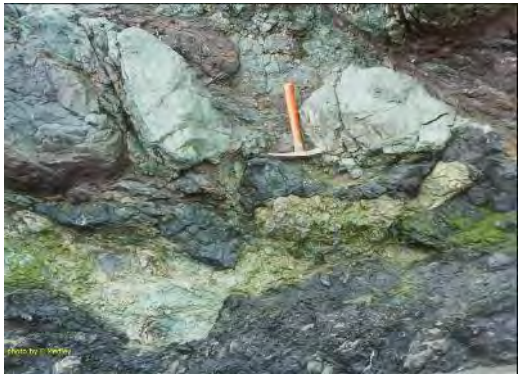
Keynote Lecture*
25 Years of Progress in Characterizing Melanges, Bimrocks, and Similar Rock-Soil Mixtures



Dr. Edmund Medley, PE, PG, CEG, D.GE, F.ASCE
Geological Engineer

Principal Consultant
Terraphase Engineering, Oakland, CA
edmund.medley@Terraphase.com

AEG Annual Meeting 61/IAEG XIII Congress
Sept 18 2018
San Francisco, California

* *"Keynote Lecture" is Fake News; this is an unofficial Keynote lecture*

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Upon first encountering melange: exasperation/puzzlement/confusion

Franciscan Complex melange, at Terrabay Project

Landslide in colluvium composed of melange

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encountering MS/PhD, 1990-1994

Prof. Richard Goodman: and the Force was with me when he asked me to work with he and Eric Lindquist on….

.. a fundamental rock engineering problem at Scott Dam, on Eel River, N. California; founded on Franciscan Complex melange

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melanges

- Melanges reported in over 60 countries; generally associated with ancient and current mountain ranges
- geological mixtures with poly-lithologic blocks ranging in size from sand to mountains
- Controversial topic in geology thousands of papers published since 1950's which include references to melanges and their many aliases

Gwna Melange, Tryn-y-moel, Lleyn Peninsula, Wales

Franciscan Complex melange, Caspar Headland, near Mendocino, California

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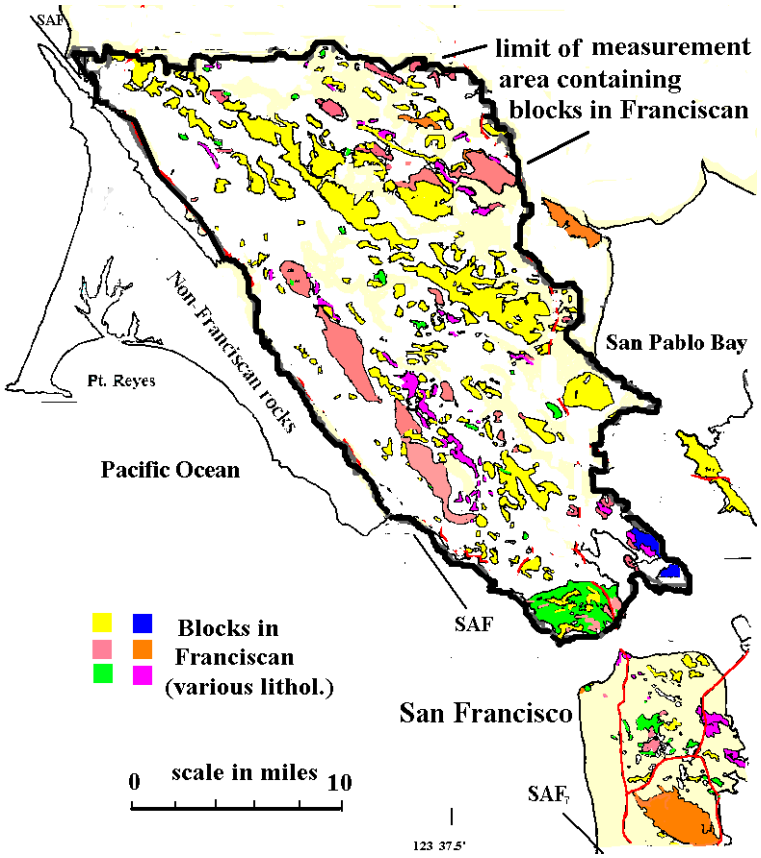
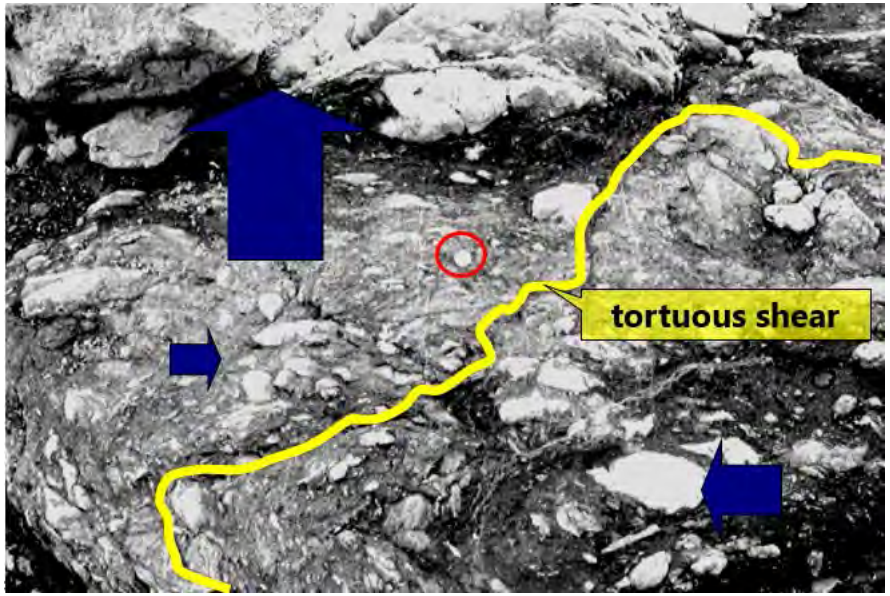
Franciscan Complex near San Francisco, California



From Medley, 1994; after Ellen and Wentworth,1995



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weak block/matrix contacts

Gwna Melange
Lleyn Peninsula,
N. Wales
photo: E . Medley

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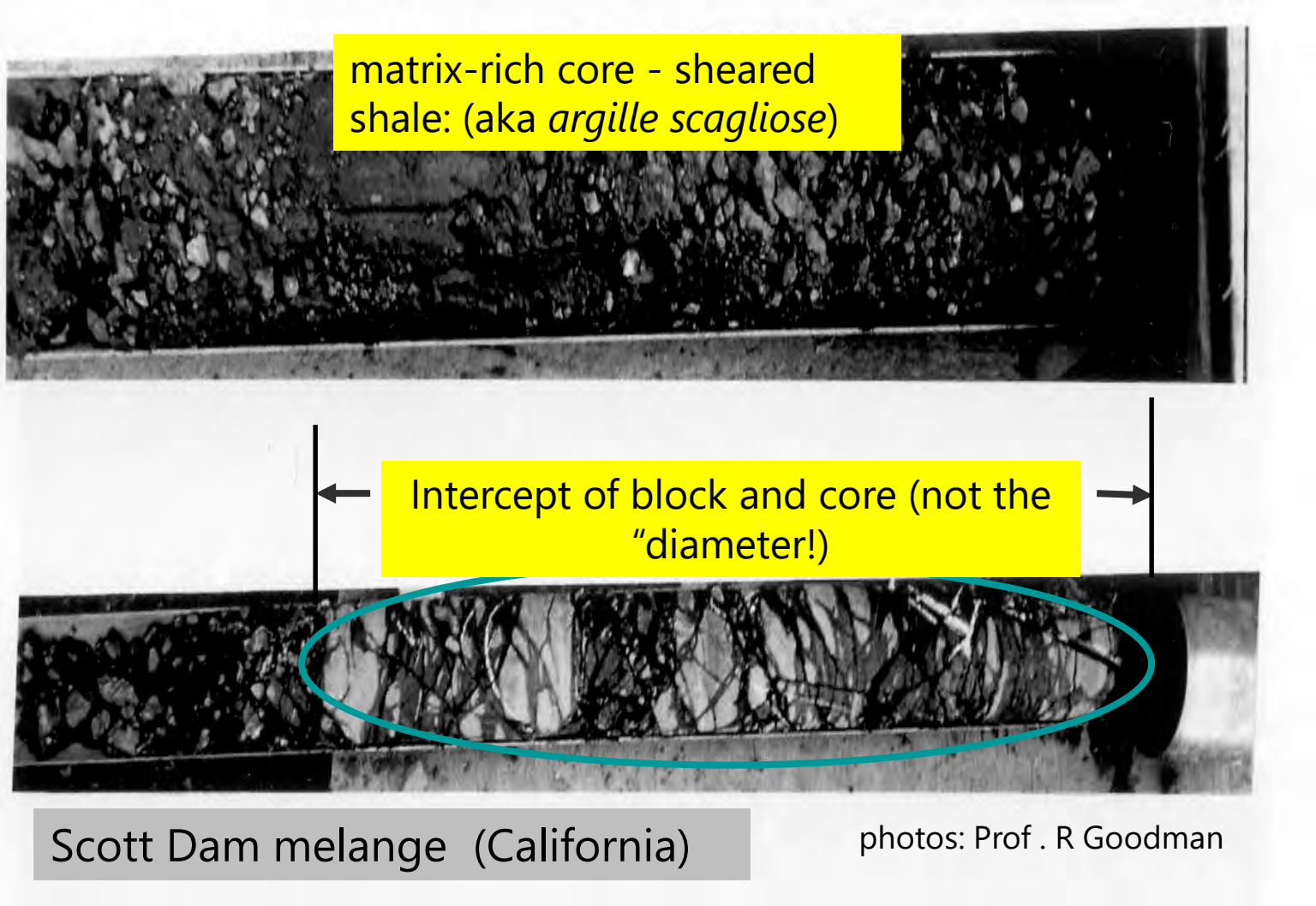
difficult to recover good drilled core in matrix!



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Questions

- What is the overall strength of a complex geological mixture composed of strong blocks within a weaker matrix??
- How much stronger do blocks have to be compared to matrix?
- Why not use the strength of the weak matrix and be “conservative”?
- Does the strength of the blocks matter?
- Is overall strength influenced by block geometries; orientations; number; etc.?
- Does the scale of interest matter?
- How do we characterize complex geological mixtures?

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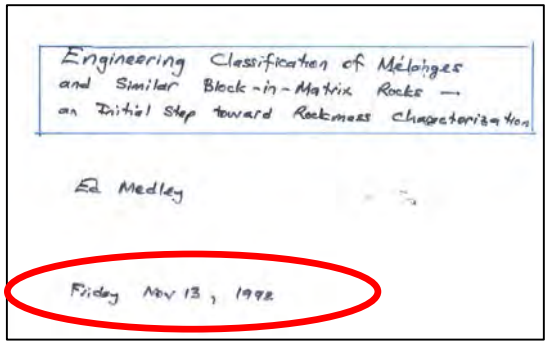
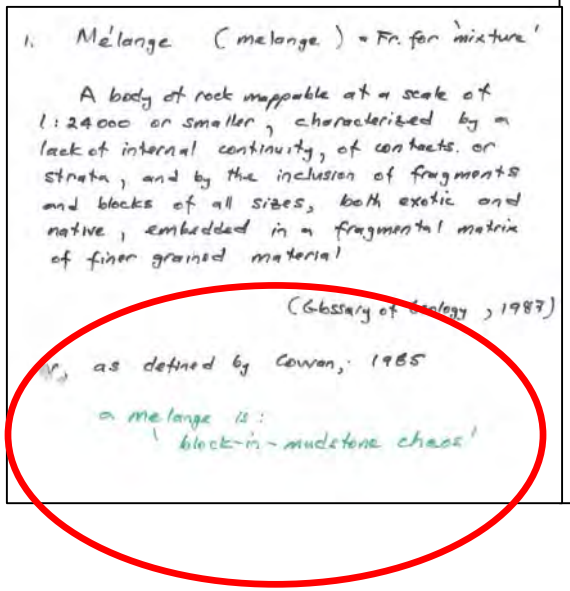
“bimrocks” coined/defined (Medley, 1992)


Engineering Classification of Mélanges and Similar Block-in-Matrix Rocks — an Initial Step toward Rockmass Characterization

E.J. Medley

Friday Nov 13, 1992

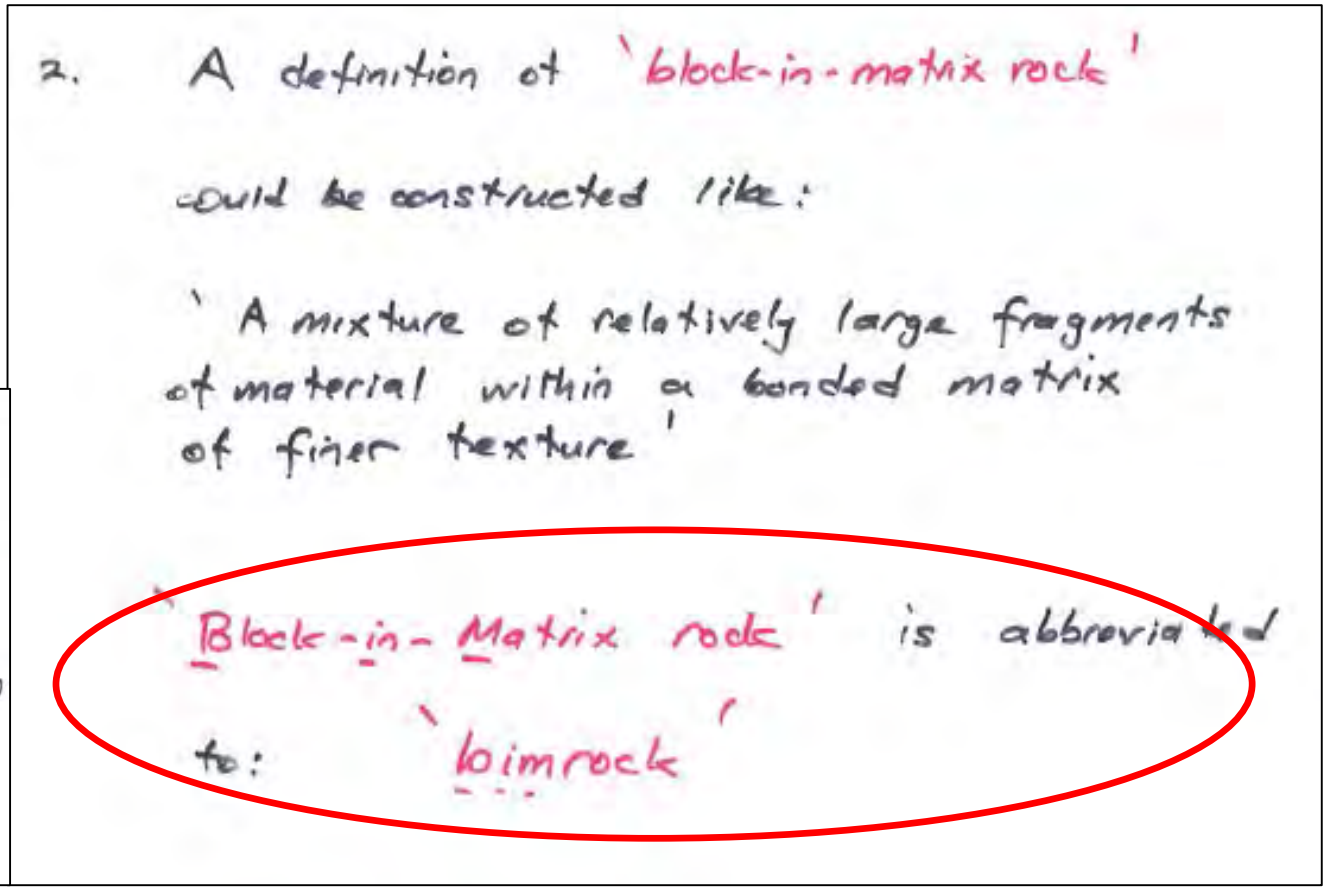

1. Mélange (melange) = Fr. for 'mixture'

A body of rock mappable at a scale of 1:24000 or smaller, characterized by a lack of internal continuity, of contacts, or strata, and by the inclusion of fragments and blocks of all sizes, both exotic and native, embedded in a fragmental matrix of finer grained material

(Glossary of Geology, 1987)

as defined by Cowan, 1985

a melange is:
'block-in-mudstone chaos'


2. A definition of 'block-in-matrix rock' could be constructed like:

'A mixture of relatively large fragments of material within a bonded matrix of finer texture'

'Block-in-Matrix rock' is abbreviated to:

'bimrock'

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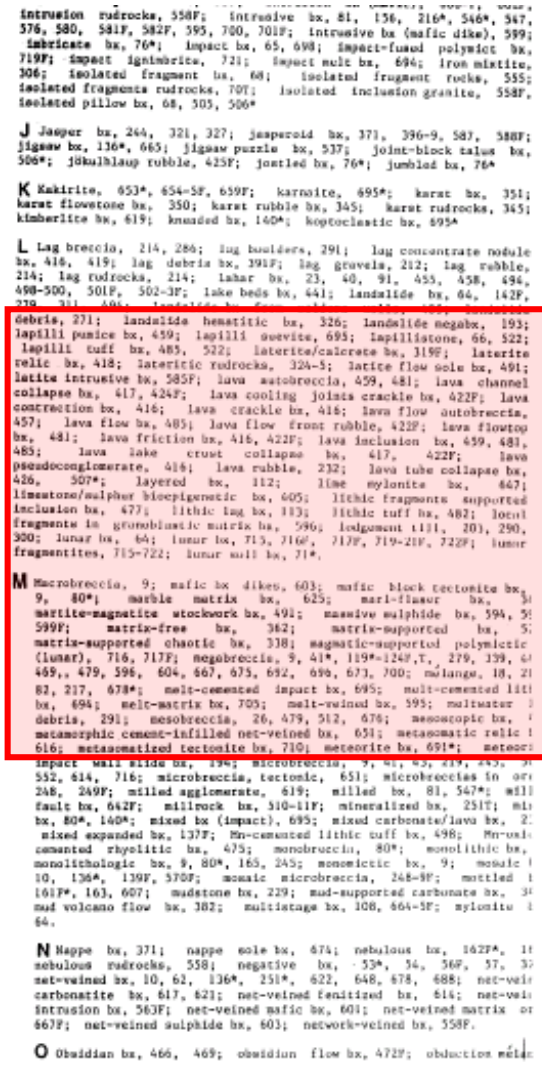
..and > 1000 geological words/terms for fragmented rocks and complex mixtures



debris, 271; landslide hematitic bx, 326; landslide megabx, 193; lapilli pumice bx, 459; lapilli suevite, 695; lapillistone, 66, 522; lapilli tuff bx, 485, 522; laterite/calcrete bx, 319F; laterite relic bx, 418; lateritic rudrocks, 324-5; latite flow sole bx, 491; latite intrusive bx, 585F; lava autobreccia, 459, 481; lava channel collapse bx, 417, 424F; lava cooling joints crackle bx, 422F; lava contraction bx, 416; lava crackle bx, 416; lava flow autobreccia, 457; lava flow bx, 485; lava flow front rubble, 422F; lava flowtop bx, 481; lava friction bx, 416, 422F; lava inclusion bx, 459, 481, 485; lava lake crust collapse bx, 417, 422F; lava pseudoconglomerate, 416; lava rubble, 232; lava tube collapse bx, 426, 507*; layered bx, 112; lime mylonite bx, 647; limestone/sulphur bioepigenetic bx, 405; lithic fragments supported inclusion bx, 477; lithic lag bx, 113; lithic tuff bx, 482; local fragments in granoblastic matrix bx, 596; lodgement till, 203, 290, 300; lunar bx, 64; lunar bx, 715, 716F, 717F, 719-21F, 722F; lunar fragmentites, 715-722; lunar soil bx, 71*.

M Macrobreccia, 9; mafic bx dikes, 603; mafic block tectonite bx, 9, 80*; marble matrix bx, 625; marl-flaser bx, martite-magnetite stockwork bx, 491; massive sulphide bx, 594, 599F; matrix-free bx, 362; matrix-supported bx, matrix-supported chaotic bx, 338; magmatic-supported polymictic (lunar), 716, 717F; megabreccia, 9, 41*, 119*-124F,T, 279, 339, 469,, 479, 596, 604, 667, 675, 692, 696, 673, 700; mélange, 18,

Laznicka, 1988

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bimrocks and bimsoils

Non-geological word ***"bimrocks*** focuses geopractitioner attention on mechanical aspects of block-in-matrix fabric – thus avoiding geological terms

bimrocks definition (Medley, 1994) :

> ***b**lock-**i**n-**m**atrix **rocks** - mixtures of rocks composed of geotechnically significant blocks within a bonded matrix of finer texture*

(melanges, fault rocks, weathered rocks, etc.)

Geotechnical significance: means that there is mechanical contrast between blocks and matrix, **and** the geometry and proportion of the blocks influence the properties of a rock/soil mass underlying a slope, **at the scales of engineering interest** (centimeters to hundreds of meters) i.e.: scale matters!

bimsoils are analogous to bimrocks but with little or no bond in the matrix; or between blocks and matrix (debris flow deposits, glacial tills, colluvium, mine waste, etc.)

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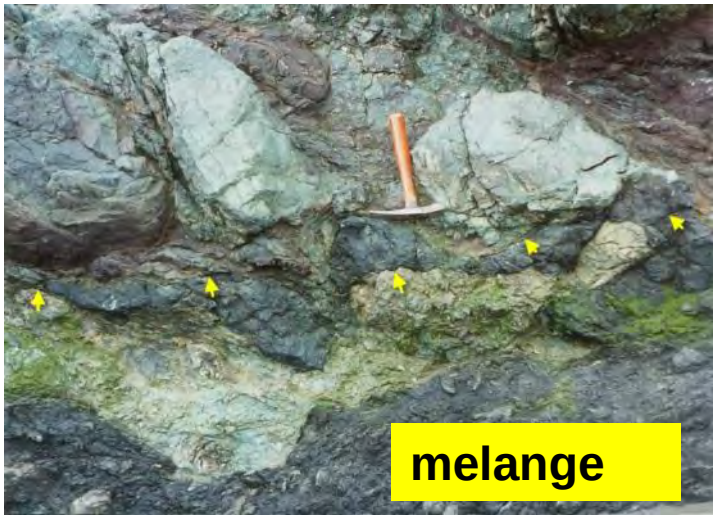
bimrocks: strong blocks, weak matrix- a common fabric



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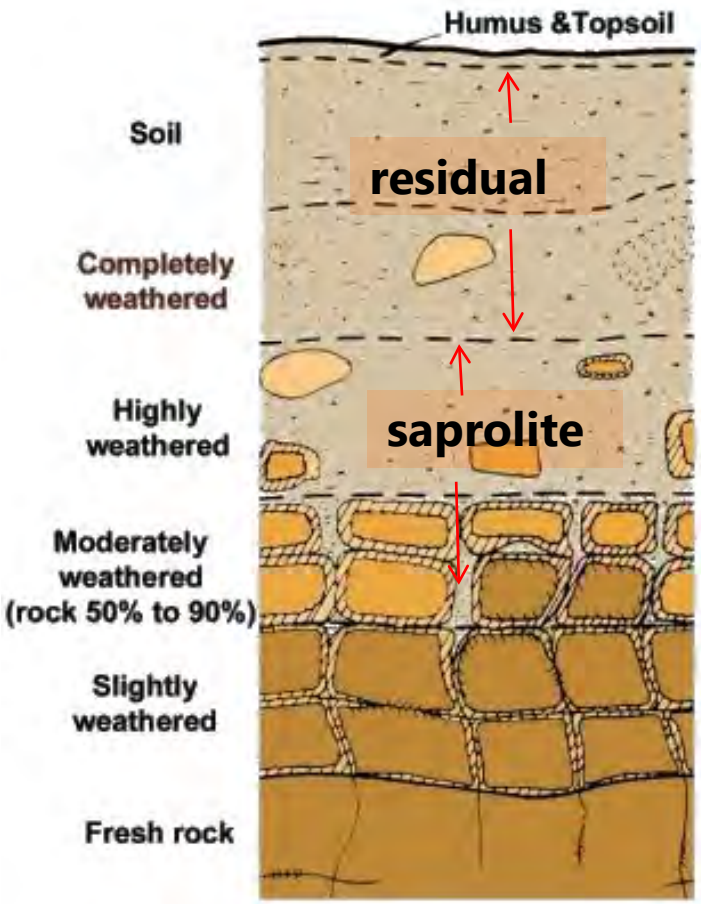
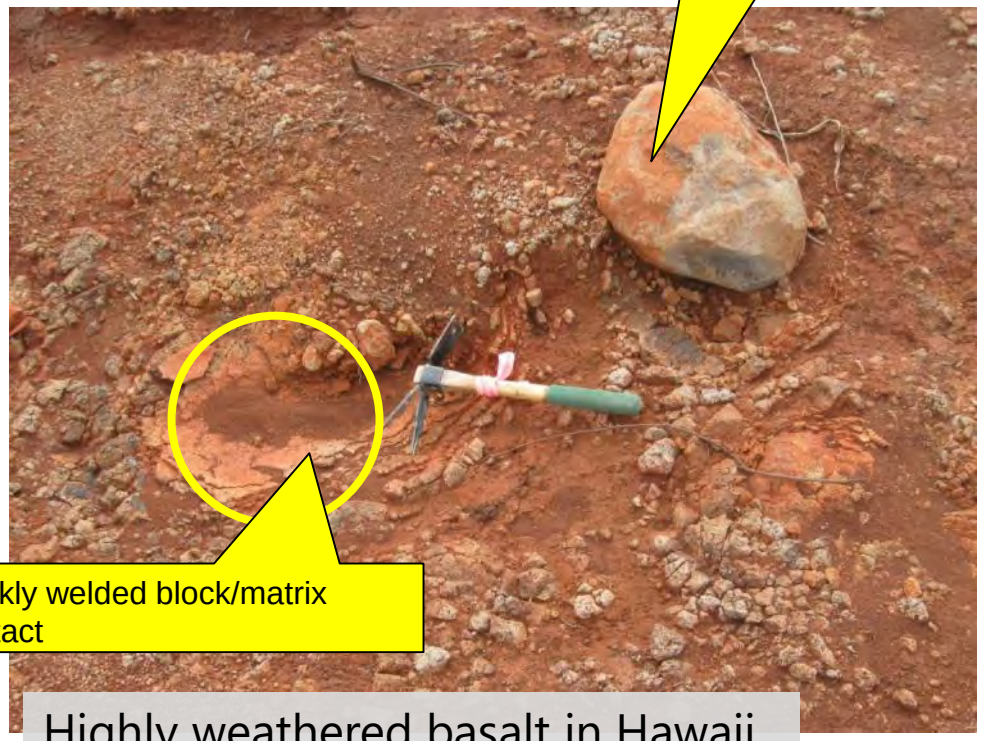
weathered rock: bimrock or bimsoil



residual HW Soils diagram (http://echo2.epfl.ch/VICAIRE/mod/3/chapt/pictures_fig1_7.jpg).jpg



Highly weathered basalt in Hawaii

Highly to moderately weathered rock could be a bimrock/bimsoil (depends on state of matrix and the block/matrix contact)

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Colluvium: bimsoil ("rock/soil mixture")

Colluvium in Medellín, Colombia photo by Prof. O. Ludger Suárez-Burgoa

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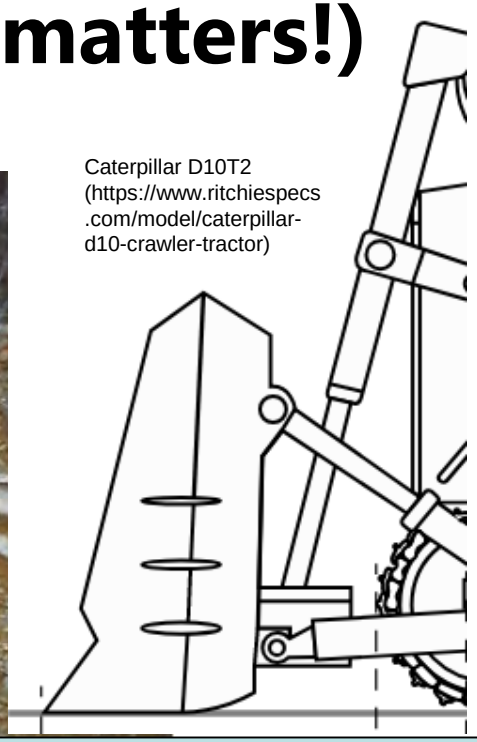
coarse alluvium bimsoil (scale matters!)

Road cut Hwy 1
near Carmel, CA
E. Medley, 1990



Caterpillar D10T2
(https://www.ritchiespecs
.com/model/caterpillar-
d10-crawler-tractor)

HARD cobbles and boulders: troublesome to work with? Depends on excavation method

Scale matters! bimsoil at lab scale and for a micro-tunnel, likely for a scraper and D-10 bulldozer; possibly for a 20 ft dia. TBM; not for a slope 100 feet high.

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Summarizing: block-in-matrix fabric is common

Bimrocks/bimsoils often have **severe spatial variability and mechanical/lithological heterogeneity-** depends on scale of interest!

SO WHAT? Mischaracterizations of bimrocks **co$t -** so important to Contractors, Owners and Lawyers

Geopractitioners must consider blocks (size, lithology, shape, orientation, block/matrix contacts, SIZE etc..)

Dr. Julien Waeber, PE, PG, CEG
Geological Engineer

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Bimrocks: what they are not

- Not BIM: BIM is Building Information Modelling (1980's)
- Not the blocks themselves
- Not *bimsteins* (pumice)
- Not SRM (soil rock mixtures) with unwelded block-matrix contacts and limited scales of interest
- Not "interlayered x and y" (e.g.: "interlayered shale and sandstone")
- Not "miscellaneous soils"

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bimrock strength

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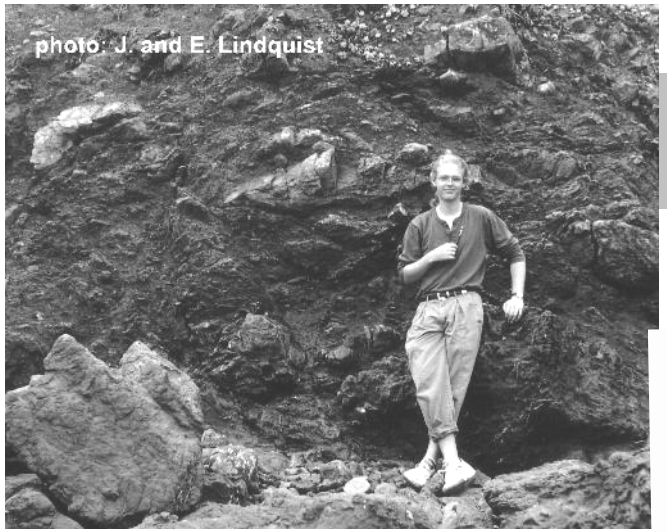
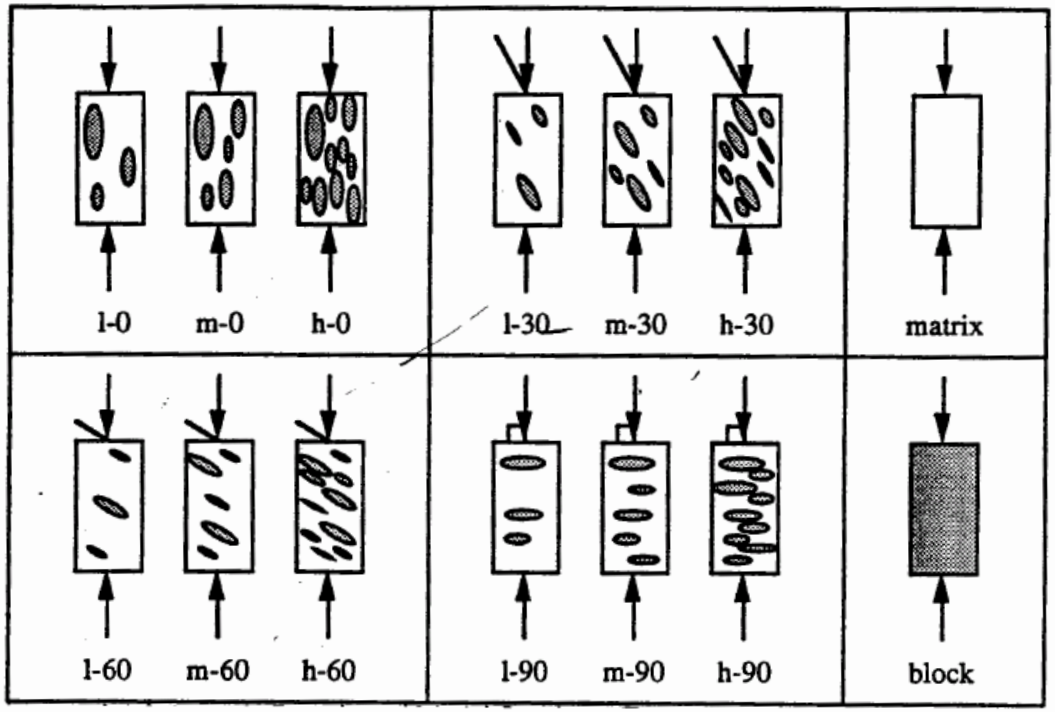
Eric Lindquist and physical model melanges



Dr Eric Lindquist, 1994, Caspar Headlands, Mendocino, California



Lindquist, 1994

Eric Lindquist near Mendocino, California about 1992

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What does this bit of bimrocks definition mean?

"*Geotechnical significance means that there is mechanical contrast between blocks and matrix…*"

Block/matrix strength criteria (Kalendar et al, 2014)

Table 1
Strength and stiffness contrasts between blocks and matrix for bimrocks as defined in literature.

Criterion	References
$(E_{block} / E_{matrix}) > \sim 2.0$	Lindquist (1994)
$(\tan\phi_{block} / \tan\phi_{matrix}) > 1.5–2.0$	Medley (1994), Lindquist and Goodman (1994)
$UCS_{block} / UCS_{matrix} > 1.5$	Recommended criterion by Dr. H. Sonmez in Medley and Zekkos (2011)

E: elastic modulus; ϕ: internal friction angle; UCS: uniaxial compressive strength.

Kalender et al, 2014; An approach to predicting the overall strengths of unwelded bimrocks and bimsoils; Engineering Geology 183 (2014) 65–79

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Lindquist (1994) tested ~120 150 mm specimens of model melange

150 mm diameter Tx specimens (Lindquist, 1994)

Developed surface of Tx specimen - tracing of blocks on transparent kitchen film

Medley, 2004

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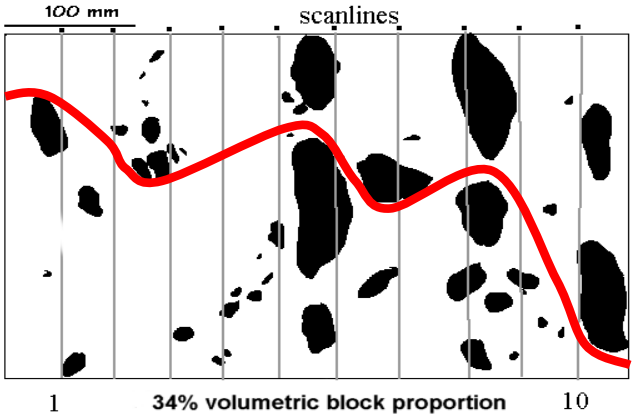
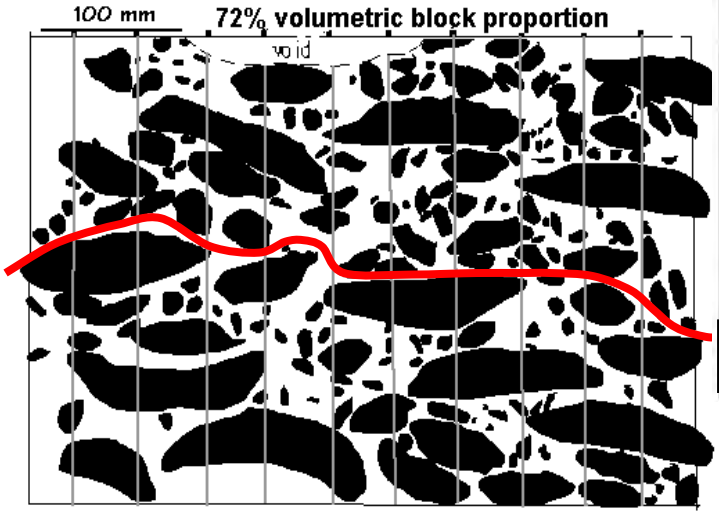
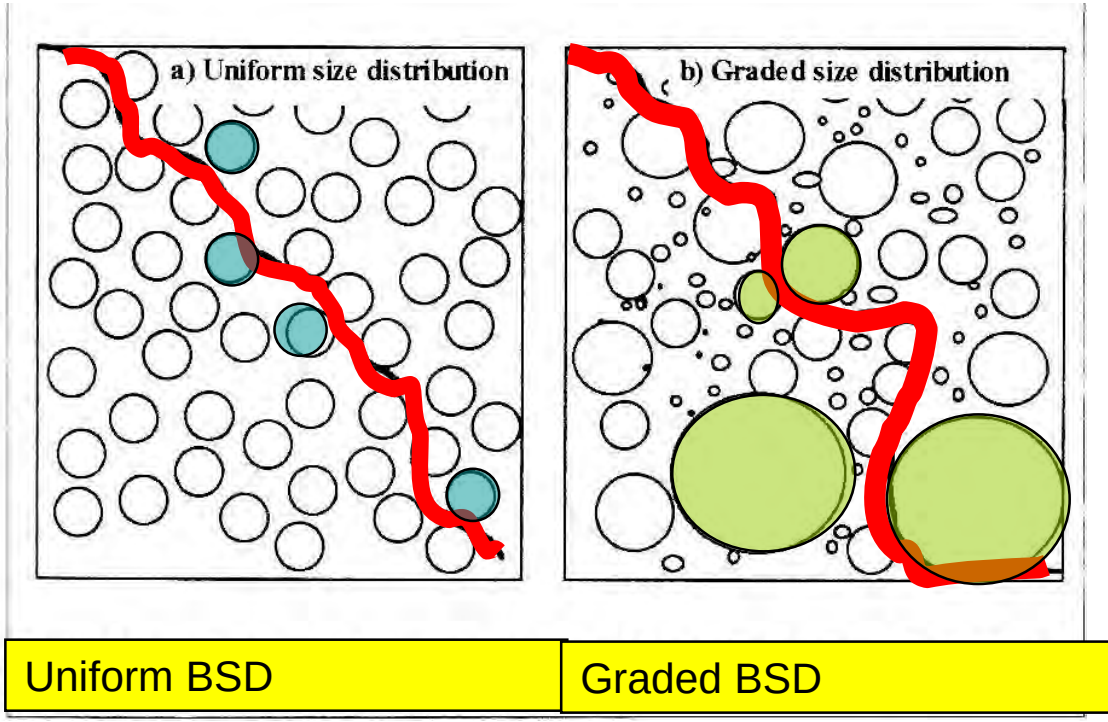
Frictional strength afforded by tortuosity of failure surfaces - affected by block proportions, shapes, size distributions, orientations, etc..







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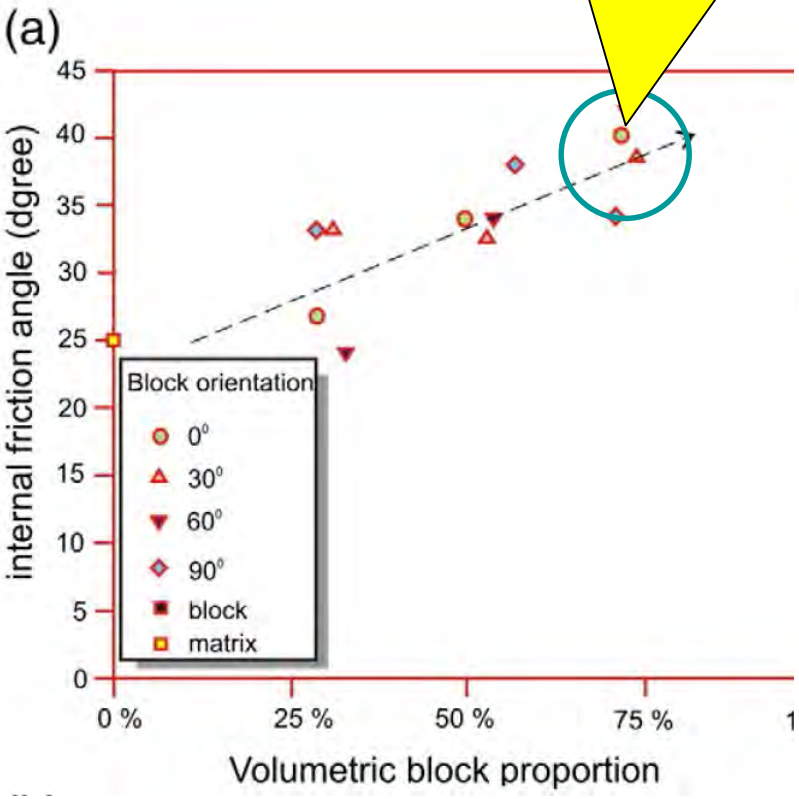
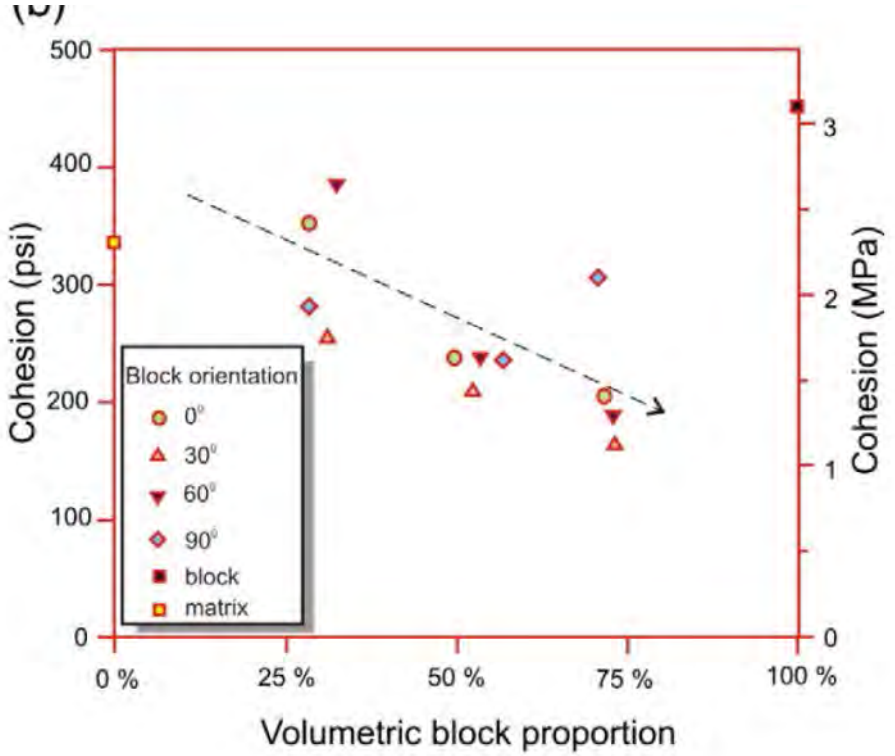
High block proportion: threshold for block-to-block contacts

Lindquist (1994) results





Kalendar et al 2014) after Lindquist, 1994

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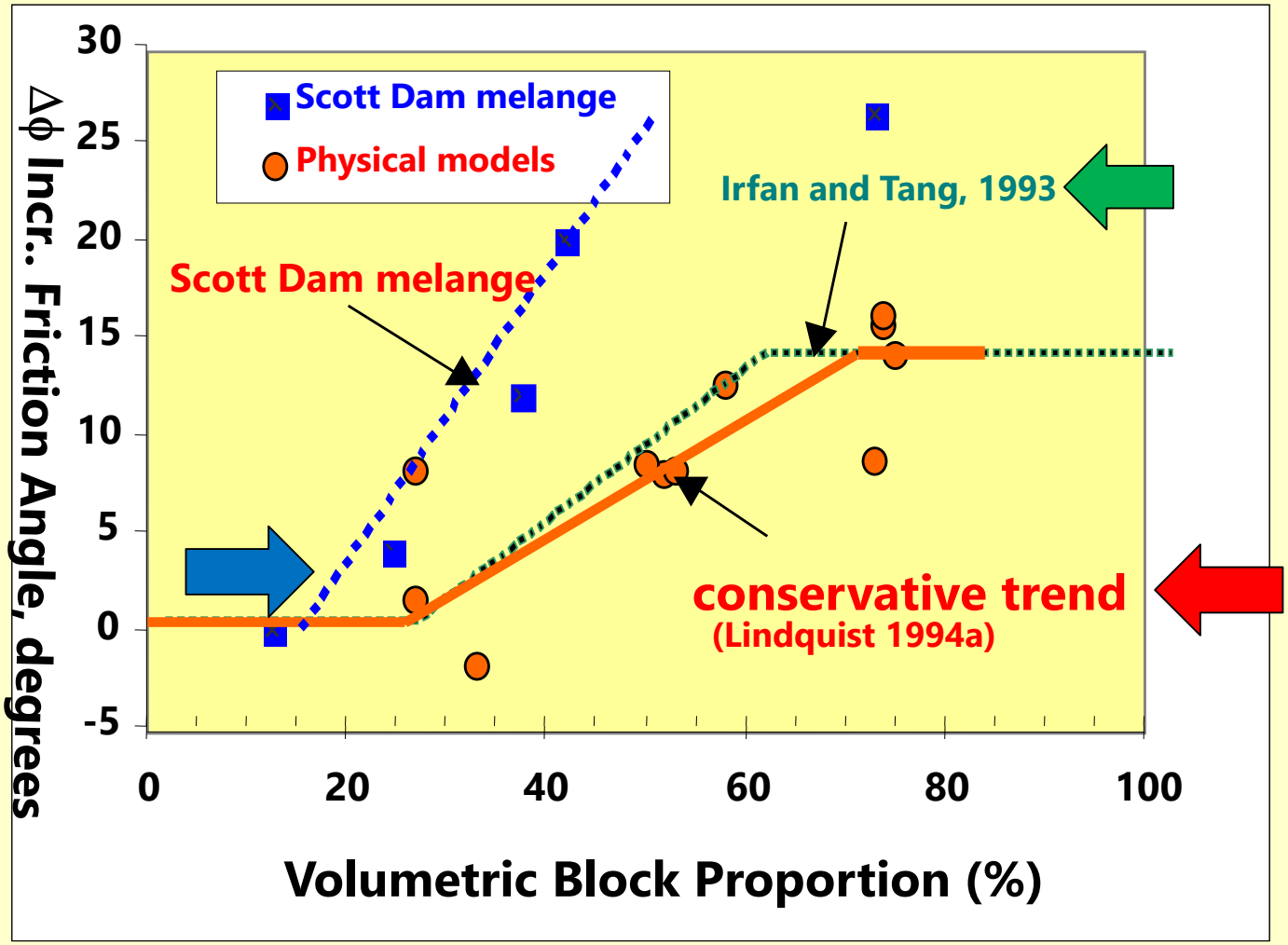
Lindquist (1994) fundamental finding: Overall strength of a bimrock depends simply on volumetric block proportion



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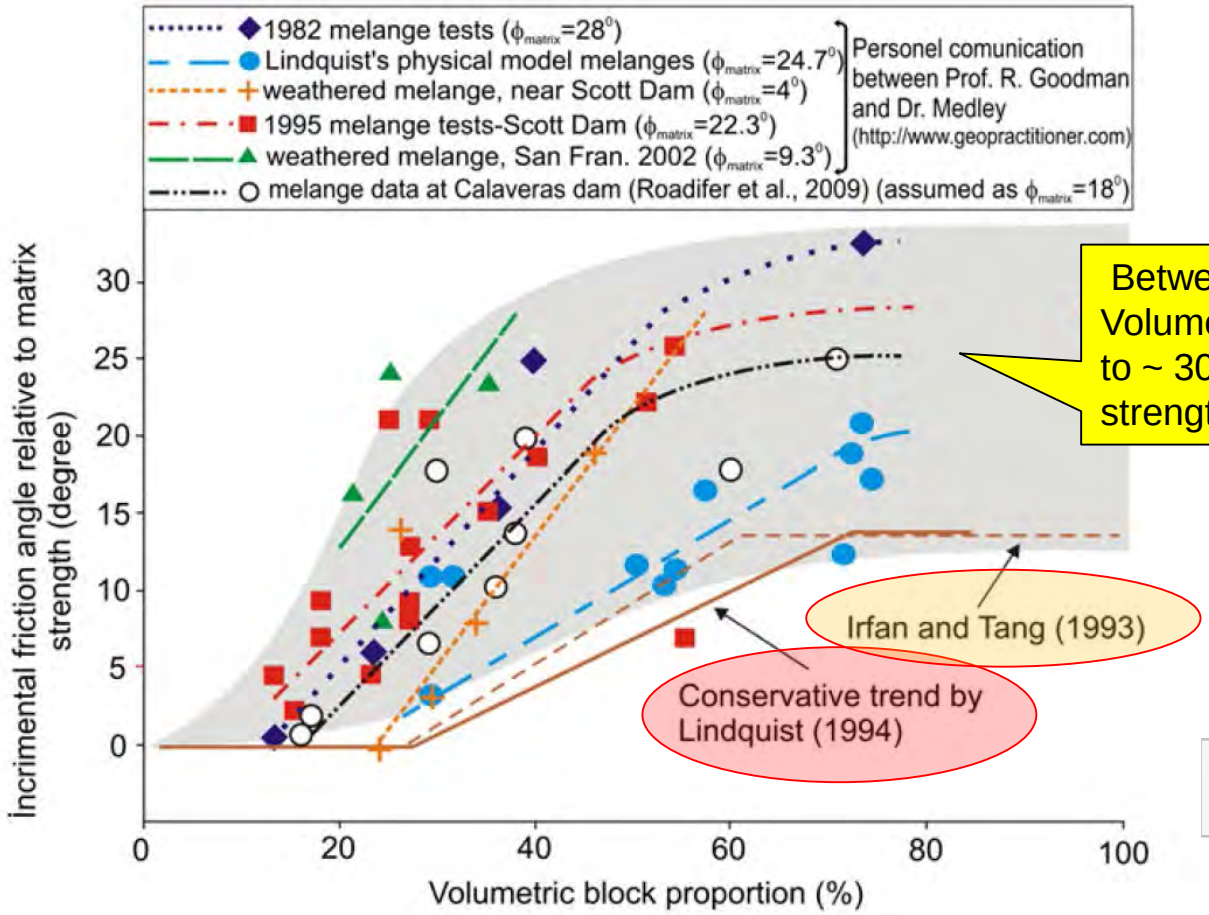
More data: Friction Angle increases with Volumetric Block Proportion



Between about 10% and 70% Volumetric Block Proportion - gain up to ~ 30 degrees of added friction strength, relative to matrix strength

After Kalendar et al, 2014, after various contributors

Fig. 9. Incremental internal friction angle relative to matrix strength versus VBP, and possible incremental zone.
Lindquist (1994) and pers. comm. R. E. Goodman and E. Medley.

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2018: Lab testing of bouldery soil using large lab equipment

Fig. 2. Material bouldery soils in Bukit Salam area

max. block size 250 mm (10")

Fig.1. View and detail calibration chamber in geotechnical laboratory of Parahyangan Catholic University, Bandung.

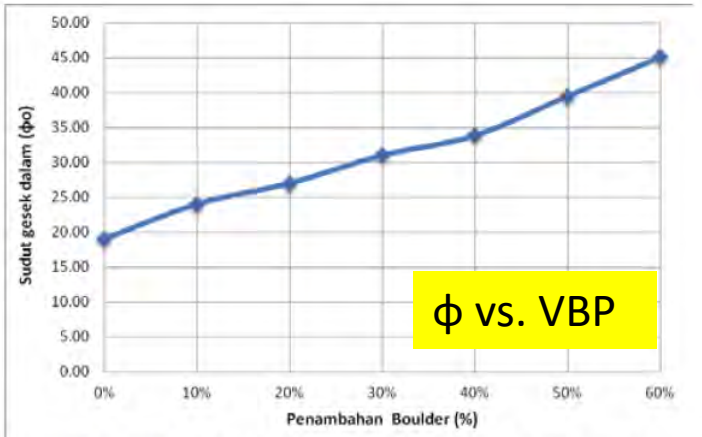

Figure 14. Effect of boulder composition by adding the percentage of boulder to the internal friction angle (φ) bouldery soils.

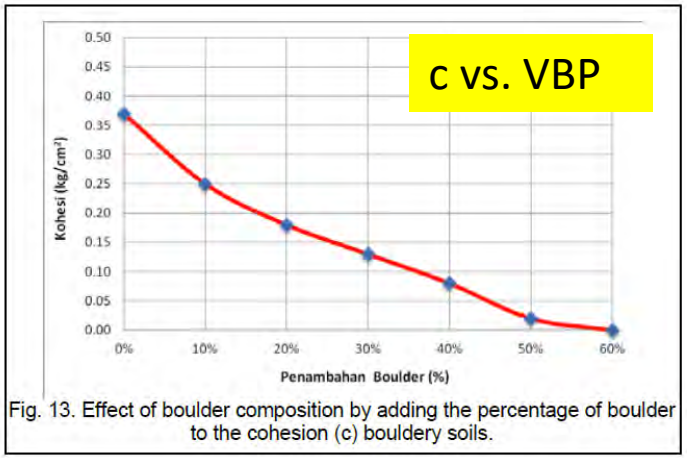

Fig. 13. Effect of boulder composition by adding the percentage of boulder to the cohesion (c) bouldery soils.

Peregrinus Dhae Siga Taa, Paulus Pramono Rahardjo, A.Aziz Djayaputra; 2018; *Experimental study on the determination of shear strength parameter of bouldery soils using large triaxial calibration chamber*; International Journal of Scientific & Engineering Research, Volume 9, Issue 7, July-2018 ISSN 2229-5518 pp1592-1600

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2018: Lab testing of model colluvial SRM using TX tests and CT scanning

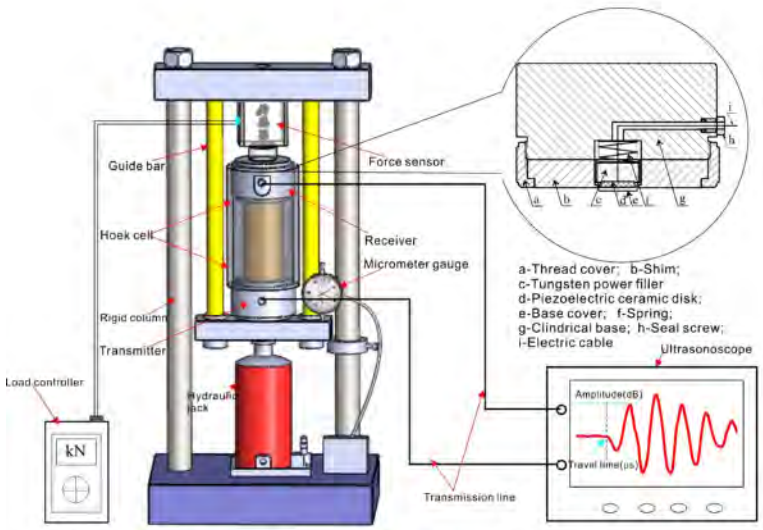
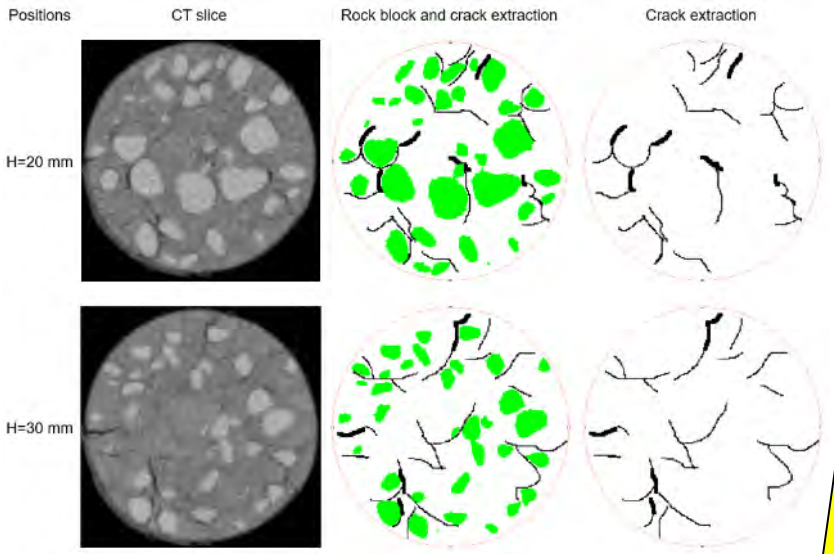


Fig.3 The real-time ultrasonic testing system for the bimsoil sample under triaxial deformation



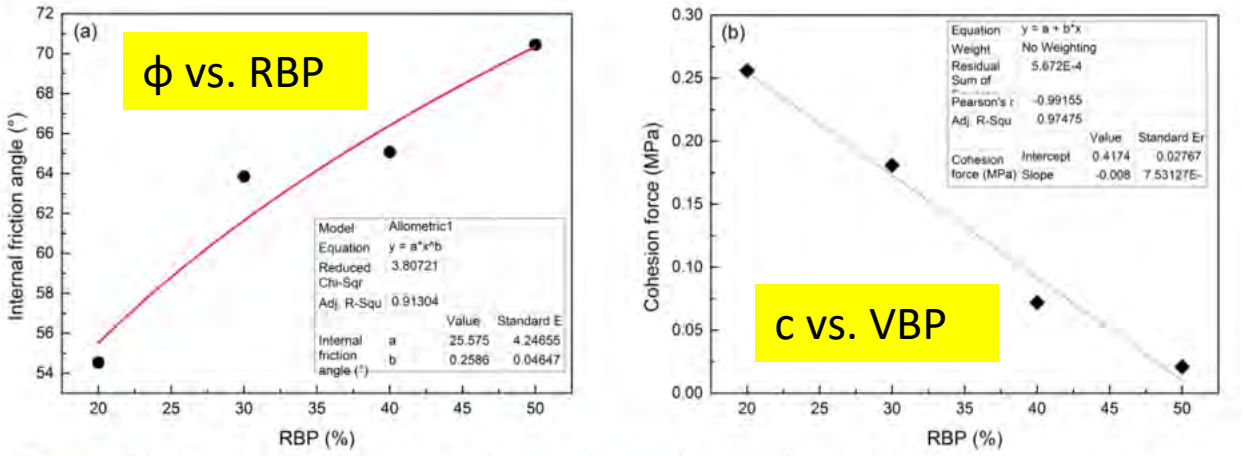


Fig.11-12 Correlation between the internal friction angle (a) , cohesion force (b) and rock block percentage (RBP)

CT scanning at various locations of specimen during TX loading

Y. Wang, C. H. Li, Z. Q. Hou, 2018; Mechanical behaviors of bimsoils during triaxial deformation revealed using real-time ultrasonic detection and post-test CT image analysis; Arabian J. Geological Sciences ***(IN REVIEW)***

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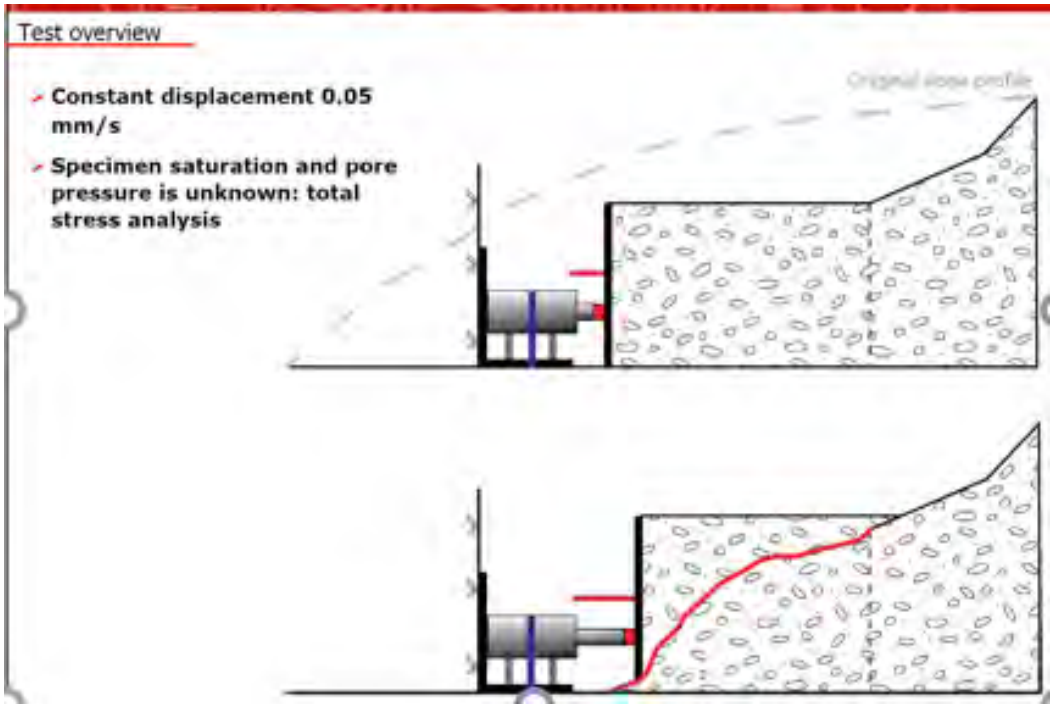
BimTest

- overcome the size limitation of laboratory specimens
- investigate the mechanical behaviour of the bimrock by properly taking into account the influence of blocks

- No lateral deformation
- Constant horizontal displacement
- No vertical load

Coli et al, 2014 (Appenines, Italy)



Coli et al, In-Situ large size non-conventional shear tests for the mechanical characterization of a bimrock, Presentation at Eurock 2010

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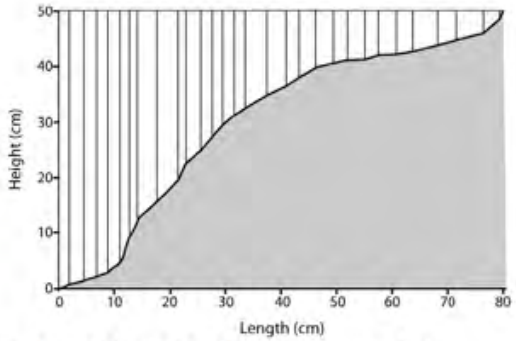
B/M threshold = block/matrix threshold

Correlation of strength parameters with the volumetric block content (VBC) inside each specimen

- **B/M threshold: 1 cm (L_c: max specimen linear dimension)**
- **Evaluation of VBC inside each specimen by means of in situ large-size sievings**

Coli et al, In-Situ large size non-conventional shear tests for the mechanical characterization of a bimrock, Presentation at Eurock 2014

Determination of strength parameters



Coli et al, 2014 (Appenines, Italy)

- **A pair of *c* and *φ* parameters was calculated for each specimen by means of a limit equilibrium analysis performed on cross sections of the sliding surfaces**

Test	φ (°)	c (kPa)
P1	43	6
P2	29	49
P3	48	6
P4	48	7
P5	-	-
P6	45	4

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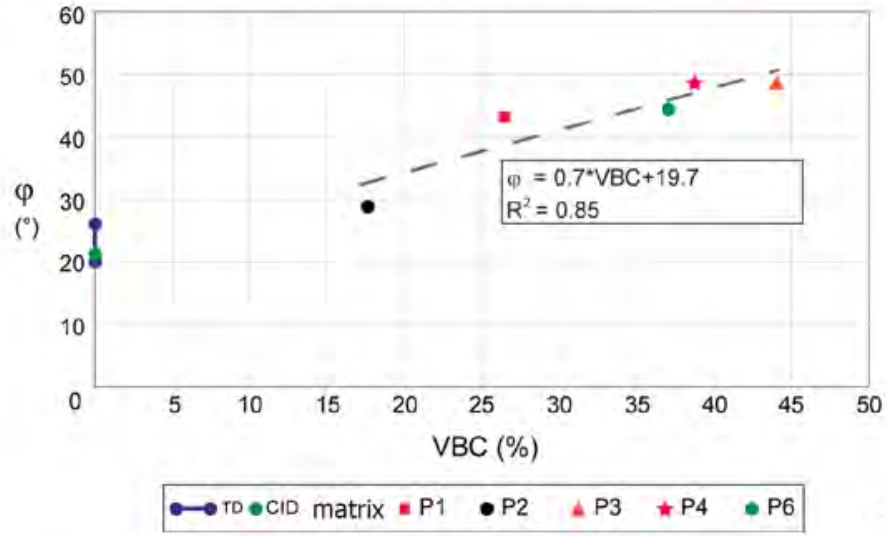
- **Very good correlation VBC – φ (R^2 = 0.85)**
- **Increase in φ with VBC according to the relationship φ = 0.7*VBC+19.7**

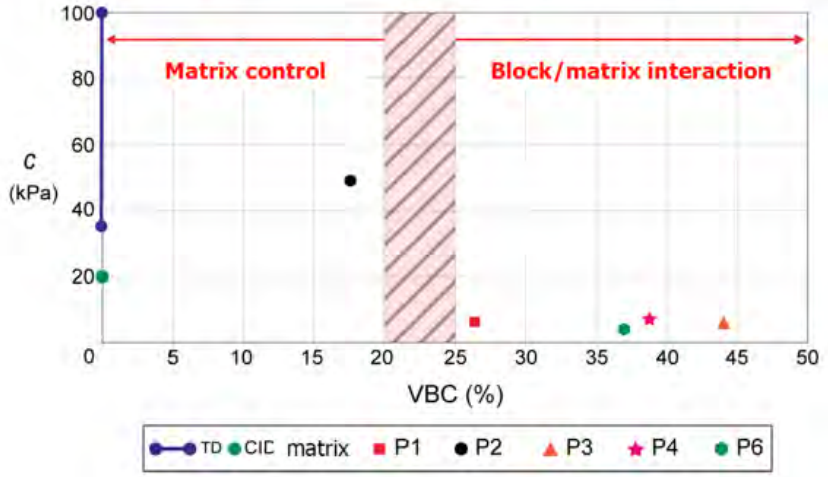


Coli et al, 2014 (Appenines, Italy)

NOTE

1. Increase in frictional strength for VBC < 25%
2. Frictional strength at VBC ~ 50% is ~ 25 degrees > matrix strength
3. Cohesion for VBP < 25% ~ c_{matrix}
4. Cohesion for VBP>25% ~ << c_{matrix}

- **VBC > 25% → very low *c*, slight correlation with VBC**
- **VBC < 25% → *c* values close to the ones of the clayey matrix**



Coli et al, In-Situ large size non-conventional shear tests for the mechanical characterization of a bimrock, Presentation at Eurock 2010

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strength and deformation properties of melange bimrocks

Overall strength increase over matrix-only strength is **directly related to volumetric block proportion**

Strength and deformation of melanges are independent of block strengths

The presence of blocks increases frictional strength of the bimrock, stiffens the mixture, reduces cohesion and induces tortuous failure surfaces negotiating around blocks

Must perform geotech tests with blocks in specimens because many bimrocks at lab scales are models of bimrocks at site scales

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In-situ testing of Soil-Rock Mixtures

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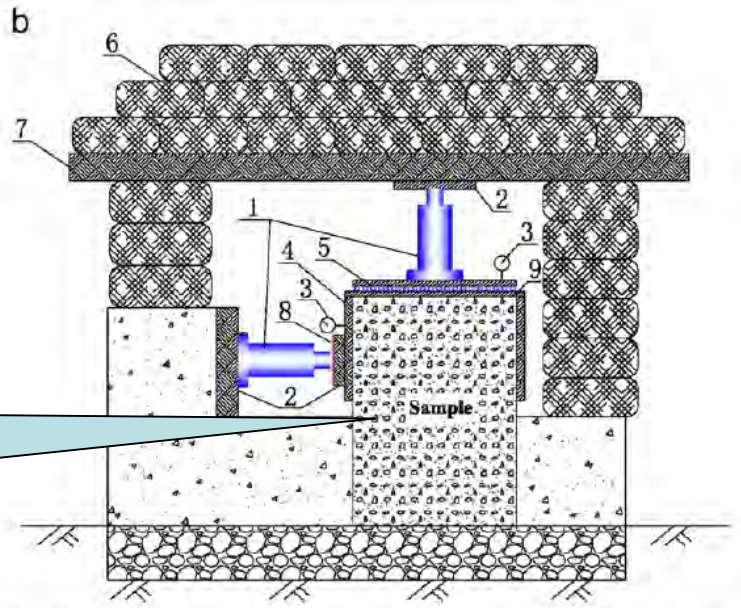
In-situ testing installation (Xu et al, 2011)

reconstituted soil-rock mixtures tested in shear boxes



reconstituted soil-rock mixtures tested in shear boxes

Fig. 11. Test equipment of the large-scale direct shear test of S-RM in field: (a) overall perspective of the field test, (b) profile of the test equipment. 1—jacks; 2—crosstie; 3—dial indicator; 4—shear box; 5—sliding steel plate; 6—back pressure system; 7—beam; 8—slideway; 9—bearing plate.

Wen-Jie Xu, Qiang Xu, Rui-Lin Hu, 2011*; Study on the shear strength of soil–rock mixture by large scale direct shear test*; International Journal of Rock Mechanics & Mining Sciences 48 (2011) 1235–1247

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In-situ soil-rock mixture: coarse alluvium (Xu et al, 2011)

"prospecting drift" used to photograph typical exposures of soil-rock mixture (as below)

Wen-Jie Xu, Qiang Xu, Rui-Lin Hu, 2011*; Study on the shear strength of soil–rock mixture by large scale direct shear test*; International Journal of Rock Mechanics & Mining Sciences 48 (2011) 1235–1247

Fig. 1. Main material of the Xiazanri S–RM slope: (a) river phase cobble and grave and (b) S–RM.

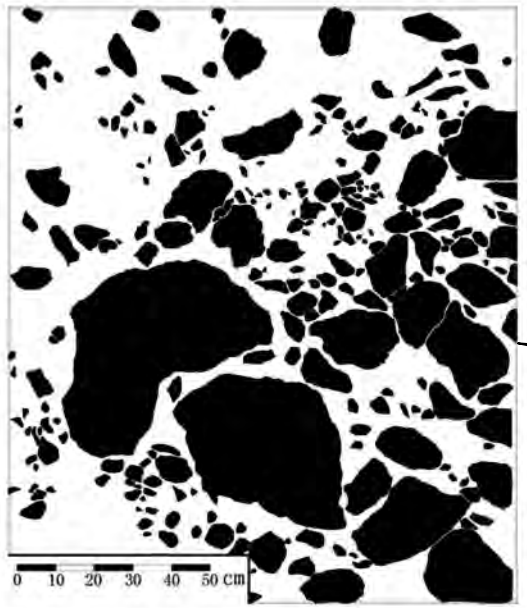

Fig. 5. Binary image of the S–RM's internal structure after digital image processing.

Digital image processing of an outcrop of soil-rock mixture

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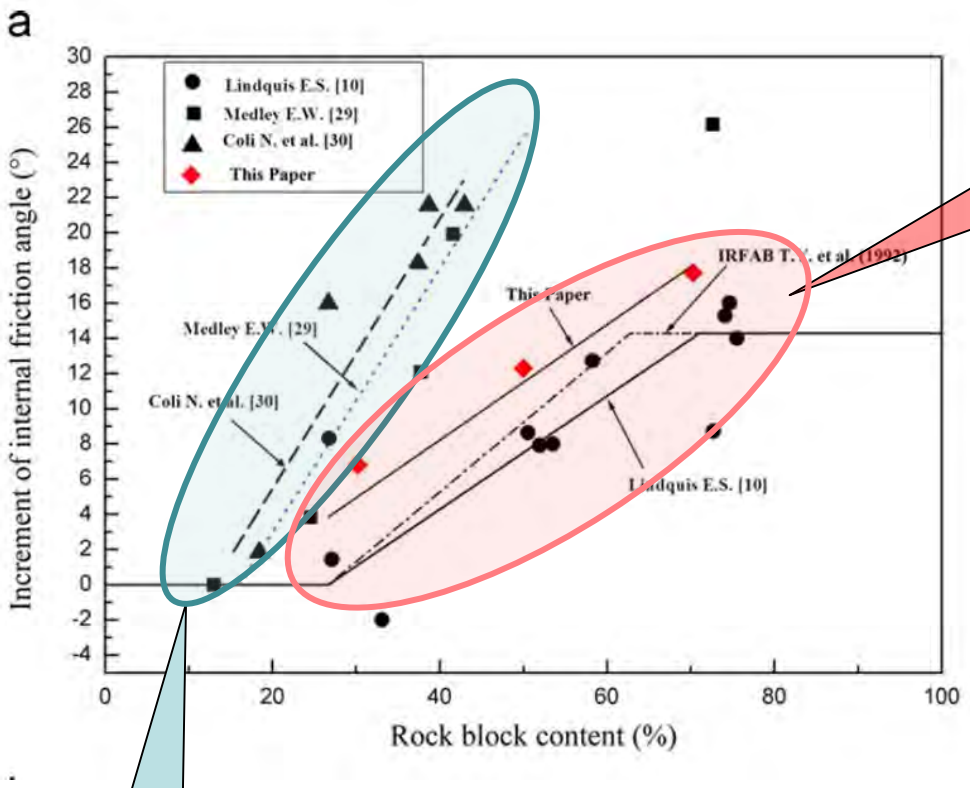
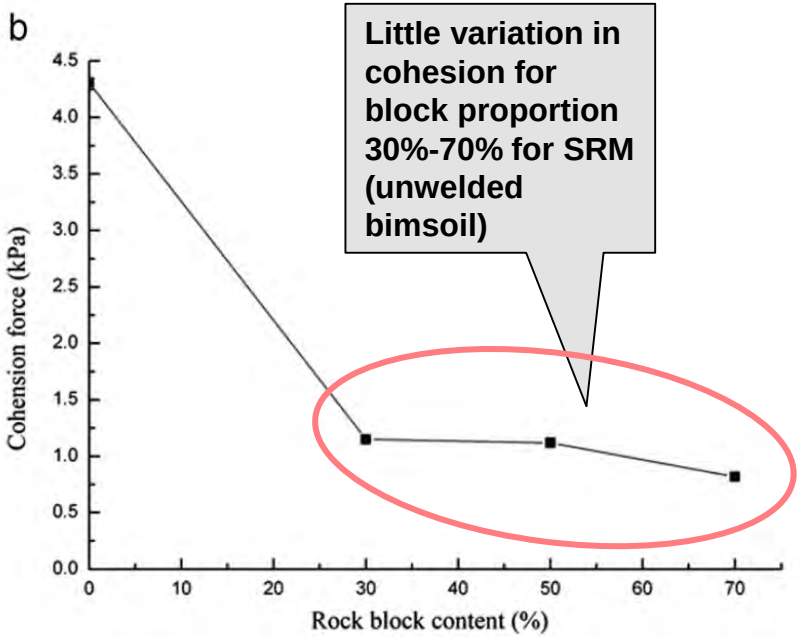
In-situ test results for Soil-Rock Mixtures (Xu et al, 2011)



Test data for soil-rock mixture/ boulder colluvium, and physical model bimrocks **(unwelded bimrocks and bimsoils)**

test data for natural melanges **(welded bimrock)**



Little variation in cohesion for block proportion 30%-70% for SRM (unwelded bimsoil)

Wen-Jie Xu, Qiang Xu, Rui-Lin Hu, 2011; *Study on the shear strength of soil–rock mixture by large scale direct shear test*; International Journal of Rock Mechanics & Mining Sciences 48 (2011) 1235–1247

Fig. 16. Relationship between the shear strength of S–RM and its rock block proportion: (a) relationship between the increment of internal friction angle and rock block proportion (after [28]). (b) Relationship between the cohesion and rock block proportion.

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Hydraulic Cylinder Testing of SRM in earth-filled dam (N. Spain)

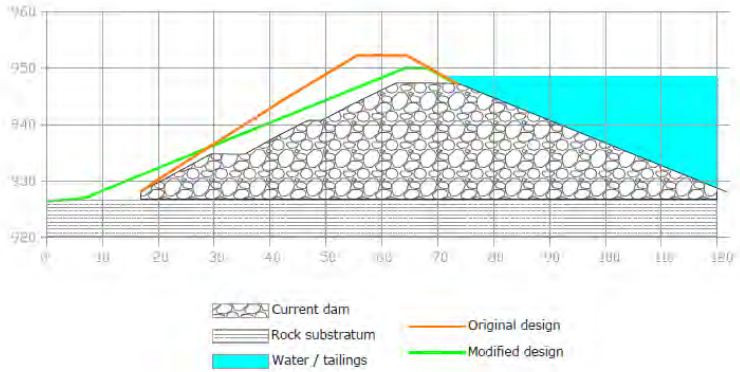

Fig. 15 Modified design

HCT is similar to Plate Loading Test except horizontal loading instead of vertical loading.

Estimation of geotechnical properties also used the Bim strength approach of Kalender et al, 2014.

Rodriquez et al, 2015; Application of hydraulic cylinder testing to determine the geotechnical properties of earth-filled dams; Geomechanics and Engineering, Vol. 9, No. 4 (2015) 483-498
DOI: http://dx.doi.org/10.12989/gae.2015.9.4.483

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Kalendar et al (2014) Bim strength empirical method

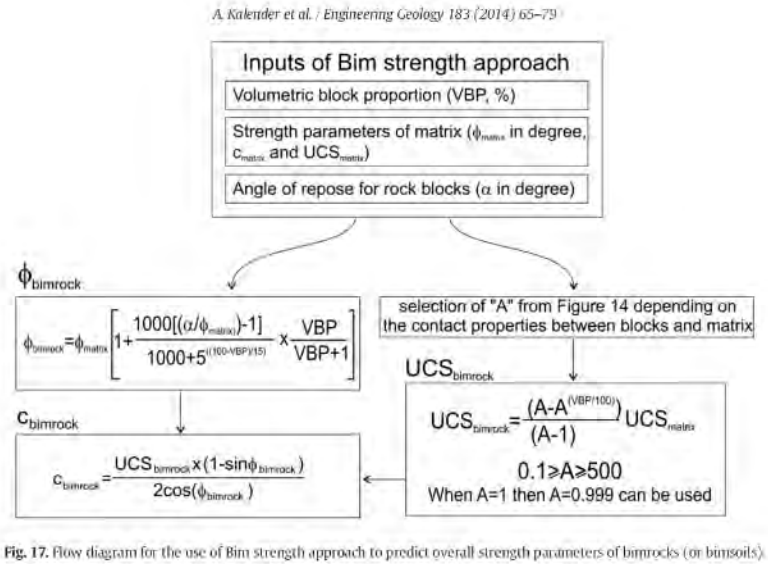

Fig. 17. Flow diagram for the use of Bim strength approach to predict overall strength parameters of bimrocks (or bimsoils).

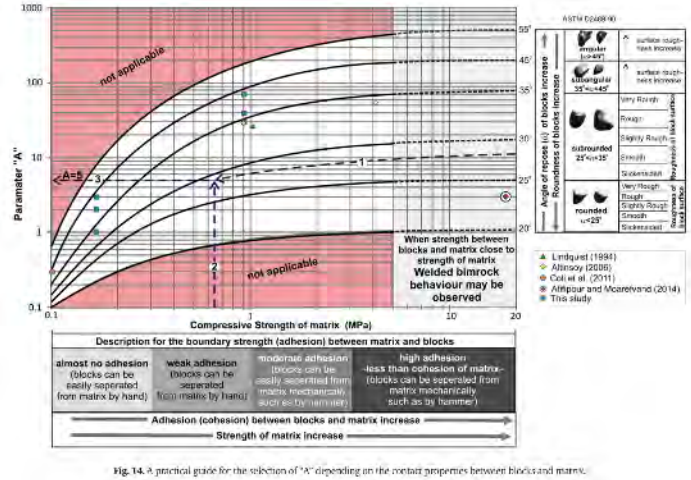

Fig. 14. A practical guide for the selection of "A" depending on the contact properties between blocks and matrix.

- Kalendar et al (2014) method based on large database of geotech data for bimrocks
- simple input parameters such as UCS, c, ϕ of matrix, VBP, shape and angularity of blocks, and angle of repose of blocks
- Method requires estimate of Parameter "A" - a measure of block/matrix contact strength - using a handy selection chart

Kalender et al, 2014; An approach to predicting the overall strengths of unwelded bimrocks and bimsoils; Engineering Geology 183 (2014) 65–79

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V. Marinos (2017) GSI chart for heterogeneous rock masses

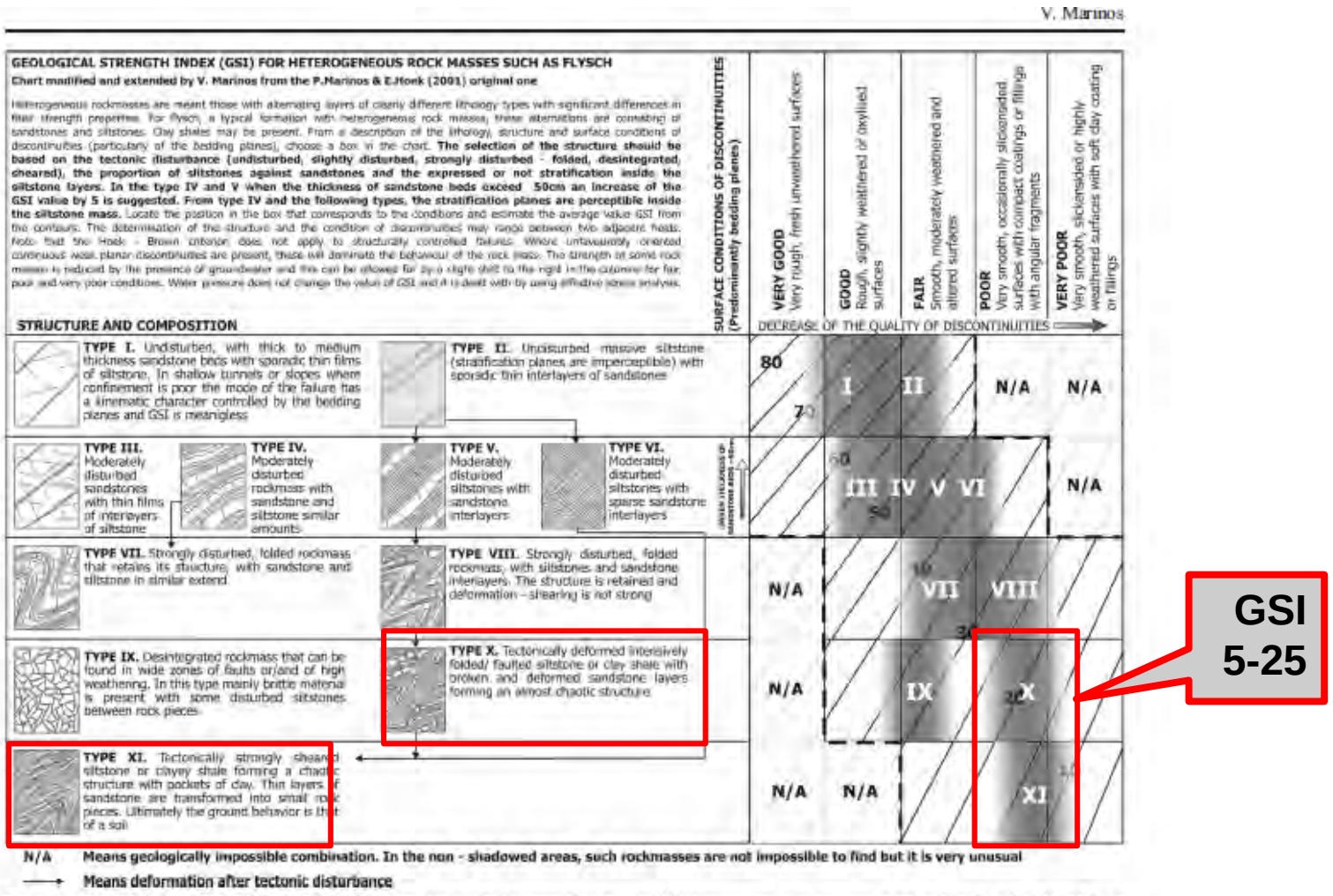

Fig. 7 A new, revised, geotechnical classification GSI system for tectonically disturbed heterogeneous rock masses, such as flysch, with the fields of most probable occurrence. The chart is modified and extended from the original one (Marinos and Hoek 2001)

Marinos, V,, 2017; A revised, geotechnical classification GSI system for tectonically disturbed heterogeneous rock masses, such as flysch; ; Bull Eng Geol Environ DOI 10.1007/s10064-017-1151-z

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Scale Independence

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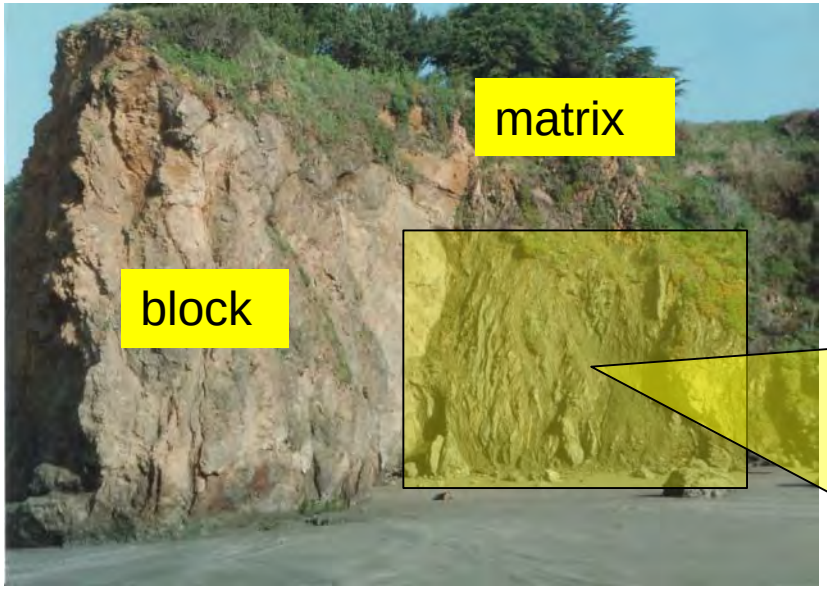
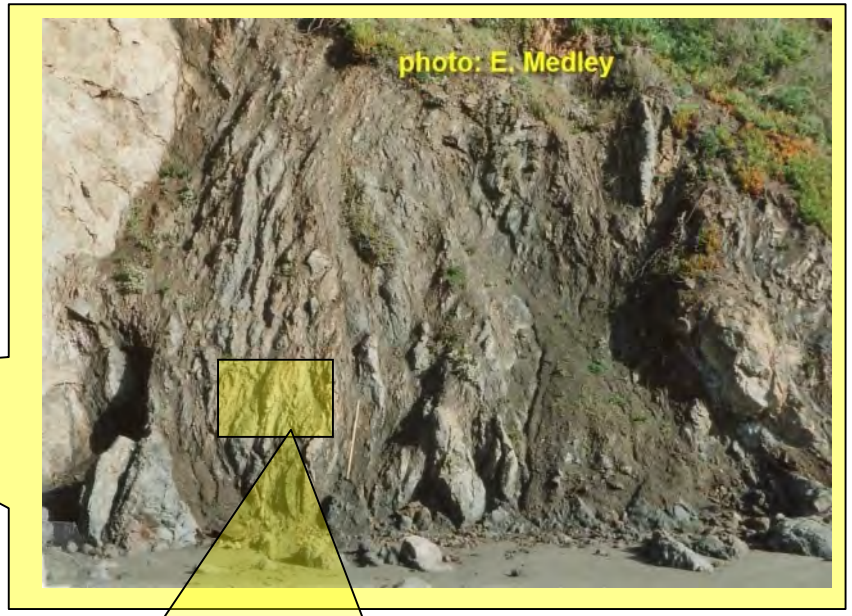
a Franciscan Complex melange: **blocks at many scales**



Caspar Headlands Mendocino area, CA E Medley



Huge blocks, big blocks, small blocks, tiny blocks – all depends on your scale of interest

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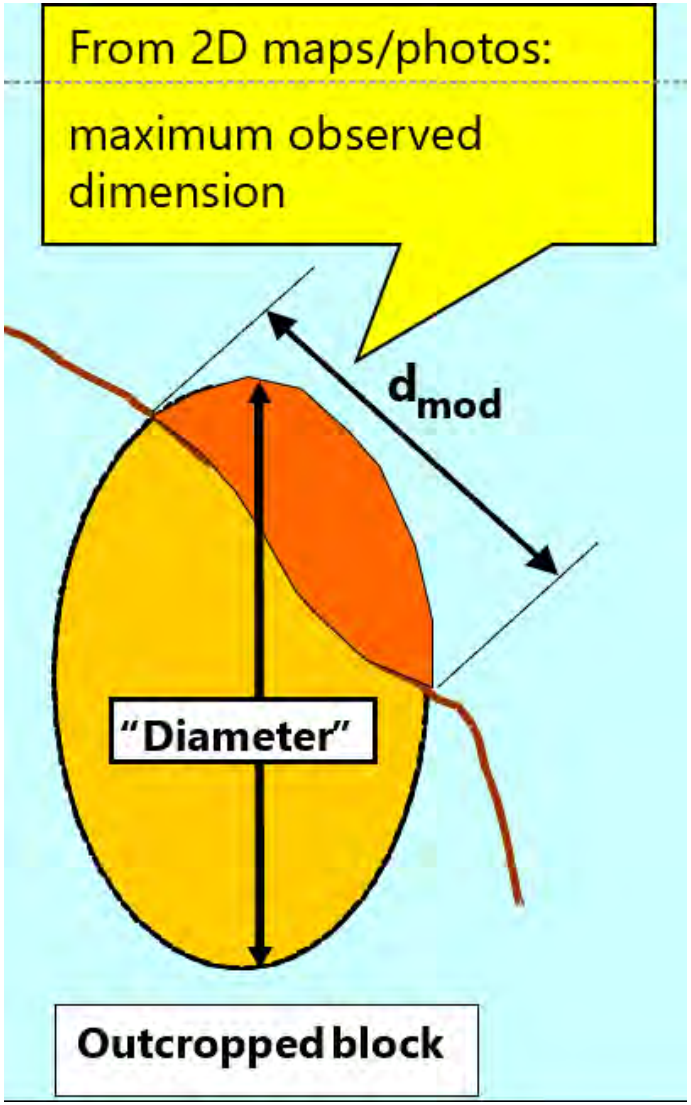
surface mapping/photography most likely will not reveal the actual maximum dimension of blocks



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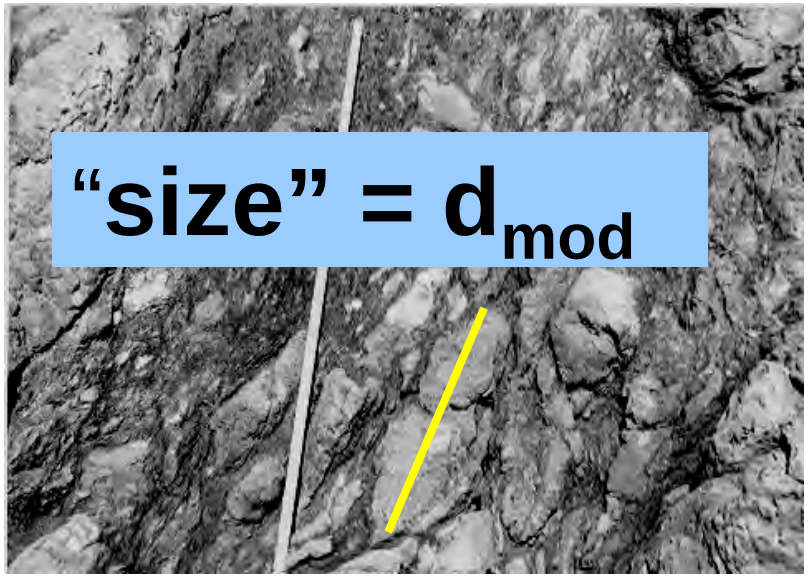
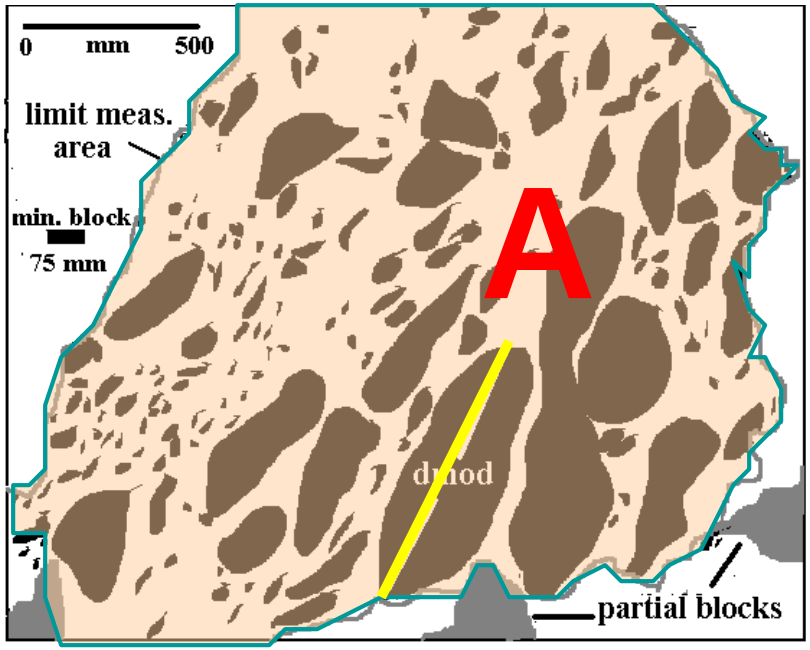


Measuring block sizes (and size distributions) in 2-dimensions



Outcrop scale of interest

A< 1 m^2

Medley, 1994

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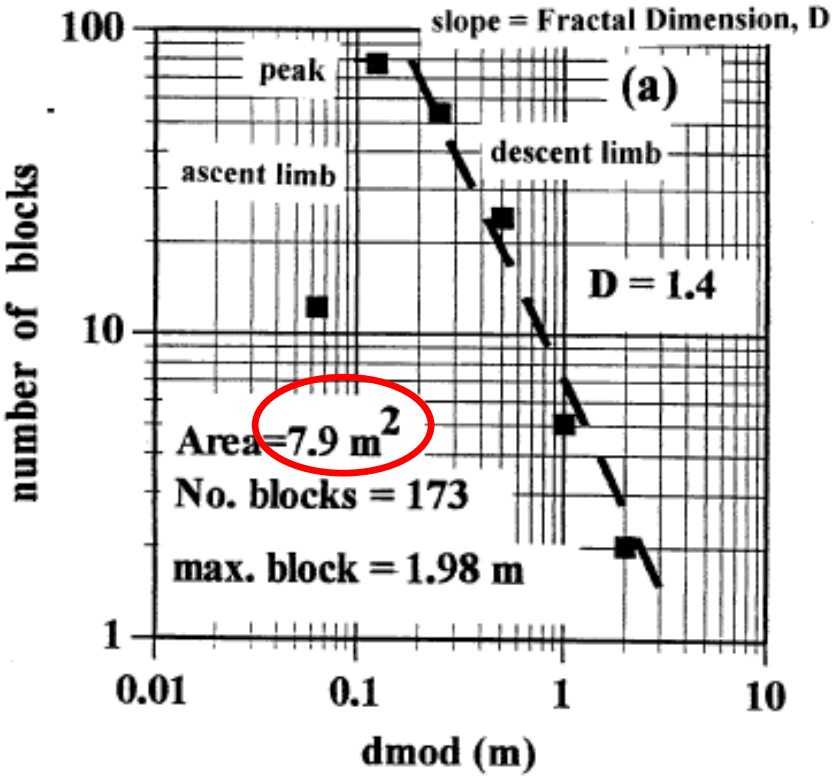
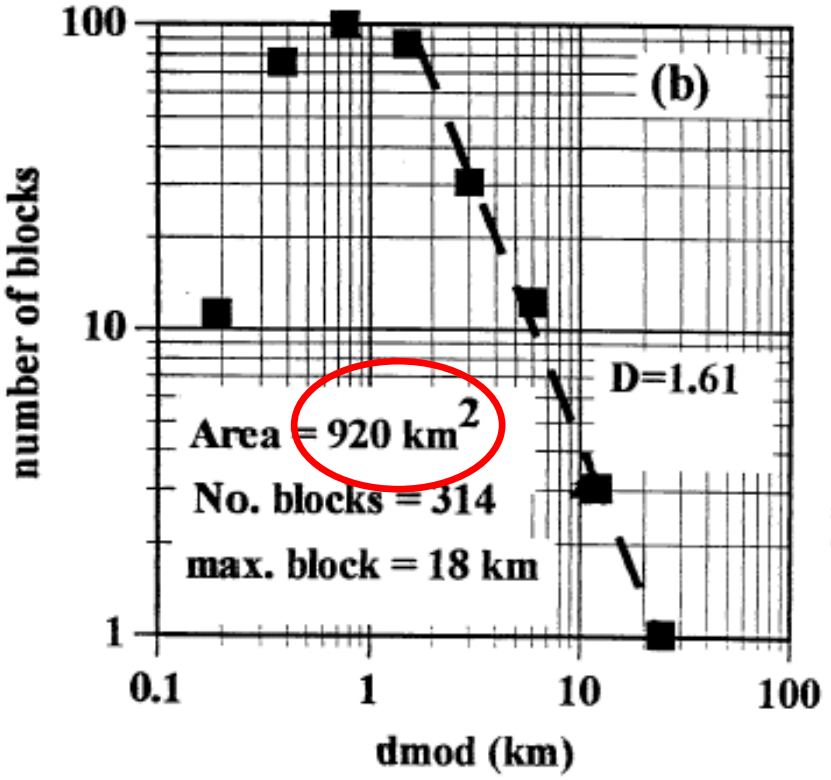
Log histograms at different scales





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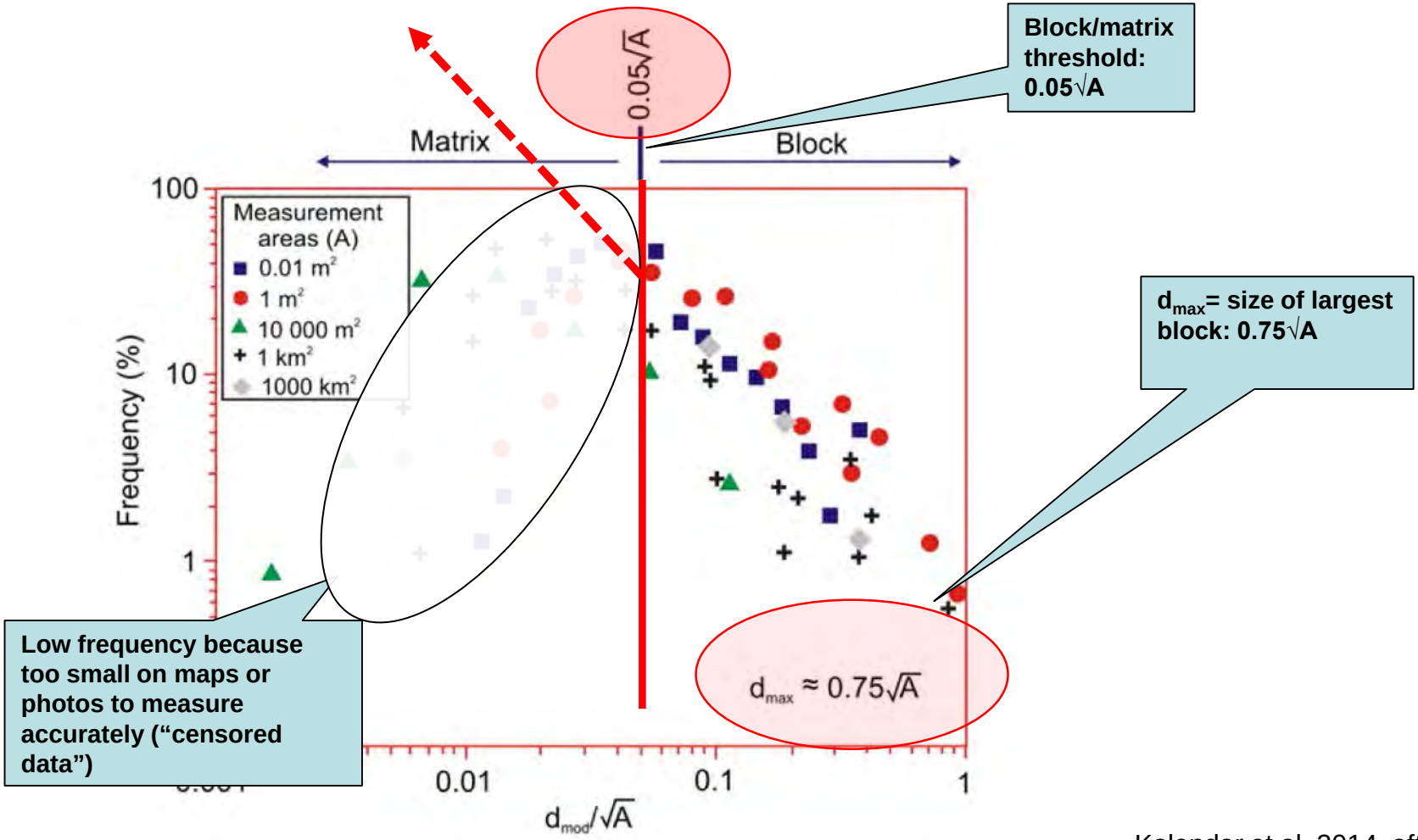
Scale-independent block size distributions of some Franciscan Complex melanges



Plotted as a Log-Histogram

Kalendar et al, 2014, after Medley, 1994

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Scale independence of many melanges: block sizes range >14 orders of magnitude

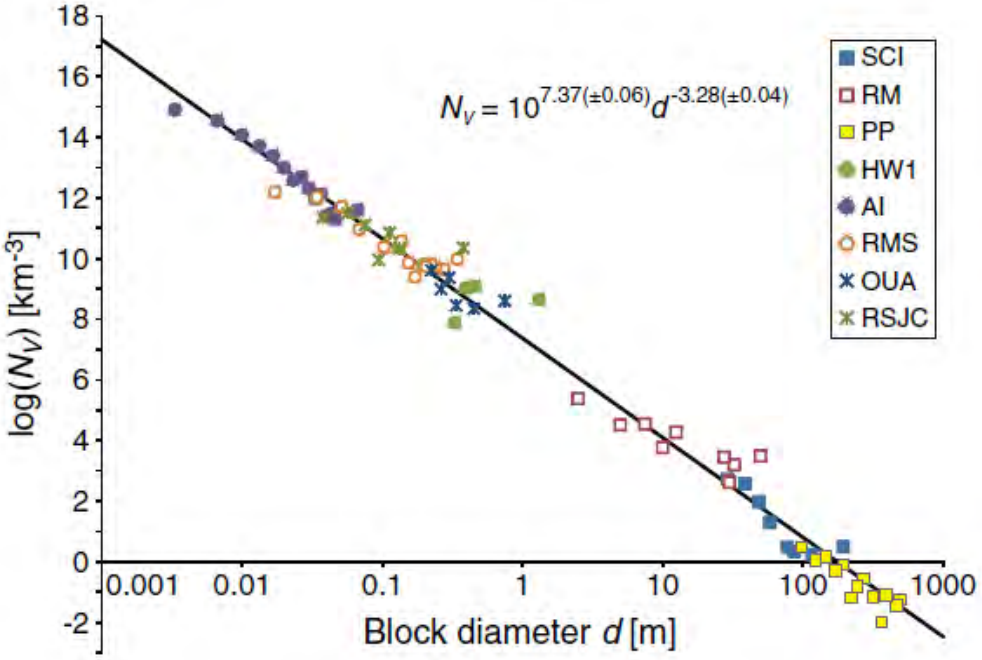

Fig. 7. Log–log plot of volumetric block frequency N_V [km^{-3}] versus block diameter d [m] illustrating self-similarity of investigated block-in-matrix structures. Considerably more small blocks than large blocks can be expected from this plot. SCI: Santa Catalina Island, RM: Ring Mountain, PP: Pacheco Pass, HW1: Highway 1, AI: Angel Island: AI, RMS: Ring Mountain Serpentinite, OUA: Ouaième, New Caledonia, RSJC: Rio San Juan Complex, Dominican Republic.

Grigull et al, 2012; "Order from chaos": A field-based estimate on bulk rheology of tectonic mélanges formed in subduction zones; Tectonophysics 568–569 (2012) 86–101

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Blocks in Franciscan Complex melange

- Blocks range in size cms to km; and will always be present
- Characterization must take blocks into account
- Block size distributions are scale independent and fractal (power law) - they look much the same; regardless of scale – one or two large blocks, and increasing numbers of smaller blocks
- Need a **characteristic dimension** (L_c) to scale the bimrock mass to the scale of engineering interest (L_c is lab specimen diameter, height of slope, width of footing, thickness of expected failure zone, $\sqrt{A}$, etc.)
- **At block/matrix threshold - smallest blocks are: ~ $0.05L_c$**
- **largest block is: ~ 0.75Lc**

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Comments on scale-independence

- For melanges, fault rocks: valid for scales cm to 100's of meters: lab to project sites
- Laboratory specimens are scale models of in-situ bimrock masses
- Weathered may rock yields blocks with scale-independent BSDs if parent rock blocks had power-law or exponential BSDs?
- SRMs - like colluvium and coarse alluvium - may have limited scale independence over range of scales of cm to meters

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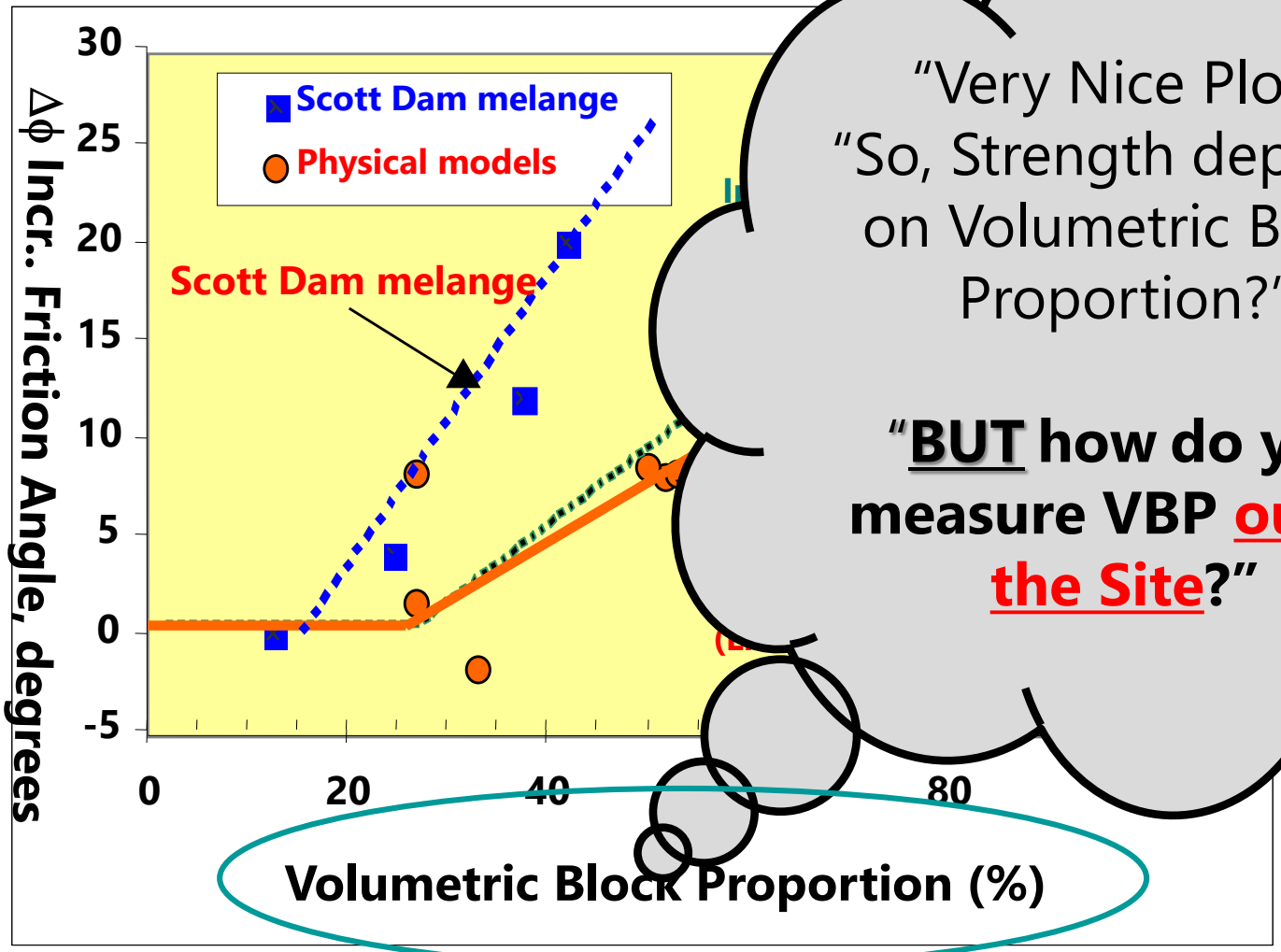
Time to ask a good Question



"Very Nice Plot!!
"So, Strength depends on Volumetric Block Proportion?"

"**BUT how do you measure VBP out at the Site?**"

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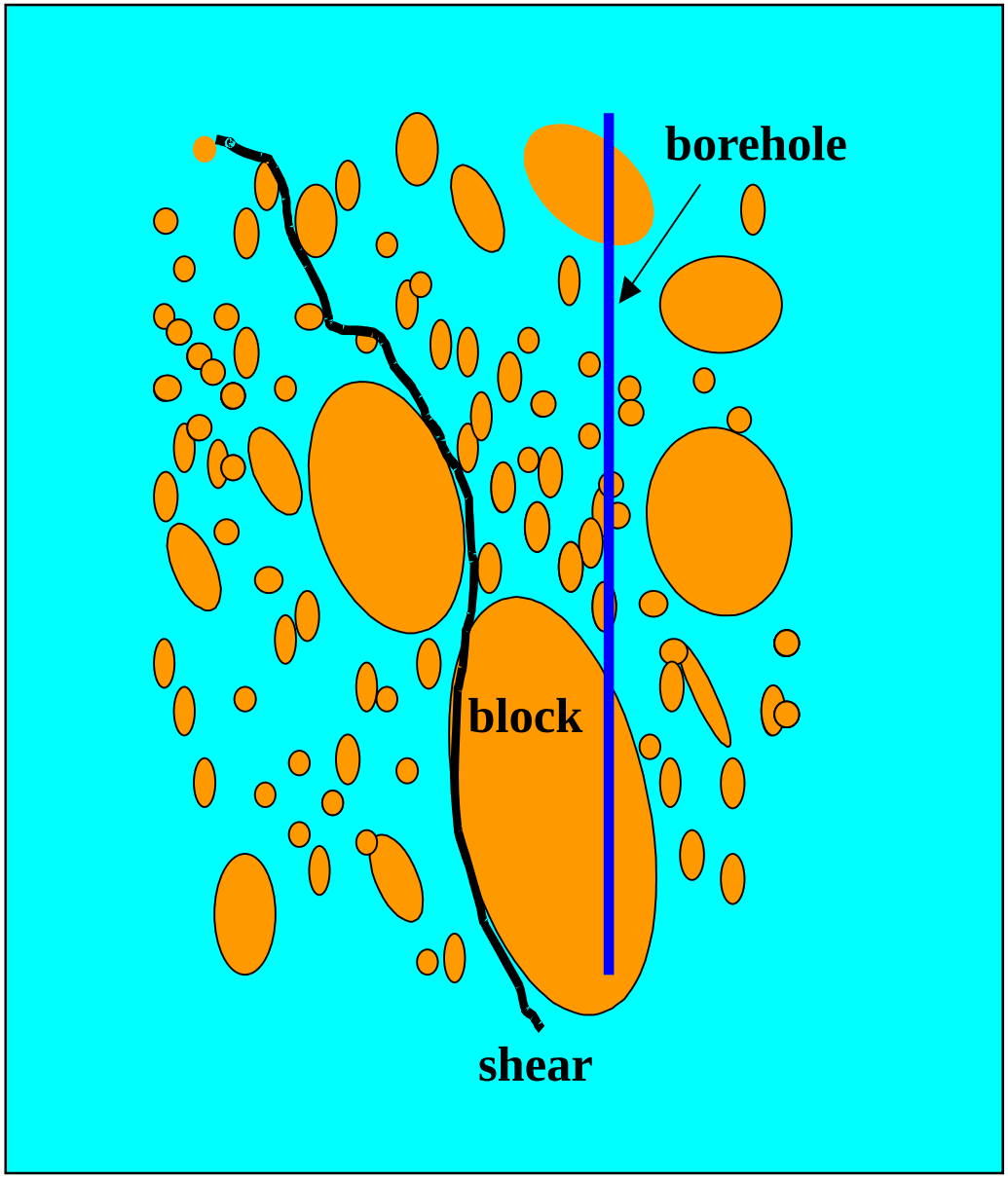
PROBLEM!!

Can we estimate 3D VBP with ID boreholes and 2D maps or photos?



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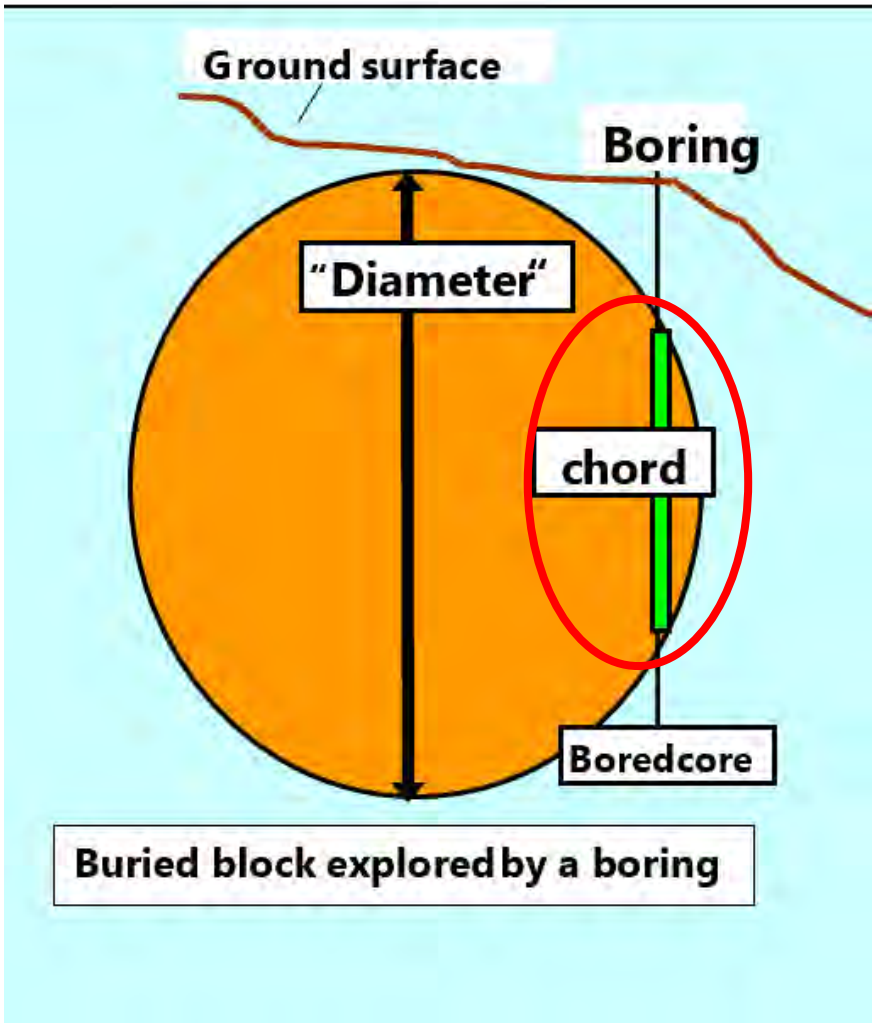
Drilling most likely will not reveal the actual maximum dimension of blocks



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The Hand Game

The Hand Game: a Jahns Lecture April 9 2009 Raleigh. NC Photo: E Medley

https://fr.dreamstime.com/photographie-stock-jeune-femme-regardant-heureusement-par-ses-doigts-image35842352

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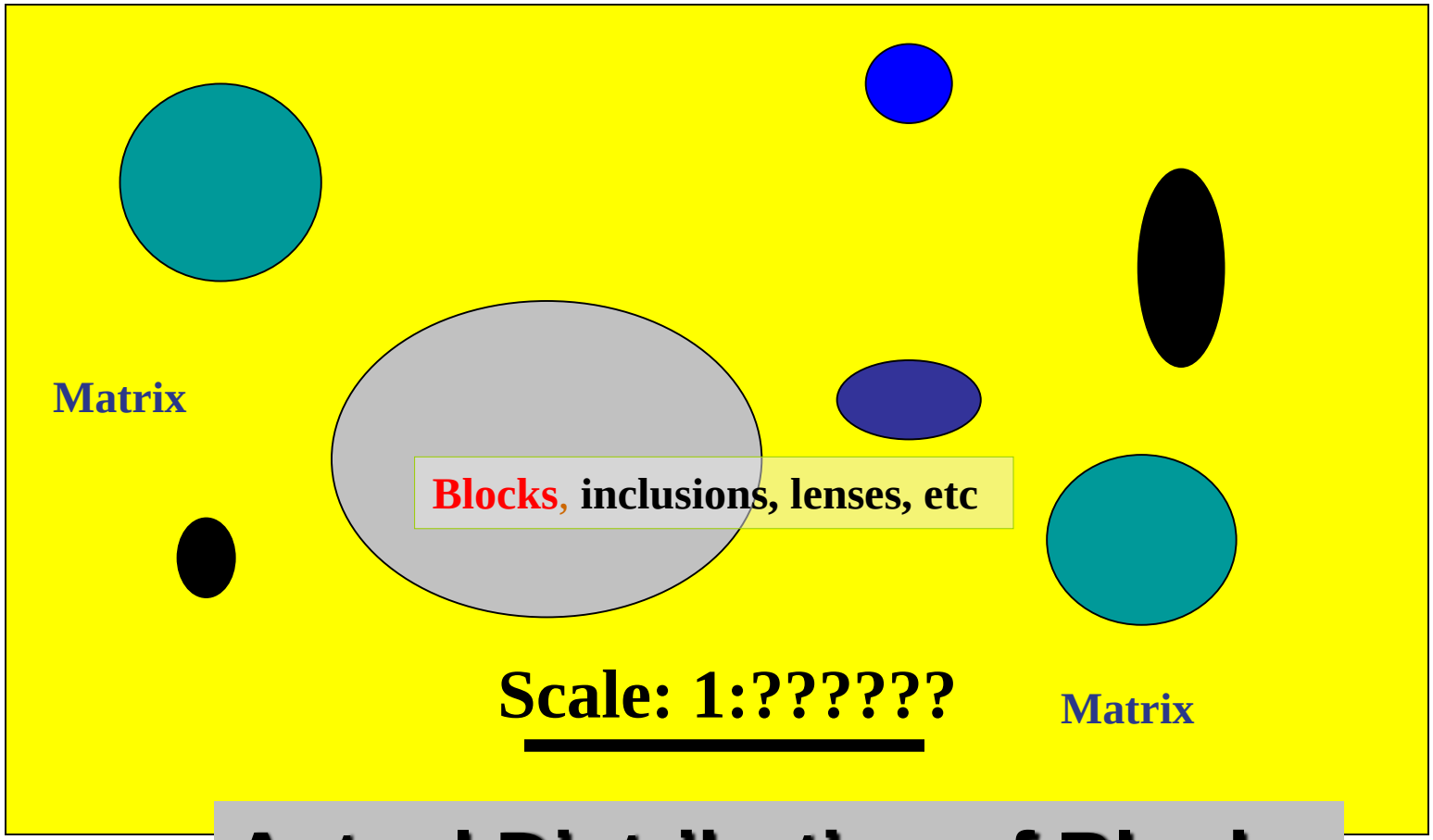
Actual conditions



Actual Distribution of Blocks

Medley, 2000

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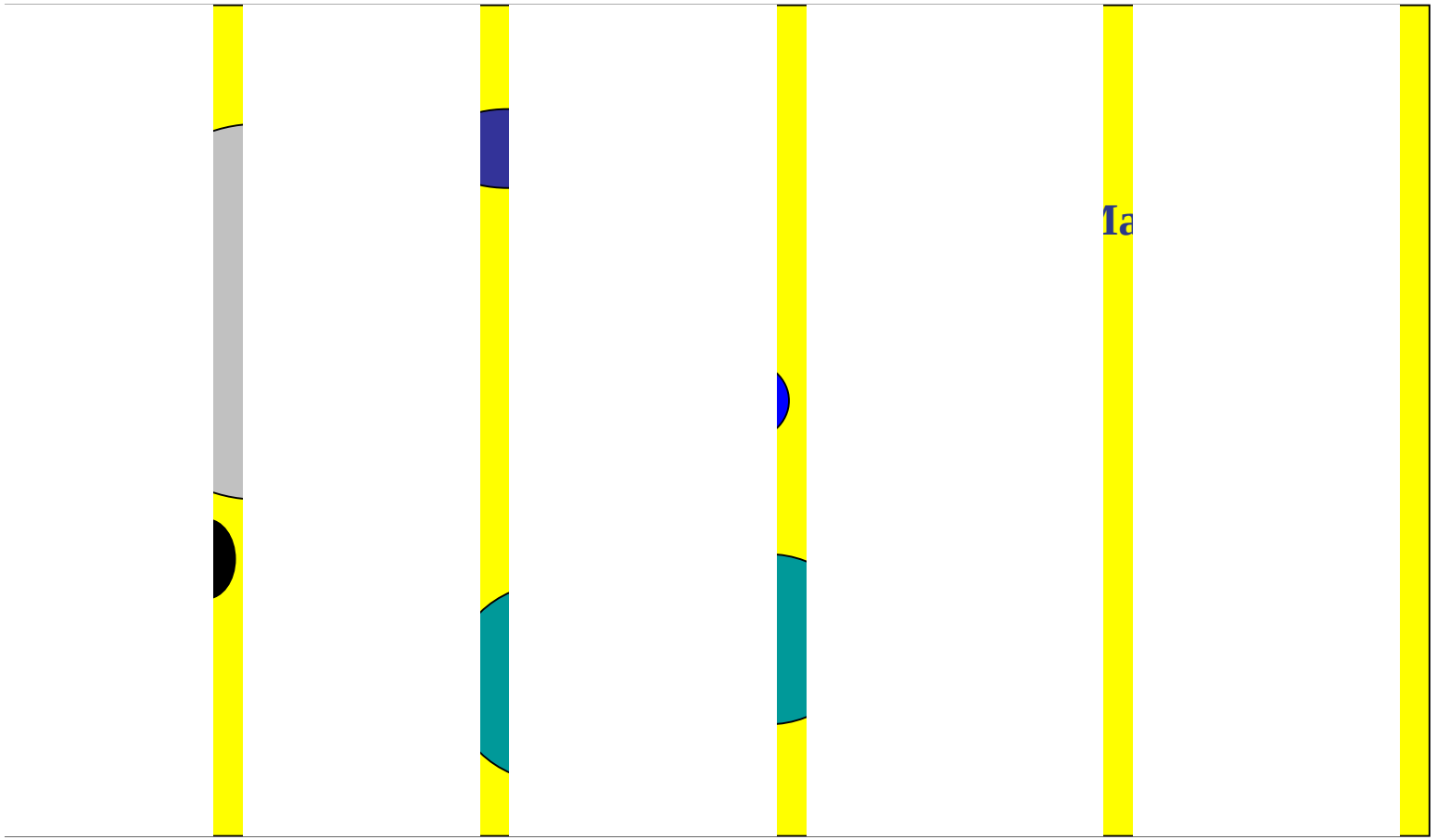
What we have to work with



What we see

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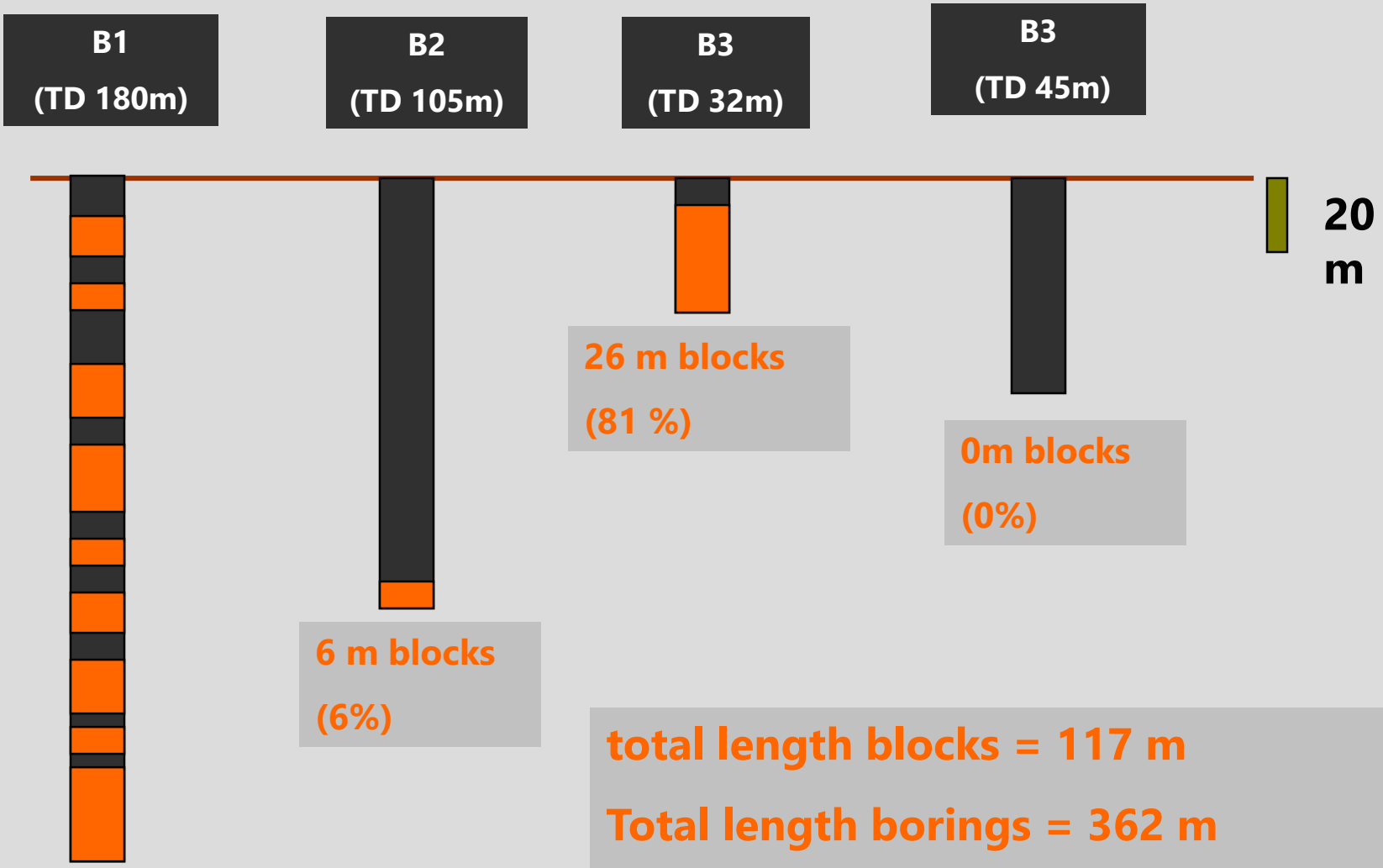
Willis, 2000

Calculating Linear Block Proportions based on core/block intercepts



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Estimating volumetric block proportion from drill core/scanlines

Apply ***stereological*** **principle**:

linear proportion = areal proportion = volumetric proportion

True only for lots of data!

BUT: How **wrong** would we be if we **did** make the assumption:

Volumetric Block Proportion = Linear Block Proportion ??

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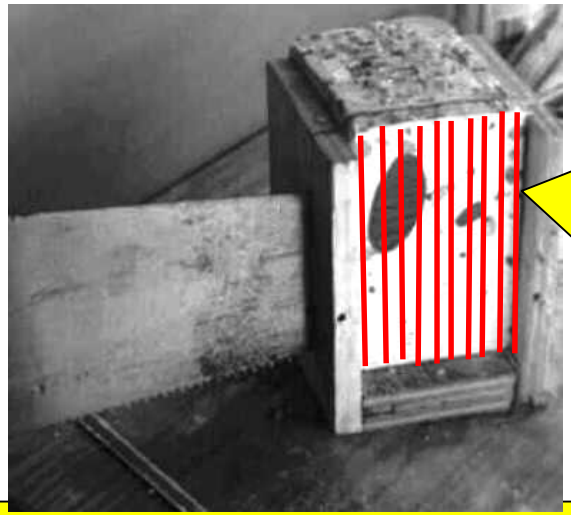
Fabrication of 4 physical bimmodels



- Cut and photographed 10 slices per model
- Drew 10 "borings" per slice
- Measured 100 linear proportions per model

Fabricated 4 models with known block size distributions and different Volumetric Block Proportions

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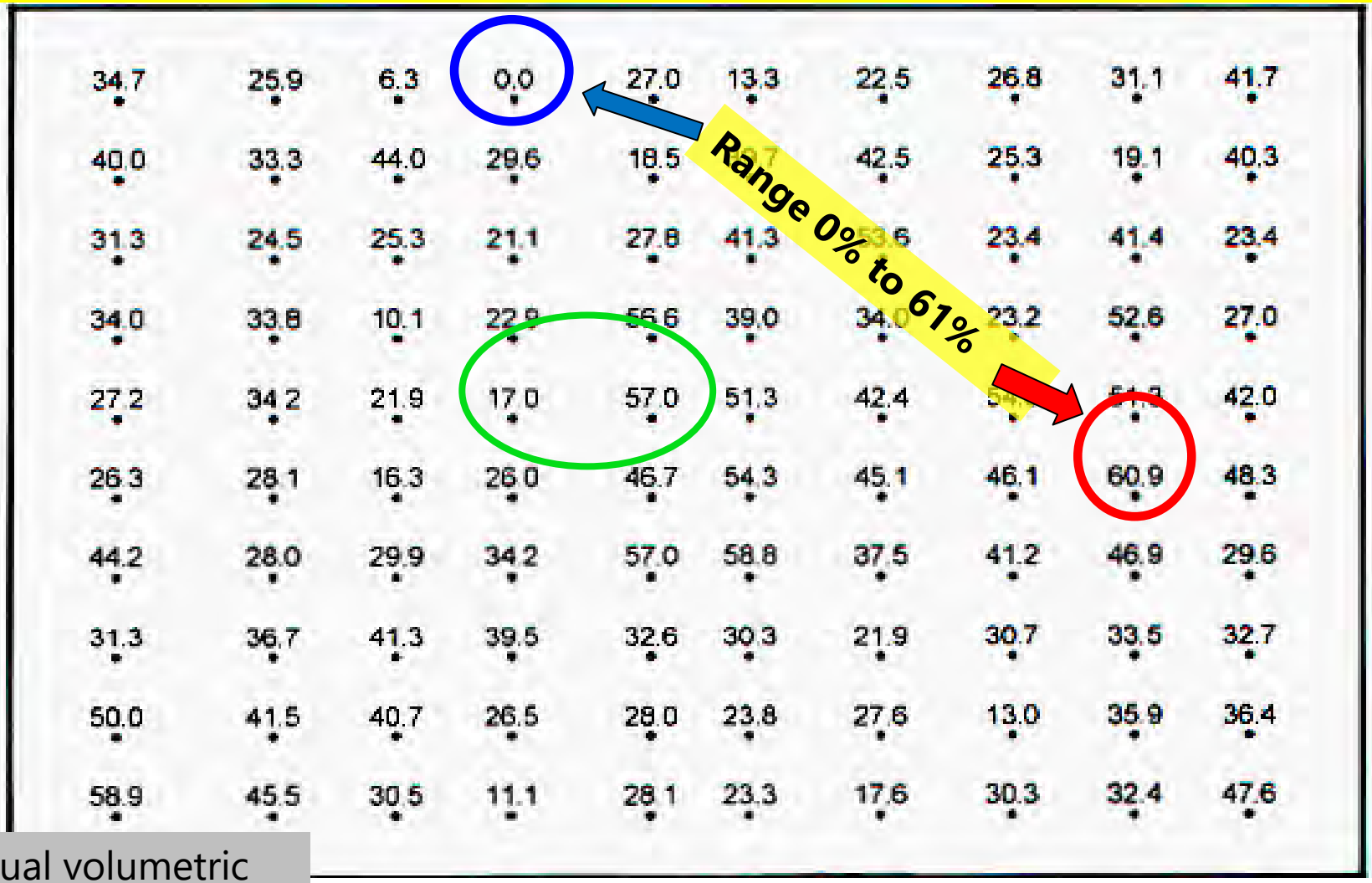
How wrong can you be when you drill the site and try to estimate the actual volumetric block proportion???



actual volumetric proportion = 32%

Plan view of bimmodel with 100 linear%s from "drilling"

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Estimates of VBP from drill core/scanlines be very wrong

For:
1. assumed VBP ~30%-60%; and,
2. total length of drilled core is less than ~ 10dmax:

expect VBP to be LBP+/- (0.05 to 0.20)*LBP

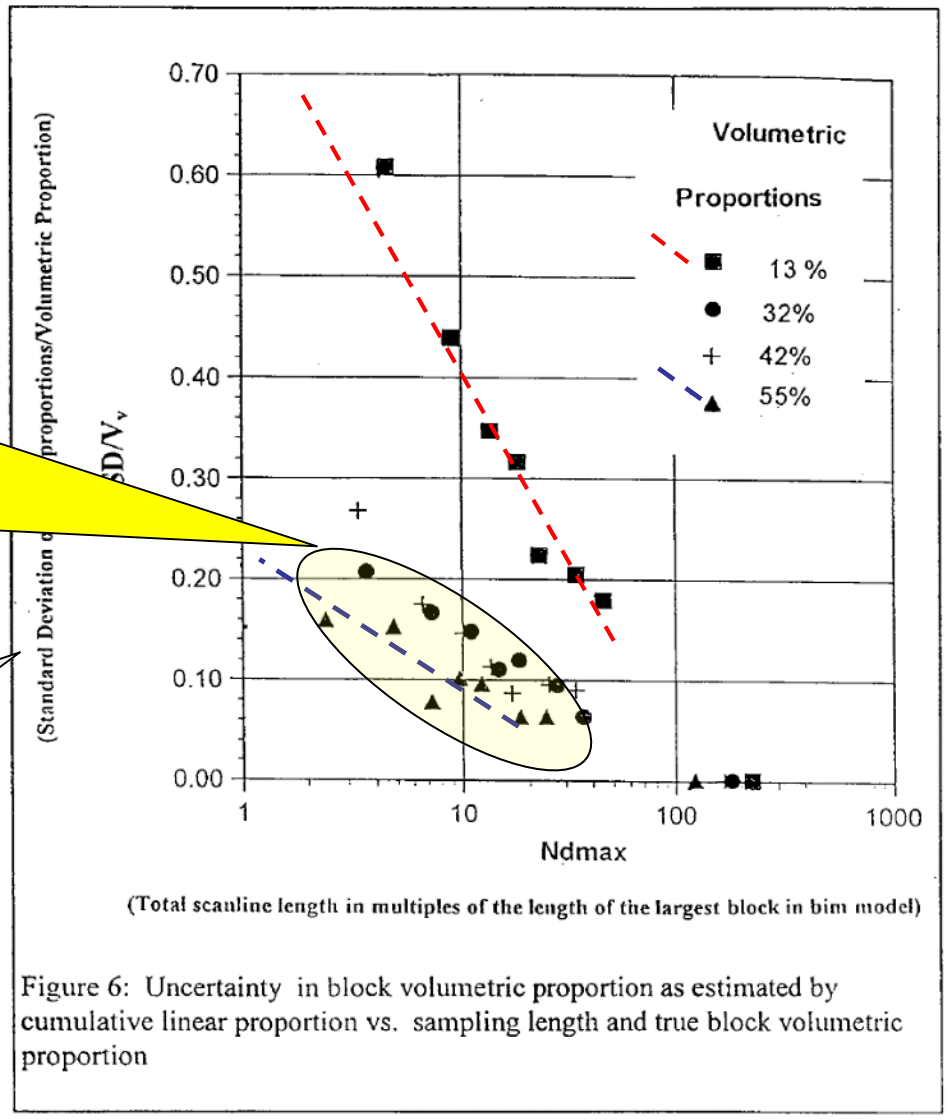

Figure 6: Uncertainty in block volumetric proportion as estimated by cumulative linear proportion vs. sampling length and true block volumetric proportion

Medley, 1997

NOTE:

Uncertainty is actually the Co-efficient of Variations (CoV) or Standard Deviation divided by the Mean of the data.

BUT the means are close to the true Volumetric Proportion so it is OK to say that the Uncertainty is the Standard Deviations divided by the VBPs

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Too-simple a chart !!! NEEDS THOROUGH CHECKING!

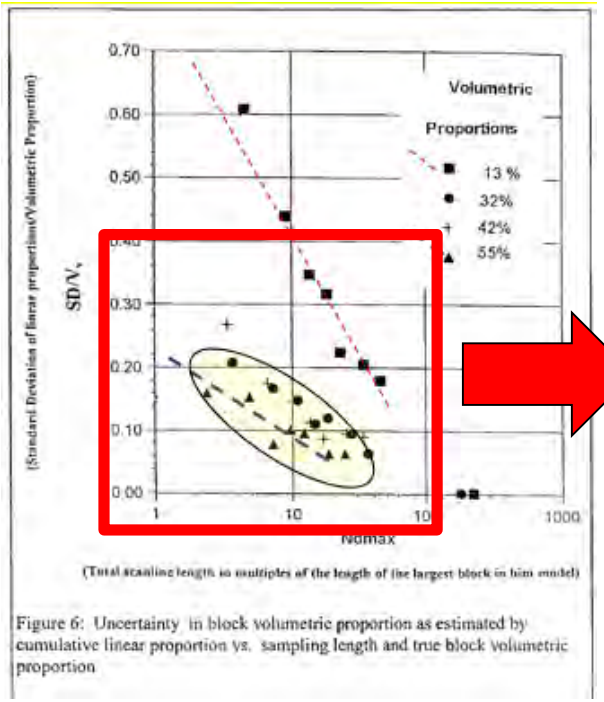
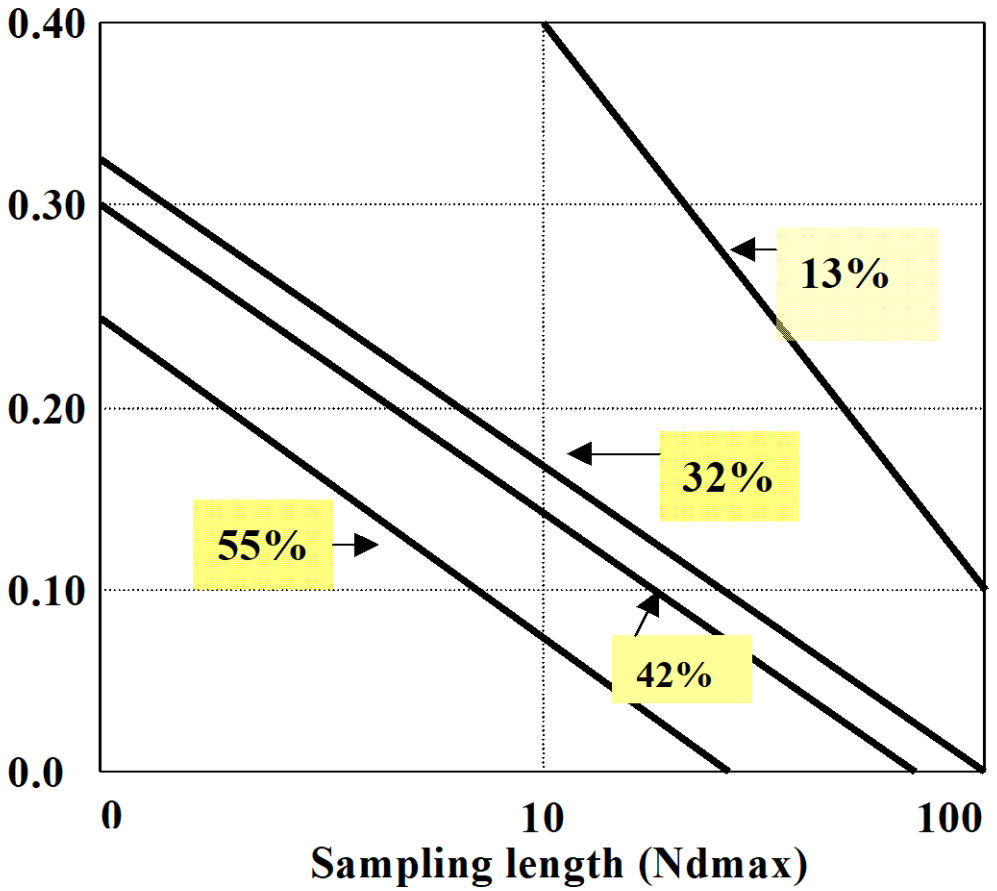


Figure 6: Uncertainty in block volumetric proportion as estimated by cumulative linear proportion vs. sampling length and true block volumetric proportion

uncertainty



Medley, 1997

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Old Research Needs Updating!

- Practitioners are using the **crude** Medley, 1997 chart. **The kitchen experiments need to be updated**!!
- Since much numerical modelling of bimrocks currently being performed, a useful by-product would be to “drill” and “map slices” of the models, measure LBP and ABP and compare to known model VBPs to identify Uncertainties.
- Can also better understand how to estimate BSDs from drilling data

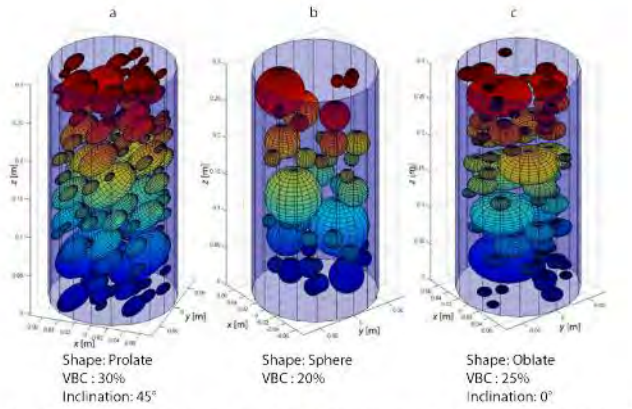
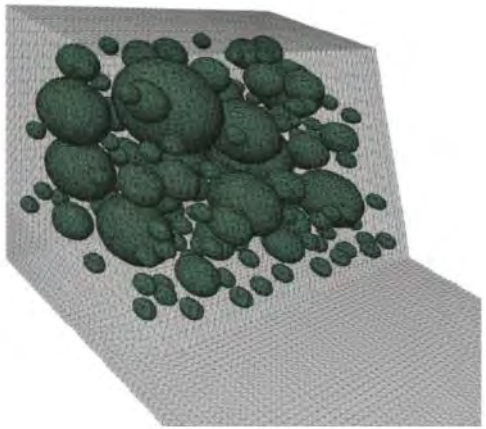


Figure 2. Example of virtual specimens: a) prolate ellipsoid inclusions (30% VBC and major axes inclined at 45° to the horizontal plane); b) spherical inclusions (20% VBC); c) oblate ellipsoid inclusions (25% VBC). The cylindrical sample size is 0.3 m high by 0.075 m base radius.

Coli et al, 2012, Modeling of complex geological rock mixtures under triaxial conditions ; Eurock 2012



Amini et al, 2018 Statistical analysis of bimslope stability using physical and numerical models; IJRMMS (IN REVIEW),

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VBP=ABP=LBP?? Generally: NO!

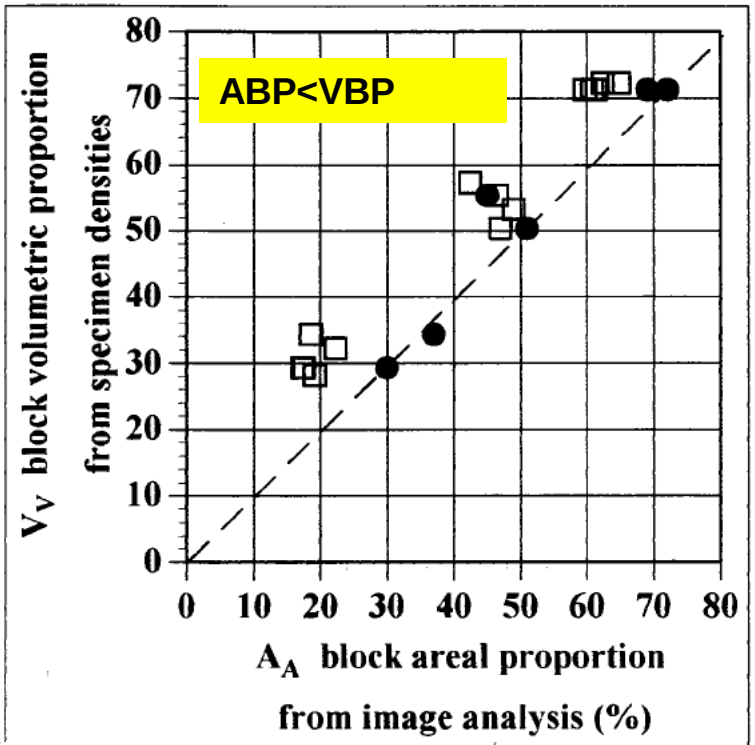
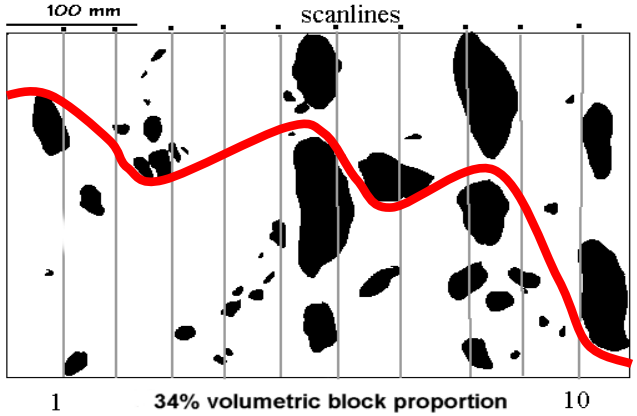
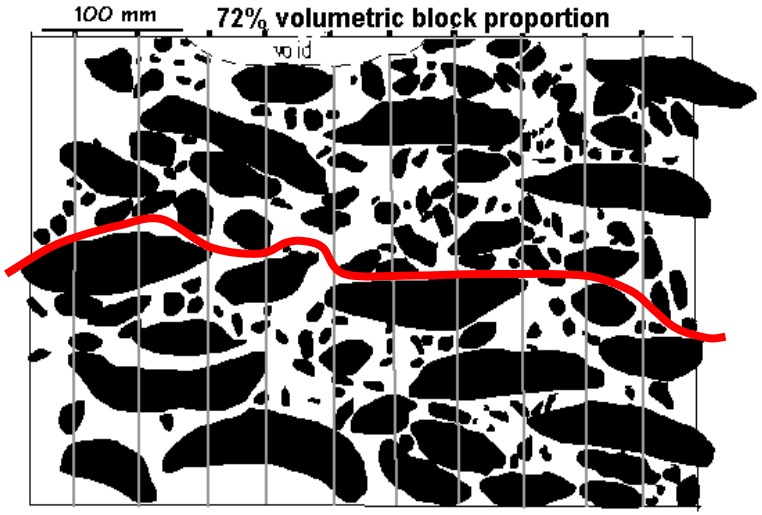


Figure 2. 20 Scatter plot of block areal proportions, A_A (open squares) of 14 triaxial specimens based on the measurements of blocks traced from the surface of the cylinders; compared to actual volumetric proportion V_V determined by Lindquist (1994b) from specimen densities. Filled circles represent areal proportions measured from cross-sections through 6 specimens. The dashed line is the ideal, $A_A = V_V$





Medley, 1994 (dissertation)

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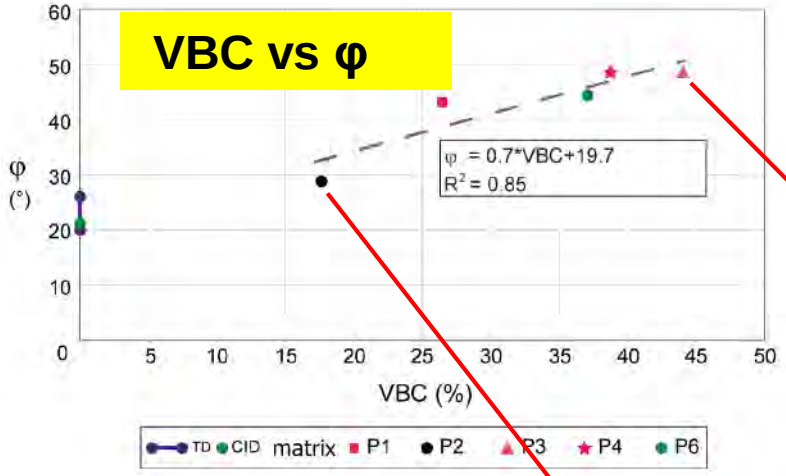
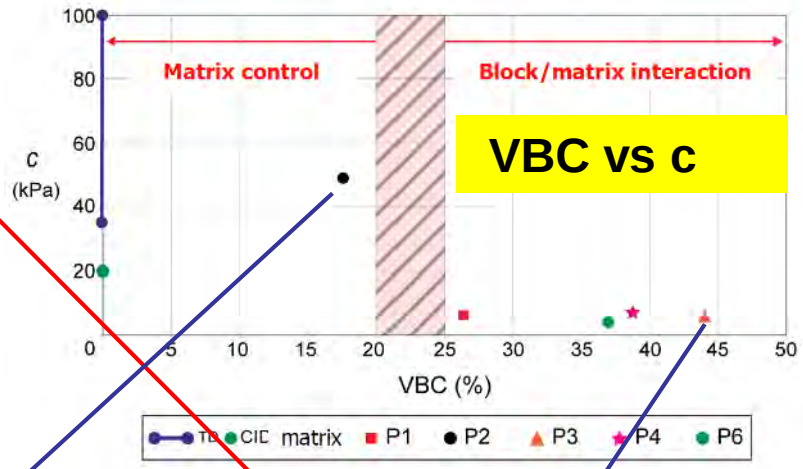
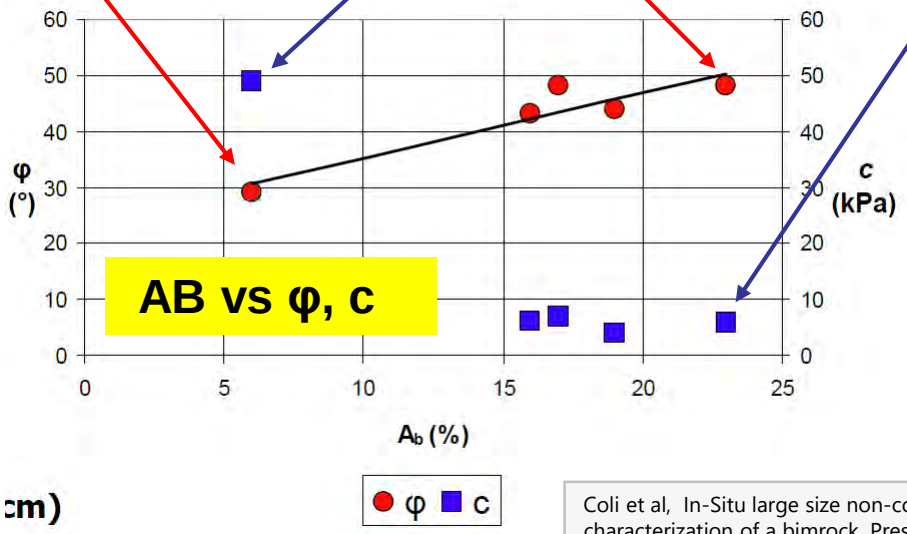
Compare Areal and Volumetric block proportions

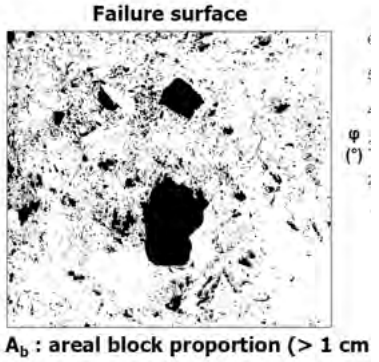




For same φ and c, Areal Block Proportions are ~ 10% to 20% less than Volumetric Block Proportions i.e.:

ABP ≠VBP





Coli et al, In-Situ large size non-conventional shear tests for the mechanical characterization of a bimrock, Presentation at Eurock 2010

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Estimating block size distribution from borings: Thoughts

- **There are often needs to estimate in-situ BSDs**
- **Using drilling (or mapped) data, you will likely get the BSD very wrong because chords almost always smaller than "diameters" of blocks.**
- **This is also a topic that needs more research**

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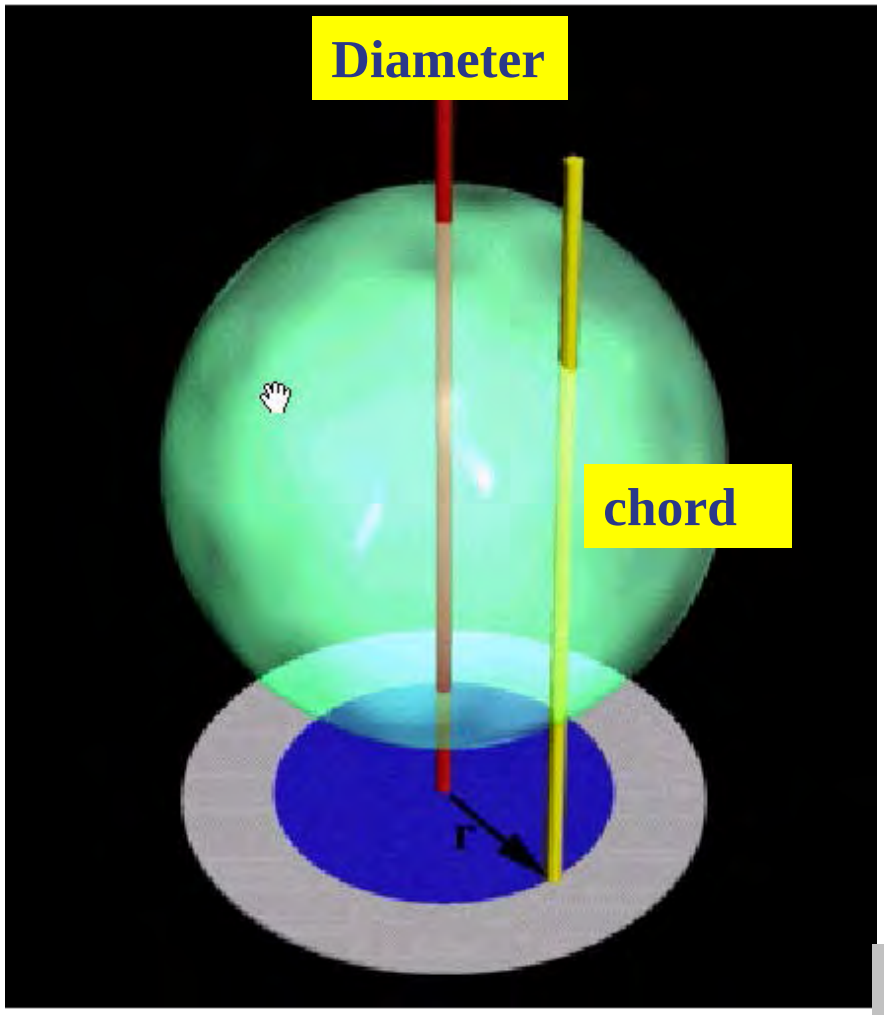
Drilling through a block: chords and diameters



Only rarely will a drilled chord be the same as the diameter. Generally assume the length you drill IS NOT the diameter of the blcok

So: When drilling bimrocks be careful when you use the words: "block diameter"

After Russ and Dehuff (2000), "Practical Stereology"

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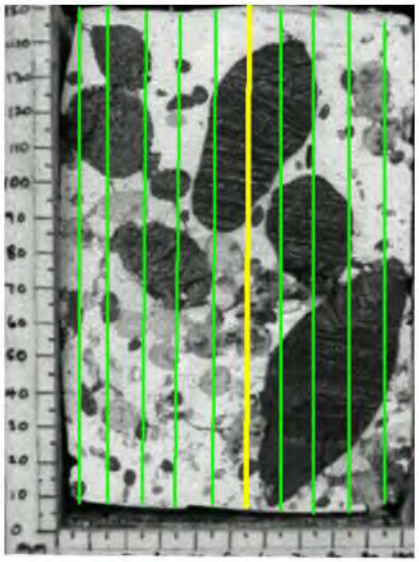
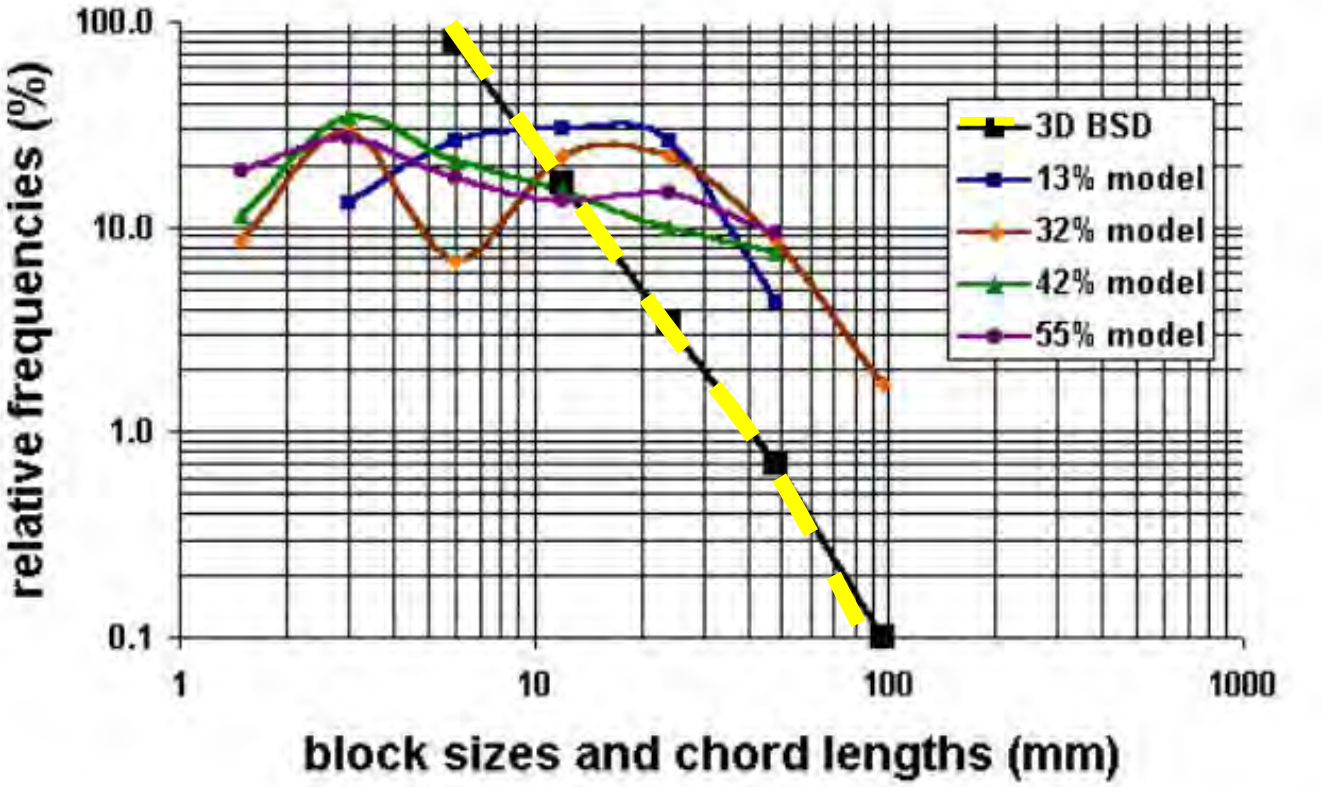
Estimation of Block Size Dist. from 10 scanlines per model

Generous amount of "drilling" still insufficient to estimate actual 3D BSD.





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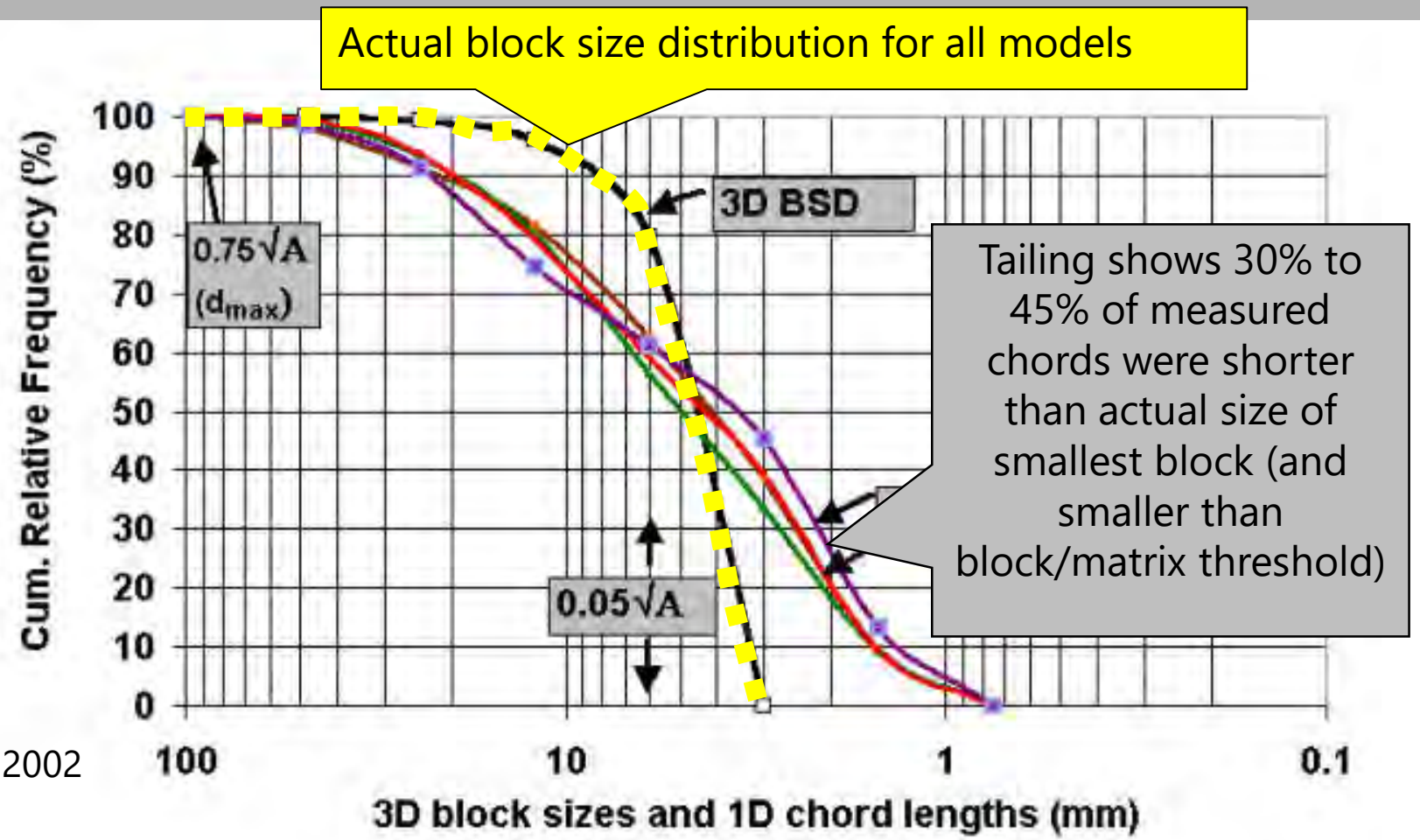
"PSD"-style plot of chord lengths for all models (**~2150 chords**)

Despite abundant data, still cannot duplicate original 3D BSD with chords…



Medley, 2002

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bimrocks and slopes

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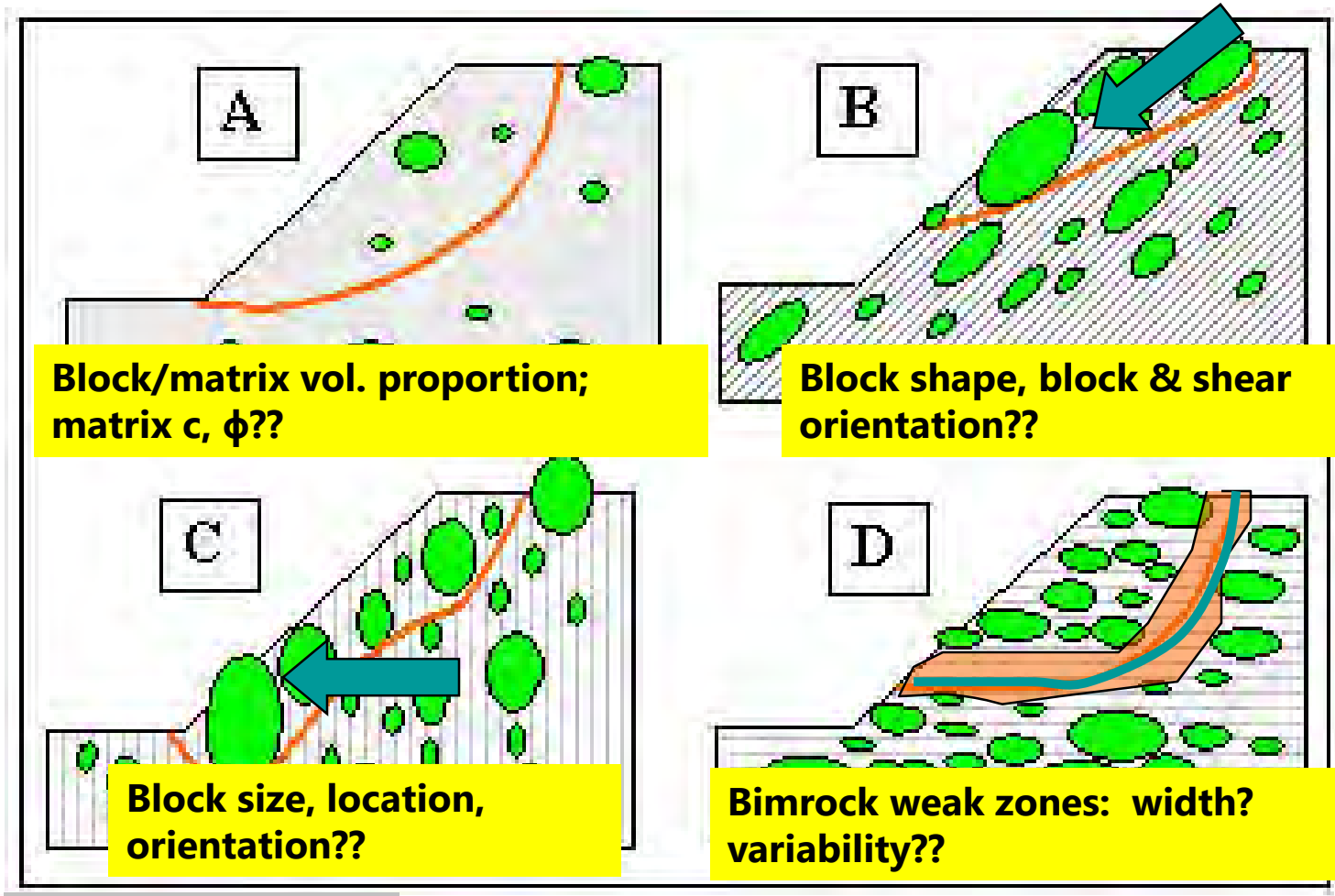
What are the influences on slope stability in bimrocks?



Medley & Sanz, 2004

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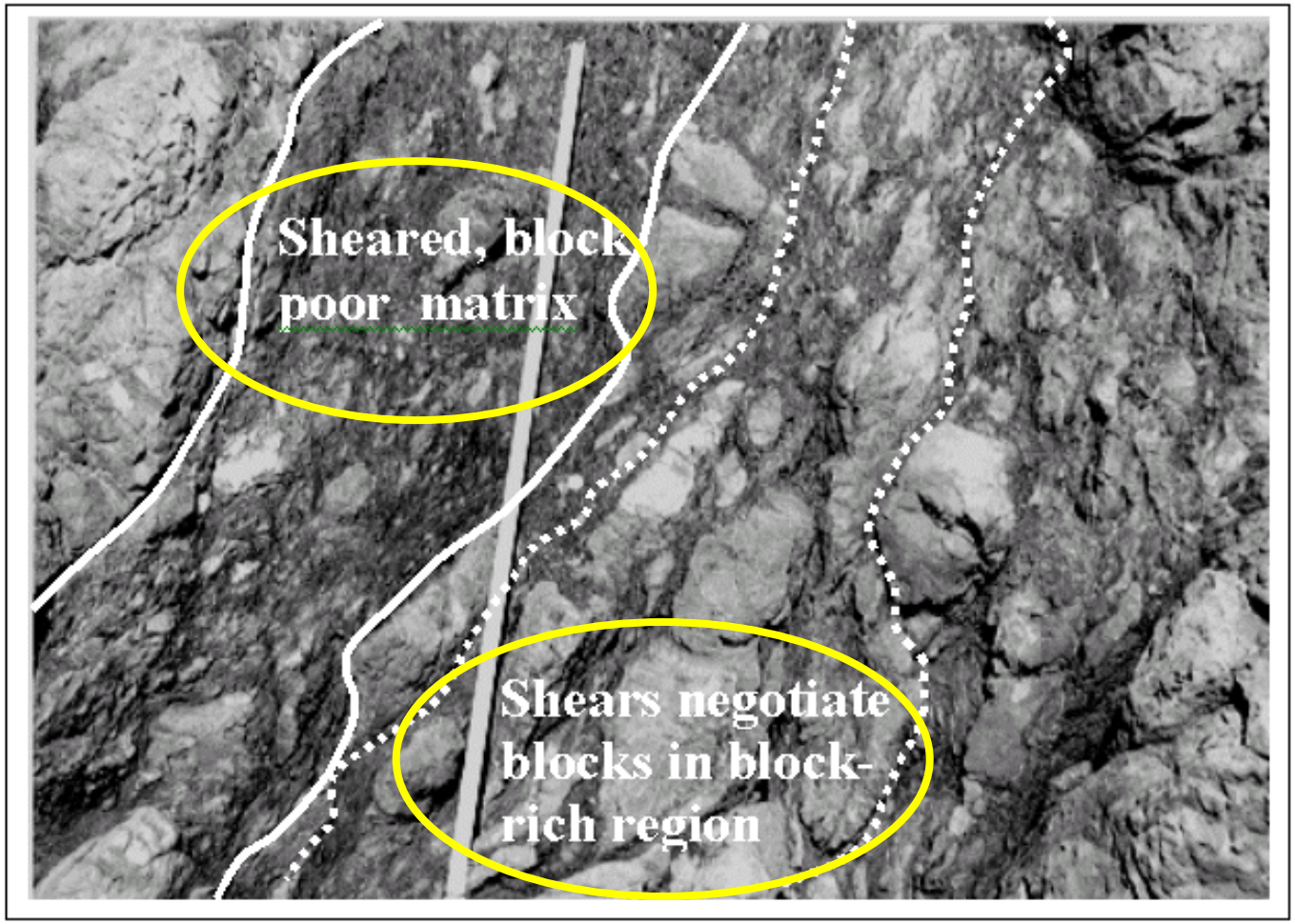
Critically influential for slope stability: zones of low-block proportions



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Blocks apparently stabilize slopes: but HOW MUCH??

Photo: Ed Medley

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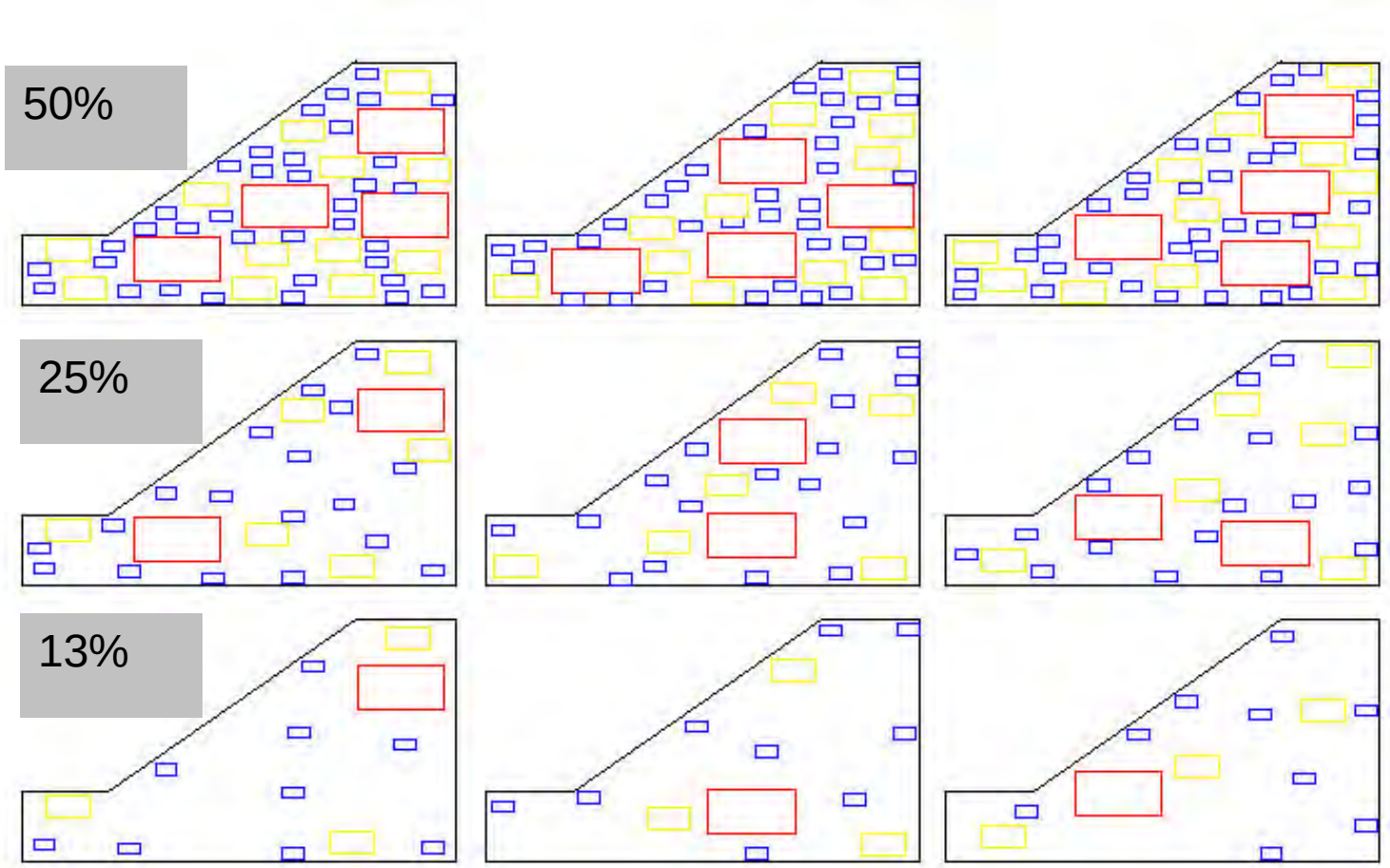
Medley and Sanz, 2004: Simple random arrays of blocks



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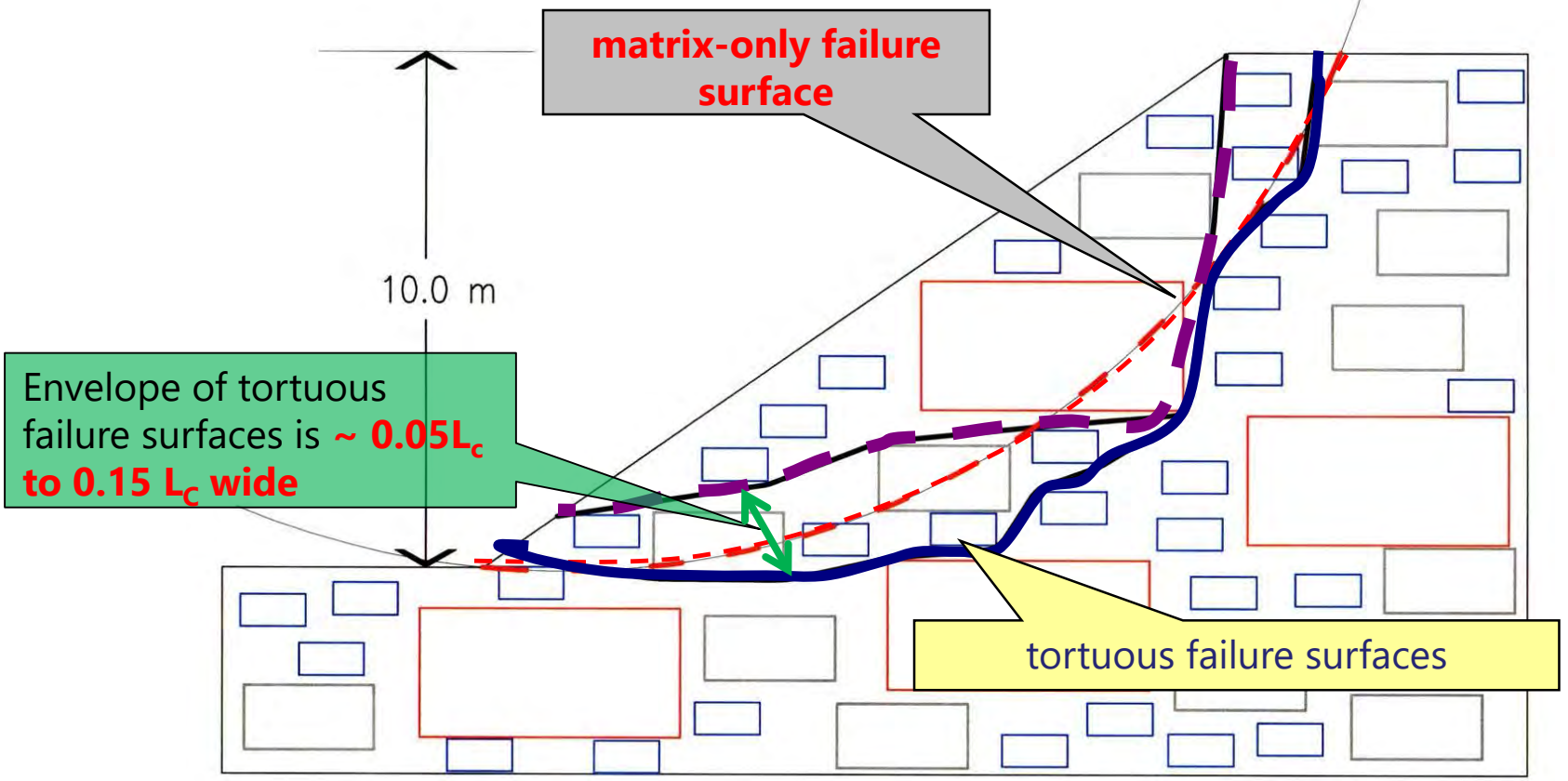
Simple analysis of slope stability in model bimrock: add blocks to the matrix

- ~ 50% Areal Block Proportion
- typical Franciscan block size distribution
- NO Block strengths



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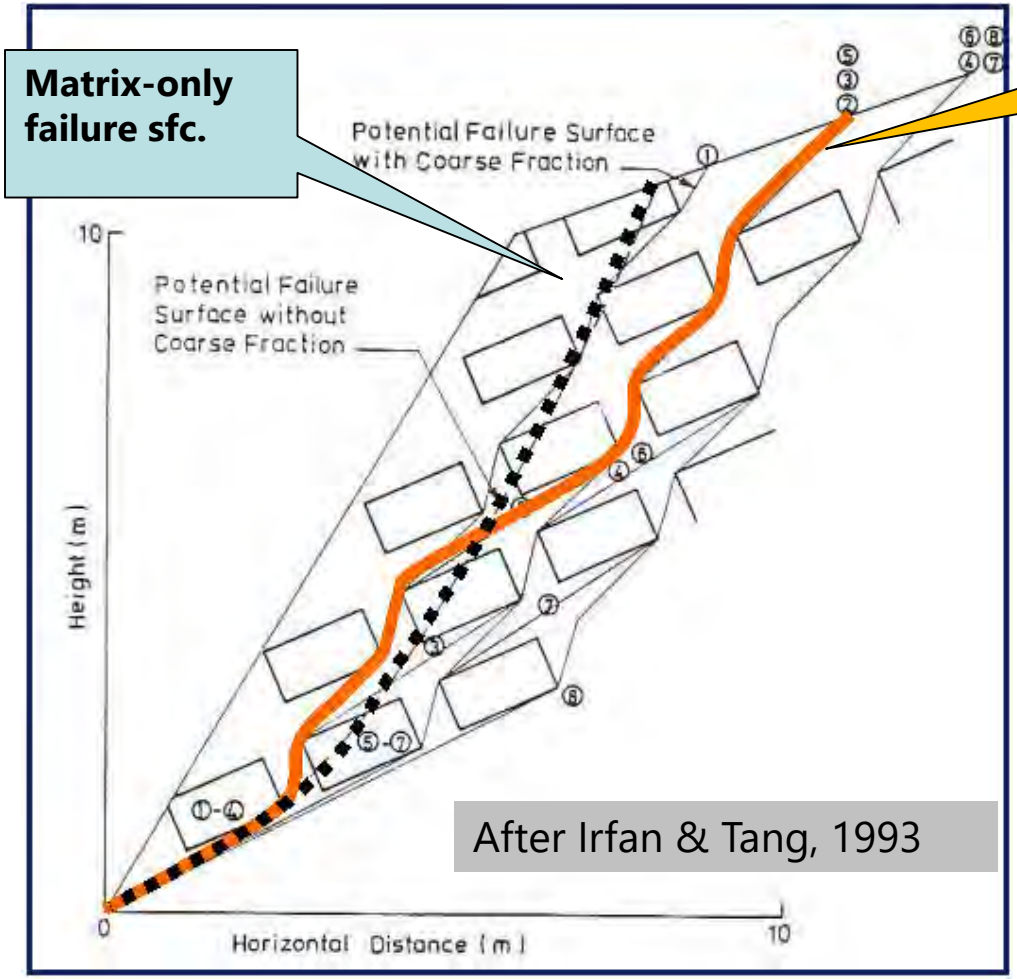
Hong Kong bouldery colluvium: Trial tortuous failure surfaces with blocks oriented out-of-slope



Hong Kong GEO TN 4/92

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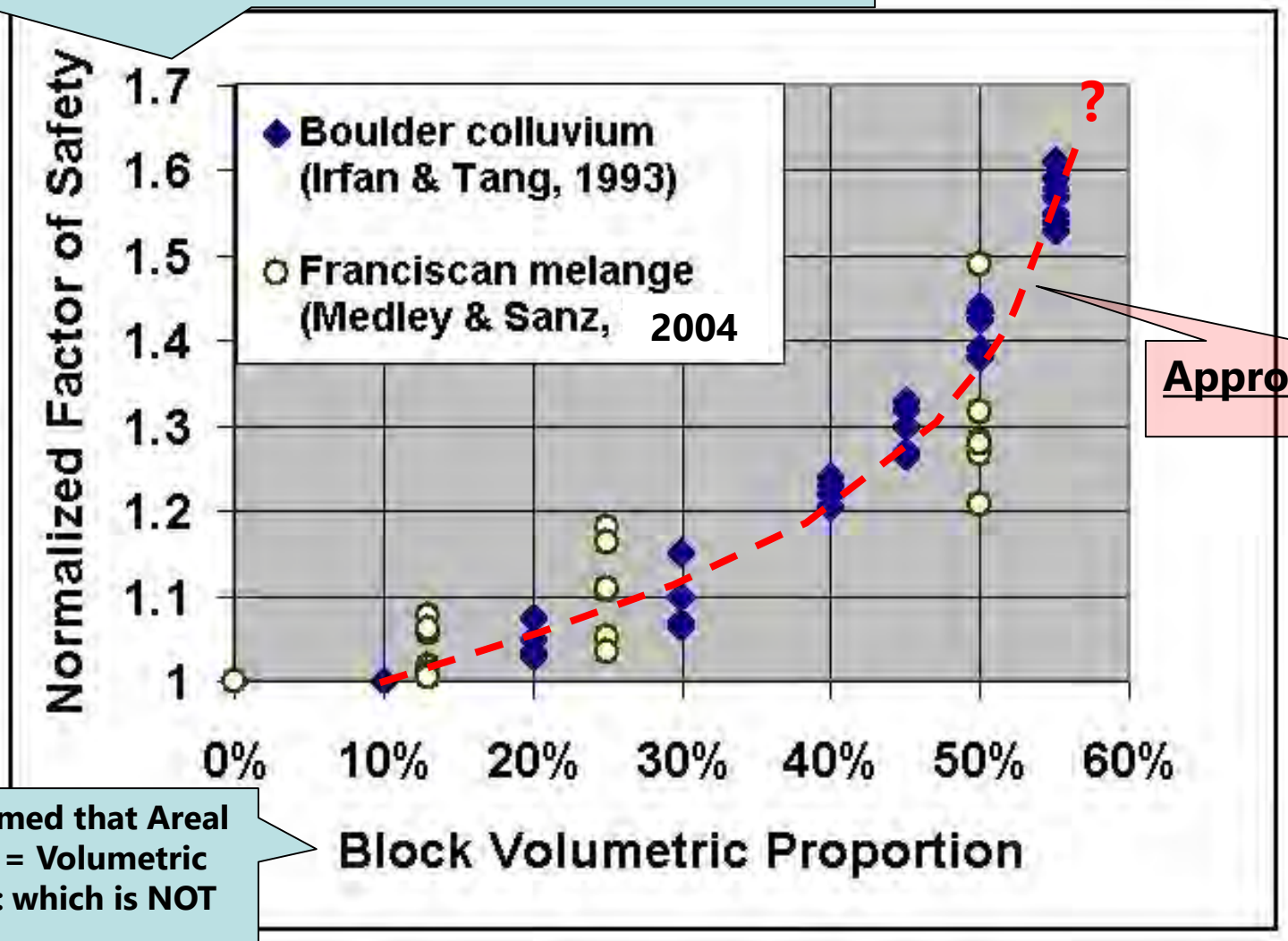
Medley and Sanz, 2004: blocks increases slope stability FS

Normalized: ratio of FS of tortuous sfc to FS of matrix-only sfc



Approx. fit line

NOTE: assumed that Areal Proportion = Volumetric Proportion: which is NOT TRUE!

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Amini et al, 2018 Current research on slope stability: physical models

using tilt table to rotate physical models to failure (various VBPs, known BSD, initial horizontal orientations, fixed shapes)

Amini et al, 2018 Statistical analysis of bimslope stability using physical and numerical models; IJRMMS (IN REVIEW),

(g) (h) (i)

Fig. 10. Tilt test on a physical bimslope with VBP=40%: (a-g) preparing model and (h-i) result of trial

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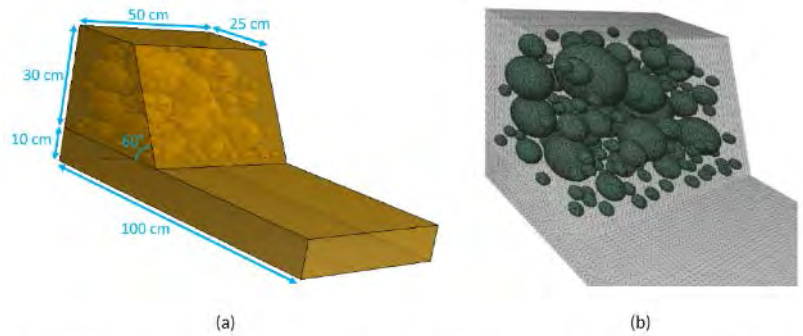
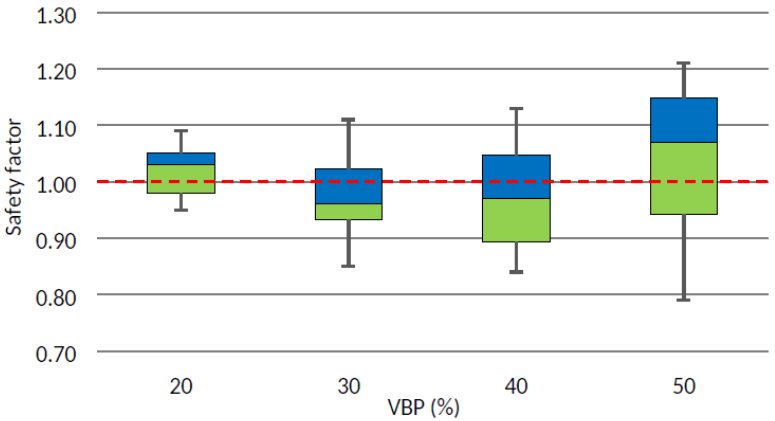
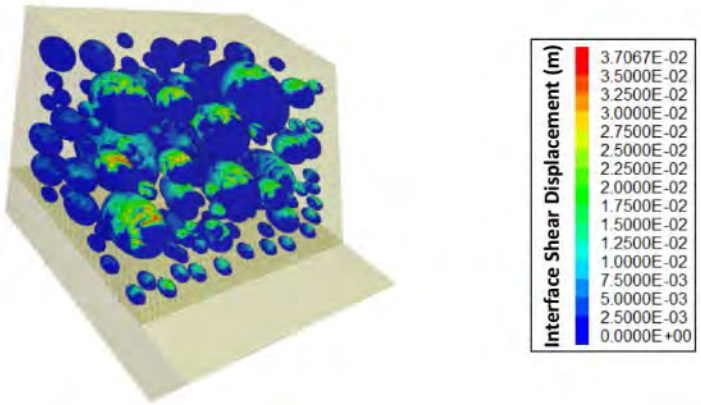
Amini et al, 2018: Current research on slope stability-numerical models

using numerical models rotated to failure (various VBPs, known BSD, initial horizontal orientations, fixed shapes): **blocks may decrease stability**!



ig. 11. A numerical model of bimslope with VBP=30%: (a) geometry and (b) finite difference model with mesh





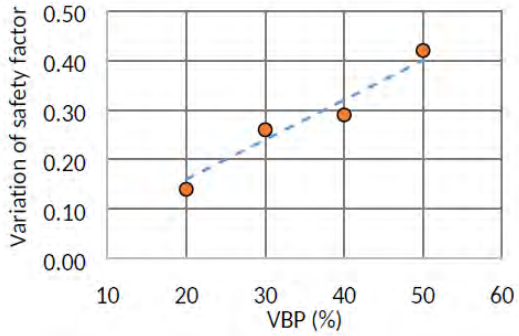


Fig. 17. Variation range of safety factor versus VBP obtained from numerical modeling

Amini et al, 2018 Statistical analysis of bimslope stability using physical and numerical models; IJRMMS (IN REVIEW),

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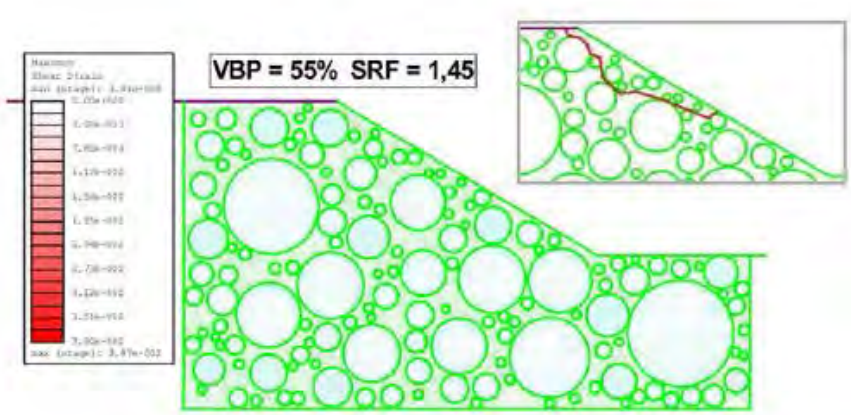
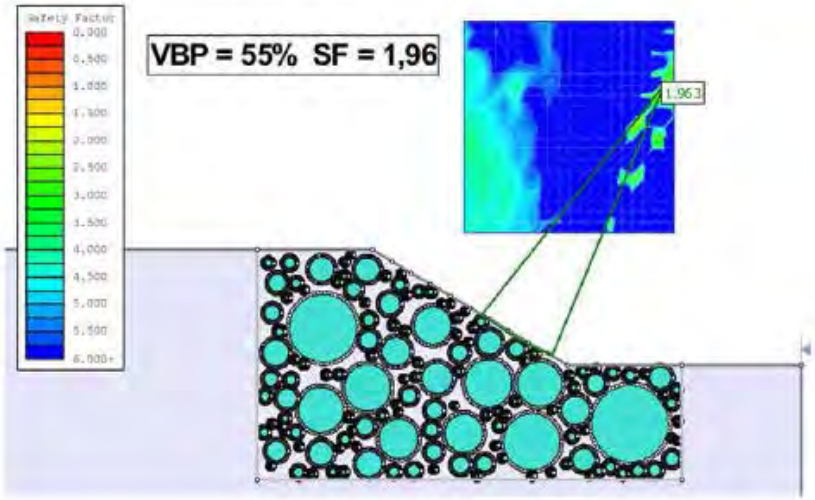
Napoli et al, 2018:
Current research on slope stability - numerical models

using numerical models with randomly-generated blocks, random locations, 4 known VBPs, known BSDs, fixed shapes with LEM and FEM analyses





SRF: Strength Reduction Factor=SF
SF= Safety Factor
FEM: Finite Element Analysis (Phase^2)
LEM= Limit Equilibrium Method using Slide v. 5.0 (Bishop's Simplified and Spencer's methods)

Block arrays in bimrocks are unknowable- so we should analyze many possible surfaces

For same block array: FEM SRF = 1.45 LEM SF = 1.96 . **Safer to perform stochastic FEM**

Napoli et al, 2018; A stochastic approach to slope stability analysis in bimrocks; Int. J. of Rock Mechanics and Mining Sciences 101 (2018) 41–49

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Napoli et al, 2018: slope stability- stochastic numerical analyses

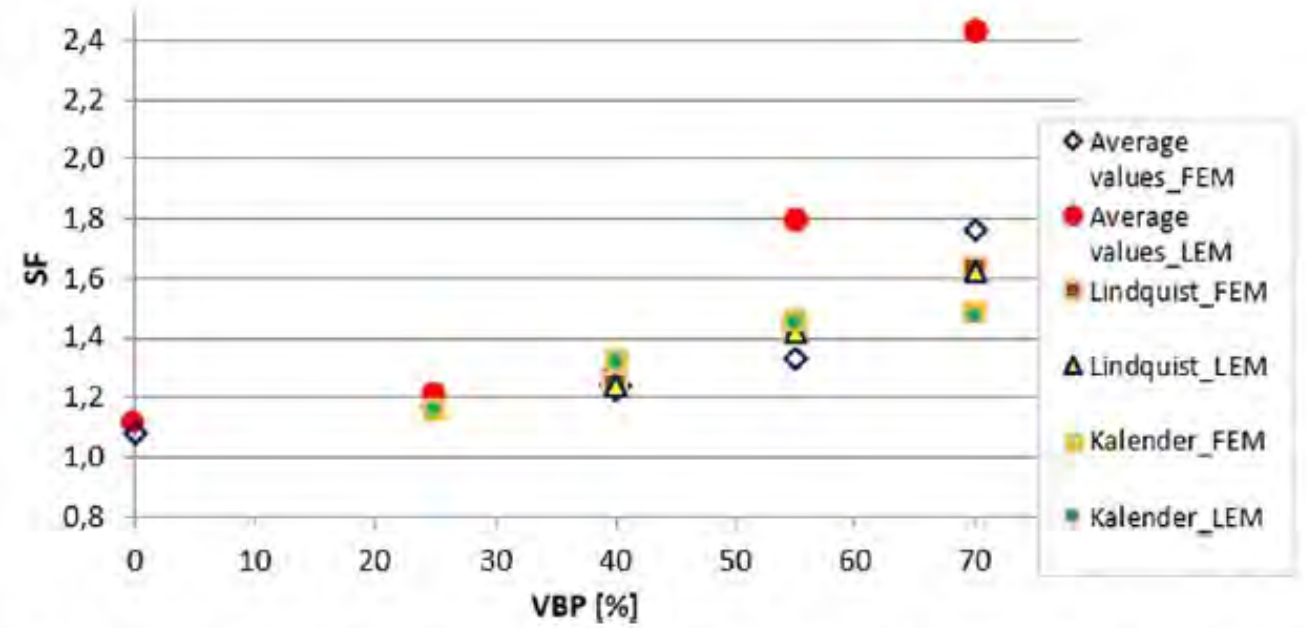

Fig. 7. Average safety factors versus VBP obtained with LEM and FEM analyses for heterogeneous (bimrock configurations) and homogeneous (Lindquist criterion) bimrock models.

- Stochastic approach with FEM is superior to use of assumed "homogeneous slope" using Lindquist or Kalander strength criteria.
- Deterministic estimates of block locations is unconservative – need to stochastically generate many different arrays

Napoli et al, 2018; A stochastic approach to slope stability analysis in bimrocks; Int. J. of Rock Mechanics and Mining Sciences 101 (2018) 41–49

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Summary: Fundamental Answers

- What is the overall strength of a complex geological mixture composed of strong blocks within a weaker matrix?? **Variable. Depends on Volumetric Block Proportion**
- Why not just use the strength of the weak matrix and be “conservative”? **Uneconomic and during construction blocks will be discovered**
- How much stronger do blocks have to be compared to matrix? **Modestly.**
- Does the strength of the blocks matter? **No - except during excavation**
- Is overall strength influenced by block geometries; orientations; number; etc.? **Yes. In complex interactions…**
- Does the scale of interest matter? **Yes. Some bimrocks/bimsoils may limited range of scale independence. Lab results may not fully apply to site scales.**
- How do we characterize complex geological mixtures? **In much the same way we characterize other geological materials.**

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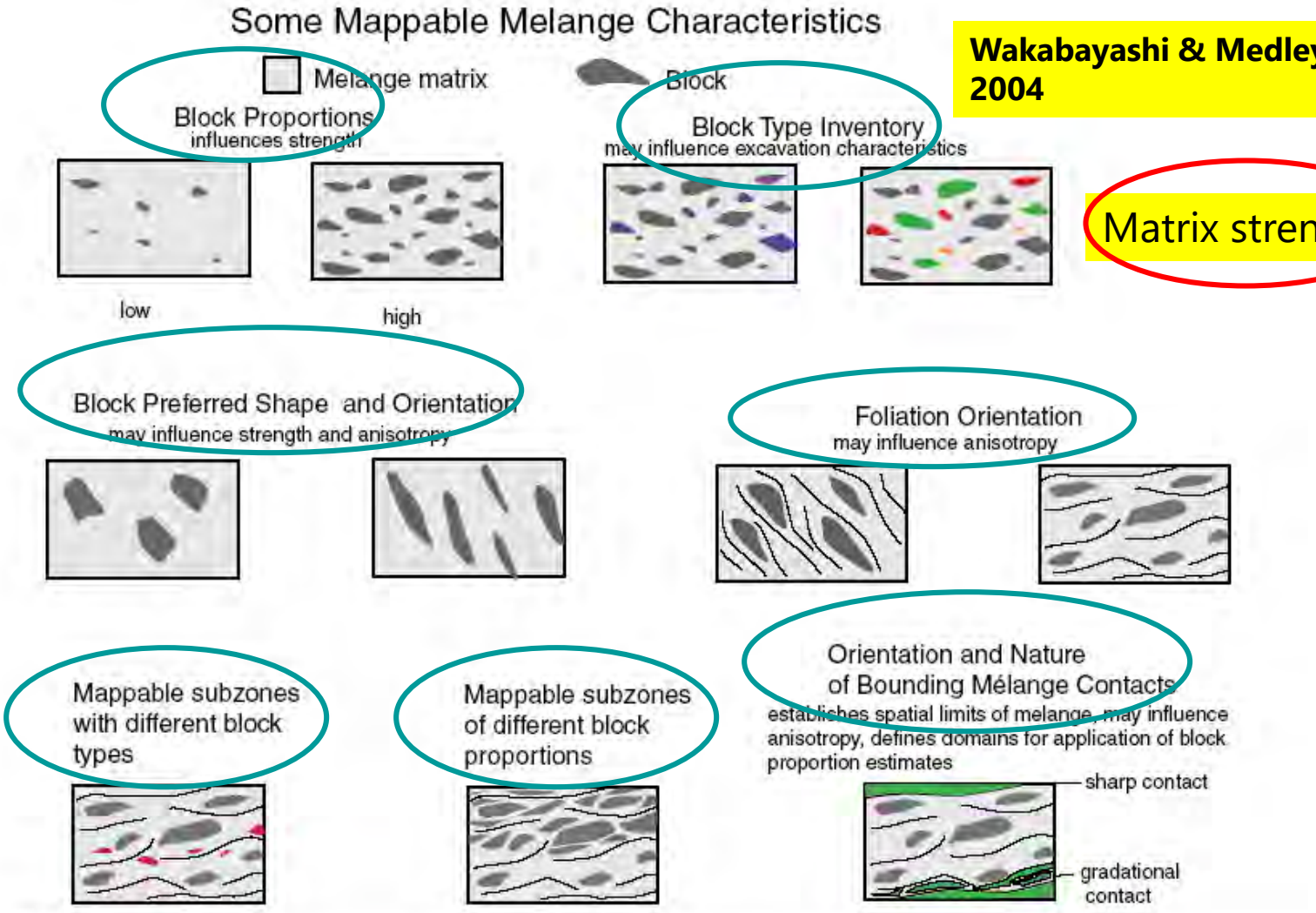
Systematic investigation of chaos



Wakabayashi & Medley, 2004

Matrix strength

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Thank You!

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