WORKSHOP ON PENETRATION TESTING AND OTHER GEOMECHANICAL ISSUES
Pisa 14 June 2016 – ROOM F8

FEM vs. DEM ANALYSIS OF CAVITIES IN COMPETENT MARBLE ROCK MASSES

Alessia Pierotti, Diego Lo Presti, Martino Leoni, Domenico Gullì

(alessia.pierotti@for.unipi.it)

UNIVERSITA' DI PISA

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Ordine dei Geologi della Toscana

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LECTURE OUTLINE

- **BACKGROUND**
- **OBJECTIVES**
- **CHARACTERIZATION OF CARRARA MARBLE**
- **NUMERICAL MODELING**
- **RESULTS**

INTRODUCTION

Stability analysis of rock masses

The realization of an Underground Excavation includes different issues such as:

– geometry

– excavation's evolution

– state of stress

– characterization of rock mass

– orientation of discontinuity plans

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INTRODUCTION

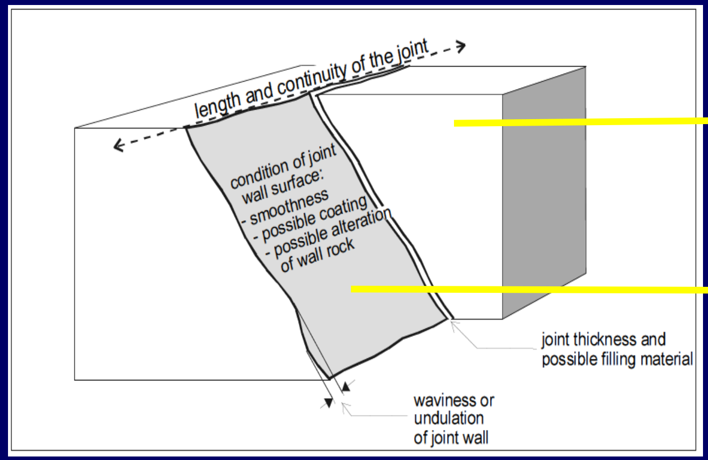
Numerical modeling, supported by experimental measurements and laboratory tests, is a valid support for designers and for the evaluation of different operational solutions.

Focus on:

- ***Modeling approach*** **(continuous or discontinuous)**
- ***Model's parameters***

MODELING APPROACH

Discontinuous model



INTACT ROCK

DISCONTINUITY

Continuous model

EQUIVALENTE MODEL

Strength parameters of intact rock are properly reduced in order to consider the absence of fractures and discontinuities wich aren't modeled.

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OBJECTIVES

- COMPARISON BETWEEN CONTINUOUS AND DISCONTINUOUS MODELS
- USE OF INTACT ROCK PARAMETERS AND REDUCED ROCK MASS PARAMETERS
- COMPARISON BETWEEN NUMERICAL STRESS RESULTS AND IN SITU STATE OF STRESS

THE CARRARA MINING BASIN

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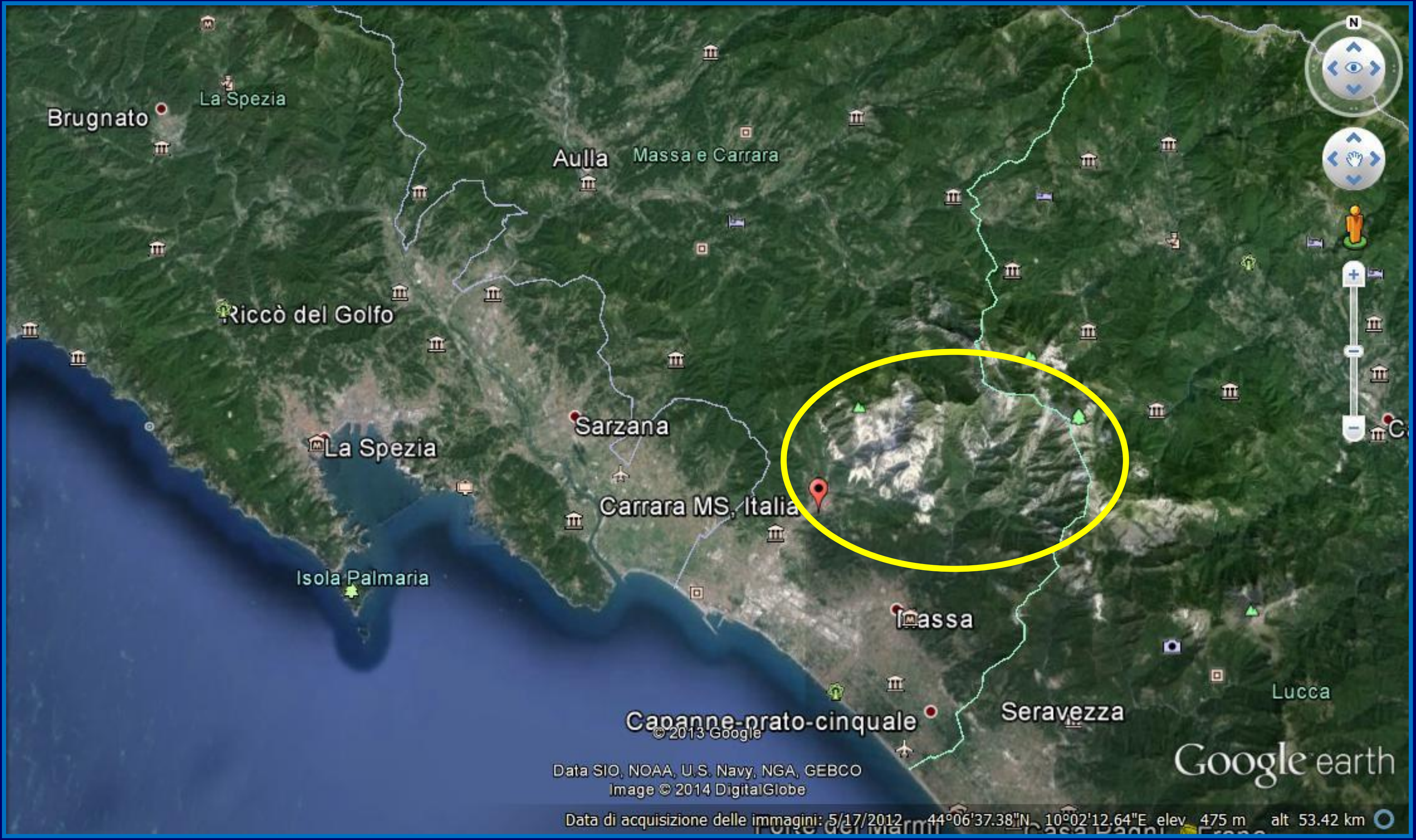


CARRARA BASIN CHARACTERISTICS

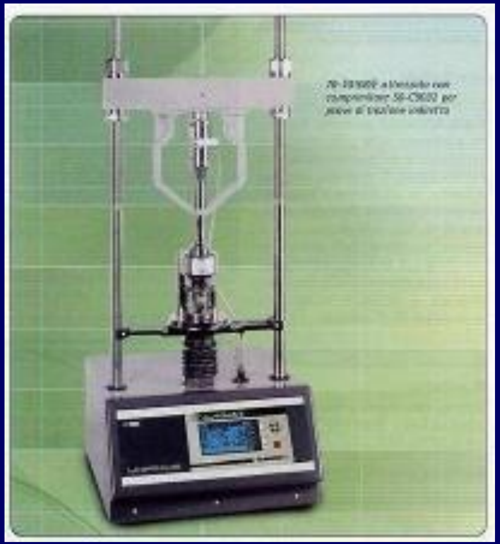
- LARGE QUARRIES AND UNDERGROUND OPENINGS WITH CONSIDERABLE DIMENSIONS
- AN HOMOGENEUS ROCK MATRIX WITH METAMORPHIC ORIGINS
- POORLY FRACTURED ROCK MASS (BLOCKY ROCK MASS)

CARRARA MARBLE CHARACTERIZATION

Laboratory tests on rock samples

⬇

Mechanical parameters of Rock Matrix



Field Measurements

⬇

Estimation of in-situ State of Stress

THE ROCK MATRIX

σ_c	σ_t	τ	c	Φ	m	s
[MPa]	[MPa]	[MPa]	[MPa]	[°]	[-]	[-]
100±20	8±3	20±5	20±5	37±3	8.5±2	1

σ_c Uniaxial Compressive Strength

σ_t Tensile Strength

τ Shear Strength

c cohesion

Φ Friction Angle

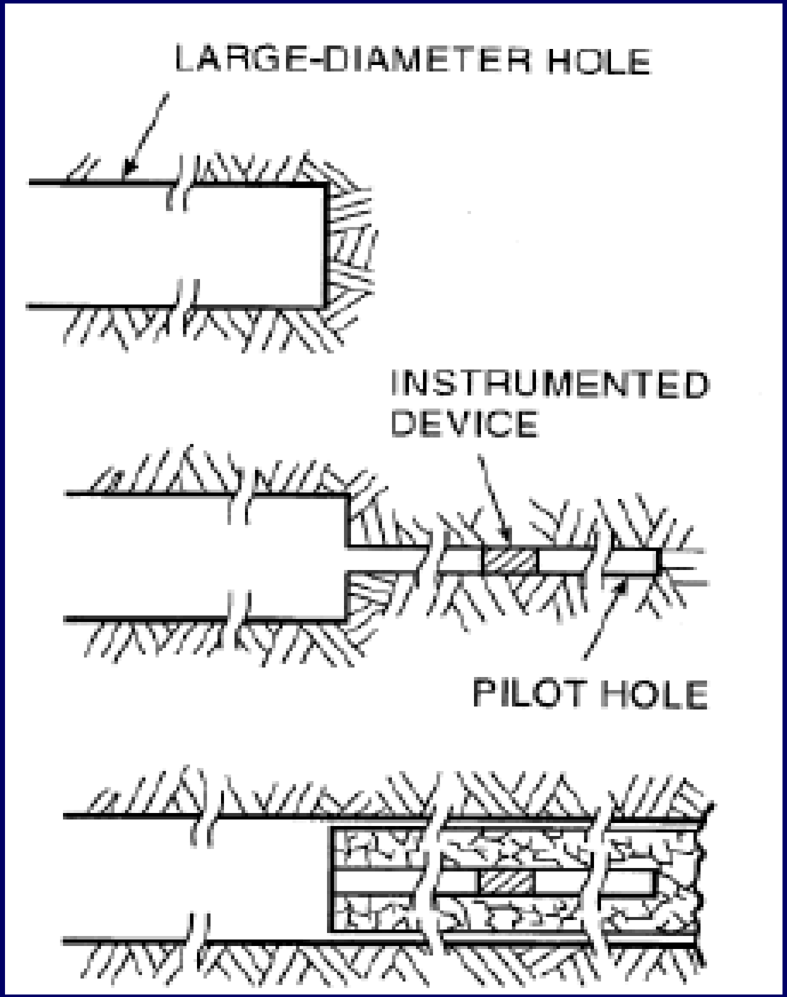
m,s Hoek-Brown parameters (HB Failure envelope on intact rock)

THE CARRARA MINING BASIN

Stress Relief Technique

A volume of Rock is relieved from the field stress acting on it and induced strain are measured

CSIRO Hi-Cell



THE CARRARA MINING BASIN

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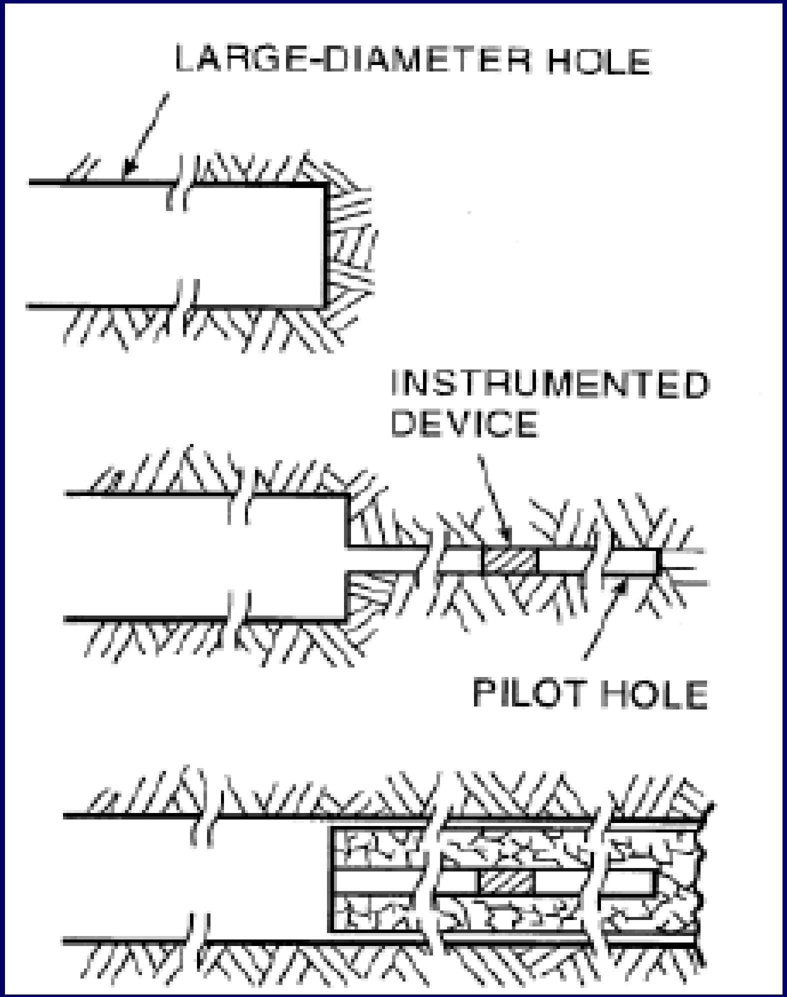
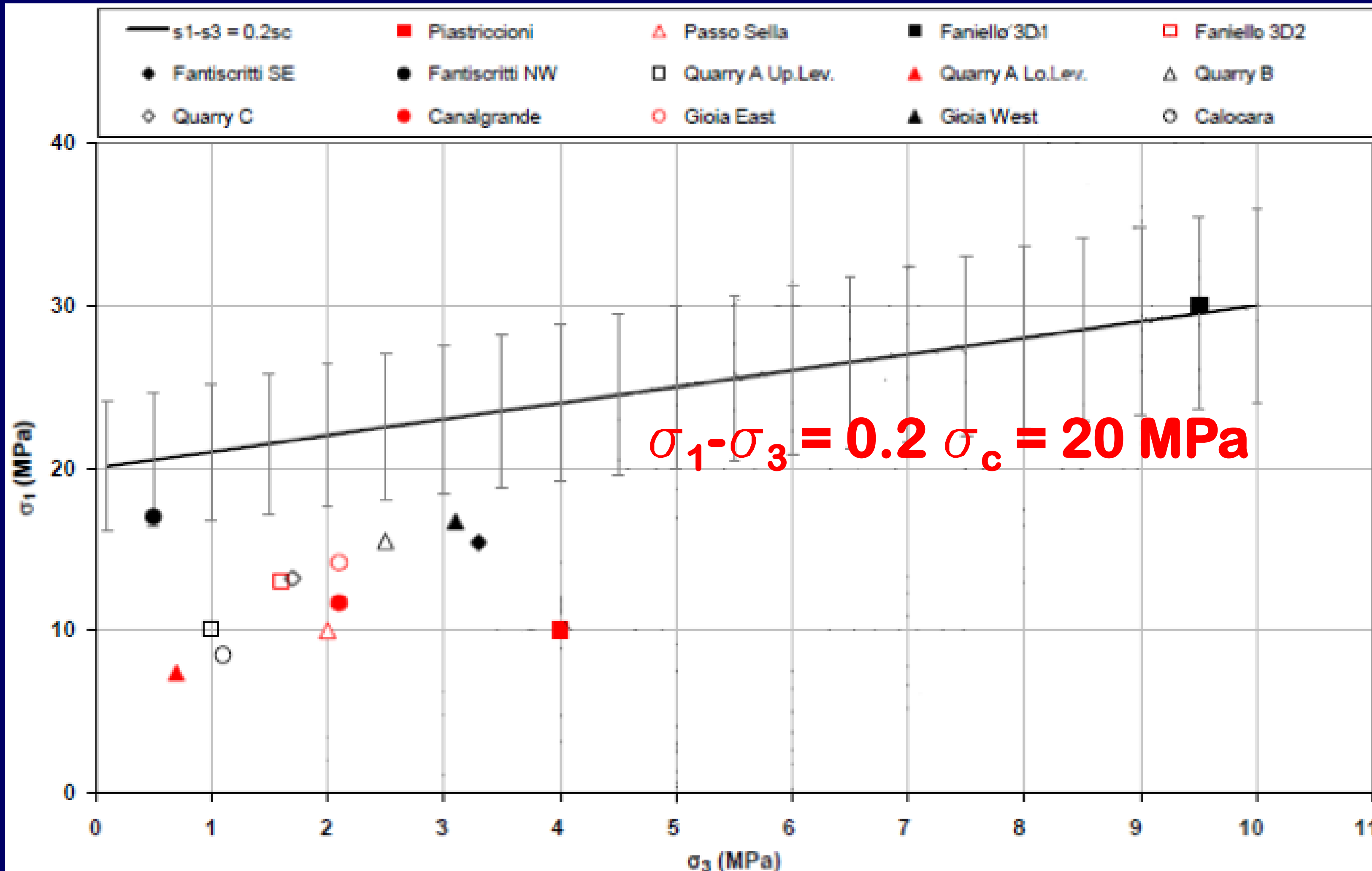


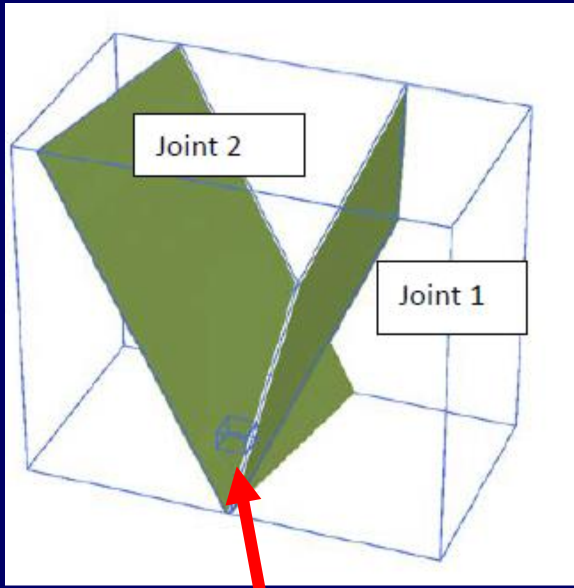
EMPIRICAL STRENGTH CRITERION



EMPIRICAL STRENGTH CRITERION

- THERE IS NO SITE WHERE THIS DEVIATORIC THRESHOLD HAS BEEN EXCEEDED
- IN SITE WHERE YOU GET CLOSE TO THIS THRESHOLD THERE ARE CLEARLY CONDITIONS OF INCIPIENT INSTABILITY

THE MODEL GEOMETRY

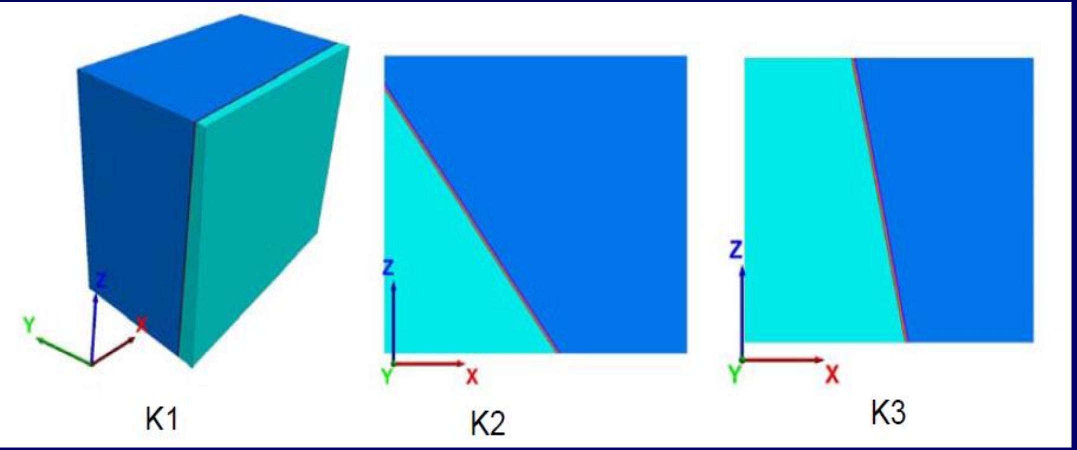


	dip [°]	dd [°]	JKN [MPa /m]	JKS [MPa /m]	Φ[°]	c [MPa]
Joint 1	66	253	30	10	20	0.01
Joint 2	63.03	100	3000	1000	30	5

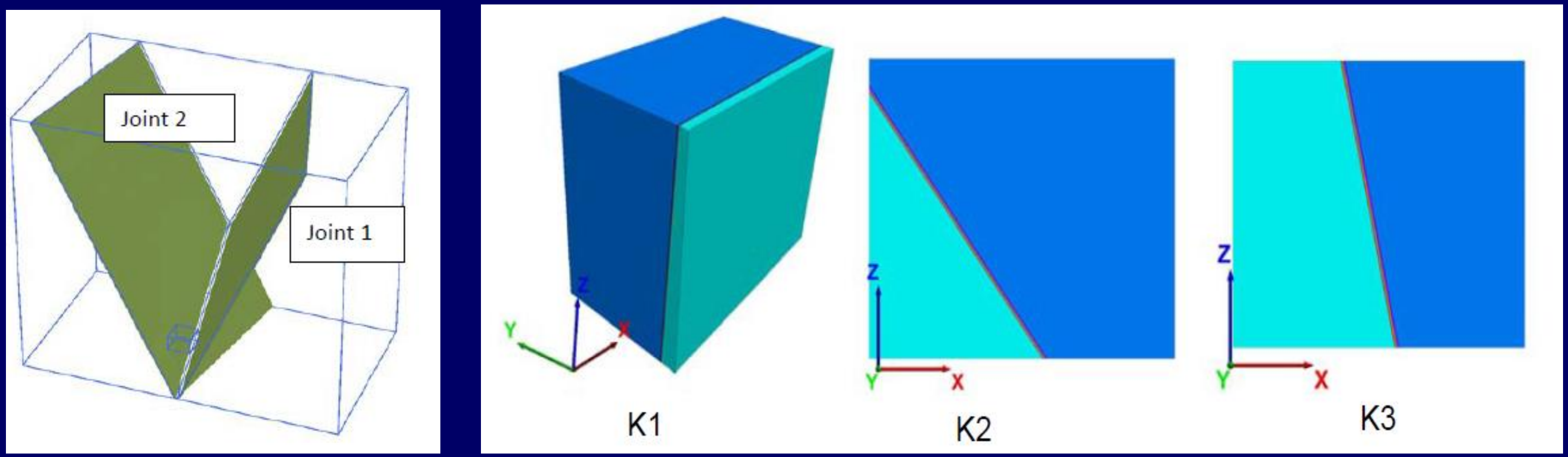
Sistema (spaziatura)	n. discontinuità	dip [°]	dd [°]	JRC	JCS	JKN [MPa]	JKS [MPa]	Φ [°]	c [MPa]
K1 (2m)	5	88	359	4-6	96.5	40	19	32.3	11.2
K2 (4m)	5	54	105	3-5	88.4	40	19	32.3	11.2
K3 (4m)	5	80	54	2-4	41.5	40	19	32.3	11.2

Chamber 49 x 50 x 30 m

Host rock
700 x 400 x 595 m



THE MODEL GEOMETRY



FEM

<u>Continuous Equivalent</u>

No K1, K2, K3 ; intact rock parameters reduced.

Software: *Plaxis 3D*

DEM

<u>Discontinuous Model</u>

Discontinuities and intact rock parameters.

Software: *3DEC*

THE DEM MODEL

3DEC: Discontinuous Model

Intact Rock

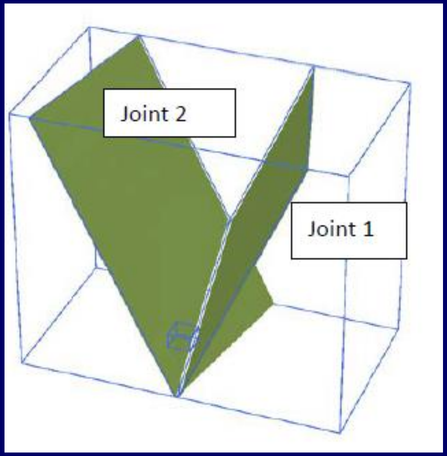
γ [kN/m^3]	c [MPa]	Φ [°]	K [GPa]	G [GPa]	σ_t [MPa]
27	20	37	29.5	25	8

Intact Rock
Joints 1,2
K1, K2, K3

Mohr-Coulomb

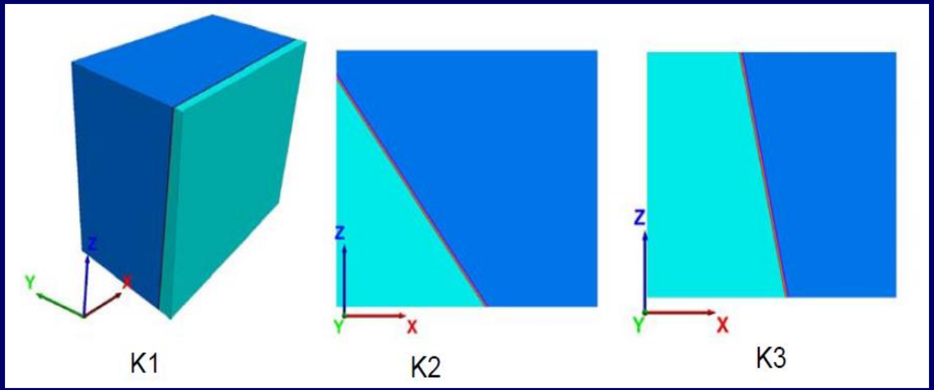
$$\tau = c + \sigma_n \cdot tan\,\phi$$

K = bulk modulus
G = shear modulus



Φ[°]	c [MPa]
20	0.01
30	5

Φ [°]	c [MPa]
32.3	11.2

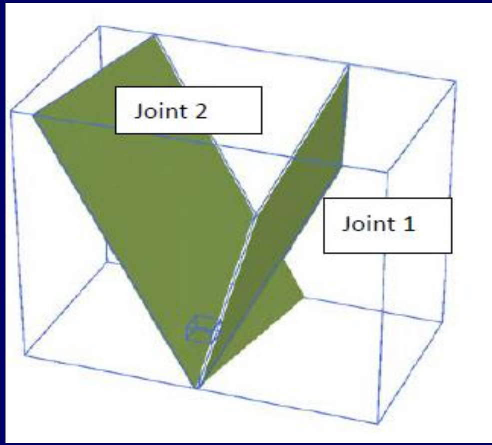


THE DEM MODEL

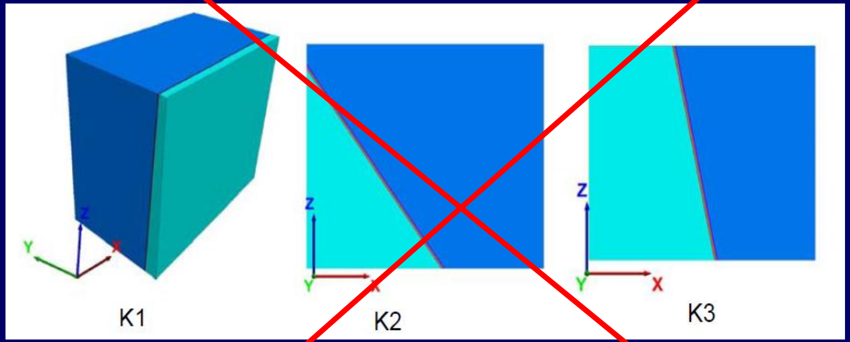
- Rock matrix and rock discontinuity mechanical features have been obtained by laboratory tests such as uniaxial compressive tests and shear test on both material and discontinuities carried according ISRM suggested methods.

- (Ferrero et al., 2013)

THE FEM MODEL



Φ[°]	c [MPa]
20	0.01
30	5



GSI = 66; D = 0;
m_i = 9; σ_c = 99 MPa

PLAXIS: Continuous Model
Hoek-Brown criterion

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_b \frac{\sigma_3}{\sigma_c} + s \right)^a$$

$$m_b = m_i \exp\left(\frac{GSI-100}{28-14D}\right)$$
$$s = \exp\left(\frac{GSI-100}{9-3D}\right)$$
$$a = 0.5 + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right)$$

THE FEM MODEL

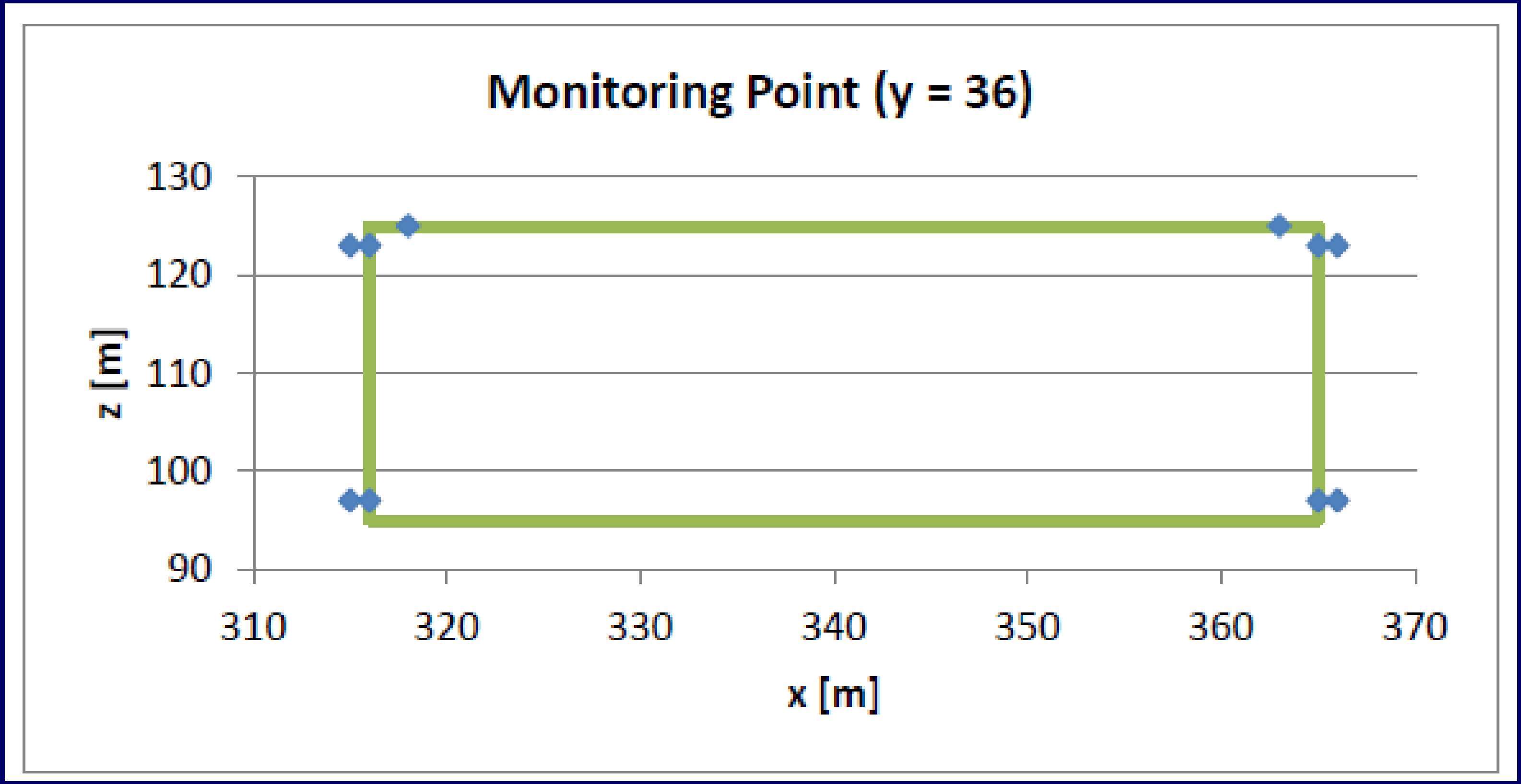
GSI = RMR -5 = 66

$$RMR = R_1 + R_2 + R_3 + R_4 + R_5$$

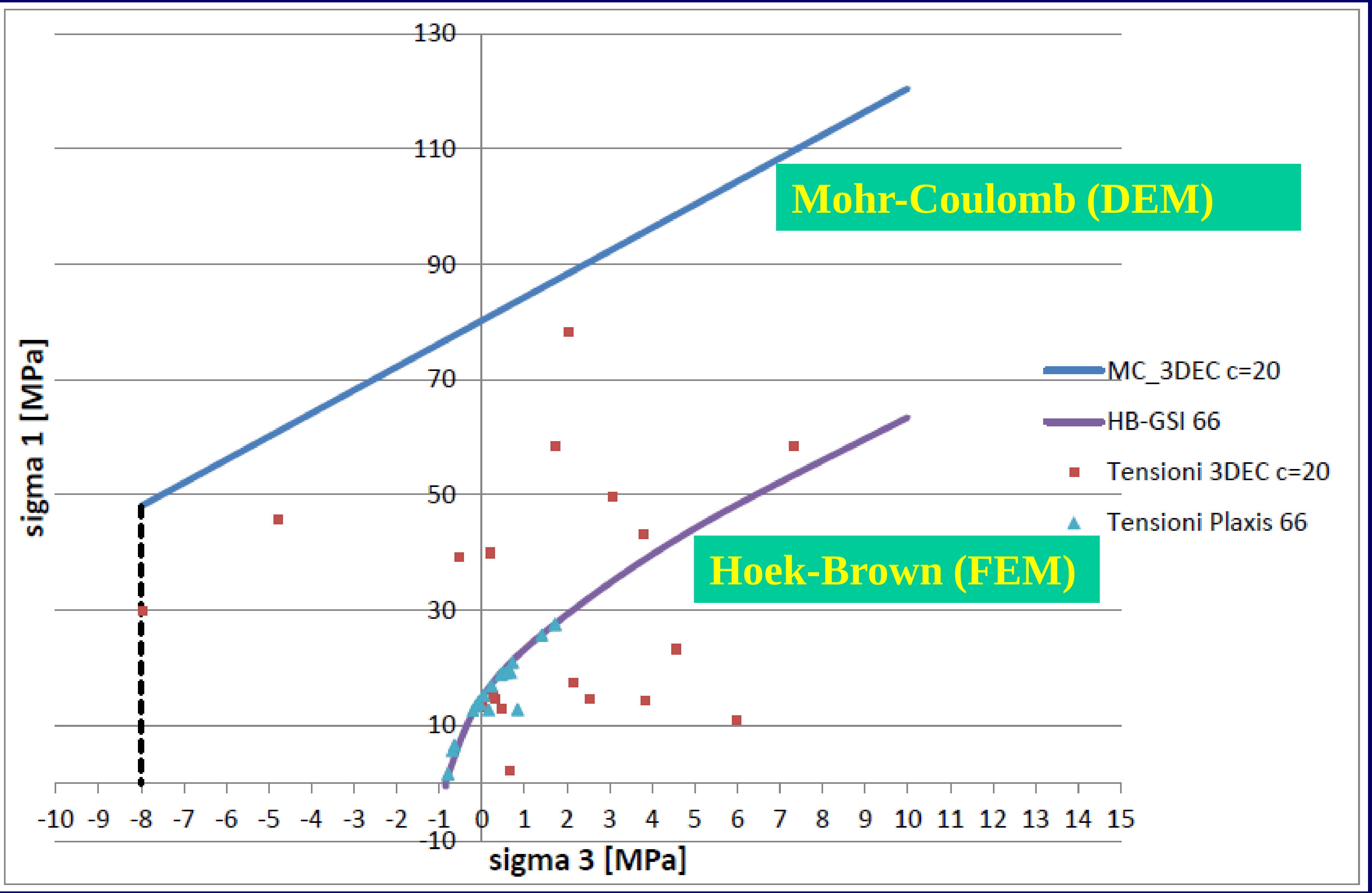
		Range	Punteggio
R1	Resistenza roccia intatta [MPa]	250-100	9
R2	RQRD [%]	90-75	17
R3	Spaziatura delle discontinuità [m]	>2	20
R4	Condizioni delle discontinuità	Superfici lisce o laminate o riempimento <5mm o apertura 1-5 mm _ Discontinuità continue	10
R5	Condizioni idrauliche	Assenza di acqua	15
	RMR		71

(Bienawski Z., 1989)

ANALYSIS METHODS



RESULTS

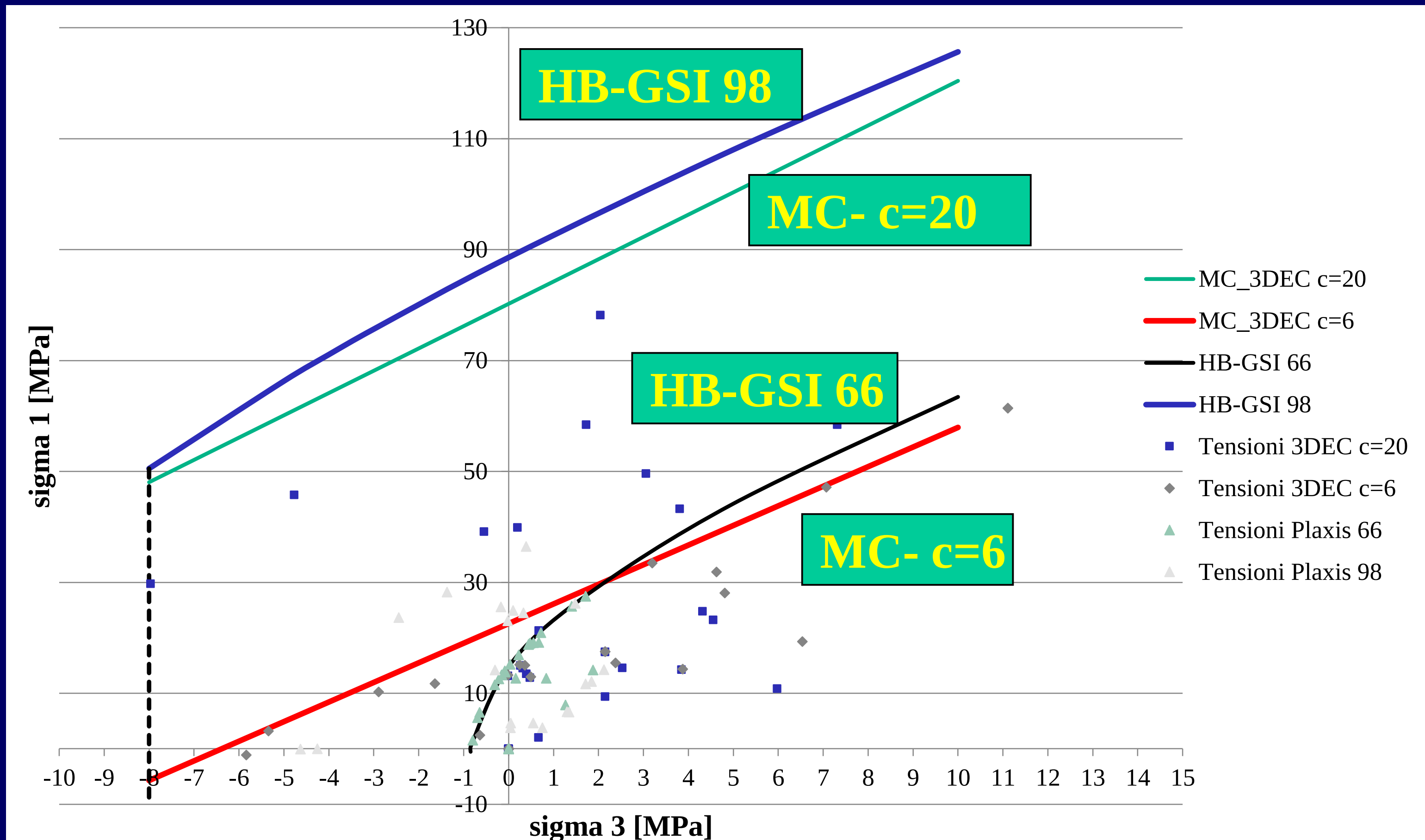


Mohr-Coulomb (DEM)
Hoek-Brown (FEM)
MC_3DEC c=20
HB-GSI 66
Tensioni 3DEC c=20
Tensioni Plaxis 66
sigma 1 [MPa]
sigma 3 [MPa]
130
110
90
70
50
30
10
-10
-10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

EQUIVALENT STRENGTH ENVELOPES

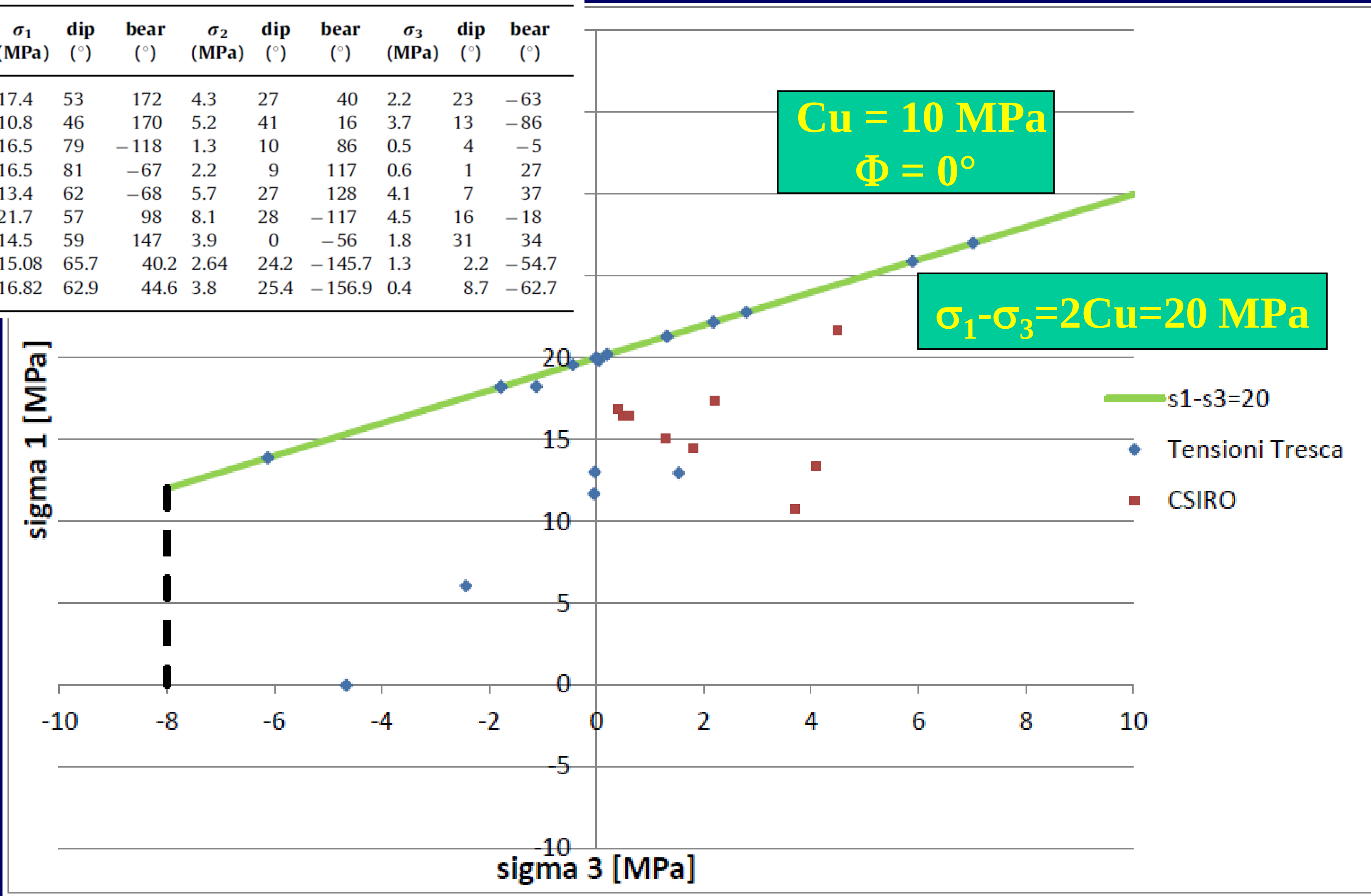
Hoek-Brown (PLAXIS)		Mohr-Coulomb Fit Parameters		Mohr-Coulomb (3DEC)		Hoek-Brown Fit Parameters	
σ_c	99 MPa	c	6.34 MPa	c	20 Mpa	σ_c	99 MPa
GSI	66					GSI	98
m_i	9	Φ	34.2°	Φ	37°	m_i	6
D	0					D	0

Equivalent Parameters_RocLab

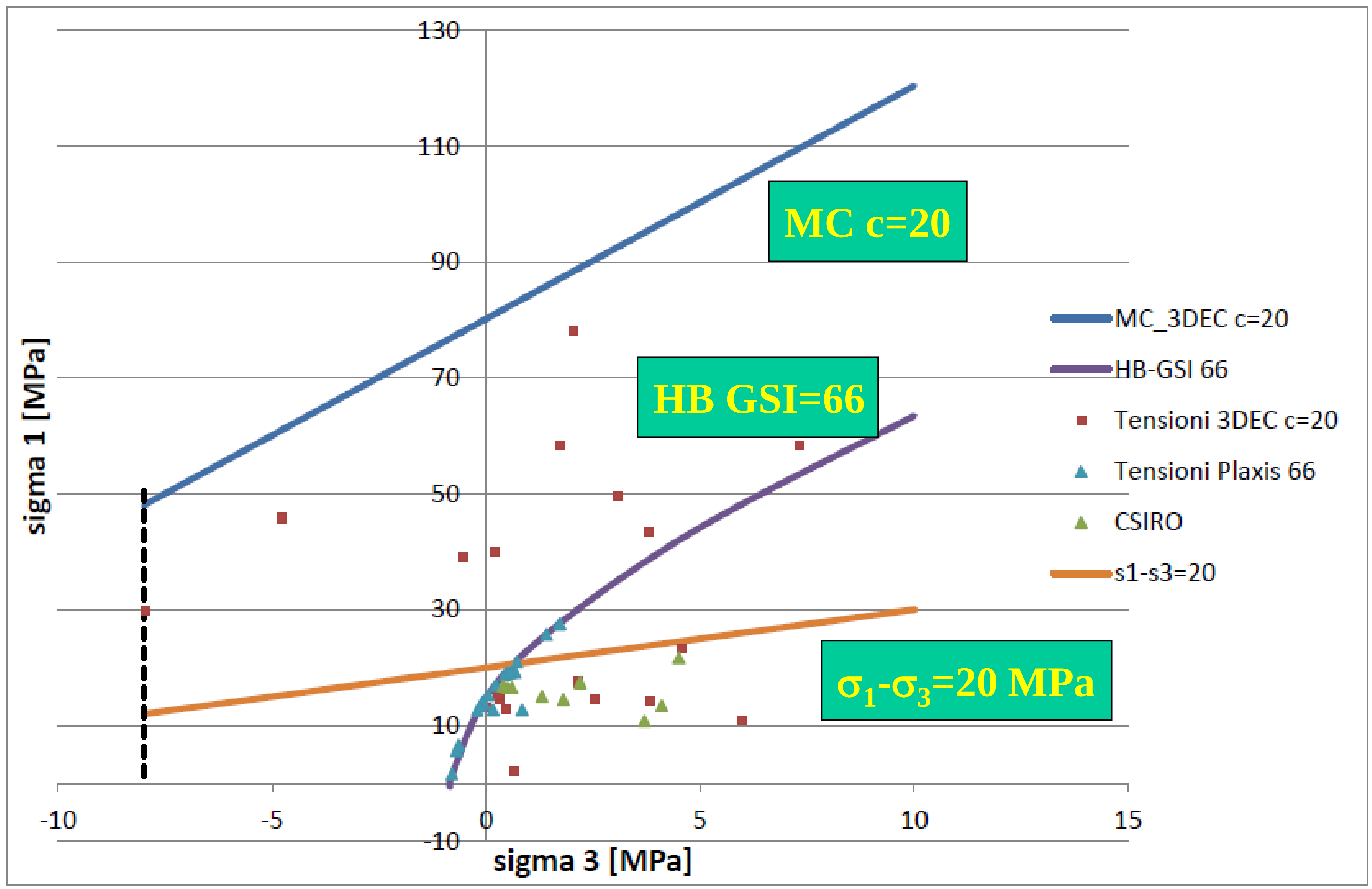


EMPIRICAL STRENGTH CRITERION

Borehole	σ_1 (MPa)	dip (°)	bear (°)	σ_2 (MPa)	dip (°)	bear (°)	σ_3 (MPa)	dip (°)	bear (°)
3D_01 01	17.4	53	172	4.3	27	40	2.2	23	−63
3D_01 02	10.8	46	170	5.2	41	16	3.7	13	−86
3D_02 01	16.5	79	−118	1.3	10	86	0.5	4	−5
3D_02 02	16.5	81	−67	2.2	9	117	0.6	1	27
3D_03 01	13.4	62	−68	5.7	27	128	4.1	7	37
3D_04 01	21.7	57	98	8.1	28	−117	4.5	16	−18
3D_04 02	14.5	59	147	3.9	0	−56	1.8	31	34
3D_05 01	15.08	65.7	40.2	2.64	24.2	−145.7	1.3	2.2	−54.7
3D_05 02	16.82	62.9	44.6	3.8	25.4	−156.9	0.4	8.7	−62.7



MC, HB, TRESCA



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CONCLUSION

- **Differences in stress outputs;**
- **The use of the intact rock strength parameters (c=20 MPa and Φ = 37°), even in a discontinuous model, isn’t safely, bringing to an overestimation of the in situ strength;**
- **The overestimation of the rock mass strength that we have especially for higher values of the minor principal stress σ_3, suggests the implementation of the empirical strength criterion (Tresca).**
- **Scale problem**

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Thank you

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