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QUALIFICATION STUDIES ON THE DISTINCT ELEMENT CODE UDEC AGAINST SOME BENCHMARK ANALYTICAL PROBLEMS

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QUALIFICATION STUDIES ON THE DISTINCT ELEMENT CODE UDEC AGAINST SOME BENCHMARK ANALYTICAL PROBLEMS

PURPOSE

The purpose of this report is to present the results of studies which assess the performance of the two-dimensional distinct element code, UDEC, in analysis of some benchmark problems in the mechanics of discontinuous rock.

SCOPE

Assessment of code performance involves comparison of computed solutions for particular problems with the analytical solutions to these problems, or suitable approximations to the analytical solutions. Of the four problems considered in the report, two are static and two are dynamic. Because three joint deformation models are implemented in UDEC, each of these is exercised on the benchmark problems, where possible, to evaluate if calculated joint behavior is consistent with response indicated by the analytical solution. However, only the Mohr-Coulomb joint model in the UDEC code is compatible with the elastic-perfectly plastic joint model invoked in the analysis of the benchmark problems. For that reason, qualification of the UDEC code for discontinuum analysis via a benchmark problem must be based primarily on analyses employing the Mohr-Coulomb joint.

1. INTRODUCTION

This report presents the first of a series of reports to be prepared on qualification studies of the performance of existing analytical joint models and the computer codes which execute these models as outlined in Task 3, Assessment of Analytical Models/Computer Codes, Seismic Rock Mechanics Project (Hsiung et al., 1989). The purpose of the comparative studies on code performance is to determine which codes identified in an earlier effort (Kana et al., 1989) are appropriate and efficient simulators of the behavior of jointed rock masses under repeated dynamic loading. The studies are of two types, which together are intended to evaluate the constitutive relations for rock masses and discontinuities and their implementation in various codes for seismic analysis of excavations in jointed rock. The first type of study is intended to confirm that a code can reproduce the response of several well-established conceptual models of the performance of a jointed rock mass. In the second type of study, each qualified code from the first study will be used to analyze the dynamic response of well-designed and executed laboratory experiments to be performed in Task 2 (Hsiung et al., 1989) on elements of jointed rock. At the conclusion of these studies, it will be established which codes satisfactorily represent the fundamental dynamics of jointed rock, and which can predict the behavior of a representative element of a jointed rock mass to an acceptable engineering tolerance.

In an earlier effort, several codes which may be applicable to the analysis of dynamic loading of excavations in a jointed, brittle, partially saturated, welded tuff rock mass were identified as current candidates for assessment. The identified codes include the distinct element codes UDEC and 3DEC (Cundall, 1988), the discrete element code DECICE (Williams et al., 1985), the finite element codes HONDO and SPECTROM-331 (Key, 1986), and the boundary element code BEST3D (Banerjee et al., 1985). These codes may model the dynamic performance of jointed rock masses. The particular feature of each code which qualifies it for consideration in the comparative studies is the formulation of an interface element on which rigid body slip or separation can occur under static or dynamic loading. Whether the interface meets the requirements for satisfactory simulation of discontinuous deformation of jointed rock is the concern of these studies.

The benchmark problems selected for the qualification studies represent increasing degrees of complexity in the loading and performance of jointed rock. A jointed block subject to cyclic loading (Olsson, 1982; Brady et al., 1985) is the only static problem for which an exact solution is available. Several problems involving circular excavations in the vicinity of a joint (Brady and Brown, 1985) may also be used to assess joint slip and separation under static conditions. For dynamic analysis, solution for the transmission of a harmonic incident shear wave across a cohesive interface in a bar (Miller, 1978) and a dynamic source in an infinite body containing a slip-prone interface (Day, 1985) are exact. Each of the identified codes may be assessed from the correspondence of the respective computed solutions with the analytical solutions to these problems. Codes which show acceptable performance in these studies will be qualified for subsequent analysis of an experimental study of joint deformation in direct shear tests.

Qualification studies are in progress for several of the codes noted above. Those for UDEC have been completed, and are reported here. They include analyses of the four problems described previously. Because the analytical solutions are based on variants of the Mohr-Coulomb joint deformation model, only the computational analyses based on this model can be compared validly with the analytical solutions. Two other joint deformation models, the Barton-Bandis model (Barton et al., 1985) and the Continuously-Yielding model (Cundall and Hart, 1985; Lemos, 1987) have been implemented in UDEC. Because they are not consistent with the Mohr-Coulomb model employed in the analytical solutions to the benchmark problems, rigorous comparison of computed solutions with the analytical solutions is not possible. However, suitable choice of joint parameters of both models permits their approximation to the Mohr-Coulomb model. For that reason, several problems are considered in which the Barton-Bandis and Continuously-Yielding models are exercised. Such studies permit qualitative evaluation of the performance of these models, but do not provide a basis for establishing their validity.

2. CYCLIC LOADING OF A SPECIMEN WITH A SLIPPING CRACK

2.1 PROBLEM STATEMENT

This problem concerns an elastic block with an inclined internal closed crack (Fig. 2.1) subject to a cycle of uniaxial loading.

A constant axial displacement u_a is applied to one end of the block, and the other end is fixed. The resulting load causes inelastic slip on the crack. At some point, the sense of displacement on the end of the block is reversed until the original position is re-established. Olsson (1982) showed that the stress-displacement relation for the loaded specimen is composed of three distinct components (Fig. 2.2):

(1) a loading segment (OA) which involves elastic deformation of intact rock and inelastic slip along the crack;

(2) an initial unloading segment (AB), where the crack does not slip; and

(3) a final unloading segment (BO), again with elastic rock deformation and joint slip.

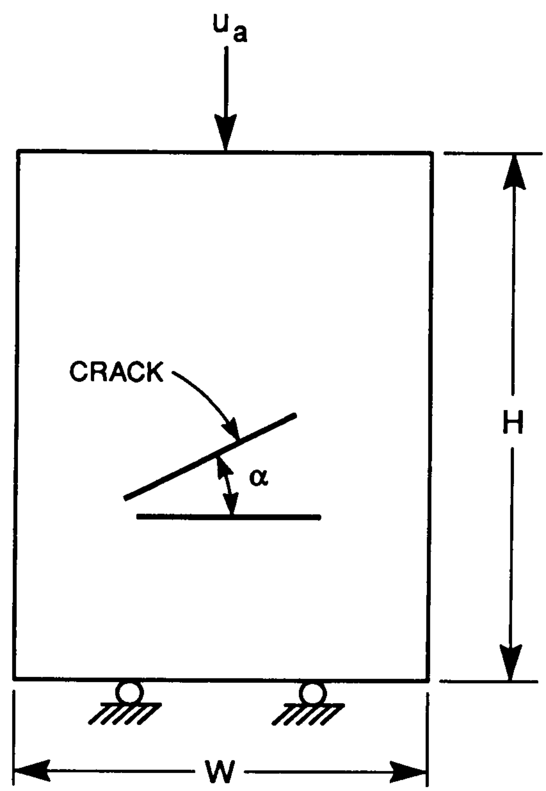

Figure 2.1 Specimen with Embedded Crack

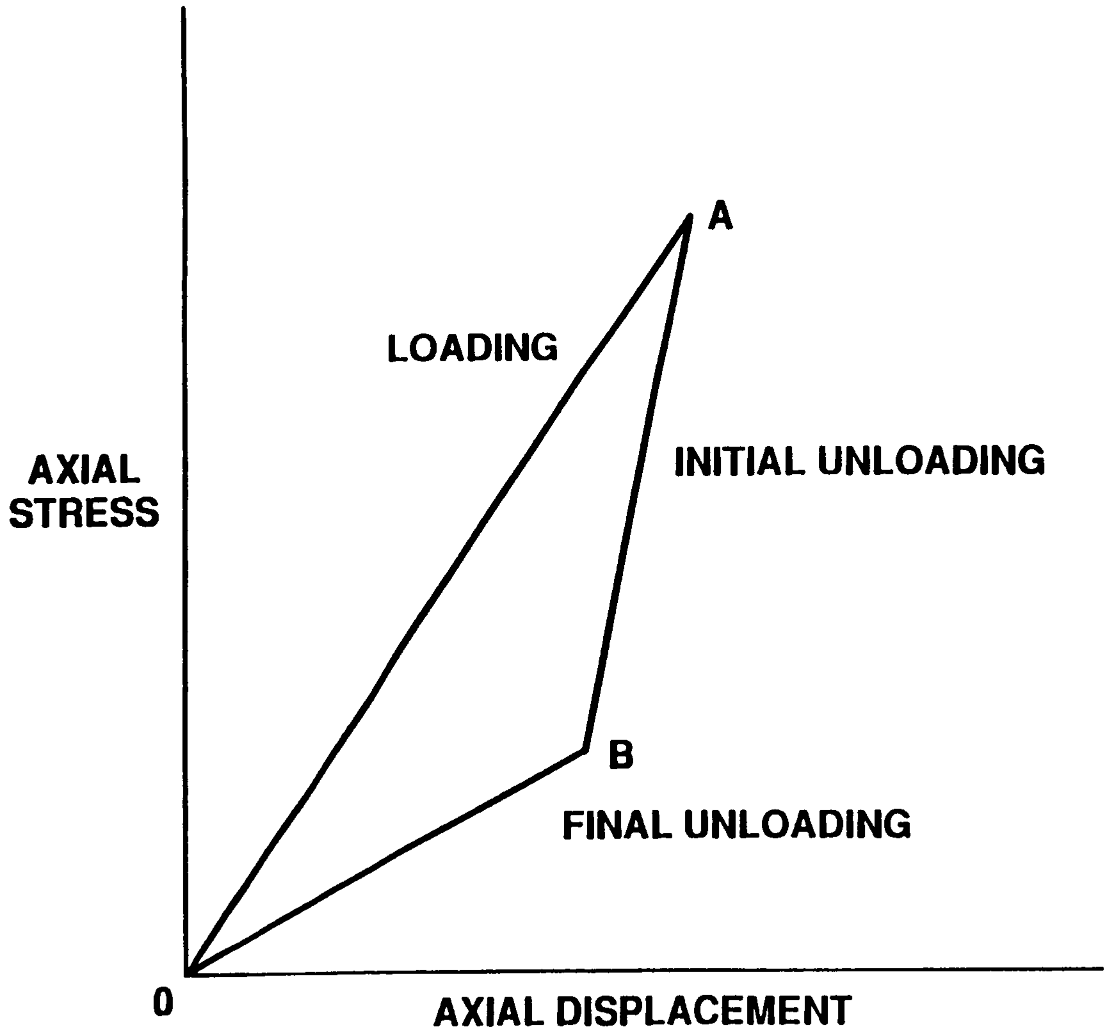

Figure 2.2 Stress-Displacement Relation for Elastic Specimen with Embedded Crack Subjected to Uniaxial Load Cycle [after Olsson, 1982]

2.2 PURPOSE

The purpose of this problem is to demonstrate satisfactory simulation of discontinuous rock deformation, and to test joint constitutive relations in UDEC. Other code functions tested by this problem include:

(a) the ability of the code to model solid elastic behavior;

(b) the ability of the code to model quasi-static behavior using adaptive damping; and

(c) the ability of the code to use displacement boundary conditions.

2.3 PROBLEM SPECIFICATION

A single inclined crack is located in an elastic medium. The mechanical properties of the medium and the dimensions of the specimen are listed below.

Young's modulus (E')	88.9 GPa
Poisson's ratio (ν')	0.26
height (H)	2 m
width (W)	1 m

The properties of the crack are as follows.

joint normal stiffness (K_n)	220 GPa/m
joint shear stiffness (K_s)	220 GPa/m
joint friction angle (ϕ)	16°
joint inclination (α)	45°
slipping portion of crack (l)	0.54 m

2.4 ASSUMPTIONS

The material in which the crack is embedded is linearly elastic, homogeneous, and isotropic. The numerical analysis assumes that the specimen is restrained perpendicular to the plane of analysis (i.e., plane strain conditions). It is further assumed that the crack can be represented by a single through-going discontinuity with only the central section of the discontinuity allowed to slip. The ends of the discontinuity are prevented from slipping by setting the frictional resistance to a high value over these regions.

2.5 CONCEPTUAL MODEL

Several investigators have proposed simple conceptual models of a single, closed crack to explain phenomena associated with the deformational response of jointed rock (Walsh, 1965; Jaeger and Cook, 1976). One such model is a single crack embedded in an elastic solid subjected to a cycle of uniaxial compression.

Brady et al. (1985) present relations for the three slopes in Fig. 2.2 in terms of the elastic stiffness of the solid, the elastic and frictional properties of the crack, and the orientation of the crack. The conceptual model is illustrated in Fig. 2.3.

In the conceptual model, k is the equivalent axial elastic stiffness of the specimen, including the through-going discontinuity. The equivalent elastic stiffness for the specimen with unit thickness is given by

$$\frac{1}{k} = \frac{H}{WE'} + \frac{\cos^2\alpha}{K_n L} + \frac{\sin^2\alpha}{K_s L} \tag{2.1}$$

L = W/cosα.

uld be noted that the term (H/WE′) in Eq. 2.1 represents the uniaxial elastic stiffness of the solid ;ptual model for plane stress conditions. The analysis in UDEC is based on plane strain conditions. ;train solution can be determined from the plane stress solution with the following substitutions:

$$E = \frac{1+2\nu'}{(1+\nu')^2} E' \tag{2.2}$$

$$\nu = \frac{\nu'}{1+\nu'} \tag{2.3}$$

where E' and ν' are the Young's modulus and the Poisson's ratio of the medium, and
E and ν are the equivalent plane strain parameters.

tiffnesses for the three slopes are given, therefore, as

$$\text{slope OA} = \frac{k}{1 + \dfrac{k \sin\alpha \sin(\alpha - \phi)}{K_s (L - l) \cos\phi}} \tag{2.4}$$

$$\text{slope AB} = k \tag{2.5}$$

$$\text{slope BO} = \frac{k}{1 + \dfrac{k \sin\alpha \sin(\alpha + \phi)}{K_s (L - l) \cos\phi}} \tag{2.6}$$

IERICAL MODEL

: UDEC analysis, the elastic blocks are discretized into constant strain finite difference triangles n Fig. 2.4.

'ollowing alternatives for the joint constitutive relation have been studied:

Case A – linear deformation, Mohr-Coulomb model

Case B – Continuously-Yielding model

Case C – Barton-Bandis model

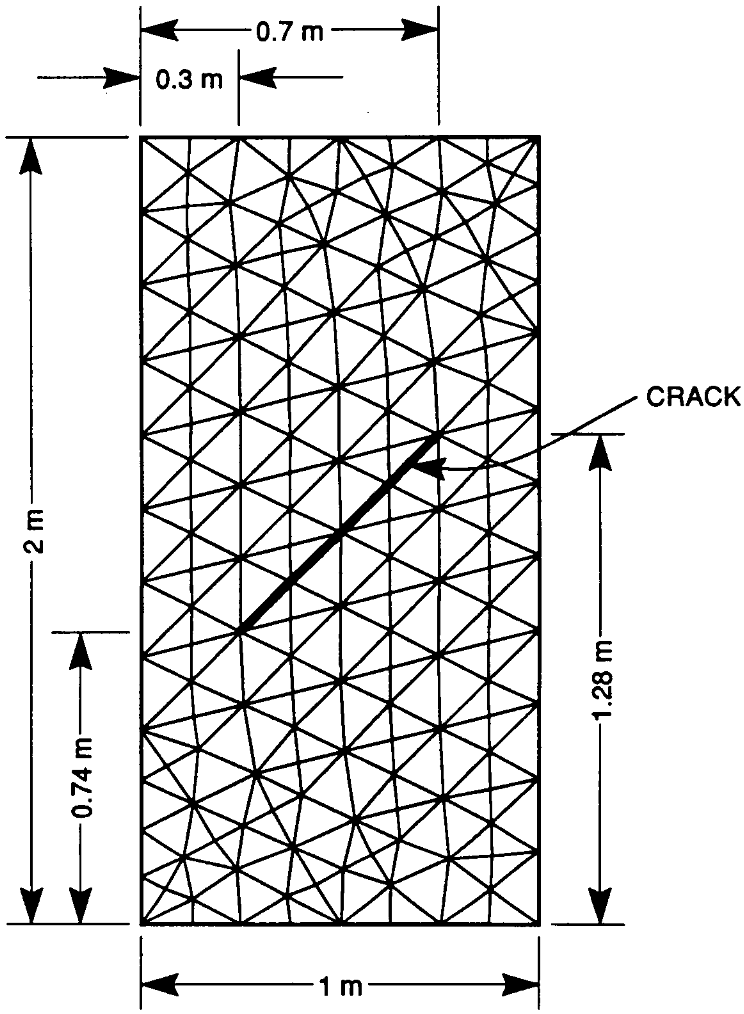

Figure 2.4 Discretization of Elastic Medium into Constant Strain Finite Difference Triangles

In all problems, the elastic, non-slipping sections of the crack were modeled using the standard Mohr-Coulomb model (JCONS=2), with the friction parameter set high enough to prevent any slip, and the center section of the crack was assigned parameters which would permit slip to occur. The specific UDEC parameters used for each joint relation were as shown in Table 2.1.

Table 2.1 Joint Parameters

Mohr-Coulomb (JCONS=2)	Continuously-Yielding (JCONS=3)	Barton-Bandis (JCONS=7)
JKN = 220 GPa/m	JKN = 220 GPa/m	JKN = 220e3 MPa
JKS = 220 GPa/m	JKS = 220 GPa/m	JKS = 220e3 MPa
JFRIC = 0.287	JFRIC = 0.287	JRC = 1
	JEN = 0	JCS = 100 MPa
	JES = 0	SIGMAC = 120 MPa
	JIF = 0.279 rad	LO = 100 m
	JR = 1.0e-10 m	LN = 2e-4
		PHIR = 16°

The Mohr-Coulomb model used in UDEC is a linear elastic-perfectly plastic relation (Fig. 2.5) and is consistent with the concepts used in developing the expressions for three stiffnesses (Eqs. 2.4-2.6) in the conceptual model. The other two joint relations are nonlinear and, therefore, do not comply with the concepts used to develop the conceptual model. The parameters selected for the Continuously-Yielding and the Barton-Bandis models, for the purpose of this study, were found by fitting these models to the results for a Mohr-Coulomb joint in direct shear under constant normal stress. For the Continuously-Yielding model, the normal stress-normal displacement relation used in this study is linear (Fig. 2.6), with K_n = 220 GPa/m, but the shear behavior is non-linear (Fig. 2.5). The shear stress-shear displacement response for the Continuously-Yielding model, based on the parameters defined in Table 2.1 approximates the Mohr-Coulomb slip.

For the Barton-Bandis model, both shear and normal behavior are non-linear. For the purposes of this study, the Barton-Bandis parameters shown in Table 2.1 were chosen to produce a reasonable approximation to the Coulomb slip model for direct shear loading. Figure 2.5 presents results for the response in shear, and comparison with the Mohr-Coulomb and Continuously-Yielding models. The behavior in normal compression is shown in Fig. 2.6.

2.7 RESULTS

The results for each of the joint deformation models is compared with the conceptual model in Table 2.2. Global stiffnesses were calculated directly from UDEC results using average vertical stresses and maximum vertical displacements (found using **PRINT MAX**) for each load step. The table shows good agreement for all models. Graphical results for the complete load cycle for the Mohr-Coulomb model are shown in Fig. 2.7. In this analysis, the compression is considered to be positive.

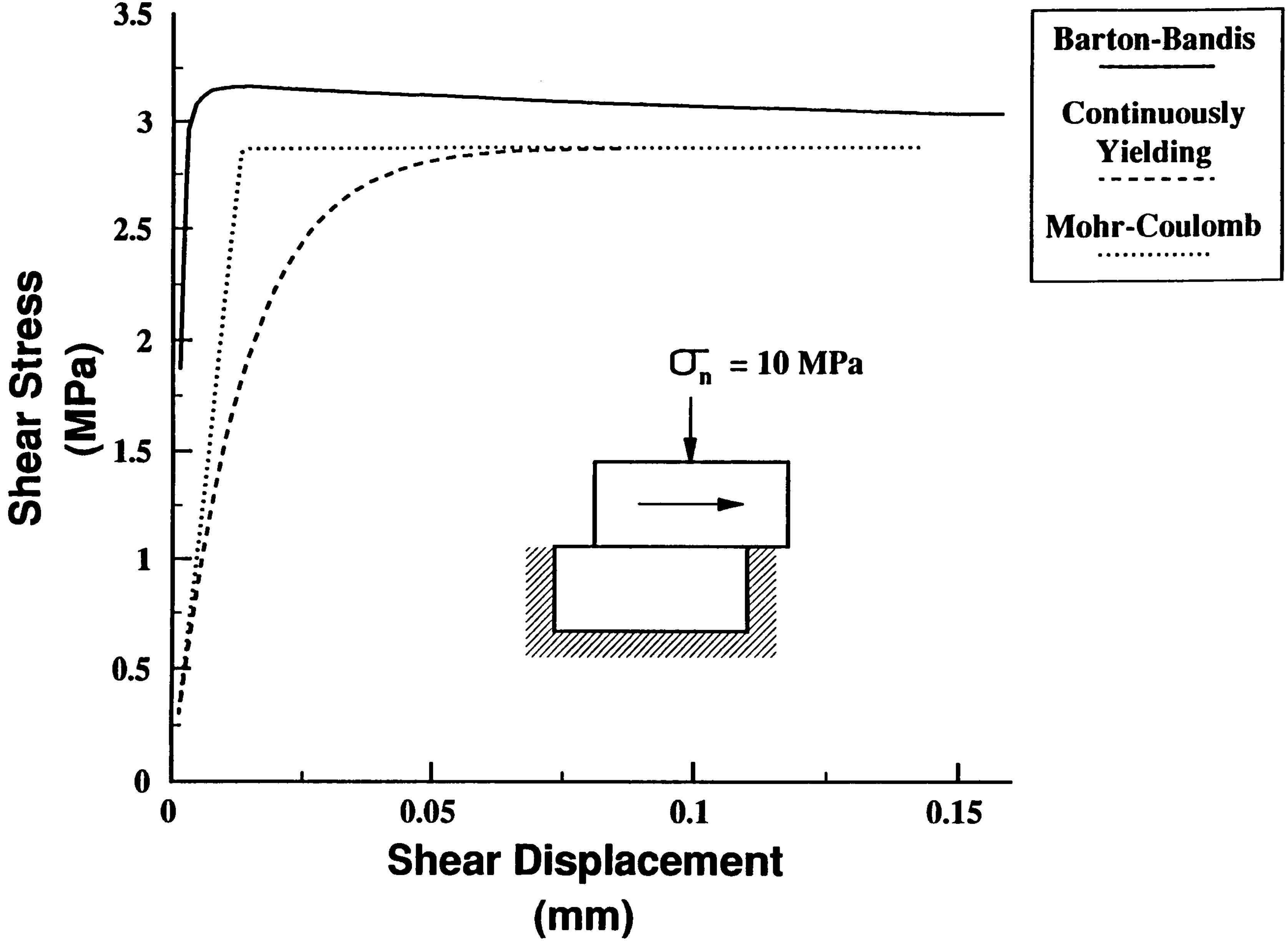

Figure 2.5 Joint Shear Stress vs Shear Displacement for Constant Normal Stress Direct Shear Test

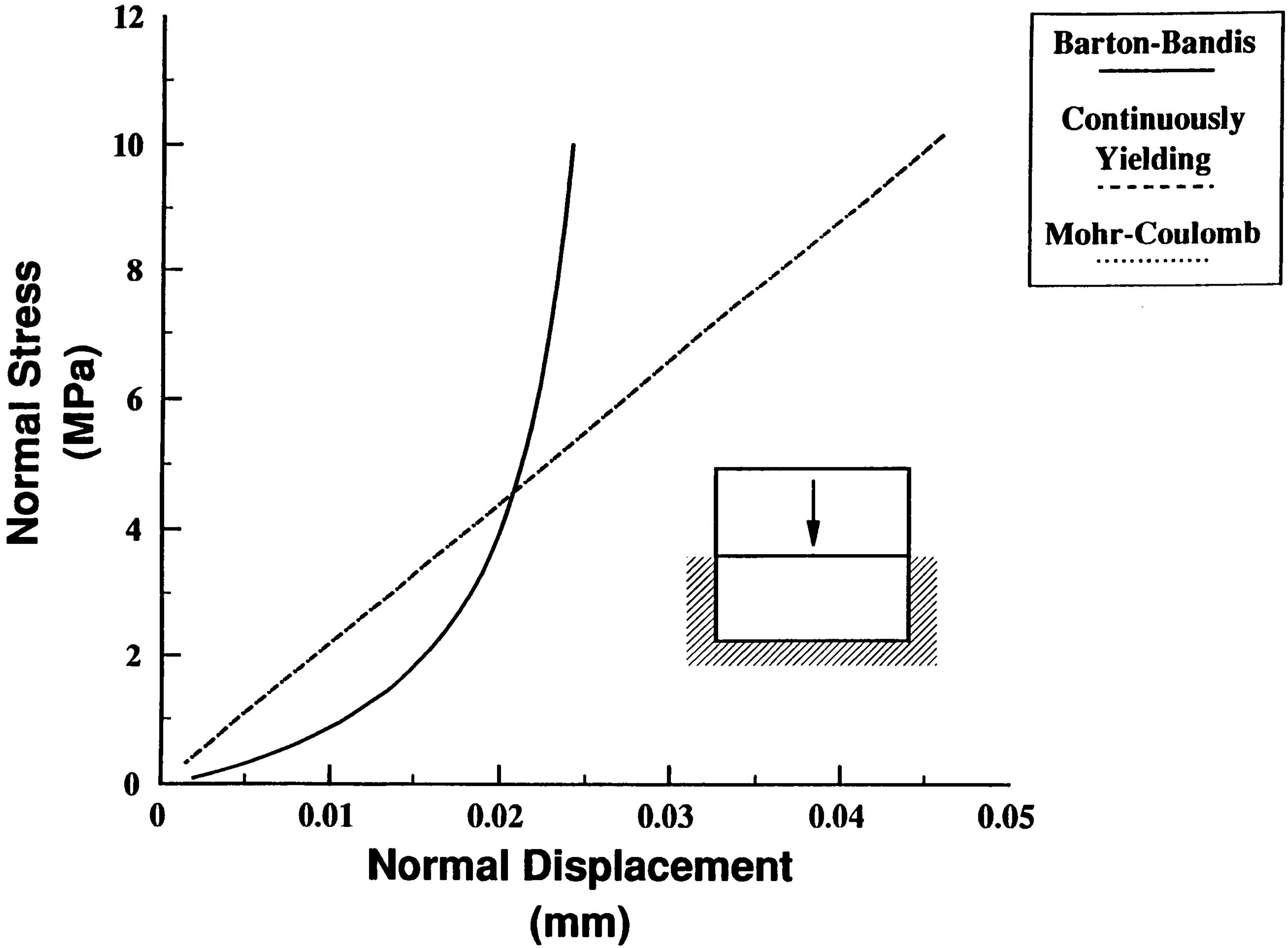

Figure 2.6 Joint Normal Stress vs Normal Displacement for Simple Compression Test, Using Parameters Selected for This Study (Note that the Continuously-Yielding response is generally non-linear.)

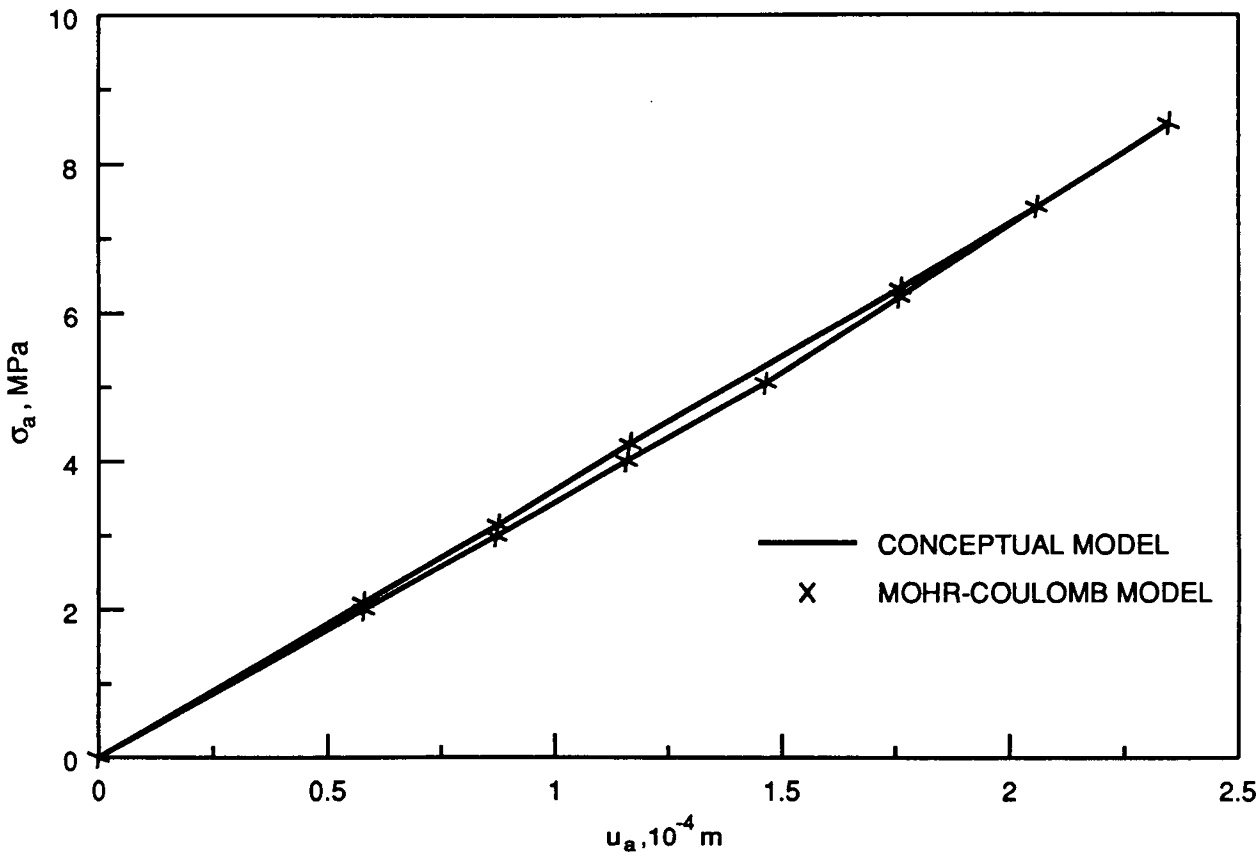

Figure 2.7 Axial Stress vs Axial Displacement for the Problem Involving Cyclic Loading for a Specimen with Slipping Crack Modeled with the Mohr-Coulomb Friction Law

Table 2.2 Comparison of UDEC Results Using Various Joint Models with Conceptual Model Solution for Cyclic Loading of a Specimen with a Slipping Crack

	Conceptual Model	Mohr-Coulomb		Continuously-Yielding		Barton-Bandis	
Loading Segment	Stiffness (GPa/m)	Stiffness (GPa/m)	Error (%)	Stiffness (GPa/m)	Error (%)	Stiffness (GPa/m)	Error (%)
Load (OA)	36.34	36.04	0.82	36.11	0.65	35.31	2.8
Unload (AB)	38.89	38.91	-0.05	38.77	0.31	38.77	0.31
Unload (BO)	34.52	34.14	1.1	34.18	0.98	33.8	2.1

2.8 DISCUSSION

There is no simple and completely rigorous analytical solution to the problem of an elastic body with an internal slipping crack. Nevertheless, the simple conceptual model described here captures the essential features of the problem (i.e., three distinctly different global stiffnesses) observed in cyclic loading. The UDEC results agree well with the conceptual model. However, the results agree less closely as the length of the slipping crack increases with respect to the width of the specimen. This observation is expected because the conceptual model assumes uniform distribution of normal stress on the crack and the elastic bridges and stress concentrations become more significant as the length of the elastic bridge between the crack and the specimen boundary decreases.

Parameters selected to approximate a Mohr-Coulomb joint with the Continuously-Yielding model and particularly the Barton-Bandis model were not optimized to give the "best" results. It is conceivable that other parameters could give even closer agreement with the conceptual model. It should also be noted that the parameters used in the Barton-Bandis model do not necessarily correspond to any reasonable physical parameters. For the Continuously-Yielding joint, the deformation response under normal stress, although consistent with the Mohr-Coulomb model, was restrictive in terms of realistic simulation of joint behavior. In both cases, parameters could be selected to yield results which were in reasonable agreement with the Mohr-Coulomb model.

3. CIRCULAR EXCAVATION WITH AN ADJACENT DISCONTINUITY IN AN INFINITE ELASTIC MEDIUM

3.1 PROBLEM STATEMENT

This problem concerns the influence of a plane of weakness transgressing a circular excavation or its zone of influence in an infinite elastic medium. Figure 3.1 shows the following five specific cases described originally by Brady and Brown (1985) for the study of this problem:

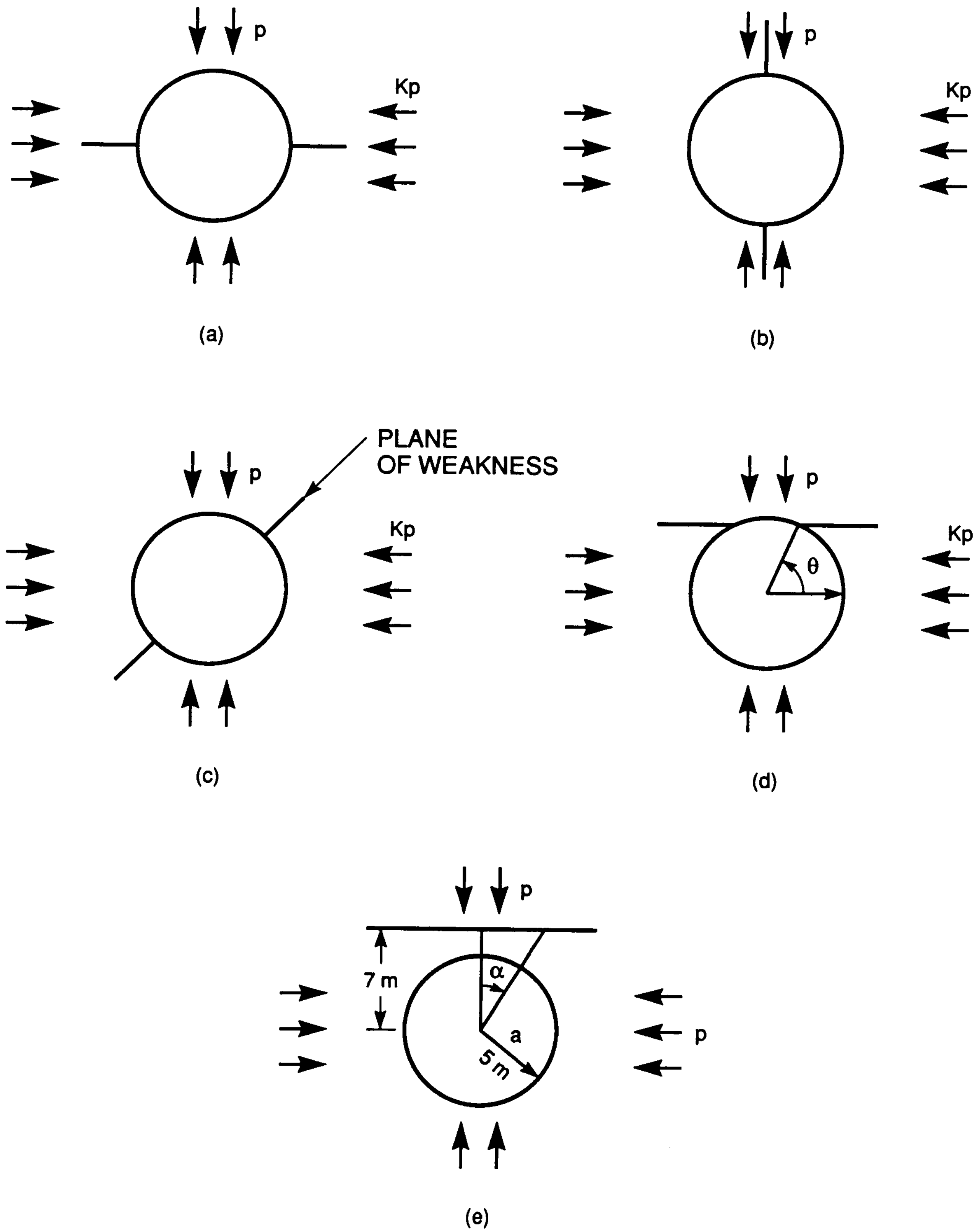

Figure 3.1 Five Specific Cases for a Circular Excavation with an Adjacent Discontinuity

(1) A plane of weakness transecting an opening along the diameter perpendicular to the major principal stress;

(2) A plane of weakness intersecting an opening along the diameter parallel to the major principal stress;

(3) A plane of weakness intersecting an opening along a diameter with a 45° angle with respect to the major principal stress;

(4) A plane of weakness perpendicular to the major principal stress and intersecting a circular opening non-diametrically;

(5) A plane of weakness transgressing the zone of influence of a circular opening.

The closed-form solutions according to Kirsch (1898) for the stress distributions around a circular opening in an infinite elastic medium without a discontinuity (Fig. 3.2) are as follows:

$$\begin{aligned}
\sigma_{rr} &= \frac{p}{2}\left[\left(1+K\right)\left(1-\frac{a^2}{r^2}\right)-\left(1-K\right)\left(1-4\frac{a^2}{r^2}+3\frac{a^4}{r^4}\right)\cos 2\theta\right] \\
\sigma_{\theta\theta} &= \frac{p}{2}\left[\left(1+K\right)\left(1+\frac{a^2}{r^2}\right)+\left(1-K\right)\left(1+3\frac{a^4}{r^4}\right)\cos 2\theta\right] \qquad (3.1) \\
\sigma_{r\theta} &= \frac{p}{2}\left[\left(1-K\right)\left(1+2\frac{a^2}{r^2}-3\frac{a^4}{r^4}\right)\sin 2\theta\right]
\end{aligned}$$

where a = radius of the circular opening,

r = distance from the center of the opening,

p = magnitude of a field principal stress,

K = ratio of the field principal stresses,

θ = counter clockwise angle between the x-axis and the line passing through the point where the stresses are calculated and the center of the opening (see Fig. 3.2),

σ_{rr} = radial stress,

$\sigma_{\theta\theta}$ = tangential stress, and

$\sigma_{r\theta}$ = shear stress.

However, no closed-form solutions are available to deal with the condition in which a discontinuity and a circular excavation are co-existent. For the purpose of this study, the simple treatment proposed by Brady and Brown (1985) was adopted to approximate the response of a discontinuity to the presence of a circular excavation. In this simple treatment, a discontinuity was assumed to be non-dilatant in shear and its shear strength and tensile strength are defined by:

$$\begin{aligned}
\tau &= \sigma_n \tan \phi \\
T &= 0
\end{aligned} \qquad (3.2)$$

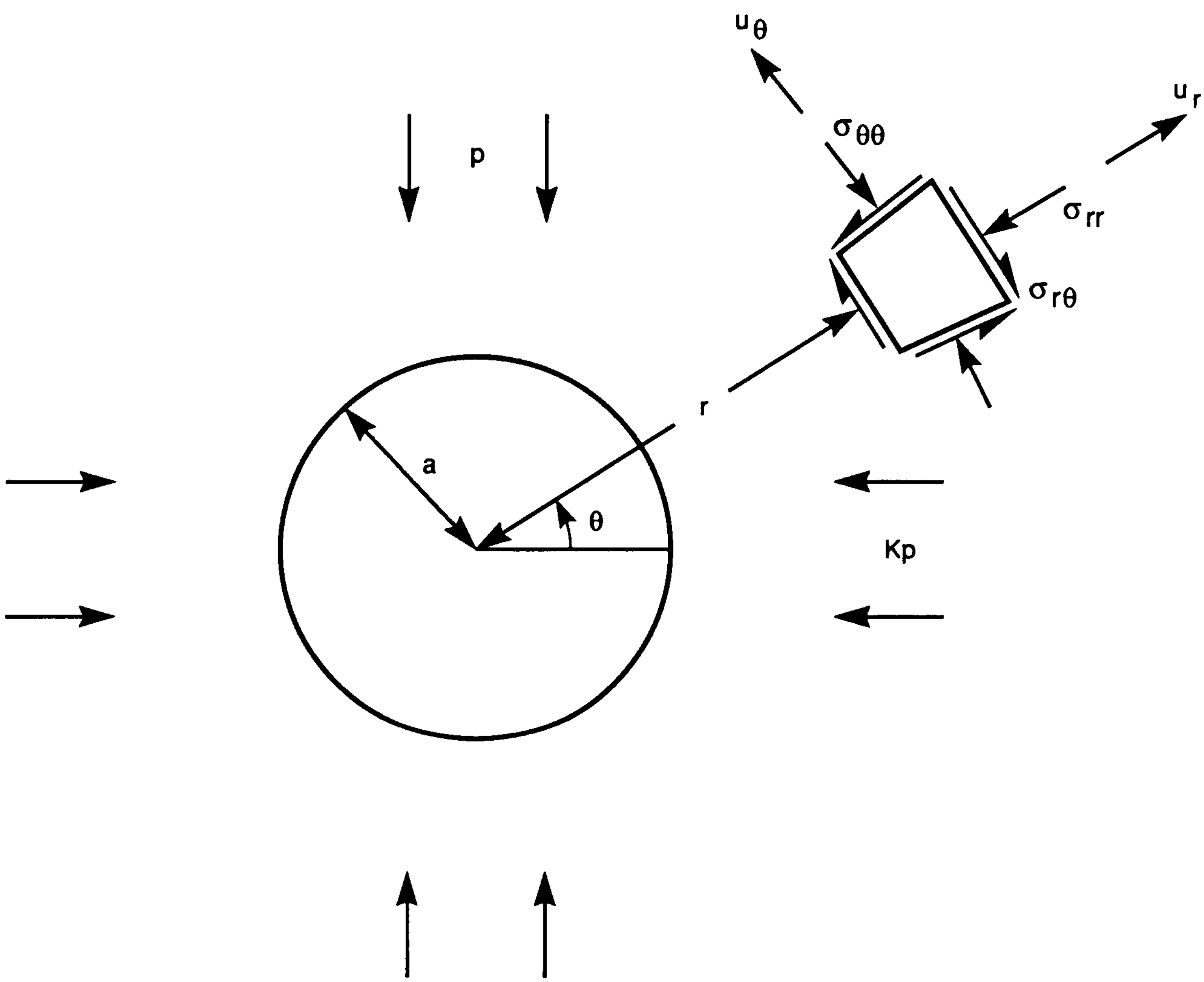

Figure 3.2 State of Stress and Displacement Around a Circular Opening in a Biaxial Stress Field

where τ = limiting shear stress along a discontinuity,

σ_n = normal stress perpendicular to the discontinuity,

ϕ = angle of friction of the discontinuity, and

T = tensile strength of the discontinuity.

If the state of stress in an area of a discontinuity calculated from the Kirsch solution (Eq. 3.1) exceeds the limiting criteria set by Eq. 3.2, slip or separation is indicated in that area. It should be noted that this treatment is by no means a rigorous one. It is only capable of predicting the initiation of slip or separation. Any prediction made beyond that state through this treatment is an approximation. Nevertheless, the simple treatment reveals sufficient information for the purpose of the study, and is justified because of the absence of other rigorous solutions.

The five typical cases noted above were modeled using the UDEC code and the results were compared to the predictions from the Kirsch solution subject to the limitations of Eq. 3.2. The results and discussion are presented in a case-by-case basis. The following material properties of the continuous medium and the plane of weakness were used throughout this study:

(a) Elastic properties and mass density

Mass density (ρ) = 10 kg/m^3
Shear modulus (G) = 35 GPa
Bulk modulus (K) = 60 GPa

Note that the Kirsch solution for stress distribution around a circular opening was derived under the assumption of zero mass density. However a mass density must be defined in UDEC. For convenience, it is set to an arbitrarily small value.

(b) Joint properties

The following three joint deformation models have been studied:

(i) Mohr-Coulomb Model

(ii) Continuously-Yielding Model

(iii) Barton-Bandis Model

The specific UDEC parameters used for each joint model to simulate the plane of weakness were as follows:

(i) Mohr-Coulomb Model (JCONS=2)

JKN = 200 GPa/m
JKS = 200 GPa/m
JCOH = 0 MPa
JTENS = 0 MPa

(ii) Continuously-Yielding Model (JCONS=3)

JKN = 200 GPa/m
JKS = 200 GPa/m
JEN = 0
JES = 0
JIF = 1.0e-10 rad
JR = 1.0e-10 m

(iii) Barton-Bandis Model (JCONS = 7)

JKN = 200 GPa/m
JKS = 200 GPa/m
JRC = 0.0001
JCS = 100 MPa
LO = 100 m
LN = 1 m
PHIR = 0.0001°
APER = 0.05 mm

The continuous medium was modeled in the UDEC analysis with elastic, fully deformable blocks which were further discretized into triangular finite-difference zones. Joints simulated in the UDEC model other than the plane of weakness were assigned high cohesion and tensile strength, to impose continuous response.

3.2 PURPOSE

The purpose of this set of problems is to assess the capacity of UDEC to simulate slip and separation on joints under conditions of heterogeneous local stress distribution. The intention is to determine if joint response predicted with UDEC is consistent with the various modes of response indicated by the approximation to the response inferred from the Kirsch solution.

3.3 CASE 1: Discontinuity Oriented Parallel to the Minor Principal Stress

Analytical Assessment

The problem illustrated in Fig. 3.1a concerns a circular opening which is transected by a plane of weakness oriented along the diameter perpendicular to the major principal field stress; i.e., the angle between the discontinuity and the minor principal field stress is zero. Based on Eq. 3.1, the state of stress along the discontinuity can be shown to be:

$$\sigma_n = \sigma_{\theta\theta} = \frac{p}{2}\left[(1+K)\left(1+\frac{a^2}{r^2}\right)+(1-K)\left(1+3\frac{a^4}{r^4}\right)\right] \tag{3.3}$$

$$\tau = 0$$

The zero shear stress along the plane of weakness indicates that no slip can occur. In other words, for a high joint normal stiffness, the plane of weakness will have no effect on stress distribution around the circular opening.

Numerical Model

Figure 3.3 shows the Case 1 geometry modeled with the UDEC code. The y-axis is a line of symmetry. The width and height of the model are 30 m and 60 m, respectively. The radius, a, of the circular opening is 5 m, and the plane of weakness was located at y = 0. The major principal stress, 20 MPa, was applied vertically to the top and bottom of the model. The K value, which in this case is the ratio of applied minor principal stress to major principal stress, was 0.4.

Results

The Mohr-Coulomb joint represents linear elastic, perfectly-plastic joint behavior while the Continuously-Yielding and the Barton-Bandis joints are non-linear models. Nevertheless, the normal stresses along the plane of weakness for Case 1 as calculated by the UDEC utilizing each joint model are very similar. Figure 3.4 shows the normal stresses along the plane of weakness for Case 1. The UDEC results for normal stress distribution using each joint model are in good agreement with the Kirsch solution. The normal stress predicted by the UDEC code at the intersection of the plane of weakness and the circular opening is slightly higher than that from the Kirsch solution. This arises from the high stress gradient near the excavation boundary.

The UDEC result indicates zero shear stress on the plane of weakness, which is consistent with the Kirsch solution. Some very minor dependence of computed stresses on the assigned value of the friction angle was noted, but the effect is of no consequence in practice.

3.4 CASE 2: Discontinuity Oriented Parallel to the Major Principal Stress

Analytical Assessment

This problem concerns a circular opening which is transected by a plane of weakness oriented along the diameter parallel to the major principal stress, as illustrated in Fig. 3.1b. The angle θ between the discontinuity and the minor principal stress in this case is 90°, reducing Eq. 3.1 to:

$$\begin{aligned}
\sigma_{rr} &= \frac{p}{2}\left[\left(1+K\right)\left(1-\frac{a^2}{r^2}\right)+\left(1-K\right)\left(1-4\frac{a^2}{r^2}+3\frac{a^4}{r^4}\right)\right] \\
\sigma_{\theta\theta} &= \frac{p}{2}\left[\left(1+K\right)\left(1-\frac{a^2}{r^2}\right)-\left(1-K\right)\left(1+3\frac{a^4}{r^4}\right)\right] \qquad (3.4) \\
\sigma_{r\theta} &= 0
\end{aligned}$$

The state of stress along the plane of weakness can be expressed by:

$$\begin{aligned}
\sigma_n &= \sigma_{\theta\theta} = \frac{p}{2}\left[\left(1+K\right)\left(1-\frac{a^2}{r^2}\right)-\left(1-K\right)\left(1+3\frac{a^4}{r^4}\right)\right] \qquad (3.5) \\
\tau &= 0
\end{aligned}$$

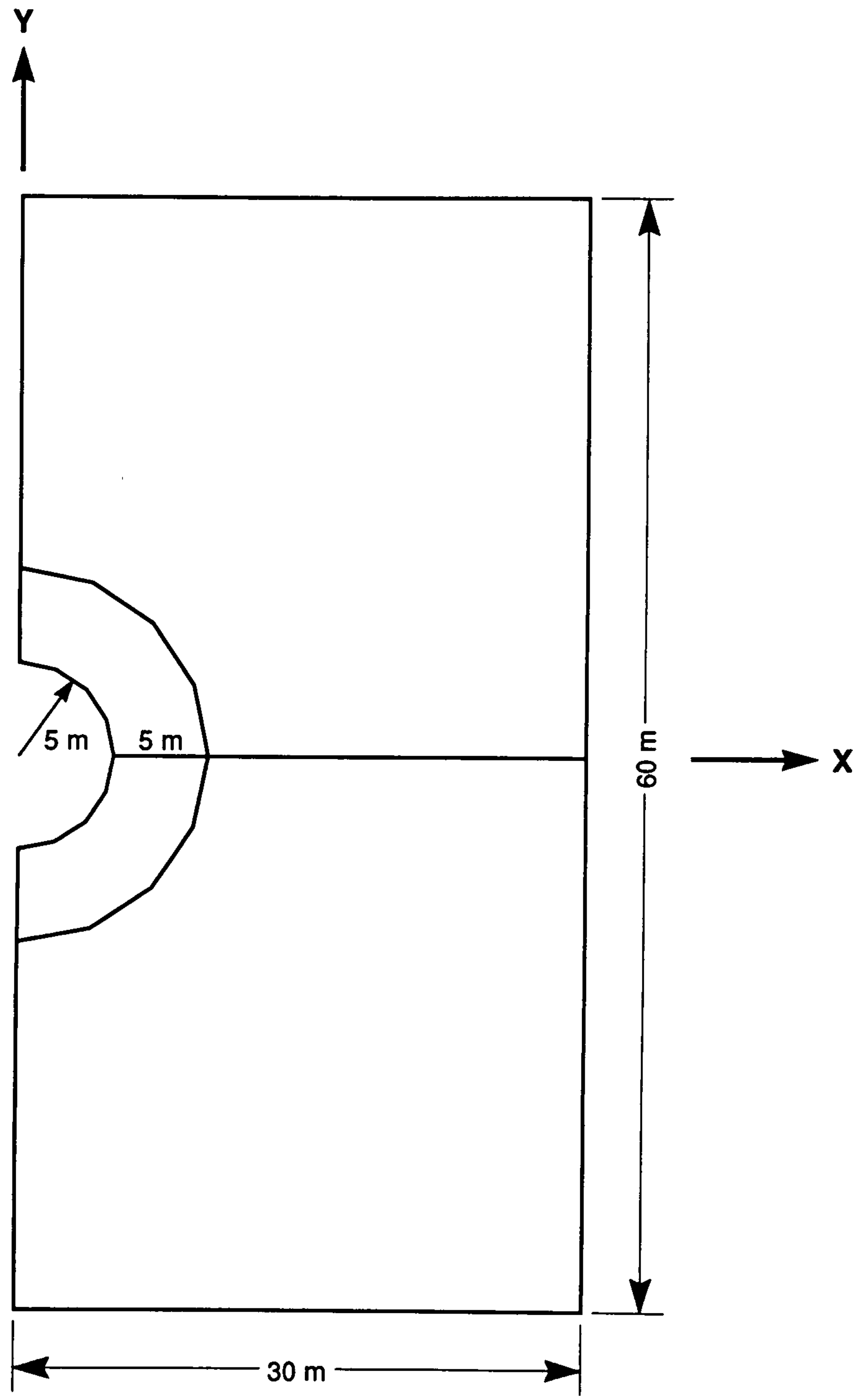

Figure 3.3 UDEC Model for Case 1

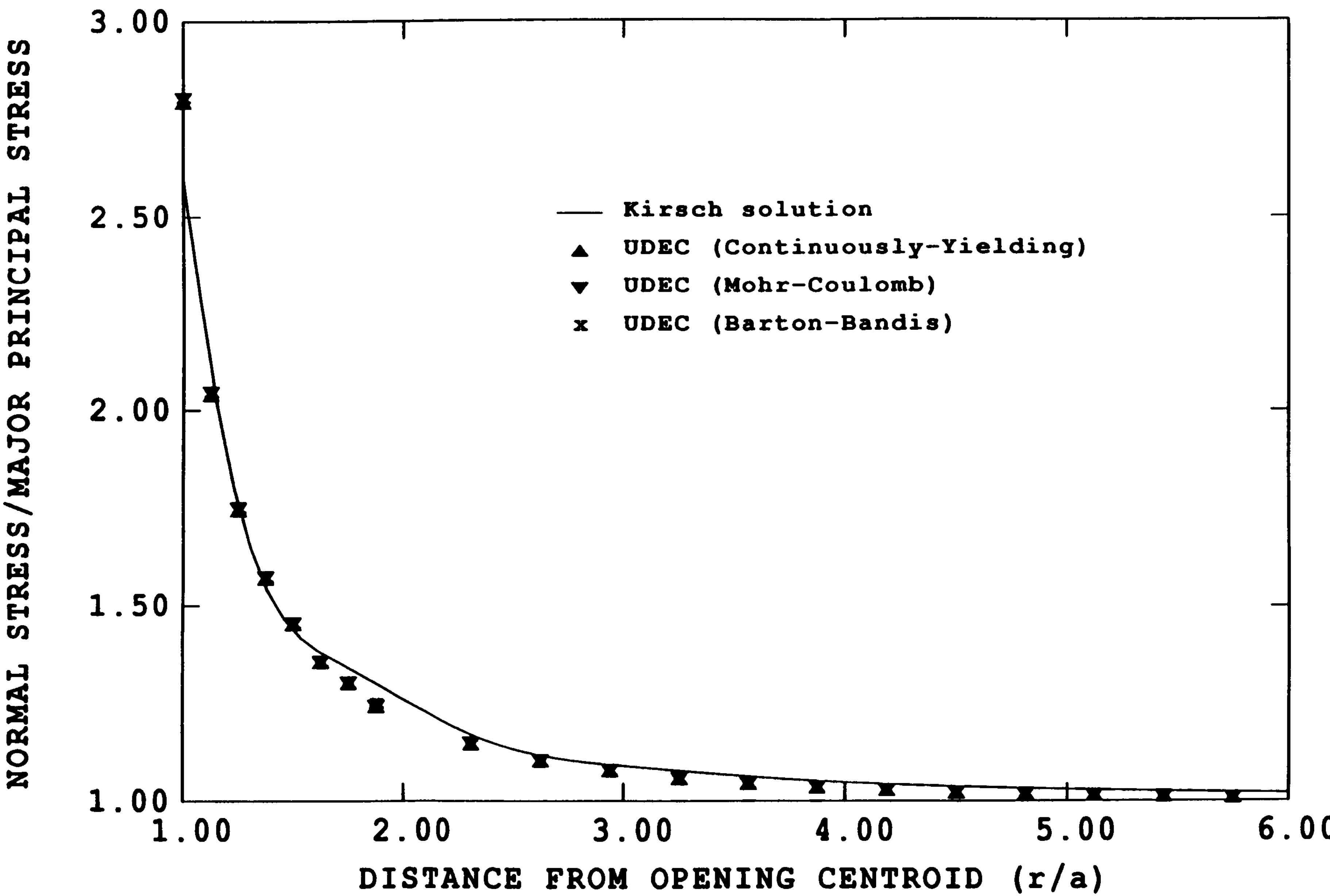

Figure 3.4 Normal Stress on Plane of Weakness, Case 1

As for Case 1, the state of zero shear stress along the plane indicates that no slip should occur and the elastic stress distribution will be sustained. The possibility of separation on the plane of weakness arises if tensile stresses exceed tensile strength in the crown of the opening, i.e. if $K < 1/3$. The height, h, of separation along the plane of weakness may be approximated by locating the zero joint normal stress (Brady and Brown, 1985).

$$h = a\left(\frac{1-3K}{2K}\right) \tag{3.6}$$

For $K \geq 1/3$, the elastic stress distribution will not be affected since neither slip nor separation is indicated along the plane of weakness.

Numerical Model

Figure 3.5 shows the geometry for Case 2 modeled with UDEC. The plane of weakness is located at $x = 0$. The major principal field stress was 24 MPa and was applied along the model boundaries located at $y = 12a$ and $y = -12a$, where a was the radius of the opening. The radius, a, of the circular opening was 5 m.

Results

The results for Case 2 are considered in terms of stresses along the plane of weakness and height of separation of the joint above the crown of the excavation.

Stresses Along Plane of Weakness

The distribution of normal stress along the plane of weakness calculated with the various joint models are indicated in Fig. 3.6. For the selected K value of 0.5, there is no substantial difference between the results from each analysis, the data points being scattered around the stress distribution from the Kirsch solution. The anomaly at $r/a = 3.0$ is probably associated with the triple joint intersection there. The discrepancy near the boundary, between all numerical solutions and the closed-form solution, is clearly due to the high stress gradient close to the boundary and the relatively coarse discretization of the problem domain.

The closed-form solution predicts zero shear stress along the plane of weakness considered here. For no joint friction, i.e. JFRIC = 0, the same results were obtained from UDEC analysis with the Mohr-Coulomb or the Continuously-Yielding models. Small but insignificant shear stress was returned by the Barton-Bandis model. Further, for non-zero values of JFRIC, all joint models indicated non-zero joint shear stresses. However, in all cases the calculated shear stresses were negligibly small in comparison with the field stresses.

Height of Separation

The Kirsch solution predicts the threshold of separation on the plane of weakness when $K = 1/3$. According to the Brady and Brown's approximation (Eq. 3.6), the relation between K and the height of separation is as shown in Fig. 3.7 by the solid line. The UDEC solutions with the various joint models are also shown as discrete data points. It is clear that all three joint relations slightly underestimate the K value for separation to initiate at the crown of the opening.

Figure 3.7 shows heights of separation under various K values for the three joint models. The height of separation has been calculated roughly by assuming a linear relation for the displacements between two

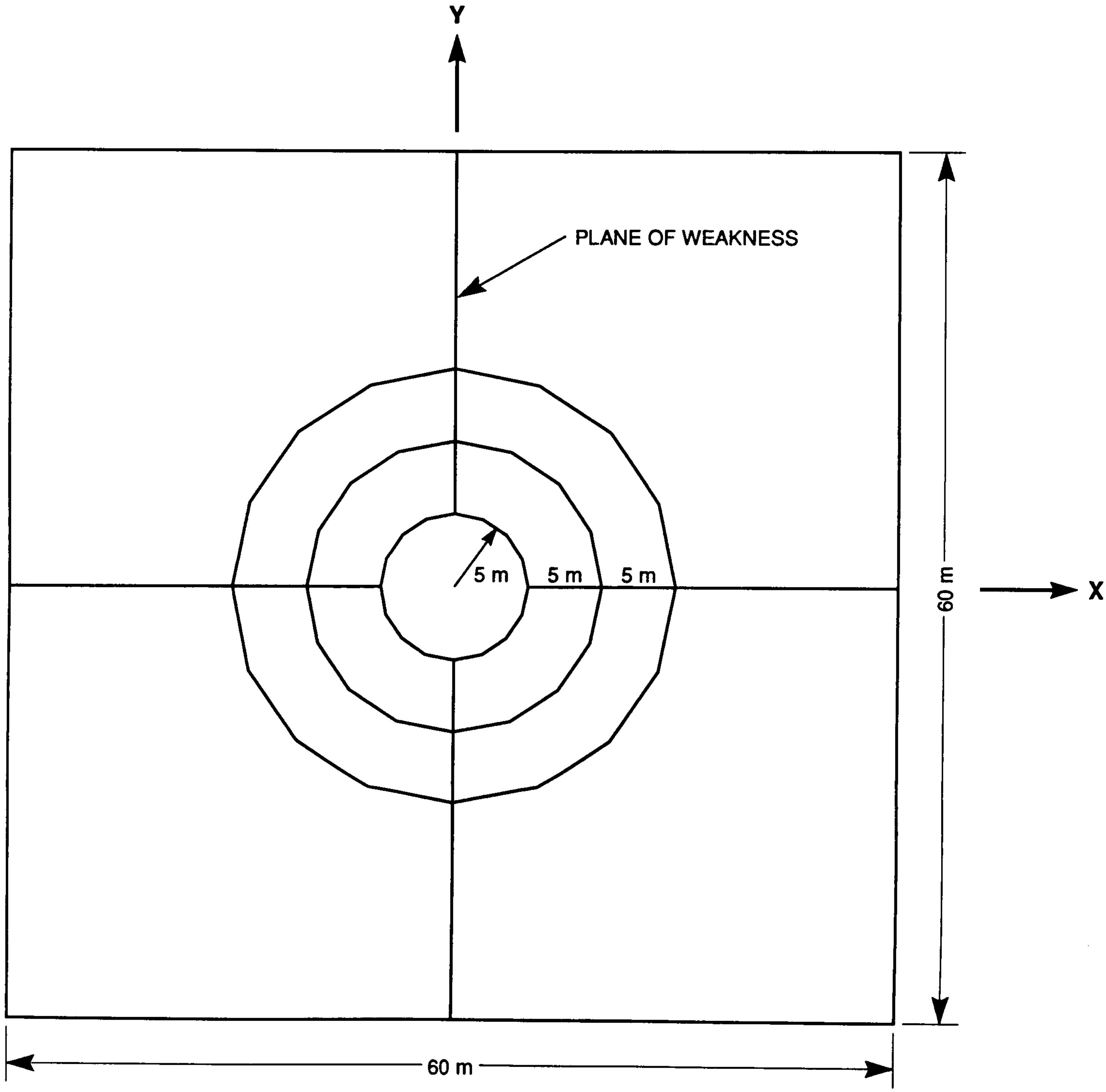

Figure 3.5 UDEC Model for Case 2

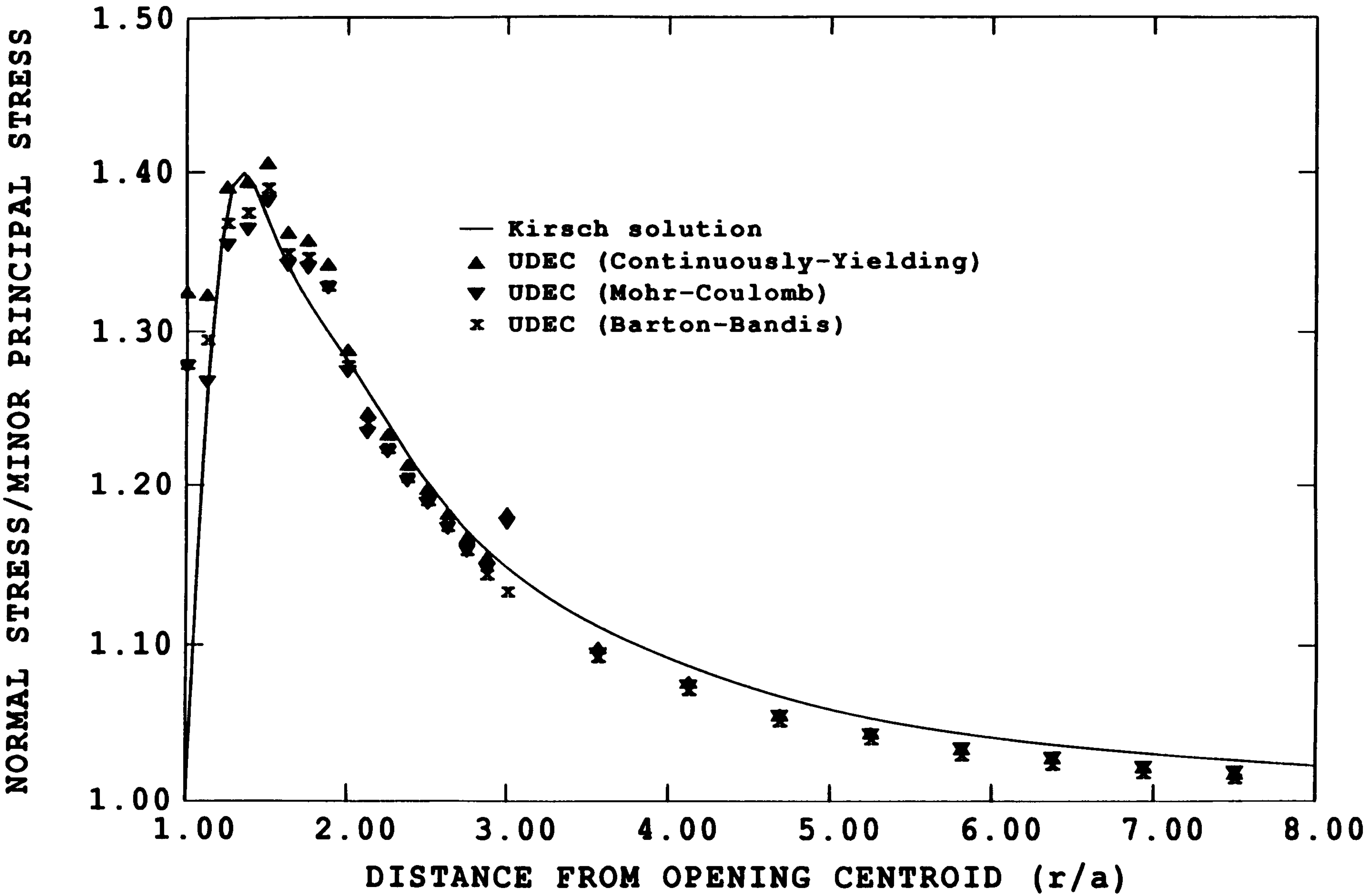

Figure 3.6 Normal Stress on Plane of Weakness, Case 2 (K=0.5)

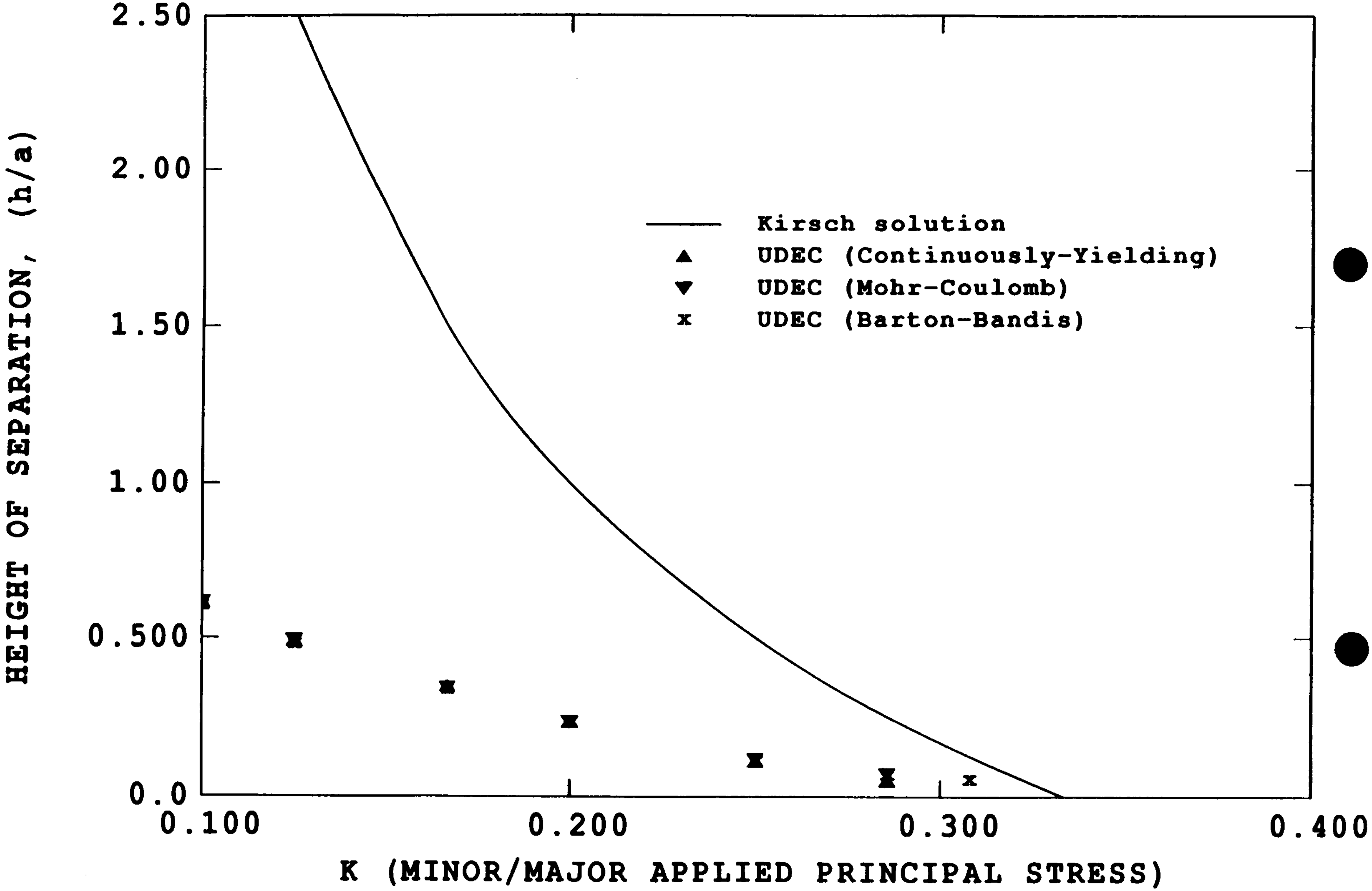

Figure 3.7 Height of Separation with Respect to K, Case 2

adjacent contact points. The height of separation indicated by UDEC is less than the value calculated using Eq. 3.6. However, in a region where the stress and displacement gradients are high and discretization relatively coarse, the gross disparities are readily explicable.

3.5 CASE 3: Inclined Diametral Joint

Analytical Assessment

Case 3 considers a circular opening which is intersected by a plane of weakness along the diameter inclined at 45° with respect to the applied major principal stress (Fig. 3.1c). The elastic solution for the normal and shear stresses along this plane according to the Kirsch equations (Eq. 3.1) is:

$$\sigma_n = \sigma_{\theta\theta} = \frac{p}{2}\left[\left(1+K\right)\left(1+\frac{a^2}{r^2}\right)\right]$$

$$\tau = \sigma_{r\theta} = \frac{p}{2}\left[\left(1-K\right)\left(1+2\frac{a^2}{r^2}-3\frac{a^4}{r^4}\right)\right] \tag{3.7}$$

For K = 0.5, the maximum value for the ratio of τ/σ_n as calculated by Brady and Brown (1985) from Eq. 3.7 is 0.3573 at a location 2.54a from the center of the opening. This ratio is equivalent to a mobilized angle of friction of 19.7°; i.e., for $\phi > 19.7°$, no slip is possible on the joint. The mobilized angle of friction at infinity is 18.4°. It is interesting to note that the difference between these two angles is only about 1.3°, and indicates the very restricted range within which joint slip can be investigated using the Kirsch equations.

Numerical Model

Figure 3.8 shows the geometry for Case 3 modeled with UDEC. The plane of weakness is inclined at 45°. The major principal field stress was 24 MPa and applied to the model boundaries at y = 12a and y = -12a.

Results

The results of the analysis for Case 3 are considered in terms of elastic stress distribution and the range of slip under conditions of limiting friction.

Elastic Stress Distribution

Figures 3.9 and 3.10 show the elastic distributions of normal and shear stress along the plane of weakness obtained from the closed-form solution (Eq. 3.7) and the UDEC analysis. Inspection of Fig. 3.9 indicates there is no discernible difference between the normal stresses determined from the various joint models in UDEC. Further, there is satisfactory correspondence with the closed-form solution, except at the boundary of the excavation, where the stress gradient is high.

The distributions of shear stress calculated from UDEC and the various joint models and the closed-form solutions are shown in Fig. 3.10. The important comparison is between the UDEC analysis (elastic Mohr-Coulomb joint) and the Kirsch solution. Although the correspondence between the two solutions is not exact, for the relatively coarse simulation the agreement is considered adequate. No significance can be attached to the apparent better agreement between the Barton-Bandis analysis and the Kirsch solution, because the joint parameters chosen for the UDEC analysis in that case are quite arbitrary.

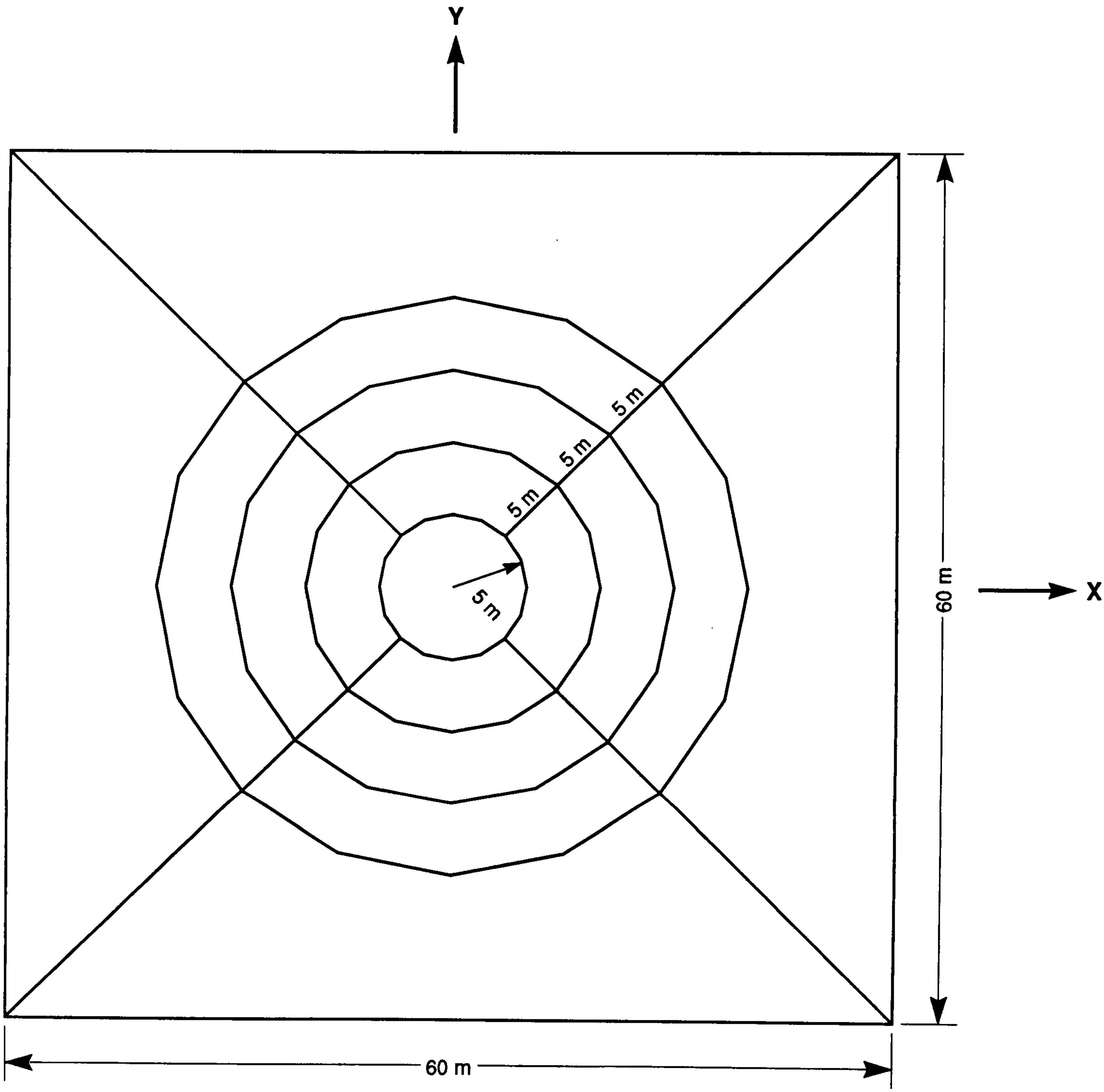

Figure 3.8 UDEC Model for Case 3

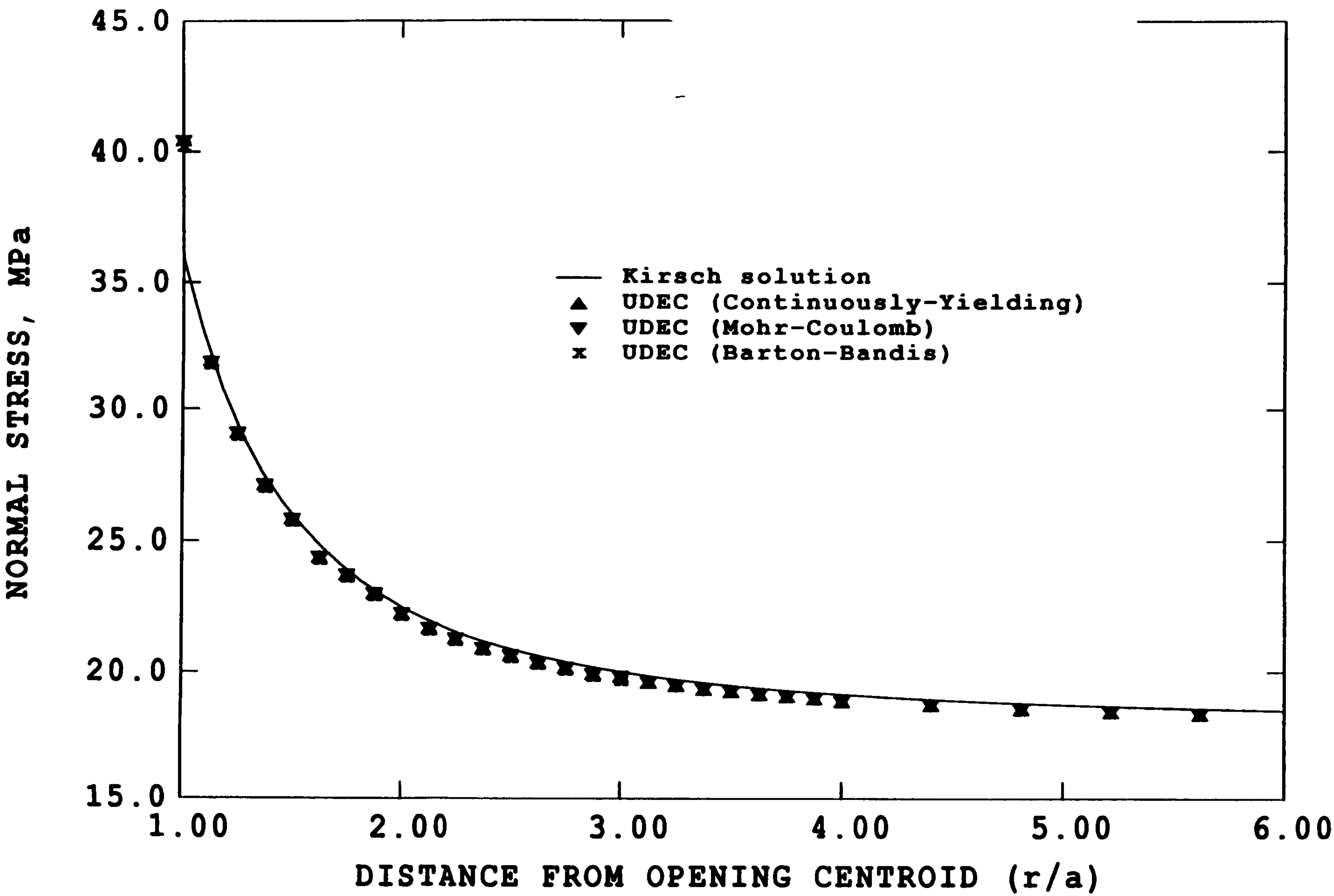

Figure 3.9 Normal Stress on Plane of Weakness, Case 3

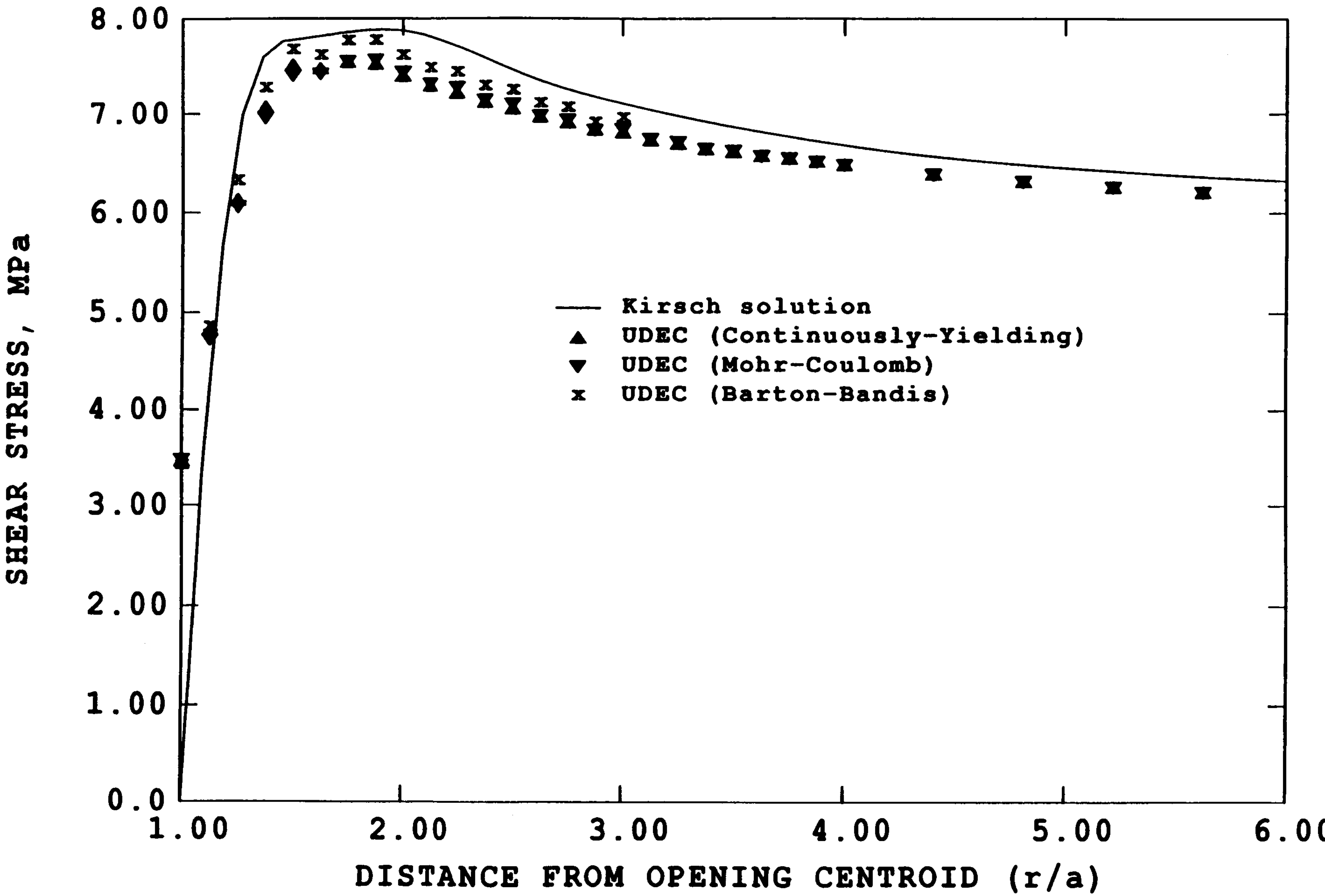

Figure 3.10 Shear Stress on Plane of Weakness, Case 3

Range of Slip

An estimate of the range of slip can be obtained most readily from a plot of τ/σ_n versus radial distance, as shown in Fig. 3.11. The plot indicates a difficulty with this benchmark problem. For r/a greater than about 2.5, the τ/σ_n plot along the joint, from the Kirsch solution, is relatively flat. This implies that small changes in the angle of joint friction, in the range $19.7° > \phi > 18.4°$, can have a substantial influence on the range of joint slip. The same behavior is observed for the UDEC solutions. Although only moderate agreement is indicated in Fig. 3.11 between the distributions of τ/σ_n from the Kirsch and UDEC solutions, the same trend is obvious, and thus similar sensitivity of range of slip to small changes in joint friction angle may be expected. This is confirmed in Table 3.1, where inferred ranges of slip are compared. While no absolute significance can be attached to the ranges of slip, the comparable sensitivity of the ranges calculated from the UDEC analysis and the closed-form solution suggest that the UDEC code performs satisfactorily on this problem.

Both the Barton-Bandis and Continuously-Yielding joint models were exercised on this problem. However, because neither model identifies the condition of joint slip explicitly, the only valid observation from the studies was that an angle of joint friction greater than 18.4° was required to establish a stable initial condition, consistent with the principles of simple statics.

Table 3.1 Comparison of Predicted Slip Length and Location From UDEC and Kirsch Solutions

ϕ	Length, m		Location	
	UDEC	Kirsch	UDEC	Kirsch
19.44°	0.31	6.45	2.94a-3a	2.1a-3.39a
19.4°	1.87	7.26	2.94a-3.31a	2.07a-3.52a
19.29°	8.82	9.35	2.44a-4.2a	2a-3.87a

3.6 CASE 4: Horizontal Joint Near Crown of Excavation

Analytical Assessment

The problem considered in this case is the response to construction of an excavation of a plane of weakness which is perpendicular to the direction of the major principal field stress and transects the excavation non-diametrically. The problem geometry is shown in Fig. 3.1d. Consideration of the state of stress on the plane of weakness shows that, at the intersection with the excavation, slip occurs when $\theta > \phi$, where θ defines the angular coordinate of the joint intersection, and ϕ is the angle of friction of the joint. Static equilibrium can be achieved only if, at the boundary-joint intersection:

$$\tau = 0$$
$$\sigma_n = 0 \tag{3.8}$$

Equation 3.8 can be satisfied only if $\sigma_{\theta\theta} = 0$ at the boundary. This implies that substantial re-distribution of stress, accompanied by joint slip, may occur if $\theta > \phi$.

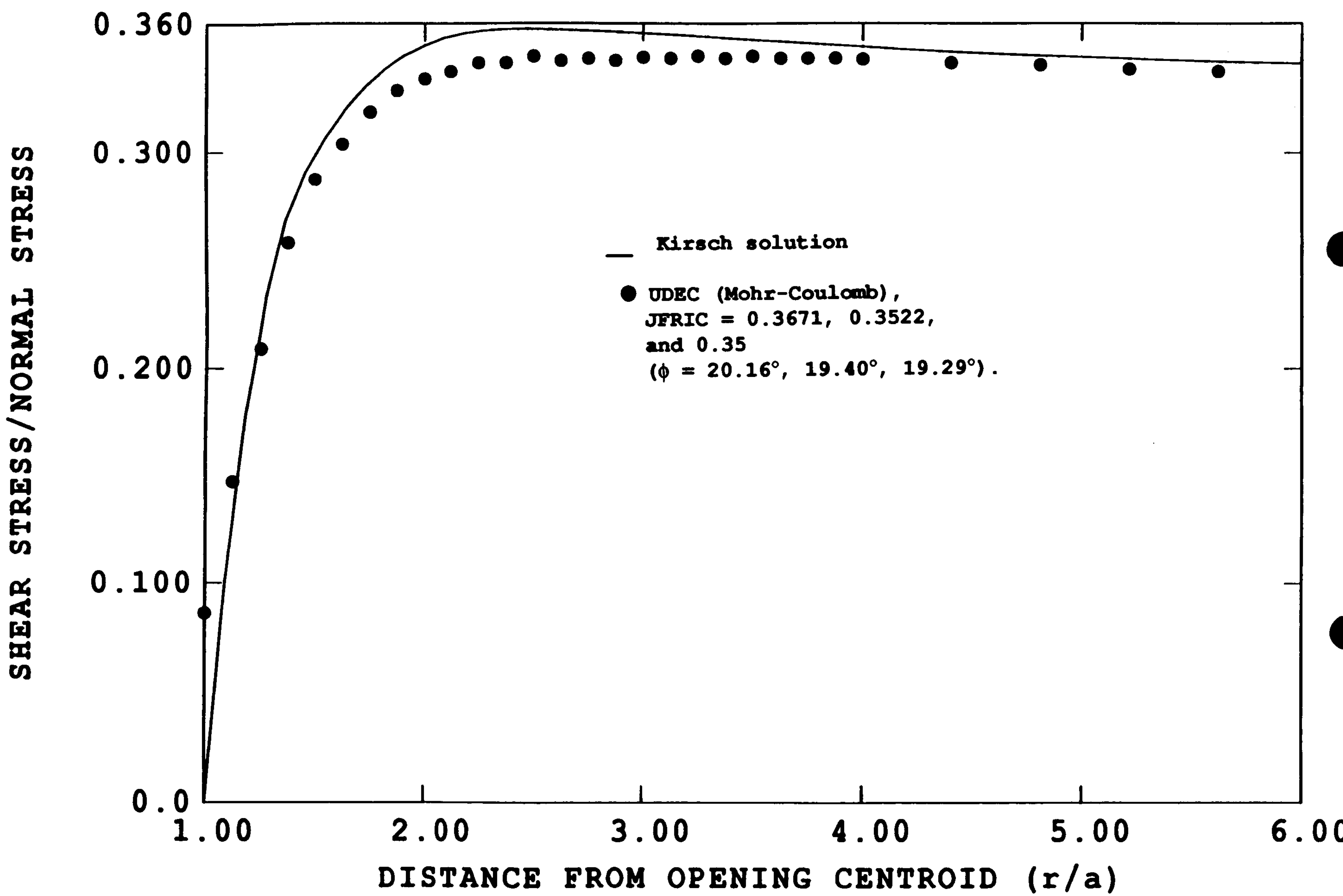

Figure 3.11 Ratio of Shear vs Normal Stress, Case 3

Numerical Model

Fig. 3.12 shows the problem geometry for Case 4 modeled with UDEC. The model consisted of a section which was symmetrical about the vertical centerline through the circular opening, of radius a = 5 m. With the horizontal plane of weakness located at y = 4.33 m, its angular orientation is defined by $\theta = 60°$. The vertical principal field stress was 24 MPa, applied on the model boundaries located at y = 12a and y = -12a. The horizontal principal field stress was of magnitude 24 MPa, corresponding to K = 1.

Results

The results of the analysis are shown in Figs. 3.13, 3.14, and 3.15. In Fig. 3.13, the tangential component of boundary stress ($\sigma_{\theta\theta}$) is presented as a polar plot, i.e., perpendicular to the boundary location at which the stress component is calculated. It is observed that, despite the very high boundary stress gradient near the intersection of the plane of weakness and the excavation, the stress magnitude calculated with UDEC converges on the results predicted analytically, i.e., $\sigma_{\theta\theta} \rightarrow 0$. It is also notable that compared with the elastic solution, the boundary stress is reduced in the crown of the excavation and increased in the floor. This is consistent with slip outwards from the excavation on the upper side of the plane of weakness, and inwards on the lower side, as is indicated in the formal analysis.

A comparison between the results of the UDEC analysis and an independent boundary element analysis of this problem, due to Crotty and Brady (1990), is presented in Fig. 3.14. The comparison is between normal and tangential components of traction (i.e., normal and shear stresses). The elastic solutions for the stresses, corresponding to the conditions prior to joint slip, are also presented for completeness. It is observed that, although the elastic solution with UDEC for the shear stress is a little irregular, after slip occurs, both the normal and shear stress distributions correspond closely with the independent solution.

Further indication of the satisfactory performance of UDEC in predicting the range of slip is provided in Fig. 3.15. This indicates that the range of joint slip extends over a range (x/a) of about 1.6, consistent with the independent solution. More importantly, the plot indicates that the ratio τ/σ on the plane of weakness is consistently equal to the coefficient of friction of the joint (i.e., 0.29) over the range of slip. This includes the region close to the boundary of the excavation, where each of the stresses is diminishingly small.

The observation from Figs. 3.13, 3.14, and 3.15 is that in terms of boundary stresses, range of slip and state of stress on the joint after slip, the UDEC solution for this problem is completely consistent with the independent solutions.

3.7 CASE 5: Plane of Weakness Adjacent to Excavation

Analytical Assessment

The problem considered in this case is the response of a plane of weakness located within the zone of influence of a circular excavation, but not intersecting it. The problem geometry is shown in Fig. 3.1e. For convenience in the study, the initial state of stress is taken to be hydrostatic. According to Brady and Brown (1985), the normal and shear stresses on the plane of weakness can be calculated from the expressions:

$$\sigma_n = p\left(1 - \frac{a^2}{r^2}\cos 2\alpha\right) \tag{3.9}$$

$$\tau = p\frac{a^2}{r^2}\sin 2\alpha$$

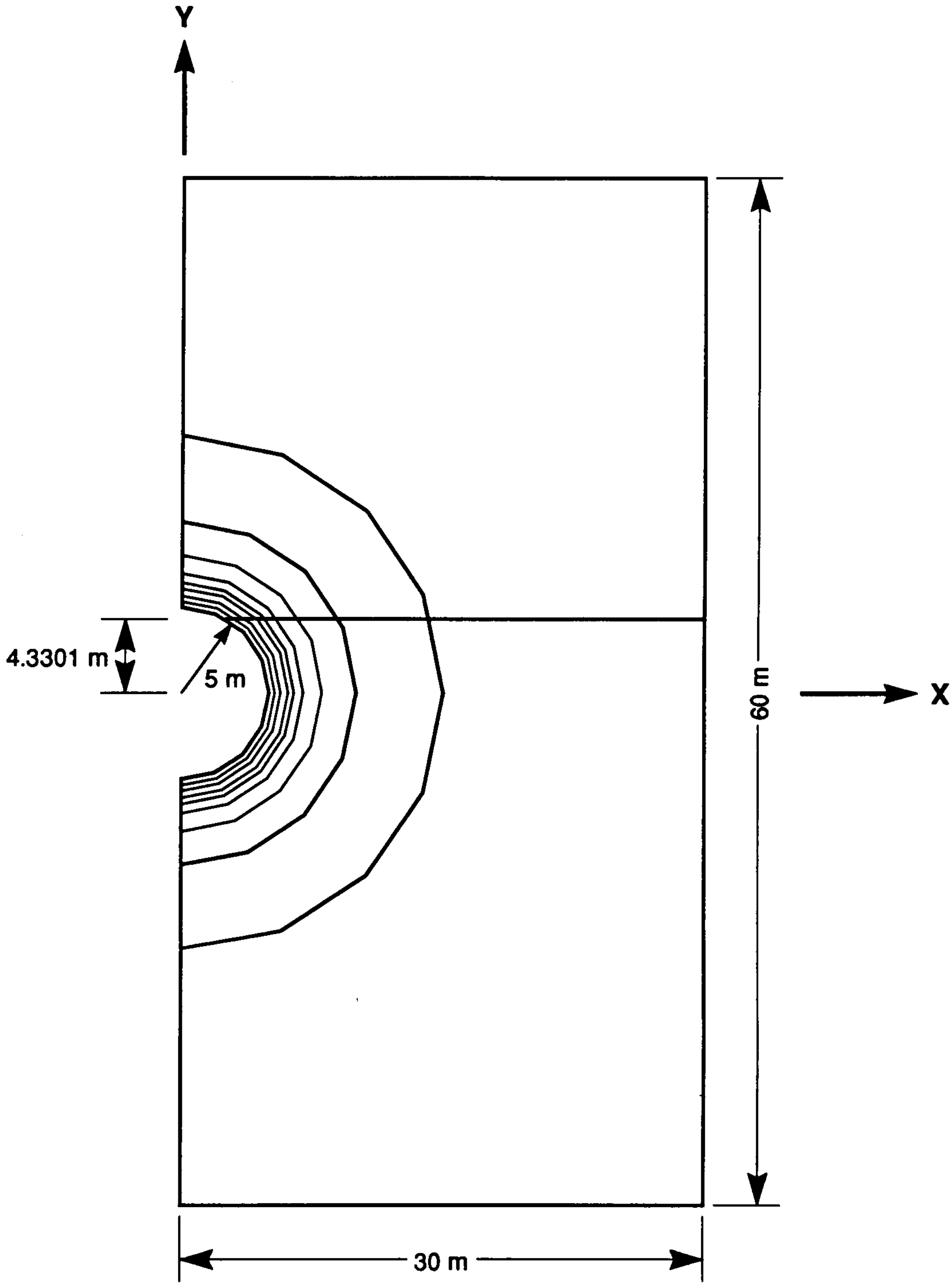

Figure 3.12 UDEC Model for Case 4

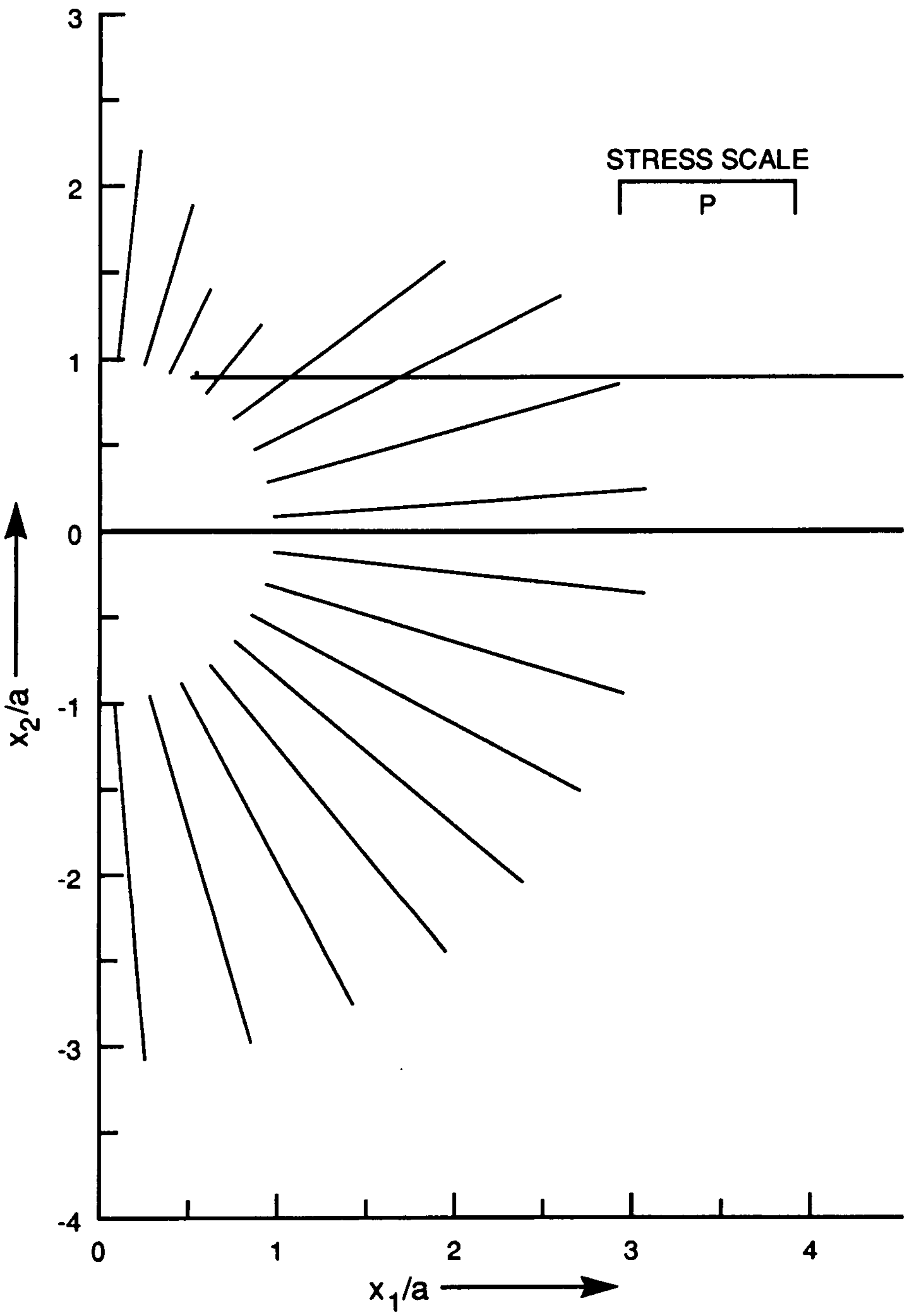

Figure 3.13 Polar Plot of Tangential Component of Boundary Stress Around a Circular Excavation Intersected Non-Diametrically by a Plane of Weakness

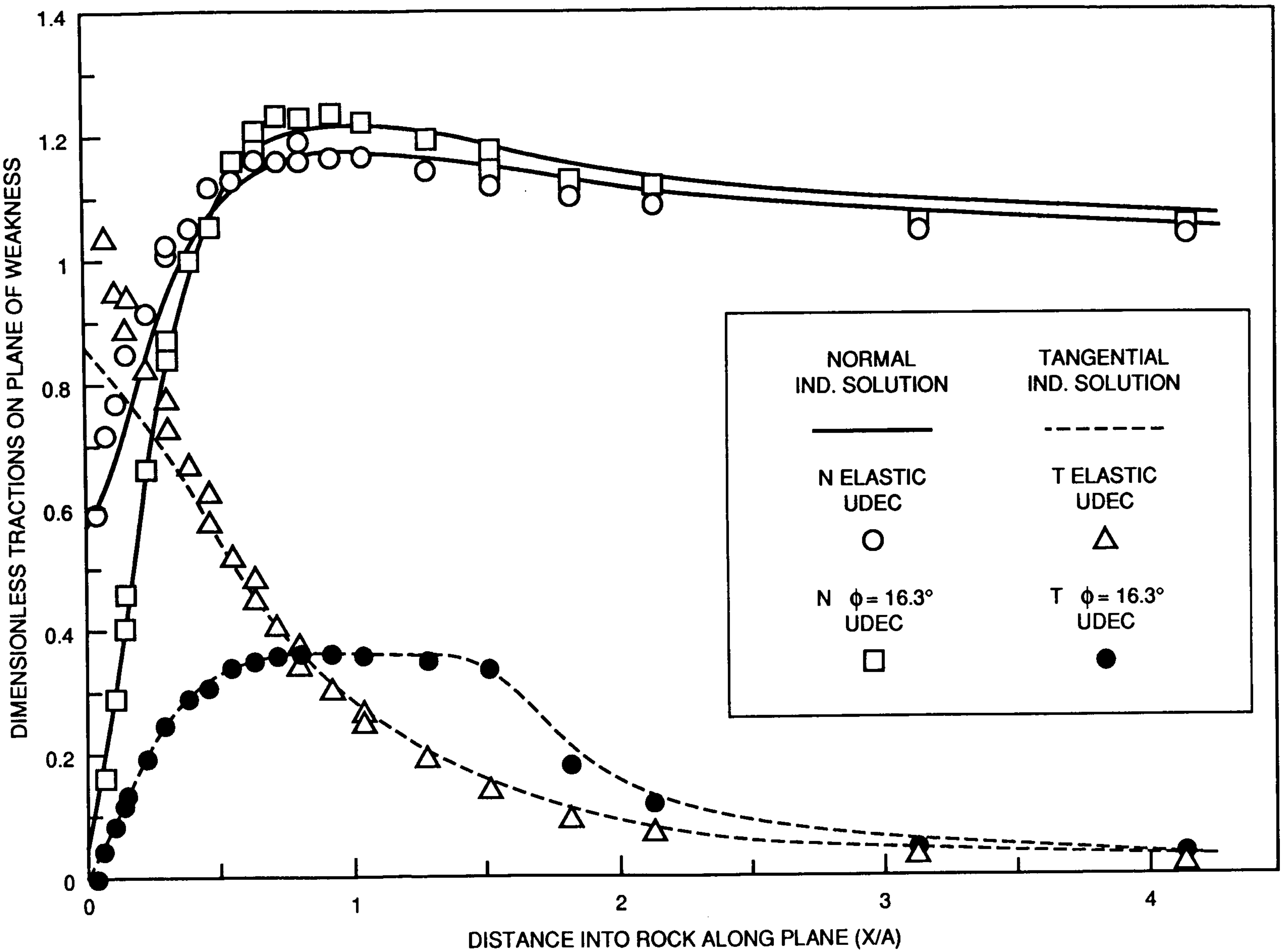

Figure 3.14 Plots of Normal and Shear Stress Distributions on Plane of Weakness, Before and Following Joint Slip

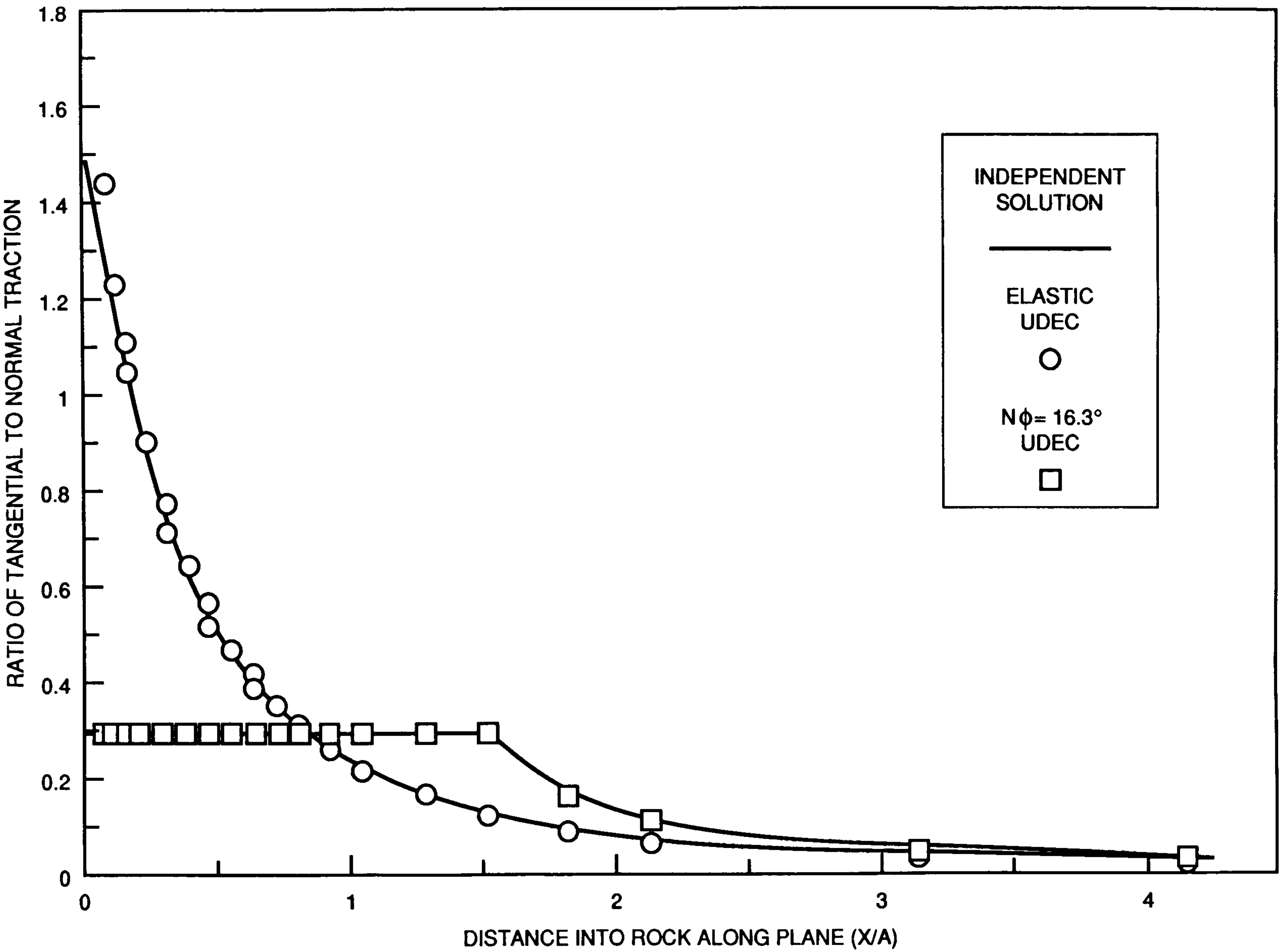

Figure 3.15 Plot of Shear/Normal Stress Ratio Along Joint Showing Effect of Joint Slip

where α is the angle measured from the radius perpendicular to the joint to the radius passing through the point of interest on the plane.

For the cohesionless joint, slip is possible on the plane of weakness when the ratio of τ/σ_n defined by Eq. 3.9 exceeds the coefficient of friction for the surface.

Numerical Model

The UDEC model for the problem is shown in Fig. 3.16. The cross-section is symmetrical about the y-axis. With the excavation of 5 m radius, the joint lying at y = 7 m is 2 m above the crown of the opening. The magnitude of the hydrostatic stress was 24 MPa.

Results

Elastic distributions of normal and shear stress on the plane of weakness, determined from the Kirsch solution and UDEC with the joint shear strength set high, are shown in Figs. 3.17 and 3.18. There is a reasonable correspondence between the stress distributions obtained from the various analyses. Although the distribution of shear stress obtained from the UDEC analysis (Continuously-Yielding joint model) is apparently different from the analytical solution, the difference is probably not significant, because the parameters for the joint model were chosen arbitrarily.

Slip on the plane of weakness is controlled by the τ/σ_n ratio, which is plotted in Fig. 3.19. From Eq. 3.9, the maximum value of the ratio is 0.445, corresponding to a mobilized angle of friction of 24°. Thus, for an angle of friction for the joint exceeding 24°, no slip will occur. Conversely, according to the elastic solution, an angle of friction less than 24° will permit joint slip and stress re-distribution. For the purposes of this study, an angle of friction of 22° was selected for the joint surface. The range of slip predicted from the elastic solution is denoted by the interval ab in Fig. 3.19. For the UDEC analysis (Mohr-Coulomb joint model), the indicated range of joint slip is the interval cd, which is fairly consistent with the elastic solution.

Assessments of the range over which slip may be inferred were also conducted with the Barton-Bandis and Continuously-Yielding joint models. The results are shown in Fig. 3.19. It is observed that the range of slip inferred from the Barton-Bandis joint model in UDEC is comparable with the elastic and Mohr-Coulomb solutions. Although the results from the analysis with the Continuously-Yielding joint model lack close consistency with the other results, this is probably not significant, reflecting the choice of parameters necessary to approximate the Mohr-Coulomb response.

3.8 DISCUSSION

The preceding sections examined the capacity of the UDEC code to simulate slip and separation on planes of weakness subject to the heterogeneous states of stress developed around excavations in stressed rock. Because the benchmark problems assume elastic-perfectly plastic joint deformation, only the Mohr-Coulomb joint model could be properly exercised against the analytical solutions. In general, analytical and numerical solutions to the benchmark problems corresponded, within an engineering tolerance. Any discrepancies between the different solutions usually occurred in the vicinity of the excavation, where stress and displacement gradients are relatively high, or could be ascribed to fairly coarse discretization of the problem domain. The conclusion is therefore that the UDEC code implementing the Mohr-Coulomb joint model is a valid simulator of the discontinuous performance of jointed rock, for the highly ideal joint behavior described by the elasto-plastic joint.

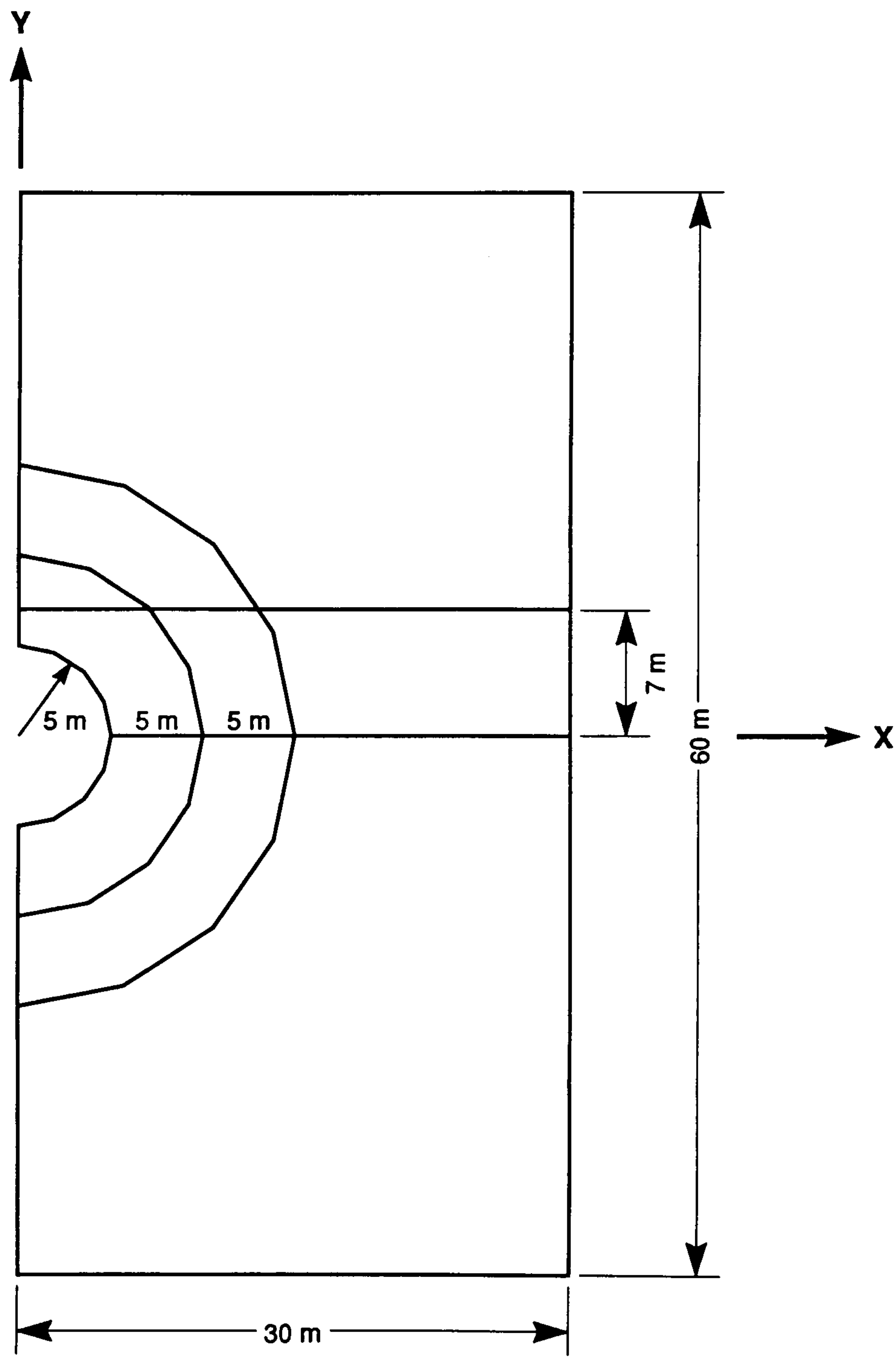

Figure 3.16 UDEC Model for Case 5

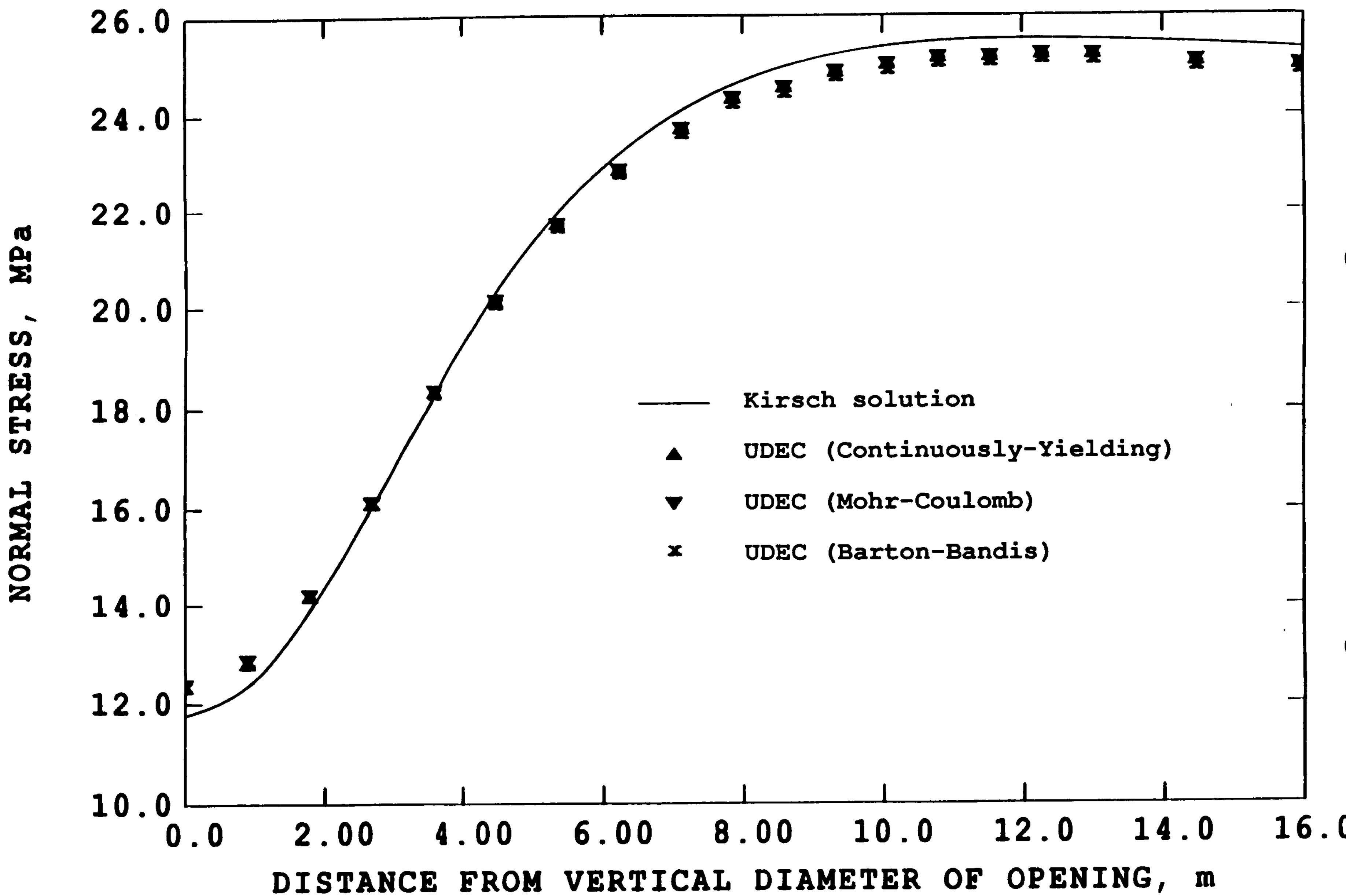

Figure 3.17 Normal Stress on Plane of Weakness, Case 5

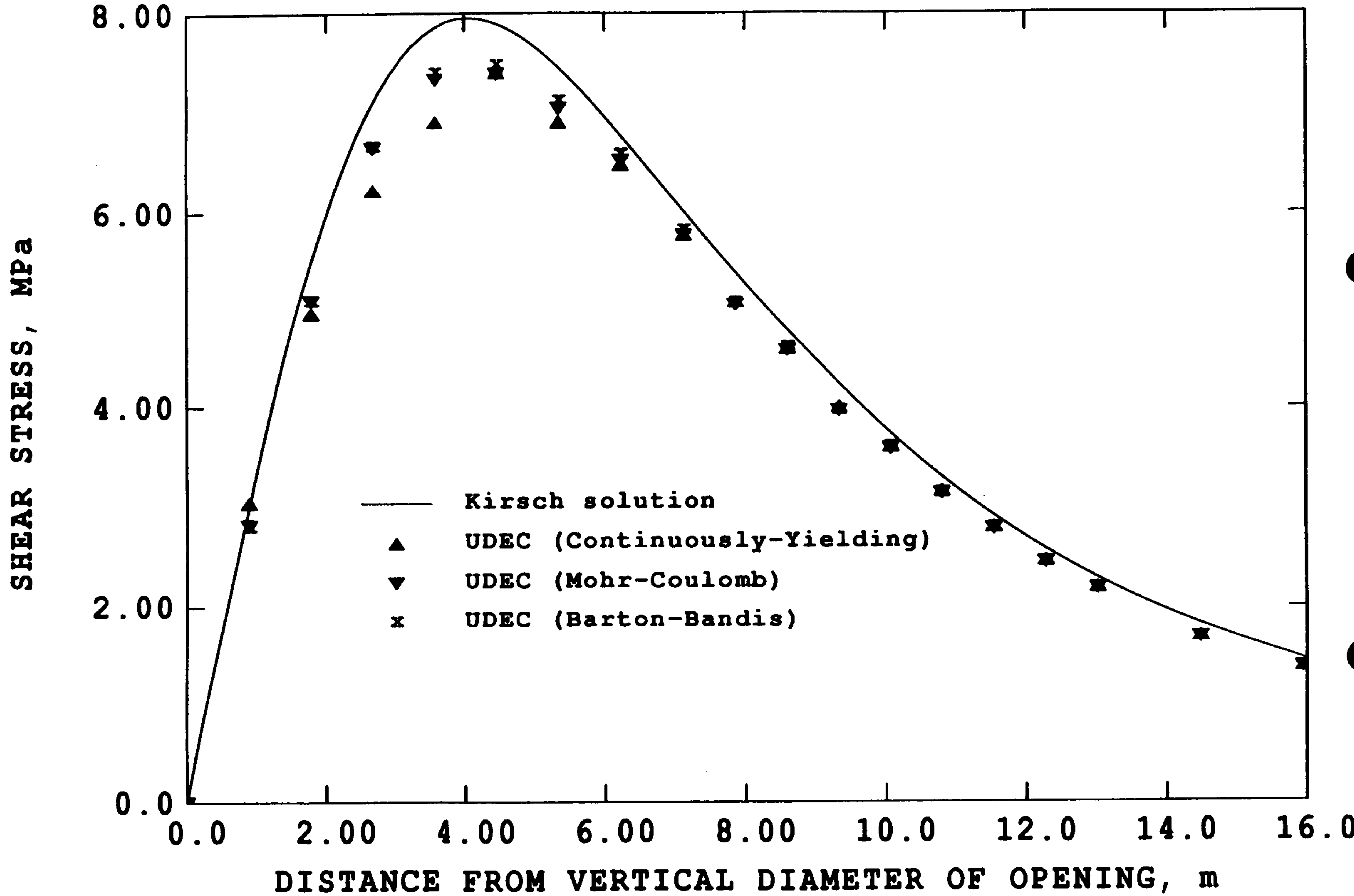

Figure 3.18 Shear Stress on Plane of Weakness, Case 5

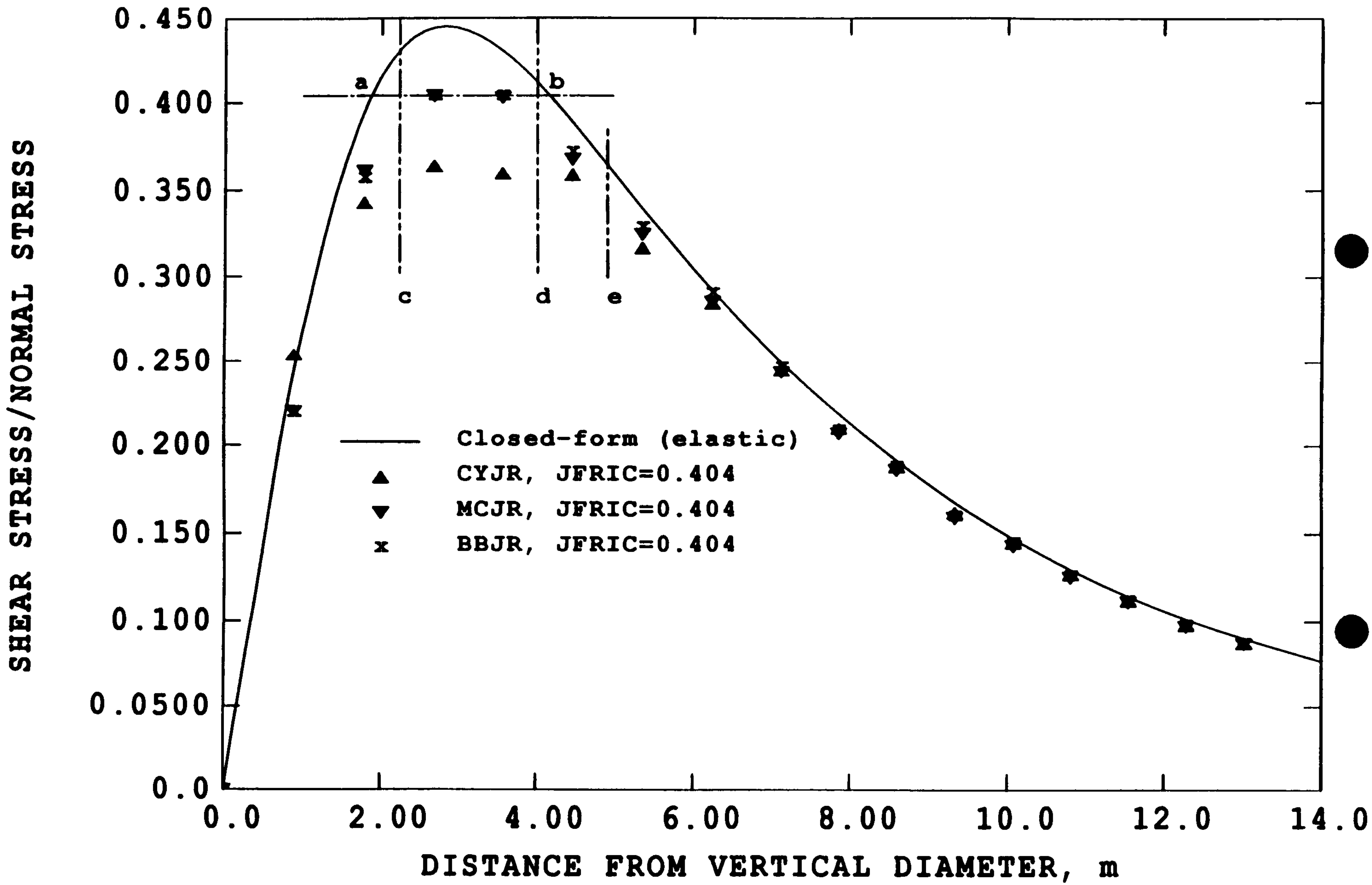

Figure 3.19 Stress Ratio on Plane of Weakness, Case 5

The Barton-Bandis and Continuously-Yielding joint models both simulate damage accumulation in a joint during shear displacement. Such behavior is not consistent with the elastic-perfectly plastic behavior represented in the benchmark problems, so that thorough evaluation of the implementation of these joint models in UDEC is impossible in this type of study. However, by suitable choice of joint model parameters, it is possible to suppress the modes of response which render the Barton-Bandis and Continuously-Yielding models appropriate simulators of real joints, and to approximate the Mohr-Coulomb joint model. When UDEC with these attenuated models was exercised against the benchmark problems, reasonable correspondence was observed between the numerical and analytical solutions. However, care needs to be exercised in evaluating the results of such studies. The results imply the models perform satisfactorily. It is not possible to conclude that one joint model is superior to another on the basis of these analyses, because calculated joint performance reflects the arbitrary and probably unrealistic choice of model parameters required to approximate Mohr-Coulomb joint behavior.

4. SLIP IN A JOINTED BODY INDUCED BY A HARMONIC SHEAR WAVE

4.1 PROBLEM STATEMENT

This problem concerns the dynamic behavior of a plane discontinuity when loaded by a plane harmonic shear wave. The problem, shown in Fig. 4.1, consists of a plane discontinuity, of limited shear strength τ_s, separating two homogeneous, isotropic, semi-infinite elastic bodies, and a normally incident, plane harmonic shear wave. If the transient shear stress induced by the shear wave exceeds the shear strength of the joint, slip will occur at the interface. As a result, energy is partitioned between reflected and transmitted waves and absorption at the interface. In an analysis of this problem by Miller (1978), closed-form solutions were derived for the transmission, reflection, and absorption coefficients.

4.2 PURPOSE

The purpose of this study is to evaluate the capacity of UDEC to model the dynamic performance of a discontinuity subject to loading by a harmonic shear wave. The evaluation involves determination of the transmission, reflection, and absorption coefficients from the numerical analysis and comparison with the closed-form solutions. The efficacy of non-reflecting boundaries implemented in UDEC may also be determined in these studies.

4.3 ANALYTICAL SOLUTION

Miller (1978) solved the wave propagation problem considering dissimilar media, 1 and 2, on opposite sides of the interface. Referring to Fig. 4.1, the incident wave is described by the expression:

$$u_i = U \sin\left(\frac{\omega x}{C_i} - \omega t\right) \tag{4.1}$$

where C_i = $(G_i/\rho_i)^{1/2}$ (i = 1,2) represents the wave velocity in medium i

U = amplitude

ω = frequency

Miller showed that the shear displacement at the interface may be described by:

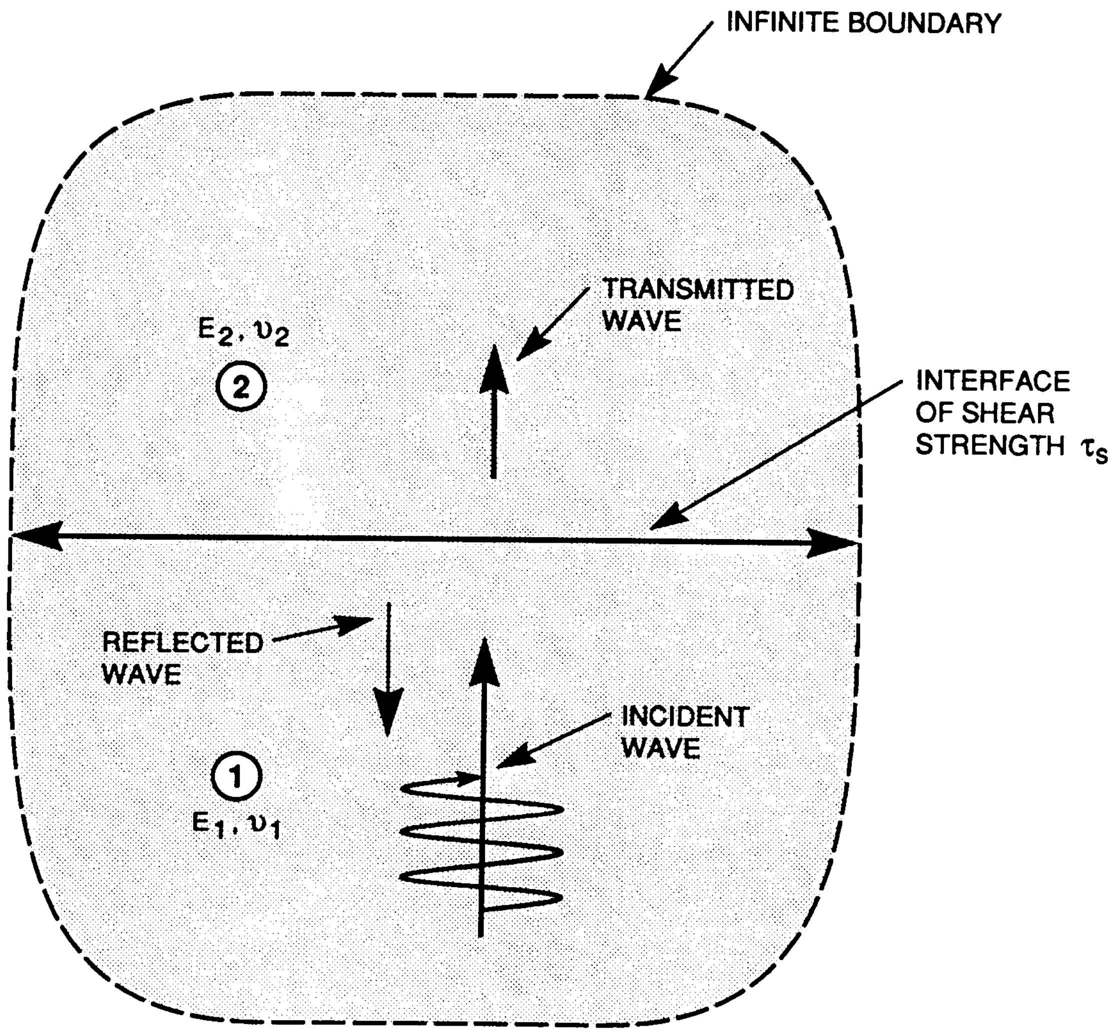

Figure 4.1 Problem Definition for Wave Propagation in a Jointed Continuum

$$d(t) = D\cos(\omega t - \phi) \tag{4.2}$$

where D = amplitude of joint shear

ϕ = phase shift occurring at the boundary

The solution for D is obtained from the expression:

$$C^2(D) + [\omega_1\gamma_1\gamma_2 D/(\gamma_1+\gamma_2) - S(D)]^2 = [2\omega U\gamma_1\gamma_2/(\gamma_1+\gamma_2)^2] \tag{4.3}$$

where
$$C(D) = \frac{1}{\pi}\int_0^{2\pi} \tau_s(D\cos\theta, -\omega D\sin\theta)\cos\theta\, d\theta$$
$$S(D) = \frac{1}{\pi}\int_0^{2\pi} \tau_s(D\cos\theta, -\omega D\sin\theta)\sin\theta\, d\theta$$
$$\gamma_i = (\rho_i G_i)^{1/2}$$

If τ_s is independent of displacement, as is assumed for a cohesive interface, considerable simplification of these expressions is possible.

After solving for D, the associated phase angle is given by:

$$\phi = \tan^{-1}\{[S(D) - \omega\gamma_1\gamma_2 D\ /\ (\gamma_1+\gamma_2)]\ /\ C(D)\} \tag{4.4}$$

Motion in the transmitted and reflected waves is defined by:

$$u_T(x,t) = TU\sin\left(\frac{\omega x}{C_2} - \omega t + \phi_T\right)$$
$$u_R(x,t) = RU\sin\left(\frac{\omega x}{C_1} + \omega t + \phi_R\right) \tag{4.5}$$

where T and R are the transmission and reflection coefficients

ϕ_T and ϕ_R (determined by ϕ) are phase shifts at the boundary.

By satisfying displacement conditions at the interface, it is found that:

$$T = \left\{[(D/U)\sin\phi - 2]^2 + (D/U^2)\cos^2\phi\right\}^{1/2}\gamma_1\ /\ (\gamma_1+\gamma_2) \tag{4.6}$$

$$R = \left\{(D/U)^2\cos^2\phi + [(D/U)\sin\phi + (\gamma_1+\gamma_2) - 1]^2\right\}^{1/2}\gamma_2\ /\ (\gamma_1+\gamma_2) \tag{4.7}$$

Equations 4.6 and 4.7 permit direct calculation of the transmission and reflection coefficients from the properties of the medium and the interface, and the wave characteristics.

An alternative interpretation of wave propagation coefficients T and R is in terms of the energy flux in the transmitted and reflected waves. If E_I, E_R and E_T are the energy fluxes per unit area per cycle of oscillation for the incident, transmitted and reflected waves respectively, it may be shown that:

$$T = (\gamma_1 / \gamma_2)^{1/2} (E_T / E_I)^{1/2} \tag{4.8}$$

$$R = (E_R / E_I)^{1/2} \tag{4.9}$$

Further, energy is absorbed at the boundary by the dissipative nature of joint slip. An absorption coefficient is defined by:

$$A = [1 - R^2 - (\gamma_2 / \gamma_1) T^2]^{1/2} \tag{4.10}$$

In the assessment of UDEC performance in modeling of joint slip, a technique is required to determine energy fluxes in the incident, transmitted and reflected waves. For the plane incident wave, the energy flux, E_I, per unit area and per unit cycle oscillation is given by Kolsky (1963):

$$E_I = \rho\, C \int_{t_1}^{t_1+T} v_I^2 \, dt \tag{4.11}$$

where $v_I(t)$ = the particle velocity in the incident wave

T = period of ground motion

= $2\,\pi/\omega$

Similar experessions apply to fluxes in the transmitted and reflected waves. The various fluxes may be determined in a UDEC analysis by numerical integration of the plots of v^2 versus time. From these fluxes, Eqs. 4.8, 4.9, and 4.10 may be used to calculate the transmission, reflection, and absorption coefficients. They may be compared with the coefficients calculated from the analytical solutions.

4.4 UDEC ANALYSIS

Numerical Model

Figure 4.2 shows the problem geometry modeled with UDEC. The plane of discontinuity EF was simulated with high normal stiffness and high shear stiffness, but limited cohesion. The continuous media were modeled with elastic, fully deformable blocks which were further discretized into triangular finite-difference zones. In specifying the boundary conditions, viscous boundaries were applied at the model boundaries CD and GH, and the two vertical boundaries CG and DH were constrained to move in the horizontal direction. A sinusoidal wave was applied at the boundary CD, the base of the model. The applied maximum stress and frequency of the incident wave were 1.0 MPa and 1 Hz respectively.

Material Properties of Continuous Media and Discontinuity

(a) Medium properties

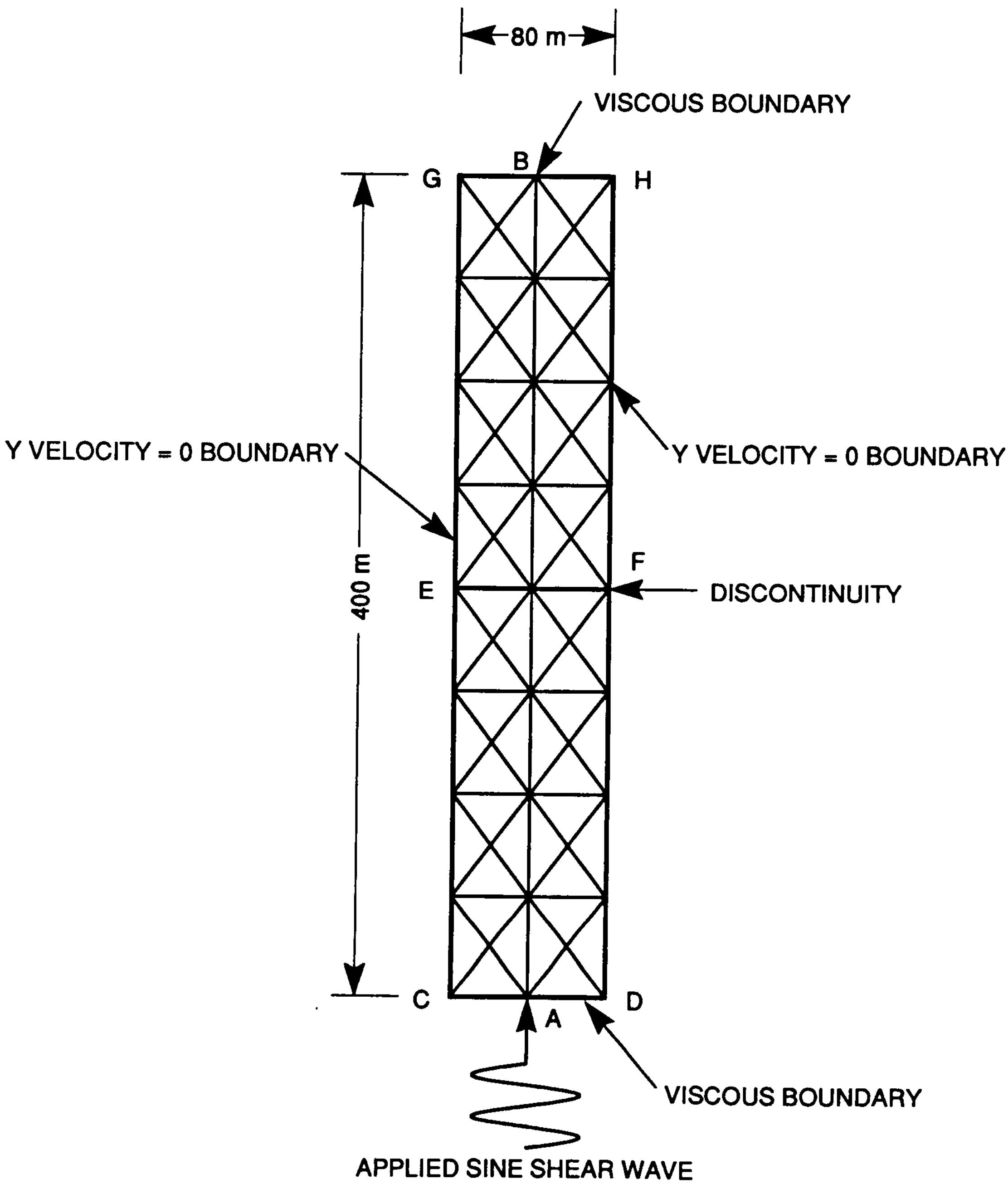

Figure 4.2 UDEC Model for the Study of Slip Induced by a Propagating Harmonic Shear Wave

Mass density (ρ) = 2.650 kg/m^3
Shear modulus (G) = 10 GPa
Bulk modulus (K) = 60 GPa

These correspond to a solid with Young's Modulus of 28.42 MPa, and Poisson's Ratio of 0.42.

(b) Discontinuity properties

The problem solved by Miller assumes joint shear is characterized by a limiting shear resistance, τ_s.

In the current work, it is assumed that the coefficient of friction is zero and the shear resistance is cohesive. The implicit assumption is that the joint is elastic-perfectly plastic in shear. In UDEC, the only joint model which is absolutely compatible with this mode of joint shear is the Mohr-Coulomb joint. Therefore, the main basis for comparison of UDEC performance with the analytical solution is from the results using the Mohr-Coulomb joint model. In the current work, for yielding joints, the joint cohesion has been taken in the range 0.02 MPa - 0.8333 MPa.

Neither the Continuously-Yielding nor the Barton-Bandis joint model is compatible with the interface deformation properties exploited in the Miller analysis. However, suitable choice of parameters for these models permits approximation of the frictional component of shear strength of a Mohr-Coulomb joint. To represent the cohesive, frictionless joint invoked in the Miller analysis, a constant normal stress, σ_n, may be maintained on a frictional joint. The limiting frictional shear resistance ($\sigma_n \tan \phi$) then may be set equivalent to the limiting joint cohesion. For example, by setting the coefficient of friction to 0.5, and the normal stress to 1 MPa, the limiting shear strength of the joint is 0.5 MPa.

The UDEC parameters applied in the various joint models were as follows:

(i) Mohr-Coulomb Joint (JCONS=2)
JKN = 10 GPa/m
JKS = 10 GPa/m
JFRIC = 0
JCOH = 0.5 MPa

(ii) Continuously-Yielding Joint (JCONS=3)

JKN = 200 GPa/m
JKS = 200 GPa/m
JEN = 0
JES = 0
JIF = 0.463 6476 rad.
JR = 1e-10
JFRIC = 0.5
JTENS = 1 MPa

(iiI) Barton-Bandis Joint (JCONS=7)

JKN = 200 GPa/m
JKS = 200 GPa/m
JRC = 1
JCS = 100

LO = 10000 m
PHIR = 26.565
APER = 0.05 mm

4.5 RESULTS

The performance of UDEC has been assessed in terms of elastic transmission of a wave across the interface, and by comparison of the various acoustic coefficients calculated from UDEC with those determined from the closed-form solution.

For each of the joint models, some initial calculations were executed in which the joint shear strength was set higher than the peak shear stress in the elastic wave. In the current analysis, the peak applied shear stress was 1 MPa. In Fig. 4.3, the time history of shear stress is shown at points on opposite sides of the discontinuity. The identical wave traces, of peak amplitude 1 MPa and separated by a time increment equivalent to the wave transmission time between the reference points indicated in Fig. 4.2, confirms that the joint transmits the elastic wave perfectly. Similar results were obtained for each of the three joint models.

The capacity of UDEC and the Mohr-Coulomb joint to model slip under dynamic conditions is indicated in Fig. 4.4. When the joint cohesion is 0.5 MPa, the shear wave transmitted across the interface has that peak amplitude of shear stress. This is confirmed in Fig. 4.4, where the transmitted wave is equivalent to the incident waveform clipped to a magnitude of 0.5 MPa. It is noted further that the time history for the point at the base of the model is the result of superposition of the incident wave and the reflected wave.

Comparison of the acoustic coefficients for the wave propagation is conducted in terms of the dimensionless stress, τ_d, of the incident wave, defined by:

$$\tau_d = \omega \gamma U / \tau_s \tag{4.12}$$

From Eq. 4.12, it is seen that the dimensionless stress can be adjusted by introducing different values of joint cohesion, τ_s; the values of τ_s used were 0.8333, 0.6662, 0.5, 0.1, and 0.2 MPa.

In the calculation of the energy flux, E_I, for the incident wave, the time history of the x-component of the velocity at the base of the model, for an elastic joint, was used as the argument in a numerical integration scheme. For the various values of joint cohesion, the energy flux in the transmitted wave, E_T, was calculated from the x-component of velocity at the reference point at the top of the model. The energy flux in the reflected wave, E_R, was determined by calculating the x-component of velocity in the reflected wave from the difference between the velocity components for the elastic problem and the case when the interface was subject to slip. The wave propagation coefficients (T, R and A) could then be calculated directly from Eqs. 4.8, 4.9, and 4.10.

Figure 4.5 provides a comparison of the acoustic coefficients, determined from the UDEC analysis with the Mohr-Coulomb joint and from the closed-form solution, for the various values of the dimensionless stress. Good correspondence is observed between the numerical and analytical solutions, over the range of dimensionless stresses. For purposes of completeness, the acoustic coefficients are also presented in Table 4.1.

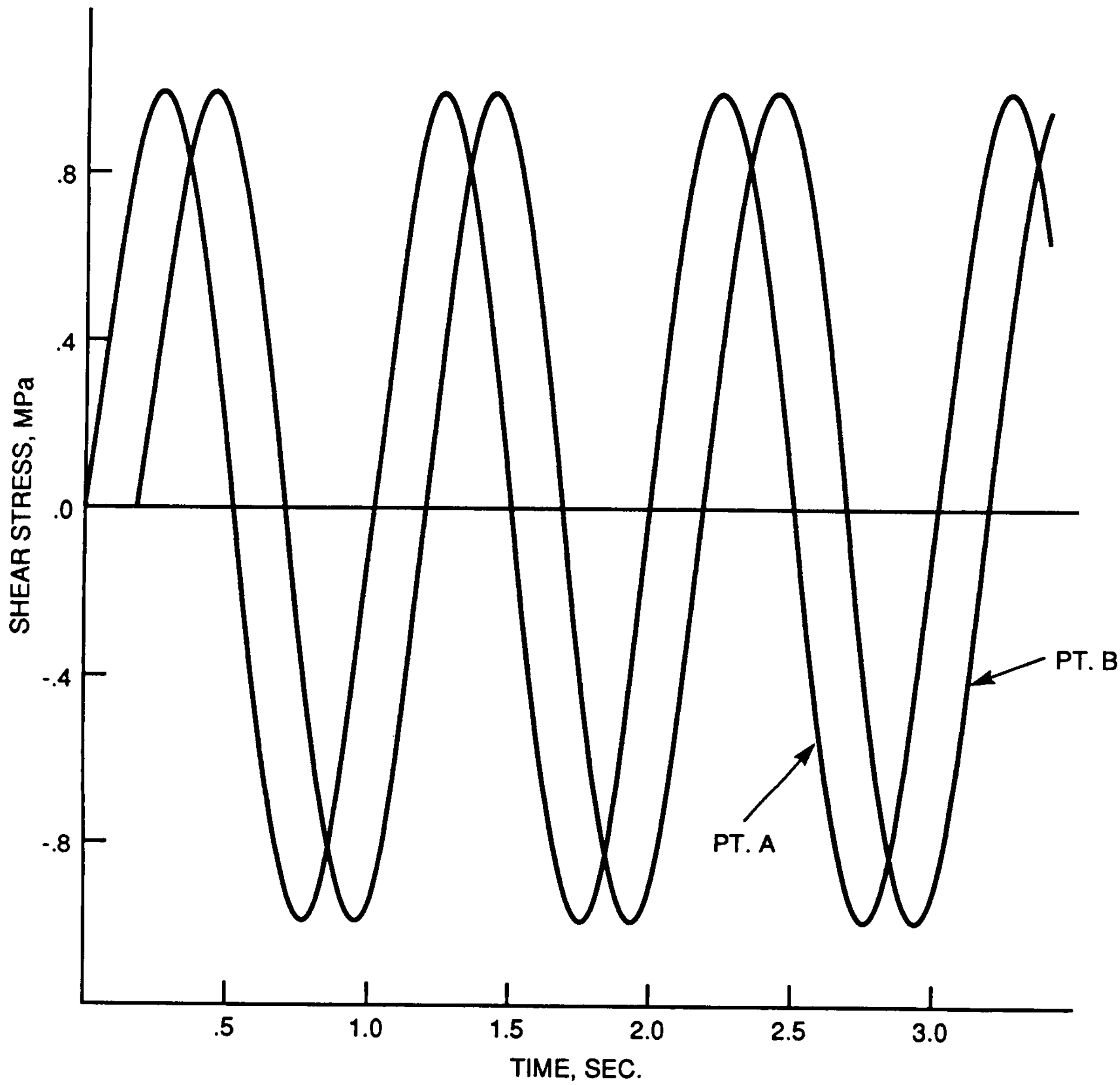

Figure 4.3 Time History of Shear Stress at Points A (-160,-200) and B (-160,200) for the Case of Elastic Discontinuum

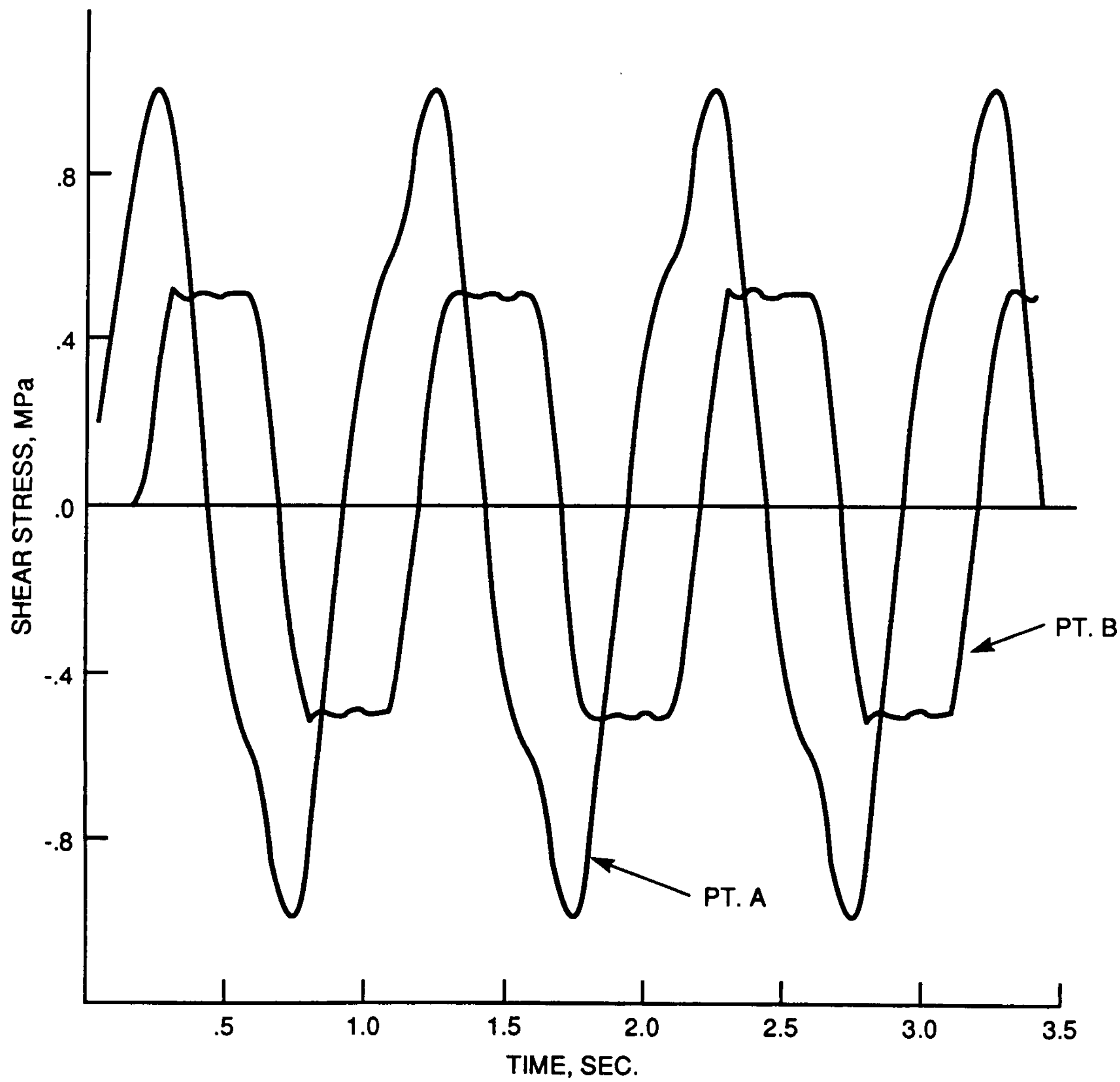

Figure 4.4 Time History of Shear Stress at Points A and B for the Case of Slipping Discontinuity (Cohesion = 0.50 MPa)

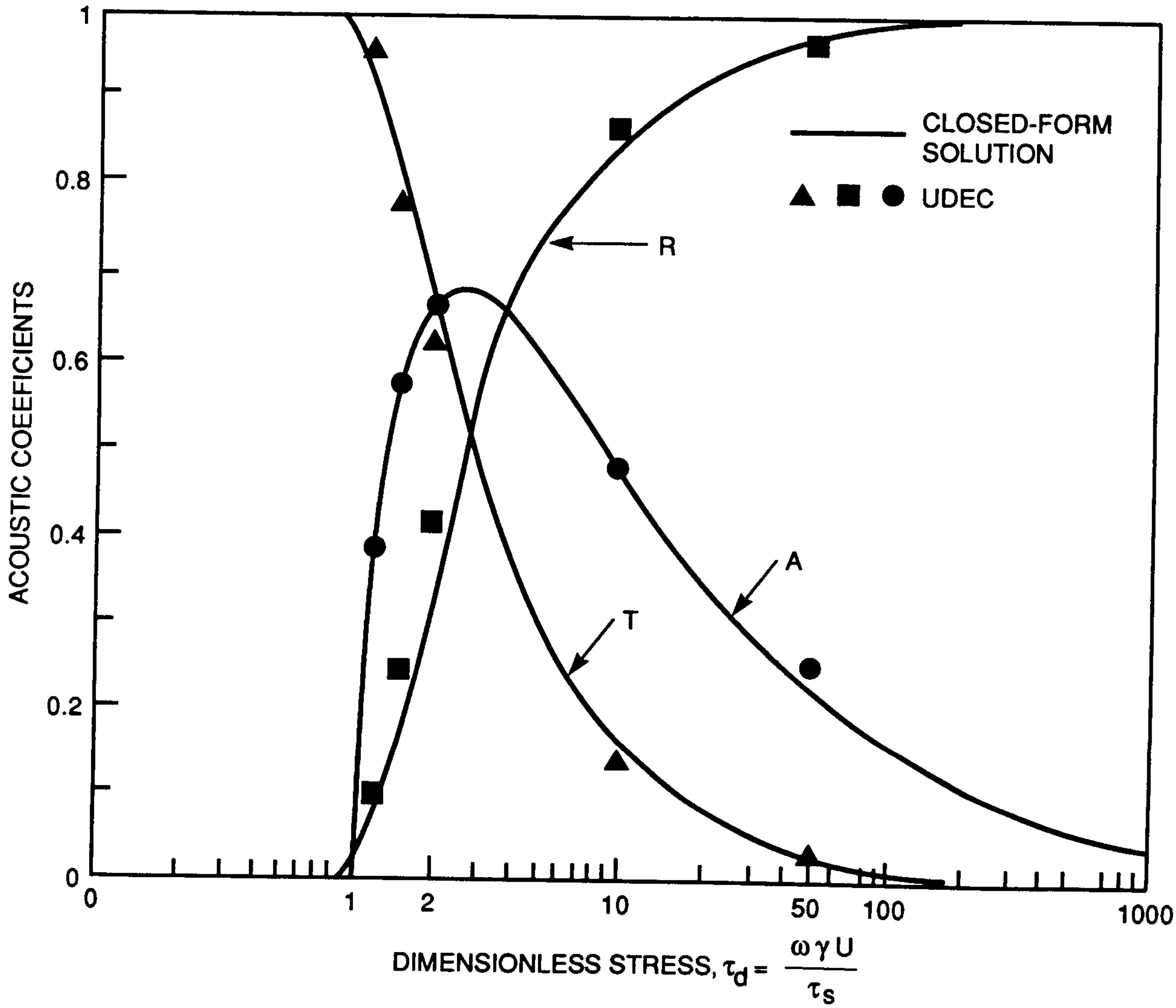

Figure 4.5 Comparison of Transmission, Reflection, and Absorption Coefficients from Closed-Form Solution and UDEC Analysis (Mohr-Coulomb Joint)

Table 4.1 Coefficients of Reflection, Transmission, and Absorption Determined with UDEC (with Mohr-Coulomb Joint) at Various Dimensionless Stresses

Dimensionless Stress	Coefficient		
	Reflection (R)	Transmission (T)	Absorption (A)
1.2	0.1034	0.9171	0.3850
1.5	0.2470	0.7847	0.5685
2	0.4125	0.6201	0.6673
10	0.8691	0.1366	0.4755
50	0.9672	0.0280	0.2526

Wave propagation coefficients were also determined at a dimensionless stress of 2 from the UDEC analysis incorporating the Continuously-Yielding joint and the Barton-Bandis joint. A comparison of the coefficients is presented in Table 4.2. It is observed that there is no substantial difference between the coefficients calculated from the different joint models.

Table 4.2 Coefficients of Reflection, Transmission, and Absorption Determined with UDEC for Various Joint Models (Dimensionless Stress=2)

	Coefficient		
Joint Model	Reflection (R)	Transmission (T)	Absorption (A)
Mohr-Coulomb	0.41	0.62	0.68
Continuously-Yielding	0.43	0.60	0.68
Barton-Bandis	0.41	0.61	0.69

4.6 DISCUSSION

Modeling of a slip-prone joint under harmonic shear loading confirmed four aspects of the performance of UDEC for dynamic analysis. First, it showed that each of the three joint models provided perfect elastic transmission of waves across a joint at stress levels in the wave less than the joint shear strength. Second, comparison of wave transmission, reflection, and absorption coefficients from the numerical analysis with closed-form solutions provided close correspondence between the independent solutions, over a wide range of dimensionless stress for joint dynamic loading. This indicated that the Mohr-Coulomb joint model in UDEC is a valid simulation of dynamic joint deformation in the idealized formulation of elastic-perfectly plastic joint response assumed in the formal analysis. Third, by constraining the Continuously-Yielding and Barton-Bandis joint models to approximate a Mohr-Coulomb joint, it was demonstrated that UDEC analysis based on these joints produced wave propagation coefficients consistent with the closed-form solutions. This result implies that the Continuously-Yielding and Barton-Bandis joint models may simulate dynamic loading of joints adequately in an analytical sense. However, it does not confirm that they are valid models of real joint behavior under dynamic conditions. Finally, the correspondence between analytical and numerical solutions for wave propagation coefficients calculated near the problem boundaries implies that the non-reflecting boundaries used in UDEC perform satisfactorily.

5. LINE SOURCE IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY

5.1 PROBLEM STATEMENT

This problem concerns the dynamic behavior of a single discontinuity under explosive loading. The problem shown in Fig. 5.1 consists of a planar crack of infinite lateral extent in an elastic medium and a dynamic load at some distance, h, from the discontinuity. The closed-form solution to this problem was derived by Day (1985) as a special symmetric condition for the general problem of slip of an interface due to a dynamic point source (Salvado and Minster, 1980). The results from numerical and analytical solutions are compared and discussed.

5.2 PURPOSE

The purpose in analysis of this problem is to test the following functions of UDEC:

(a) the ability to model dynamic performance of a jointed rock mass under impulsive loading;

(b) the ability to simulate a high frequency dynamic wave emanating from a buried explosion; and

(c) the ability to simulate non-reflecting boundary conditions.

5.3 ANALYTICAL SOLUTION

The closed-form solution for crack slip as a function of time was derived by Day (1985) and is given by:

$$\delta u(x,t) = \frac{2\, m_o\, \beta^2}{\pi\, \rho\, \alpha^2} \operatorname{Re}\left[\frac{p\, \eta_\alpha\, \eta_\beta}{R(p)}\right]\left[\tau + \frac{2r}{\alpha}\right]^{-1/2} \tau^{-1/2} H(\tau) \tag{5.1}$$

where r = $(x^2 + h^2)^{1/2}$, distance from the point source to the point on the crack where the slip is monitored,

$H(\tau)$ = step function,

τ = $t - (r/\alpha)$

m_o = source strength,

α = velocity of pressure wave,

β = velocity of shear wave,

ρ = density, and

η_α = $(\alpha^{-2} - p^2)^{1/2}$, $\operatorname{Re} \eta_\alpha \geq 0$

η_β = $(\beta^{-2} - p^2)^{1/2}$, $\operatorname{Re} \eta_\beta \geq 0$

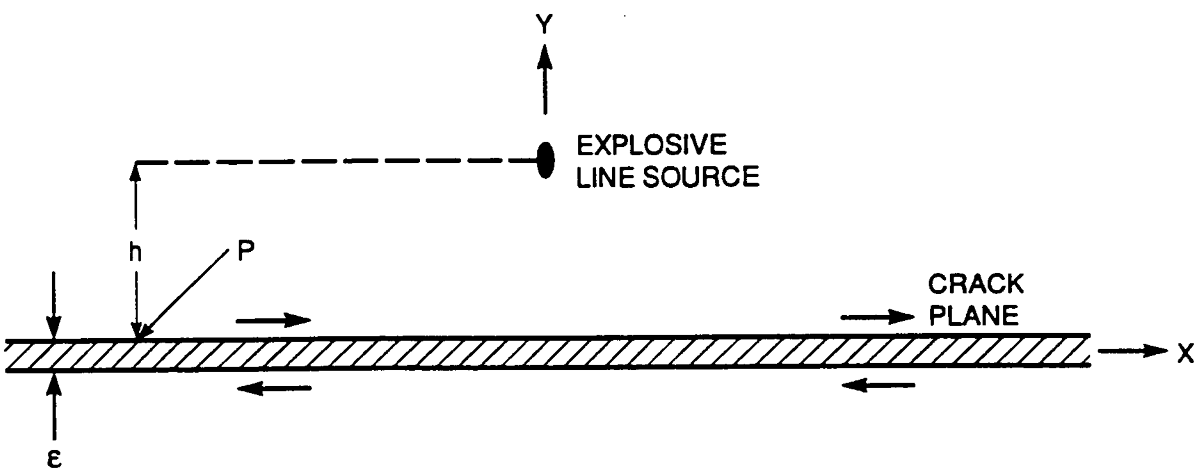

Figure 5.1 Problem Geometry for an Explosive Source Near a Slip-Prone Discontinuity

$$R(p) = (1 - 2\beta^2 p^2)^2 + 4\beta^4 \eta_\alpha \eta_\beta p^2 + 2\beta\eta_\beta \gamma$$

$$p = \frac{1}{r^2}\left[\left(\tau + \frac{r}{\alpha}\right) x + i \left(\tau + 2\frac{r}{\alpha}\right)^{1/2} \tau^{1/2} h\right]$$

The slip response of the discontinuity for any source history S(t) can be obtained by convolution of Eq. 5.1 and the source function S(t). Fig. 5.2 shows the dimensionless analytical results of slip history at a point P for a smooth step function:

$$S(t) = \left[\begin{array}{ll} 0.5\,(1 - \cos(\pi t/0.6)) & t < 0.6 \\ 1.0 & t \geq 0.6 \end{array} \right. \qquad (5.2)$$

and for the following values of the variables:

$\alpha^2 = 3\beta^2$

$h = x$

$\gamma = 0$

5.4 UDEC ANALYSIS

Model Set-up

Fig. 5.3 shows the problem geometry modeled by UDEC. The source is located at the origin of the coordinate axes and the discontinuity is located at y = -h. The y-axis is a line of symmetry and non-reflecting boundaries were used on the other three sides of the model. The dynamic input was applied at the semi-circular boundary of radius 0.05h. The slip movement is monitored at point P on the discontinuity.

The continuous medium was modeled with elastic, fully deformable blocks, as shown in Fig. 5.4, and each block was further discretized into triangular finite-difference zones. All the joints except for the discontinuity are "glued," i.e., assigned high cohesion, and have high normal and shear stiffness in order to model a continuous elastic medium. The discontinuity was assigned zero shear strength, a high normal stiffness, and high tensile strength in order to meet the assumptions implied in the analytical solution.

Properties of Joints and Continuous Medium

A. Material Properties

The following material properties were used in these analyses:

	Values	Typical Units
Geometric Scale:	h = 10	(m)
Block Properties:		
Mass density (ρ)	= 1	(kg/m^3)
Shear modulus (G)	= 100	(Pa)

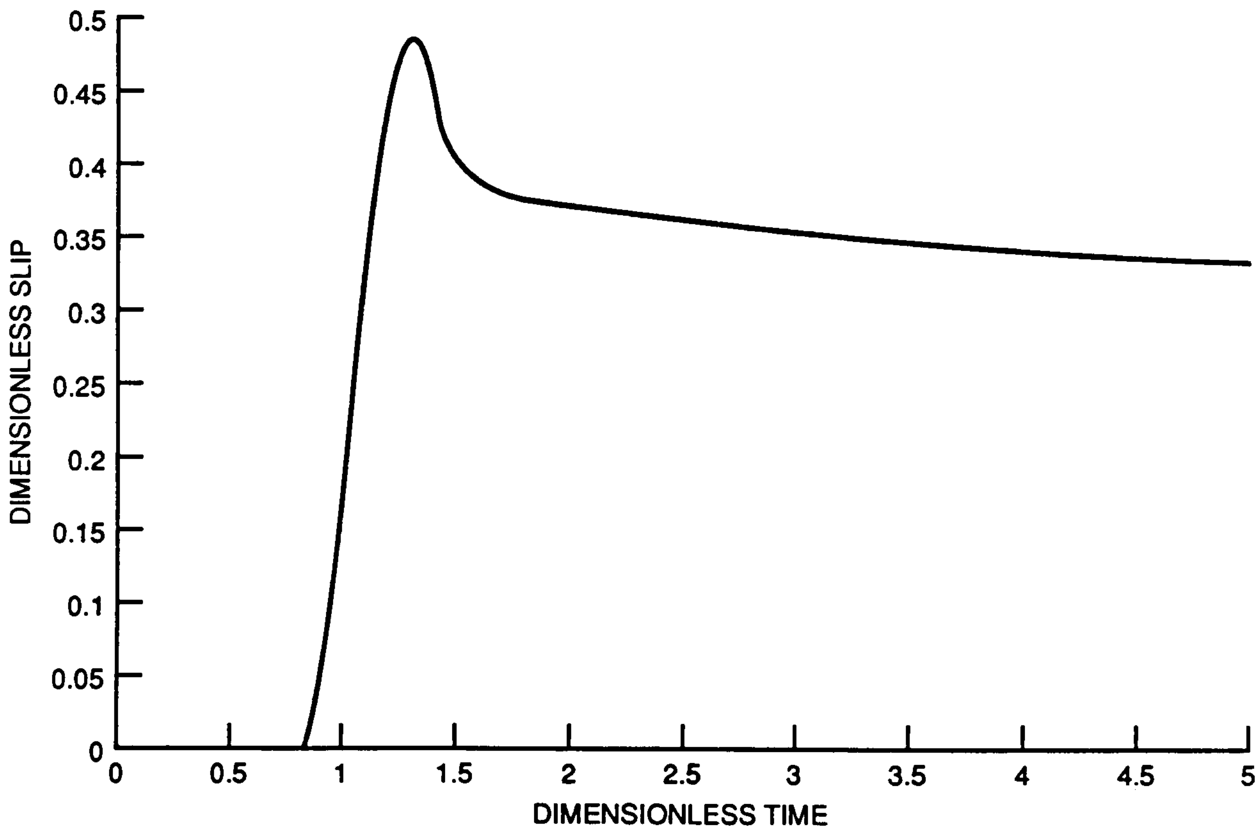

Figure 5.2 Dimensionless Analytical Results for Slip History at Point P (from Day, 1985), Dimensionless Slip = $(4h\rho\beta^2/m_o)\delta u$, Dimensionless time = $t\beta/h$

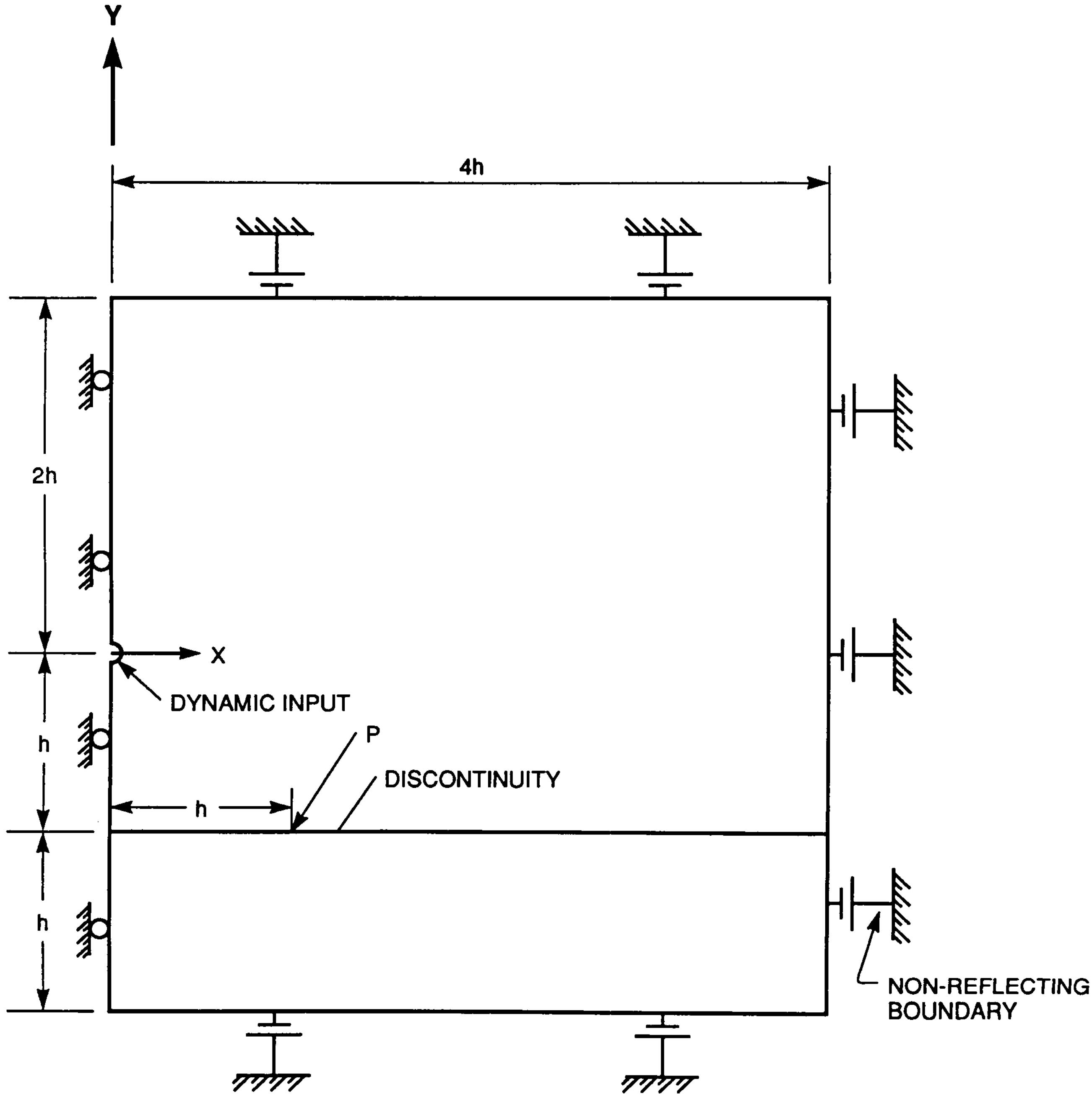

Figure 5.3 Problem Geometry and Boundary Conditions for Numerical Model

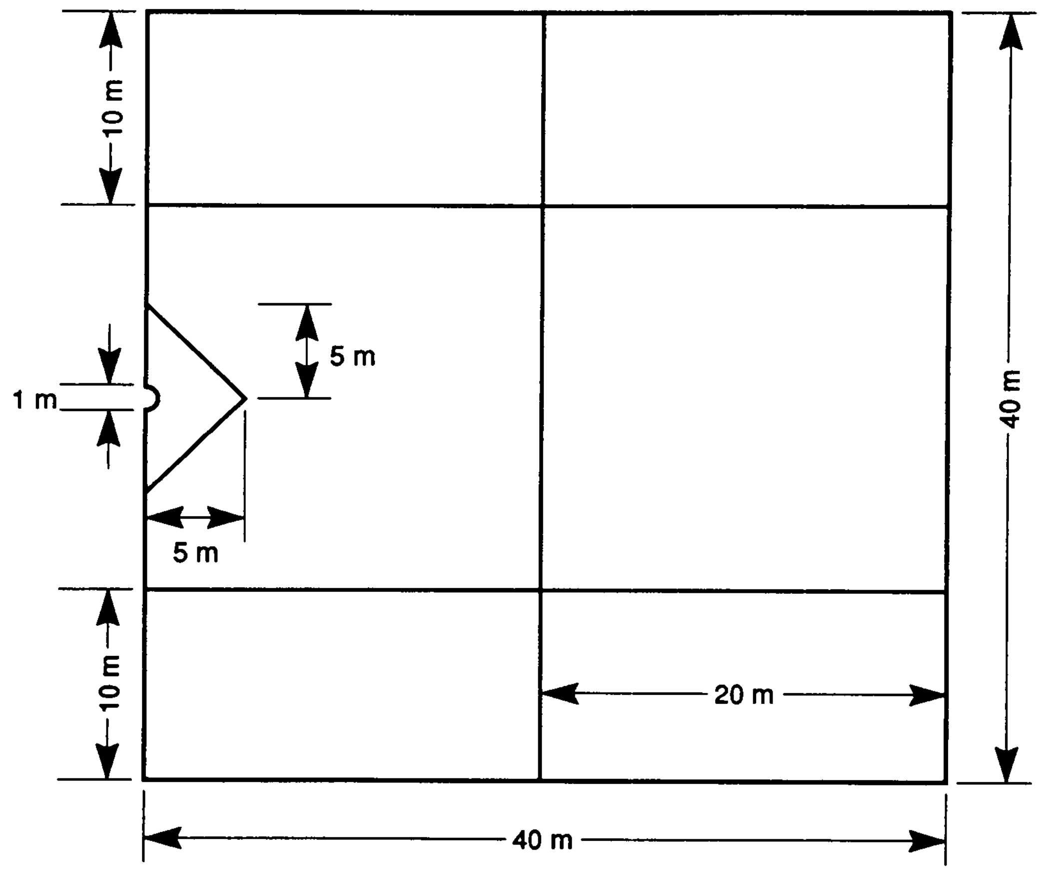

Figure 5.4 UDEC Model Showing Semi-Circular Source and "Glued" Joints Used to Provide Appropriate Zoned Discretization

Bulk modulus (K)	= 166.67	(Pa)
P-wave velocity (α)	= 17.32	(m/sec)
S-wave velocity (β)	= 10.00	(m/sec)

B. Joint Properties:

The following models of joint deformation were used:

(i) Mohr-Coulomb model

(ii) Continuously-Yielding model

(iii) Barton-Bandis model

The specific UDEC parameters used for each joint model are as follows:

(i) Mohr-Coulomb model (JCONS=2)

JKN = 10 kPa/m
JKS = 0.1 Pa/m
JFRIC = 0

(ii) Continuously-Yielding model (JCONS=3)

JKN = 10 kPa/m
JKS = 0.1 Pa/m
JFRIC = 0.00001
JEN = 0
JES = 0
JIF = 1.0e-10 (rad)
JR = 1.0e-4 m

(iii) Barton-Bandis model (JCONS=7)

JKN = 10 kPa/m
JKS = 10 kPa/m
JRC = 0.0001 MPa
JCS = 100 MPa
LO = 100 m
LN = 1 m
PHIR = 0.0001 degree
APER = 0.05 mm

Dynamic Loading

Two kinds of dynamic input load were applied at the source: (1) pressure input and (2) velocity input. To avoid problems with the singularity at the source, both the inputs were applied over a surface distant 0.05h from the nominal point source.

A. Pressure Input

The radial pressure applied on the semi-circular boundary was calculated from the static solution in an infinite medium, due to Love (1946). The radial stress at a distance r from a compressive line source is given by:

$$\sigma_{rr} = \frac{1}{2\pi} \frac{2G}{\lambda + 2G} \frac{1}{r^2} m_o \tag{5.3}$$

where $\lambda = \dfrac{2\upsilon G}{1 - 2\upsilon}$

and υ = Poisson's ratio

For the properties used in this problem, the stress component σ_{rr} at distance r = 0.05h (h=10m) is 0.4244 Pa. The time history of the applied pressure is given by Eq. 5.2 and is shown in Fig. 5.5.

B. Velocity Input

Radial velocities corresponding to the dynamic solution for a line source in an infinite medium were enforced at the semi-circular boundary. The velocities were calculated in the following manner.

The solution for the displacement due to a center of dilation in an infinite medium, due to Achenbach (1973), is described by the expression:

$$u_i = \frac{1}{4\pi C_p^2} \frac{\partial}{\partial x_i} \left[\frac{1}{r} f(t - r/C_p) \right] \tag{5.4}$$

where $r^2 = x^2 + y^2 + z^2$

C_p = P-wave velocity

$f(t)$ = source time history

Integration of Eq. 5.4 along the z-axis leads to the solution for a line source of compression (Lemos, 1987) when f(t) is taken as a step function:

$$f(t) = \begin{bmatrix} 0, & t < 0 \\ 1, & t \geq 0 \end{bmatrix} \tag{5.5}$$

The two-dimensional solution for radial displacement becomes:

$$u = -\frac{1}{2\pi C_p} \frac{t}{r^2} \left[\frac{t^2 C_p^2}{r^2} - 1 \right]^{-1/2}, \quad t > r/C_p \tag{5.6}$$

where $r^2 = x^2 + y^2$

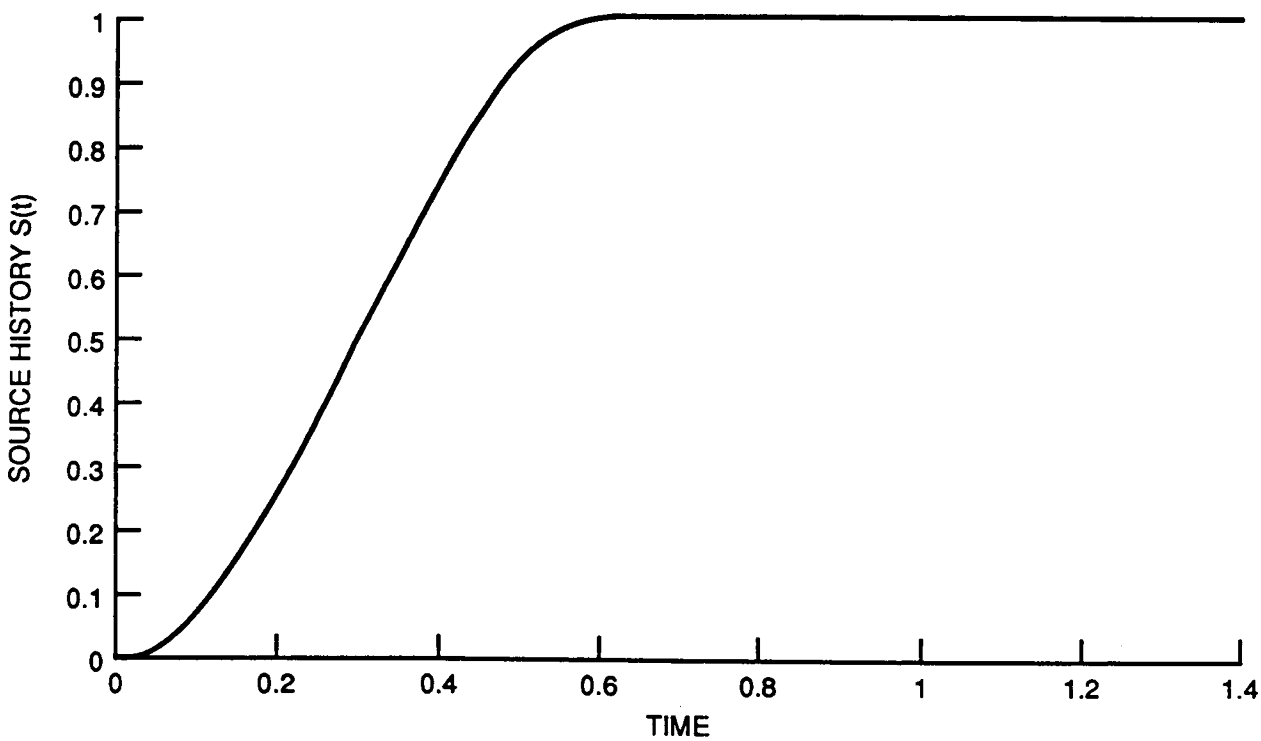

Figure 5.5 Input Radial Pressure Time History at r = 0.05 h

The corresponding velocity is:

$$v = -\frac{1}{2\pi C_p}\frac{1}{r^2}\left[\frac{t^2C_p^2}{r^2} - 1\right]^{-3/2}, \quad t > r/C_p \tag{5.7}$$

The actual input velocity record at r = 0.05h as shown in Fig. 5.6 was obtained by convoluting Eqs. 5.1, 5.7, and 5.2.

5.5 RESULTS

Four factors are considered in assessing the results of the analysis: dynamic input, mesh size, joint model, and boundary conditions.

A. Dynamic Input

The dimensionless slip at point P vs dimensionless time for the Mohr-Coulomb model is shown in Fig. 5.7. This compares the results from UDEC for velocity input and pressure input with the analytical solution. The velocity input gives a better match with the analytical solution than the pressure input. The error at the peak slip for velocity input is 5.21% and that of pressure input is 9.81%. This suggests that the velocity boundary provides an accurate representation of the dynamic stress at r = 0.05h compared to the pressure input. The reason for this is that in the pressure input, the source function is simply scaled by static stress magnitude and neglects the inertial effects of dynamic stress at the input boundary.

B. Mesh Size

The results shown in Fig. 5.7 were obtained with a mesh of maximum zone length of 0.065h. The slip response on the discontinuity involves higher frequency components because of zero friction along the discontinuity and this requires finer mesh for accurate representation. It has been shown by Lemos (1987) that if the maximum zone length is 0.033h then the UDEC solution due to velocity input is within 1% of the analytical solution and the pressure input is within 2.5%. These results suggest a requirement of 35 zones within the distance of the dominant wavelength of the input wave in order to provide good accuracy.

C. Joint Model

Figure 5.7 shows the results of joint slip based on the Mohr-Coulomb joint model. The Mohr-Coulomb joint model is a linear elastic, perfectly-plastic formulation of joint deformation. The Continuously-Yielding and the Barton-Bandis joint models are both non-linear formulations of joint deformation. Figures 5.8 and 5.9 compare joint slip as a function of time for the Mohr-Coulomb, Continuously-Yielding and Barton-Bandis joint models for velocity input and pressure input, respectively.

It is observed that for the particular joint parameters chosen for the Continuously-Yielding and Barton-Bandis models, the slip response is virtually identical to that of the Mohr-Coulomb model for both pressure and velocity input.

D. Boundary Conditions

As seen in Fig. 5.3, non-reflecting boundaries are used along the top, bottom and right boundaries. A line of symmetry boundary condition is used on the left boundary. The viscous boundaries, designed to absorb normally incident P- and S-waves, cannot be fully effective in this dynamic slip problem because the

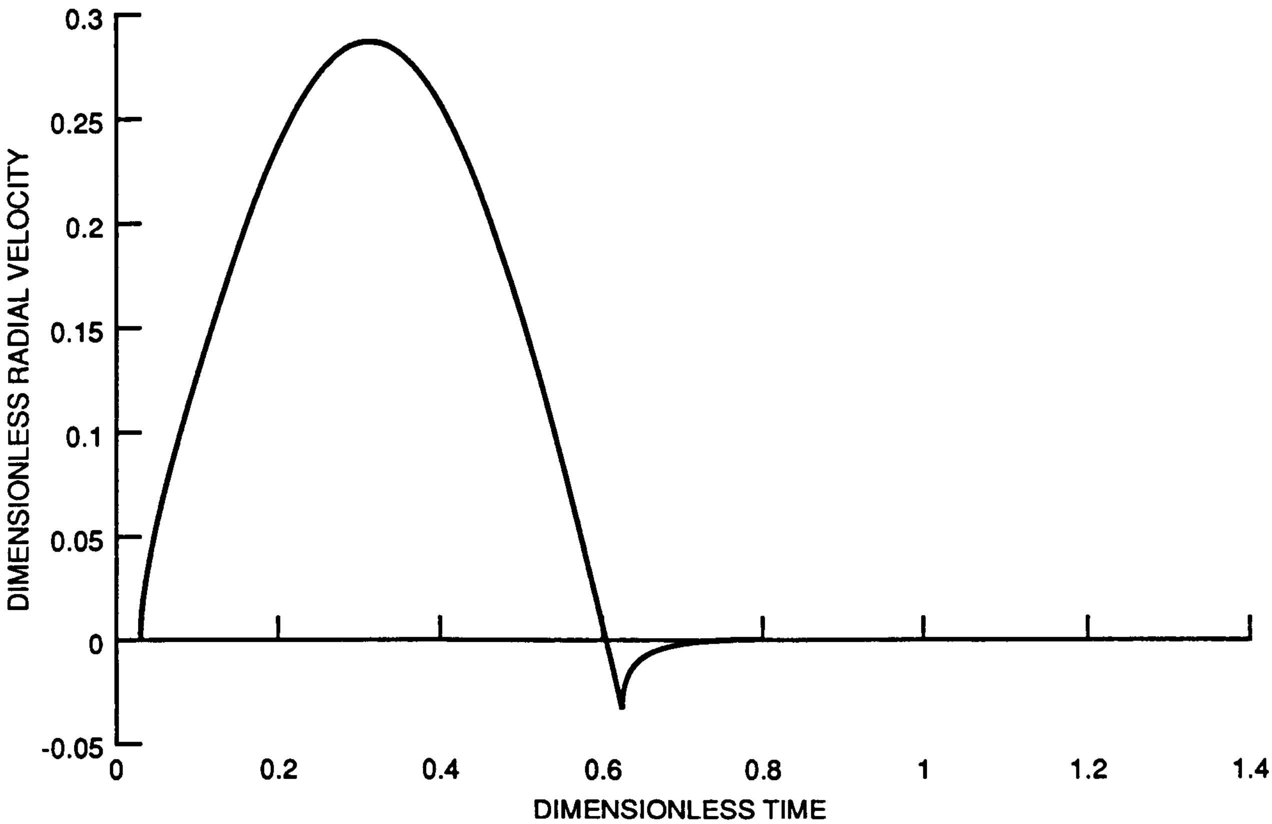

Figure 5.6 Input Radial Velocity Time History Prescribed at r = 0.05 h, Dimensionless Velocity = $(h^2\rho\beta/m_o)v$, Dimensionless time = $t\beta/h$

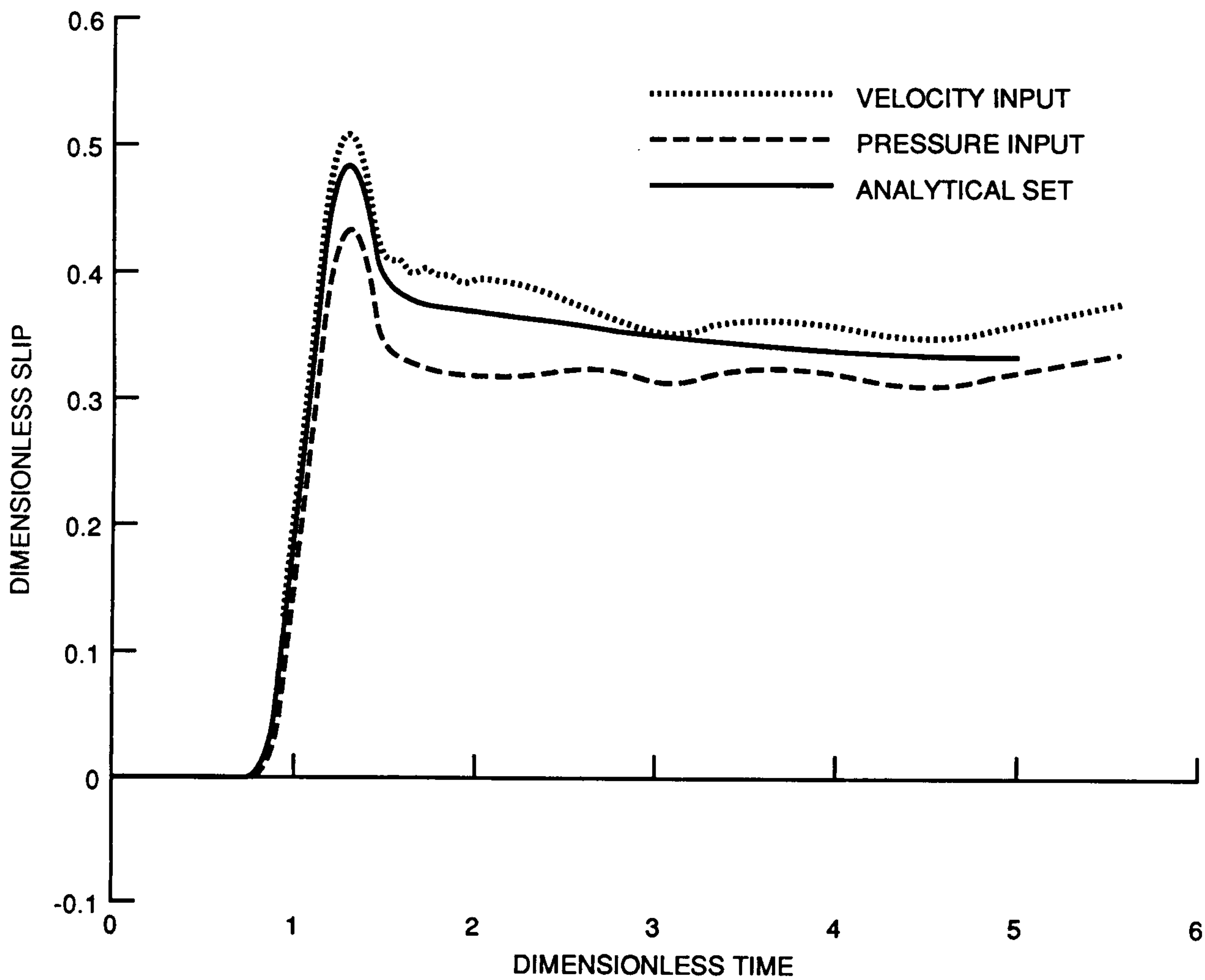

Figure 5.7 Comparison of Dimensionless Slip at Point P with Mohr-Coulomb Joint Model, Dimensionless Slip = $(4h\rho\beta^2/m_o)\delta u$, Dimensionless time $= t\beta/h$

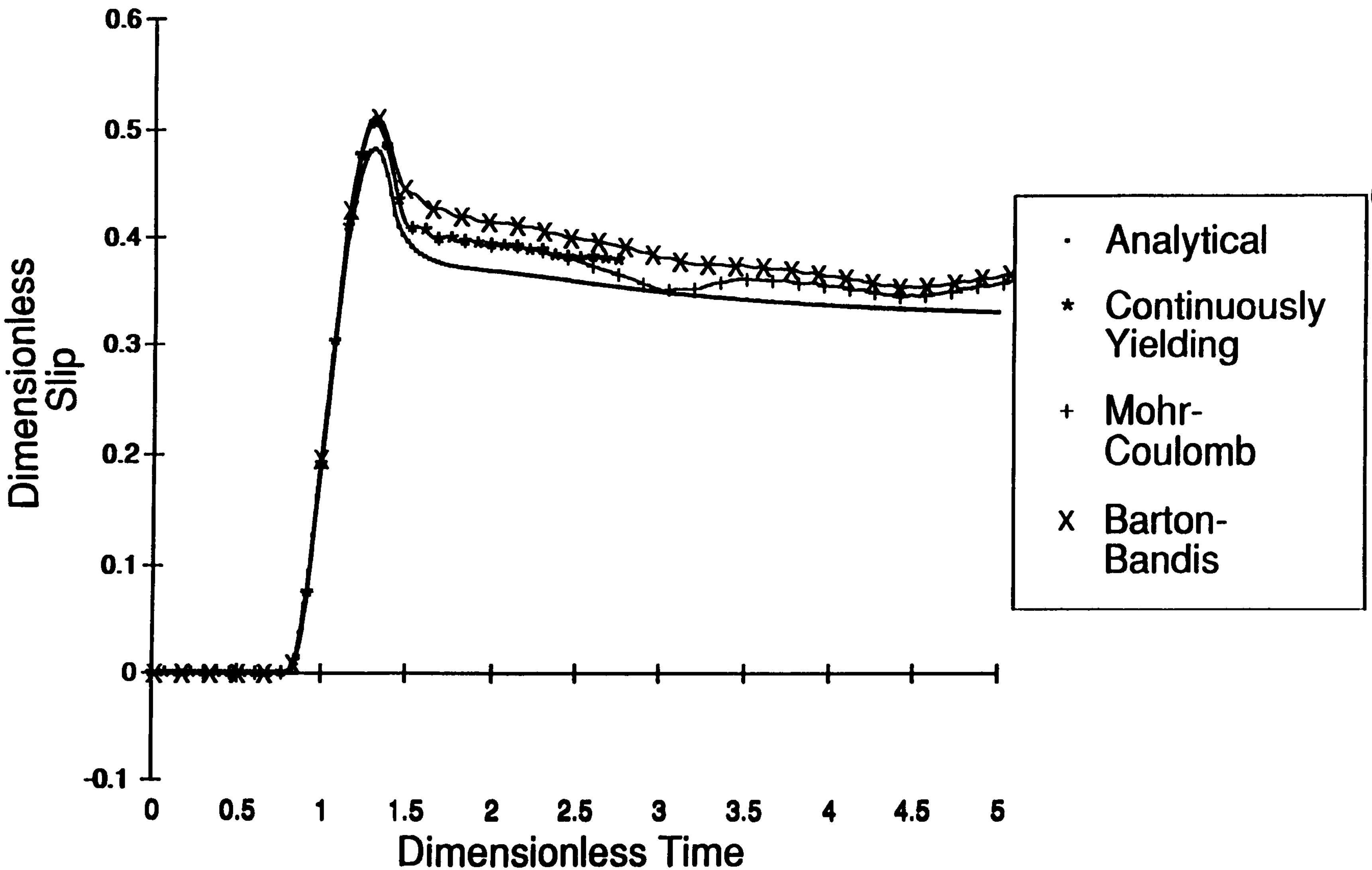

Figure 5.8 Comparison of Dimensionless Slip for Three Different Joint Relations for Velocity Input, Dimensionless Slip = $(4h\rho\beta^2/m_o)\delta u$, Dimensionless time $= t\beta/h$

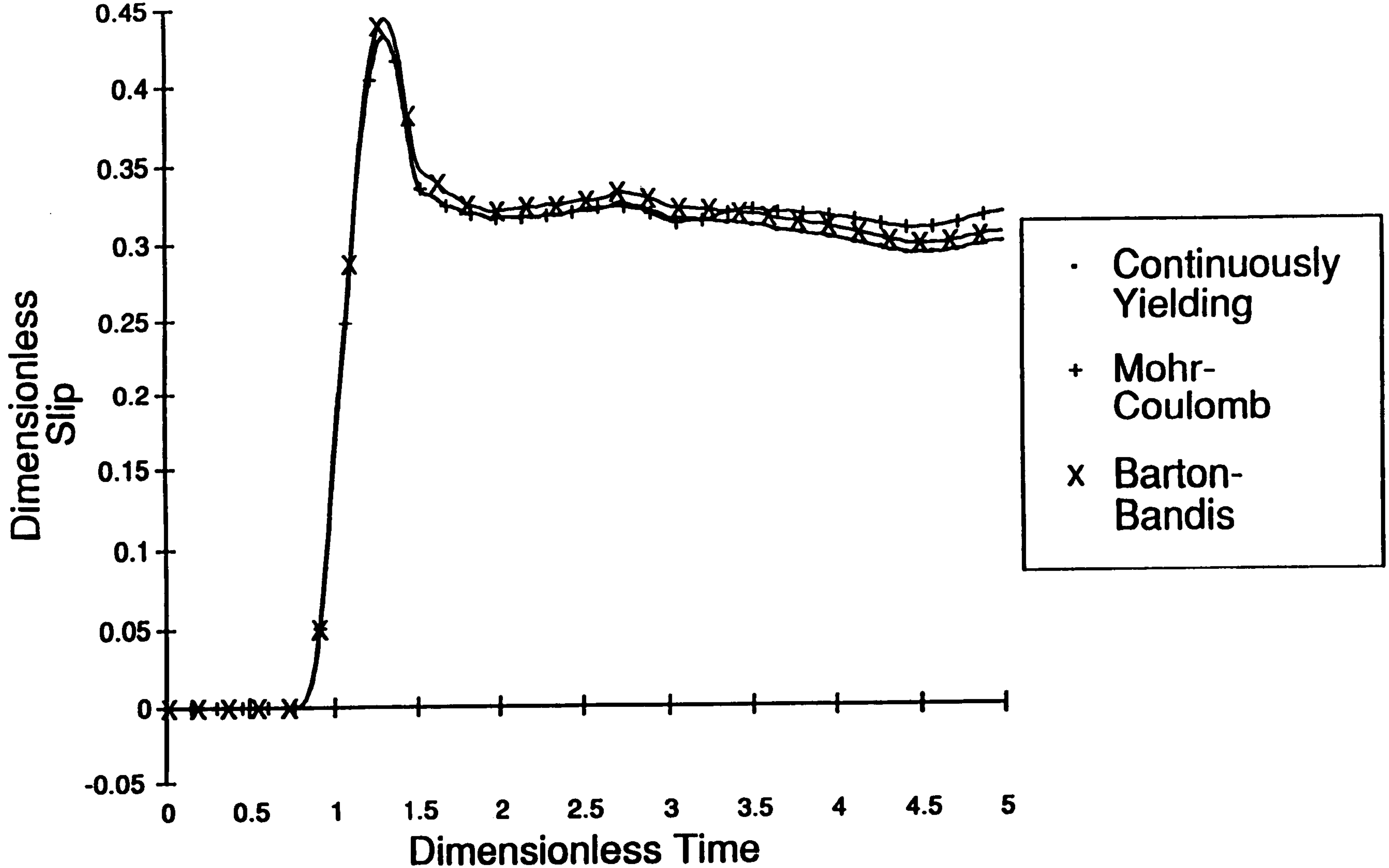

Figure 5.9. Comparison of Dimensionless Slip for Three Different Joint Relations for Pressure Input

discontinuity crosses the boundary. Viscous boundaries, however, are preferable to roller boundaries. Lemos (1987) studied the effects of boundary reflection on slip response by varying the model size and obtained improved performance with a model size of 4h × 4h. As shown in Fig. 5.3, this problem geometry has been employed in this analysis.

5.6 DISCUSSION

Analysis of the problem of a line source in a jointed medium confirmed several aspects of the performance of UDEC and of the joint models implemented in the code. The main conclusion was that the code has the capacity to analyze problems involving impulsive loading of jointed rock under the condition of high frequency composition of the transient load pulse. Recognition of the relation between zone size in the UDEC model and wavelength composition of the load pulse permits accurate analysis of practical problems in rock dynamics where this mode of loading applies.

The capacity of each of the three joint models to predict dynamic joint slip adequately under impulsive load confirms the correctness of the algorithms which are implemented in UDEC. That is not to say that the joint models are themselves complete and adequate simulations of the behavior of rock joints under dynamic loading conditions. Confirmation of those aspects of numerical modeling of the dynamic behavior of joints requires a separate study, in which experimented observations of joint deformation under impulsive loading are compared with the results of numerical analysis.

6. CONCLUSIONS

The broad purpose of the qualification studies on UDEC was to determine if the code, and the various formulations of joint deformation implemented in it, provide an adequate model of the mechanics of discontinuous rock, under conditions of static and dynamic loading. The basis for making the determination was a comparison between analytical solutions to a set of benchmark problems in the mechanics of discontinuous solids and numerical solutions to these problems using the UDEC code. The problems considered in the qualification studies were chosen to exercise the code under conditions of increasing complexity in either mode of response of the medium or the load applied to it. For the series of studies, this involved a gradation in the loading of jointed rock in conditions ranging from a nominally homogeneous stress field and static loading to a highly heterogeneous stress field and impulsive loading.

A feature common to all the benchmark problems is that a plane of weakness totally or partly transects an elastic solid. In all the closed-form solutions to the benchmark problems, the deformation of the plane of weakness is represented by a rigid-perfectly plastic mode of response, with the limiting shear stress defined by either Mohr-Coulomb friction or a cohesion. In UDEC, the Mohr-Coulomb joint is the only joint deformation model which is completely compatible with the formulation of joint deformation in the benchmark problems. For this reason, qualification of UDEC against the benchmark problems has been based on comparison of the results of computational analysis exploiting the Mohr-Coulomb joint model with results from the closed form solutions. However, by suitable choice of the parameters describing the Continuously-Yielding and Barton-Bandis joint models, it was possible to impose joint response approximating the Mohr-Coulomb joint. This provided a means of evaluating the consistency of the numerical performance of these joint formulations, but not of demonstrating that they are valid descriptions of the behavior of real joints, which they are intended to be.

The simplest problem considered in the test series involved static cyclic loading of a block partly transected by an inclined joint. This test is an acute discriminator of the performance of the code, because subtle hysteresis effects are expressed in a load-unload cycle. The UDEC analysis with the Mohr-Coulomb joint produced results for the stiffnesses in loading and unloading which were virtually identical with the independent, closed-form solution. Satisfactory performance of the Continuously-Yielding and Barton-Bandis joint formulations were also observed in analysis of this problem.

In a series of problems involving static slip and separation on joints in the vicinity of a circular excavation in stressed rock, the factor of additional complexity was joint deformation in a highly heterogeneous stress field. By assigning high cohesion to the joints, it was shown that the elastic stress distribution around the excavation was properly determined in the UDEC analysis, when due account was taken of the relatively coarse discretization of the problem domain in some of the test cases. When the joint strength parameters were relaxed, UDEC analysis predicted slip or separation on joints consistent with predictions made from approximations to the ranges of inelastic deformation developed from independent elastic analysis. Similar results were obtained when the three different joint models were employed in the UDEC analysis.

Two benchmark problems were analyzed to confirm the performance of UDEC in the analysis of dynamic problems. In the first, code performance was assessed by calculating the coefficients defining transmission, reflection and absorption of a plane harmonic shear wave normally incident on a low shear strength interface in an elastic solid. The values of the various acoustic coefficients calculated with UDEC and the Mohr-Coulomb joint were consistent with those derived from the analytical solution to the problem. Satisfactory performance was also observed for the Continuously-Yielding and Barton-Bandis joint formulations in calculating the acoustic coefficients.

To examine code performance in analysis of problems involving impulsive loading of a jointed medium, UDEC was used to analyze the response of an elastic solid containing a slip-prone joint, under loading applied by an explosive pulse. The problem is solved in terms of the magnitude of slip induced on the joint by the explosive-induced local load. In the UDEC analysis, each of the three joint deformation models in UDEC provided satisfactory correspondence with the analytical solution, confirming that the distinct element scheme and the various joint models provided a coherent basis for dynamic analysis of jointed rock. This exercise and that involving harmonic loading of a jointed medium also confirmed the satisfactory performance of the viscous (nonreflecting) boundaries for the UDEC problem domain.

Consideration of the performance of UDEC on the suite of benchmark problems indicates that the code is a valid simulation of jointed rock, to the extent that the mechanics of these media may be represented by the conceptual models expressed in the various problems. However, the qualification study does not confirm that UDEC is a valid simulation of the engineering behavior of jointed rock. Confirmation of those aspects of code performance requires laboratory studies to verify the Continuously-Yielding and Barton-Bandis joint formulations, and field studies to evaluate the behavior in a proper engineering setting.

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APPENDIX 1 - UDEC INPUT DATA FILES

CYCLIC LOADING OF A SPECIMEN WITH A SLIPPING CRACK

INPUT DATA FILES

Coulomb Model

```
set log on
* verification test a
* load cycling a specimen with a slipping crack
* friction angle = 16 degrees
*
* crack extension - no slip
prop mat=1 d=2850 k=48.25e9 g=35.277e9 jkn=220e9 jks=220e9
jf=100.0
* crack properties,  Coloumb friction model
prop mat=2 d=2850 k=48.25e9 g=35.277e9 jkn=220e9 jks=220e9
jf=0.287
round 0.001
*
block 0,0 0,2 1,2 1,0
split 0 .5 1 1.5
gen 0 1 0 2 auto 0.2
ch jmat=1 jcon=2
change 0.3 0.7 0.74 1.28 jmat=2
damp auto
hist n=15 ydis 0.5 2.0 syy 0.5 2.0 syy 0.2 2.0 syy 0.8 2.0 type 1
*
*  fix the bottom boundary
*
bound -0.1,1.1 -0.1 .1 yvel=0
*
* y-disp. increment (load step 1)
*
*bound -0.1 1.1 1.9 2.1 yvel=-0.1221
bound -0.1 1.1 1.9 2.1 yvel=-0.061
cyc 200
*
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
*
* y disp. increment (load step 2)
*
*bound -0.1 1.1 1.9 2.1 yvel=-0.1221
bound -0.1 1.1 1.9 2.1 yvel=-0.061
cyc 200
```

```
*
Coulomb Model (continued)

bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. increment (load step 3)
*
*bound -0.1 1.1 1.9 2.1 yvel=-0.1221
bound -0.1 1.1 1.9 2.1 yvel=-0.061
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. increment (load step 4)
*
*bound -0.1 1.1 1.9 2.1 yvel=-0.1221
bound -0.1 1.1 1.9 2.1 yvel=-0.061
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 1)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 2)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
```

Coulomb Model (continued)

```
* y disp. decrement (unload step 3)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 4)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0311
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 5)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 6)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
save prob61x.sav
ret
```

Continuously-Yielding Model

```
set log on
* verification test a
* load cycling a specimen with a slipping crack
* friction angle = 16 degrees
*
* crack extension - no slip
prop mat=1 d=2850 k=48.25e9 g=35.277e9 jkn=220e9 jks=220e9
jf=100.0
* crack properties,  continuously yielding joint model
prop mat=2 d=2850 k=48.25e9 g=35.277e9 jkn=220e9 jks=220e9
jf=0.287
prop m 2 jen 0 jes 0 jif 0.279 jr 1e-10
*
round 0.001
*
block 0,0 0,2 1,2 1,0
split 0 .5 1 1.5
gen 0 1 0 2 auto 0.2
ch jmat=1 jcon=2
change 0.3 0.7 0.74 1.28 jmat=2 jcons=3
*
damp auto
hist n=15 ydis 0.5 2.0 syy 0.5 2.0 syy 0.2 2.0 syy 0.8 2.0 type 1
*
*  fix the bottom boundary
*
bound -0.1,1.1 -0.1 .1 yvel=0
*
* y-disp. increment (load step 1)
*
*bound -0.1 1.1 1.9 2.1 yvel=-0.1221
bound -0.1 1.1 1.9 2.1 yvel=-0.061
cyc 200
*
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
*
* y disp. increment (load step 2)
*
```

Continuously-Yielding Model (continued)

```
*bound -0.1 1.1 1.9 2.1 yvel=-0.1221
bound -0.1 1.1 1.9 2.1 yvel=-0.061
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. increment (load step 3)
*
*bound -0.1 1.1 1.9 2.1 yvel=-0.1221
bound -0.1 1.1 1.9 2.1 yvel=-0.061
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. increment (load step 4)
*
*bound -0.1 1.1 1.9 2.1 yvel=-0.1221
bound -0.1 1.1 1.9 2.1 yvel=-0.061
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 1)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 2)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
```

Continuously-Yielding Model (continued)

```
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 3)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 4)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0311
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 5)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 6)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
save prob62x.sav
ret
```

Barton-Bandis Model

```
set log on
* verification test a
* load cycling a specimen with a slipping crack
* friction angle = 16 degrees
*
* crack extension - no slip
prop mat=1 d=2850e-6 k=48.25e3 g=35.277e3 jkn=220e3 jks=220e3
jf=100.0
* crack properties,  Barton-Bandis Model
prop mat=2 d=2850e-6 k=48.25e3 g=35.277e3 jkn=220e3 jks=220e3
prop mat=2 jrc=1 jcs=100 sigmac=120 lo=100 ln=2e-4 phir=16
round 0.001
*
jhist on .01
block 0,0 0,2 1,2 1,0
split 0 .5 1 1.5
gen 0 1 0 2 auto 0.2
ch jmat=1 jcon=2
change 0.3 0.7 0.74 1.28 jmat=2 jcon=7
damp auto
hist n=15 ydis 0.5 2.0 syy 0.5 2.0 syy 0.2 2.0 syy 0.8 2.0 type 1
*
*  fix the bottom boundary
*
bound -0.1,1.1 -0.1 .1 yvel=0
*
* y-disp. increment (load step 1)
*
*bound -0.1 1.1 1.9 2.1 yvel=-0.1221
bound -0.1 1.1 1.9 2.1 yvel=-0.061
cyc 200
*
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
*
* y disp. increment (load step 2)
*
*bound -0.1 1.1 1.9 2.1 yvel=-0.1221
bound -0.1 1.1 1.9 2.1 yvel=-0.061
cyc 200
*
```

<u>Barton-Bandis Model</u> (continued)

```
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. increment (load step 3)
*
*bound -0.1 1.1 1.9 2.1 yvel=-0.1221
bound -0.1 1.1 1.9 2.1 yvel=-0.061
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. increment (load step 4)
*
*bound -0.1 1.1 1.9 2.1 yvel=-0.1221
bound -0.1 1.1 1.9 2.1 yvel=-0.061
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 1)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 2)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 3)
*
```

Barton-Bandis Model (continued)

```
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 4)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0311
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 5)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
* y disp. decrement (unload step 6)
*
*bound -0.1 1.1 1.9 2.1 yvel=0.0611
bound -0.1 1.1 1.9 2.1 yvel=0.0305
cyc 200
*
bound -0.1 1.1 1.9 2.1 yvel=-0.0
cyc 100
pr max
*
save prob63x.sav
ret
```

```
set log on
************************************************************************
*
*  UDEC code verification
*
*  EXCAVATION IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY
*
*  Case 1: A plane of weakness along the diameter of a circular
*          opening with a 90d angle to the major principal stress
*
*   K = 0.4
*
************************************************************************

start
head excavation near-field problem; Case 1
round 0.001
block 0 -60 0 60 60 60 60 -60
split 0 0 60 0
t 0 0 5 16
t 0 0 10 16
gen 0 10 -10 10 edge 1
gen 10 60 -60 60 edge 2
save v2csa2.sav
****************************************************
*
*    JFRIC = 0., CYM
*
****************************************************
restart v2csa2.sav
head
excavation near-field problem, Case 1, CYM
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change 0 60 -0.001 0.001 jmat 2 jcon 3
bo stress -8 0 -20
insitu stress -8 0 -20
bo -0.01 0.001 -61 61 xvel=0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -0.01 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 0 60 0 0.001
****************************************************
```

```
*
*    JFRIC = 0., MCFM
*
****************************************************

restart v2csa2.sav
head
excavation near-field problem, Case 1, MCFM
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.
+ coh 20
change jmat=1 jcon 2
change 0 60 -0.001 0.001 jmat 2 jcon 2
bo stress -8 0 -20
insitu stress -8 0 -20
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 0 60 0 0.001
****************************************************
*
*    JFRIC = 0.0175, CYM
*
****************************************************
restart v2csa2.sav
head
excavation near-field problem, Case 1, CYM
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.0175
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change 0 60 -0.001 0.001 jmat 2 jcon 3
bo stress -8 0 -20
insitu stress -8 0 -20
bo -0.01 0.001 -61 61 xvel=0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -0.01 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
```

```
del -4 4 -4 4
cyc 500
pr max
pr j 0 0 60 0 0.001
****************************************************
*
*    JFRIC = 0.0175, MCFM
*
****************************************************
restart v2csa2.sav
head
excavation near-field problem, Case 1, MCFM
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.0175
+ coh 20
change jmat=1 jcon 2
change 0 60 -0.001 0.001 jmat 2 jcon 2
bo stress -8 0 -20 i
insitu stress -8 0 -20
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 0 60 0 0.001
****************************************************
*
*    JFRIC = 0.5774, CYM
*
****************************************************
restart v2csa2.sav
head
excavation near-field problem, Case 1, CYM
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.5774
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change 0 60 -0.001 0.001 jmat 2 jcon 3
bo stress -8 0 -20
insitu stress -8 0 -20
bo -0.01 0.001 -61 61 xvel=0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
```

```
bo -0.01 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 0 60 0 0.001
****************************************************
*
*    JFRIC = 0.5774, MCFM
*
****************************************************
restart v2csa2.sav
head
excavation near-field problem, Case 1, MCFM
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.5774
+ coh 20 change jmat=1 jcon 2
change 0 60 -0.001 0.001 jmat 2 jcon 2
bo stress -8 0 -20
insitu stress -8 0 -20
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 0 60 0 0.001
****************************************************
*
*    JFRIC = 0.2679,CYM
*
****************************************************
restart v2csa2.sav
head
excavation near-field problem, Case 1, CYM
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.2679
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change 0 60 -0.001 0.001 jmat 2 jcon 3
bo stress -8 0 -20
insitu stress -8 0 -20
bo -0.01 0.001 -61 61 xvel=0
damp auto
```

```
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -0.01 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 0 60 0 0.001
*****************************************************
*
*    JFRIC = 0.2679, MCFM
*
*****************************************************
restart v2csa2.sav
head
excavation near-field problem, Case 1, MCFM
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.2679
+ coh 20 change jmat=1 jcon 2
change 0 60 -0.001 0.001 jmat 2 jcon 2
bo stress -8 0 -20
insitu stress -8 0 -20
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 0 60 0 0.001
set log off
```

```
set log on
**********************************************************************
*
*  UDEC code verification
*
*  EXCAVATION IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY
*
*  Case 2: A plane of weakness intersecting a opening along the diameter
*          parallel to major principal stress
*
*  Joint Model:   Mohr-Coulomb, JFRIC = 0, K = 1/3 1/3.25
*
**********************************************************************
start
head
excavation near-field problem; (ii) vertically diametric joint
round 0.001
block -60 -60 -60 60 60 60 60 -60
split 0 -60 0 60
t 0 0 5 16
split -60 0 60 0
t 0 0 10 16
t 0 0 15 16
gen -15 15 -15 15 edge 1
gen -60 -15 -60 60 edge 3
gen 15 60 -60 60 edge 3
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0
+ coh 20 jen 0 jes 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 2
change -0.001 0.001 -60 60 jmat 2 jcon 2
save v2csb3.sav
****************************************************************
*
*   K = 1/3.25
*
****************************************************************
bo stress -7.3846 0 -24
insitu stress -7.3846 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
**************************************************************
```

```
*
*   K= 1/2
*
*****************************************************************
restart v2csb3.sav
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
*****************************************************************
*
*    K = 1/3
*
*****************************************************************
restart v2csb3.sav
bo stress -8 0 -24
insitu stress -8 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
*****************************************************************
*
*   K= 1/3.5
*
*****************************************************************
restart v2csb3.sav
bo stress -6.8571 0 -24
insitu stress -6.8571 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
```

```
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
****************************************************************
*
*    K = 1/4
*
****************************************************************
restart v2csb3.sav
bo stress -6 0 -24
insitu stress -6 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
***************************************************************
*
*   K= 1/5
*
***************************************************************
restart v2csb3.sav
bo stress -4.8 0 -24
insitu stress -4.8 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
****************************************************************
*
*    K = 1/6
*
```

```
*****************************************************************
restart v2csb3.sav
bo stress -4 0 -24
insitu stress -4 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
*****************************************************************
*
*   K= 1/8
*
*****************************************************************
restart v2csb3.sav
bo stress -3 0 -24
insitu stress -3 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
*****************************************************************
*
*    K = 1/10
*
*****************************************************************
restart v2csb3.sav
bo stress -2.4 0 -24
insitu stress -2.4 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
```

```
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
set log off
```

```
set log on
***********************************************************************
*
*  UDEC code verification
*
*  EXCAVATION IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY
*
*  Case 2: A plane of weakness intersecting a opening along the diameter
*   parallel to major principal stress
*
*  Joint Model:  Continuously-Yielding , K = 1/2, 1/3, 1/3.5 1/4, 1/5
*                                              1/6, 1/8, 1/10
*
***********************************************************************
start
head
excavation near-field problem; (ii) vertically diametric joint
round 0.001
block -60 -60 -60 60 60 60 60 -60
split 0 -60 0 60
t 0 0 5 16
split -60 0 60 0
t 0 0 10 16
t 0 0 15 16
gen -15 15 -15 15 edge 1
gen -60 -15 -60 60 edge 3
gen 15 60 -60 60 edge 3
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0
+ coh 20 jen 0 jes 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change -0.001 0.001 -60 60 jmat 2 jcon 3
save v2cyb1.sav
***************************************************************
*
*   K= 1/2
*
***************************************************************
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
```

```
*************************************************************
*
*    K = 1/3
*
*************************************************************
restart v2cybl.sav
bo stress -8 0 -24
insitu stress -8 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
************************************************************
*
*   K= 1/3.5
*
************************************************************
restart v2cybl.sav
bo stress -6.8571 0 -24
insitu stress -6.8571 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
*************************************************************
*
*    K = 1/4
*
*************************************************************
restart v2cybl.sav
bo stress -6 0 -24
insitu stress -6 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
```

```
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
*****************************************************************
*
*   K= 1/5
*
*****************************************************************
restart v2csb1.sav
bo stress -4.8 0 -24
insitu stress -4.8 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
*****************************************************************
*
*    K = 1/6
*
*****************************************************************
restart v2cyb1.sav
bo stress -4 0 -24
insitu stress -4 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
*****************************************************************
*
*   K= 1/8
```

```
*
*************************************************************
restart v2cybl.sav
bo stress -3 0 -24
insitu stress -3 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
**************************************************************
*
*    K = 1/10
*
**************************************************************
restart v2cybl.sav
bo stress -2.4 0 -24
insitu stress -2.4 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
set log off
```

```
set log on
**********************************************************************
*
*  UDEC code verification
*
*  EXCAVATION IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY
*
*  Case 3: A plane of weakness intersecting a opening along the diameter
*          with 45d angle to major principal stress
*
*  Joint Model:   Mohr-Coulomb, K = 1/2
*
**********************************************************************
start
head
excavation near-field problem; (ii) inclined diametric joint
round 0.001
block -60 -60 -60 60 60 60 60 -60
split -60 -60 60 60
t 0 0 5 16
split -60 60 60 -60
t 0 0 10 16
t 0 0 15 16
gen -15 15 -15 15 edge 1
gen -60 -15 -60 60 edge 3
gen 15 60 -60 60 edge 3
gen -60 60 15 60 edge 3
gen -60 60 -60 -15 edge 3
save v2csd2.sav
*****************************************************
*
*    JFRIC = 0.3522, MCFM
*
*****************************************************
restart v2csd2.sav
head
excavation near-field problem, Case 3, MCFM
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.3522
+ coh 20
change jmat=1 jcon 2
change reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 jmat 2 jcon 2
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
```

```
del -4 4 -4 4
cyc 500
pr max
pr j 0 0 60 60 0.001

*****************************************************
*
*    JFRIC = 0.35, MCFM
*
*****************************************************
restart v2csd2.sav
head
excavation near-field problem, Case 3, MCFM
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.35
+ coh 20
change jmat=1 jcon 2
change reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 jmat 2 jcon 2
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 0 60 60 0.001
start
head
excavation near-field problem; (ii) inclined diametric joint
+ v2csd2.dat
*****************************************************
*
*    JFRIC = 0.3671
*
*****************************************************
restart v2csd2.sav
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.3671
+ coh 20
change jmat=1 jcon 2
change reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 jmat 2 jcon 2
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
```

```
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j -40 -40 40 40 0.001
*****************************************************
*
*    JFRIC =0.353
*
*****************************************************
restart v2csd2.sav
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.353
+ coh 20
change jmat=1 jcon 2
change reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 jmat 2 jcon 2
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j -40 -40 40 40 0.001
*****************************************************
*
*    JFRIC = 0.3327
*
*****************************************************
restart v2csd2.sav
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.3327
+ coh 20
change jmat=1 jcon 2
change reg -60 -60.001 -60 59.999 60 60.001 60 59.999 jmat 2 jcon 2
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
```

```
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j -40 -40 40 40 0.001
set log off
```

```
set log on
*********************************************************************
*
*  UDEC code verification
*
*  EXCAVATION IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY
*
*  Case 3: A plane of weakness intersecting a opening along the diameter
*          with 45d angle to major principal stress
*
*  Joint Model:   Continuously-Yielding, K = 1/2
*
*********************************************************************
start
head
excavation near-field problem; (ii) inclined diametric joint
round 0.001
block -60 -60 -60 60 60 60 60 -60
split -60 -60 60 60
t 0 0 5 16
split -60 60 60 -60
t 0 0 10 16
t 0 0 15 16
gen -15 15 -15 15 edge 1
gen -60 -15 -60 60 edge 3
gen 15 60 -60 60 edge 3
gen -60 60 15 60 edge 3
gen -60 60 -60 -15 edge 3
****************************************************
*
*    JFRIC = 0.3522, CYM
*
****************************************************
save v2csd2.sav
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.3522
+ coh 20 jen 0 jes 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 jmat 2 jcon 3
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
```

```
pr j -40 -40 40 40 0.001
*****************************************************
*
*   JFRIC = 0.3671
*
*****************************************************
restart v2csd2.sav
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1

prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.3671
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 jmat 2 jcon 3
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j -40 -40 40 40 0.001
*****************************************************
*
*   JFRIC =0.35
*
*****************************************************
restart v2csd2.sav
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jes 0 jen 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.35
+ coh 20 jen 0 jes 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change reg -60 -60.001 -60 -69.999 60 60.001 60 59.999 jmat 2 jcon 3
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
```

```
pr max
pr j -40 -40 40 40 0.001
*****************************************************
*
*    JFRIC = 0.353
*
*****************************************************
restart v2csd2.sav
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.353
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 jmat 2 jcon 3
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j -40 -40 40 40 0.001
*****************************************************
*
*    JFRIC = 0.3327
*
*****************************************************
restart v2csd2.sav
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jes 0 jen 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.3327
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 jmat 2 jcon 3
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
```

```
pr max
pr j -40 -40 40 40 0.001
set log off
```

```
set log on
********************************************************************
*
*   UDEC code verification
*
*   EXCAVATION IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY
*
*   Case 4: A plane of weakness intersecting a circular opening
*           nondiametrically
*
********************************************************************
start
head
excavation near-field problem; Case 4
round 0.005
block 0 -60 0 60 60 60 60 -60
split 0 4.33013 60 4.33013
t 0 0 5 32
t 0 0 5.4 32
t 0 0 5.9 32
t 0 0 6.5 32
t 0 0 7.2 32
t 0 0 8.0 16
t 0 0 9.0 16
t 0 0 11.0 16
t 0 0 15.0 8
t 0 0 25.0 8
gen 1.4 1.5 4.85 4.95 edge .2
gen 3.7 3.8 -1.12 -1.11 edge .2
gen 1.8 1.9 5.1 5.2 edge .5
gen 4.05 4.1 -1.5 -1.4 edge .5
gen 2.3 2.4 5.5 5.6 edge .6
gen 4.4 4.5 -1.9 -1.8 edge .6
gen 2.8 2.9 5.9 6.0 edge .7
gen 4.9 5.0 -2.4 -2.3 edge .7
gen 3.3 3.4 6.4 6.5 edge .8
gen 5.4 5.5 -2.9 2.8 edge .8
gen 3.9 4.0 7 7.1 edge 1
gen 6 6.1 -3.4 -3.3 edge 1
gen 4.9 5.0 7.9 8.0 edge 2
gen 7 7.1 -4.4 -4.3 edge 2
gen 6.7 6.8 9.8 9.9 edge 3
gen 8.8 8.9 -6.2 -6.1 edge 3
gen 11 12 14 15 edge 5
gen 13 14 -11 -10 edge 5
gen edge 10
save v2csc2.sav
```

```
*****************************************************
*
*    JFRIC = 0.2924, MCFM, K = 1
*
*****************************************************
restart v2csc2.sav
set ovtol 1e-3
prop mat=1 g 35000 k 60000 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0
prop mat 2 jfric 0.2924
change jmat=1 jcon 2
change 0 60 4.33 4.3302 ang -.1 .1 jmat 2 jcon 2
bo -1 61 59 61 xvel 0 yvel 0
bo 59 61 -61 61 xvel 0 yvel 0
bo -1 61 -61 -59 xvel 0 yvel 0
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel 0
damp auto
hist unbal
hist ydis 0 5 ty 2
m on
head
excavation near-field problem, Case 4, MCFM, JFRIC=0.2924
set jmatdf 2
set dscan 20000
set upcon 20000
set cscan 20000
set delcon off
cy 1000
* make excavation
del bl 457
del bl 1127
cyc 2000
pr max
pr j 0 4.3301 60 4.3301 0.01
save case4c.sav
```

```
***************************************************
*
*    JFRIC = 1.732, MCFM, K = 1
*
***************************************************
restart v2csc2.sav
set ovtol 1e-3
head
excavation near-field problem, Case 4, MCFM; JFRIC=1.732
prop mat=1 g 35000 k 60000 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 jfric 1.732
change jmat=1 jcon 2
change 0 60 4.33 4.3302 ang -.1 .1 jmat 2 jcon 2
bo -1 61 59 61 xvel 0 yvel 0
bo 59 61 -61 61 xvel 0 yvel 0
bo -1 61 -61 -59 xvel 0 yvel 0
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel 0
damp auto
hist unbal
hist ydis 0 5 ty 2
m on
set jmatdf 2
set dscan 20000
set upcon 20000
set cscan 20000
set delcon off
cy 1000
* make excavation
del bl 457
del bl 1127
cyc 2000
pr max
pr j 0 4.3301 60 4.3301 0.01
save case4a.sav
ret
*  ------------------------------
```

```
set log on
**********************************************************************
*
*  UDEC code verification
*
*  EXCAVATION IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY
*
*  Case 5: A plane of weakness transgressing the zone of influence
*          of a circular opening
*
*  K = 1
*
***********************************************************************
start
head
excavation near-field problem; Case 5
round 0.001
block 0 -60 0 60 60 60 60 -60
split 0 7 60 7
t 0 0 5 16
t 0 0 10 16
t 0 0 15 16
split 0 0 60 0
gen 0 15 -15 15 edge 1
gen 15 60 -60 60 edge 2
save v2cse2.sav
****************************************************
*
*   JFRIC = 0.5, CYM
*
****************************************************
head
excavation near-field problem, Case 5, CYM, JFRIC=0.5
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.5
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change 0 60 6.999 7.001 jmat 2 jcon 3
bo stress -24 0 -24
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel=0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -0.01 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 7 60 7 0.1
```

```
***************************************************
*
*    JFRIC = 0.5, MCFM
*
***************************************************
restart v2cse2.sav
head
excavation near-field problem, Case 5, MCFM, JFRIC=0.5
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.5
+ coh 20
change jmat=1 jcon 2
change 0 60 6.999 7.001 jmat 2 jcon 2
bo stress -24 0 -24
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 7 60 7 0.1
***************************************************
*
*    JFRIC = 0.404, CYM
*
***************************************************
restart v2cse2.sav
head
excavation near-field problem, Case 5, CYM, JFRIC=0.404
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.404
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change 0 60 6.999 7.001 jmat 2 jcon 3
bo stress -24 0 -24
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel=0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -0.01 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
```

```
del -4 4 -4 4
cyc 500
pr max
pr j 0 7 60 7 0.1
***************************************************
*
*    JFRIC = 0.404, MCFM
*
***************************************************
restart v2cse2.sav
head
excavation near-field problem, Case 5, MCFM, JFRIC=0.404
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.404
+ coh 20
change jmat=1 jcon 2
change 0 60 6.999 7.001 jmat 2 jcon 2
bo stress -24 0 -24
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 7 60 7 0.1
***************************************************
*
*    JFRIC = 0.4122, CYM
*
***************************************************
restart v2cse2.sav
head
excavation near-field problem, Case 5, CYM, JFRIC=0.4122
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.4122
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
change jmat=1 jcon 3
change 0 60 6.999 7.001 jmat 2 jcon 3
bo stress -24 0 -24
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel=0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
```

```
bo -0.01 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 7 60 7 0.1
*****************************************************
*
*    JFRIC = 0.4122, MCFM
*
*****************************************************
restart v2cse2.sav
head
excavation near-field problem, Case 5, MCFM, JFRIC=0.4122
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.4122
+ coh 20
change jmat=1 jcon 2
change 0 60 6.999 7.001 jmat 2 jcon 2
bo stress -24 0 -24
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 7 60 7 0.1
set log off
```

```
set log on
**********************************************************************
*
*  UDEC code verification
*
*  EXCAVATION IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY
*
*  Case 1: A plane of weakness along the diameter of a circular
*          opening with a 90d angle to the major principal stress
*
*   K = 0.4, Barton-Bandis Joint Relation
*
**********************************************************************
start
head
excavation near-field problem; Case 1
round .001
block 0 -60 0 60 60 60 60 -60
t 0 0 5 16
t 0 0 10 16
split 0 0 60 0
gen 0 10 -10 10 edge 1
gen 10 60 -60 60 edge 2
save v2csa2.sav
****************************************************
*
*    JFRIC = 0., BB
*
****************************************************
restart
v2csa2.sav
head
excavation near-field problem, Case 1, BB
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0. + coh
20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
+ tens=1.0e6 jtens=1.0e6  ln 1 aper .050
prop mat=2 jrc .0001 jcs 100 sigmac 120 lo 100 phir .0001
change jmat=1 jcon 2
change 0 60 -0.001 0.001 ang -.1 .1 jmat 2 jcon 7
bo stress -8 0 -20
insitu stress -8 0 -20
bo -0.01 0.001 -61 61 xvel=0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -0.01 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
```

```
hist unbal
cyc 500
pr max
pr j 0 0 60 0 0.001
*****************************************************
*
*    JFRIC = 0.0175, BB
*
*****************************************************
restart
v2csa2.sav
head
excavation near-field problem, Case 1, BB
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.0175
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
+ tens=1.0e6 jtens=1.0e6  ln 1 aper .050
prop mat=2 jrc .0001 jcs 100 sigmac 120 lo 100 phir 1
change jmat=1 jcon 2
change 0 60 -0.001 0.001 ang -.1 .1 jmat 2 jcon 7
bo stress -8 0 -20
insitu stress -8 0 -20
bo -0.01 0.001 -61 61 xvel=0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -0.01 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
hist unbal
cyc 500
pr max
pr j 0 0 60 0 0.001
*****************************************************
*
*    JFRIC = 0.5774, BB
*
*****************************************************
restart
v2csa2.sav
head
excavation near-field problem, Case 1, BB
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.5774
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
+ tens=1.0e6 jtens=1.0e6  ln 1 aper .050
prop mat=2 jrc .0001 jcs 100 sigmac 120 lo 100 phir 30
change jmat=1 jcon 2
change 0 60 -0.001 0.001 ang -.1 .1 jmat 2 jcon 7
```

```
bo stress -8 0 -20
insitu stress -8 0 -20
bo -0.01 0.001 -61 61 xvel=0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -0.01 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
hist unbal
cyc 500
pr max
pr j 0 0 60 0 0.001
****************************************************
*
*    JFRIC = 0.2679,BB
*
****************************************************
restart
v2csa2.sav
head
excavation near-field problem, Case 1, BB
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.2679
+ coh 20 jes 0 jen 0 jif 1.0e-10 jr 1.0e-10
+ tens=1.0e6 jtens=1.0e6  ln 1 aper .050
prop mat=2 jrc .0001 jcs 100 sigmac 120 lo 100 phir 15
change jmat=1 jcon 2
change 0 60 -0.001 0.001 ang -.1 .1 jmat 2 jcon 7
bo stress -8 0 -20
insitu stress -8 0 -20
bo -0.01 0.001 -61 61 xvel=0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -0.01 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
hist unbal
cyc 500
pr max
pr j 0 0 60 0 0.001
********************************************************************
*
*  UDEC code verification
*
*  EXCAVATION IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY
```

```
*
*  Case 2: A plane of weakness intersecting a opening along the diameter
*          parallel to major principal stress
*
*  Joint Model:   Barton-Bandis, JFRIC = 0
*
*********************************************************************** start
head
excavation near-field problem; (ii) vertically diametric joint
round 0.001
block -60 -60 -60 60 60 60 60 -60
split 0 -60 0 60
t 0 0 5 16
split -60 0 60 0
t 0 0 10 16
t 0 0 15 16
gen -15 15 -15 15 edge 1
gen -60 -15 -60 60 edge 3
gen 15 60 -60 60 edge 3
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40 jen 0 jes 0 jif 1.035 jr 1
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0
+ coh 20 jen 0 jes 0 jif 1.0e-10 jr 1.0e-10
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=.0001
prop mat=2 ln 1 jcs=100
change jmat=1 jcon 2
change -0.001 0.001 -60 60 ang 89.9 90.1 jmat 2 jcon 7
save v2csb3.sav
****************************************************************
*
*   K = 1/3.25
*
****************************************************************
bo stress -7.3846 0 -24
insitu stress -7.3846 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
**************************************************************
*
*   K= 1/2
*
**************************************************************
restart v2csb3.sav
```

```
bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
*************************************************************
*
*    K = 1/3
*
*************************************************************
restart v2csb3.sav
bo stress -8 0 -24
insitu stress -8 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
************************************************************
*
*   K= 1/3.5
*
************************************************************
restart v2csb3.sav
bo stress -6.8571 0 -24
insitu stress -6.8571 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
```

```
cyc 500
pr max
pr j 0 -60 0 60 0.001
**************************************************************
*
*    K = 1/4
*
**************************************************************
restart v2csb3.sav
bo stress -6 0 -24
insitu stress -6 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
*************************************************************
*
*   K= 1/5
*
*************************************************************
restart v2csb3.sav
bo stress -4.8 0 -24
insitu stress -4.8 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
**************************************************************
*
*    K = 1/6
*
**************************************************************
restart v2csb3.sav
bo stress -4 0 -24
insitu stress -4 0 -24
damp auto
```

```
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
*************************************************************
*
*   K= 1/8
*
*************************************************************
restart v2csb3.sav
bo stress -3 0 -24
insitu stress -3 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
**************************************************************
*
*    K = 1/10
*
**************************************************************
restart v2csb3.sav
bo stress -2.4 0 -24
insitu stress -2.4 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 -60 0 60 0.001
```

```
***********************************************************************
*
*  UDEC code verification
*
*  EXCAVATION IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY
*
*  Case 3: A plane of weakness intersecting a opening along the diameter
*          with 45d angle to major principal stress
*
*  Joint Model:   Barton-Bandis, K = 1/2
*
*********************************************************************** start
head
excavation near-field problem; (ii) inclined diametric joint
round 0.001
block -60 -60 -60 60 60 60 60 -60
split -60 -60 60 60
t 0 0 5 16
split -60 60 60 -60
t 0 0 10 16
t 0 0 15 16
gen -15 15 -15 15 edge 1
gen -60 -15 -60 60 edge 3
gen 15 60 -60 60 edge 3
gen -60 60 15 60 edge 3
gen -60 60 -60 -15 edge 3
save v2csd2.sav
****************************************************
*
*   JFRIC = 0.3522, BB
*
****************************************************
restart v2csd2.sav
head
excavation near-field problem, Case 3, BB
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.3522
+ coh 20
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=19.4
prop mat=2 ln 1 jcs=100
change jmat=1 jcon 2
ch reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 ang 44.9 45.1 jmat=2
jcon=7 bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
```

```
del -4 4 -4 4
cyc 500
pr max
pr j 0 0 60 60 0.001

****************************************************
*
*   JFRIC = 0.35, BB
*
****************************************************
restart v2csd2.sav
head
excavation near-field problem, Case 3, BB
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.35
+ coh 20
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=19.29
prop mat=2 ln 1 jcs=100
change jmat=1 jcon 2
ch reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 ang 44.9 45.1 jmat=2
jcon=7 bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 0 60 60 0.001
start
head
excavation near-field problem; inclined diametric joint
+ v2csd2.dat
****************************************************
*
*   JFRIC = 0.3671
*
****************************************************
restart v2csd2.sav
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.3671
+ coh 20
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=20.16
prop mat=2 ln 1 jcs=100
change jmat=1 jcon 2
```

```
ch reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 ang 44.9 45.1 jmat=2
jcon=7 bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j -40 -40 40 40 0.001
****************************************************
*
*    JFRIC =0.353
*
****************************************************
restart v2csd2.sav
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.353
+ coh 20
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=19.44
prop mat=2 ln 1 jcs=100
change jmat=1 jcon 2
ch reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 ang 44.9 45.1 jmat=2
jcon=7 bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j -40 -40 40 40 0.001
****************************************************
*
*    JFRIC = 0.3327
*
****************************************************
restart v2csd2.sav
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.3327
```

```
+ coh 20
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=18.4
prop mat=2 ln 1 jcs=100
change jmat=1 jcon 2
ch reg -60 -60.001 -60 -59.999 60 60.001 60 59.999 ang 44.9 45.1 jmat=2
jcon=7 bo stress -12 0 -24
insitu stress -12 0 -24
damp auto
m on
cyc 100
bo -60.01 -59.999 -61 61 xvel 0
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j -40 -40 40 40 0.001
********************************************************************
*
*  UDEC code verification
*
*  EXCAVATION IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY
*
*  Case 4: A plane of weakness intersecting a circular opening
*          nondiametrically
*
********************************************************************
start
head
excavation near-field problem; Case 4
round 0.001
block 0 -60 0 60 60 60 60 -60
split 0 4.3301 60 4.3301
t 0 0 10 16
t 0 0 15 16
cr 0 5 1.2941 4.8296
cr 1.2941 4.8296 2.5 4.3301
cr 2.5 4.3301 3.5355 3.5355
cr 3.5355 3.5355 4.3301 2.5
cr 4.3301 2.5 4.8296 1.2941
cr 4.8296 1.2941 5 0
cr 5 0 4.8296 -1.2941
cr 4.8296 -1.2941 4.3301 -2.5
cr 4.3301 -2.5 3.5355 -3.5355
cr 3.5355 -3.5355 2.5 -4.3301
cr 2.5 -4.3301 1.2941 -4.8296
cr 1.2941 -4.8296 0 -5
gen 0 15 -15 15 edge 1
gen 15 60 -60 60 edge 2
save v2csc2.sav
***************************************************
```

```
*
*    JFRIC = 1.732, BB, K = 1
*
****************************************************
restart v2csc2.sav
head
excavation near-field problem, Case 4, BB
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 1.732
+ coh 20
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=60
prop mat=2 ln 100 jcs=100
change jmat=1 jcon 2
change 0 60 4.33 4.3302 ang -0.1 0.1 jmat=2 jcon=7
bo stress -24 0 -24
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del 0 4.5 -4.5 5
cyc 500
pr max
pr j 0 4.3301 60 4.3301 0.001
****************************************************
*
*    JFRIC = 1.732, BB, K = 0.5
*
****************************************************
restart v2csc2.sav
head
excavation near-field problem, Case 4, BB
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 1.732
+ coh 20
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=60
prop mat=2 ln 100 jcs=100
change jmat=1 jcon 2
change 0 60 4.33 4.3302 ang -0.1 0.1 jmat=2 jcon=7
bo stress -12 0 -24
insitu stress -12 0 -24
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
```

```
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del 0 4.5 -4.5 5
cyc 500
pr max
pr j 0 4.3301 60 4.3301 0.001
****************************************************
*
*    JFRIC = 0.9004, BB, K = 1
*
****************************************************
restart v2csc2.sav
head
excavation near-field problem, Case 4, BB
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.9004
+ coh 20
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=42
prop mat=2 ln 100 jcs=100
change jmat=1 jcon 2
change 0 60 4.33 4.3302 ang -0.1 0.1 jmat=2 jcon=7
bo stress -24 0 -24
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del 0 4.5 -4.5 5
cyc 500
pr max
pr j 0 4.3301 60 4.3301 0.001
****************************************************
*
*    JFRIC = 0.6745, BB, K = 0.5
*
****************************************************
restart v2csc2.sav
head
excavation near-field problem, Case 4, BB
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.6745
+ coh 20
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=34
prop mat=2 ln 100 jcs=100
change jmat=1 jcon 2
change 0 60 4.33 4.3302 ang -0.1 0.1 jmat=2 jcon=7
```

```
bo stress -12 0 -24
insitu stress -12 0 -24
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del 0 4.5 -4.5 5
cyc 500
pr max
pr j 0 4.3301 60 4.3301 0.001
*********************************************************************
*
*  UDEC code verification
*
*  EXCAVATION IN AN INFINITE ELASTIC MEDIUM WITH A DISCONTINUITY
*
*  Case 5: A plane of weakness transgressing the zone of influence
*          of a circular opening
*
*  K = 1
*
**********************************************************************
start
head
excavation near-field problem; Case 5
round 0.001
block 0 -60 0 60 60 60 60 -60
split 0 7 60 7
t 0 0 5 16
t 0 0 10 16
t 0 0 15 16
split 0 0 60 0
gen 0 15 -15 15 edge 1
gen 15 60 -60 60 edge 2
save v2cse2.sav
****************************************************
*
*   JFRIC = 0.5, BB
*
****************************************************
restart v2cse2.sav
head
excavation near-field problem, Case 5, BB, JFRIC=0.5
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.5
+ coh 20
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=26.565
prop mat=2 ln 1 jcs=100
```

```
change jmat=1 jcon 2
change 0 60 6.999 7.001 ang -0.1 0.1 jmat=2 jcon=7
bo stress -24 0 -24
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 7 60 7 0.1
****************************************************
*
*    JFRIC = 0.404, BB
*
****************************************************
restart v2cse2.sav
head
excavation near-field problem, Case 5, BB, JFRIC=0.404
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.404
+ coh 20
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=22
prop mat=2 ln 1 jcs=100
change jmat=1 jcon 2
change 0 60 6.999 7.001 ang -0.1 0.1 jmat=2 jcon=7
bo stress -24 0 -24
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 7 60 7 0.1
****************************************************
*
*    JFRIC = 0.4122, BB
*
****************************************************
restart v2cse2.sav
```

```
head
excavation near-field problem, Case 5, BB, JFRIC=0.4122
prop mat=1 g 35000 k 60000 coh 20 jfric 10 d 0.00001
+ jkn 200000 jks 200000 jc 40 jtens 40
prop mat 2 jkn 200000 jks 200000 jc 0 jtens 0 g 35000 k 60000 jfric 0.4122
+ coh 20
prop mat=2 aper=0.05 jrc=.0001 sigmac=120 lo=100 phir=22.4
prop mat=2 ln 1 jcs=100
change jmat=1 jcon 2
change 0 60 6.999 7.001 ang -0.1 0.1 jmat=2 jcon=7
bo stress -24 0 -24
insitu stress -24 0 -24
bo -0.01 0.001 -61 61 xvel 0
damp auto
m on
cyc 100
bo 59.999 60.01 -61 61 xvel 0
bo -61 61 -60.01 -59.999 yvel 0
bo -61 61 59.999 60.01 yvel 0
reset disp
reset jdisp
del -4 4 -4 4
cyc 500
pr max
pr j 0 7 60 7 0.1
set log off
```

```
set log on
*******************************************************************
*
* No slipping, Jcoh 2.5
*
*******************************************************************
start
head
VERIFICATION TEST A1 -- NORMALLY INCIDENT SHEAR WAVE; NO SLIPPING
wind -400 0 -200 200
prop mat=1 kn=5000 jkn=10000 jks=10000 jcoh=2.5 jtens=1e6
prop mat=5 d=0.00265 k=16667 g=10000
round 0.1
edge=10.0
block -200 -200 -200 200  -120 200 -120 -200
split -210,0 201 0
change mat=5 cons=1
gen -200 200  -200 200 auto 60
change jmat=1 jcons=2
bound mat=5
bound  -201,201 -201,-199 xvisc yvisc
bound -201 201 199 201 xvisc yvisc
bound -201 201 -201 -199 stress 0,2,0
bound -201,-199 -201,201 yvel=0
bound -121,-119 -201 201 yvel=0
bound hist sine (1,5.0)
hist n=25 sxy -160,-200 sxy -160,200  type=1
hist      xvel(-160,-200)  xvel(-160,200) xd -160 -200 xd -160 200
insitu stress 0 0 -1e-6
cyc 1500
pr max
pr hist 1 2 3 4 5 6
*******************************************************************
*
* Slipping joint, jcoh=0.8333
*
*******************************************************************
start
head
VERIFICATION TEST A2 -- NORMALLY INCIDENT SHEAR WAVE; SLIPPING JOINT
wind -400 0 -200 200
prop mat=1 kn=5000 jkn=10000 jks=10000 jcoh=0.8333 jtens=1e6
prop mat=5 d=0.00265 k=16667 g=10000
round 0.1
edge=10.0
block -200 -200 -200 200  -120 200 -120 -200
split -210,0 201 0
change mat=5 cons=1
gen -200 200  -200 200 auto 60
change jmat=1 jcons=2
bound mat=5
bound  -201,201 -201,-199 xvisc yvisc
bound -201 201 199 201 xvisc yvisc
bound -201 201 -201 -199 stress 0,2,0
```

```
bound -201,-199 -201,201 yvel=0
bound -121,-119 -201 201 yvel=0
bound hist sine (1,5.0)
hist n=25 sxy -160,-200 sxy -160,200  type=1
hist      xvel(-160,-200)  xvel(-160,200) xd -160 -200 xd -160 200
insitu stress 0 0 -1e-6
cyc 1500
pr max
pr hist 1 2 3 4 5 6
*******************************************************************
*
* slipping joint, jcoh 0.6667
*
*******************************************************************
start
head
VERIFICATION TEST A3 -- NORMALLY INCIDENT SHEAR WAVE; SLIPPING JOINT
wind -400 0 -200 200
prop mat=1 kn=5000 jkn=10000 jks=10000 jcoh=0.6667 jtens=1e6
prop mat=5 d=0.00265 k=16667 g=10000
round 0.1
edge=10.0
block -200 -200 -200 200  -120 200 -120 -200
split -210,0 201 0
change mat=5 cons=1
gen -200 200  -200 200 auto 60
change jmat=1 jcons=2
bound mat=5
bound  -201,201 -201,-199 xvisc yvisc
bound -201 201 199 201 xvisc yvisc
bound -201 201 -201 -199 stress 0,2,0
bound -201,-199 -201,201 yvel=0
bound -121,-119 -201 201 yvel=0
bound hist sine (1,5.0)
hist n=25 sxy -160,-200 sxy -160,200  type=1
hist      xvel(-160,-200)  xvel(-160,200) xd -160 -200 xd -160 200
insitu stress 0 0 -1e-6
cyc 1500
pr max
pr hist 1 2 3 4 5 6
*******************************************************************
*
* Slipping joint, jcoh 0.5
*
*******************************************************************
start
head
VERIFICATION TEST A4 -- NORMALLY INCIDENT SHEAR WAVE; SLIPPING JOINT
wind -400 0 -200 200
prop mat=1 kn=5000 jkn=10000 jks=10000 jcoh=0.5 jtens=1e6
prop mat=5 d=0.00265 k=16667 g=10000
round 0.1
edge=10.0
block -200 -200 -200 200  -120 200 -120 -200
```

```
split -210,0 201 0
change mat=5 cons=1
gen -200 200  -200 200 auto 60
change jmat=1 jcons=2
bound mat=5
bound  -201,201 -201,-199 xvisc yvisc
bound -201 201 199 201 xvisc yvisc
bound -201 201 -201 -199 stress 0,2,0
bound -201,-199 -201,201 yvel=0
bound -121,-119 -201 201 yvel=0
bound hist sine (1,5.0)
hist n=25 sxy -160,-200 sxy -160,200  type=1
hist      xvel(-160,-200)  xvel(-160,200) xd -160 -200 xd -160 200
insitu stress 0 0 -1e-6
cyc 1500
pr max
pr hist 1 2 3 4 5 6
*******************************************************************
*
* Slipping joint, jcoh 0.1
*
*******************************************************************
start
head
VERIFICATION TEST A5 -- NORMALLY INCIDENT SHEAR WAVE; SLIPPING JOINT
wind -400 0 -200 200
prop mat=1 kn=5000 jkn=10000 jks=10000 jcoh=0.1 jtens=1e6
prop mat=5 d=0.00265 k=16667 g=10000
round 0.1
edge=10.0
block -200 -200 -200 200  -120 200 -120 -200
split -210,0 201 0
change mat=5 cons=1
gen -200 200  -200 200 auto 60
change jmat=1 jcons=2
bound mat=5
bound  -201,201 -201,-199 xvisc yvisc
bound -201 201 199 201 xvisc yvisc
bound -201 201 -201 -199 stress 0,2,0
bound -201,-199 -201,201 yvel=0
bound -121,-119 -201 201 yvel=0
bound hist sine (1,5.0)
hist n=25 sxy -160,-200 sxy -160,200  type=1
hist      xvel(-160,-200)  xvel(-160,200) xd -160 -200 xd -160 200
insitu stress 0 0 -1e-6
cyc 1500
pr max
pr hist 1 2 3 4 5 6
*******************************************************************
*
* Slipping joint, jcoh 0.02
*
*******************************************************************
start
```

```
head
VERIFICATION TEST A6 -- NORMALLY INCIDENT SHEAR WAVE; SLIPPING JOINT
wind -400 0 -200 200
prop mat=1 kn=5000 jkn=10000 jks=10000 jcoh=0.02 jtens=1e6
prop mat=5 d=0.00265 k=16667 g=10000
round 0.1
edge=10.0
block -200 -200 -200 200  -120 200 -120 -200
split -210,0 201 0
change mat=5 cons=1
gen -200 200  -200 200 auto 60
change jmat=1 jcons=2
bound mat=5
bound  -201,201 -201,-199 xvisc yvisc
bound -201 201 199 201 xvisc yvisc
bound -201 201 -201 -199 stress 0,2,0
bound -201,-199 -201,201 yvel=0
bound -121,-119 -201 201 yvel=0
bound hist sine (1,5.0)
hist n=25 sxy -160,-200 sxy -160,200  type=1
hist       xvel(-160,-200)  xvel(-160,200) xd -160 -200 xd -160 200
insitu stress 0 0 -1e-6
cyc 1500
pr max
pr hist 1 2 3 4 5 6
set log off
```

UDEC Data File for Miller Problem
(Continuously-Yielding Joint Model)

```
set log on
head
VERIFICATION TEST -- NORMALLY INCIDENT SHEAR WAVE; C-Y FRICTION
JOINT; ELASTIC
prop mat=1 jkn=1000 jks=1000 jfric=5.0 jtens=1e6 jr 1e-10 jif 1.5
prop mat 1 jes 0 jen 0
prop mat=5 d=0.00265 k=16667 g=10000
round 0.02
edge=10.0
block -200 -200 -200 200  -120 200 -120 -200
split -210,0 201 0
change mat=5 cons=1
gen -200 200  -200 200 auto 60
change jmat=1 jcons=3
bound mat=5
bound  -201,201 -201,-199 xvisc
bound -201 201 199 201 xvisc
bound -201 201 -201 -199 stress 0,2,0
bound yvel 0
bound hist sine (1.0,5.0)
hist n=5 sxy -160,-200 sxy -160,200  type=1
hist      xvel(-160,-200)  xvel(-160,200)
insitu stress 0 0 -1
cyc 1000
pr max
pr hist 1 2 3 4
save vta1cy.sav
hist write 3 cyel3.prn
start
head
VERIFICATION TEST -- NORMALLY INCIDENT SHEAR WAVE; C-Y FRICTION
JOINT;SLIPPING
prop mat=1 jkn=1000 jks=1000 jfric=0.5 jtens=1e6 jr 1e-10 jif
.4636476
prop mat 1 jes 0 jen 0
prop mat=5 d=0.00265 k=16667 g=10000
round 0.02
edge=10.0
block -200 -200 -200 200  -120 200 -120 -200
split -210,0 201 0
change mat=5 cons=1
gen -200 200  -200 200 auto 60
change jmat=1 jcons=3
bound mat=5
bound  -201,201 -201,-199 xvisc
```

```
bound -201 201 199 201 xvisc
bound -201 201 -201 -199 stress 0,2,0
bound yvel 0
bound hist sine (1.0,5.0)
hist n=5 sxy -160,-200 sxy -160,200  type=1
hist      xvel(-160,-200)  xvel(-160,200)
insitu stress 0 0 -1
cyc 1000
pr max
pr hist 1 2 3 4
save vta2cy.sav
hist write 3 cysl3.prn
hist write 4 cysl4.prn
ret
```

UDEC Data File for Miller Problem
(Barton-Bandis Joint Model)

```
set log on
head
VERIFICATION TEST -- NORMALLY INCIDENT SHEAR WAVE; B-B FRICTION
JOINT; ELASTIC
jhist on .01
prop mat=1 jkn=20000 jks=20000 jfric=5.0 jtens=1e6 aper .05
prop mat 1 jrc 1 jcs 100 sigmac 120 phir 0.0001
prop mat 1 lo 10000 jrc 0.001
prop mat=5 d=0.00265 k=16667 g=10000
round 0.025
edge=10.0
block -200 -200 -200 200  -120 200 -120 -200
split -210,0 201 0
change mat=5 cons=1
gen -200 200  -200 200 auto 60
change jmat=1 jcons=7
bound stress 0 0 -1
* bound xvel 0
damp auto
cy 1000
save vta0.sav
bound stress 0 0 1
cy 1
prop mat 1 phir 45
reset time
damp 0 0
bound mat=5
bound  -201,201 -201,-199 xvisc
bound -201 201 199 201 xvisc
bound -201 201 -201 -199 stress 0,2,0
bound yvel 0
bound hist sine (1.0,5.0)
hist n=5 sxy -160,-200 sxy -160,200  type=1
hist      xvel(-160,-200)  xvel(-160,200)
cyc 1500
pr max
pr hist 1 2 3 4
save vta1bb.sav
hist write 3 bbel3.prn
rest vta0.sav
head
VERIFICATION TEST -- NORMALLY INCIDENT SHEAR WAVE; B-B FRICTION
JOINT;SLIPPING
bound stress 0 0 1
cy 1
```

```
prop mat 1 phir 26.565
reset time
damp 0 0
bound mat=5
bound  -201,201 -201,-199 xvisc
bound -201 201 199 201 xvisc
bound -201 201 -201 -199 stress 0,2,0
bound yvel 0
bound hist sine (1.0,5.0)
hist n=5 sxy -160,-200 sxy -160,200  type=1
hist      xvel(-160,-200)  xvel(-160,200)
* insitu stress 0 0 -1
cyc 1500
pr max
pr hist 1 2 3 4
save vta2bb.sav
hist write 3 bbsl3.prn
hist write 4 bbsl4.prn
ret
```

COMPUTER PROGRAM

Code Name : CILVPR.FOR

```
c****************   Dynamic verification problem   *************
c*
c*    This program evaluates the radial velocity input profile at
c*     r=0.05h
c*****************************************************************
c
      common a(5000,5), ta(5000)
      real v(5000),fp(5000),vh(5000)
      character*80 title
c*
      cl=17.32
      per=1.2
      tt=1.4
      x=.5
      nt=1000
      nx=0
c
c
      write (*,*) ('cl   per   tt   x    nt  ')
      write (*,*) cl,per,tt,x,nt
      read(*,100) char
 100  format(a1)
c
c      if (x.le.0.0) go to 200
      nx=nx+1
c
      pi=4.0*atan(1.0)
      w=2.0*pi/per
      dt=tt/nt
      ca=-1.0/(2.0*pi*cl)
      cb=ca/(x*x)
      cc=cb*dt
c
      do 20 i=1,nt
      t=(i-1)*dt
      if (t.lt.0.5*per) then
        fp(i)=0.5*w*sin(w*t)
cxxxx          fp(i)=0.5*w*w*cos(w*t)
          nfp=i
      else
          fp(i)=0.0
```

```
      endif
   20 continue
c
      t0=x/cl
      j0=t0/dt
      j0=j0+1
c
      do 30 j=1,nt
         if(j.lt.j0) then
             vh(j)=0.0
         else
             t=t0+0.5*dt+(j-j0)*dt
             cf=t*cl/x
             cf2=cf*cf
             cs=sqrt(cf2-1.0)
c
c   velocity
           cg=(cf2-1.0)**1.5
            vh(j)=cc/cg
c   displacement
cxxxx                  cg=cs/t
cxxxx                  vh(j)=cc/cg
      endif
   30 continue
c
      v(1)=0.0
      do 60 i=2,nt
c     t=(i-1)*dt
      v(i)=0.0
      j1=min(nfp,i-1)
cccc   if (j1.lt.j0) goto 60
      do 40 j=1,j1
c     v(i)=v(i)+fp(j)*vh(i-j+1)
      v(i)=v(i)+fp(j)*vh(i-j)
   40 continue
   60 continue
      vmax=0.0
      do 80 i=1,nt
      ta(i)=(i-1)*dt
      a(i,nx)=v(i)
      vi=abs(v(i))
      vmax=amax1(vmax,vi)
   80 continue
   90 format ('  x= ',f6.3,'   nt= ',i5,5x,'   max= ',e12.4)
c
c       if (x.le.0.0) then
        open (3,file='cilvdx.out')
        write (3,*) title
```

```
         write (3,101) nt,dt
         write (3,102) (ta(j),a(j,nx),j=1,nt)
         close (3)
c       endif
  101 format (2x,i5,2x,f10.4)
  102 format (2(2x,e10.4))
c
      stop
      end
```

COMPUTER PROGRAM

Code Name : LSJEM.FOR

```
c*************    Dynamic verification problem *****************
c
c*    This program evaluates the dynamic response of the slip of
c*    a single discontinuity of infinite extent caused by an
c*    explosive loading. Analytical solution of a line source in
c*    an elastic medium with a  discontinuity is given by
c*    S.M. Day
c
c*****************************************************************
          dimension duf(2000),fil(2000)
          common /gplot/ nt,tt(2000),du(2000)
          complex cp,cetap,cetas,cr
c
      open(2,file='line.out')
c
c  input data nt=1000, dt=0.005, x=1 h=1 gamma=0 per=0.6 rho=1.0
c
 999  write (*,888)
 888  format (' nt dt x h gamma per rho',/)
      read(*,*) nt
      if(nt.eq.0) goto 1000
      read(*,*) dt,x,h,gamma,per,rho
      pi=3.14159
      vp=sqrt(3.)
      vs=1.
      xmin=0
      ymin=0
      r=sqrt(x*x+h*h)
      do 1 i=1,nt
      t=float(i)*dt
      tt(i)=t
      tau=t-r/vp
      if(tau.gt.0.) then
       t2r2=sqrt(t**2-(r/vp)**2)
        cp=cmplx(t*x/r**2,t2r2*h/r**2)
       cetap=csqrt(1./vp**2-cp**2)
       cetas=csqrt(1./vs**2-cp**2)
       cr=(1.-2.*vs**2*cp**2)**2+4.*vs**4*cetap*cetas*cp**2
       cr=cr+2.*vs*cetas*gamma
       dut=2.*vs**2/(pi*rho*vp**2)
       dut=dut*real(cp*cetap*cetas/cr)/t2r2
```

```
        du(i)=dut
       else
             du(i)=0.
       end if
    1  continue
       nf=int(per/dt+0.0001)
       if(nf.gt.1000) goto 1200
       do 2 j=1,nf
       ph=float(j)*dt/per
       if(ph.lt.1.) then
         fil(j)=sin(pi*ph)
       else
         fil(j)=0.
       end if
    2  continue
       sum=0.
       do 5 j=1,nf
    5  sum=sum+fil(j)
       do 4 i=1,nt
       duf(i)=0
       n=min(nf,i)
       do 3 j=1,n
    3  duf(i)=duf(i)+du(i-j+1)*fil(j)
    4  duf(i)=duf(i)/sum
       dmx=0.
       write(2,400)
  400  format (/,'   time     norm. slip',/)
c
       do 6 i=1,nt
       if(mod(i,10).eq.0) then
       time=float(i)*dt
       ftduf=4.*duf(i)
       write(2,500) time,ftduf
  500    format(1p,e12.4,5x,1p,e12.4)
       endif
       if(duf(i).gt.dmx) then
       dmx=duf(i)
       tmx=float(i)*dt
       endif
    6  continue
       ftdmx=4.*dmx
       print *,'max value of du = ',ftdmx
       print *,'time at max du = ',tmx
       go to 999
c
 1200  write(*,898)
  898  format(' nf exceeds fil dimension')
 1000  stop
       end
```

INPUT DATA FILE

```
****************************************************************
*
*  Verification problem for dynamic analysis using UDEC1.5
*
*    Joint model:    Coulomb
*    Dynamic Input:  Pressure
*
****************************************************************
*
*  INITIAL PROBLEM GEOMETRY
*
*   create block geometry
*
round 0.002
bl 0,-20 0,-.5 0.1913,-0.4619 0.3536,-0.3536 0.4619,-0.1913 &
   0.5,0 0.4169,0.1913 0.3536,0.3536 0.1913,0.4619 0,0.5    &
   0,20 40,20 40,-20
*
crack -5,-10 45,-10
crack -5,10 45,10
crack 20,-21 20,21
crack -1,-6 6,1
crack -1,6 6,-1
*
jdel
crack 5.01,0 21,0
jdel
*
* create finite difference zones
*
gen 0,40 -20,20 auto 0.65
*
save verf31bl.sav
*
*---------------------------------------------------------------
*  set material and joint properties
*
prop mat=1 d=1.0 k=166.67 g=100.0 &
           jkn=10000.0 jks=0.1 &
           tens=1.0e6 jtens=1.0e6
prop mat=2 jkn=10000.0 jks=10000.0 &
           jtens=1.0e6 coh=1.0e6 jcoh=1.0e6
```

```
*
change -1,41 -10.1,-9.9 ang -1 1 jmat=1 jcons=2
change -1,41 -21,-10.1  jmat=2   jcons=2
change -1,41 -9.9,21    jmat=2   jcons=2
*
*  set boundary material property
bound mat=1
*
*  set viscous boundary conditions along three sides
*
bound -1,41 -20.1,-19.9 xvisc yvisc
bound -1,41 19.9,20.1   xvisc,yvisc
bound 39,41 -21,21      xvisc,yvisc
*bound -0.1,0.6 -0.6,0.6 stress -1,0,-1
*  set stress boundary conditions along the semi-circular notch
bound -0.1,0.6 -0.6,0.6 stress -0.4244,0,-0.4244
*  set symmetry boundary conditions along the remaining side
bound -0.1,0.1 -21,21   xvel=0
*
*  set time function of the applied stress
bound hist sine 30 0.6
*
bound hist=func
*
insitu stress -1.0e-9,0,-1.0e-9
*
*  set histories
* contact address at coordinate 10,-10 is 1445
*
hist n=10 yvel (0,.6) xvel (.6,0) yvel (.6,0) yvel (0,-.6)
hist xvel (1.0,0.) yvel (1.0,0) xvel (10.,0) yvel (10.,0) xvel
(39.5,0)
hist yvel (39.5,0) syy (.6,0) sxx (.6,0) syy (39.5,0) sxx
(39.5,0)
hist add=1445,15
*
cyc 4000
save ver31st.sv2
ret
*
```

INPUT DATA FILE

```
*****************************************************************
*
*  Verification problem for dynamic analysis using UDEC1.5
*
*    Joint model:    Coulomb
*    Dynamic Input:  Velocity
*
*****************************************************************
*
*  INITIAL PROBLEM GEOMETRY
*
*   create block geometry
*
round 0.002
bl 0,-20 0,-.5 0.1913,-0.4619 0.3536,-0.3536 0.4619,-0.1913 &
   0.5,0 0.4169,0.1913 0.3536,0.3536 0.1913,0.4619 0,0.5    &
   0,20 40,20 40,-20
*
crack -5,-10 45,-10
crack -5,10 45,10
crack 20,-21 20,21
crack -1,-6 6,1
crack -1,6 6,-1
*
jdel
crack 5.01,0 21,0
jdel
*
gen 0,40 -20,20 auto 0.65
*
save verf31bl.sav
*----------------------------------------------------------------
*
*  set material and joint properties
*
prop mat=1 d=1.0 k=166.67 g=100.0 &
           jkn=10000.0 jks=0.1 &
           tens=1.0e6 jtens=1.0e6
prop mat=2 jkn=10000.0 jks=10000.0 &
           jtens=1.0e6 coh=1.0e6 jcoh=1.0e6
*
change -1,41 -10.1,-9.9 ang -1 1 jmat=1 jcons=2
change -1,41 -21,-10.1  jmat=2   jcons=2
change -1,41 -9.9,21    jmat=2   jcons=2
```

```
*
*  set boundary material property
bound mat=1
bound -1,41 -20.1,-19.9 xvisc yvisc
bound -1,41 19.9,20.1   xvisc,yvisc
bound 39,41 -21,21      xvisc,yvisc
bound -0.1,0.1 -21,21   xvel=0
*
*  set velocity boundary conditions along the semi-circular
boundary
bo -.05,.05 -.55,-.45 xvel=0 yvel=-1.0
bo .17,.21 -.48,-.45 xvel=0.383 yvel=-0.924
bo .33,.37 -.37,-.33 xvel=0.707 yvel=-0.707
bo .43,.47 -.21,-.17 xvel=0.924 yvel=-0.383
*
bo .48,.52 -0.05,0.05 xvel=1.0 yvel=0.0
*
bo .41,.45 .17,.21 xvel=.924 yvel=.383
bo .33,.37 .33,.37 xvel=.707 yvel=.707
bo .17,.21 .43,.47 xvel=0.383 yvel=0.924
bo -0.05,0.05 .45,.55 xvel=0 yvel=1
*
*  read time variation of velocity input from an external data
file
*  cilvdx.out is output from program cilvpr.for
*
bound hread=1 cilvdx.out
*
bound hist=1
*
insitu stress -1.0e-9,0,-1.0e-9
*
*  set histories
* contact address at coordinate 10,-10 is 1445
*
hist n=10 yvel (0,.5) xvel (.5,0) xvel (.35,0) yvel (.35,.35)
hist xvel (.19,-.46) yvel (.19,-.46)
hist  add=1445,15
*
cyc 4000
save ver31vl.sv2
stop
*-----------------------------------------------------------------
```

```
*
*    Verification of UDEC ICG1.5 for CNWRA: dynamic analysis
*
*    The problem is to determine the response of crack slip as a
     function of time caused by explosive loading along a
*    line source.  Analytical solution to this problem is given
*    by S.M. Day
*
*
*    velocity input
*
*****************************************************************
*---------------------------------------------------------------
round 0.002
bl 0,-20 0,-.5 0.1913,-0.4619 0.3536,-0.3536 0.4619,-0.1913 &
   0.5,0 0.4619,0.1913 0.3536,0.3536 0.1913,0.4619 0,0.5    &
   0,20 40,20 40,-20
*
crack -5,-10 45,-10
crack -5,10 45,10
crack 20,-21 20,21
crack -1,-6 6,1
crack -1,6 6,-1
*
jdel
crack 5.01,0 21,0
jdel
*
gen 0,40 -20,20 auto 0.65
*
save verf31bl.sav
*
*
res verf31bl.sav
*---------------------------------------------------------------
*
jhist on .01
prop mat=1 d=1.0 k=166.67 g=100.0 &
           jkn=10000.0 jks=10000. &
           tens=1.0e6 jtens=1.0e6  ln 2e-4 aper .050
prop mat=1 jrc .0001 jcs 100 sigmac 120 lo 100 phir .0001
prop mat=2 jkn=10000.0 jks=10000.0 &
           jtens=1.0e6 coh=1.0e6 jcoh=1.0e6
*
change -1,41 -10.1,-9.9 ang -1 1 jmat=1 jcons=7
change -1,41 -21,-10.1  jmat=2   jcons=2
change -1,41 -9.9,21    jmat=2   jcons=2
*
bound mat=1
bound -1,41 -20.1,-19.9 xvisc yvisc
bound -1,41 19.9,20.1   xvisc,yvisc
bound 39,41 -21,21      xvisc,yvisc
bound -0.1,0.1 -21,21   xvel=0
```

```
*
bo -.05,.05 -.55,-.45 xvel=0 yvel=-1.0
bo .17,.21 -.48,-.45 xvel=0.383 yvel=-0.924
bo .33,.37 -.37,-.33 xvel=0.707 yvel=-0.707
bo .43,.47 -.21,-.17 xvel=0.924 yvel=-0.383
*
bo .48,.52 -0.05,0.05 xvel=1.0 yvel=0.0
*
bo .41,.45 .17,.21 xvel=.924 yvel=.383
bo .33,.37 .33,.37 xvel=.707 yvel=.707
bo .17,.21 .43,.47 xvel=0.383 yvel=0.924
bo -0.05,0.05 .45,.55 xvel=0 yvel=1
*
*
bound hread=1 cilvdx.out
*
bound hist=1
*
insitu stress -1.0e-5,0,-1.0e-5
*
* contact address at coordinate 10,-10
*
hist n=10 yvel (0,.5) xvel (.5,0) xvel (.35,0) yvel (.35,.35)
hist xvel (.19,-.46) yvel (.19,-.46)
* hist add=1652,15 add=818,15
hist add 1445,15
hist sdis 1445
*
cyc 4000
save verf31.sav
ret
```

INPUT DATA FILE

```
*******************************************************************
*
*  Verification problem for dynamic analysis using UDEC1.5
*
*    Joint model:    Continuously-Yielding
*    Dynamic Input:  Pressure
*
*******************************************************************
*
*  INITIAL PROBLEM GEOMETRY
*
*   create block geometry
*
round 0.002
bl 0,-20 0,-.5 0.1913,-0.4619 0.3536,-0.3536 0.4619,-0.1913 &
   0.5,0 0.4169,0.1913 0.3536,0.3536 0.1913,0.4619 0,0.5    &
   0,20 40,20 40,-20
*
crack -5,-10 45,-10
crack -5,10 45,10
crack 20,-21 20,21
crack -1,-6 6,1
crack -1,6 6,-1
*
jdel
crack 5.01,0 21,0
jdel
*
gen 0,40 -20,20 auto 0.65
*
save verf31bl.sav
*------------------------------------------------------------------
*  set material and joint properties
*
*
prop mat=1 d=1.0 k=166.67 g=100.0 &
           jkn=10000.0 jks=0.1  jfric 0.00001 &
           tens=1.0e6 jtens=1.0e6 jen=0 jes=0 jif=1e-10 jr=1.0e-4
prop mat=2 jkn=10000.0 jks=10000.0 &
           jtens=1.0e6 coh=1.0e6 jcoh=1.0e6
*
*
change -1,41 -10.1,-9.9 ang -1 1 jmat=1 jcons=3
change -1,41 -21,-10.1  jmat=2   jcons=2
```

```
change -1,41 -9.9,21    jmat=2   jcons=2
*
*  set boundary material property
bound mat=1
*
*  set viscous boundary conditions along three sides
*
bound -1,41 -20.1,-19.9 xvisc yvisc
bound -1,41 19.9,20.1   xvisc,yvisc
bound 39,41 -21,21      xvisc,yvisc
*
*  set stress boundary conditions along the semi-circular notch
bound -0.1,0.6 -0.6,0.6 stress -0.4244,0,-0.4244
*  set symmetry boundary conditions along the remaining side
bound -0.1,0.1 -21,21   xvel=0
*
*  set time function of the applied stress
bound hist sine 30 0.6
*
bound hist=func
*
insitu stress -1.0e-9,0,-1.0e-9
*
*  set histories
* contact address at coordinate 10,-10 is 1445
*
hist n=10 yvel (0,.6) xvel (.6,0) yvel (.6,0) yvel (0,-.6)
hist xvel (1.0,0.) yvel (1.0,0) xvel (10.,0) yvel (10.,0) xvel
(39.5,0)
hist yvel (39.5,0) syy (.6,0) sxx (.6,0) syy (39.5,0) sxx
(39.5,0)
hist add=1445,15
*
cyc 4000
save ver41st.sv2
ret
*
*-----------------------------------------------------------------
*
```

INPUT DATA FILE

```
*****************************************************************
*
*  Verification problem for dynamic analysis using UDEC1.5
*
*    Joint model:    Continuously-Yielding
*    Dynamic Input:  Velocity
*
*****************************************************************
*
*  INITIAL PROBLEM GEOMETRY
*
*   create block geometry
*
round 0.002
bl 0,-20 0,-.5 0.1913,-0.4619 0.3536,-0.3536 0.4619,-0.1913 &
   0.5,0 0.4169,0.1913 0.3536,0.3536 0.1913,0.4619 0,0.5    &
   0,20 40,20 40,-20
*
crack -5,-10 45,-10
crack -5,10 45,10
crack 20,-21 20,21
crack -1,-6 6,1
crack -1,6 6,-1
*
jdel
crack 5.01,0 21,0
jdel
*
gen 0,40 -20,20 auto 0.65
*
save verf31bl.sav
*
*----------------------------------------------------------------
*
*
*  set material and joint properties
*
prop mat=1 d=1.0 k=166.67 g=100.0 &
           jkn=10000.0 jks=0.1  jfric 0.00001 &
           tens=1.0e6 jtens=1.0e6 jen=0 jes=0 jif=1e-10 jr=1.0e-4
prop mat=2 jkn=10000.0 jks=10000.0 &
           jtens=1.0e6 coh=1.0e6 jcoh=1.0e6
*
change -1,41 -10.1,-9.9 ang -1 1 jmat=1 jcons=3
```

```
change -1,41 -21,-10.1   jmat=2   jcons=2
change -1,41 -9.9,21     jmat=2   jcons=2
*
*  set boundary material property
bound mat=1
*  set viscous boundary conditions along three boundaries
bound -1,41 -20.1,-19.9 xvisc yvisc
bound -1,41 19.9,20.1    xvisc,yvisc
bound 39,41 -21,21       xvisc,yvisc
*  set symmetry boundary conditions along the remaining boundary
bound -0.1,0.1 -21,21    xvel=0
*
*  set velocity boundary conditions along the semi-circular
boundary
bo -.05,.05 -.55,-.45 xvel=0 yvel=-1.0
bo .17,.21 -.48,-.45 xvel=0.383 yvel=-0.924
bo .33,.37 -.37,-.33 xvel=0.707 yvel=-0.707
bo .43,.47 -.21,-.17 xvel=0.924 yvel=-0.383
*
bo .48,.52 -0.05,0.05 xvel=1.0 yvel=0.0
*
bo .41,.45 .17,.21 xvel=.924 yvel=.383
bo .33,.37 .33,.37 xvel=.707 yvel=.707
bo .17,.21 .43,.47 xvel=0.383 yvel=0.924
bo -0.05,0.05 .45,.55 xvel=0 yvel=1
*
*  read time variation of velocity input from an external data
file
*  cilvdx.out is output from program cilvpr.for
*
*
bound hread=1 cilvdx.out
*
bound hist=1
*
frac 0.05 .5
insitu stress -1.0e-9,0,-1.0e-9
*
*  set histories
* contact address at coordinate 10,-10 is 1445
*
hist n=10 yvel (0,.5) xvel (.5,0) xvel (.35,0) yvel (.35,.35)
hist xvel (.19,-.46) yvel (.19,-.46)
hist add=1445,15
*
*
cyc 4000
save ver41vl.sv2
stop
```