3 BARTON-BANDIS JOINT MODEL

3.1 Background

A series of empirical relations has been developed by Drs. Nick Barton and Stavros Bandis to describe the effects of surface roughness on discontinuity deformation and strength. These relations, known collectively as the Barton-Bandis joint model, have been implemented into *UDEC*.* A complete explanation of these relations can be obtained from Barton (1982) and Bandis et al. (1985). In summary, the Barton-Bandis joint model encompasses the following features.

Joint Normal Behavior

- hyperbolic stress-displacement path
- hysteresis due to successive load/unload cycles
- normal stiffness increase due to successive load/unload cycles
- normal stiffness change due to surface mismatch caused by shear displacement
- hydraulic aperture calculation based on joint closure and joint roughness

Joint Shear Behavior

- dilation as function of normal stress and shear displacement
- joint damage due to post-peak shear
- reduced secondary peak shear upon post-peak shear reversal

The implementation of these features of the Barton-Bandis model in *UDEC* is described in the following sections.

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* The Barton-Bandis joint model is a separate module that can be included in *UDEC* at an additional cost.

3.2 Joint Normal Behavior

The equation that controls the normal stress-displacement path (Figure 3.1) for the Barton-Bandis model is

$$\sigma_n = \frac{-u_{nc} \cdot K_{ni}}{1 - \frac{u_{nc}}{v_{mi}}} \tag{3.1}$$

where u_{nc} = current normal displacement (mm);

K_{ni} = initial normal stiffness (MPa/mm); and

v_{mi} = maximum allowable closure (mm) for load cycle i.

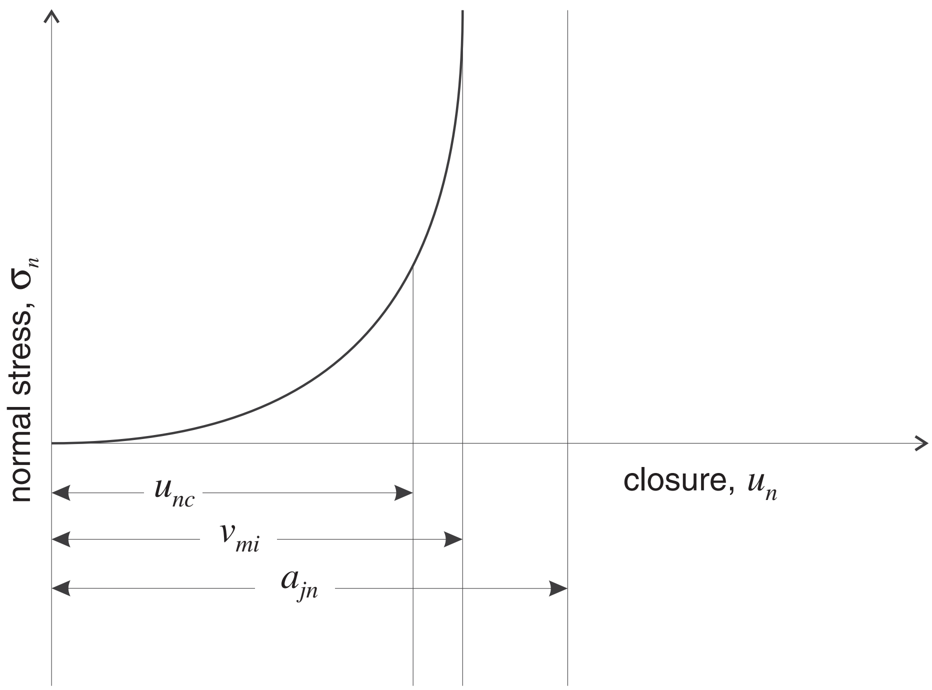

Figure 3.1 Parameters used to calculate normal stress during load cycle

The initial joint stiffness (K_{ni}), which changes with load cycle number, is calculated by

$$K_{ni} = 0.0178 \left[\frac{JCS_o}{a_{jn}}\right] + 1.748\, JRC_o - 7.155 \tag{3.2}$$

where JCS_o = laboratory-scale joint wall compression strength;

a_{jn} = joint aperture at zero normal stress; and

JRC_o = laboratory-scale roughness coefficient.

The maximum allowable closure (v_{mi}) for load cycle i is given by

$$v_{mi} = A_i + B_i\,(JRC_o) + C_i \left[\frac{JSC_o}{a_{jn}} \right]^{D_i} \tag{3.3}$$

where A_i, B_i, C_i, D_i are constants associated with load cycle number. The constants are summarized in Table 3.1.

Table 3.1 Constants used for calculation of v_{mi}

Constant	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**
A_i	−0.296	−0.1005	−0.1031	−0.1031
B_i	−0.0056	−0.0073	−0.0074	−0.0074
C_i	2.241	1.0082	1.135	1.135
D_i	−0.245	−0.230	−0.251	−0.251

To calculate the path for an unload cycle following a load cycle, a new v_{mi} and K_{ni} are calculated. K_{ni} is calculated from Eq. (3.2) using a new aperture value, a_{jn}, which is reduced by the irrecoverable closure (v_{irr}). v_m is recalculated from Eq. (3.3), also using a_{jn}, reduced by v_{irr}. The irrecoverable closure, v_{irr}, is calculated from Eq. (3.4),

$$v_{irr} = \left[C_1 - C_2 \left[\frac{JCS_o}{a_{jn}} \right] \right] \frac{u_{nl}}{100} \tag{3.4}$$

where u_{nl} is the maximum closure for a completed load cycle; and

C_1,C_2 are empirical constants for the current cycle.

The parameters used to calculate normal stress during an unload a cycle are illustrated in Figure 3.2. The constants used for v_{irr} are given in Table 3.2.

Table 3.2 Constants used for calculation of v_{irr}

Constant	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**
C_1	84.77	44.37	31.38	20.00
C_2	0.02	0.01	0.01	0.01

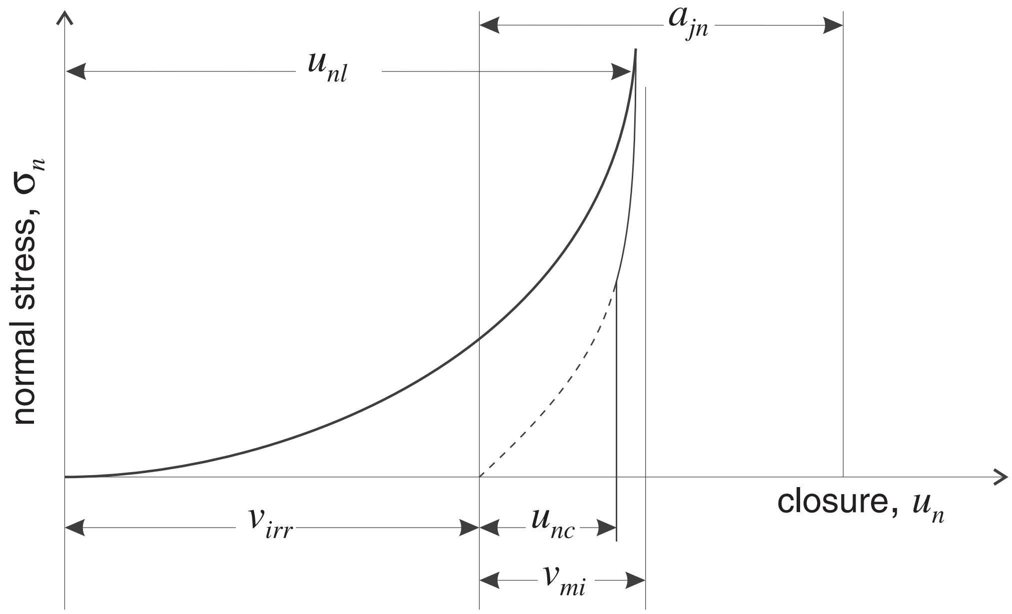

Figure 3.2 Parameters used to calculate normal stress during unload cycle

To maintain displacement continuity, v_{irr} is added to the sum of the previous irrecoverable closures (u_{npc}) and subtracted from the current closure (u_{nc}). For the next load cycle, K_{ni} remains constant, and a new v_m is calculated using Eq. (3.3) and the constants for the next load cycle. If a partial unload was done, the hyperbolic curve is shifted on the x-axis, and v_{mi} is modified to provide load continuity.

Successive load/unload cycles will continue to stiffen the joint normal behavior. (See Figure 3.3.) The empirical constants derived by Barton and Bandis do not change after cycle 4, but the aperture will continue to decrease. The load cycle number will not increase beyond 10, and the load and unload curves will become identical. To maintain numerical stability, the stiffness of the model is limited to the joint normal stiffness (**st-n**) value specified with the **block contact property** command. A linear stiffness function is substituted into the stress displacement calculations when the stiffness of the Barton-Bandis model exceeds **st-n**. The values printed for aperture and normal displacement are corrected to follow the actual hyperbolic curve. The value of u_{nc} printed will reflect the actual displacement.

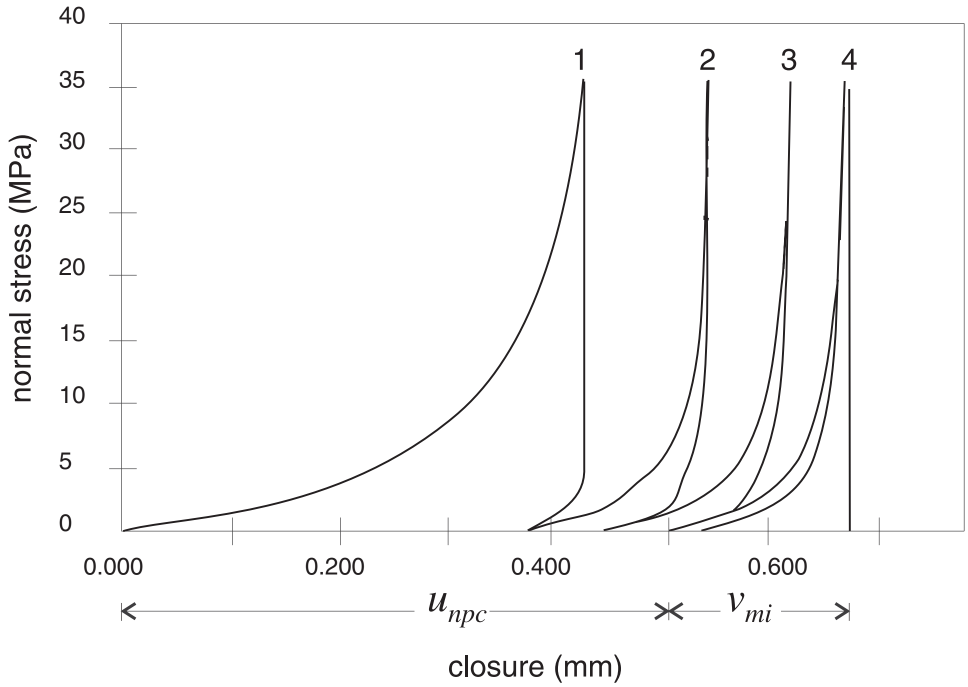

Figure 3.3 Joints numerically cycled to load cycle 4 at start of execution

When the **jhist off** command is specified, load and unload cycles follow the same curves. If **jhist on** is specified, a new set of parameters is calculated for each load and unload cycle (in both the shear and normal directions). To represent an undisturbed joint in a rock mass, all joints are numerically cycled three times from zero normal stress to 60% of the joint wall compressive strength (Figure 3.3). Therefore, each joint starts at normal load cycle 4 and shear cycle 1. This was done under the assumption that the increasing normal stiffness from successive load cycles seen in laboratory tests is largely a result of disturbance of the joint in test preparation. A joint that has remained undisturbed for a long time will not experience such a radical change in stiffness. If the joint surfaces in the model lose contact, the model will return to load cycle 1 upon reloading. The load cycle reversal tolerance ratio (***crtol***) is used to determine how much movement will be considered a cycle reversal (i.e., change from a load cycle to unload). This tolerance is necessary to prevent small oscillations from causing numerous load cycle changes. Cycle reversal is only allowed if cr exceeds ***crtol***. cr is defined by the expression

$$cr = \frac{u_{nmax} - u_{nc}}{u_{nmax}} \tag{3.5}$$

where u_{nc} is the current normal displacement, and u_{nmax} is the maximum normal displacement that has occurred during the present load cycle.

3.3 Joint Shear Behavior

The shear resistance of a joint is calculated using the concept of mobilized roughness. The mobilized roughness coefficient ($JRC_{mob.}$) is a function of the joint properties length, normal load, current shear displacement and shear displacement history. The relation between normalized shear displacement (δ/δ_{peak}) and the normalized mobilized roughness coefficient ($JRC_{mob.}/JRC_{peak}$) is shown in Figure 3.4.

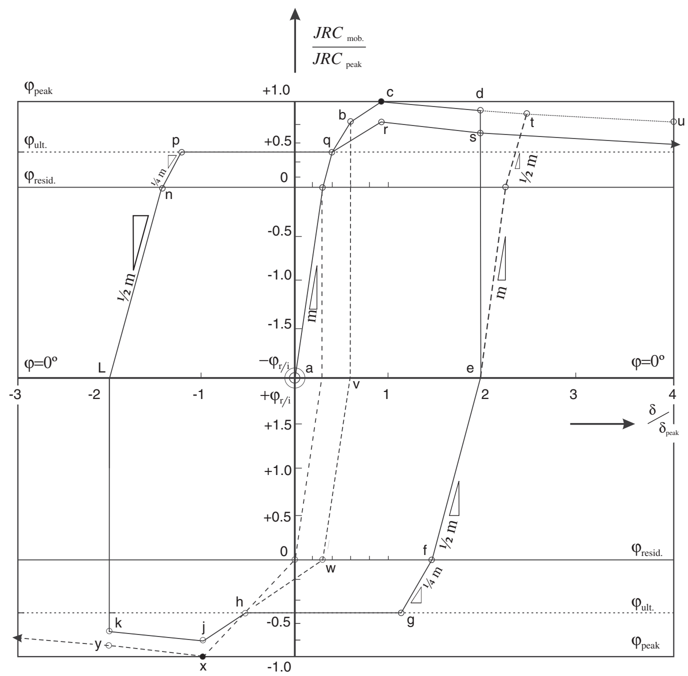

Figure 3.4 Model for simulating the effects of displacement on shear strength of joints (see Barton 1982 for definition of symbols)

To implement the shear stress model, a limiting shear stress, $\sigma_s{}^l$, is calculated from the full-scale roughness coefficient (JRC_n), the joint wall compressive strength (JCS_n) and the peak shear displacement (δ_{peak}):

$$JRC_n = JRC_o \cdot (\frac{L_n}{L_o})^{-0.02\ JRC_o} \tag{3.6}$$

$$JCS_n = JCS_o \cdot (\frac{L_n}{L_o})^{-0.03\ JRC_o} \tag{3.7}$$

$$\delta_{peak} = \frac{L_n}{500} \cdot (\frac{JRC_n}{L_o})^{0.33} \tag{3.8}$$

where L_o = laboratory-scale joint length; and

L_n = field-scale joint length.

The roughness contribution ($RUFF$) is

$$RUFF = JRC_n \cdot \log_{10}(\frac{JCS_n}{\sigma_n}) \tag{3.9}$$

where σ_n = current normal stress. The mobilized joint roughness coefficient, $JRC_{mob.}$, is

$$JRC_{mob.} = B \cdot JRC_n \tag{3.10}$$

The B value in Eq. (3.10) is obtained from Table 3.3. To get B, calculate the ratio of current shear displacement to peak shear displacement, and find that ratio in column A. The mobilized roughness ratio (B) is read from column B.

The limiting shear stress (${\sigma_s}^l$) is now calculated:

$${\sigma_s}^l = \sigma_n \cdot tan(JRC_{mob.} \cdot \log_{10}(JCS_n / \sigma_n) + \phi_r) \tag{3.11}$$

where ϕ_r = residual friction angle.

The shear stress approaches the limiting shear stress incrementally by multiplying the shear displacement increment by a stiffness. The stiffness is defined as one of two initial linear segments of the load path, depending on shear displacement. The incremental shear stress is calculated from the expression

$$\Delta\sigma_s = \Delta u_s \cdot bbjks \tag{3.12}$$

where

$$bbjks = \sigma_n(\frac{tan(0.75)\ \phi_{resid}}{0.2\ \delta_{peak}})\ L \qquad \text{for } (\frac{\delta}{\delta_{peak}}) < 0.20 \tag{3.13}$$

or

$$bbjks = \sigma_n(\frac{tan(0.25\ \phi_{resid})}{0.1\ \delta_{peak}})\ L \qquad \text{for } (\frac{\delta}{\delta_{peak}}) > 0.20 \tag{3.14}$$

and where ϕ_{resid} = residual friction angle;

δ_{peak} = peak shear displacement;

L = joint length;

σ_n = normal stress;

$\Delta\sigma_s$ = shear stress increment; and

Δu_s = shear displacement increment.

Table 3.3 Values used for calculating mobilized roughness $JRC_{mob.}$

A	B
$\left[\frac{\delta}{\delta_{peak}}\right]$	$\left[\frac{JRC_{mob.}}{JRC_n}\right]$
0.00	$-\phi_r/RUFF$
0.20	$-0.25 \cdot \phi_r/RUFF$
0.30	0.00
0.45	0.50
0.60	0.75
0.80	0.90
1.00	1.00
1.50	0.90
2.00	0.85
3.00	0.75
4.00	0.70
6.00	0.60
8.00	0.55
10.00	0.50
20.00	0.40
40.00	0.30
60.00	0.20
80.00	0.10
100.00	0.00

The mobilized dilation is also calculated from the mobilized roughness. The formulation calculates a dilation increment, Δu_n, based on the shear displacement increment and the current normal stress:

$$\Delta u_n = \Delta u_s \cdot tan(0.5\ JRC_{mob.} \log_{10}(JCS_n/\sigma_n)) \tag{3.15}$$

When successive shear cycles of forward and reverse shear occur, the mobilized roughness is reduced by 50% each time the peak shear displacement is passed.

Excessive dilation can cause a problem with the geometric calculations in *UDEC* if joints have large shear displacements and the blocks are free to move in the normal direction. There are two ways to address this problem: prevent contacts from being deleted, or limit the amount of dilation. The **block contact delete-open off** command can be used to prevent *UDEC* from deleting contacts that appear to be separating as a result of dilation. Alternatively, the property keyword **bbdmax** can be specified to limit the dilation. By default, dilation is not limited. The property keyword **bbdmin** can also be specified to set a lower limit to the dilation. The default dilation is zero. If negative dilation is a desired behavior, the **bbdmin** property value can be set to a negative value. Please note that the units for dilation in the Barton-Bandis model are mm.

Shearing a joint in relaxation (i.e., no normal stress, and not yet considered open) can cause dilation to occur. Relaxation can be recognized in a **block list contact** output as those joints with normal stress of 10^{-10}. Joints that are open cannot cause dilation when shearing.

Shear reversals always unload following the bilinear stiffness (segment e-t on Figure 3.4). However, the shearing will not be considered to be a reversal until the value is reached such that $JRC_{mob.}/JRC_{peak}$ is equal to zero.

When a joint is sheared past the peak shear strength, damage occurs to the joint surface and reduces its roughness. To simulate this effect in the Barton-Bandis model, a damage factor is applied to $JRC_{mob.}$. The damage factor changes each time the peak $JRC_{mob.}$ is passed. The default damage factors applied to $JRC_{mob.}$ are 1.0, 0.75, 0.625, 0.5625 and 0.53125. These factors are derived from Figure 3.4, in which $\phi_{peak} - \phi_{ult}$ is reduced by 50% for each cycle. This will cause ϕ_{peak} to approach ϕ_{ult} on each successive cycle. The damage factors can be user-defined by using the **bbdtable** property keyword to specify a damage table.

In Figure 3.4, the plateau regions of the shear reversal model (segments g-h and p-q) are not reduced upon successive reversal cycles. This behavior has an effect on the dilation, which is a function of $JRC_{mob.}$. The same damage factors can be applied to the plateau values as are applied to the peak values, by specifying the **bbdplateau** property keyword.

The **jhist on** command must be specified for shear damage to accumulate. If **jhist off** is given, the peak $JRC_{mob.}$ values will not be reduced.

It is possible to prevent joints from slipping by assigning a negative value to the residual friction angle, via property keyword **phir**.

3.4 Input Instructions for the Barton-Bandis Joint Model

3.4.1 UDEC Commands

All commands have the same structure as those in the standard version of *UDEC*. Note that most of the commands are invoked by new keywords used with existing commands in the standard version.

block **cont**act **ch**ange **mo**del *7*

model *7* selects the optional Barton-Bandis joint model. This version uses the material properties stored by use of the **block contact property** command. The local parameter storage version stores properties for each individual contact, and is invoked by the **block contact cmodel assign barton-bandis** command.

block **cont**act **cm**odel **b**arton-**b**andis keyword ***v*** <keyword ***v***. . . >

This command associates the Barton-Bandis joint model and properties with one or more joint contacts. Each contact has its own local set of properties when the **block contact cmodel assign** command is used. This version of the Barton-Bandis joint model uses more memory than the version invoked by the **block contact change model = 7** version. The following material properties are assigned for the Barton-Bandis joint model. Because the model is scale-dependent and uses empirical constants, the specified units must be used.

aper ***value***

initial aperture for Barton-Bandis joint (mm). This will be calculated, if not specified.

bbdmax ***value***

maximum value of dilation allowed for this material type. The dilation may need to be limited in some cases to prevent loss of contacts as blocks separate. The **block contact delete-open off** command may also be used for this purpose. The units for this parameter are mm. (default = 10^{20})

bbdmin ***value***

minimum value of dilation allowed for this material type. In some cases, negative dilations may be calculated by the Barton-Bandis model. The units for this parameter are mm. (default = 0)

bbdplateau *0*

1

determines whether the damage factors are applied to the plateau region of the shear stress values during shear reversal. Setting this parameter equal to ***1*** will result in more realistic dilation calculations. The default, **bbdplateau** = ***0***, is consistent with the original definition of the Barton-Bandis model.

bbdtable *n*

Barton-Bandis shear damage factor table. Up to 10 damage factors may be specified in a table by using the **table** command. The factors are used to reduce the peak shear for each shear cycle. The first value is normally 1.0, and is applied to shear cycle 1. Each additional value will apply to the next shear cycle. The last value given will be used for all subsequent cycles. The default factors are 1.0, 0.75, 0.625, 0.5625 and 0.53125.

jcso *value*

laboratory-scale joint wall compressive strength (MPa)

st-normal *value*

normal stiffness of joint at expected normal loads. It is used to calculate stable timestep.

st-shear *value*

initial shear stiffness of joint at expected normal loads. It is used to calculate joint shear stress for the **block insitu stress** command.

jrco *value*

laboratory-scale joint roughness coefficient

ln *value*

field-scale joint length (m). If not specified, the program will calculate lengths from model geometry.

lo *value*

laboratory-scale joint length (m)

phir *value*

residual angle of friction (degrees). If set to a negative number, the joint is locked; this can be used to prevent excessive shear displacement during consolidation.

sigmac *value*

intact rock uniaxial compressive strength (MPa)

block **cont**act **cm**odel **as**sign **de**fault *7*

New contacts created during the solution process will be assigned constitutive model number 7 for Barton-Bandis joints originally specified via the **block contact change model 7** command.

block **cont**act **cm**odel **as**sign **de**fault **bb**

New contacts created during the solution process will be assigned the Barton-Bandis constitutive model for contacts originally specified via the **block contact cmodel assign bartis** command.

block **in**situ **st**ress *sxxo sxyo syyo* <**ra**nge. . . >

The **block insitu** command has been extended to include initialization of Barton-Bandis joints. The initialization consists of calculation of a normal closure based on the fourth cycle hyperbolic curve. u_{nc} (current normal closure) is set equal to the calculated closure. The normal displacement of the joint is set equal to $u_{nc} + u_{npc}$. (u_{npc} is the closure from the first three load cycles.) The shear displacement of the joint is calculated using the joint shear stiffness, **st-s**, which should always be set equal to the initial elastic slope of the Barton-Bandis model in shear.

jhist **on** <*crtol*> **off**

The **jhist** command turns **on** (or **off**) the joint reversal logic for Barton-Bandis joints. If the logic is **off**, load and unload cycles will follow the same paths, and no joint damage will be calculated. (default = **off**)

The optional variable ***crtol*** sets the displacement tolerance for load cycle reversals (default = 0.10). If set too low, excessive reversals will occur due to small oscillations.

block **cont**act **li**st keyword <keyword. . . > <**ra**nge. . . >

The following keyword may be used to print history data for Barton-Bandis joints.

jhist keyword

history data for Barton-Bandis joints. The following keywords are available.

aperture data for apertures

The column headings are as follows.

cond joint conductivity

contact contact address

curr current mechanical aperture

hydr current hydraulic aperture

max maximum allowable mechanical aperture

normal data for normal behavior

The column headings are as follows.

contact contact address

cyc joint normal load cycle:
cyc $>$ 0 indicates load cycle
cyc $<$ 0 indicates unload cycle

jcsn full-scale joint wall compressive strength

jrcn full-scale joint roughness coefficient

kni initial joint normal stiffness

unc current normal displacement

unm maximum normal displacement (this load cycle)

unpc sum of previous irrecoverable closures

virr irrecoverable closure (unload cycle only)

vmi maximum allowable closure (this load cycle)

block **cont**act **li**st **jh**ist **norm**al data for normal behavior

The column headings are as follows.

dil	current cumulative dilation
unl	maximum normal displacement (previous load cycle)

shear data for shear behavior

The column headings are as follows.

contact	contact address
cyc	current shear cycle (sign indicates "forward" direction)
dil	current cumulative dilation
jcsn	full-scale joint wall compressive strength
jrcn	full-scale joint roughness coefficient
usc	current shear displacement
uscr	current shear-displacement ratio (current shear-displacement/displacement at peak shear strength)
usm	maximum shear-displacement ratio this shear cycle (shear displacement)/(displacement at peak shear strength)
usmb	maximum shear-displacement ratio previous shear cycle (shear displacement)/(displacement at peak shear strength)

block **co**ntact **li**st **pro**perty keyword

joint properties for local contacts when the **block contact cmodel assign barton-bandis** command is used. The following keywords apply.

aper	initial aperture for Barton-Bandis joint
bbdmax	maximum value of dilation allowed
bbdmin	minimum value of dilation allowed
jcso	laboratory-scale joint wall compressive strength
st-n	normal stiffness of joint
st-s	initial shear stiffness of joint
jrco	laboratory-scale joint roughness coefficient
ln	field-scale joint length
lo	laboratory-scale joint length
phir	residual angle of friction of joint
sigmac	intact rock uniaxial compressive strength

block **cont**act **li**st **pro**perty keyword

joint data for local contacts calculated for the **block contact cmodel assign barton-bandis** command. The following keywords are used.

bbdil	current dilation
bbjcsn	full-scale joint compressive wall strength
bbjrcn	full-scale roughness coefficient
bbkni	current initial normal stiffness
bbnc	joint normal load cycle: + = load cycle, − = unload cycle
bbsc	joint shear cycle
bbunc	current normal closure
bbunl	maximum closure for previous cycle
bbunm	maximum/minimum closure for this load cycle
bbunpc	closure due to previous load cycles
bbusc	current shear displacement
bbusm	(shear displacement) / (displacement at peak shear stress) maximum for this shear cycle
bbusmb	(shear displacement) / (displacement at peak shear stress) maximum from previous cycle
bbvirr	current irrecoverable closure
bbvmi	current maximum allowable closure

block **cont**act **pro**perty **mat**erial ***n*** keyword ***v*** <keyword ***v***. . . >

The following material properties are assigned for the Barton-Bandis joint model (**block contact change model = 7**). Because the model uses empirical constants and is scale-dependent, the specified units must be used. If you are using the local property storage version of the Barton-Bandis model (**block contact cmodel assign barton-bandis**), you must use the **block contact property** command to assign the properties.

aper ***value***

initial aperture for Barton-Bandis joint (mm). This will be calculated, if not specified.

bbdmax ***value***

maximum value of dilation allowed for this material type. The dilation may need to be limited in some cases to prevent loss of contacts as blocks separate. The **SET delc off** command may also be used for this purpose. The units for this parameter are mm. (default = 10^{20})

bbdmin ***value***

minimum value of dilation allowed for this material type. In some cases, negative dilations may be calculated by the Barton-Bandis model. The units for this parameter are mm. (default = 0)

bbdplateau ***0***

1

determines whether the damage factors are applied to the plateau region of the shear stress values during shear reversal. Setting this parameter equal to ***1*** will result in more realistic dilation calculations. The default, **bbdplateau** = ***0***, is consistent with the original definition of the Barton-Bandis model.

bbdtable *n*

Barton-Bandis shear damage factor table. Up to 10 damage factors may be specified in a table by using the **TABLE** command. The factors are used to reduce the peak shear for each shear cycle. The first value is normally 1.0, and is applied to shear cycle 1. Each additional value will apply to the next shear cycle. The last value given will be used for all subsequent cycles. The default factors are 1.0, 0.75, 0.625, 0.5625 and 0.53125.

jcso *value*

laboratory-scale joint wall compressive strength (MPa)

st-n ormal*value*

normal stiffness of joint at expected normal loads. It is used to calculate stable timestep.

st-shear *value*

initial shear stiffness of joint at expected normal loads. It is used to calculate joint shear stress for the **block insitu stress** command.

jrco *value*

laboratory-scale joint roughness coefficient

ln *value*

field-scale joint length (m). If not specified, the program will calculate lengths from model geometry.

lo *value*

laboratory-scale joint length (m)

phir *value*

residual angle of friction (degrees). If set to a negative number, the joint is locked; this can be used to prevent excessive shear displacement during consolidation.

sigmac *value*

intact rock uniaxial compressive strength (MPa)

block **me**chanical **re**set keyword <keyword. . . >

The following Barton-Bandis variables may be reset.

jhist ***n***

This command resets the joint history terms for Barton-Bandis joints. New normal and shear displacements are recalculated in the same manner as in the **block insitu** command. This command should be used when changing from a **block contact change model = 1**, **2** or **5** joint to a **model = 7** joint, or whenever the material properties for a Barton-Bandis joint are changed. ***n*** is the material type number for the joints to be reset. This command must be given for all material types changed.

3.4.2 Program Guide

FISH programs have access to the Barton-Bandis linked-list data structure. The file "BB.FIN" provides symbolic names for the indices of items related to the Barton-Bandis model. (See Example 3.1.) Note that the indices in "BB.FIN" can only be used for joint models assigned with the **JOINT** command.

The indices are relative to an extension index stored in the linked list associated with each contact (see Section 4 in the ***FISH* volume**). The extension for local joint properties is **c_jex**. The property symbols are all preceded by the **$** sign, so that they are invisible to the casual user who gives a **block contact list** command. The *FISH* programmer may simply use numbers for indices, or the symbols provided in the "BB.FIN" file. It is better to specify indices in symbolic form because the resulting *FISH* program will work correctly with future versions of *UDEC*, in which indices may be different. An example application of "BB.FIN" is given in Sections 3.5.1 and 3.5.2.

Example 3.1 Barton-Bandis joint model include file – "BB.FIN"

3.5 Example Problems

Several examples are presented to demonstrate the Barton-Bandis joint model in *UDEC*.

3.5.1 Direct Shear Test

A simple direct shear test is simulated to illustrate the behavior of the Barton-Bandis model. The problem parameters listed in Table 3.4 are used for this example.

Table 3.4 Barton-Bandis model properties for direct shear test

Property Keyword	Description	Value
density	ρ (block mass density)	2600 kg/m^3
shear	G (shear modulus of block)	30 GPa
st-n	a_n (joint normal stiffness)	40 GPa/m
st-s	a_s (joint shear stiffness)	40 GPa/m
jrco	JRC_o (lab-scale roughness coefficient)	8
jcso	JCS_o (lab-scale joint wall compressive strength)	30 MPa
bulk	K (bulk modulus of block)	45 GPa
lo	L_o (lab-scale joint length)	0.1 m
phir	ϕ_{resid} (residual angle of friction)	20°
sigmac	σ_{unc} (intact rock uniaxial compressive strength)	50 MPa

Figure 3.5 shows the model for the direct shear test. A constant normal stress of 10 MPa is applied on the joint first. Then, the top block is moved at a constant horizontal velocity. A *FISH* function, **`av_str`**, is used to calculate the average shear stress and normal and shear displacements along the joint. The data file for the test is given in Example 3.2.

Figure 3.6 shows a plot of shear stress versus shear displacement. Figure 3.7 shows a plot of dilation versus shear displacement. Note that the *FISH* include file “BB.FIN” is used to access the symbolic names assigned the Barton-Bandis parameters that are monitored for these plots. (See Section 3.4.2.)

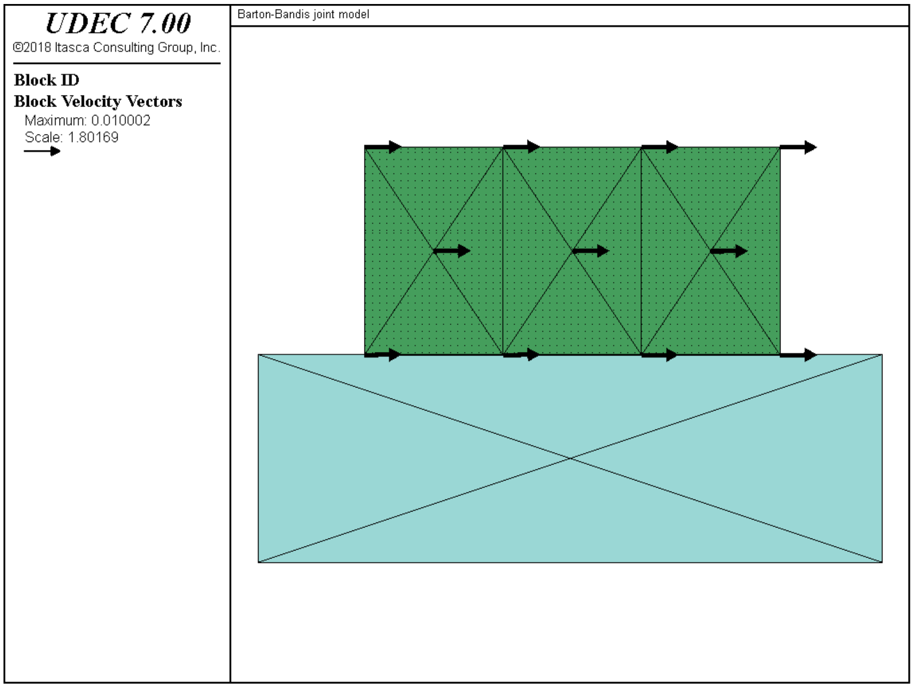

Figure 3.5 UDEC model for direct shear test

Example 3.2 Direct shear test with Barton-Bandis joint model

```
model new
;file 'BB_1.dat'
;
model title 'Barton-Bandis joint model'
;   direct shear test
;
block config barton-bandis
block tolerance corner-round-length 0.001
block create polygon -0.05 -0.1 -0.05 0.1 0.25 0.1 0.25 -0.1
block cut crack -1 0 1 0
block cut crack 0 0.1 0 0
block cut crack 0.2 0.1 0.2 0
block delete range pos-x -0.05 0 pos-y 0 0.1
block delete range pos-x 0.2 0.25 pos-y 0 0.1
;
block zone gen quad 0.4 0.11 range pos-x 0 1 pos-y -1 0
block zone gen quad 0.07 0.11 range pos-x 0 1 pos-y 0 1
;
block property material 1 density 2.60e-3 bulk 45000 shear 30000
; B-B joint model
block contact cmodel assign barton-bandis
```

```
block contact property st-normal 40000 st-shear 40000 jrco 8 jcso 30 ...
  sigmac 50 lo .1 phir 20
block contact cmodel default barton-bandis
;
; apply boundary conditions
block gridpoint apply velocity-x 0 range pos-x -0.06 -0.04 pos-y -1 1
block gridpoint apply velocity-x 0 range pos-x 0.24 0.26 pos-y -1 1
block gridpoint apply velocity-y 0 range pos-x -1 1 pos-y -0.11 -0.09
; apply normal load
block edge apply stress 0 0 -10 range pos-x -1 1 pos-y 0.09 0.11
;
;
block solve
;
; functions to calculate average joint stresses
; and average joint displacements
;
call 'bb.fin'
;
fish define av_str
  whilestepping
  sstav = 0.0
  njdil  = 0.0
  njusc  = 0.0
  ncon = 0
  jl   = 0.2              ; joint length
  ic = block.contact.head
  loop while ic # 0
      ncon = ncon+1
      sstav = sstav + block.contact.force.shear(ic)
      cmext = block.contact.extension(ic)
      njdil  = njdil + fmem(cmext+$bb_dil)
      njusc  = njusc + fmem(cmext+$bb_usc)
      ic = block.contact.next(ic)
  endloop
  if ncon # 0
    sstav = sstav / jl
    njdil  = njdil / ncon
    njusc = njusc / ncon
  endif
end
;
block contact reset displacement
block gridpoint init displacement-x 0
block gridpoint init displacement-y 0
hist reset
```

```
;
hist  interval 1
hist  @sstav
hist @njdil
hist @njusc
hist name 1 label 'Average Shear Stress (MPa)'
hist name 2 label 'Average Joint Dilation (mm)'
hist name 3 label 'Shear Displacement (mm)'
;
; apply shear load by imposing x-velocity on top block
block gridpoint apply velocity-x 0.01 range pos-x -.01 .21 pos-y -.01 .11
;
block cycle 24000
;
;plot hold hist 1 vs 3 yr
;plot hold hist 2 vs 3
;
model save 'bb1.sav'
;
return
```

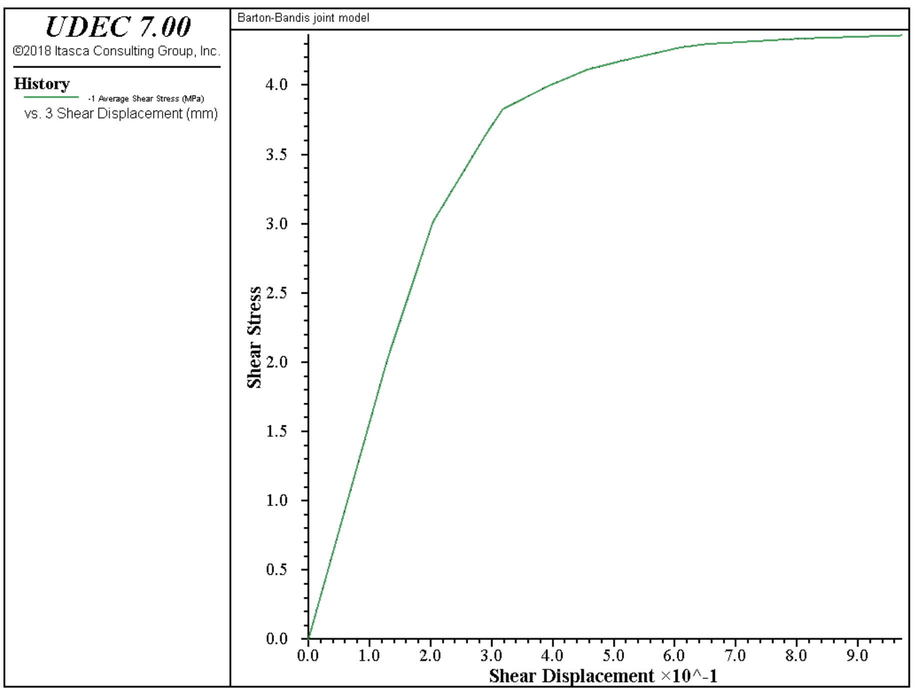

Figure 3.6 Average shear stress (MPa) versus shear displacement (mm)

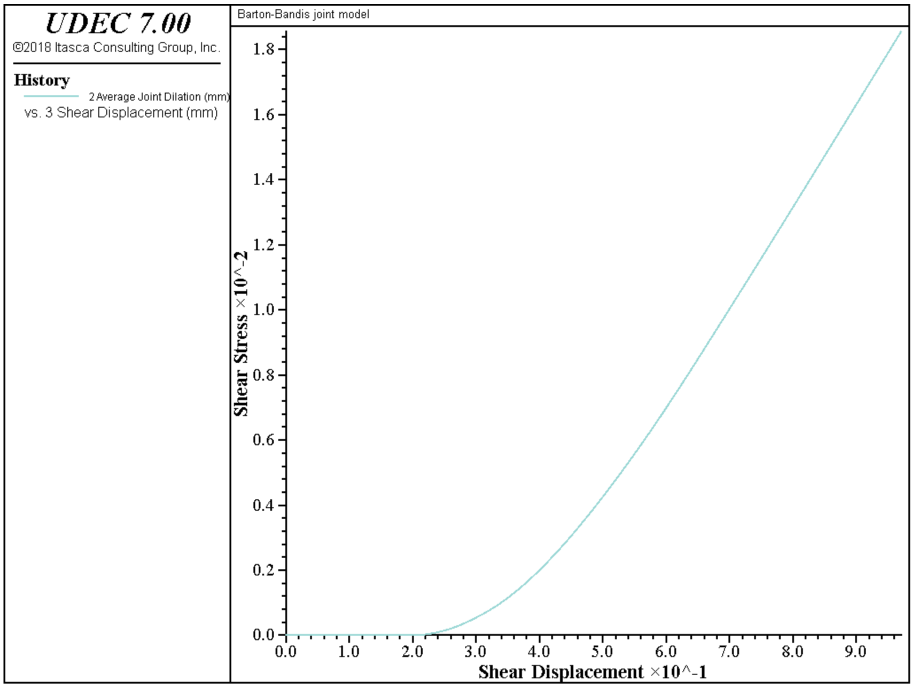

Figure 3.7 Average dilation (mm) versus shear displacement (mm)

3.5.2 Shear Reversal Tests

Three examples that demonstrate the behavior of Barton-Bandis joints upon shear-displacement reversal are provided. The examples demonstrate the following joint features as shown in laboratory tests by Huang et al. (1993):

1. Changes in shear strength occur upon load reversal.
2. Joint dilation that occurs for shearing in one direction is recovered during reverse shearing.

The examples use the joint properties listed in Table 3.5.

Table 3.5 Barton-Bandis model properties for shear reversal tests

Property Keyword	Description	Value
density	ρ (block mass density)	2000 kg/m^3
g	G (shear modulus of block)	0.7 GPa
st-n	a_n (joint normal stiffness)	93.926 GPa/m
st-s	a_s (joint shear stiffness)	18.984 GPa/m
jrco	JRC_o (lab-scale roughness coefficient)	8
jcso	JCS_o (lab-scale joint wall compressive strength)	80 MPa
k	K (bulk modulus of block)	1.0 GPa
lo	L_o (lab-scale joint length)	0.1 m
ln	L_o (field-scale joint length)	0.1 m
phir	ϕ_{resid} (residual angle of friction)	26°
sigmac	σ_{unc} (intact rock uniaxial compressive strength)	100 MPa

The first two tests demonstrate the ability of the Barton-Bandis model to simulate the shear reversal features. The **JHIST on** command is used to turn on the joint shear reversal logic. (If the logic is off, no damage will occur to the joint upon shear reversal.) The data file for these tests is listed in Example 3.3.

Example 3.3 Shear reversal test with Barton-Bandis joint model

```
;
; Test of BB model's shear reversal behavior
; Five passes through the peak are performed
;
model new
;  create 'shear box geometry'
config barton-bandis
block tolerance corner-round-length .001
block create polygon 0 0 0 .1 .605 .1 .605 0
block cut crack 0 .02 .605 .02
block cut crack .051 .02 .051 .1
block cut crack .254 .02 .254 .1
block delete range pos-x 0 .05 pos-y .02 .1
block delete range pos-x .254 .605 pos-y .02 .1
block zone gen edge 1
;
;  assign material properties
;
block property material 1 density 2e-3 bulk 1e3 shear .7e3
; local storage joint
```

```
block contact cmodel assign barton-bandis
block contact property stiffness-normal 93926 stiffness-shear 18984 ...
  jcso 80 sigmac 100 phir 26 lo .1 ln .1 jrco 8
block contact cmodel default barton-bandis
; Global property version
;block contact change model 7 mat 1
;block prop mat 1 st-n 93926 st-s 18984 jcs 80 sigmac 100 phir 26 ...
;  lo .1 ln .1 jrc 8
;block contact cmodel default model 7
block contact delete-open off
;
; set boundary conditions
;
block gridpoint apply velocity-y 0 range pos-x 0 .605 pos-y 0 .01
block gridpoint apply velocity-x 0 range pos-x 0 .605 pos-y 0 .01
block gridpoint apply velocity-x 0 range pos-x 0 .001 pos-y -.01 .021
block edge apply stress 0 0 -5 range pos-x 0 .605 pos-y .099 .1041
;
; consolidate under normal stress
;
block solve
;
; functions to calculate average joint stresses
; and average joint displacements
;
call 'bb.fin'
;
fish define av_str
  whilestepping
  sstav = 0.0
  njdil  = 0.0
  njusc  = 0.0
  ncon = 0
  jl   = 0.2              ; joint length
  ic = block.contact.head
  loop while ic # 0
      ncon = ncon+1
      sstav = sstav + block.contact.force.shear(ic)
      njdil  = njdil + fmem(block.contact.extension(ic)+$bb_dil)
      njusc  = njusc + fmem(block.contact.extension(ic)+$bb_usc)
      ic = block.contact.next(ic)
  endloop
  if ncon # 0
    sstav = sstav / jl
    njdil  = njdil / ncon
    njusc = njusc / ncon
```

```
  endif
end
;
fish define move_cor
  for_shear = .1176
  rev_shear = -1.0 * for_shear
end
;
@move_cor
;
fish define move_right
  command
    block grid apply vel-x @for_shear range pos-x .01 .5 pos-y -.01 .11
  endcommand
end
;
fish define move_left
  command
    block grid apply vel-x @rev_shear range pos-x .01 .5 pos-y -.01 .11
  endcommand
end
;
; set histories
fish history @sstav
fish history @njdil
fish history @njusc
history name 1 label 'Average Shear Stress (MPa)'
history name 2 label 'Average Joint Dilation (mm)'
history name 3 label 'Shear Displacement (mm)'
;
;
; set joint history checking on (required for damage to accumulate)
jhist on .1
;
; turn on plateau damage
;block contact property bbdplateau 1
;
; move top block to right (forward shear)
@move_right
block cycle 9000
;
; move top block to left (reverse shear)
@move_left
block cycle 18000
;
; move top block to right (forward shear)
```

```
@move_right
block cycle 18000
;
; move top block to left (reverse shear)
@move_left
block cycle 18000
;
; move top block to right (forward shear)
@move_right
block cycle 18000
model save 'bb2a.sav'
```

In the first test, the shear stress is reduced upon reversal, and the peak shear stress occurs after the shear displacement passes the displacement origin. No damage occurs in the plateau region of the shear stress during shear reversal. The dilation also reverses upon shear reversal. Note that because the minimum dilation is set to zero, the dilations are truncated. These features are illustrated in Figures 3.8 and 3.9.

In the second test, damage is allowed to occur in the plateau region by specifying the **block contact property bbdplateau 1** ***1*** command. Damage factors are applied to the plateau region; these factors can be user-controlled with the **block contact property bbdtable** command. The results for this test are given in Figures 3.10 and 3.11 for comparison with the previous two figures. Note that now there is no truncation of the dilation.

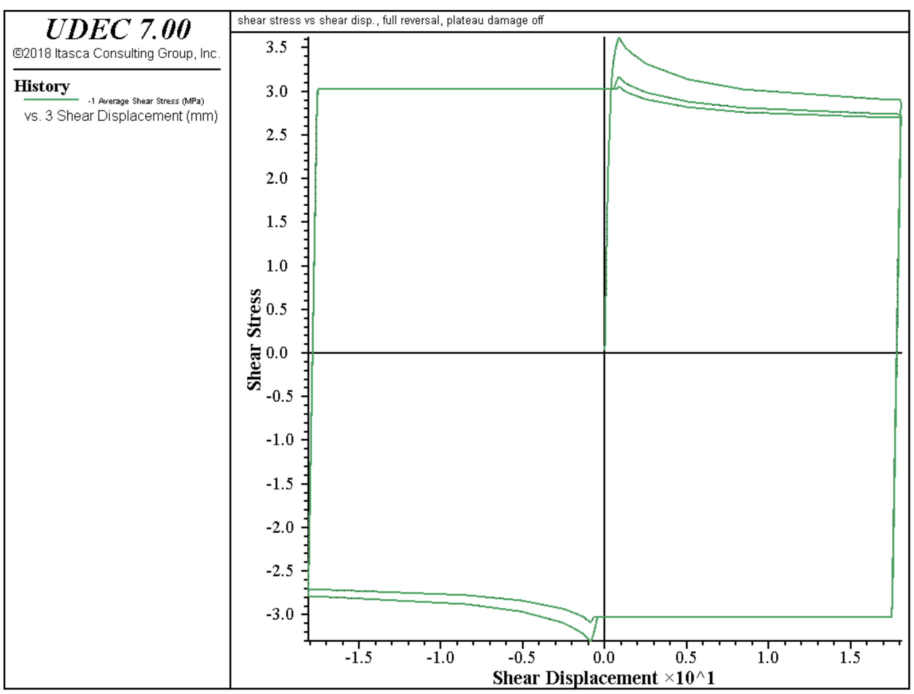

Figure 3.8 Average shear stress (MPa) versus shear displacement (mm) for shear reversal with no plateau damage

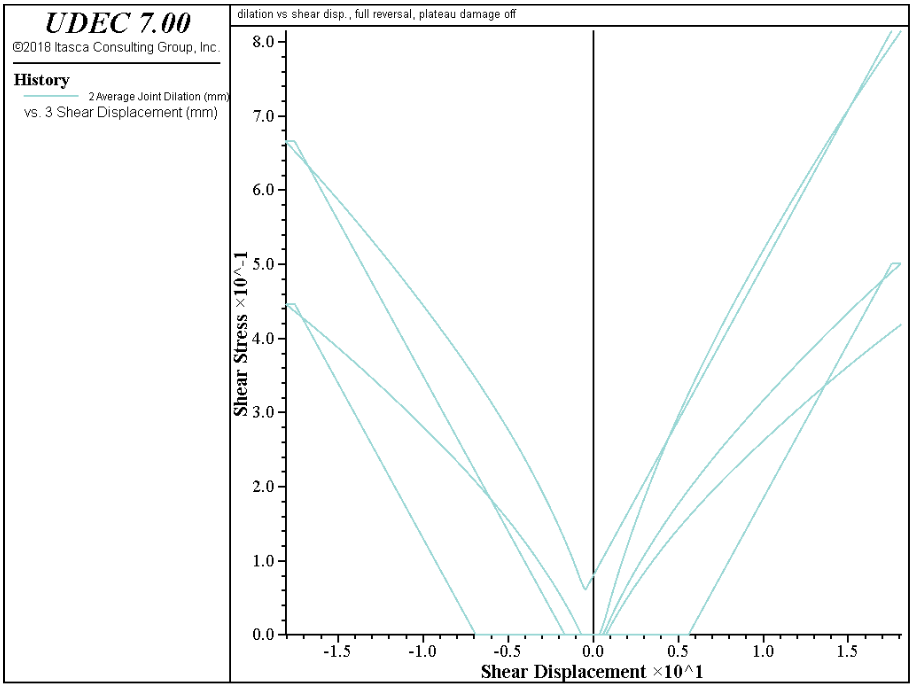

Figure 3.9 Average dilation (mm) versus shear displacement (mm) for shear reversal with no plateau damage

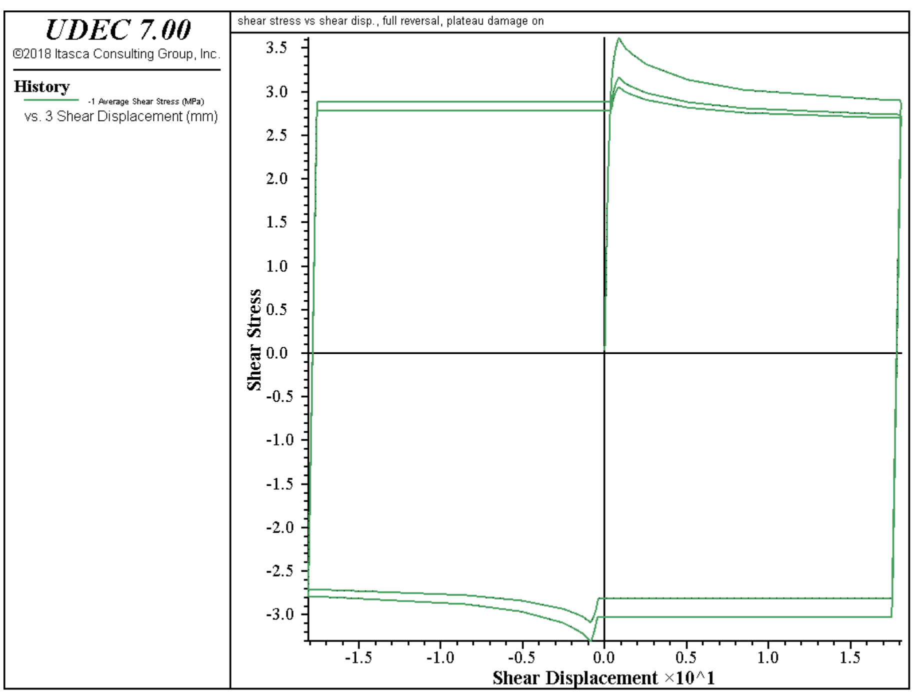

Figure 3.10 Average shear stress (MPa) versus shear displacement (mm) for shear reversal with plateau damage

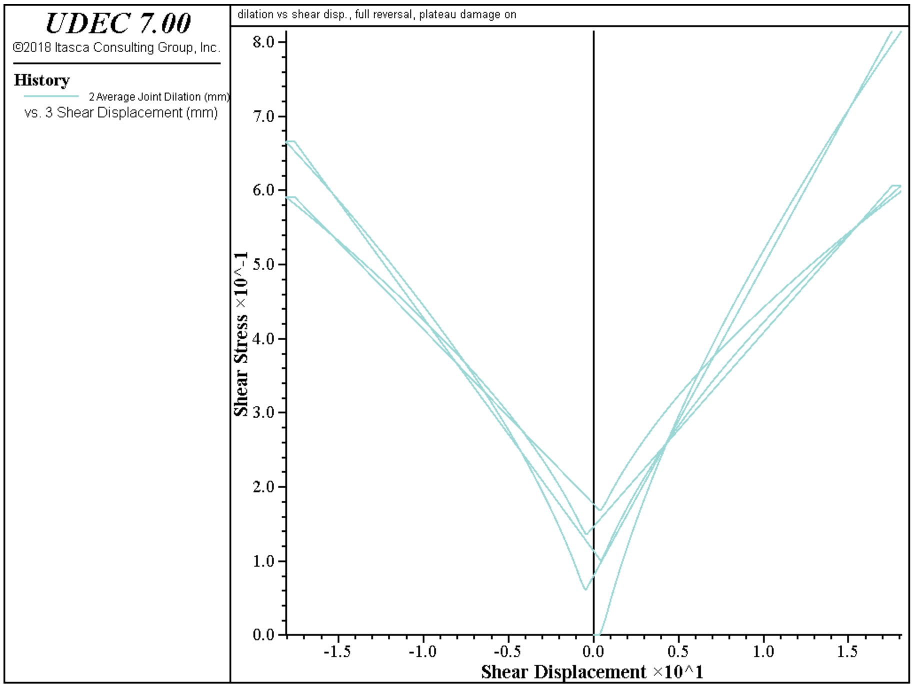

Figure 3.11 Average dilation (mm) versus shear displacement (mm) for shear reversal with plateau damage

In the third test, the ability of the Barton-Bandis model to simulate partial reversal and reloading is demonstrated. The data file for this test is listed in Example 3.4.

Example 3.4 Partial shear reversal test with Barton-Bandis joint model

```
model new
;
; Test of BB model's shear reversal behavior
; Reversals are small and do not return to the origin
; Three reversals are performed
;
;  create 'shear box geometry'
config barton-bandis
block tolerance corner-round-length .001
block create polygon 0 0 0 .1 .605 .1 .605 0
block cut crack 0 .02 .605 .02
block cut crack .051 .02 .051 .1
block cut crack .254 .02 .254 .1
block delete range pos-x 0 .05 pos-y .02 .1
block delete range pos-x .254 .605 pos-y .02 .1
block zone gen edge 1
;
```

```
;  assign material properties
;
block property material 1 density 2e-3 bulk 1e3 shear .7e3
; local storage joint
block contact cmodel assign barton-bandis
block contact property stiffness-normal 93926 stiffness-shear 18984 ...
  jcso 80 sigmac 100 phir 26 lo .1 ln .1 jrco 8
block contact cmodel default barton-bandis
; Global property version
;block contact change model 7 mat 1
;block cont prop mat 1 st-n 93926 st-ss 18984 jcs 80 sigmac 100 ...
;  phir 26 lo .1 ln .1 jrc 8
;block contat cmodel default model 7
block contact delete-open off
;
; set boundary conditions
;
block gridpoint apply velocity-y 0 range pos-x 0 .605 pos-y 0 .01
block gridpoint apply velocity-x 0 range pos-x 0 .605 pos-y 0 .01
block gridpoint apply velocity-x 0 range pos-x 0 .001 pos-y -.01 .021
block edge apply stress 0 0 -5 range pos-x 0 .605 pos-y .099 .1041
;
; consolidate under normal stress
;
block solve
;
; functions to calculate average joint stresses
; and average joint displacements
;
call 'bb.fin'
;
fish define av_str
  whilestepping
  sstav = 0.0
  njdil  = 0.0
  njusc  = 0.0
  ncon = 0
  jl   = 0.2              ; joint length
  ic = block.contact.head
  loop while ic # 0
      ncon = ncon+1
      sstav = sstav + block.contact.force.shear(ic)
      njdil  = njdil + fmem(block.contact.extension(ic)+$bb_dil)
      njusc  = njusc + fmem(block.contact.extension(ic)+$bb_usc)
      ic = block.contact.next(ic)
  endloop
```

```
  if ncon # 0
    sstav = sstav / jl
    njdil  = njdil / ncon
    njusc = njusc / ncon
  endif
end
;
fish define move_cor
  for_shear = .1176
  rev_shear = -1.0 * for_shear
end
;
@move_cor
;
fish define move_right
  command
    block grid apply vel-x @for_shear range pos-x .01 .5 pos-y -.01 .11
  endcommand
end
;
fish define move_left
  command
    block grid apply vel-x @rev_shear range pos-x .01 .5 pos-y -.01 .11
  endcommand
end
;
; set histories
fish history @sstav
fish history @njdil
fish history @njusc
hist name 1 label 'Average Shear Stress (MPa)'
hist name 2 label 'Average Joint Dilation (mm)'
hist name 3 label 'Shear Displacement (mm)'
;
;
; set joint history checking on (required for damage to accumulate)
jhist on .1
;
; move top block to right (forward shear)
@move_right
block cycle 5000
;
; move top block to left (reverse shear)
@move_left
block cycle 100
;
```

```
; move top block to right (forward shear)
@move_right
block cycle 5000
;
; move top block to left (reverse shear)
@move_left
block cycle 100
;
; move top block to right (forward shear)
@move_right
block cycle 15000
;
; move top block to left (reverse shear)
@move_left
block cycle 100
;
; move top block to right (forward shear)
@move_right
block cycle 25000
;
model save 'bb3.sav'
return
```

As can be seen in Figure 3.12, the reloading after partial reversal results in a new peak shear stress. It can also be seen that each new peak is smaller than the previous peak; this is controlled by the damage factors. The dilation that accumulates during this type of behavior appears to exceed that obtained from a monotonic load to the same shear displacement, as illustrated in Figure 3.13. This is because the dilation is a function of JRC_{mob}, which keeps increasing. Also, the displacements in the reverse direction are not significant enough to reduce the dilation.

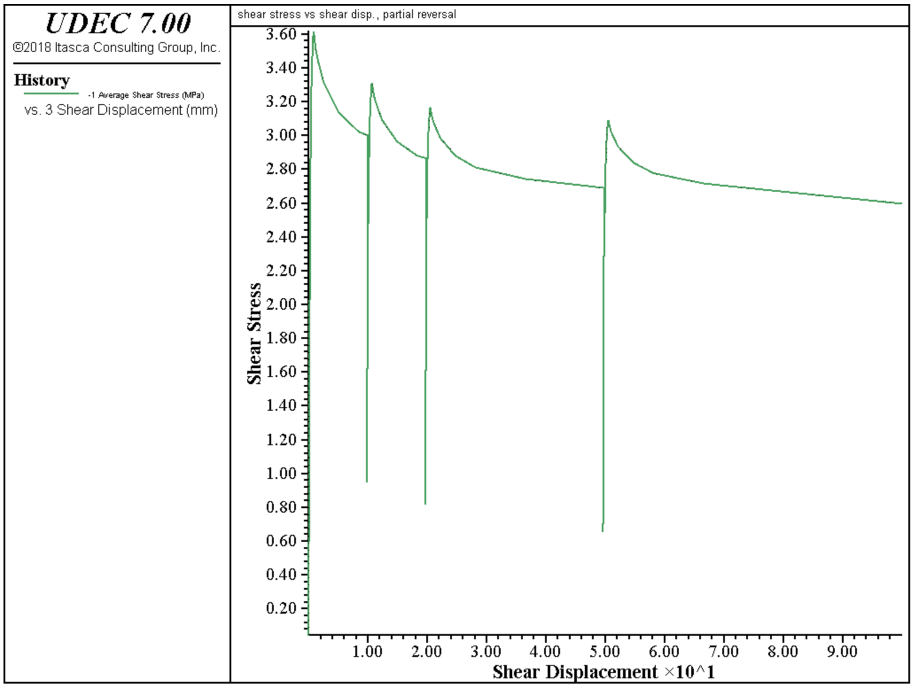

Figure 3.12 Average shear stress (MPa) versus shear displacement (mm) for partial shear reversal

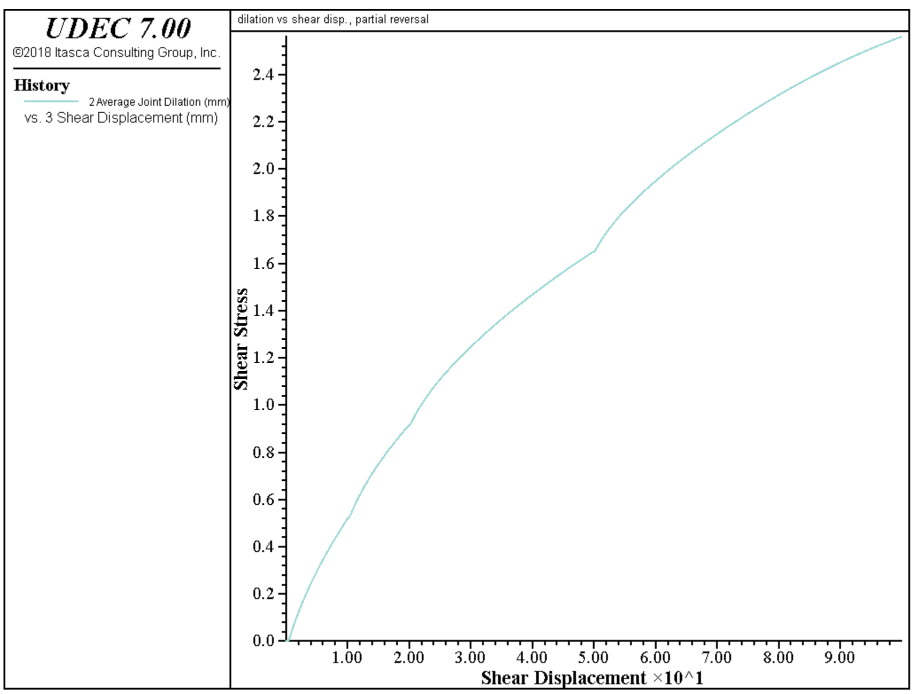

Figure 3.13 Average dilation (mm) versus shear displacement (mm) for partial shear reversal

3.6 References

Bandis, S. C., N. R. Barton and M. Christianson. "Application of a New Numerical Model of Joint Behaviour to Rock Mechanics Problems," in ***Fundamentals of Rock Joints (Proceedings of the International Symposium on Fundamentals of Rock Joints, Björkliden, Sweden, September 1985)***, pp. 345-356. Luleå, Sweden: Centek Publishers (1985).

Barton, N. "Modelling Rock Joint Behavior from In-Situ Block Tests: Implications for Nuclear Waste Repository Design," ONWI-308 (September 1982).

Huang, X., et al. "An Investigation of the Mechanics of Rock Joints – Part I. Laboratory Investigation," *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, ***30***(3), 257-269 (1993).