AD FALCON API Manual

Hoek-Brown Model

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1 Hoek-Brown Model

Elastic-plastic Hoek-Brown failure surface in principal-stress space with a tensile cutoff and a non-associated plastic potential controlled by `HB_md`.

1.1 Syntax

This model is configured in `% Materials` as a user-defined mechanical material. Use `@UMAT:` with category `Mechanical` and pass the parameters as `name=value` pairs.

Example:

```
@UMAT: path/to/HoekBrownModelUMAT.cpp path/to/HoekBrownModelUMAT.hpp
Mechanical \
    HB_mb=10 HB_s=1e-4 HB_a=0.5 Sigma_ci=100 HB_md=5 \
    E=1e4 Nu=0.30 STOL=1e-7 FTOL=1e-5 LTOL=1e-6
```

For readability, this example is wrapped across multiple lines; in input files you should write the full `@UMAT:` directive on a single line.

Use the parameter names listed below.

1.2 Material parameters

Symbol	Keyword in input	Units	Required	Description
m_b	`HB_mb`	–	✓	Hoek-Brown material constant controlling confinement dependence.
s	`HB_s`	–	✓	Hoek-Brown material constant shifting the failure envelope.
a	`HB_a`	–	✓	Hoek-Brown exponent.
σ_{ci}	`Sigma_ci`	stress	✓	Intact uniaxial compressive strength.

Symbol	Keyword in input	Units	Required	Description
m_d	`HB_md`	–	✓	Plastic-potential parameter controlling dilatancy / non-associativity.
E	`E`	stress	✓	Young's modulus.
ν	`Nu`	–	✓	Poisson's ratio.
`STOL`	`STOL`	–	✓	Stress-integration tolerance.
`FTOL`	`FTOL`	–	✓	Yield-surface tolerance.
`LTOL`	`LTOL`	–	✓	Load-unload detection tolerance.

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Basic admissibility enforced by the implementation:

- `HB_mb >= 0`
- `HB_s >= 0`
- `HB_a > 0`
- `Sigma_ci > 0`
- `HB_md >= 0`
- `E > 0`
- `-1 < Nu < 0.5`

1.3 Custom state variables

This UMAT does not require hardening variables in the `@UMAT:` line, but it now supports the same cumulative plastic-strain custom variables used by the GCC implementation.

If you declare them in `CustomVariable=...`, the UMAT updates them cumulatively:

- `PlasticStrainIncXX`
- `PlasticStrainIncYY`
- `PlasticStrainIncZZ`
- `PlasticStrainIncZY`
- `PlasticStrainIncZX`
- `PlasticStrainIncXY`

Behavior:

- elastic steps leave these values unchanged
- plastic steps add the current plastic strain increment component-wise
- `initializeCustomVariable(...)` initializes missing entries to zero

1.4 Stress convention and principal stresses

FALCON stores stresses in the usual tension-positive tensor convention used by the codebase. The Hoek-Brown driver pages often report compression-positive invariants for interpretation:

$$p_c = -\frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3}, \qquad q_c = (-\sigma_{yy}) - (-\sigma_{xx})$$

The UMAT evaluates the yield function in principal-stress space. Let:

- σ_1 be the algebraically largest principal stress
- σ_3 be the algebraically smallest principal stress

Then the corresponding compression-positive principal stresses are:

$$\sigma_{1c} = -\sigma_3, \qquad \sigma_{3c} = -\sigma_1$$

so that σ_{1c} is the major compressive principal stress and σ_{3c} is the minor compressive principal stress.

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1.5 Hoek-Brown yield surface

The coded Hoek-Brown branch is:

$$f_{\mathrm{HB}} = \sigma_{1c} - \sigma_{3c} - \sigma_{ci} \left(m_b \frac{\sigma_{3c}}{\sigma_{ci}} + s \right)^a$$

The argument

$$X = m_b \frac{\sigma_{3c}}{\sigma_{ci}} + s$$

must remain positive for the Hoek-Brown branch to be active.

1.5.1 Tensile cutoff

The implementation also applies a tensile cutoff:

$$f_t = \sigma_1 - \sigma_t, \qquad \sigma_t = \max\left(0, \frac{s\,\sigma_{ci}}{m_b}\right)$$

and uses

$$f = \max(f_{\mathrm{HB}}, f_t)$$

as the active yield function.

This means the model follows the Hoek-Brown branch in compression and switches to the tensile cutoff when that branch is less restrictive than the tension limit.

1.6 Plastic potential and dilation

The flow rule is non-associated when `HB_md` differs from `HB_mb`. In the coded plastic potential gradient, `HB_md` replaces `HB_mb` inside the cap-like Hoek-Brown argument used for the plastic potential:

$$X_g = m_d \frac{\sigma_{3c}}{\sigma_{ci}}$$

with `HB_md = 0` giving the least dilatant packaged response and larger positive `HB_md` activating stronger dilation.

Practical interpretation:

- `HB_md = 0` gives a non-dilatant plastic potential in the packaged triaxial examples.
- Increasing `HB_md` increases dilatancy in plastic loading.
- In the packaged mini examples, the undrained case uses `HB_md = 5.0` so dilation is active.

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1.7 Elastic law

The elastic predictor uses linear isotropic elasticity:

$$K = \frac{E}{3(1-2\nu)}, \qquad G = \frac{E}{2(1+\nu)}$$

with the standard 6×6 isotropic tangent in Voigt form.

1.8 FALCON mini

The packaged mini tool id is `HoekBrown`. It lives under `mini_tools/HoekBrown`.

1.8.1 How to run

Run any packaged analysis by passing its case directory:

```
falcon --mini-root /path/to/UMATLIB_FALCON/falcon_minis --mini-tool
HoekBrown --mini-input
/path/to/UMATLIB_FALCON/falcon_minis/HoekBrown/cases/drained
```

Packaged simulation families:

- drained triaxial: `cases/drained/input.txt`

- undrained triaxial: `cases/undrained/input.txt`
- drained parameter examples: `cases/drained_hbmb5/input.txt`, `cases/drained_sigmaci150/input.txt`, `cases/drained_hbmd5/input.txt`

1.8.2 Input syntax

`input.txt` uses whitespace-delimited `Key Value` pairs, one item per line, for example:

```
Mode Drained
HB_mb 10.0
Sigma_ci 100.0
StressXX -100.0
```

The main driver selector is `Mode`.

`Mode` value	Meaning in the standalone mini	Hydraulic assumption / constraint
`Drained`	Saturated drained triaxial loading. The driver applies axial strain and solves a radial strain increment that keeps the radial stress approximately constant.	No suction or retention update is used.
`Undrained`	Saturated constant-volume triaxial loading. The driver applies axial strain with the axisymmetric constant-volume relation used by the standalone code.	No suction or retention update is used.

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Mini inputs used by the packaged cases:

Input key	Used by	Required / choices / defaults	Meaning
`Mode`	all cases	Required; packaged mini currently uses `Drained` for the featured cases	Selects the loading program executed by the standalone driver.

Input key	Used by	Required / choices / defaults	Meaning
`HB_mb`	all cases	Required in packaged cases	Hoek-Brown material constant controlling confinement sensitivity.
`HB_s`	all cases	Required in packaged cases	Hoek-Brown material constant that shifts the failure surface.
`HB_a`	all cases	Required in packaged cases	Hoek-Brown exponent.
`Sigma_ci`	all cases	Required in packaged cases	Intact uniaxial compressive strength.
`HB_md`	all cases	Required in packaged cases	Plastic-potential parameter controlling dilation / non-associativity.
`E`	all cases	Required in packaged cases	Young's modulus for the elastic predictor.
`Nu`	all cases	Required in packaged cases	Poisson's ratio for the elastic predictor.
`STOL`	all cases	Optional; UMAT default if omitted	Stress-integration tolerance used by the UMAT.
`FTOL`	all cases	Optional; UMAT default if omitted	Yield-surface tolerance used by the UMAT.
`LTOL`	all cases	Optional; driver default if omitted	Load-detection tolerance used by the standalone driver.
`StressXX`, `StressYY`, `StressZZ`	all cases	Required in packaged cases	Initial total stress components. The packaged cases use an isotropic starting state.
`VoidRatio`	all cases	Required in packaged cases	Initial void ratio reported and updated in the standalone output.

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Input key	Used by	Required / choices / defaults	Meaning
`dEpsAxial`	all cases	Required in packaged cases	Axial strain increment applied at each step.
`nSteps`	all cases	Required in packaged cases	Number of imposed load increments in the packaged case.

1.8.3 Hydromechanical assumptions

The packaged Hoek-Brown mini is purely saturated mechanical triaxial loading:

- no SWRC, suction, or effective-stress weighting is used in the standalone mini
- `Drained` and `Undrained` here refer only to the kinematic boundary condition applied by the triaxial driver
- the `VoidRatio` column is tracked as part of the standalone driver output, but there is no unsaturated hydraulic coupling in this mini

1.8.4 Sample input

Drained triaxial example Path: `mini_tools/HoekBrown/cases/drained/input.txt`

```
Mode Drained
HB_mb 10.0
HB_s 1.0e-4
HB_a 0.5
Sigma_ci 100.0
HB_md 0.0
E 10000.0
Nu 0.30
StressXX -100.0
StressYY -100.0
StressZZ -100.0
VoidRatio 0.60
dEpsAxial -1.0e-4
nSteps 400
```

This packaged drained case is the baseline Hoek-Brown triaxial compression example. It uses `HB_md = 0`, so the plastic potential is non-dilatant in the sense used by this standalone driver.

Additional drained parameter examples used in the sensitivity plot:

- `mini_tools/HoekBrown/cases/drained_hbmb5/input.txt`: lower `HB_mb`

- `mini_tools/HoekBrown/cases/drained_sigmaci150/input.txt`: higher `Sigma_ci`
- `mini_tools/HoekBrown/cases/drained_hbmd5/input.txt`: higher `HB_md`

1.8.5 Output files and columns

Each run writes `stress_results.csv`.

Output file	Produced by	Main use
`stress_results.csv`	all cases	Main step-by-step mechanical history used by the packaged Hoek-Brown plots.

Main columns in `stress_results.csv`:

Output column	Meaning
`step`	Load-step index written by the standalone driver.
`exx`, `eyy`, `ezz`, `ezy`, `ezx`, `exy`	Strain components for the accepted step state.
`sxx`, `syy`, `szz`, `szy`, `szx`, `sxy`	Stress components for the accepted step state.
`q`	Deviatoric stress measure written directly by the standalone driver.
`p`	Mean stress measure written directly by the standalone driver.
`qc`, `pc`	Compression-positive stress invariants reported for interpretation alongside `q` and `p`.
`ev`	Volumetric strain measure reported by the standalone driver.
`q_theory`	Hoek-Brown comparison curve written by the driver for the current confinement state.
`e`	Void ratio.
`epxx`, `epyy`, `epzz`, `epzy`, `epzx`, `epxy`	Cumulative plastic-strain components carried in the custom-state variables.

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When reading the packaged outputs, the main columns to inspect are:

- `q` and `p` for the triaxial stress path
- `qc` and `pc` if you want compression-positive reporting
- `q_theory` for comparison with the analytical Hoek-Brown stress level
- `e` and `ev` for the volumetric response

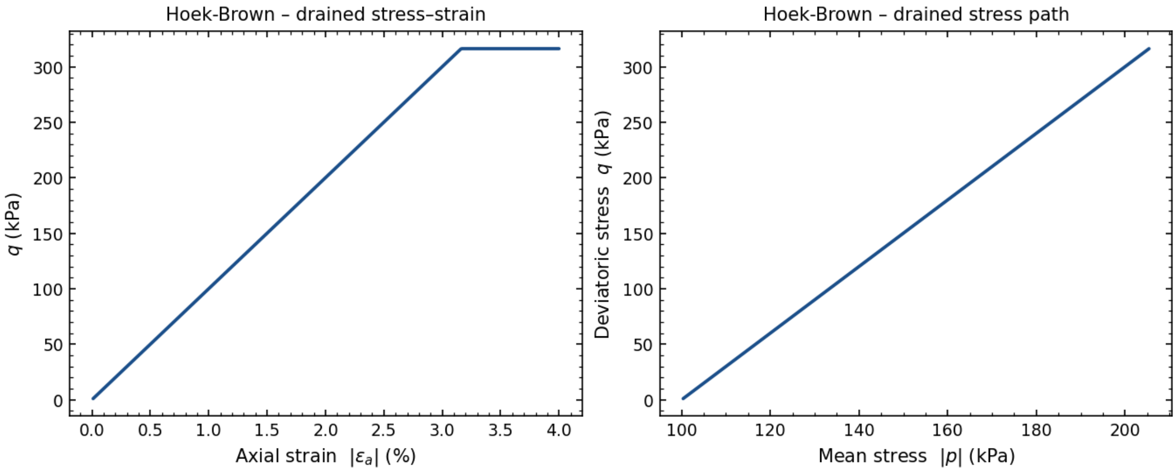

Figure 1: Drained Hoek-Brown response

- `epxx` to `epxy` for cumulative plastic strain

The plots in the next section are generated from these packaged case CSVs.

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1.9 Results

The plots below are produced directly from the packaged Hoek-Brown case directories. The baseline drained case uses `HB_mb = 10`, `HB_s = 1e-4`, `HB_a = 0.5`, `Sigma_ci = 100 kPa`, `HB_md = 0`, `E = 10 GPa`, `Nu = 0.30`, and the initial isotropic stress state `StressXX = StressYY = StressZZ = -100 kPa`.

1.9.1 Drained reference case

Bundled input: `mini_tools/HoekBrown/cases/drained/input.txt`

Left: deviatoric response of the packaged drained triaxial case. Right: the corresponding `q-p` stress path. This bundled case is long enough to reach the Hoek-Brown plateau for the chosen confinement.

1.9.2 Drained parameter influence

Bundled inputs:

- `mini_tools/HoekBrown/cases/drained/input.txt`
- `mini_tools/HoekBrown/cases/drained_hbmb5/input.txt`
- `mini_tools/HoekBrown/cases/drained_sigmaci150/input.txt`
- `mini_tools/HoekBrown/cases/drained_hbmd5/input.txt`

Top left: reducing `HB_mb` lowers the confinement sensitivity and changes the drained triaxial strength curve. Top right: increasing `Sigma_ci` raises the overall strength level.

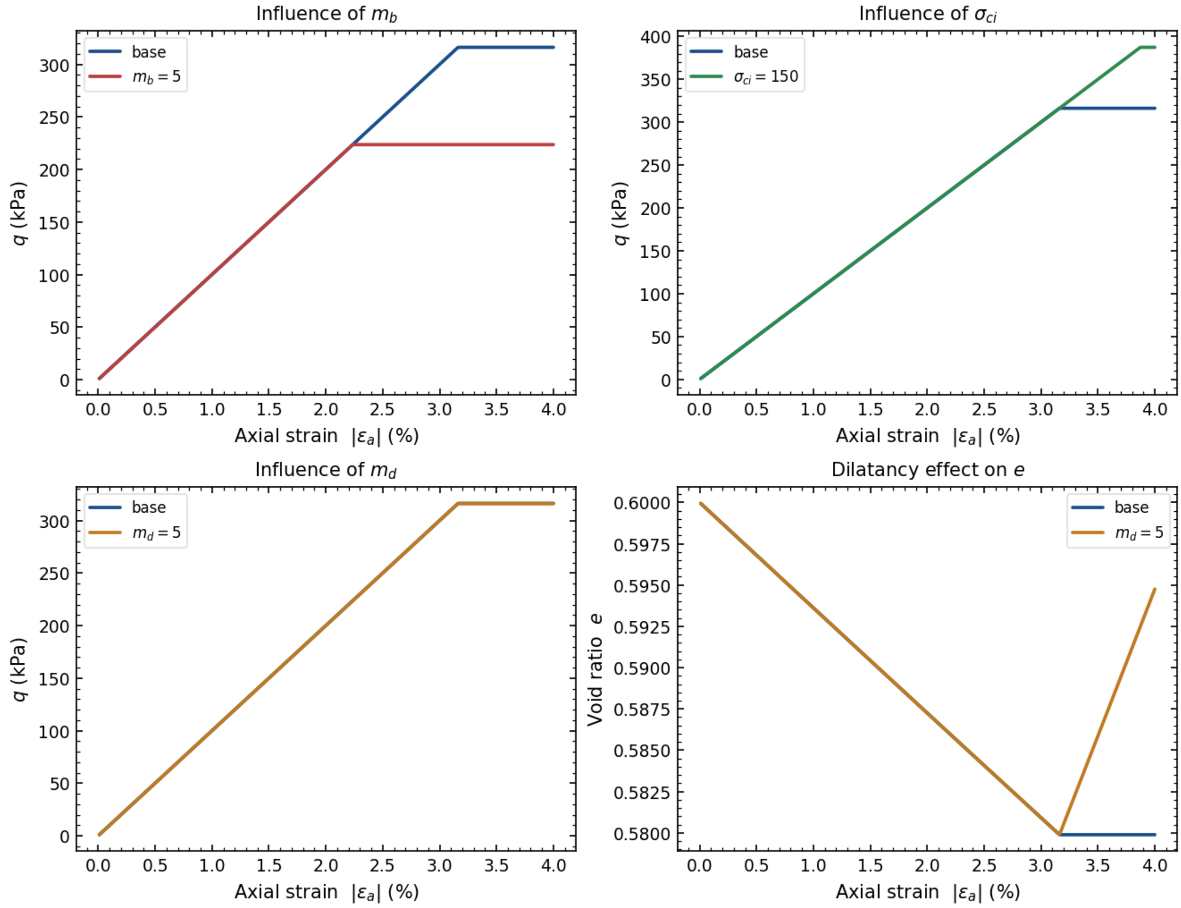

Figure 2: Drained Hoek-Brown parameter influence

Bottom left: increasing `HB_md` changes the drained response through the plastic potential. Bottom right: the same `HB_md` change shown through the void-ratio response, which is the clearest place to see the dilatancy effect.

1.10 Applications and limitations

- Best suited to rock and rock-mass strength problems where Hoek-Brown behavior is more appropriate than a soil friction model.
- Appropriate for uncoupled and effective-stress-based coupled formulations, but it is not an intrinsic unsaturated soil constitutive law.
- Not intended for critical-state soil behavior, suction hardening, or advanced cyclic sand response.

1.11 References

- Hoek, E. and Brown, E.T. (1980). *Underground Excavations in Rock*. Institution of Mining and Metallurgy.
- Hoek, E., Carranza-Torres, C. and Corkum, B. (2002). *Hoek-Brown failure criterion - 2002 edition*. Proceedings of NARMS-TAC.

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