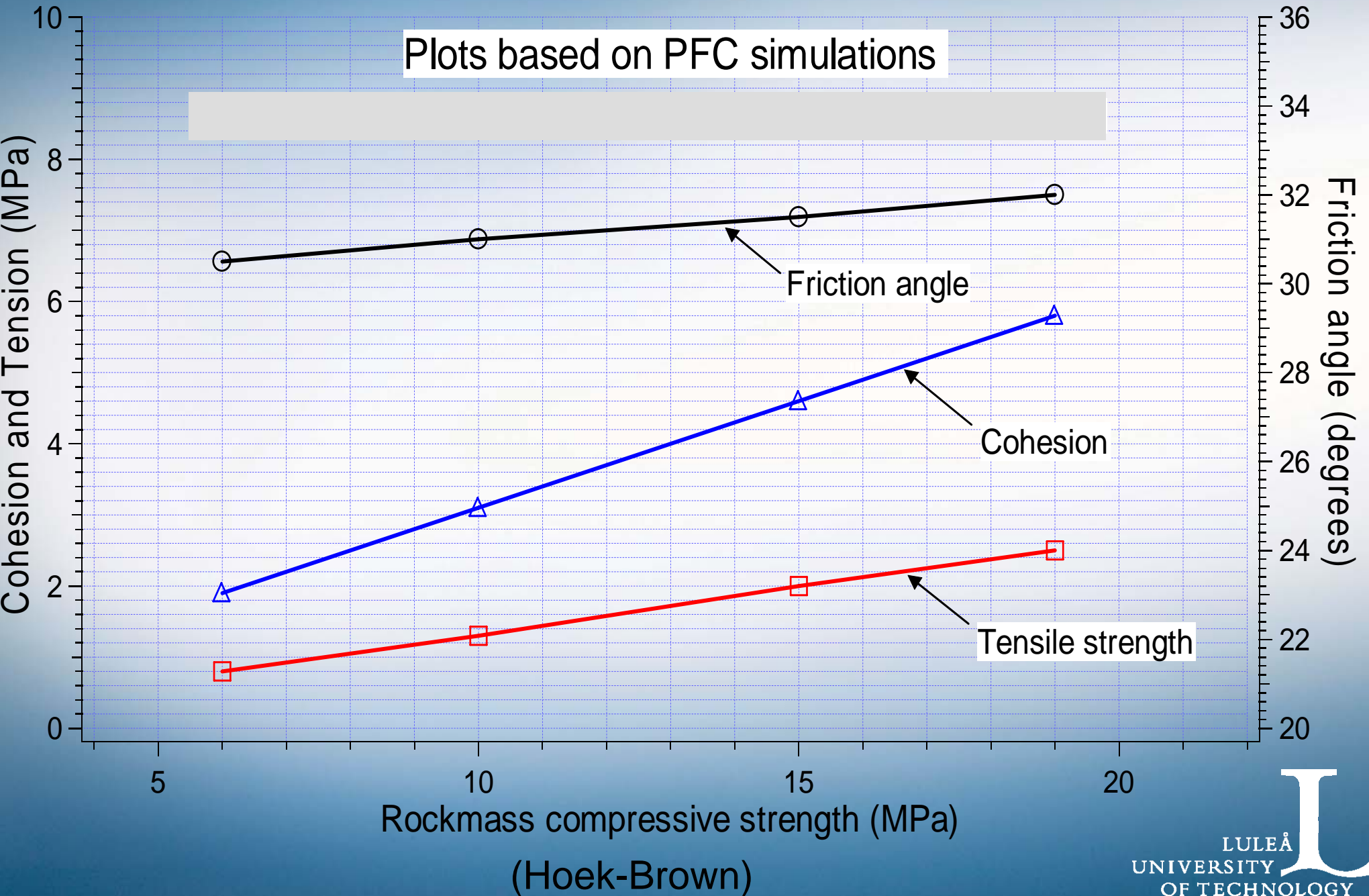
## Strength parameters

	Peak		Residual	
	URMS	DRMS	URMS	DRMS
Cohesion, $c$ (MPa)	5.8	3.1	0.6	0.4
Friction angle, $\phi$	32°	31°	35°	38°
Tension, $\sigma_t$ (MPa)	2.5	1.3	0	0
Dilation angle, $\psi$	9°	7°	-	-

## Volumetric strains at yield, peak and residual

	URMS	DRMS
Yield strain (%)	0.05	0.04
Peak strain (%)	0.06	0.05
Residual strain (%)	0.46	0.35

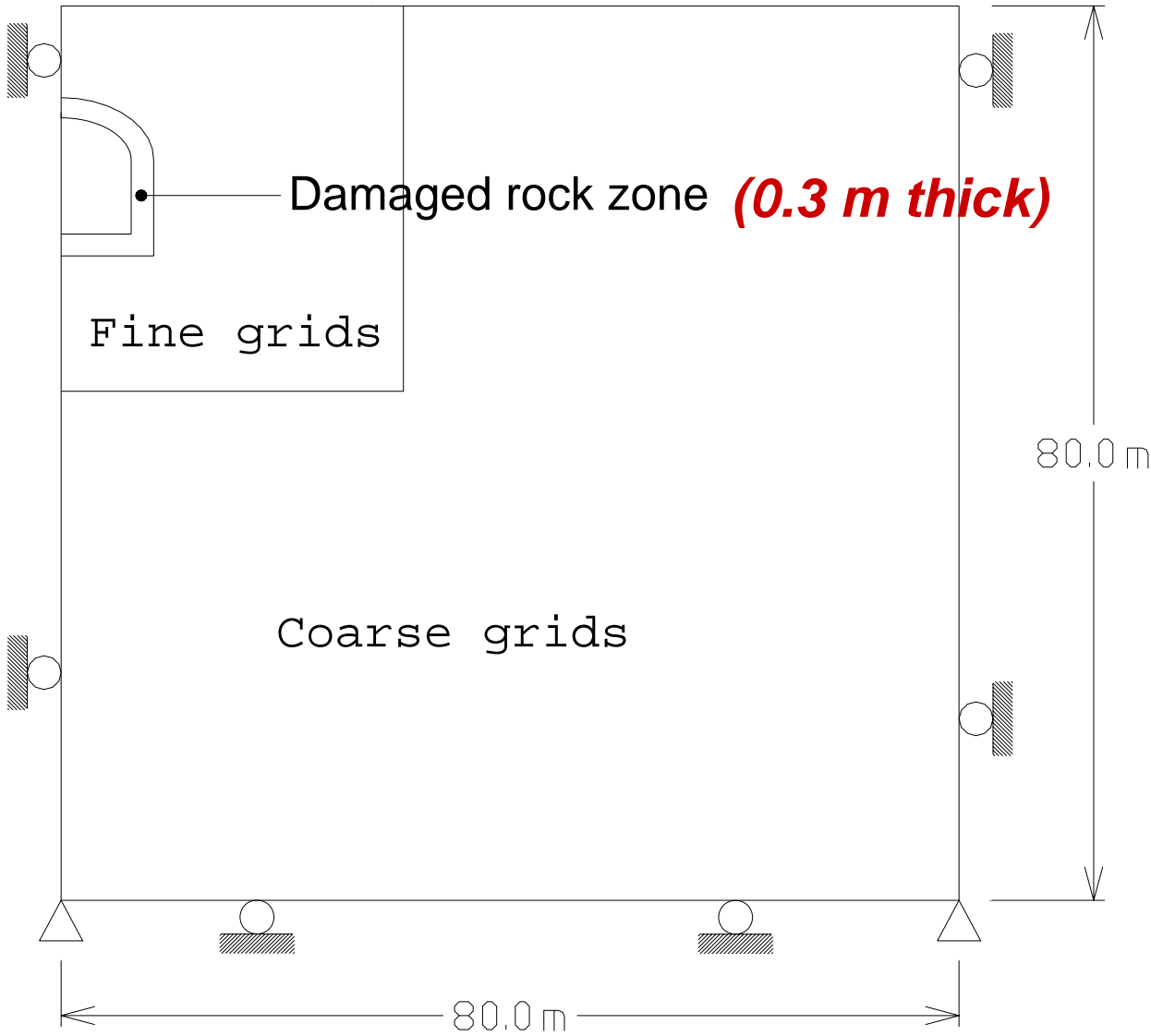
# Strength component chart from PFC simulations



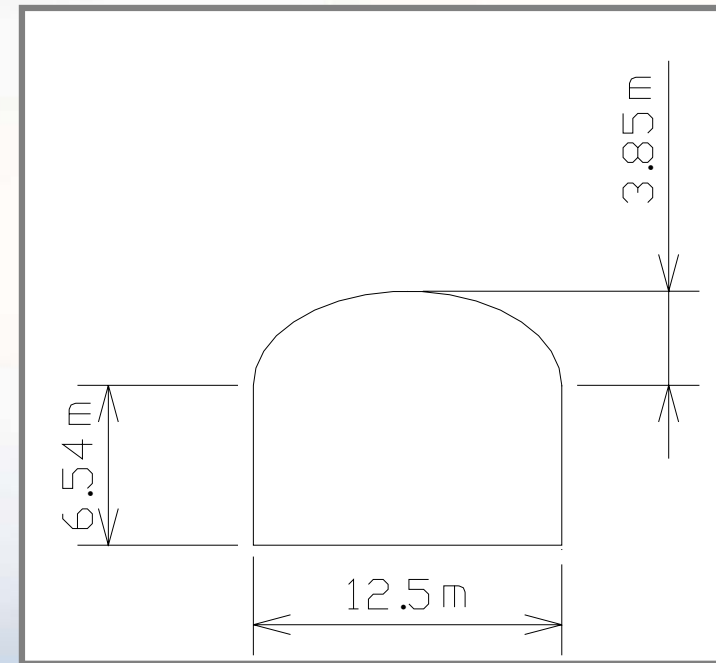
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# FLAC SIMULATION



**\* 10 m rock cover**



# Constitutive models

- Mohr-Coulomb (MC)
- Mohr-Coulomb Strain-Softening (MC-SS)

# Inputs

## Strength parameters

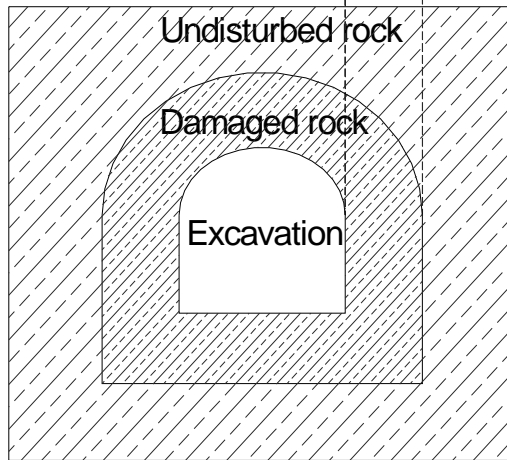
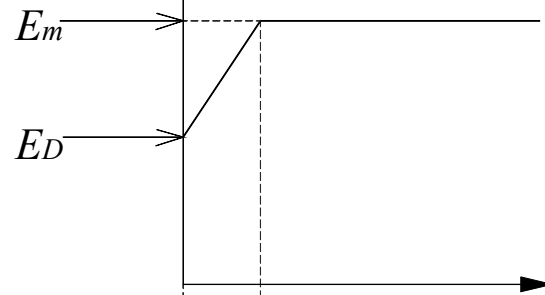
Parameter	Peak – PFC		Residual – PFC		Hoek-Brown	
	URMS	DRMS	URMS	DRMS	URMS	DRMS
Cohesion, $c$ (MPa)	5.8	3.1	0.6	0.4	2.6	1.4
Friction angle, $\phi$	32°	31°	35°	38°	68°	64°
Tension, $\sigma_t$ (MPa)	2.5	1.3	0	0	0.4	0.2
Dilation angle, $\psi$	9°	7°	-	-	-	-

## Volumetric strains at yield, peak and residual

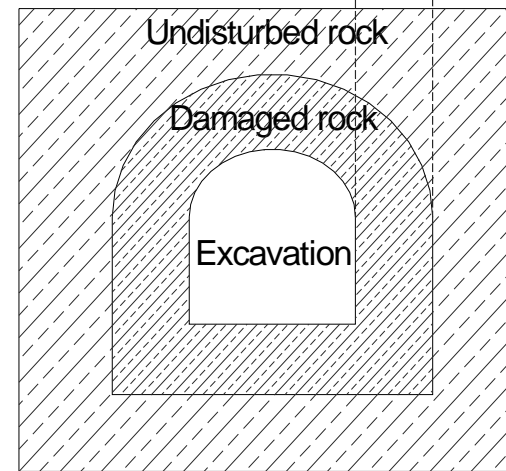
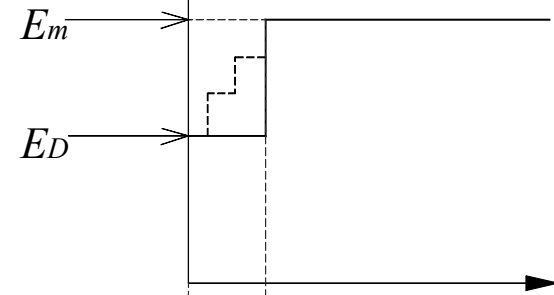
	URMS	DRMS
Yield strain (%)	0.05	0.04
Peak strain (%)	0.06	0.05
Residual strain (%)	0.46	0.35

# Modulus variation

Deformation Modulus



Deformation Modulus



## In-situ stress regime (Stephansson, 1993)

$$\sigma_v = \rho g z$$

$$\sigma_H = 6.7 + 0.044z$$

$$\sigma_h = 0.8 + 0.034z$$

# FLAC Results

## With damaged zone

MC with inputs from  
HB-GSI method

Ground surface



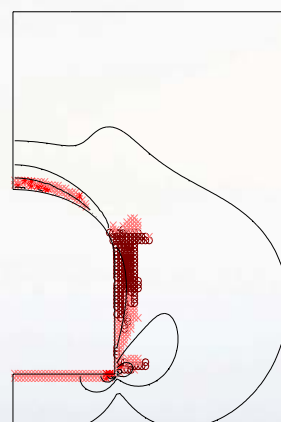
Plasticity Indicator

\* at yield in shear or vol.  
X elastic, at yield in past  
o at yield in tension

Max. shear strain increment  
Contour interval= 1.00E-04  
Minimum: 0.00E+00  
Maximum: 5.00E-04

MC with inputs from PFC  
models

Ground surface



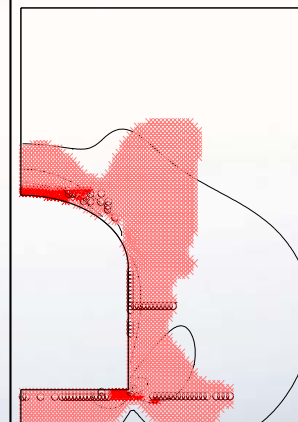
Plasticity Indicator

\* at yield in shear or vol.  
X elastic, at yield in past  
o at yield in tension

Max. shear strain increment  
Contour interval= 1.00E-04  
Minimum: 0.00E+00  
Maximum: 5.00E-04

MC-SS with inputs from  
PFC models

Ground surface




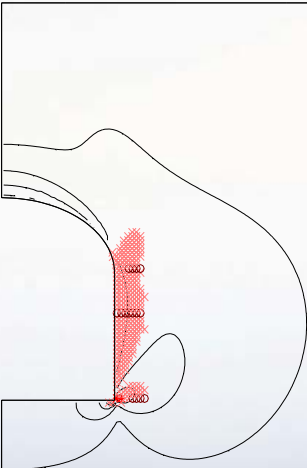
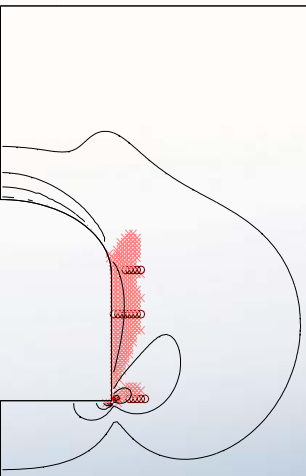
Plasticity Indicator

\* at yield in shear or vol.  
X elastic, at yield in past  
o at yield in tension

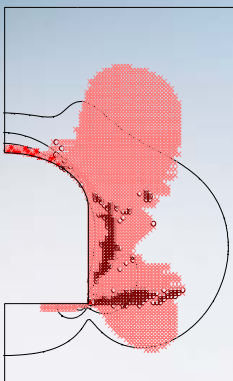
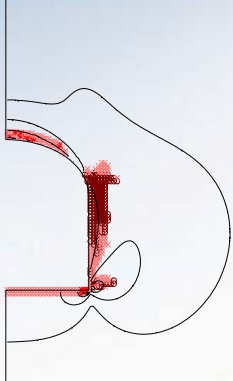
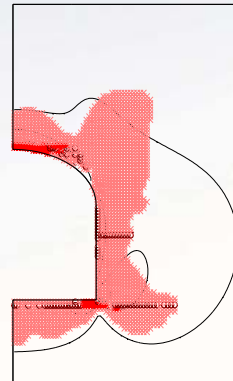
Max. shear strain increment  
Contour interval= 1.00E-04  
Minimum: 0.00E+00  
Maximum: 5.00E-04

# FLAC Results

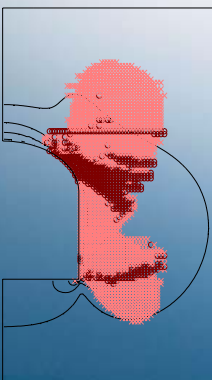
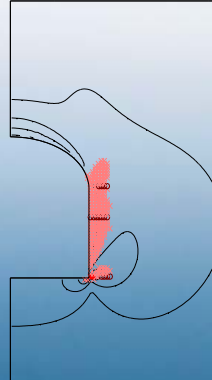
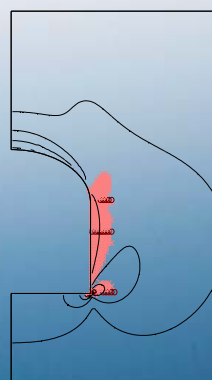
## Without damaged zone

MC with inputs from HB-GSI method	MC with inputs from PFC models	MC-SS with inputs from PFC models
<p>Ground surface</p>  <p>Plasticity Indicator            * at yield in shear or vol.            X elastic, at yield in past            o at yield in tension</p> <p>Max. shear strain increment            Contour interval= 1.00E-04            Minimum: 0.00E+00            Maximum: 5.00E-04</p>	<p>Ground surface</p>  <p>Plasticity Indicator            * at yield in shear or vol.            X elastic, at yield in past            o at yield in tension</p> <p>Max. shear strain increment            Contour interval= 1.00E-04            Minimum: 0.00E+00            Maximum: 5.00E-04</p>	<p>Ground surface</p>  <p>Plasticity Indicator            * at yield in shear or vol.            X elastic, at yield in past            o at yield in tension</p> <p>Max. shear strain increment            Contour interval= 1.00E-04            Minimum: 0.00E+00            Maximum: 5.00E-04</p>

## With damaged rock mass

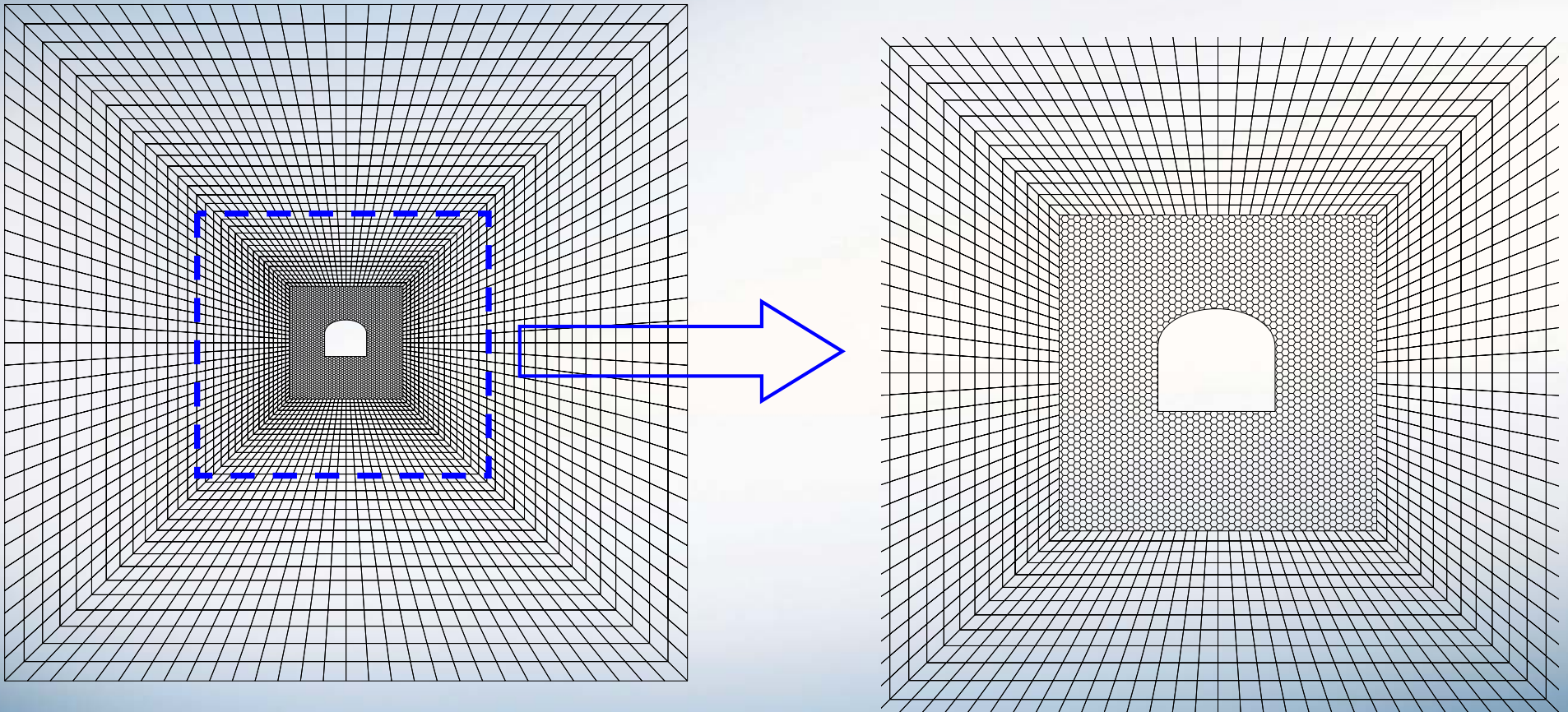
MC with inputs from HB-GSI method	MC with inputs from PFC models	MC-SS with inputs from PFC models
<p style="text-align: center;">Ground surface</p>  <p style="margin-left: 20px;"> <b>Plasticity Indicator</b>                      * at yield in shear or vol.                      X elastic, at yield in past                      o at yield in tension                 </p> <p style="margin-left: 20px;"> <b>Max. shear strain increment</b>                      Contour interval= 1.00E-04                      Minimum: 0.00E+00                      Maximum: 5.00E-04                 </p>	<p style="text-align: center;">Ground surface</p>  <p style="margin-left: 20px;"> <b>Plasticity Indicator</b>                      * at yield in shear or vol.                      X elastic, at yield in past                      o at yield in tension                 </p> <p style="margin-left: 20px;"> <b>Max. shear strain increment</b>                      Contour interval= 1.00E-04                      Minimum: 0.00E+00                      Maximum: 5.00E-04                 </p>	<p style="text-align: center;">Ground surface</p>  <p style="margin-left: 20px;"> <b>Plasticity Indicator</b>                      * at yield in shear or vol.                      X elastic, at yield in past                      o at yield in tension                 </p> <p style="margin-left: 20px;"> <b>Max. shear strain increment</b>                      Contour interval= 1.00E-04                      Minimum: 0.00E+00                      Maximum: 5.00E-04                 </p>

## Without damaged rock mass

MC with inputs from HB-GSI method	MC with inputs from PFC models	MC-SS with inputs from PFC models
<p style="text-align: center;">Ground surface</p>  <p style="margin-left: 20px;"> <b>Plasticity Indicator</b>                      * at yield in shear or vol.                      X elastic, at yield in past                      o at yield in tension                 </p> <p style="margin-left: 20px;"> <b>Max. shear strain increment</b>                      Contour interval= 1.00E-04                      Minimum: 0.00E+00                      Maximum: 5.00E-04                 </p>	<p style="text-align: center;">Ground surface</p>  <p style="margin-left: 20px;"> <b>Plasticity Indicator</b>                      * at yield in shear or vol.                      X elastic, at yield in past                      o at yield in tension                 </p> <p style="margin-left: 20px;"> <b>Max. shear strain increment</b>                      Contour interval= 1.00E-04                      Minimum: 0.00E+00                      Maximum: 5.00E-04                 </p>	<p style="text-align: center;">Ground surface</p>  <p style="margin-left: 20px;"> <b>Plasticity Indicator</b>                      * at yield in shear or vol.                      X elastic, at yield in past                      o at yield in tension                 </p> <p style="margin-left: 20px;"> <b>Max. shear strain increment</b>                      Contour interval= 1.00E-04                      Minimum: 0.00E+00                      Maximum: 5.00E-04                 </p>

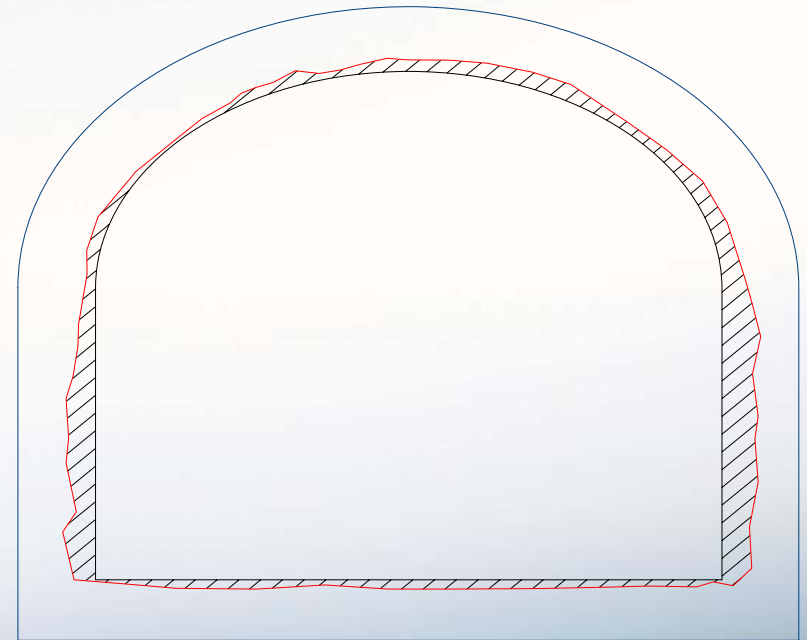
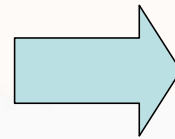
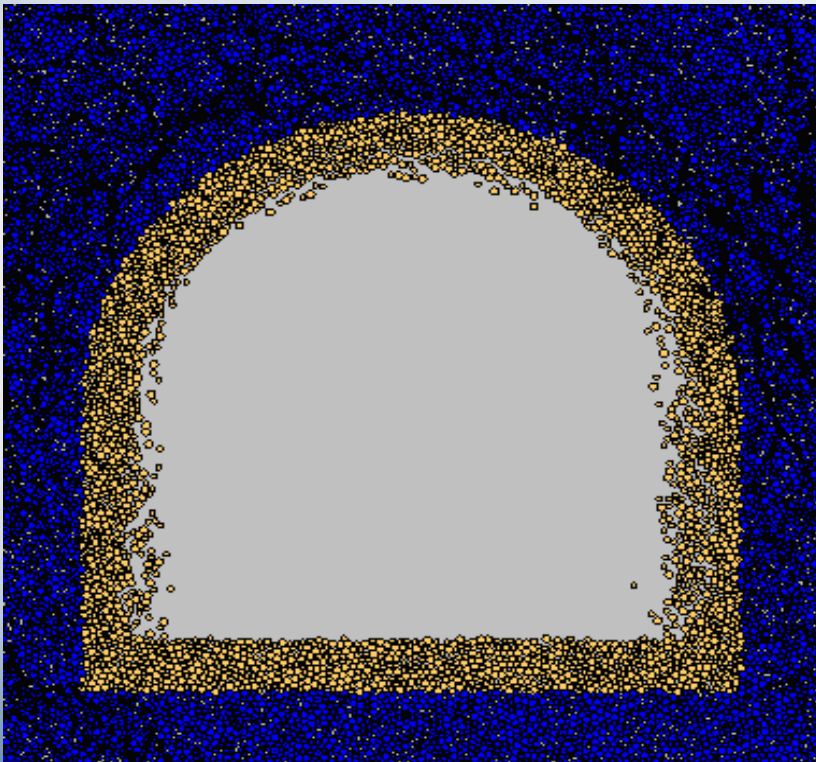
# Some results from current work ....

## FLAC-PFC coupled simulations



# Some results from current work ....

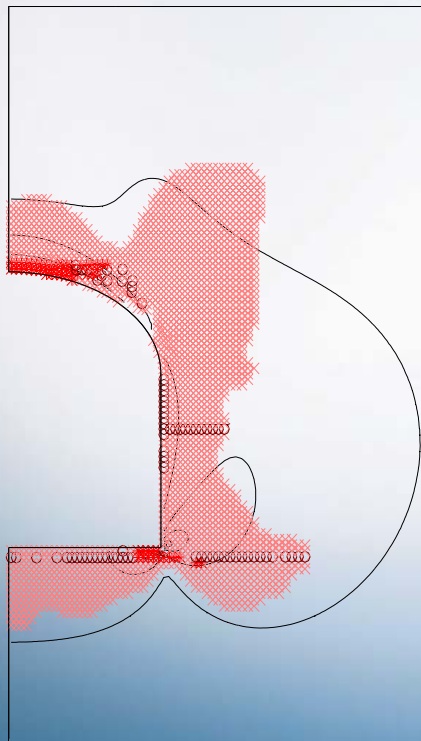
## FLAC-PFC coupled simulations



# Some results from current work ....

## FLAC – volumetric yield contour

Ground surface



Plasticity Indicator

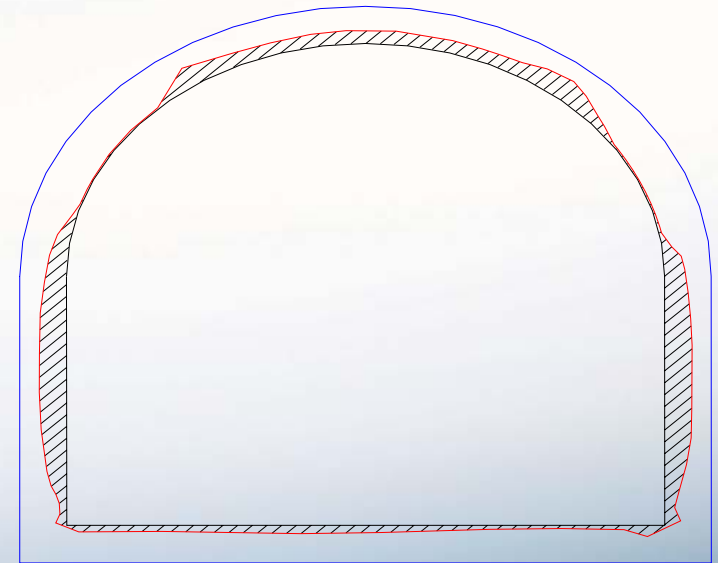
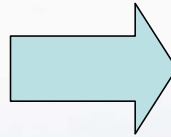
\* at yield in shear or vol.  
X elastic, at yield in past  
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Max. shear strain increment

Contour interval= 1.00E-04

Minimum: 0.00E+00

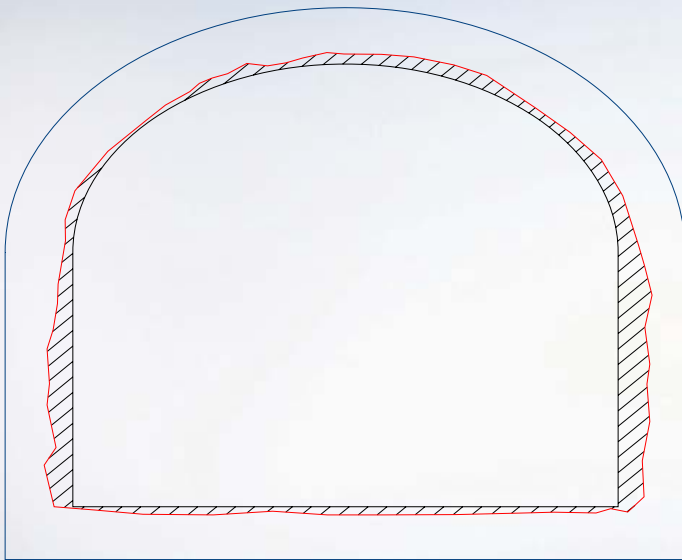
Maximum: 5.00E-04



# Some results from current work ....

## Mapped failed zones from numerical models

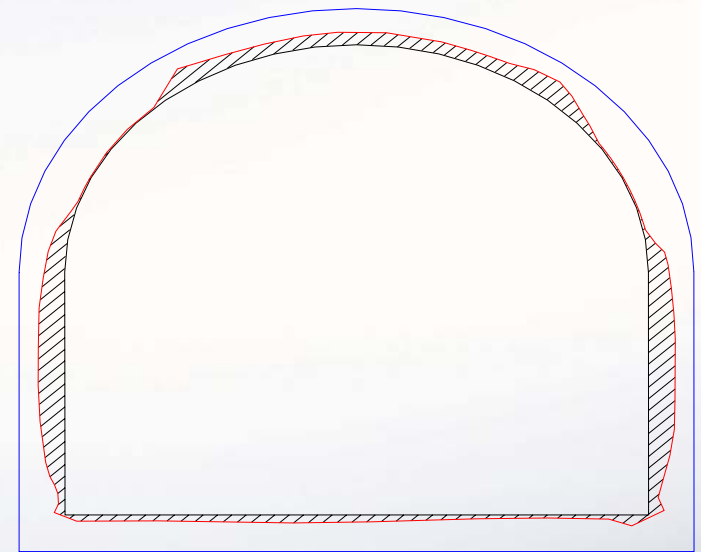
PFC-FLAC coupled model



### Depth of failed zone

- Roof: 7 cm
- Wall: 23 cm

FLAC model

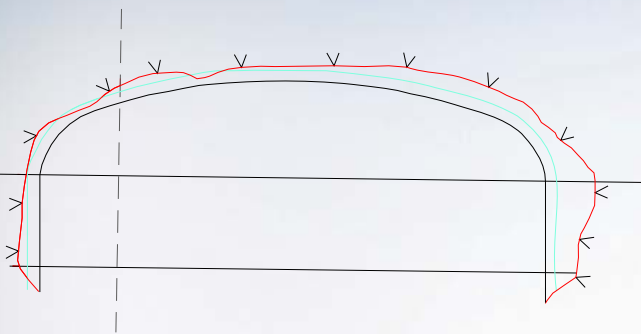


### Depth of failed zone

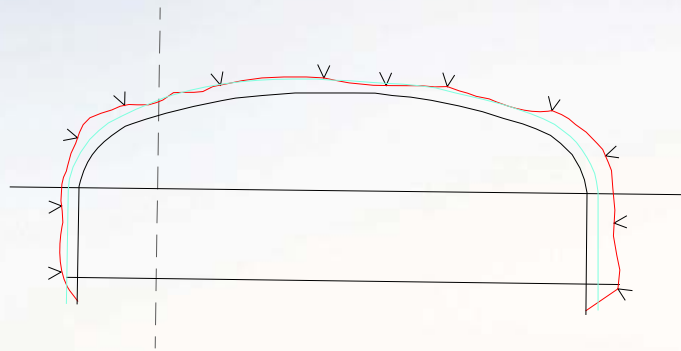
- Roof: 12 cm
- Wall: 29 cm

# Case Tunnel

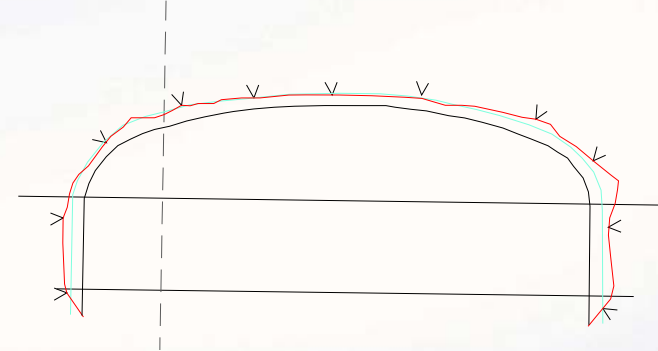
Section 39/289



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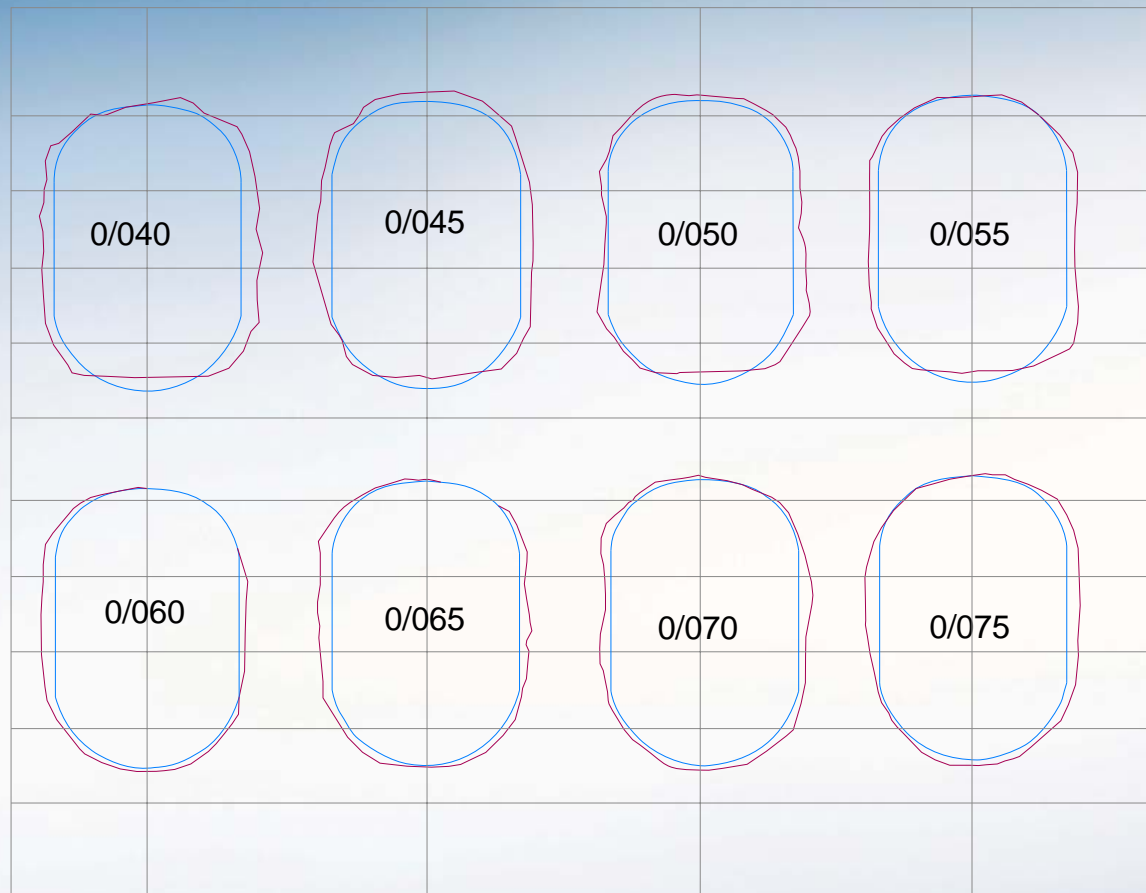


Section 39/324



- Fallout in the sidewalls is upto 50 cm
- Fallout in the roof is less than 10 cm

# Case from SveBeFo Investigation



SveBeFo measured fallouts in some deep underground excavations and found the fallout depth to be within the range of 20 to 50 cm

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# Conclusions

- **It is possible to use PFC to determine the inputs for continuum model.**
- Inputs obtained via PFC model yield results that were consistent with observations
- PFC models also showed a cohesion weakening – friction hardening phenomenon.
- MC-SS model was sensitive to the presence of damaged rock mass, due to strain-softening characteristics of this zone.
- Volumetric yield in FLAC models conforms well with critical volumetric strains observed in the PFC models. These results are also consistent with field observations (as well as the coupled FLAC-PFC model)

# Inputs derived via PFC models

## Strength parameters

	Peak		Residual	
	URMS	DRMS	URMS	DRMS
Cohesion, $c$ (MPa)	5.8	3.1	0.6	0.4
Friction angle, $\phi$	32°	31°	35°	38°
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Dilation angle, $\psi$	9°	7°	-	-

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Yield strain (%)	0.05	0.04
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THANK YOU

- END -