Itasca Constitutive Model for Advanced Strain Softening (IMASS)

Background and Applied Examples

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Agenda

- Brief introduction to strain-softening constitutive models
- Theory of IMASS
- Examples
- Questions and answer session

✨ Please type any questions in the question panel and we’ll answer them at the end of the webinar
Introduction

A numerical model that represents the damage around an excavation, slope or caving process must account for the progressive failure and disintegration of the rock mass from an intact/jointed condition to a bulked material. Four critical factors that control the overall behavior of the rock mass matrix during this process are:

- Cohesion and Tension Weakening and Frictional Strengthening
- Post Peak Brittleness
- Modulus Softening
- Dilatational Behavior

This overall process – loading the rock mass to its peak strength, followed by a post-peak reduction in strength to some residual level with increasing strain – often is termed a “strain-softening” process and is the result of strain-dependent material properties.
The Itasca Constitutive Model for Advanced Strain Softening (IMASS) is a successor to the original CaveHoek constitutive model (first appearing in 2010).

In terms of strength envelopes, CaveHoek is characterized by two bounding yield surfaces (peak and residual).

After many successful projects and new discoveries about brittle rock behavior, a new strain softening model has been created (Itasca Model for Advanced Strain Softening).

IMASS contains two softening (residual) yield surfaces.
Damage and disturbance in IMASS

1. Peak Strength
   - Damage due to fracturing of intact rock
   - Small (negligible) bulking
   - Small strain processes
   - Damage is dependent on the accumulation of plastic shear strain

2. Post-Peak Strength
   - Disturbance due to rearrangement of rock blocks
   - Significant increase in bulking
   - Large strain processes
   - Disturbance is dependent on the accumulation of volumetric strain

3. Ultimate Strength

Low Confinement

High GSI

Low GSI

Damage due to fracturing of intact rock
Small (negligible) bulking
Small strain processes
Damage is dependent on the accumulation of plastic shear strain

Disturbance due to rearrangement of rock blocks
Significant increase in bulking
Large strain processes
Disturbance is dependent on the accumulation of volumetric strain

Damaged rock

Disturbed rock
Conceptual stress-strain curve

Stress

Peak

Post-peak

Ultimate strength

From peak to post-peak is controlled by accumulated plastic shear strain

From post-peak to ultimate strength is controlled by bulking

Damage

Disturbance

Strain

Peak is controlled by accumulated plastic shear strain

Post-peak to ultimate strength is controlled by bulking

Stress

Strain
Strength weakening in IMASS

- IMASS constitutive model is defined by three Hoek-Brown strength envelopes

- The GSI, $m_i$, and UCS parameters control the shape of the peak Hoek-Brown envelope (Hoek et al., 2002)

- The Hoek-Brown parameters of the residual strength envelopes are calculated in order to approximate Barton & Kjaernsli (1981) shear strength for rockfill material:

$$
\tau = \sigma_n \tan \left( R \log \left( \frac{S}{\sigma_n} \right) + \phi_b \right)
$$
Residual strength envelopes in IMASS

- At post-peak strength the rock mass is assumed to have undergone fracturing, but the resulting rock fragments are still fully interlocked hence porosity is considered to be zero.

- The ultimate strength envelope represents the true rock mass residual strength. At this point, the degree of rock fragments interlocking is at its minimum, and the porosity is maximized (maximum porosity of 40% is assumed).

- Ideally, the first and second residual envelops describe the behavior of cohesionless perfectly frictional material with different degrees of interlocking.

\[ \tau = \sigma_n \tan \left( R \log \left( \frac{S}{\sigma_n} \right) + \emptyset_b \right) \]
Residual strength envelopes in IMASS

When the shear strength from the Barton & Kjaersnli (1981) equation is converted to a strength envelope in $\sigma_1 - \sigma_3$ space, it can be approximated by a Hoek-Brown envelope with the following parameters:

$$s = 0$$

$$a = 0.6 + \frac{\text{porosity}}{\text{porosity}_{\text{max}}} \times [(1 - 0.075 \times ri) - 0.6]$$

$$m_b = 0.1614 \times e^{0.0836 \times \text{in}_\text{weak}_\text{phi}_b}$$

where,

- $ri$ is the roundedness index (with $ri = 0$ for partly rounded/smooth blocks, $ri = 1$ for angular/rough blocks, and $ri = 2$ for very sharp, angular/very rough blocks).
- $\text{in}_\text{weak}_\text{phi}_b$ is equivalent to $\phi_b$ (in degrees and default = 30 deg)

Extrapolated to 0% porosity
When the shear strength from the Barton & Kjaernsli (1981) equation is converted to a strength envelope in $\sigma_1 - \sigma_3$ space, it can be approximated by a Hoek-Brown envelope with the following parameters:

$$s = 0$$

$$a = 0.6 + \frac{\text{porosity}}{\text{porosity}_{\text{max}}} \times [(1 - 0.075 \times ri) - 0.6]$$

$$m_b = 0.1614 \times e^{0.0836 \times \text{in\_weak\_phib}}$$

The Hoek-Brown approximation of Barton & Kjaernsli (1981) shear strength criteria for rockfill that is implemented in IMASS assumes formation and interaction of very sharp, angular and very rough fragments during the course of bulking, from porosity 0% to 40%.

$$a = 0.6 + \left(\frac{V_{SI}}{0.67} \times 0.25\right)$$
Characteristics of IMASS residual envelopes

- Zero or near zero apparent cohesion and high friction angle at low confinement for the post-peak envelope
- Lower friction angle at low confinement for the ultimate strength envelope
- Both post-peak and ultimate strength envelopes continue to use peak Hoek-Brown envelope at higher confinement above brittle-ductile transition
Post-peak brittleness

From peak to post-peak is controlled by accumulated plastic shear strain. From post-peak to ultimate strength is controlled by bulking.

\[ \varepsilon_{c}^{p} = 12.5 - 0.125 \times \frac{GSI}{100 \times d} \]

(Lorig & Pierce, 2000)
Critical Strain sensitivity

Multiplier $\text{ecrit} = 1.0$

$\text{ecrit} \sim 30\%$

Vertical tunnel closure $\sim 1\%$

Horizontal tunnel closure $\sim 2\%$

Multiplier $\text{ecrit} = 0.1$

$\text{ecrit} \sim 3\%$

Vertical tunnel closure $\sim 1\%$

Horizontal tunnel closure $\sim 3.5\%$

Multiplier $\text{ecrit} = 0.01$

$\text{ecrit} \sim 0.3\%$

Vertical tunnel closure $\sim 2\%$

Horizontal tunnel closure $\sim 8\%$
Cohesion weakening

Multiplier $ecrit = 1.0$
$ecrit \sim 30\%$
Vertical tunnel closure $\sim 1\%$
Horizontal tunnel closure $\sim 2\%$

Multiplier $ecrit = 0.1$
$ecrit \sim 3\%$
Vertical tunnel closure $\sim 1\%$
Horizontal tunnel closure $\sim 3.5\%$

Multiplier $ecrit = 0.01$
$ecrit \sim 0.3\%$
Vertical tunnel closure $\sim 2\%$
Horizontal tunnel closure $\sim 8\%$
Frictional strengthening

Multiplier $\varepsilon_{\text{crit}} = 1.0$
- $\varepsilon_{\text{crit}} \approx 30\%$
- Vertical tunnel closure $\approx 1\%$
- Horizontal tunnel closure $\approx 2\%$

Multiplier $\varepsilon_{\text{crit}} = 0.1$
- $\varepsilon_{\text{crit}} \approx 3\%$
- Vertical tunnel closure $\approx 1\%$
- Horizontal tunnel closure $\approx 3.5\%$

Multiplier $\varepsilon_{\text{crit}} = 0.01$
- $\varepsilon_{\text{crit}} \approx 0.3\%$
- Vertical tunnel closure $\approx 2\%$
- Horizontal tunnel closure $\approx 8\%$
Porosity-dependent softening/weakening

From peak to post-peak is controlled by accumulated plastic shear strain

From post-peak to ultimate strength is controlled by bulking

Plastic part of strain increment between peak to post-peak

\[ B = \frac{\Delta V}{V_i} = \frac{n}{1 - n} \]

• Residual strength can weaken and strengthen between post-peak and ultimate strength envelopes as a function of porosity
• This would allow for capturing strength gain in material due to recompaction
Two cases of initial compaction

Highly Compacted
Initial VSI ~ 0 (porosity 0%)

Low Compacted
Initial VSI ~ 0.2 (porosity 17%)
Cave propagation

FLAC3D 7.00
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Scalars
Mark Type: Sphere
- Air
- Mobilized Active
- Mobilized Inactive
Scale: 1.5

Geometry Set
- Drift Level 1
Cave-back
Color By: Uniform
Isosurface Value 1
Zone
Calculated by: Volumetric Averaging

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Highly Compacted

Low Compacted
Tension weakening in *IMASS*

The mechanism of independent tensile softening is implemented in *IMASS*, i.e., in addition to softening tension and cohesion at the same rate based on plastic shear strain, tension is allowed to soften independently of the cohesion in the instance of a tensile yield state within a zone.

Alternatively, a table that correlates tension weakening to accumulated plastic tensile strain can be assigned to zones to control the tension weakening.
Modulus softening

The rock mass Young's modulus \( (E_{rm}) \) can be estimated from the intact Young's modulus \( (E_i) \) and GSI using Hoek and Diederichs’ (2006) equation:

\[
E_{rm} = E_i \left( 0.02 + \frac{1}{60 - GSI} \right)
\]

- Pappas and Mark (1993) show that the modulus of rock drops in a non-linear fashion with increased bulking, and that the rate of modulus change is a function of fragment shape and intact strength.
- In IMASS the modulus is updated constantly via the zone-based volumetric strains. This allows for both modulus softening (during bulking) and modulus hardening (e.g., during recompaction).
Intact rock
Young’s modulus

Rock mass modulus

GSI
Modulus softening

Different maximum bulking factors (VSI)
Dilational behavior

- Within IMASS, the dilation angle is set as a standard material property and drops to zero once the user-defined maximum bulking factor is reached. This prevents zones from expanding to unrealistic levels during shear.

- A constant dilation angle can be assigned to the rock mass (i.e., equal everywhere) based on the available guidelines such as those provided by Hoek and Brown (1997).

- Alternatively, a more advanced dilation model is available that constantly updates the dilation angle for each zone as a function of confining stress and porosity (or VSI).

Currently being tested and validated by Itasca
Dilational behavior

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- A constant dilation angle can be assigned to the rock mass (i.e., equal everywhere) based on the available guidelines such as those provided by Hoek and Brown (1997).

- Alternatively, a more advanced dilation model is available that constantly updates the dilation angle for each zone as a function of confining stress and porosity (or VSI).

\[ \tau = \sigma_n \tan \left( R \log \left( \frac{S}{\sigma_n} \right) + \phi_b \right) \]
sloss – an indicator for damage in IMASS

sloss changes between [1,-1]:
- Between Peak and post-peak envelope, sloss = 1 – (plastic shear strain/critical plastic shear strain)
- Between post-peak and ultimate strength envelope sloss = – (volumetric strain/max allowable volumetric strain)
sloss example
No signs of damage or fracturing in most of the level – in line with observations.

Damage on this level corresponds to an area of observed damage along the wall of the drift.

Mobilized Zone

Fractured Zone
Current Conditions

Full cohesion loss
Bulked to ~4%

Intact strength

Damage seen on site

Stope
Year 3

Full cohesion loss Bulked to ~4% porosity

Mobilized Zone
Color By: Uniform Iso-surface value -2 Zone

Intact strength

Geometry
Contour of Property emer_weak_sloss

1.0000E+00
9.4000E-01
8.8000E-01
8.2000E-01
7.6000E-01
7.0000E-01
6.4000E-01
5.8000E-01
5.2000E-01
4.6000E-01
4.0000E-01
3.4000E-01
2.8000E-01
2.2000E-01
1.6000E-01
1.0000E-01
4.0000E-02
-2.0000E-02
-8.0000E-02
-1.0000E-01

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Full cohesión loss Bulked to ~4% porosity

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Geometry
Contour of Property emer_weak_sloss

Intact strength

Mobilized Zone
Color By: Uniform
Iso-surface value -2

Year 6
Year 7

Full cohesion loss
Bulked to ~4%

Mobilized Zone
Color By: Uniform ISO-surface value -2

Geometry
Contour of Property emr_weak_sloss
Intact strength

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Year 8

Full cohesion loss
Bulked to ~4% porosity

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Year 9

Full cohesion loss Bulked to ~4% porosity

Intact strength

Geometry
Contour of Property emer_weak_sloss

[Color Scale]
1.0000E+00
9.4000E-01
8.8000E-01
8.2000E-01
7.6000E-01
7.0000E-01
6.4000E-01
5.8000E-01
5.2000E-01
4.6000E-01
4.0000E-01
3.4000E-01
2.8000E-01
2.2000E-01
1.6000E-01
1.0000E-01
4.0000E-02
-2.0000E-02
-8.0000E-02
-1.0000E-01
Full cohesion loss Bulked to ~4% porosity
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Geometry
Contour of Property emer_weak_sloss
1.0000E+00
9.4000E-01
8.8000E-01
8.2000E-01
7.6000E-01
7.0000E-01
6.4000E-01
5.8000E-01
5.2000E-01
4.6000E-01
4.0000E-01
3.4000E-01
2.8000E-01
2.2000E-01
1.6000E-01
1.0000E-01
4.0000E-02
-2.0000E-02
-8.0000E-02
-1.0000E-01

Intact strength Full cohesion loss Bulked to ~4% porosity

Mobilized Zone
Color By: Uniform Iso-surface value -2 Zone

Year 11

Full cohesion loss Bulked to ~4% porosity

GEOMECHANICS • HYDROGEOLOGY • MINING • CIVIL • ENERGY
Fracture limit defined as isosurface of total strain = 0.005
Fracture limit defined as isosurface of total strain $= 0.005$
Fracture limit defined as isosurface of total strain = 0.005
Fracture limit defined as isosurface of total strain = 0.005
Fracture limit defined as isosurface of total strain $= 0.005$
Fracture limit defined as isosurface of total strain = 0.005
Fracture limit defined as isosurface of total strain = 0.005
Fracture limit defined as isosurface of total strain = 0.005
Fracture limit defined as isosurface of total strain $= 0.005$
Fracture limit defined as isosurface of total strain = 0.005
Rock mass degradation behind a slope
Rock mass degradation behind a slope

Potential failure of the slope (volume in red)

Unstable Volume defined by velocities

Circular rock mass failure accommodated by UJ failure at the toe

Section A
Some other important components of IMASS

- Density adjustment based on zone-based volumetric strain
- Weakness planes defined by Ubiquitous Joints
- Option between one or two residual envelopes
- Tracking stresses at failure

- *IMASS uses the latest Itasca constitutive model framework and techniques for apex correction, automatic testing, and property update and management.*
Installation and usage

- **IMASS** is built into **FLAC3D 7.0** and **3DEC 7.0**
- Invoking the model:

  ```
  model config imass
  zone cmodel assign imass
  zone initialize density [_density]
  zone property in_stren_gsi [_gsi]
  zone property in_stren_uksi [_uksi]
  zone property in_stren_mi [_mi]
  zone property in_mod_youngintact [_young]
  zone property in_weak_multecrit [_mult]
  ```

These are the only properties required to have all default behaviors active
Research and improvements

- IMASS is a constitutive model based on empirical relationships, its formulation is ever-evolving with the state-of-the-art knowledge of strength and post-peak behavior of brittle rock masses. The current focus on refinement of the IMASS behavior include:

  ◦ A more robust criteria for estimation of critical plastic shear strain (post-peak brittleness)
  ◦ Characterization of the upper- and lower-bound for the equivalent roughness (R) (especially for porosities below 15%)
  ◦ Refinement of the dilation model consistent with the upper- and lower-bound R and how it transitions between those values with increasing rock mass porosity
Final remarks

- *IMASS* has been developed to represent the rock-mass response to stress changes using strain-dependent properties that are adjusted to reflect the impacts of dilation and bulking as a rock mass undergoes plastic deformation.

- The two-mode softening in *IMASS* allows for mobilization of a high apparent friction angle at low confinement when the fragments are formed in the rock mass. This is followed by reduction in friction angle as the rock mass bulks allow for a realistic simulation of the rock mass post-peak behavior.

- *IMASS* and its predecessor, *CaveHoek*, have been developed and refined over the past decade with mining applications being their core purpose. They have been used successfully by Itasca on numerous operations and projects.
Questions & Answers

Learn more about IMASS at www.itascainternational.com/software/imass