Understanding the Use of a Continuum Joint Model for the Analysis of an Excavated Drift

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Abstract

The response of an underground excavation in a geostatic stress field is simulated using a continuum representation of a jointed rock mass which averages the effects of individual joints with the matrix rock. To understand the rock mass response predicted by this model, the analysis is compared to predictions from an alternate model which uses explicit representations of the joints near the drift. The continuum model predicts joint response that is much greater than realized using explicitly-modeled joints. Certain structural effects of the intact rock between discrete joints near the drift are not well represented by the continuum model; this is primarily a local effect. The response of the rock mass farther from the drift compares relatively well.

Introduction

Finite element analyses are sometimes used to assist in the design of an excavated drift. If a drift is to be excavated in rock containing regularly spaced joints, the jointed rock can be represented by a continuum model which incorporates the anisotropic nature of the joints. Continuum models combine the response of individual joints and the intact matrix rock to predict the gross response of the material.

Several assumptions must be made to accept the gross response as a valid prediction of the behavior of jointed rock. One of these assumptions is that the characteristic length of a problem be large compared to the spacing of the joints. In the analysis of an excavated drift, the characteristic length of the problem will be determined by the size of the excavation and the magnitude of the stress gradients around the drift. If the size of the drift is of the same order as the joint spacing, the results predicted by the continuum material may smear some very significant effects of the interaction of individual joints with the matrix rock near the excavated drift. To more accurately observe the joint/matrix interaction, an alternate method of modeling the joints in the region of the drift was proposed by Blanford and Key (1987). In the region of the drift the joints are modeled using the continuum model in a *quasi-discrete* sense. The joints near the drift are modeled as thin strips of elements using continuum joint material and are separated by regions of isotropic elastic rock.

The purpose of this study was to gain insight into the smearing effects inherent in a continuum model by examining the differences between the quasi-discrete modeling and the continuum modeling for an excavated drift. These results are also compared to those obtained assuming isotropic elastic rock with a reduced modulus to account for the presence of the joints. The simulated excavation of the drift is instantaneous, and the results to be observed are the equilibrium stresses, displacements, joint closure and movement along joints around the drift as a result of the excavation. The following sections provide descriptions of each material representation and present a comparison of the results for each representation of the jointed rock mass.

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Continuum-Joint Description

Continuum descriptions for a rock mass containing sets of regularly spaced joints have been proposed by Morland (1974), Goodman (1976), and others. The gross response of a rock mass is calculated, combining the elastic response of the matrix rock and the shear and normal displacements of the joints. Morland identified several assumptions necessary for the continuum description to be a valid prediction of the behavior of a jointed rock mass: 1. The length scale in a problem is large compared to the joint spacing. 2. The thickness of the joint is small compared to the joint spacing. 3. The relative displacement across joints is small compared with joint spacing. 4. A representative element contains several joints. 5. The stress is approximately uniform over a representative element. 6. The tractions on each joint of a given parallel set are the same (i.e., each joint set within an element has the same response).

The Joint Empirical Model (JEM) (Blanford et al, 1987) combines the continuum description with constitutive laws for joint behavior that were derived by Barton (1982). Barton's constitutive laws are based on an empirical formulation in which the joint behavior is characterized by three parameters: the joint roughness, the joint wall compressive strength, and the residual friction angle. Barton's treatment of joints assumes that the joint's response is frictional in nature. The shear strength of a joint is directly proportional to the normal stress acting on it, and the joint will not slip unless its current shear strength is exceeded.

JEM was developed for use in two- or three-dimensional finite element programs. It solves for stress equilibrium between the matrix elastic material and up to four sets of joints at arbitrary orientations. The behavior of each of these joint sets is defined by their normal and shear response to a loading. The normal and shear stresses across the joint are continuous with the stresses in the intact matrix rock. The strain in the matrix material and the strain on the joint are additive. Given a strain increment produced from an increment of applied load, JEM solves for simultaneous equilibrium between the matrix and all the joint sets.

Quasi-Discrete Representation

The quasi-discrete representation of joints in a rock mass employs the JEM continuum model in a thin strip of elements at the location of a joint (Blanford and Key, 1987). The properties of the continuum material are retained except for the joint spacing, which is set equal to the width of the strip. The strip imitates a discretely-modeled joint (hence the term *quasi-discrete*), with intact elastic, isotropic material on each side of the strip. The major advantage to using a quasi-discrete representation for the jointed rock is that in regions of high stress gradients, the sections of the intact elastic rock can carry significant stresses compared to the joint. The continuum model distributes the effect of jointing across each element; but the quasi-discrete model distinguishes the effects of jointing from the matrix, thus allowing greater resolution of the stress and displacement field and the increased strength between joints. The major disadvantages are the additional time required to build the finite element mesh and some additional computation time that may be required by the finite element program.

Blanford and Key (1987) have used the continuum description to model joints in the quasi-discrete sense for an analysis of a pressurized slot. They found that the displacements and the extent of the stress relief from the excavation of the slot were significantly greater using the continuum model than predicted with the quasi-discrete model.

Isotropic Elastic Representation

Isotropic elastic material models have been used to represent jointed rock masses by reducing elastic material property constants to account for the presence of in situ joints. The reduction in the elastic modulus to account for the presence of joints is most significant in the direction normal to the joint set, but isotropic elastic constants can be obtained by averaging the constants from each direction or by assuming the same reduction in each direction. The method adopted here for reducing the elastic constants follows Blanford and Key (1987); the derivation is founded on basic principles of a continuum description of jointed rock described by Morland (1974). Regardless of the method of calculating reduced isotropic elastic constants, the anisotropy and reduced shear strength due to jointing will obviously not be accounted for by this approach.

Problem Description

A plane strain analysis simulated a 3-m wide by 4.5-m high instantaneous excavation in a rock mass containing horizontal joints spaced 1 m apart. Symmetry at the centerline of the drift allowed the analysis region to be reduced. Assuming a series of drifts were excavated in parallel (such as for a waste repository), the right vertical boundary was also a symmetry plane. One hundred meters above the drift the overburden was simulated by an applied pressure boundary of 5 MPa, and gravity loading was applied throughout the domain. The lower boundary was one hundred meters below the floor of the drift and was restrained vertically. The finite element mesh (Fig. 1) used for all the analyses contained 2100 nodes and 1976 four-node quadrilaterals. The various representations of the jointed rock mass described above were accommodated by simply varying the material designations within this single mesh. The ten strips used to model the quasi-discrete joints in the region of the excavated drift are darkened in Fig. 1 for identification.

The analysis begins with initial equilibrium stresses and ends with the equilibrium stresses computed after an instantaneous excavation. SANCHO (Stone et al, 1985), a dynamic relaxation finite element computer code for the quasistatic, large deformation, inelastic response of two-dimensional solids, was used for each of the calculations.

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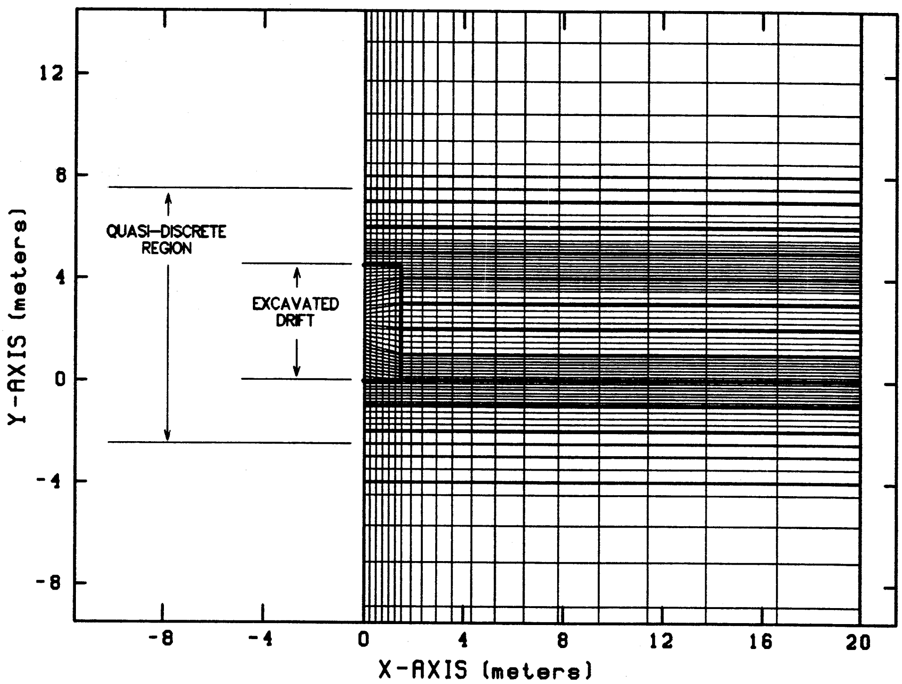

Figure 1: Closeup of the Finite Element Mesh.

Results

A comparison of results illustrates distinct differences between the continuum and quasi-discrete representations of the rock mass. In the quasi-discrete model, the response of each section of intact rock separating the joints resembles the behavior of a slab with a distributed load. Shear displacement occurs on the joints (between the slabs) as the slabs bend inward toward the excavated region. We might expect the continuum representation to simply smear these results and provide displacements that are averages of the joint and slab interaction. But more than a simple average is involved in the continuum model, and the results can be very misleading near the drift.

Fig. 2 compares the horizontal displacements calculated by the two jointed rock mass representations. This sketch utilizes the symmetry of the analysis region by plotting the results of the quasi-discrete representation on the left side and the results of the continuum representation on the right side. The locations of the quasi-discrete joints are easily observed at 1-m intervals from 2 m below to 7 m above the floor of the excavated drift. For the continuum, contours of the same displacement extend about five percent farther from the drift than for the quasi-discrete case.

The bending of the elastic slabs in the quasi-discrete representation is easily observed in a vertical profile comparing the horizontal stress along the centerline of the excavated drift. Fig. 3a shows the stress calculated by the continuum joint model (solid line), the isotropic elastic calculation (dotted line) and the quasi-discrete model (dashed line). Since the horizontal stress can be discontinuous across horizontal joint planes, the stress computed in each quasi-discrete element is simply indicated by an "×" in this figure. As the elastic slabs above and below the drift bend inward, the edges closer to the drift experience tension relative to the in situ stress and the outer edges experiences relative compression. In the continuum representation horizontal stresses above and below the drift are relatively unaffected by the excavation. Averaging the effects of the joints in the continuum reduces the shear strength, so the material cannot develop the resistance to bending that is inherent in a slab structure. The isotropic elastic representation retains some of the bending response of the rock above and below the drift, but it is not nearly so pronounced as when there are separate slabs of material. The material in the elastic model experiences relative tension close to the drift and relative compression at about a meter depth into the modeled rock.

Fig. 3b and c compare the joint response along the vertical slice with the greatest quasi-discrete joint

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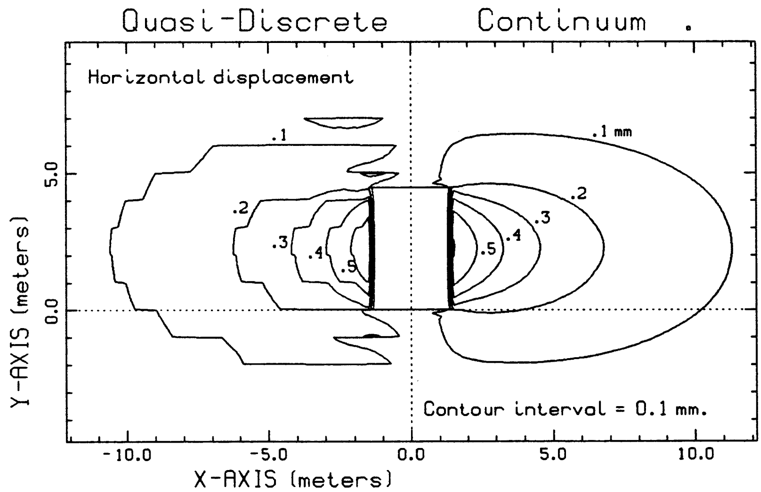

Figure 2: Comparisons of Horizontal Displacement around the Excavated Drift.

movement; this occurs approximately 0.9 m from the centerline of the drift. Joint shear was initially zero throughout the domain. Upon excavation, joints near the drift experience shear deformation in response to the stress redistribution. The continuum model predicts shear in excess of 1 mm near the drift, shown by the solid line in Fig. 3b. When individual joints are isolated—as in the quasi-discrete calculation—no single joint slips more than 0.2 mm. A similar effect is seen for changes in joint aperture in Fig. 3c. Initially compressed to about 20 μm of closure by the in situ stress, the joint opening caused by the excavation appears to be in excess of 30 μm as predicted by the continuum model. In another location the calculated joint opening exceeded 50 μm. The quasi-discrete calculation shows that actual joint opening at this location is of the order of 10 μm. The differences in the two calculations are related to the strength of the intact rock section that may exist around an excavated drift. The structural support of the slabs serves to restrain the deflection of the rock into the drift. Without this support, the continuum material exhibits unrealistically high shear displacements and joint opening near the excavated surface.

A horizontal profile along the location of the quasi-discrete joint one-half meter above the roof of the drift (Fig. 4a,b) also illustrates these effects. The width of the excavated drift extends to 1.5 m on these profiles. Above the excavated drift the continuum model has very little normal stress on the joints to retain any joint closure or prevent joint shear. The joints are also opened in the quasi-discrete model but the unloaded region of the joint is much narrower because of the structural effects of the slab. The exaggerated response of the continuum material is confined primarily to the regions immediately above and below the drift. The response in the region of the pillar does not differ between the two representations of the rock.

Conclusions

The continuum model tends to exaggerate the joint response near an excavated drift. In this region the quasi-discrete model allows a better representation of the structural effects of the intact rock between joints. In actuality, the continuum assumptions on which the continuum modeling is based are easily

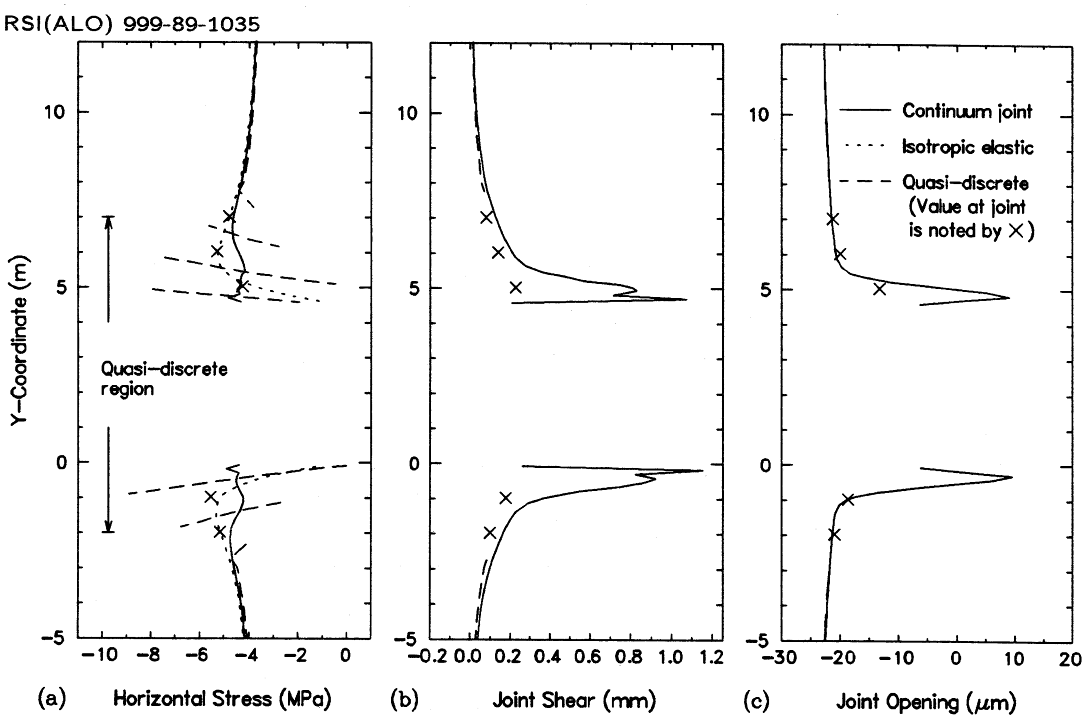

Figure 3: Comparison of Calculated Results along a Vertical Profile.

violated near the drift so that the predictions are simply not valid. To obtain accurate predictions of joint slippage and joint opening near an excavation, the quasi-discrete representation is a suitable alternative to the continuum representation.

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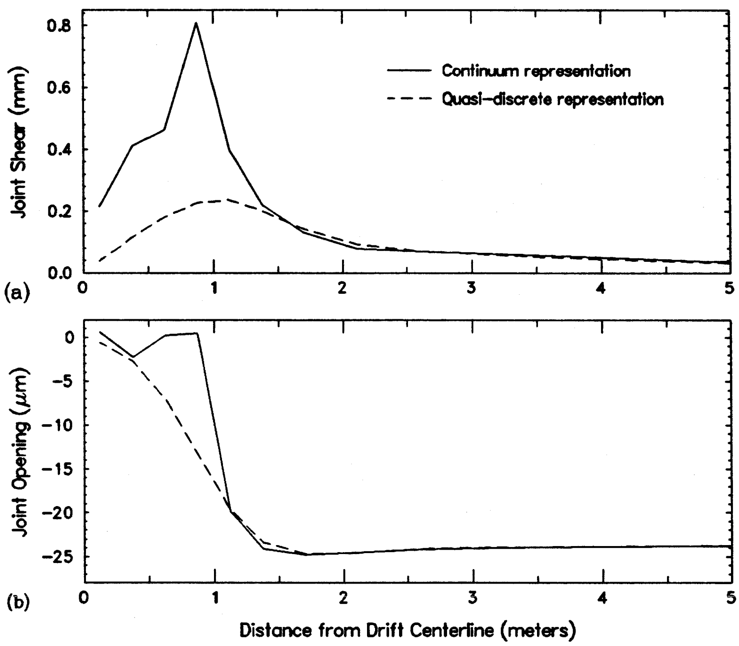

Figure 4: Comparisons of (a) Joint Shear and (b) Joint Opening along Location of Quasi-Discrete Joint One-Half Meter above the Drift.

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