5. Slopes, tunnels and construction in bimrocks

Dr. Edmund Medley, PE, CEG, D.GE, F.ASCE
Geological Engineer
Principal Consultant
Terraphase Engineering, Oakland, CA
Departamento de Ingeniería Civil
Grupo de Investigación en Geotécnica
Universidad Nacional de Colombia, Medellín
Aula Máxima Facultad de Minas
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Motivation: analysis of slopes in bimrocks
BIG CONCLUSION 1: Remember this picture!!!

Matrix

Blocks, inclusions, lenses, etc

Scale: 1:??????

Matrix

Actual Distribution of Blocks
BIG CONCLUSION 1: Remember this picture!!!

Proposed Excavation or slope

Actual Distribution of Blocks

Blocks, inclusions, lenses, etc

Matrix

Scale: 1:???????
BIG CONCLUSION 2: Remember this picture as well!!!
Up Front: A Few Construction Considerations

• **EXPECT** unexpected surprises when working with bimrocks
• Run WHAT IF? Scenarios - Adopt the Geotechnical Observation Method
• If you neglect blocks in your analysis, and then forgot them – the Contractor will find them and remind you
• Large HARD blocks happen – estimate conservatively
• Wide, weak shears are common adjacent to large blocks
• During slope excavations, maybe OK to leave well-rooted blocks in hillsides (probe to evaluate size)
• Hydraulic augers may not work well for long – drained blocks may initially gush, then eventually dribble
Much of this lecture is possible thanks to the use of slides and photographs permitted by:

Gruppe Geotechnik Graz, Austria

Prof. Dick Goodman
SLOPE STABILITY of bimrocks
Remember this story?
Mischaracterization of bimrocks for slope constructions = “$$misery$$”
Case Study

Egnatia Motorway, Greece

Tunnels in thrust duplexes

Tunnels in a tectonic melange and olistostrome
Alpine forearc region, containing chaotic rock mass of predominantly shale, sandstone, siltstone, limestone and ophiolitic lithologies

The chaotic deposits include olistostromes and tectonic melanges, which characteristically contain a chaotic arrangement of competent blocks (limestone and ophiolitic olistoliths and/or phacoids) in an irregularly sheared weak matrix consisting of shale, sandstone, siltstone and gouge

This chaotic rock mass from different geological environments can be characterized from the engineering perspective as „block-in-matrix rocks“
Case Study: Egnatia Motorway, Greece

*Limestone Olistolith (Block) Embedded in an Irregularly Foliated Matrix of Shale, Siltstone and Sandstone*
Case Study: Egnatia Motorway, Greece

Limestone Olistolith Embedded in an Irregularly Foliated Matrix of Shale, Siltstone and Sandstone
Slope Excavated for Motorway
Case Study: Egnatia Motorway, Greece

Development of Landslides Caused by the Construction of the Motorway
Case Study: Egnatia Motorway, Greece

*Damaged Pre-Cut of the Tunnel M2 West Portal*
Blocks stabilize melange at coast
Melange Fabric in a Slope

Typical Melange Showing Diverse Elongate Blocks and Irregular Foliated Matrix (S-M-C-Cataclasites)

- Shears negotiate around blocks tortuously
- Not smooth rotational “failure surfaces” but chaotic trajectories
Franciscan Complex melange
weak block/matrix contacts
Landslide in Franciscan melange...
block-rich melange at toe resisted movement
..leading to back-facing scarps
Blocks added strength to matrix: but HOW MUCH??
(a motivation for some analysis..)

Photo: Ed Medley
Effects on slope stability of TORTUOSITY of failure surfaces negotiating around blocks
Tortuosity influenced by Block Size Distribution (BSD) and block shapes

a) Uniform size distribution

b) Graded size distribution

Uniform BSD  Graded BSD
Failed physical model melanges

150 mm diameter Tx specimens (Lindquist, 1994)

failure surfaces tortuously negotiate blocks
Tortuosity of failure surfaces influenced by low block proportion and vertical orientation
Tortuosity influenced by high proportion but horizontal orientation
Zones of variable block proportions

Sheared, block-poor matrix

Shears negotiate blocks in block-rich region
What are the influences on slope stability in bimrocks?

Block/matrix vol. proportion; matrix c, φ??
Block shape, block & shear orientation??
Block size, location, orientation??
Bimrock weak zones: width? variability??

Medley & Sanz, 2004
What are the influences on slope stability in bimrocks?

i.e.: really complex problem – how then should we analyze slope stability in bimrocks??

For now - use a soils engineering approach (although rock engineering methods are more appropriate when working with rocks)
Simple Investigation of effects of volumetric block proportion on slope stability

(Medley & Sanz, 2004)
Factor of Safety (FS)

\[ FS = \frac{\text{Resisting Moment}}{\text{Driving Moment}} \]

\[ = \frac{RSL}{Wx} \]

\[ 1.263 \]

\[ R \]

\[ W \]

\[ S \]

\[ L \]
Simple analysis of slope stability in a model Franciscan bimrock - start with matrix only

Critical failure surface for matrix-only case

$H = 10 \text{ m}$

Slope angle 35 degrees

c' = 10 kPa (200 psf)
Φ' = 26 degrees
unit wt = 1.92 (120 pcf)
NO GWT

FS for matrix only: 1.26
Analyses Assumptions

- **matrix**: $\Phi = 25^\circ$ $c = 10$ kPa (~200 psf)
- block strengths not considered
- no block/matrix contact strengths
- no water
Analyses Assumptions (cont.)

- BSD (Block Size Distribution) = part 2D Franciscan (~2n^{1.3})
- horizontal block orientations
- random arrays of blocks
- Areal = Volumetric block proportions
- failure surfaces pass around blocks
- 2D analyses suffice (for now...)
Simple random arrays of blocks

50%

25%

13%
Model Assumptions

\[ A_A = V_V \]

areal block proportion = volumetric proportion
(but generally it does not!)

trial surfaces negotiate blocks, tortuosity reflects many factors
Abstract trial failure surfaces, perform slope stability analyses using matrix strength only

Matrix-only failure surface $FS = 1.26$

Tortuous failure surface; using matrix strength $FS = 1.65$

Normalized $FS = 1.65/1.26 = 1.31$

Medley and Sanz Reherrmann, 2004
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

Envelope of tortuous failure surfaces is ~ 0.05L_c to 0.15 L_c wide
“First cut”: Slope stability increases with block proportion

Conclusion: Need MANY more iterations

Threshold 15% -25%?
Slope stability of Hong Kong Bouldery Colluvium
Hong Kong bouldery colluvium: Trial tortuous failure surfaces with blocks oriented out-of-slope

After Irfan & Tang, 1993

Matrix-only failure sfc.

Potential Failure Surface with Coarse Fraction

Potential Failure Surface without Coarse Fraction

failure sfc. negotiating blocks

After Irfan & Tang, 1993
Hong Kong experience:
blocks add strength

Irfan & Tang, 1993 GEO SPR 15/92

Figure 6.2 - Locations of Typical Potential Failure Surfaces in the Theoretical Slope Model

Figure 7.3 - Summary of the Hong Kong Study and the Recommendation for Mass Strength Increases For Slope Analysis in Colluvium

Irfan & Tang, 1993 GEO SPR 15/92
Combine analyses: **presence** of blocks increases slope stability FS

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

Approx. fit line

Block proportion of 30% raises bimrock FS to 1.5 from matrix-only FS of 1.3

(1.3)*1.15=1.5

NOTE: assumed that Areal Proportion = Volumetric Proportion

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Slope Analysis Cartoon 2: Temporarily forget the blocks..

- $c$, $\gamma$, $\phi$ of bimrock ($\alpha$ Vol. Prop. Blocks)
- $c$, $\gamma$, $\phi$ of failure zone dependent on block/shear contact ratio ($\alpha$ Vol. Prop Blocks)
- A trial failure zone 0.05H to 0.15H thick
Shortcomings and good intentions

• Must incorporate block/matrix contact strengths
• Must generalize procedures for other block shapes, orientations, etc.
• Must perform Monte Carlo-type analyses
• Need 3D numerical modeling to incorporate blocks
Some Observations on Bimrocks in Slopes

• Blocks add to slope stability by virtue of tortuosity of failure surfaces negotiating blocks (little to do with block strength)

• Tortuosity is most influenced by block proportions and block orientations

• Increased block proportions means increased tortuosity and increased stability

• Actual block distributions in bimrocks are unknowable so we can never predict the actual trajectories of tortuous failure surfaces in slopes

• Assume envelope of tortuous trajectories is about 0.05H to 0.15H thick (using slope height as \( L_c \))
BIG CONCLUSION 1: Remember this picture!!!

Actual Distribution of Blocks

Proposed Excavation or slope

Matrix

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BIG CONCLUSION 2: Remember this picture as well!!!
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BIG CONCLUSION 2: Remember this picture as well!!!

Proposed Tunnel

Apparent Distribution of Blocks

Willis, 2000
Tunneling failures can occur in relatively coherent rock-masses, so they are even more expected to occur in complex geology!
Some Rock Mass BEHAVIOUR TYPES
Tunneling in fault rocks and melanges can result in failures

Collapsed Tunnel M2, Egnatia Motorway, Greece
Tunnel Collapse in unexpected bimrock

Galgenberg Tunnel, Austria
Example Case Study of Geotechnical Hazard Assessment

Project Data
Upgrading of the river for energy production.
• Headrace tunnel (length 9km, diameter 9.0m
• Power house

Tasks
Geotechnical hazard assessment and optimization of design prior to construction
Geotechnical Longitudinal Section for the Tender Design

“faulted” rock
Site mapping in faulted rocks
Site mapping

Geotechnical Hazard Assessment
Site mapping of geological structures
Site mapping of bimrock...

Isolated blocks protruding from the ground are a BIG CLUE as to possible trouble rock mass!!
Revised Geotechnical Longitudinal Section

Fault zones with bimrocks

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emedley@bimrock.com
Consulting Geological Engineer
Compare to the revised profile where faulted zone is very much longer!!

“faulted” rock
BIMROCK EFFECTS in TUNNELS

- **Mixed face** conditions require different excavation methods on the same section

- **Strong variation** of rock mass quality

- **Stress redistribution** and deformations extremely influenced by arrangement of blocks and matrix

- **Prediction** of displacements and lining utilization extremely difficult

- **Danger of brittle failures in blocks**

- **Difficulty of determination of proper support**
Displacements depend on the length of the weak zone between two stiff blocks.
Final displacements influenced by zone length and stiffness contrast between blocks and matrix
Stress concentration in blocks depend on stiffness contrast and distance between blocks.

Graph showing stress distribution with different factors and variables.
BIMROCK EFFECTS

STRESS CONCENTRATIONS

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Engineer    emedley@bimrock.com
Consulting Geological
### BIMROCK EFFECTS

**Model 1.1**

<table>
<thead>
<tr>
<th>MODEL 1.1</th>
<th>advance</th>
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<tbody>
<tr>
<td>STIFF</td>
<td>SOFT</td>
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### Final Stresses Normalised

<table>
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<th>Final Stresses Normalised</th>
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<tr>
<td>( \frac{\sigma_2}{\sigma_{NPBE}} )</td>
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**Final Settlements**

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<td>settlement [m]</td>
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**Vector Orientation Trend**

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<th>Vector Orientation Trend</th>
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<td>trend = 0.5 D</td>
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**Relative Stress Increase**

- Relative stress increase in stiff material

**Relative Stress Decrease**

- Relative stress decrease in soft material

**Trough Shaped Displacement**

- Trough shaped displacement

**Change of Displacement Vector Orientation near Transition**

- Change of displacement vector orientation near transition
Stress concentrations can cause brittle failure in stiff blocks.

Resulting stress redistribution leads to additional displacements in the matrix material.

- Knowledge of the spatial distribution of blocks and matrix essential to properly estimate stress situation.
- Short term prediction and prediction of displacements extremely important.
- Support / reinforcement of blocks necessary to avoid brittle failure and long term stress redistribution, frequently mistaken for creeping.
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Medley, 2000
BIG CONCLUSION 2: Remember this picture as well!!!

Proposed Tunnel

Apparent Distribution of Blocks

Willis, 2000
Extras
13% block proportion: FS for a tortuous trial surface

FS ~1.38