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24 May 1988

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"NRC Technical Assistance
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Dear Naiem:

Enclosed is Itasca Document Review 006-01-59, "Modification of Rock Mass Permeability in the Zone Surrounding a Shaft in Fractured Welded Tuff" (SAND86-7001). Please call me if you have any questions.

Sincerely,

Roger D. Hart

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Program Manager

cc: R. Ballard, Engineering Branch
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ITASCA DOCUMENT REVIEW

File No.: 006-01-59

Document Title: "Modification of Rock Mass Permeability in the Zone Surrounding a Shaft in Fractured Welded Tuff" by John B. Case and Peter C. Kelsall (SAND86-7001, March 1987)

Reviewer: Itasca Consulting Group, Inc. (K. Wahi, M. Christianson and L. Lorig)

Approved: M Board Itasca

Date Approved: May 24, 1988

Significance to NRC Waste Management Program

Changes in the host rock permeability can adversely affect the performance of a repository site in terms of its ability to limit the radionuclide release rate via groundwater and/or air flow. The zone surrounding an opening, such as a drift or a shaft, experiences stress changes and possible rock failure as a result of excavation. Stress redistribution as well as excavation-induced damage can increase rock permeability in the vicinity of an opening. The subject document presents a model of permeability changes as a function of radial distance from a shaft opening. This model, among others, has been used by DOE in making preliminary estimates of the extent of a damaged zone. The results and recommendations are likely to be relied on in performance assessments presented in support of a license application. The quantitative nature of the predicted changes in permeability for the modified zone provides a reasonable basis for performing sensitivity analyses. Yet, the assumptions inherent in the model and analyses presented need careful evaluation.

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Summary of the Document

Excavation of vertical shafts to provide access to the repository horizon has the potential to damage the surrounding rock. This, in turn, could create a preferential pathway for groundwater and/or air flow and radionuclide transport. The extent of a zone surrounding a shaft opening in which the permeability might be modified by the excavation process is investigated. The dominant processes leading to permeability changes are postulated as being stress redistribution and blast damage. Fracturing of originally intact rock and opening/closing of preexisting fractures are two mechanisms associated with stress redistribution thought to affect permeability. Simple analyses of a circular shaft in a homogeneous, isotropic and linear elastic medium show that the maximum tensile or compressive stresses at the shaft wall (at repository depth) are a small fraction of the strengths. Although, creation of new fractures due to stress redistribution is unlikely, the effects of stress changes across fractures may have a significant effect on permeability. The four vertical shafts are planned to be excavated by blasting. Some damage to the adjacent rock is expected that could enhance permeability in the zone in which new fractures are created. The proposed model development consists of five steps.

1. Obtain analytical solution (elastic or elastoplastic) of modified stress field due to shaft excavation assuming an initially uniform stress field.

2. Establish stress versus permeability relation(s) based on published field and laboratory data.

3. Calculate rock mass permeability as a function of radial distance based on results of Steps 1 and 2.

4. Estimate additional permeability change due to blasting based on case histories.

5. Integrate results of Steps 3 and 4 to quantify effects on permeability of stress redistribution and blasting.

At any point from the shaft wall into the rock mass, the stress field can be calculated using the Kirsch solution. In a horizontal cross-section, when $\sigma_{h1} = \sigma_v = 6.84$ MPa and $\sigma_{h2} = 1.71$ MPa, the maximum compressive and tensile stresses at the shaft wall are calculated as 18.82 MPa and -1.72 MPa. Both values are roughly 10% of the respective compressive or tensile strength for intact rock. Analyses with further simplifications, in which $\sigma_{h1} = \sigma_{h2}$, were conducted in support of the modified permeability zone calculations. Kirsch's elastic and an elasto-plastic solution based on the failure criterion of Hoek and Brown were used to predict the stress-strain response around the shaft opening. Two laboratory tests and field test data from the G-Tunnel Block Test were used to construct a fracture permeability versus normal stress relation. Effects of pore pressure and temperature were ignored. Analyses conducted at shaft depths of 100m and 310m represent a range of expected rock conditions. Upper- and lower-bound estimates of permeability change are computed by considering expected mean and extreme values of rock strength, in-situ stress, and postulated permeability-stress relation. Intact rock compressive strength range of 110-230 MPa, Rock Mass Quality (RMQ) range of 48-84, and an in-situ stress ratio range of 0.25-1.00 are used. At both depths, inelastic behavior adjacent to the shaft wall is predicted when the lower-bound rock mass strength and upper-bound in-situ stress condition are used. For all other cases, the predicted behavior is elastic and the associated permeability increase is less than an order of magnitude.

The predicted permeability increase for the inelastic response case, when the upper-bound sensitivity of permeability to stress is used, is up to two orders of magnitude. The width of blast damage is known to vary from roughly 0.3m to 2.0m, depending on the blasting method. The combined effects of stress redistribution and blast damage provide a series of models for the modified permeability zone. An equivalent rock mass permeability in the modified zone is defined by averaging the predicted permeability over an annulus one radius wide around the shaft and normalized to the permeability of undamaged rock, as shown in Table 1. The equivalent permeability for the "expected" conditions at 310m depth is estimated as being 20 times that of the undisturbed rock mass. For the upper-bound conditions, the equivalent permeability is 80 times the undisturbed value.

Table 1

EQUIVALENT PERMEABILITY OF THE MODIFIED PERMEABILITY ZONE[a]
[adapted from SAND86-7001, March 1987]

| DEPTH | STRESS REDISTRIBUTION WITHOUT BLAST DAMAGE | | EXPECTED CASE[b] | UPPER BOUND CASE[c] |
|---|---|---|---|---|
| | ELASTIC | ELASTOPLASTIC | | |
| 100 | 15 | 20 | 20 | 40 |
| 310 | 15 | 40 | 20 | 80 |

[a]Equivalent permeability is averaged over an annulus 1 radius wide around the 4.4 m (14.5 ft) diameter exploratory shaft.

[b]This is based upon an elastic analysis with expected strength, insitu stress, sensitivity of permeability to stress, and a 0.5 m wide blast damage zone.

[c]This is based upon an elastoplastic analysis with lower bound strength, upper bound insitu stress, greatest sensitivity of permeability to stress, and a 1.0 m wide blast damage zone.

Problems, Limitations and Deficiencies

The lower- and upper-bound sensitivity of permeability to stress may be the primary factor in the predicted increase in rock mass permeability, rather than elastic versus inelastic conditions as implied on p. 3 of the document.

It is unclear whether the absolute radius of the shaft has any influence on the width of the blast damage since multiple charge holes and rounds are used in excavating to the final shaft size. It is possible that charge density may drop as the blasted volume increases.

The two-dimensionality of the stress analysis and the simplified assumption of equal horizontal stresses rule out the shear failure mode. In addition, permeability enhancement due to slip or shear movement along joints (or fracture) has not been investigated.

The fracture density and fracture frequency values quoted give no indication of the directional spacing (i.e., vertical horizontal, or angled). Vertical direction aperture changes of horizontally oriented fractures are ignored due to the cross-section and the analysis method chosen.

It is not clear whether the borehole diameter referred to in Fig. 5 on p. 15 is meant to be the charge hole diameter. If it is meant to imply the size of the excavated hole (e.g., 4.4 m ES diameter), the blast damage zone could be considerably larger than the 0.3 to 2.0m assumed elsewhere in the document.

The assertion that a higher horizontal to vertical stress ratio is an upper bound condition is questionable because it ignores the larger differential stresses for the case when the stress ratio is lower. Similarly, using a lower stress ratio might result in elastoplastic rather than elastic response obtained otherwise.

In Fig. 9 (p. 28) it is not clear if the variation of the plastic zone size with depth is computed by using constant values of RMR and $\sigma_u$.

On p. 32, the statement "Peters et al. (1984, Tables A.8-A.11) calculated that the equivalent smooth wall aperture at maximum closure changed from about 3 μm to about 38 μm" appears to be in error—unless the word "changed" is meant to be "ranged".

It is unclear why the extensive data base from the G-Tunnel Heated Block Test is not used in support of this discussion (see Zimmerman et al. 1986, pp. 11-17).

The purported insensitivity to stress change above a stress level of 3 to 4 MPa (p. 37) is marginally supported by the data presented in Fig. 15 (p. 38). The field data presented consist of a total of four data points of a load-unload test and do not lead to the stated conclusion. Only one of the two laboratory tests supports the assertion that permeability is insensitive above a stress change of 3 or 4 MPa. Although all field data from the G-Tunnel Heated Block are not discussed, many more measurements were taken showing a near complete insensitivity above 4 MPa.

It is not clear how the curves in Fig. 16 (p. 39) were derived. It does not appear that the curves were obtained from laboratory data or from Peters et al. (1984). Exhibit 1 shows a comparison of the actual laboratory data in Fig. 15 (p. 38) plotted on the same scale as estimated upper and lower bounds in Fig. 16. Exhibit 1 indicates that both curves in Fig. 16 lie above the corresponding laboratory data.

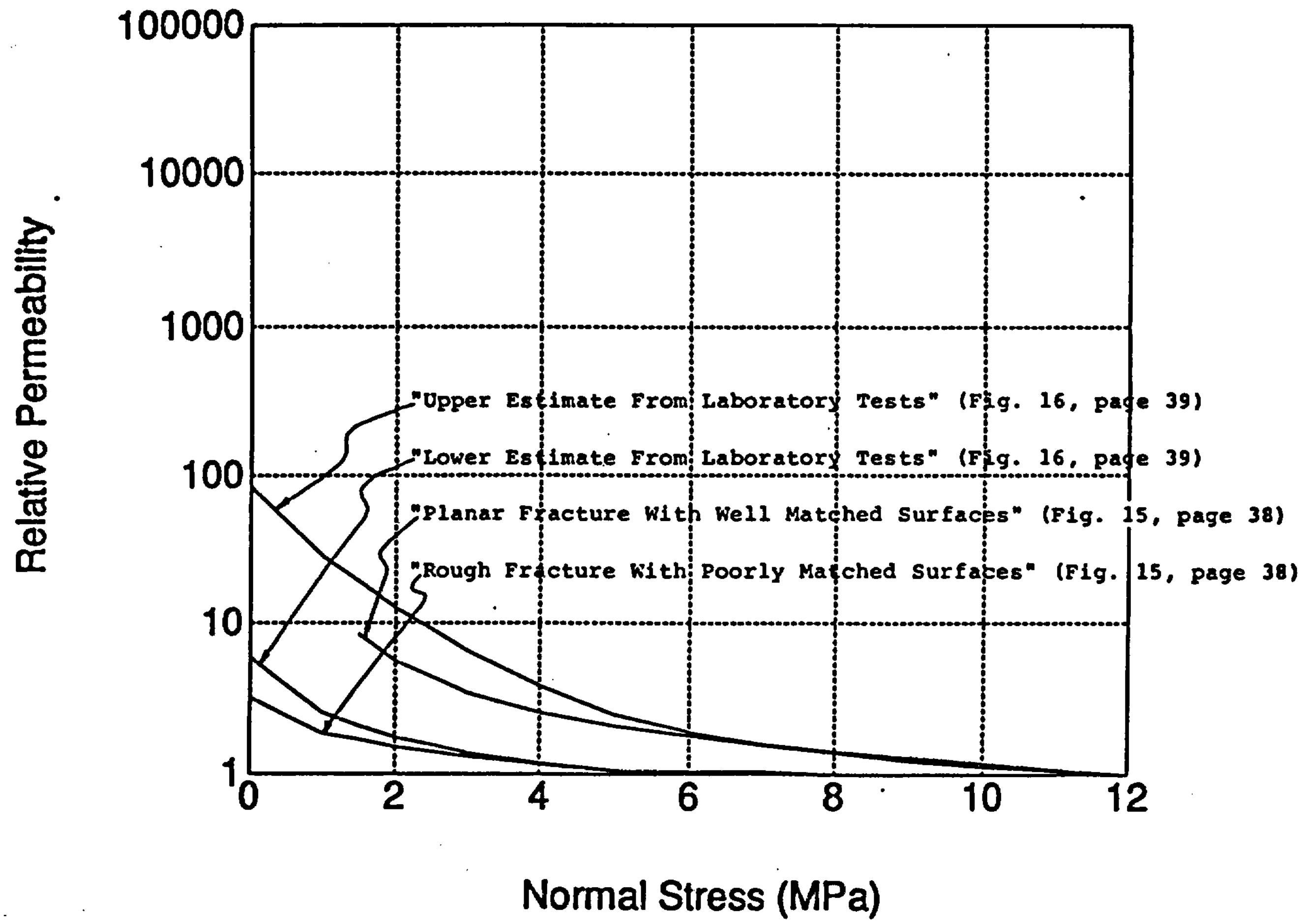


Exhibit 1 Comparison of Reported and Estimated Laboratory Relations Between Effective Normal Stress and Relative Permeability

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It also does not appear that Peters et al. (1984) has been used to calculate curves in Fig. 16. Rewriting the normal stress-closure relation [Eq. (1)] given by Peters et al., the aperture can be calculated as:

$$\sigma_n = A \left[ \frac{U_n}{U_n^0 - U_n} \right]^m \tag{1}$$

where, for cases in which m = 1,

$\sigma_n$ = normal stress,

$U_n$ = normal closure,

A = half-closure stress, and

$U_n^0$ = unstressed aperture.

We can rewrite Eq. (1) to solve for $U_n$:

$$U_n = \frac{U_n^0 \sigma_n}{A + \sigma_n} \tag{2}$$

Solving for current aperture, b,

$$b = U_n^0 \left[ 1 - \frac{\sigma_n}{A + \sigma_n} \right] \tag{3}$$

Using Eq. (3) and the values of A and $U_n^0$ reported in Appendix O of the SCP-CDR (SNL, 1987), the aperture at any normal stress can be calculated. For relative permeability calculations, $U_n^0$ becomes unimportant, and any changes in the value of A cause relative permeability changes. The permeability ratios are calculated relative to the aperture at 12 MPa normal stress. This results in a relative permeability increase, at 0 MPa, of 343 to

15,625 for values of A of 2 to 0.5, respectively, as shown in Exhibit 2. It is important to note that, at low values of normal stress, the injection fluid pressure becomes a very important factor because the fluid pressure can cause an increase in aperture.

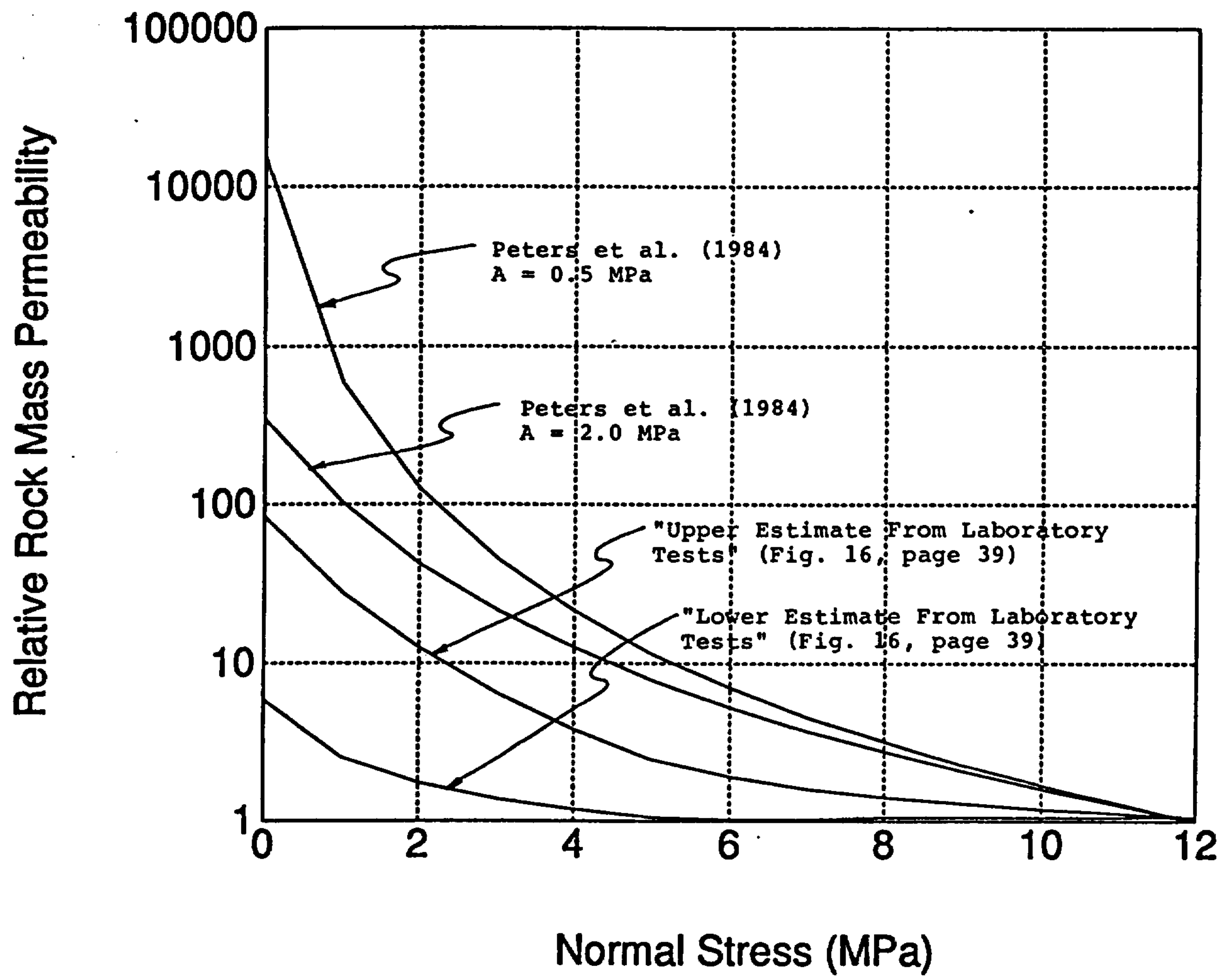


Exhibit 2 Comparison of Two Estimated Laboratory Relations [Case and Kelsall (1987) and Peters et al. (1984)] Between Normal Stress and Relative Permeability

The term "axial" rock mass permeability has been used (p. 41) but not defined. One can only assume that it refers to aperture width in a horizontal plane through which vertical flow can occur. This should be clarified.

Only one of the fourteen case histories, shown in Table 3 (p. 45) of measured blast damage pertains to tuff.

The 1-radius wide annulus over which the modified permeability zone is averaged appears to be an arbitrary selection that might give the false impression that damage is limited to one radius. Admittedly, lower equivalent permeability increases would result when a wider annulus is considered. Nevertheless, a realistic dimension over which significant permeability change occurs should be considered as well.

The document makes no comment on the implication on seal design or a need for seals.

The constitutive relations presented in Section 4 are possibly outdated. A number of papers have been published more recently (i.e., after 1981) that should have been considered in the analysis.

## Recommendations

The work reported in the document is a very good first step that needs to be carried further. The concepts are acceptable, but the specific methods and analyses utilized could be improved. More site-specific data (and laboratory measurements) are needed to construct a more reliable permeability versus stress data base.

Greater consideration of the actual joint orientation in calculation of flow around the shaft needs to be considered. The flow is likely to be anisotropic due to the effects of isolated permeable features rather than a continuum, isotropic phenomena. Perhaps greater emphasis should be placed on case histories of shaft sinking in actual mines.

The analyses need to consider the anisotropic stress field that actually exists at the site. This will necessitate three-dimensional models and analyses. It will also permit a consideration of other important failure modes (e.g., shear) and possible permeability modification in all three directions.

The effects of alternative shaft construction methods should also be addressed.

Data should be obtained during the site characterization which would permit construction of peak particle velocity versus radial distance curves (such as those illustrated in Fig. 23 of the document) at charge densities of interest. An identification of the particle velocities at which incipient fracturing in the host rock (Topopah Spring tuff) occurs is also necessary in order to estimate the extent of the blast damage.

A more up-to-date consideration of the constitutive relation between permeability and stress is necessary. Much work has been reported by LBL researchers in the last six to eight years that is relevant to the problem at hand.

NRC should consider performing independent evaluation of the assumptions, models, and results shown in the document. Appendix A of this review gives an example of the type of study possible.

## References

Peters, R. R., E. A. Klavetter, I. J. Hall, S. C. Blair, P. R. Heller and G. W. Gee. Fracture and Matrix Hydrologic Characterization of Tuffaceous Materials from Yucca Mountain, Nye County, Nevada. Sandia Report SAND84-1471, 1984.

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APPENDIX A

# PRELIMINARY NUMERICAL SENSITIVITY STUDY OF FACTORS INFLUENCING THE CHANGE IN PERMEABILITY IN ROCK MASS SURROUNDING A SHAFT IN TUFF

M. Christianson and L. Lorig

May 1988

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## INTRODUCTION

This appendix describes numerical analyses, using UDEC Version ICG1.4 (Itasca 1988), aimed at evaluating the sensitivity of two parameters, initial joint aperture and joint stiffness, in calculating the relative permeability changes in the rock mass surrounding a shaft in tuff. Similar calculations based on closed-form analytical solutions have been reported by Case and Kelsall (1987). These authors used changes in radial stress and relations between effective normal stress and relative rock mass permeability (see Case and Kelsall (1987), Fig. 16) to obtain estimates of relative rock mass permeability as a function of radial distance from the shaft wall (see Case and Kelsall (1987), Fig. 24). The approach followed by these authors assumes that a set of ubiquitous concentric fractures surround the shaft and that the presence of these fractures does not influence the stress distribution around the shaft. This appendix gives the results of numerical calculations which explicitly took account of the presence of the joints.

## NUMERICAL ANALYSES USING UDEC

The distinct element code UDEC was used to explicitly model a limited number of concentric fractures surrounding a shaft. The location of the fractures relative to the shaft are shown in Fig. A-1. Blocks are discretized into constant finite difference triangles, as shown in Fig. A-2. The rock was assumed to behave linearly elastically, and the following elastic properties were assigned:

$$E = 15.1 \text{ GPa}$$

$$\upsilon = 0.2$$

An isotropic in-situ stress of 7 MPa was also assumed (expected stress at 310m depth).

Joints were assumed to have constant normal and shear stiffness. Two assumptions for joint normal stiffness (JKN) were used:

$$JKN = 1E13 \text{ Pa/m}$$

or

$$JKN = 1E11 \text{ Pa/m}.$$

These two assumptions provide reasonable bounds to a non-linear joint stiffness reported by Peters et al. (1984), as shown in Fig. 3.

The modeling sequence for each analysis consisted of two stages. In the first, the model was brought to equilibrium with the assumed in-situ stresses. In the second stage, shaft excavation was simulated by removing constraints on the shaft periphery, permitting inward displacement of points outside the shaft.

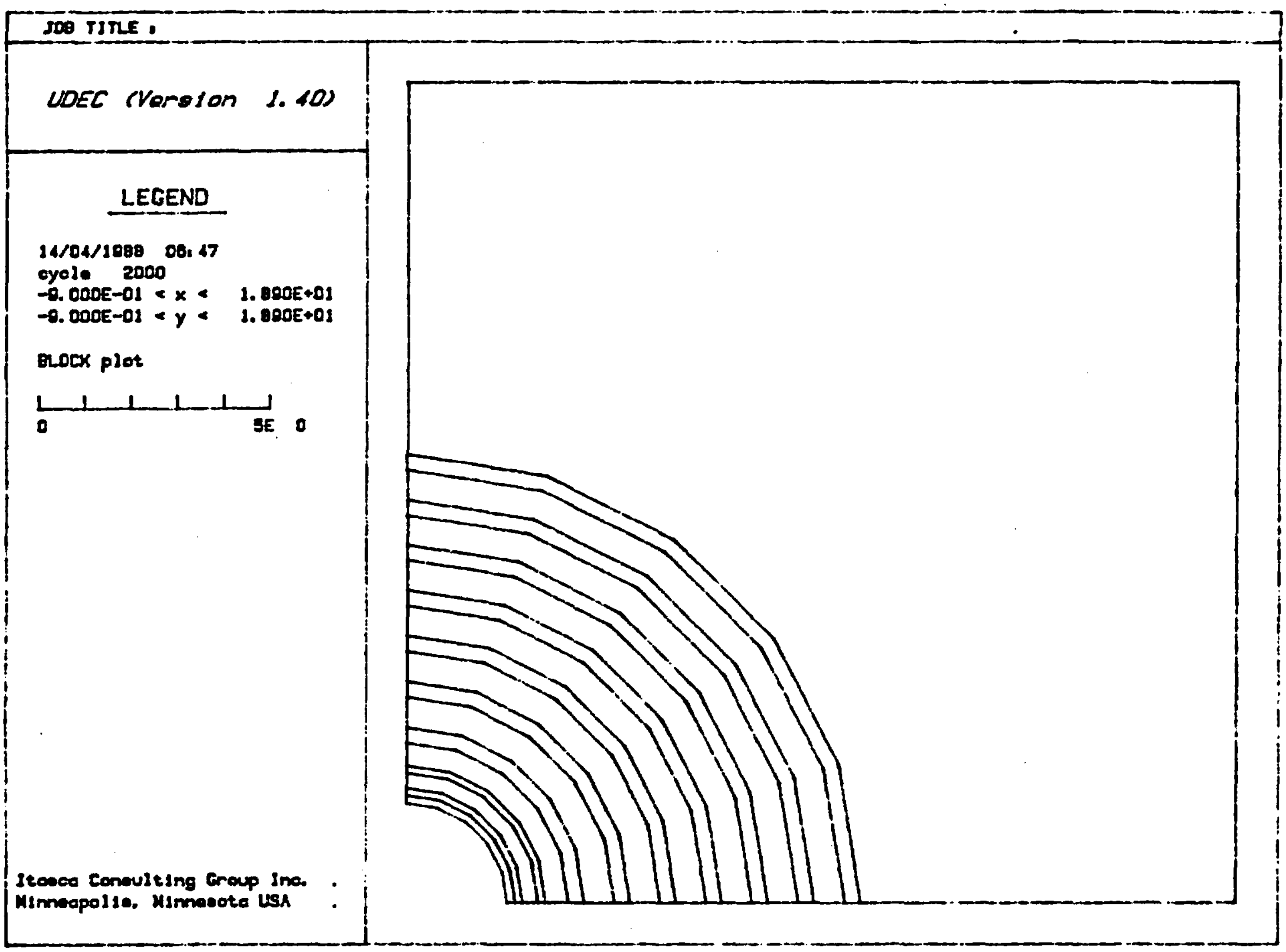


Fig. A-1(a) Boundary Locations and Joint Pattern Used in Sensitivity Study of Factors Influencing Changes in Rock Mass Permeability in Zone Surrounding a Shaft (quarter-symmetry assumed)

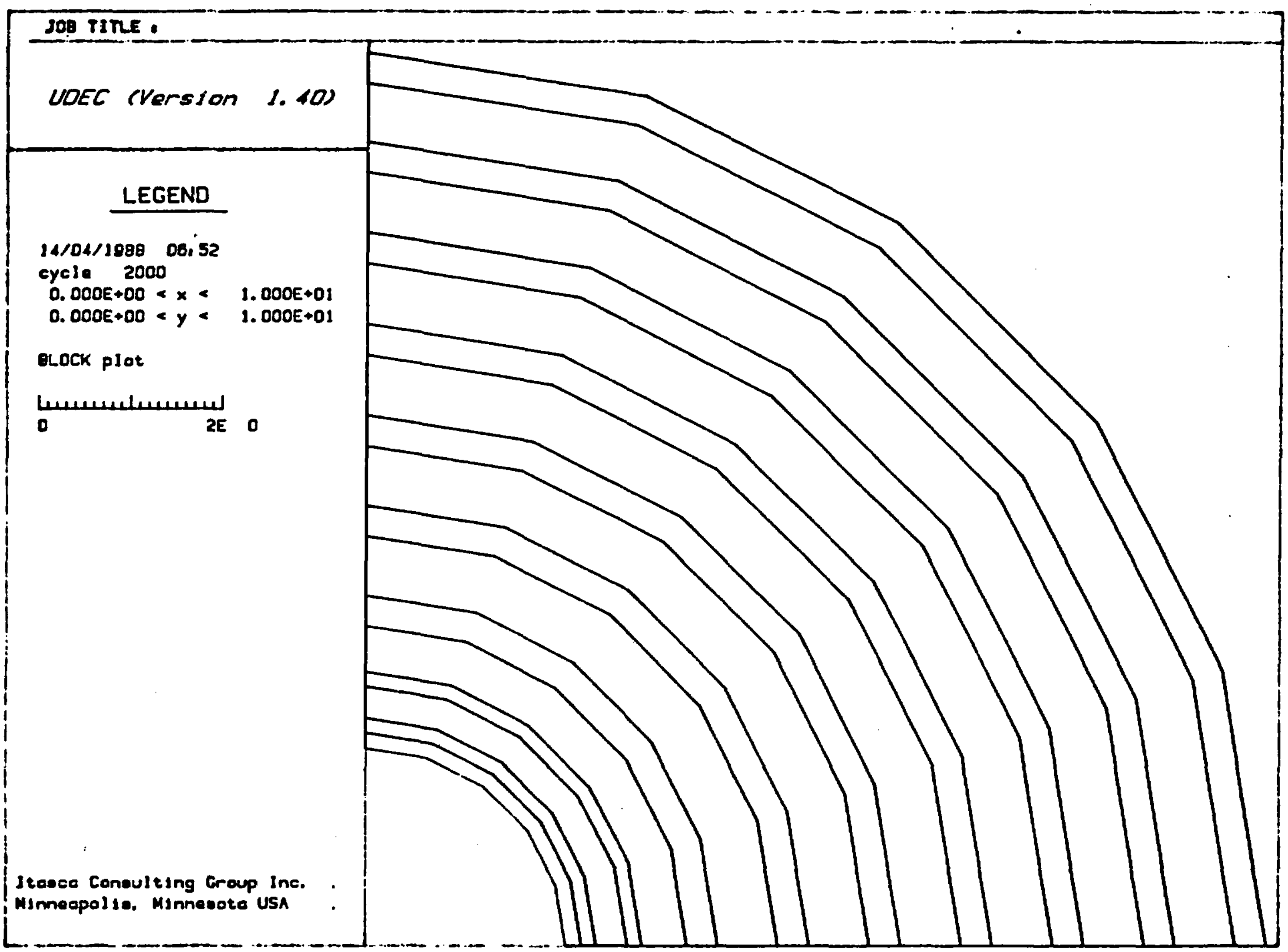


Fig. A-1(b) Close-Up View of Jointing Pattern Around Shaft
(quarter-symmetry assumed)

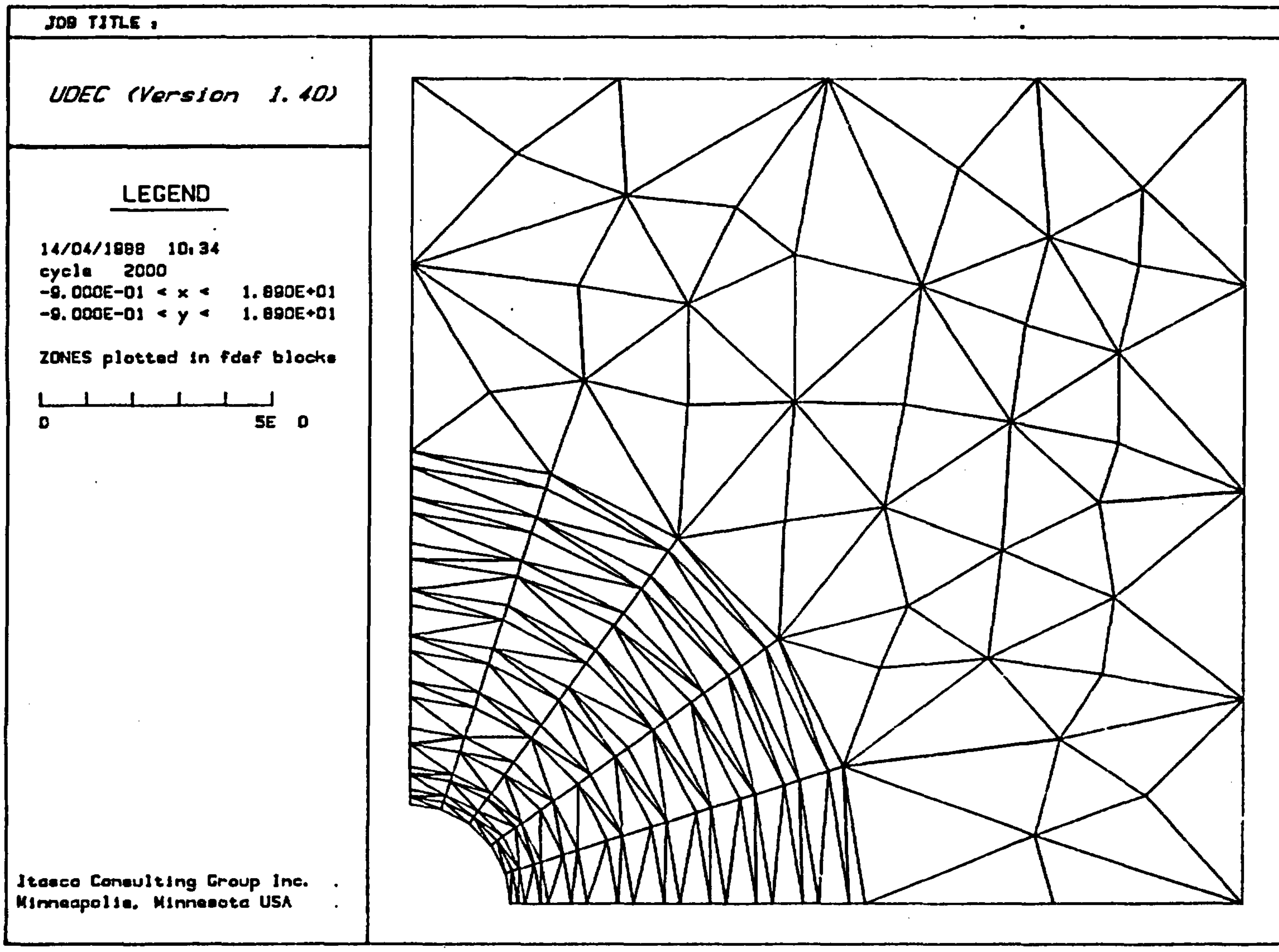


Fig. A-2 Discretization of Rock Mass Into Constant Stain Finite Difference Triangles

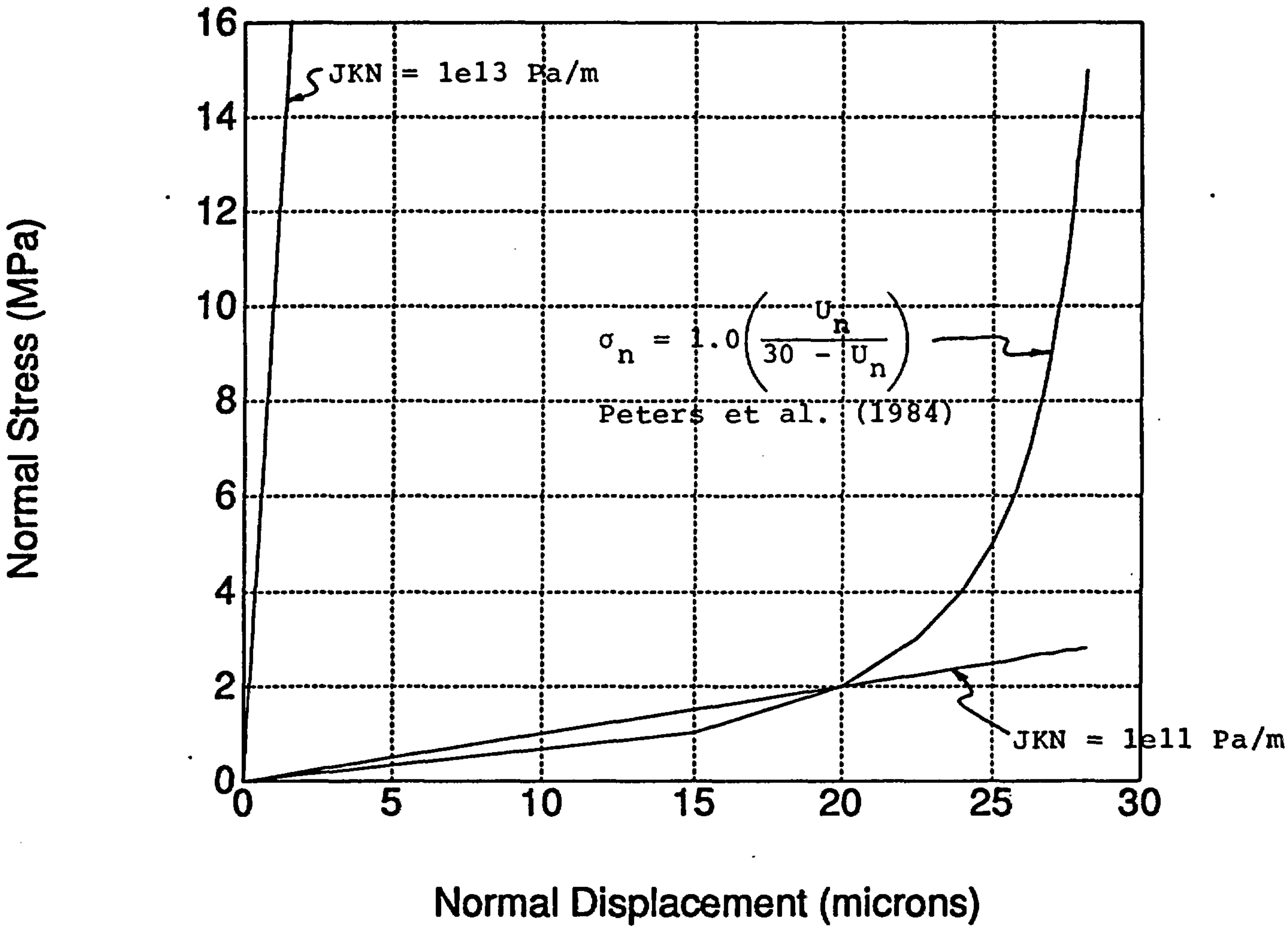


Fig. A-3 Comparison of Various Joint Normal Stiffness Assumptions

RESULTS

Figure 4 shows that the relation of joint opening to radial distance is nearly the same for both assumptions of joint stiffness. However, the magnitude of joint opening is about two orders of magnitude higher for the case where JKN = 1E11 Pa/m. If the initial joint aperture is assumed to be 3 microns [i.e., 3E-6 meters (Case and Kelsall, 1987)], then the relations between relative rock mass permeability versus radial distance shown in Fig. 5 result. Relative rock mass permeability at each radial distance was calculated by dividing the cube of the aperture change (i.e., joint opening) by the cube of the initial aperture. However, if the initial aperture is assumed to be 38 microns (Case and Kelsall, 1987), the plot of relative rock mass permeability versus radial distance changes drastically, becoming virtually indistinguishable from the similar curve given in Fig. 24 of Case and Kelsall (1987) [Fig. 6].

CONCLUSIONS

1. Plots of relative permeability versus radial distance are extremely sensitive to the assumption of initial aperture because joint permeability is a function of the cube of the aperture.

2. Results are also sensitive to assumptions regarding joint normal stiffness. In this case, reasonable agreement between linear and non-linear joint stiffness were obtained by choosing a linear stiffness which approximates the non-linear stiffness at low normal stress.

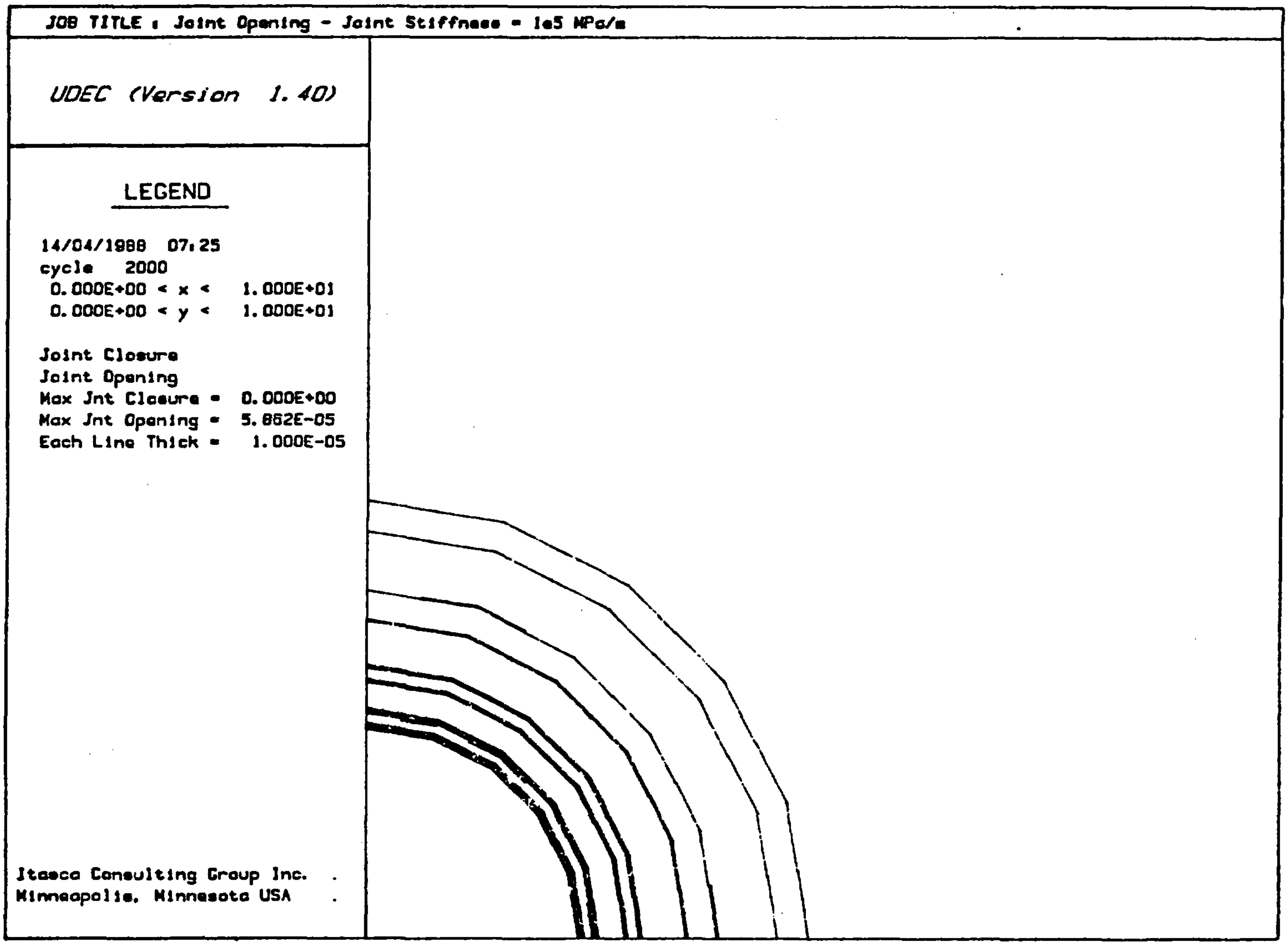


Fig. A-4(a) Pattern of Joint Opening for the Case JKN=1e11 Pa/m (maximum joint opening = 5.862E-05; each line thickness = 1.000E-05)

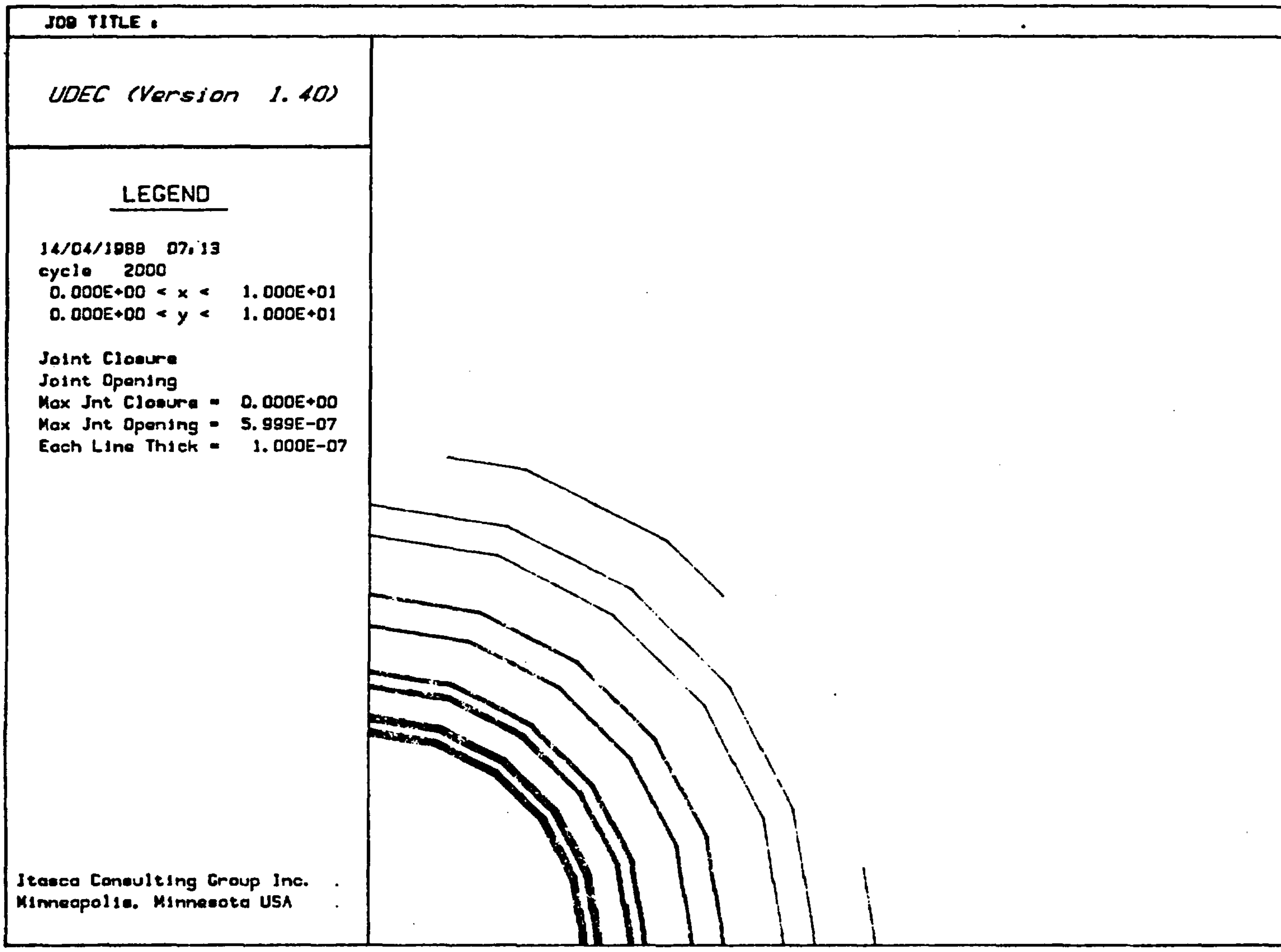


Fig. A-4(b) Pattern of Joint Opening for the Case JKN=1e13 Pa/m (maximum joint opening = 5.999E-07; each line thickness = 1.000E-07)

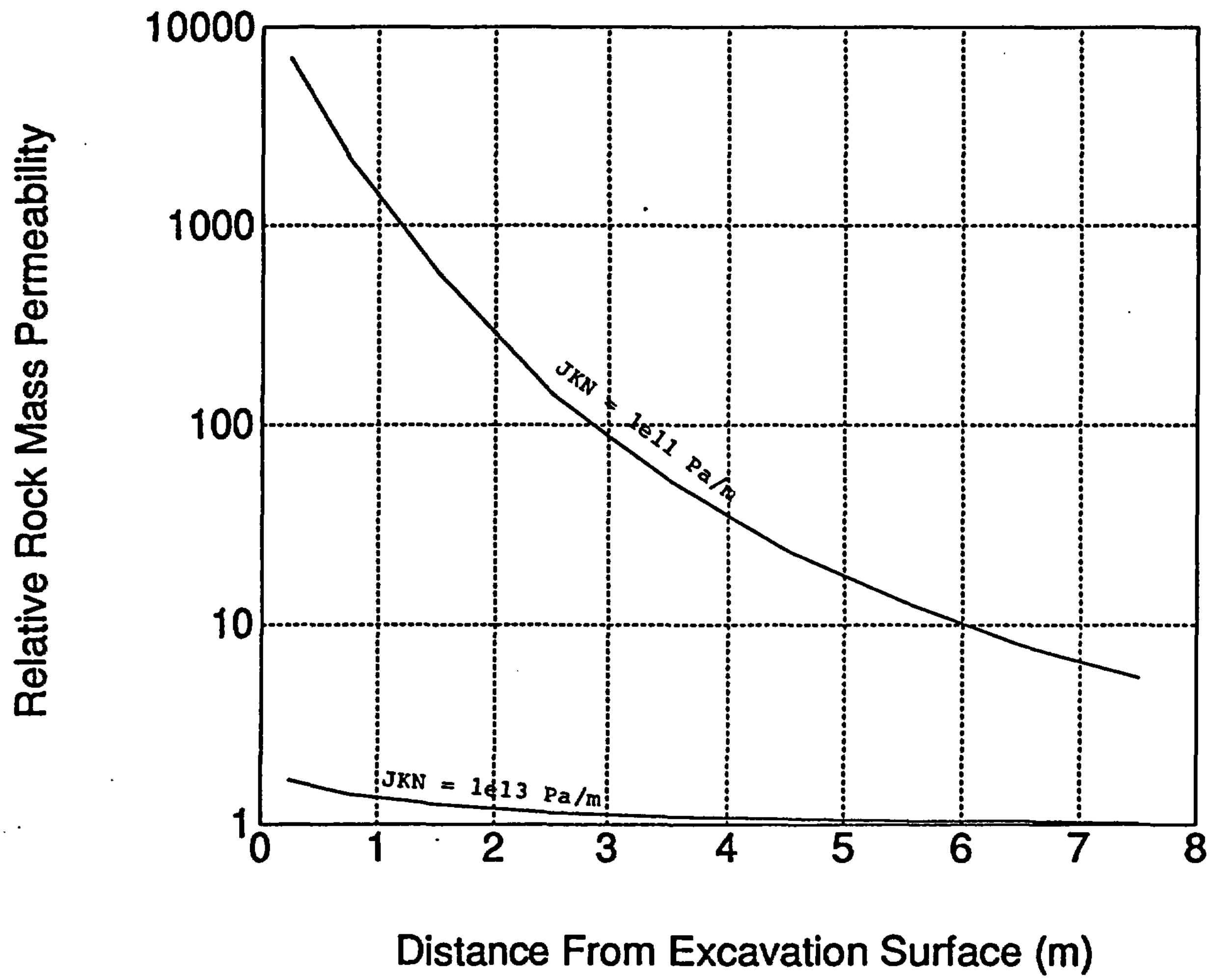


Fig. 5 Relative Rock Mass Permeability Versus Radial Distance for UDEC Analyses with Initial Joint Aperture Assumed to be 3 microns

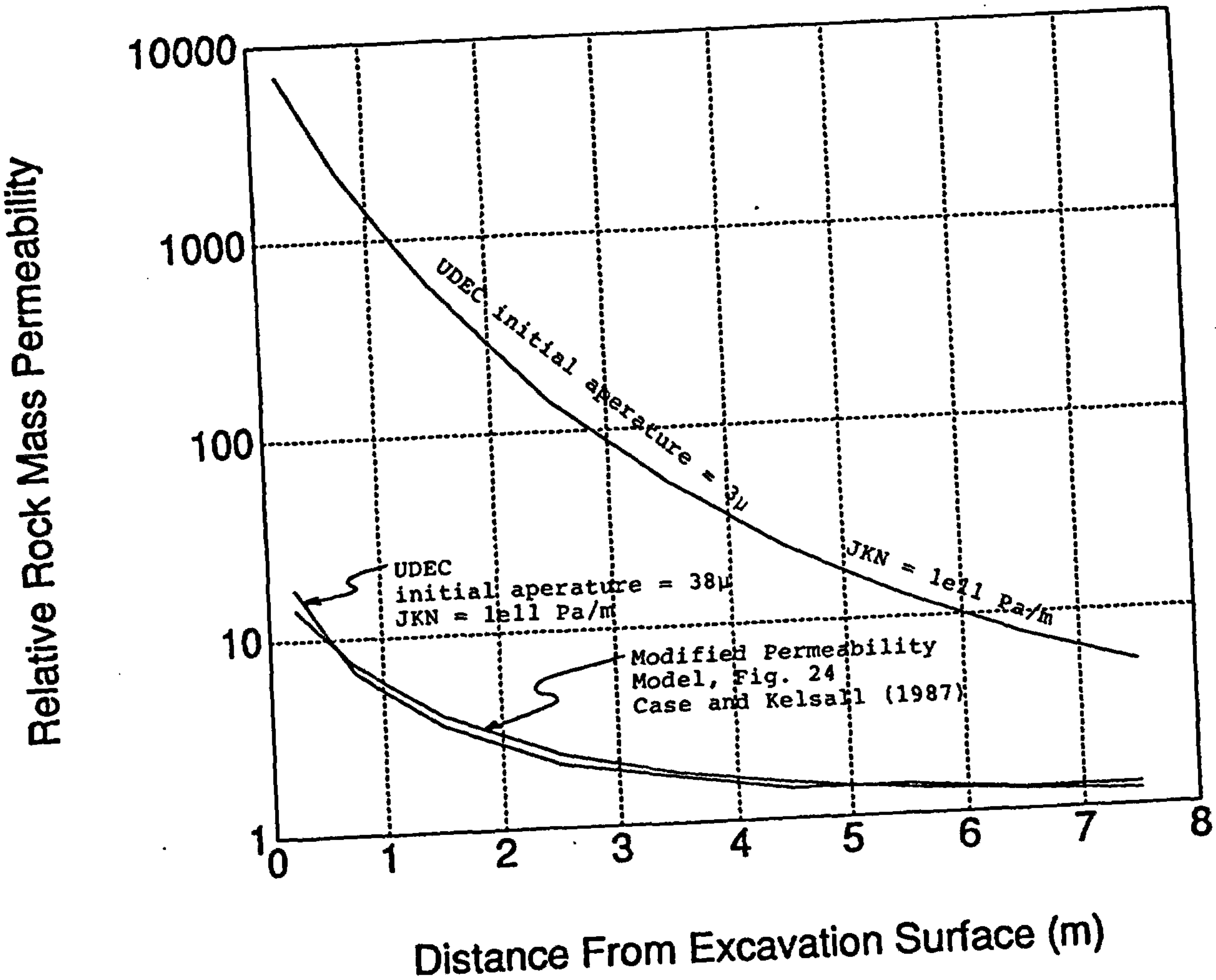


Fig. 6 Comparison of Various Modified Permeability Relations

FURTHER STUDY

The conclusions raise the following practical questions which warrant further study.

1. The relative permeability is dependent on initial aperture and stiffness. How will these be measured in situ? What assumptions will have to be made?

2. How would the results be affected if different joint constitutive relations are used? Possible joint constitutive relations which have non-linear normal stress-closure relations include the continuously-yielding model (Lemos, 1987) and the Barton-Bandis model (Barton et al., 1985).

3. How would the results be affected by using more realistic joint patterns, an anisotropic stress state, etc.?

4. Under what circumstances would it be more meaningful to use absolute rather than relative permeability?

5. To what extent would current conclusions related to performance assessment and/or sealing be affected by the results of studies such as this one, which employs more sophisticated models?

REFERENCES

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