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SENSITIVITY OF THE STABILITY
OF A WASTE EMPLACEMENT DRIFT
TO VARIATION IN ASSUMED ROCK JOINT PARAMETERS
IN WELDED TUFF

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Prepared by:

Itasca Consulting Group, Inc.
Suite 210
Minneapolis Technology Enterprise Center
1313 5th Street SE
Minneapolis, Minnesota 55414

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Task Description: analyze the relative effects of variation in joint parameters on room stability in a thermally-loaded waste emplacement drift

Prepared by: Itasca Consulting Group, Inc.
Suite 210
1313 5th Street SE
Minneapolis, Minnesota 55414

Author:

Mark C Christianson

Mark Christianson
Itasca Consulting Group, Inc.

Date: 10/31/88

Reviewer:

Terje Brandshaug

Terje Brandshaug
Itasca Consulting Group, Inc.

Date: 10/31/88

Roger D Hart

Roger D. Hart
Project Manager
Itasca Consulting Group, Inc.

Date: 11/3/88

PREFACE

This report presents the results of a numerical analysis to determine the effects of variation of rock joint parameters on stability of waste disposal rooms for vertical emplacement. Conditions and parameters used were taken from the Nevada Nuclear Waste Storage Investigation (NNWSI) Project Site Characterization Plan Conceptual Design Report (MacDougall et al., 1987).

Mechanical results are presented which illustrate the predicted distribution of stress, joint slip, and room deformations for times of initial excavation and after 50 years heating.

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1.0 INTRODUCTION

1.1 Background

The candidate repository site is at Yucca Mountain, Nevada, where the repository horizon is located in a densely welded tuff. The site is being evaluated by the Nevada Nuclear Waste Storage Investigation (NNWSI) Project as potentially the first radioactive waste repository in the United States.

The Site Characterization Plan Conceptual Design Report for Yucca Mountain (MacDougall et al., 1987), subsequently referred to as the SCPCDR, and the Consultation Draft Site Characterization Plan (U.S. DOE, 1988), subsequently referred to as the CDSCP, outline a waste emplacement panel design and provide a list of design criteria.

In jointed rock masses such as the welded tuffs of the Topopah Spring member, emplacement drift behavior is likely to be controlled in large part by existing discontinuities or joints. Key parameters to predicting jointed rock mass behavior are the joint strength parameters of cohesion and friction angle, the joint deformation parameters of dilation, normal and shear stiffness, and the geometric parameters of joint orientation, spacing, and persistence. With the exception of dilation and persistence, average values and variability of the parameters are reported in the SCPCDR. The dilation of the joints are not reported; however, representative values for other rock joints are known and can be used as a basis for assuming the parameter values in this study. The joint persistence is also not reported but is thought to play an important role in governing rock mass behavior. Extreme values of persistence will be studied to determine the importance of persistence on room stability.

There is some concern as to the ability of current test procedures to properly determine the properties needed to predict insitu joint behavior. Inability to control normal stiffness and sample rotation during shear testing may result in apparent friction angles which are too high. In addition some parameters appear to be load path dependent.

1.2 Objectives

The objective of this study is to determine the relative effects of variation in joint parameters on room stability in a thermally-loaded waste emplacement drift.

1.3 Scope

This study concentrates on the prediction of movements along pre-existing joints such as slip (caused by excessive shear stress) or opening (caused by tensile stresses). These movements may result from the excavation of the disposal rooms and the continuous heating of the rock because of the presence of the radioactive waste.

The present study is limited to the vertical waste emplacement concept, meaning that single waste containers are placed in vertical boreholes along the disposal room floor.

The heat transfer associated with the first 50 years of heating is predicted along with the induced thermal stresses, displacements, and inelastic rock behavior.

2.0 JOINTS AND JOINTED ROCK MASSES

The following discussion on joints and jointed rock masses is taken from Brady [1988(a)].

2.1 Models of Joint Behavior

Discontinuities such as joints, faults, fractures and shear zones are a pervasive feature of rock masses. Depending on the relative dimensions of the excavation and the separation of the joints, or the location and orientation of a single feature relative to excavation boundaries, they may exert a dominant influence on the performance of engineered and natural rock structures. Noting that the term "joints" includes all the structural geological features listed above, key properties affecting their mechanical performance are their relatively low shear strength, tensile strength and normal and shear stiffness compared with those of the intact material. The importance of joints in characterizing the deformation of rock masses was recently recognized through a symposium devoted to review of their properties, formal description, numerical modelling, and effect on the response of engineered structures (Stephansson, 1985).

In addition to exerting a dominant role in the static performance of rock structures, joints are also important in the creep and dynamic performance of rock masses. Creep properties of joints have been reviewed by Howing and Kutter (1985), while dynamic properties have been considered by Gu et al. (1984). Joint creep is important in the time-dependent deformation of jointed rock around surface excavations, underground excavations and along aseismic faults. Apart from the obvious relevance of joint dynamic properties in seismology and earthquake mechanics, elucidation of the mechanics of mine seismicity and rockbursts requires understanding of joint deformation mechanics under impulsive conditions, and consideration of the stability of frictional sliding [Ryder, 1987; Brady, 1988(b)].

Because joints exert such a substantial role in the static and time-dependent behavior of rock masses, their formal description and experimental characterization are an important element of the design of underground openings for nuclear waste emplacement. In particular, models of joint mechanical behavior under load, and the thermal and hydraulic performance of joints, are essential in the prediction of rock response to engineering activity, and therefore in engineering analysis and design of openings for disposal of nuclear waste. Techniques for analysis of jointed rock masses, such as those described by Shi and Goodman (1988), Blanford and Key (1987), Cundall (1988) and Hart et al. (1988) are now well developed. In the latter cases, a suitable model of joint deformation and strength is required for adequate prediction of displacements and stresses throughout the medium. In the following discussion, the limitations of present methods of joint properties characterization is discussed, with particular emphasis on laboratory testing methods. The methods of representing joint behavior in discontinuum and continuum numerical models is then described.

2.1.1 Models of Joint Behavior

Two approaches have been followed in formulation of descriptive models of joint behavior. In the first, results from laboratory tests, field observations or conceptual studies have been applied in the proposal of expressions reflecting the dominant aspects of joint behavior. Arbitrary constants appearing in the expressions are then derived from experiment or observation, reconciling response predicted from the model with observed performance. Empirical models derived in this way may not satisfy the laws of deformable body mechanics, but they have the engineering utility of providing techniques for immediate practical solution of current engineering problems.

An alternative to the empirical approach is the formal analytical development of constitutive equations for a joint, ensuring the equations of continuum mechanics are properly satisfied. This approach may seek to derive the constitutive relations from consideration of the morphology of a joint surface and the micromechanics of surface deformation. Input data to such a model are the description of the joint geometry and the mechanical properties of the rock material.

2.1.1.1 Empirical Models — Because of the state of development of several empirical models of joint behavior, it is useful to consider the formulation of each model, and how well behaved each is, under the conditions of non-monotonic normal and shear loading characteristic of a load path experienced by a joint in-situ.

(a) Barton-Bandis Model — Starting from an expression proposed in the early 1970s, for shear strength of a joint, Barton et al. (1985) proposed a comprehensive empirical model for joint deformation mechanics. For purposes of comparison with other joint models, the following summary is presented.

<u>Closure Under Normal Stress</u>:

$$\sigma_n = \Delta V_j/(a - b\Delta V_j) \tag{1}$$

where σ_n is the normal stress,

ΔV_j is joint closure,

a and b are experimentally-determined parameters,

$a = 1/K_{ni}$, and

K_{ni} is the initial stiffness.

<u>Behavior Under Shear Displacement</u>: Barton's original expression for shear strength of a joint was given by

$$\tau = c + \sigma_n \tan \left(\text{JRC} \log \left[\frac{\text{JCS}}{\sigma_n}\right] + \phi_r\right) \tag{2}$$

where JRC is the joint roughness coefficient,

JCS is the joint-wall compressive strength, and

ϕ_r is the residual angle of friction for the joint.

For shear displacement less than that corresponding to peak strength, it was proposed that the mobilized angle of friction could be related directly to the mobilized roughness:

$$\phi_{mob} = \text{JRC}_{mob} \log (\text{JCS}/\sigma_n) + \phi_r \tag{3}$$

Noting that over the range of the shear stress-shear displacement curve, the plots of JRC(mob)/JRC(peak) and δ/δ(peak) are similar for different joints, Barton et al. (1985) proposed that a standard look-up table could be employed to interpolate $\text{JRC}_{mob}/\text{JRC}_{peak}$ from δ/δ_{peak}. Shear displacement δ_{peak} corresponding to peak shear resistance was proposed to be related to specimen dimensions by the expression

$$\delta_{peak} = \frac{L_n}{500} \left[\frac{JRC_n}{L_n} \right]^{0.33} \tag{4}$$

where subscript n relates to the field scale shear unit, and L defines the length of the shear unit.

<u>Size Effects</u>: One of the more controversial aspects of the Barton-Bandis model is the postulated existence of size or scale effects (to be distinguished from the surface roughness effects considered previously). A series of shear tests on model joints, in which some joints were sectioned and tested to assess notional effects of scale, suggested both JCS and JRC were related to the size of the shear surface. For subscripts o, indicating laboratory scale, and n, denoting field scale, the scaling relations between laboratory and field values of JRC and JCS are proposed to be

$$JRC_n = JRC_o \left[\frac{L_n}{L_o} \right]^{-0.02JRC_o}$$

$$JCS_n = JCS_o \left[\frac{L_n}{L_o} \right]^{0.03JRC_o} \tag{5}$$

Equations (1)-(5) indicate that from measured values of a, b, JCS, JRC and ϕ_r (which can be obtained in simple tests), it is possible to predict the deformation of a joint through any imposed stress or displacement path. (Some extensions of the model provide information on joint hydraulic properties under load as well). The model is widely applied in predicting the hydromechanical behavior of rock masses. In spite of its successful application, some difficulties with the model need to be recorded.

The first problem involves the arbitrariness of some of the parameter definitions. For example, Eq. (2) is usually cast as

$$\tau = c + \sigma_n \tan (i + \phi) \tag{6}$$

where i is the effective roughness angle for the surface.

Since i = JRC $\log_{10}(JCS/\sigma_n)$, it is implied that i = JRC when σ_n = 0.1JCS. It is improbable that such an arbitrary definition of i could adequately predict the dilation angle for joints under low normal stress, as is required by established use of the roughness angle concept.

A second difficulty arises when σ_n > JCS. In this case, i becomes negative, yielding an effective friction angle (ϕ_r + i) less than the residual friction angle, which is logically impossible. This suggests that Eq. (1), proposed from joint shear tests at relatively low normal stress, is not appropriate to the stress levels generated in subsurface engineering practice.

An interesting feature of the model is that it assumes no reduction in roughness over a significant proportion of the pre-peak range of shear displacement. This implies a joint cycled in shear in this range would achieve a peak strength unaffected by cycling, when the load was subsequently monotonically increased. This is in direct contrast to the experimental observations of Brown and Hudson (1974).

A final point of concern about the model is the pronounced significance of scale effects. Equations 5 were derived from model tests in which joint specimens were sectioned, to determine the effect of the same joint surface tested at different length scales. The description of the experiment, indicated by Fig. 1, suggests that specimen height/width ratio varied in the test. It is possible that the associated change in loading conditions for the shear surface, arising from specimen constraint and geometry, has contributed to the purported size effects.

(b) Cundall-Lemos Model — This is an empirical joint model, described by Cundall (1985) and Lemos (1987), intended to resolve some of the inconsistencies noted in the Barton-Bandis scheme. It is a damage accumulation model of joint shear, based on the principle that all joint shear displacement results in the progressive erosion of asperities and reduction in dilatancy. In a manner similar to that followed by Barton and Bandis, the model is developed from experimental observations of joint performance under load. Instead of an expression for peak shear strength, however, the initial attention is with the stress-displacement relations for the joint. These are illustrated in Fig. 2.

Joint normal deformation in the model is related to normal stress through the relation

$$\Delta\sigma_n = k_n \, \Delta u_n \tag{7}$$

where k_n, the joint normal stiffness, is normal stress dependent, and is given by

$$k_n = a_n \sigma_n^{e_n} \tag{8}$$

In a similar way, shear deformation involves a normal stress dependent stiffness k_s:

$$\Delta\sigma_s = F k_s \, \Delta u_s \tag{9}$$

where

$$k_s = a_s \sigma_n^{e_s} \tag{10}$$

In Eq. (9), F is a term representing the fraction of the increment of shear displacement which is elastic and recoverable (the remainder, Δu_s^p being assumed to involve plastic deformation of asperities and to be irrecoverable.) The value of F is obtained from the difference between the prevailing joint shear stress and the ultimate shear strength at the prevailing normal stress, as shown in Fig. 3:

$$F = (1 - \sigma_s/\tau_m)/(1-r) \tag{11}$$

The parameter r in Eq. (11) is introduced to ensure that F approaches unity on reversal of shear load direction.

Normal and shear response are coupled in the model through the normal stress dependence of k_n, k_s and F. Also, at any state of normal stress σ_n, shear strength is given by

$$\tau_m = \sigma_n \tan \phi_m \operatorname{sign} (\Delta u_s) \tag{12}$$

when ϕ_m is the current friction angle.

The friction angle ϕ_m in Eq. (12) takes account of residual friction and a component i related to roughness and dilatancy. The latter component is assumed to be progressively reduced by shear displacement and erosion of asperities, according to

$$\Delta\phi_m = -1/R(\phi_m - \phi_r)\Delta u_s^p \qquad (13)$$

where $\Delta u_s^p = (1-F)\Delta u_s$, and

R = a roughness parameter for the surface (having the dimensions of length).

Inspection of Eqs. (7)-(13) indicates that seven parameters are required to characterize the model: a_n, e_n, a_s, e_s, ϕ_m (initial), ϕ_r and R. No conceptual or experimental difficulty is presented for the first six. However, the roughness parameter R is not yet defined in formal detail sufficient to allow its experimental determination.

The Cundall-Lemos model makes no explicit reference to a scale effect. However, it is possible that the length scale defined by the roughness parameter R is sufficient representation of such a phenomenon, if indeed it exists.

Some exercises with the model to demonstrate its performance are shown in Fig. 4. It is seen that, for the particular joint parameters selected,

(1) peak-residual behavior for different initial roughness is modeled satisfactorily [Fig. 4 (a)];

(2) a cycle of unloading-reloading shows suitable hysteretic response; and

(3) an episode of pre-peak cyclic loading results in pronounced modification of the shear-stress displacement response, with virtual elimination of peak-residual behavior, consistent with the observations of Brown and Hudson (1974).

2.1.1.2 Constitutive Models — Empirical descriptions of joint behavior represent interim solutions to the problem of analysis of jointed rock, pending the development of rigorous constitutive equations. Perhaps the most promising rigorous formulation of a joint model is due to Swan (1981, 1985). His analysis is based on the extensive literature related to friction in metals.

Swan reasserts the role of roughness (related to shearable asperities) and waviness (longer wavelength surface features not subject to shear failure, but contributing to dilatancy in shear). In the analysis of surface deformation, contact stresses are determined for a population of spherical asperities over a surface, and it is proposed that the shear strength of contacts may be estimated from hardness tests on the surface. A conclusion of the analysis is that asperity-related roughness does not contribute to scale-dependent shear strength of the surface. This is clearly contrary to the widely accepted Barton-Bandis model. It suggests some well-conceived and executed experimental work is needed to resolve the inconsistency.

In the most recent work, Cook (1988) reports work on characterization of joint topography in terms of a power spectrum for the surface. The technique appears to provide a basis for objective description of surface roughness. In reporting results of measurements by Brown et al. (1986) of joint topography, Cook considers the spatial variation of joint aperture. Observing that aperture represents only the shorter wavelengths of the joint topography, he suggests that mechanical and hydraulic properties of joints may depend on sample size. This observation also implies that above a particular sample size, such size dependence should disappear.

The assumption in the development of rigorous models of joint deformation mechanics is that, when satisfactory techniques for definition of joint topography are established, the formal analysis will readily provide constitutive equations. From the preceding discussion, there is some cause for optimism in the early elucidation of joint deformation mechanics based on fundamental principles. Support for the analysis by experimental data obtained under rigorously controlled conditions then becomes an essential aspect of model validation.

2.1.2 Joint Creep

Time dependent, non-impulsive deformation of joints has been demonstrated to be important in earthquake mechanics (Dieterich, 1972), tunnel stability (Kaiser and Morgenstern, 1979) and slope stability (Zavodni and Broadbent, 1978). The slow application of thermal loads to the rock mass following waste emplacement and the significant time periods that the openings must be maintained may result in joint creep as a significant consideration in determination of drift stability. As a general observation, time-dependent deformation of hard rock masses is pervasive and well documented in engineering practice, but there is currently no verified technique for analysis of such behavior. It appears from field observation that creep deformation in hard rock masses is concentrated at joints.

In spite of the practical significance of joint creep, there has been comparatively little experimental study of the phenomenon. Bieniawski (1970) describes some preliminary investigations. In an investigation of creep on clean, fresh artificial joints in several rock types, Amadei and Curran (1980) used both triaxial tests and direct shear tests, at normal stresses ranging from 0.3-9.5 MPa, and shear stresses 0.2-5.7 MPa (i.e., the range of engineering interest.) It was observed that joint creep depended on the ratio of the applied shear stress to the peak shear strength of the joint. The work also confirmed the report by Dieterich that joint shear strength increases with time of contact, in an asymptotic way. Clay-filled joints were considered by Howing and Kutter (1985), whose results were consistent with those of Amadei and Curran. Effects due to particle size and clay fraction in the joint in-filling were also noted.

While substantial time-dependent deformation of jointed hard rock masses has been observed, and laboratory experiments have confirmed creep behavior of joints, it appears that the results of creep tests have not been incorporated in either empirical or formal models of joint mechanics. Both the empirical models described previously, due respectively to Barton and Bandis and Lemos and Cundall, have been applied in static and dynamic analysis of jointed rock mass. The observed lack of a technique for creep analysis of jointed media might be resolved by introduction of appropriate creep terms in the stress-displacement expressions in these established joint models.

2.1.3 Dynamic Properties of Joints

The location of the Yucca Mountain site, in close proximity to the Nevada Test Site as well as a potentially active earthquake region, results in the need for concern over the dynamic stability of the underground openings. The empirical models of joint deformation mechanics discussed previously may be used for analysis of the dynamic performance of rock masses, and several examples are noted (e.g., Lemos et al., 1985). However, the shear stress-shear displacement relations in the models, which represent displacement weakening behavior of a joint, may not be adequate for the complete range of performance, particularly when a joint has reached a state of residual strength.

A particular concern with joint dynamic response is the velocity dependence of the coefficient of friction. First noted by Wells (1929), the effect was proposed as an explanation for unstable fault slip by Brace and Byerlee (1966). Since then, an extensive literature has developed on characterization of frictional resistance to slip in terms of slip velocity, state of transient stress, and state variables representing properties of the surface. The application of velocity-dependent friction relations in the analysis of jointed rock is described by Lorig and Hobbs (1988).

In addition to being driven impulsively in shear motion under dynamic conditions, joints are subject in-situ to impulsive normal loading. In the vicinity of explosions or rockbursts, for example, body waves may impose a sharp increase in normal stress on a joint. The intuitive assumption that there is an immediate increase in the shear resistance in response to an increase in normal stress is not justified (Hobbs and Brady, 1985). The current position is confused, since some subsequent experiments show no effect of normal stress history (Olsson 1987; Lockner and Byerlee 1986), while other do (Olsson 1985, 1988; Linker and Byerlee, 1986).

In the most recent studies of dynamic normal stress changes, Hobbs (1988) reports the effect of step changes in normal stress on a joint in gabbro subject to constant shear load point velocity. The form of the results is shown in Fig. 5. The time-dependent evolution of the shear resistance indicated in the figure represents a transient reduction in the coefficient of friction below the static value. Such an effect has major implications for the stability of excavations in jointed rock subject to sudden transient loading, which may be induced by explosions, earthquakes and rockbursts. Some analysis of jointed block motion near underground nuclear events reported by Hart et al. (1987) suggests transient changes in the coefficient of friction under impulsive changes in normal stress may be significant in practice.

2.1.4 Discussion

The preceding introduction is intended to identify some current concerns in the mechanics of jointed rock masses, and the related issue of the deformation mechanics of joints. This discussion has been given to highlight the present state of knowledge of the constitutive properties of joints, and to point out the areas where it is currently inadequate. It was observed that formal description of joint topography has developed considerably in the recent past, but that this has not yet been coupled with analysis of the normal and shear deformation of joint surfaces to yield applicable constitutive equations. On the other hand, empirical models of joint deformation are well developed. However, the existing models are not necessarily well behaved, and questions persist in one case about the way in which scale effects are handled or, indeed, whether a scale effect really exists. Notwithstanding these concerns, the advantage of both the empirical models is that they are capable of immediate application to static analysis of engineering design problems.

Joint creep has been identified as the dominant mechanism in the time-dependent deformation of hard-rock masses. In spite of this, there is no model of joint creep compatible with the existing empirical joint models. Progress on a capacity to design excavations in creep-prone jointed rock masses is linked directly to the formulation of a usable joint creep model, and provision of experimental data which characterizes joint creep.

The velocity dependence of joint residual shear strength is well known. Recently it has been observed that shear strength of a joint at residual strength is subject to temporal variation following an impulsive change in normal stress. In particular, a step increase in normal stress is frequently accompanied by a transient reduction in the coefficient of friction, which subsequently rises to its static value. This effect can have a considerable effect on joint stability, since a joint in a static state of stress close to limiting equilibrium can be transformed to an unstable transient state due to the sudden increase in normal stress.

In considering these aspects of the mechanics of joints, it is clear that there are several major unresolved issues, some of which can only be addressed by well designed and executed experiments. Such joint characterization techniques have been the subject of the studies conducted by Brady [1988(a)].

2.2 Joint Characterization Practice

2.2.1 Purpose

In the geo-engineering context, the purpose of joint characterization is to determine the stiffness, strength and hydraulic and other properties of a feature which describe its response to the perturbations it may experience in-situ. Because hydraulic properties are related directly to deformability, joint stiffness and strength may be regarded as the primary mechanical properties of interest. Comparison of heat transfer models to the results of in situ test such as Stripa and G-Tunnel has shown little effect of the fractured rock structure on its thermal properties.

In the preceding section, several aspects of joint behavior were considered briefly in relation to both static and time-dependent performance of rock masses. It was noted that the ultimate objective of joint characterization is the provision of a data set which is representative of the in-situ state of a rock mass, and which can be introduced in some analytical or computational scheme to predict rock mass performance. Implicit assumptions in this approach are that the conceptual model of the rock mass is mechanically sound, and that the characterization tests will reflect load conditions to which a joint will be subject in its in-situ operating environment.

2.2.2 Design of Joint Characterization Tests

The main modes of response of joints which are reflected in rock mass behavior are normal closure and relative shear displacement, under changes in the state of normal stress and shear stress imposed on the joint. In-plane rotations may also be important, but there has been comparatively little examination of this mode of response. The point to note is that the normal and shear translational modes and the in-plane rotational mode are coupled. Thus, characterization tests must take proper account of the extent to which coupled responses must be observed.

There is a voluminous literature on joint testing, describing the results of tests of various types of joints, and proposing empirical or constitutive equations to describe response. There has been less attention to the mechanics of testing. Goodman (1976) provides a concise and comprehensive discussion of various tests and notes the significance of boundary constraints and load paths imposed by test geometries on measured joint parameters. Schneider (1976, 1978) considered details of test design, performed some elementary analysis of load distribution in the direct shear test, and discussed the relevance of the test to engineering practice. An important contribution by Schneider was implicit recognition of the role of stiffness control on dilation, as opposed to stress control or completely restrained displacement considered by Goodman. In the course of describing the development of a direct shear machine, Crawford and Curran (1979) considered various ways in which tests could be conducted in a biaxial shear frame, taking account of design limits on degrees of freedom in the system.

The elementary motions during shear displacement of the opposing surfaces of a joint are shown in Fig. 6. In general, joint normal displacement, shear displacements and three (3) components of rotation result in six (6) degrees of freedom in a test. Test rigs differ in the constraints imposed on these degrees of freedom and, consequently, in distribution of load over the surface of interest.

One of the main objectives of test rig design has been to generate a uniform nominal distribution of normal and shear stress over the test surface. (The load distributions on the surface are nominal, as the surface morphology and localized contacts may create concentrated reactions at the contacts.) A particular problem is that application of shear loads with a line of action non-coincident and parallel with the joint surface, as shown in Fig. 7(a), inevitably results in an overturning moment and a non-uniform reaction over the shear surface. Test arrangements of the type shown in Fig. 7(b) are intended to minimize this effect. However, because the mean normal stress on the shear surface increases with the applied shear force, it is not possible to conduct tests at low normal stress. Laboratory test rigs, therefore, employ the load configuration in Fig. 7(a). In that case, specimen geometry and shear box relative dimensions (in particular, height/width ratio) may become significant test parameters.

By way of illustration, the biaxial shear machines shown schematically in Fig. 8 offer several options in the control of degrees of freedom of motion, and the constraints that may be imposed on the load and displacement paths. With appropriate motivating and control systems, normal load or displacement and shear load or displacement may be imposed, with the controlled parameters being measured to characterize system response.

In the conventional direct shear test, a constant normal load is applied, and shear loads required to induce particular shear displacements are measured. However, under many circumstances, the relevance of this test to in-situ load and displacement path for a joint is questionable for the following reasons:

(a) under field conditions, it is arguable whether the rigid body rotation Ω_z, shown in Fig. 8, is constrained by adjacent rock units;

(b) except in near-surface conditions, where dilation and normal displacement may be unimpeded, the imposed conditions of constant normal load may not represent the load path experienced by a joint under field conditions; and

(c) as noted earlier, the nominal uniform distribution of normal reaction over the surface is disturbed by the overturning moment generated by the shear load.

2.2.3 Displacement and Rotation Constraints

An alternative to the load path described above involves shear under controlled normal displacement. Apparently originally proposed by Ladanyi to determine the strength of sand under constrained conditions, the principle was considered by Goodman (1980) as appropriate for determination of joint strength and stiffness in conditions applying around underground excavations. The results of a constrained normal displacement (CND) direct shear test (which also results in constraint of the Ω_z component of rotation) have been synthesized in Fig. 9(c), from the normal stress-controlled tests presented in Figs. 9(a) and (b). The notable features of the shear stress-displacement plots for the CND test are that considerable increase in shear strength occurs when shearing without dilatancy and the τ-u_s response for this joint is no longer strain-softening, as it was for constant normal stress tests. Normal constraint is, therefore, demonstrated to have a substantial effect on shear resistance mobilized as a function of shear displacement.

It is not clear that the load and displacement path involved in a CND test does indeed represent in-situ constraints on degrees of freedom imposed by a joint's environment. In particular, the constraint on dilation imposed by adjacent rock is not perfectly rigid. In-situ joints are deformed in a deformable environment, the deformability being conferred by the compressibility of both joints and rock material. In a situation analogous to shear of a rock joint, the constraint on dilation during shear at the contact of a cast-in-situ concrete pile with the host medium was proposed by Johnston et al. (1987) to be represented by a condition of constant normal stiffness. This follows the idea introduced by Schneider (1976).

The conceptual arrangement for a constant normal stiffness (CNS) test is shown in Fig. 10. In this scheme, the spring stiffness may be adjusted to provide constraint on a direct shear test equivalent to that estimated to be provided by the joint's field environment.

Although the concept of stiffness control implied in Fig. 10 may be translated readily into experimental practice, servo-control techniques may be used more appropriately to control dilation as the normal stress develops during imposed shear displacement. Hutson and Dowding (1987) describe a microcomputer-controlled direct shear rig which maintains constant normal applied stiffness during a shear test. Satisfactory control was demonstrated using this system during pseudo-static testing of a joint.

Stiffness-controlled testing provides, intuitively, a most appropriate environment in which to determine joint shear stiffness and strength parameters. However, a deformable test environment also requires consideration of the overturning moment, block rotation and non-uniform distribution of nominal normal reaction on the shear surface. For characterization purposes, it is desirable that a uniform nominal normal reaction is maintained over the surface. This implies that the scope of the problem from block rotation and overturning moment on reaction distribution over the shear surface needs to be established by thorough analysis.

The preceding discussion concerned a biaxial shear test in the X-Y (vertical) plane. Referring to Fig. 6, during shear displacement in the X-direction, surface roughness may also introduce an in-plane rotation Ω_y, a lateral rotation Ω_x, and a lateral displacement, u_z. The role of the rotation Ω_x is of particular interest, since failure to take it into account may also affect the distribution of normal reaction over the shear surface.

2.2.4 Conclusions

In the design of direct shear tests to determine the static, creep and dynamic properties of joints, it is essential to:

(1) follow a load and displacement path which is analogous to that experienced by a joint in-situ; and

(2) maintain conditions of uniform normal reaction over the shear surface, so that joint performance can be related unequivocally to known imposed conditions.

Development of a suitable load path in a laboratory test to reflect in-situ conditions is achieved by control on the constraints applied to the test specimen.

In the conventional direct shear test, the load path is one appropriate to rock structures in which uninhibited joint dilation and block rotation can occur. Rock slopes and low stress underground environments may fulfill these conditions. A constrained normal displacement shear test is suitable for an in-situ environment in which joint dilation and block rotation are rigidly restrained. Relevant environments are isolated unweathered joints in high stress environments. This second case is most indicative of that to be experienced at Yucca Mountain. The most general situation, however, involves a joint loaded in a deformable environment. In this case, load path provided by a controlled normal stiffness test is most suitable.

At least two effects complicate the load distribution on a shear surface in a laboratory direct shear test. Non-colinearity of the applied shear force with the shear surface results in an overturning moment, which is compensated by generation of a non-uniform normal reaction. Roughness of the joint can result in rotation of one block relative to the other and leads, in dilation-constrained tests, to generation of non-uniform reactions against the constraining frame. It is not clear how significant the non-uniformity of normal reaction associated with these affects may be, and how the distribution may affect the results of a direct shear test.

Uncertainties about the state of stress developed during a poorly controlled direct shear test lead to questions about the relevance and value of results generated in tests conducted under such conditions. Of particular importance in the design of underground openings for waste emplacement is the relevance of laboratory-generated shear and normal stress behavior for use in numerical or empirical models.

2.3 Numerical Representation of Jointed Rock Behavior

As described above, the stability of the rock mass surrounding underground openings is largely controlled by the jointing—the spacing, continuity, shape and properties. It is important, therefore, that the jointing be included in the numerical model. This is usually done in one of two ways: the rock is considered to be a true discontinuum, or it is considered to be an equivalent continuum with appropriate constitutive model and properties.

2.3.1 Discontinuum Representation

In the discontinuum method, the rock mass is considered to be composed of a number of intact blocks separated by intervening joint surfaces. The initial development of discontinuum analysis was conducted by Trollope (Stagg and Zienkiewiz, 1968), followed by a numerical modeling approach by Cundall (1971). The early models consisted of rigid blocks with intervening joint surfaces governed by the Mohr-Coulomb yield criterion. Further refinements in the method have led to the Universal Distinct Element Code (UDEC) [Itasca, 1988(b)] in two dimensions and the 3-Dimensional Distinct Element Code (3DEC) in three dimensions [Itasca, 1987(c); Lemos et al., 1987]. These codes incorporate automated statistical generation of joints, various joint constitutive laws, internal discretization of blocks (i.e., deformability), dynamics, etc. A brief description of the distinct element method follows.

The distinct element method is based on the notion that a rock mass is composed of a series of blocks which interact across the intervening joint planes. The stiffness, friction, dilation, and cohesion properties of these planes may be represented by constitutive laws of varying complexity—the simplest model being the standard Mohr-Coulomb model. This is represented in Fig. 11 as the spring-slider system which governs force transmission at block contact points. The simplest incremental force-displacement law assumes a linear relation for normal and shear components (Fig. 12):

$$\Delta F_n = k_n \, \Delta u_n$$
$$\Delta F_s = k_s \, \Delta u_s \qquad (14)$$

where k_n, k_s = normal and shear stiffness, respectively, and

Δu_n, Δu_s = incremental normal and shear displacements, respectively.

The maximum shear force is limited by the yield function:

$$|F_s| \leq C + F_n \tan(\phi+i) \qquad (15)$$

where c = cohesion, and

ϕ,i = friction and dilation angles, respectively.

Once the forces applied to the blocks have been determined, the law of motion is used to determine the block accelerations and, thus, their translations and rotations. From these values, the resultant forces can again be determined by Eqs. (14) and (15). This process is illustrated in Fig. 13 and is repeated until the body is at an equilibrium state or until such time as the system undergoes unstable deformation.

The advantage of this method is that the non-linearities and possible fracture-controlled failure modes of the rock mass may be modeled explicitly, provided the geometry and properties of the joints are known. The problems lie in the determination of the level of detail necessary in the discretization of the rock mass to model the dominant mechanisms as well as an adequate description of the constitutive behavior of the joints. It is not reasonable to attempt to model, over a large area, the complete rock structure of a heavily-jointed rock mass (e.g., the Topopah Springs) with distinct elements. Reasonable run times, even on high-speed mainframe computers, may limit the problem size to several thousand blocks.

2.3.2 Continuum Models

Continuum numerical models (finite element, finite difference, boundary element) attempt to model the mechanical behavior of the rock mass through the use of constitutive laws which reflect the behavior of the jointed body. Three approaches have been used:

(1) the use of elastic models to determine the induced stresses around the excavations [elastic stresses are sometimes input to an empirical failure law (e.g., Hoek and Brown, 1980) to determine approximate region of failed or "overstressed" rock (RKE/PB, 1985)];

(2) the use of elastic models with reduced elastic properties in an attempt to reflect the softening influence of joints; and

(3) the use of a non-linear constitutive law (e.g., Mohr-Coulomb plasticity) to represent the influence of joints and/or internal deformations of the intact material).

2.3.2.1 Equivalent Elastic and Empirical Models — This approach to analysis is often used as an estimate by designers or constructors in the initial stages of a project where little physical property data are available. The principal stresses at varying points around the excavation are calculated from elastic analysis and then input to an empirical failure criterion such as the Hoek-Brown model (Hoek and Brown, 1980):

$$\sigma_1 = \sigma_3 + (m\,\sigma_c\sigma_3 + s\sigma_c^2)^{1/2} \qquad (16)$$

where m, s = empirical curve-fit constants, and

σ_c = uniaxial compressive strength of intact rock.

A "factor of safety" can be determined as the ratio of the calculated-to-failure stress as determined in Eq. (16).

This approach appears to be adequate for initial design studies; however, there are some problems associated with its use. The values of m and s are related to the properties of the in-situ rock mass and are not readily available. Hoek and Brown (1980) have presented a subjective list of values for these constants as a function of rock mass type and quality. The suggested values are purportedly conservative, but few field cases have been published in which this design technique has been compared to observation and field instrumentation. It must also be kept in mind that the use of this model is presently considered useful for an estimation of conservatism in design—but not a rigorous method of determining rock mass performance.

The second commonly-used method is to assume that the rock mass behaves as an equivalent elastic continuum. Here, the presence of jointing or defects in the rock mass are assumed to result in a reduction of the elastic modulus as well as a reduction in its ultimate compressive strength. Typically, the reduction in elastic properties is determined by assuming the rock mass to be isotropic with joints at some spacing, s, with normal and shear stiffnesses, k_n and k_s, respectively. The equivalent elastic modulus may be determined by assuming that the jointed and equivalent mass undergo an equal displacement for equal applied stress, σ (see, for example, Singh, 1973; Goodman, 1981). The following relations may be derived:

$$\frac{1}{E_i} + \frac{1}{k_n s} = \frac{1}{E_e}$$

$$\frac{1}{G_{xyi}} + \frac{1}{k_s s} = \frac{1}{G_{xye}} \qquad (17)$$

where E_i = intact modulus,

E_e = equivalent modulus,

G_{xyi} = intact shear modulus,

G_{xye} = equivalent shear modulus, and

s = joint spacing.

Fossum (1985) and Gerrard [1982(a); 1982(b)] have given models for equivalent elastic continua for randomly and regularly jointed masses in two and three dimensions. Others have suggested relations for empirical rock mass classifications and the elastic modulus. Bieniawski (1978) suggested that, for rocks with a rock mass rating (RMR) of 55 or greater, the deformation modulus could be approximated by

$$E_e = 2(\text{RMR}) - 100 \qquad (18)$$

where E_e = equivalent modulus (GPa), and

RMR = rock mass rating.

Again, there is little field data which support these relations.

In general practice, equivalent moduli are often determined from field compression experiments such as block tests, borehole jacking tests, flatjack tests, or plate-bearing tests. This method may work well in instances where the rock mass response is truly elastic in the working stress range, but it can lead to significant errors in instances where the behavior is non-elastic.

2.3.2.2 Equivalent Non-Linear Continuum — One of the most common modeling approaches is to assume that the rock mass behaves according to a non-linear constitutive law. The non-linearity in the constitutive law represents the effects of the defects (e.g., fractures) in the rock structure on its overall mechanical response. The various schemes of representing non-linear behavior in rock may be divided into three groups (Desai and Christian, 1977):

(1) representation of stress-strain curves by curve-fitting;

(2) non-linear elasticity; and

(3) plasticity models.

The following discussion is limited to a description of representation of jointed rock behavior using plasticity models.

2.3.2.3 Plasticity Models — There are several forms of plasticity which are used to represent rock behavior. Typical models include (Fig. 14): (1) rigid, perfectly-plastic; (2) elastic, perfectly-plastic; and (3) some form of work hardening or softening. In each case, a yield criterion or function is used to describe the stress conditions under which failure of the material occurs. The two simplest yield functions (the Tresca and the von Mises) assume that the material is non-frictional and are more appropriate for metals. The two most common yield criteria for rock are the Mohr-Coulomb and the Drucker-Prager in which the material is treated as frictional and cohesive.

At present, Mohr-Coulomb and Drucker-Prager models are used most extensively to describe rock mass behavior when material isotropy can be assumed. When the jointing has a strong directional influence, an anisotropic form of plasticity is sometimes used. These models are often referred to as "ubiquitous joint" models [e.g., Itasca, 1988(a)]. These models allow yield to occur only for certain orientations within the body which coincide with joint orientations. A typical model will rotate the stress state into alignment with the joint orientation. The Mohr-Coulomb condition is checked for yield on this plane—if it has occurred, corrections to the stresses are applied to require conformance to the yield surface. In this manner, it is possible to obtain nonuniform yield zones in a material as governed by the structure. Other continuum joint models have been proposed by Zienkiewicz and Pande (1977) which are similar to the "ubiquitous joint" model but which include time-dependent deformation for the joint surface using a simple visco-plastic model.

The primary problems with ubiquitous joint models (as well as other continuum joint models) is that: (1) the spacing of the joints is not explicitly accounted for in the constitutive relation; and (2) there is not a proper kinematic restraint to failure—failure is controlled by the stress state, and there is not a proper recognition of the relation of failure to the displacement on the joints in the body. Another group of similar continuum models which attempt to more accurately describe the effects of joints are termed "compliant joint" models. In these, the spacing of the joints and their stiffness characteristics are considered, thereby providing a means of calculating relative displacements at the joints. In the ubiquitous models above, the matrix may behave elastically or as a plastic material. Usually, slip is only allowed on the planes of weakness, and the material behaves as the matrix in compression and the joint in shear. There is, therefore, no load "sharing" between the joint and rock in the sense that stiffness is not assigned to the joints. For these reasons, the ubiquitous models are best suited in situations in which fracture frequency is high. The complaint joint models were developed in an attempt to overcome these difficulties. However, the compliant joint models still suffer from the improper modeling of the kinematics of a blocky system.

Thomas (1987) describes a compliant joint model presently being used for design at NNWSI. Here, each element of the rock mass is assumed to be an elastic solid which contains a representative number of joints. A single set of joints is modeled which have a shear stiffness cut-off and non-linear relation of normal stiffness to normal displacement (Fig. 15). The peak shearing resistance of the joints is controlled by the standard Mohr-Coulomb conditions. As compared with the previous ubiquitous joint model, the compliant joint model requires more detailed information on joint properties, including the joint half-closure stress (A) and the unstressed joint aperture (u_n). It is questionable whether accurate values for these parameters can be determined for in-situ conditions.

Blanford et al. (1987) use Barton's (1982) equations for joint compliance and dilation to construct a three-dimensional compliant joint model for a system of non-orthogonal joints. This model is incorporated into an implicit finite element scheme which uses Newton-Raphson iteration to ensure simultaneous equilibrium on all joint sets.

Detournay and St. John (1985) review the following fundamental drawbacks regarding continuum joint models.

1. There is no interaction between joints (either within a set or between sets). The stress state within the joints and matrix is homogeneous (The macroscopic normal and shear stress across the direction of each joint set is simply deduced from the overall stress using the Mohr transformation.).

2. The derivation of these equivalent continua do not follow the self-consistent method described by Hill (1967) for the characterization of composite materials. (This requires estimating the behavior of a joint in the discontinuous rock medium as that of a single discontinuity in the equivalent homogeneous body.)

3. The question of scale effect cannot be addressed with the ubiquitous models because of a lack of a characteristic length.

It would appear that, for equivalent continuum models to be of benefit, several general conditions must be met in the problem which is to be modeled (Gerrard, 1983):

(1) discontinuities occur in sets, each of which can be recognized by its regular spatial pattern;

(2) the typical spacing between joints in a set is much smaller than the critical dimension of the problem under consideration (e.g., span of an underground opening); and

(3) either the relative movements on a particular joint set are limited or the spacings between the joints in the set are extremely small.

Although some case histories have been run with equivalent continuum models, little work has been completed to define the situations under which they are applicable, as opposed to the need to explicitly model joints.

3.0 APPROACH

3.1 Assumptions and Idealizations

The emplacement drift being modelled is in the center of an emplacement panel. This assumption allows symmetry to be imposed reducing the computation time. The emplacement of waste in the panel is assumed to be instantaneous.

The analyses ignore any effects of the joint on the thermal conductivity of the rock mass. Based on the results of the G-Tunnel Heated Block Test and other tests involving thermal conductivity of rock masses, this assumption appears reasonable (Zimmerman et al., 1986). The analyses also ignore the effects of fluid (i.e., air and water) convection in the rock mass and emplacement room. The analyses ignore effects of boiling of pore water which could affect heat transfer rates. The thermal properties used assume fully saturated conditions.

A linear stiffness Mohr-Coulomb joint model is used for all analyses involving explicit representation of joints. While more complex models exist, such as the continuously yielding model (Cundall, 1988) and the Barton-Bandis model (Barton, 1982), these models vary in detail of the behavior, but the fundamental effects are similar.

3.2 Numerical Models

The two computer codes FLAC [Fast Lagrangian Analysis of Continua, [ITASCA, 1988(a)] and UDEC [Universal Distinct Element Code [ITASCA, 1988(b)] were used to simulate the thermal/mechanical response of the rock from the time of initial waste emplacement. Both codes consider a two-dimensional section of a disposal room perpendicular to the room axis at the center of an emplacement panel (i.e., plane strain conditions are assumed).

In FLAC, the rock mass is simulated using an ubiquitous joint constitutive model with a single orientation of jointing. In a ubiquitous joint model, the joints are considered to be continuous (i.e., persistent) and very closely spaced. Ubiquitous joint models are therefore often compared to a "deck of cards". Slip or opening along the vertical planes of weakness is determined by a Mohr-Coulomb criterion for joints (Goodman, 1980). Figure 16 illustrates the Mohr-Coulomb criterion for the ubiquitous vertical joints.

In the FLAC model, a Mohr-Coulomb failure may also occur in the rock matrix independent of the jointing, however this is not likely to happen due to the low stress to strength ratios calculated. Figure 17 illustrates the Mohr-Coulomb failure criterion for the rock matrix for an arbitrary state of stress. Figure 18 illustrates the finite difference mesh used in the FLAC modeling.

In UDEC, each joint is explicitly modeled with variable spacing and persistence. The matrix in UDEC is assumed to behave elastically. This means that inelastic behavior is allowed to occur only in the joints. Figure 19 illustrates the pattern of joints used in the UDEC modeling.

3.3 Conceptual Considerations

Vertical emplacement of waste is being considered in these analyses. It is assumed that the general conclusions will also apply to the horizontal emplacement alternative. Figure 20 illustrates the vertical emplacement concept.

The Areal Power Density (APD), also called thermal loading (dimensions used are W/m^2 and kW/acre), may vary depending on the geometric scale of the numerical model being considered. On a far-field scale, which includes the total repository area, the APD being considered is 14.1 W/m^2 (57 kW/acre) [Johnstone et al., 1984]. Because waste emplacement panel stand-off distances are included in the thermal load calculations, the thermal loads applied are slightly lower than the maximum near-field loading and are used for comparison purposes only. Appendix A describes in detail the calculation used to determine the thermal loading.

Using two-dimensional models requires that the discrete location of the waste containers be distributed uniformly along the disposal room. In the case of vertical emplacement, this means the location of a vertical heat-generating trench at the center of the floor along the axis of the room. Because of the transient nature of the problem as well as the geometric layout of the waste, the "trench" concept is expected to be an adequate idealization of the emplacement.

Figure 21 illustrates the conceptual model of the vertical and waste emplacement. Because of symmetry, only one half of the disposal room and pillar needs to be included. The thermal boundary conditions are adiabatic. The two horizontal boundaries have been removed sufficiently far from the heat generating waste to remain at the initial temperature of 26°C for the time period simulated.

The kinematic boundary conditions are also shown in Fig. 21, and are such that the two vertical boundaries are restricted from moving in the horizontal direction, while free to move in the vertical direction. The lower horizontal boundary is restricted from moving in the vertical direction, while free to move in the horizontal direction. The upper horizontal boundary is a free-to-move pressure boundary. The initial vertical and horizontal stresses applied to the models are -7 MPa and -3.5 MPa, respectively (MacDougall et al., 1987, Chapter 2). Note, that compressive stresses are negative.

3.4 Waste Form Characteristics

The initial power of a SF container at the time of emplacement may range from 2.3 kW to 3.4 kW (O'Brian, 1985). In this study, the initial power is set conservatively to 3.2 kW. The initial power of the DHLW container is chosen as 0.42 kW after Peters (1983). Also in this study, the power output of the two waste types is combined and treated as spent fuel.

The thermal decay characteristics of SF given by Peters (1983) for waste ten years out of the reactor:

Spent Fuel $$P(t) = 0.54 \exp(-\ln(0.5)t/89.3) + 0.44 \exp(-\ln(0.5)t/12.8)$$

where P(t) = normalized power, and

t = time in years.

The normalized power as a function of time, as described from the above equations as well as that given by Mansure (1985) for SF are shown in Fig. 22. As seen, the two approximations for SF are very similar.

4.0 MODELING SEQUENCE

The input instructions used to generate the FLAC results are presented in appendix B and the commands used to obtain the UDEC results are given in appendix C. The time sequence used for both codes was:

- EXCAVATION OF THE DISPOSAL ROOM AT TIME = 0

  (Deformations and stresses are determined throughout the rock.)

- INITIAL WASTE EMPLACEMENT AT TIME = 0

  (Heat transfer calculations start.)

- WASTE ISOLATION AT 50 YEARS

  (The thermal/mechanical response of the rock is predicted, and compared for times of 0 and 50 years. The disposal room is not ventilated during this period. Adiabatic boundaries are assumed for the emplacement drift.

5.0 MATERIAL PROPERTIES

The base thermal and mechanical properties used are consistent with the "design" rock mass properties reported in the SCPCDR. The range in properties analyzed will include the variation reported for the "recommended" properties in the SCPCDR.

Table 1

"DESIGN" VALUES AS REPORTED IN CHAPTER 2 SCPCDR

Property	BASE	MIN	MAX	Units	Comments
Rock Mass Property					
Bulk Density	2.34			g/cc	
E	15.1			GPa	
Poisson's ratio	0.20				
Compressive Stress	75.4			MPa	
Cohesion	22.1			MPa	
Friction	29.2			Degrees	
k (sat)	2.07			W/mK	
Cp (sat)	2.25			j/cm^3 K	
Therm Exp.	10.7E-06			1/K	
Joint property					
Kn	1E+05	1E+05	1E+07	MPa/m	
Ks	1E+05	1E+05	1E+07	MPa/m	
Cohesion	1.0	0.0	1.0	MPa	
Friction	0.8	0.2	0.8	Coef	
Dilation	0.0	0.0	5.0	Degrees (assumed)	

6.0 DISCUSSION OF RESULTS

A series of computer runs were made with both the FLAC and UDEC codes. The basic difference between the two methods is that the UDEC model contains explicit definitions of the jointing pattern, while the FLAC code, with its ubiquitous joints, models only the orientation of the joints, but not their loation or spacing. This allows comparison of various assumptions regarding joint persistence, intersection, and spacing. FLAC models joints as closely-spaced, non-intersecting (i.e., only one joint orientation) continuous joints. In UDEC, joints intersect, and have variable spacing and persistence.

In all of the parameter runs comparisons are made in these categories:

(1) vertical and horizontal closure of emplacement drift (SCPCDR reports design limit of 15 cm);

(2) extents of joints shear or opening around emplacement drift; and

(3) pattern of principal stresses around emplacement drifts.

The pattern of parameters variations used are as follows:

(a) base case with Cohesion=1 MPa and Friction=38.7°;

(b) cohesion reduced to 0 MPa;

(c) cohesion returned to 1 MPa and Friction reduced to 11.3°; and

(d) cohesion reduced to 0.

This pattern was repeated for each base case for 0 years and after 50 years of heating. The base cases used were: (1) UDEC with normal joint and shear stiffness at 10^5 MPa/m; (2) FLAC with vertical joints; (3) FLAC with horizontal joints; and (4) FLAC with 70° joints.

In UDEC, additional runs were made at 0 and 50 years with a dilation of 5 degrees for variation (d) above. Runs of dilation of 2.5 degrees were made for variations (a) and (d) at 50 years. Joint normal and shear stiffness were increased to 10^7 MPa/m in the UDEC runs for the base values (a) for 0 years.

6.1 Variation in Friction Angle

The friction angle was varied in the FLAC and UDEC runs from 38.7° (coefficient=.8) to 11.3° (coefficient=.2). The range in friction values represent the 'design' value and the lower bound "recommended" value from the SCPCDR.

6.1.1 Emplacement Room Closures

One of the design criteria in the SCPCDR is that room closures shall not exceed 6 inches (15 cm). Closure data was collected for each model variation and listed in Table 2. The closure data is reported for centerline displacements in the vertical and horizontal directions. While none of the calculated closures exceeded the design criteria, comparisons of effects of the joint parameters on closure are made below.

Table 2

VERTICAL AND HORIZONTAL ROOM CLOSURES

CODE	TIME (yrs)	ANGLE (deg)	STIFF (MPA/m)	COH (MPa)	FRIC (deg)	DIL (deg)	VERT* (m)	HOR (m)
UDEC	0	-	1E+05	1	38.7	0	0.017	0.004
UDEC	0	-	1E+05	0	38.7	0	0.017	0.004
UDEC	0	-	1E+05	1	11.3	0	0.029	0.007
UDEC	0	-	1E+05	0	11.3	0	0.030	0.007
UDEC	0	-	1E+05	0	11.3	5.0	0.030	0.008
UDEC	0	-	1E+07	1	38.7	0	0.013	0.003
UDEC	0	-	1E+09	1	38.7	0	0.005	0.003
UDEC	50	-	1E+05	1	38.7	0	-0.003	0.019
UDEC	50	-	1E+05	0	38.7	0	-0.003	0.019
UDEC	50	-	1E+05	1	11.3	0	0.001	0.030
UDEC	50	-	1E+05	0	11.3	0	0.001	0.030
UDEC	50	-	1E+05	1	38.7	2.5	0.004	0.018
UDEC	50	-	1E+05	0	11.3	2.5	0.012	0.027
UDEC	50	-	1E+05	0	11.3	5.0	0.012	0.027
FLAC	0	90	-	1	38.7	-	0.004	0.002
FLAC	0	90	-	0	38.7	-	0.005	0.002
FLAC	0	90	-	1	11.3	-	0.006	0.003
FLAC	0	90	-	0	11.3	-	0.012	0.007
FLAC	0	0	-	1	38.7	-	0.004	0.001
FLAC	0	0	-	0	38.7	-	0.005	0.002
FLAC	0	0	-	1	11.3	-	0.005	0.002
FLAC	0	0	-	0	11.3	-	0.012	0.003
FLAC	0	70	-	1	38.7	-	0.005	0.002
FLAC	0	70	-	0	38.7	-	0.005	0.003
FLAC	0	70	-	1	11.3	-	0.006	0.005
FLAC	0	70	-	0	11.3	-	0.022	0.011
FLAC	50	90	-	1	38.7	-	0.001	0.007
FLAC	50	90	-	0	38.7	-	0.001	0.008
FLAC	50	90	-	1	11.3	-	0.005	0.011
FLAC	50	90	-	0	11.3	-	0.011	0.019
FLAC	50	0	-	1	38.7	-	0.001	0.007
FLAC	50	0	-	0	38.7	-	0.002	0.007
FLAC	50	0	-	1	11.3	-	0.005	0.008
FLAC	50	0	-	0	11.3	-	0.015	0.011
FLAC	50	70	-	1	38.7	-	0.002	0.008
FLAC	50	70	-	0	38.7	-	0.002	0.008
FLAC	50	70	-	1	11.3	-	0.016	0.015
FLAC	50	70	-	0	11.3	-	0.037	0.022

*-sign indicates room opening.

6.1.1.1 UDEC — Comparing the time 0 runs in UDEC, it can be seen in Table 1 that the vertical closure increases from 17 mm to 30 mm when the friction is reduced to 11.3°. Horizontal closures ranged from 4 mm to 7 mm. At 50 years, the effect of heating has reversed the vertical closure for the high friction case to -3 mm (opening) and reduced friction increases closure to 1 mm. The 50-year heating causes an increase in horizontal closure to 19 mm for high friction and 30 mm for low friction.

6.1.1.2 FLAC - Vertical Joints — Comparing the results with the FLAC runs reveals that the time 0 vertical closure increases from 4 mm for high friction to 5 mm for low friction and then to 12 mm when cohesion is also reduced. Horizontal closure increased from 2 mm to 3 mm and then to 7 mm when cohesion is also reduced. At 50 years, FLAC confirms the UDEC result of reduced vertical closures from the non-heated results. Vertical closure increases from 1 mm for the high friction case to 11 mm for low friction. Horizontal displacements increased from 7 mm to 19 mm in the vertical joint case when friction is reduced.

6.1.1.3 FLAC - Horizontal Joints — The vertical closure is the same regardless of whether vertical or horizontal joints are modeled. The increase in horizontal closure is again 1 mm with a 1 mm change when cohesion is also reduced. After 50 years, vertical closure increases from 1 mm to 15 mm, and horizontal displacements increased from 7 mm to 19 mm in the horizontal joint case.

6.1.1.4 FLAC - 70 Degree Joints — When friction alone is reduced, the vertical and horizontal closures are the same for the 70° and the vertical joints cases. However, when the cohesion and friction are reduced, the vertical closure increases 12 mm to 22 mm and the horizontal closure increases from 7 mm to 11 mm.

After 50 years, the 70° joint case shows a greater effect of the reduction in friction alone than in the vertical joint case. The vertical closure increases from 2 mm to 16 mm when friction is reduced and increases again to 37 mm when cohesion is also reduced. The horizontal closure is not as strongly affected by the 70° jointing and increases from 8 mm to 15 mm for reduced friction and then to 22 mm when cohesion is also reduced. This compares with a low friction and cohesion horizontal closure for the vertical jointing of 19 mm.

6.1.2 Joint Displacements

One of the methods used to compare effects of changes in joint parameters was to look at the pattern and areal extent of joint displacements. For the UDEC results, the shear displacement magnitudes are expressed by plotting multiple parallel lines along the sliding joint. In the results shown, each line represents 1 mm of joint shear displacement. For the FLAC results, a period (.) is plotted in the zones which at some time have exceeded the slip criteria.

6.1.2.1 UDEC — Comparing the joint displacement plots for 0 years for the UDEC runs in Fig. 23 and Fig. 25, it can be seen that the joint shear takes place primarily in vertical joints. Decreasing friction causes an increase in the area of shear from 3 m above and below the room to 6 m above and below. Additional movement is seen in parallel joints in the pillar area when the cohesion is also reduced for the low friction case in Fig. 26. Figures 29 and 31 reveal that after the 50 year heating the predominant movement is along horizontal joints and the zone of influence increases from 2 m to 13 m. No additional change is seen in Fig. 30 when the cohesion is dropped for the low friction case.

6.1.2.2 FLAC - Vertical Joints — In the FLAC results, we can see in Fig. 36 a small zone of joint shear at the corners of the room of about 1m-depth after room excavation. Reducing the friction angle in Fig. 38 increases the shear zone to 5m. Combining the reduced friction with reduced cohesion in Fig. 39 the shear zone increases to 15 m.

Heating to 50 years increases the shear zone for the vertical jointed high friction case to 2 m (Fig. 40).

Reducing the friction (Fig. 42) increases the shear zone size to 9 m. Combining the low friction and zero cohesion (Fig. 43) again produces a shear zone out to 15 m.

6.1.2.3 FLAC - Horizontal Joints — Examining the horizontal jointing case in Figs. 44 and 46 reveals almost identical results to the vertical jointing case. Combining the reduced cohesion with the lower friction in Fig. 47 for the horizontal joints shows a smaller zone of 7 m in the area above and below the drift and no shear in the rib area.

Comparing the 50 year results of the horizontal joints in Fig. 48 with those for the vertical joints in Fig. 40 shows that the shear zone for high friction is about the same size but is located more to the top and bottom of the drift. Reducing the friction in Fig. 50 shows a larger shear zone in both the vertical and horizontal directions than is seen for the vertical joints in Fig. 42. The shear zone covers about 5 m horizontally and 7 m above and below the drift. Combining with reduced cohesion in Fig. 52 shows an increase in the horizontal extent of the shear zone to 7 m.

6.1.2.4 FLAC - 70 Degree Joints — Examining the 70° jointing case in Figs. 52 and 54 reveals similar development of shear zones above and below the drift, but much more extensive development of shear in the pillar than was seen with vertical joints (Fig. 38). The shear zone increases from 1 m to 3.5 m in the vertical direction and from 2 m to 9 m in the horizontal direction as the friction is reduced. When cohesion is also reduced, the area of joint displacement encompasses almost the entire model (Fig. 55). This illustrates one of the difficulties when using ubiquitous joint models. Although the drift does not actually fail, the initial stress state is close enough to the Mohr-Coulomb criterion for slip that a slight perturbation is enough to indicate slip in all zones. There is no kinematic restriction in a ubiquitous joint model, and the solution may indicate stress even when it is not physically possible for slip to occur. In this case the model reaches equilibrium without collapse but indicates that all zones exceeded the Mohr-Coulomb criterion for slip.

Comparing the 50 year results of the 70° joints in Fig. 56 with those for the vertical joints in Fig. 40 shows that the shear zone for high friction is slightly greater extending further into the pillar. Reducing the friction in Fig. 58 shows a larger shear zone in both the vertical and horizontal directions than is seen for the vertical joints in Fig. 42. The shear zone covers about 10 m horizontally and 6 m above and below the drift. Combining with reduced cohesion in Fig. 59 again indicates shear in all zones.

6.1.3 Principal Stress Patterns

By observing the principal stress patterns, relative affects of parameter changes on support requirements can be assessed. As the pressure arches move up into the drift roof the support requirements would be increased. As the arch moves further into the pillar the possibility for pillar spalling is increased.

6.1.3.1 UDEC — Comparing Fig. 62 with Fig. 60, it can be seen that there is a reduction in the compressive stresses parallel to the drift surfaces when the friction angle is decreased. This indicates that the arch support is moving further from the opening which may increase support requirements. When the cohesion is also reduced, the stress arch remains unchanged in Fig. 63.

After 50 years of heating, the major principal stress shifts from vertical to horizontal (Fig. 66). In this case, reduction in the friction does not change the stress patterns as much above and below the drift but more strongly affects the pillar area. The pressure arch moves out 5 m into the pillar. This may increase the likelihood of spalling of the ribs. Combining reduced friction with reduced cohesion in Fig. 69 produces no additional effect.

6.1.3.2 FLAC - Vertical Joints — Comparing Fig. 73 with Fig. 75, the reduction in the pressure arch seen in the UDEC results is absent. However, when the cohesion is also reduced (Fig. 76), the result is similar to the UDEC result with reduced friction alone. There is a reduction in the compressive stresses parallel to the drift surfaces and the pressure arch moves out 10 m into the pillar and 3 m into the floor. The roof arch remains unaffected.

After 50 years of heating, the major principal stress shifts from vertical to horizontal (Fig. 77). Reducing the friction (Fig. 79) in this case has a slightly greater effect below the drift moving the pressure down from 1 m to 3 m. The pressure arch in the pillar moves out from 1 m to 5 m. Combining reduced friction with reduced cohesion in Fig. 80 moves the arch out to 4 m above, 5 m below, and 10 m into the pillar.

6.1.3.3 FLAC - Horizontal Joints — Comparing Fig. 81 with Fig. 83, the reduction in the pressure arch seen in the UDEC results is absent. However, when the cohesion is also reduced (Fig. 84), the pressure arch moves out to 3 m into the pillar and 5 m into the roof and floor.

After 50 years heating, the major principal stress shifts from vertical to horizontal (Fig. 85). Reducing the friction (Fig. 87) in this case has a slightly greater effect below the drift, moving the pressure arch down from 1 m to 5 m. The pressure arch in the pillar does not move significantly. Combining reduced friction with reduced cohesion in Fig. 88 has little additional effect.

6.1.3.4 FLAC - 70 Degree Joints — The only observable effect in the reduction in friction from Fig. 89 to Fig. 91 is a very slight movement in the pressure arch in the floor and the pillar near the roof. When the cohesion is also reduced (Fig. 92), the pressure arch in the floor moves out an additional 1 m.

After 50 years heating, the major principal stress shifts from vertical to horizontal (Fig. 93). Reducing the friction (Fig. 95) in this case has a slightly greater effect below the drift moving the pressure arch, down from 1 m to 3.5 m. The pressure arch in the pillar does not move significantly. Combining reduced friction with reduced cohesion in Fig. 96 has little additional effect.

6.2 Variation in Cohesion

The value of cohesion in the FLAC and UDEC runs was decreased from 1 MPa to 0 MPa.

6.2.1 Emplacement Room Closures

As can be seen from the values listed in Table 2, there was no significant effect of reducing the cohesion on the vertical or horizontal closures in either the FLAC or UDEC runs. Nor was there any significant difference between the vertical, horizontal, or 70 degree joint models in FLAC. Only when combined with the reduced friction did reduction of cohesion produce any significant changes in closure and then only in the case of the FLAC runs.

6.2.2 Joint Displacements

6.2.2.1 UDEC — Comparing the shear plots from UDEC for the cases of reduced cohesion, Figures 23 and 24 for 0 years and Figures 29 and 30 for 50 years do not reveal any observable difference in shear zone size due to cohesion reduction.

6.2.2.2 FLAC - Vertical Joints — The shear plot results from FLAC do show some effect of the reduction in cohesion. Comparing Figs. 36 and 37, the zone of shear has connected two 1 m areas at the top and bottom of the drift into a single zone which extends about 2 m into the rib area.

The results for the vertical joint case in FLAC after 50 years (Fig. 41) appear almost identical to those for 0 years (Fig. 47) and show no addition development of the yield zone.

Comparison of these results to those reported by Johnstone et al. (1984) indicate very similar results. Comparing Figs. 36 and 37 with Fig. 97 indicates that the shear displacement zones are roughly the same size and occur in the same locations. Comparing the FLAC 50-year case (Figs. 40 and 41) with the 100-year case (Fig. 98) also reveals similar results. The major difference is that FLAC predicts a greater initial sensitivity to the reduction in cohesion and less sensitivity to the thermal loading. The end results appear similar though the development sequence of the zones is slightly different.

6.2.2.3 FLAC - Horizontal Joints — Reduction in cohesion for the case of horizontal joints in FLAC results in an increase of a 1 m zone at the top and bottom (Fig. 44) to a 2 m zone above and below the drift (Fig. 45). In this case no shear displacement occurred in the pillar.

After 50 Years in the horizontal joint case in FLAC, there is a small increase in shear zone from Fig. 48 to the reduced cohesion in Fig. 49. The shear zone in this case increases for about 2 m to 2.5 m.

6.2.2.4 FLAC - 70 Degree Joints — Reduction in cohesion for the case of 70° joints in FLAC results in an increase of a 1 m zone below the drift and a 1.5 m zone in the pillar (Fig. 52) to a 2 m zone below and a 4 m zone in the pillar (Fig. 53). These is only slightly larger than the zones in Fig. 37.

After 50 Years in the 70°, the shear zones in Fig. 57 were almost identical to those in the non-heated case (Fig. 53).

6.2.3 Principal Stress Patterns

6.2.3.1 UDEC — Comparing Fig. 71 with Fig. 72 there is no observable effect of the reduction in cohesion.

After 50 years of heating, comparing Fig. 66 with Fig. 67, there is no observable effect of the reduction in cohesion.

6.2.3.2 FLAC - Vertical Joints

Comparing Fig. 73 with Fig. 74, there is no observable effect of the reduction in cohesion.

After 50 years of heating, comparing Fig. 77 with Fig. 78, there is no observable effect of the reduction in cohesion.

6.2.3.3 FLAC - Horizontal Joints — Comparing Fig. 81 with Fig. 82, there is no observable effect of the reduction in cohesion.

After 50 years of heating, comparing Fig. 85 with Fig. 86, there is no observable effect of the reduction in cohesion.

6.2.3.4 FLAC - 70 Degree Joints — Comparing Fig. 89 with Fig. 90, there is no observable effect of the reduction in cohesion.

After 50 years of heating, comparing Fig. 93 with Fig. 94, there is no observable effect of the reduction in cohesion.

6.3 Variation in Dilation

The ubiquitous joint constitutive model in FLAC does not include dilation due to shear displacement along joints. The results in this section are from UDEC only. The dilation angle was increased from the base value of 0 to 2.5 degrees. The cohesion was then reduced to 0 MPa, and the friction reduced to 11.3°. The reduced values were then also used with a dilation of 5°. This sequence was performed only for the 50-year case. The 0-year case was run only for the 5° dilation with reduced friction and cohesion.

6.3.1 Emplacement Room Closures

Table 1 shows the effects of increase in dilation on the closures of the emplacement room drift. Although an increase in dilation leads to a greater stability in general, in this case, it also increases the inward displacement of the blocks for the high friction case. An increase in dilation from 0° to 2.5° in the high cohesion and high friction case results in change from vertical room opening of 3 mm to room closure of 4 mm. The horizontal closure remains relatively constant. In the low cohesion and friction case, the vertical closure decreases from 29 mm to 12 mm and the horizontal closure increases from 7 mm to 27 mm for dilation values of 0° and 2.5°, respectively. Further increases of dilation to 5° does not affect the closure.

6.3.2 Joint Displacements

Comparing the shear displacements for the high cohesion and high friction variation in Figs. 29 and 33, it is seen that increasing dilation to 2.5° results in the elimination of the small horizontal shear zones at the top and bottom of the drift. For the low friction and low cohesion variation (Figs. 32 and 34), the increased dilation significantly reduces the amount of shear on the horizontal joints and increases the amount shear on the vertical joints.

Increasing the dilation to 5° in Fig. 35 does not appear to cause any additional effect compared to Fig. 34.

The increase in dilation changes the shear patterns from predominantly horizontal to vertical.

Comparing the 0-year cases shown in Figs. 26 and 27 indicates that increase in dilation to 5° causes additional movement along a plane parallel to the initial shear pattern but at a depth of 4 m into the pillar.

6.3.3 Principal Stress Patterns

Comparing Fig. 63 with Fig. 64, there is no observable effect of the increase in dilation to 5°.

After 50 years of heating, comparing Fig. 66 with Fig. 69, there is a slight increase in the definition of the pressure arch in the rib. Comparing Figs. 69, 71 and 72, again, there is little effect of dilation changes in the stress patterns.

6.4 Variation in Joint Stiffness

In UDEC, the joint shear and normal stiffness are explicitly modeled. The FLAC ubiquitous model does not include a stiffness term. All results for stiffness variation will be from UDEC.

6.4.1 Emplacement Room Closures

Table 1 shows the effect of increasing the joint normal and shear stiffness on the closures of the emplacement drift. Increasing the joint stiffness from 10^5 MPa/m to 10^7 MPa/m causes a decrease in vertical closure from 17 mm to 13 mm.

6.4.2 Joint Displacements

The shear patterns resulting from the increase in stiffness in Fig. 28 as compared to Fig. 23 indicates very little difference in the area of joint displacements around the emplacement drift.

6.4.3 Principal Stress Patterns

Comparing Figs. 62 and 65 indicates that an increase in joint stiffness causes no observable change in the stress patterns.

6.5 Persistence

To estimate the effects of persistence in joints, the results for FLAC and UDEC are compared directly. The UDEC model used finite length non-continuous jointing of 0.5 m vertical and 2.0 m horizontal spacing, and FLAC represents continuous joints with close spacing. Comparing Fig. 23 with Fig. 36 shows that the small displacement zones occur in the same locations. Comparing the low friction and low cohesion variations in Figs. 26 and 39 shows the same development of the vertical shear zones above and below the drift. The FLAC results show a development of shear deeper into the pillar than do the UDEC results. Examination of the UDEC geometry given in Fig. 19 shows that the joint spacing and continuity in this area is greatly reduced. This illustrates the effect of joint persistence on the development of shear displacements.

Although not explicitly studied for this report, joint persistence plays an important role in governing the extent of discontinuity-controlled failure. If joints are persistent (i.e., continuous) for long distances, extensive volumes of rock may be bounded by such discontinuities and may be kinematically able to fail or displace into the opening. Non-persistent or discontinuous joints often provide less extensive volumes of rock which may fail, because of increased kinematic restraints. Catastrophic failure of underground openings often involves one or more persistent low-strength discontinuities.

7.0 SUMMARY AND CONCLUSIONS

The results of the parameter studies indicate that the magnitude of the closures did not exceed the design criteria of 15 cm in any of the cases modeled. For comparison purposes it was found that variation in joint parameters can be seen in changes in closure of the emplacement drift. A better indication of joint stability, however, appears to be plots of joint displacement, which more dramatically demonstrate the effects of changes in parameters. The stress pattern plots were useful in determining the effect of parameter variation on the development of the pressure arch around the drift excavation. This can provide information on the relative changes in support requirements.

The interpretations of the effects of the parameter variations indicate that the friction angle is the single most important joint parameter in terms of stability and joint movements. Changes in dilation also produced significant changes in the extent and nature of the joint displacement patterns. Variations in the cohesion and stiffness of the joints do not seem to have a significant effect on drift stability. Increases in joint persistence allows joint movements to extend further from the excavation. The results indicate that there is not a significant increase in joint displacement as a result of the 50 year heating.

It is important to note, however, that while changes in joint parameters did produce observable changes in displacements along joints around the emplacement drift, there was never any indication of drift collapse.

Based on these results, it is apparent that the emplacement drifts will be stable throughout the range in values assumed. These values were chosen to represent a range from the lower to upper bounds in currently available measured values as reported in the SCPCDR. The study does not address the possibility of intact failure of the rock matrix. It assumes failure can occur only by joint failure. This study does not address the possibility of the formation of small unstable blocks in the ribs and roof of the emplacement drift. These blocks may present a hazard to workers but would not represent a threat to emplacement drift stability. The normal practice of rock bolting or the application of a light concrete liner would be sufficient to resolve this hazard. In addition, this study does not address the problem of increased permeability zones around the excavation as this is of primary concern to the shafts. In this case the normal stiffness of the joints and associated aperture changes are of greater importance than when looking at mechanical stability.

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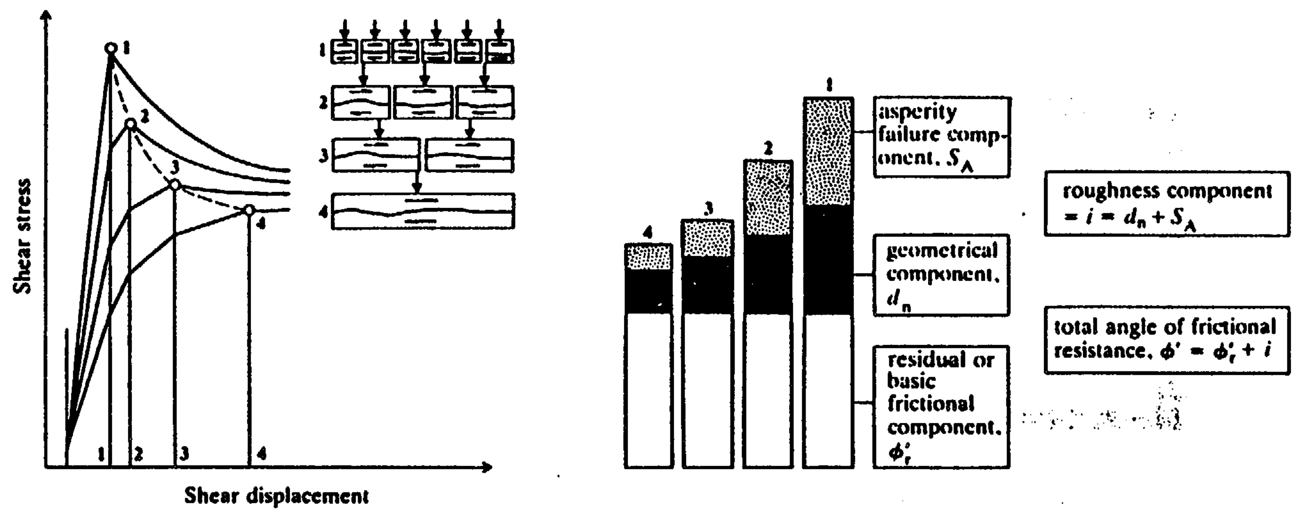


Fig. 1 Experimental Determination of Scale Effects for Joint Shear Strength [Barton et al., 1985]

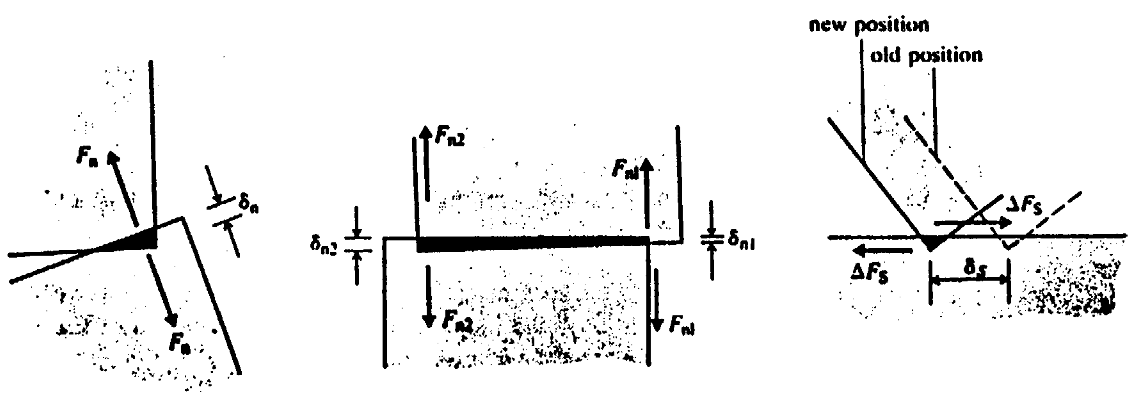


Fig. 2 Normal and Shear Modes of Interaction of Jointed Rock Units [Brady and Brown, 1985]

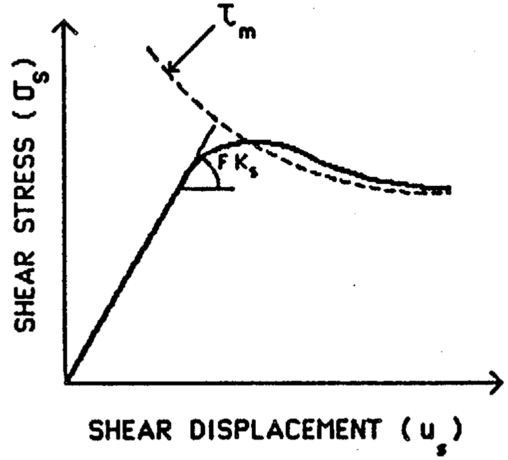


Fig. 3 Shear Stress-Shear Displacement Model and Bounding Shear Strength Curve for Continuously-Yielding Joint Model [Lemos, 1987]

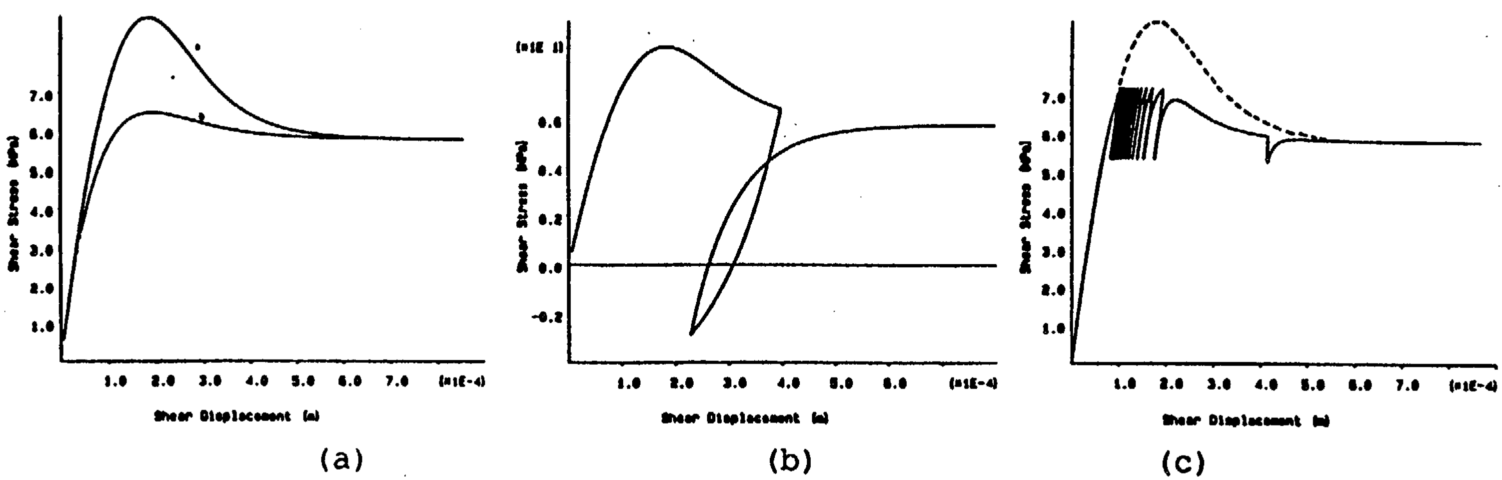


Fig. 4 Exercising of Cundall-Lemos Model: (a) peak-residual behavior; (b) hysteresis on load reversal; (c) load cycling [Lemos, 1987]

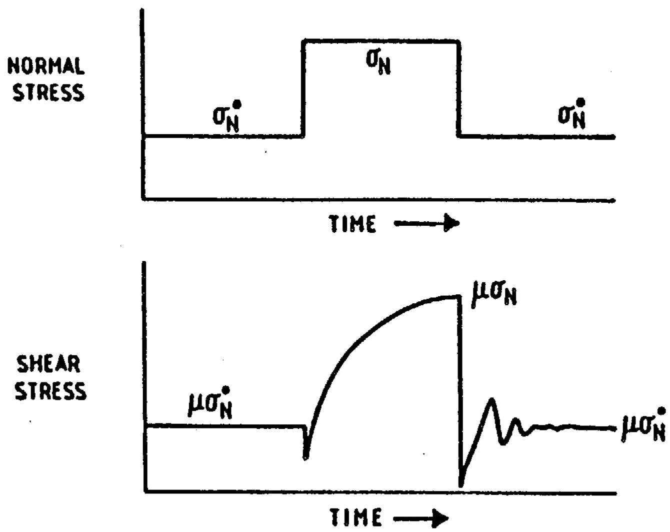


Fig. 5 Response of a Joint, Driven at Constant Velocity, to a Step Change in Normal Stress [Hobbs, 1988]

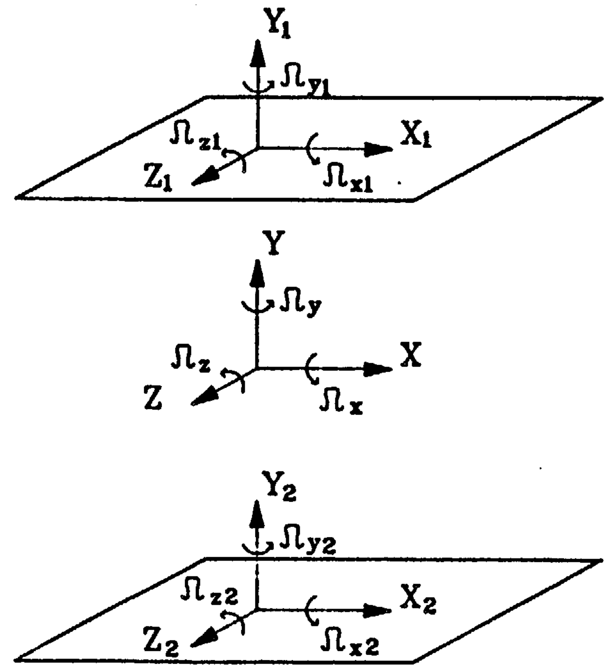


Fig. 6 Elementary Motion During Shear Displacement at Adjacent Surfaces of a Joint

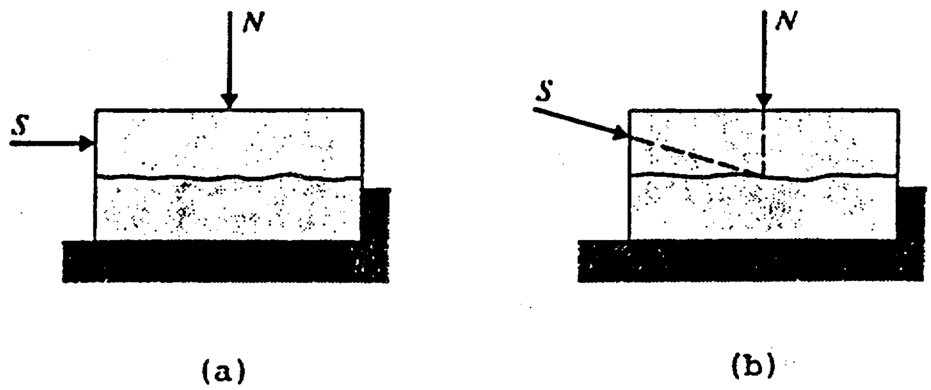


Fig. 7 Load Configurations in a Direct Shear Test

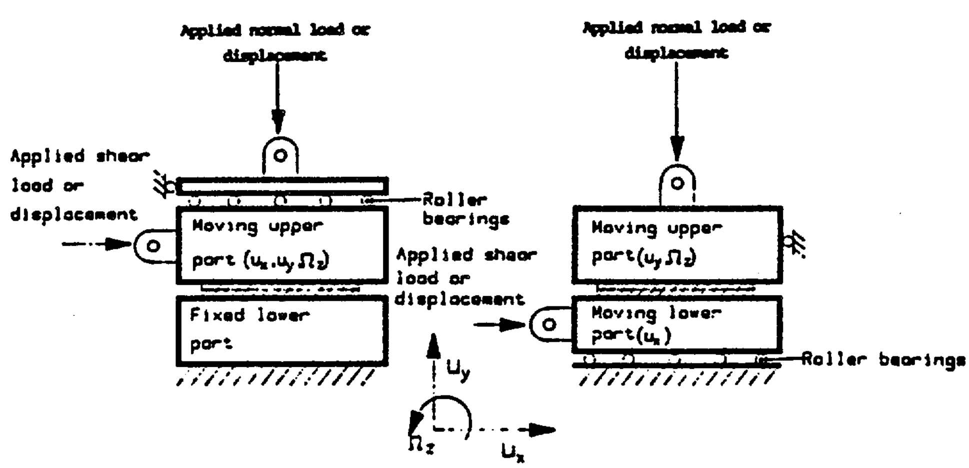


Fig. 8 Block Motion and Experiment Parameters in Conventional Biaxial Shear Rigs

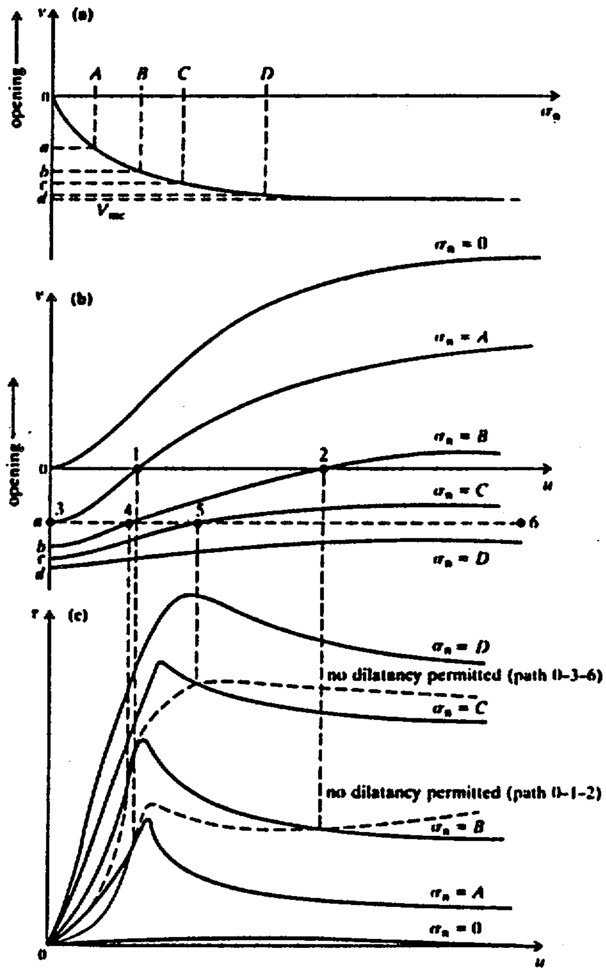


Fig. 9 Relations Between Normal Stress, Shear Stress and Shear Displacement in a Constrained Normal Displacement Test [Goodman, 1980]

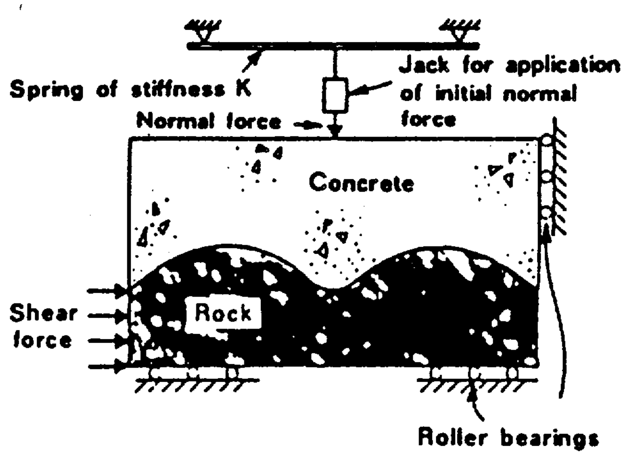


Fig. 10 Principle of the Controlled Normal Stiffness Test Technique [Johnston et al., 1987]

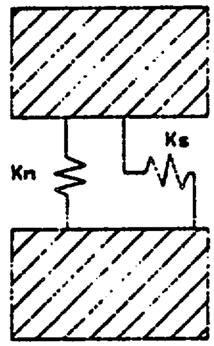


Fig. 11 Interaction Between Blocks Governed by the Normal and Shear Stiffness of Thin Contacts As Illustrated by the Normal and Shear Springs

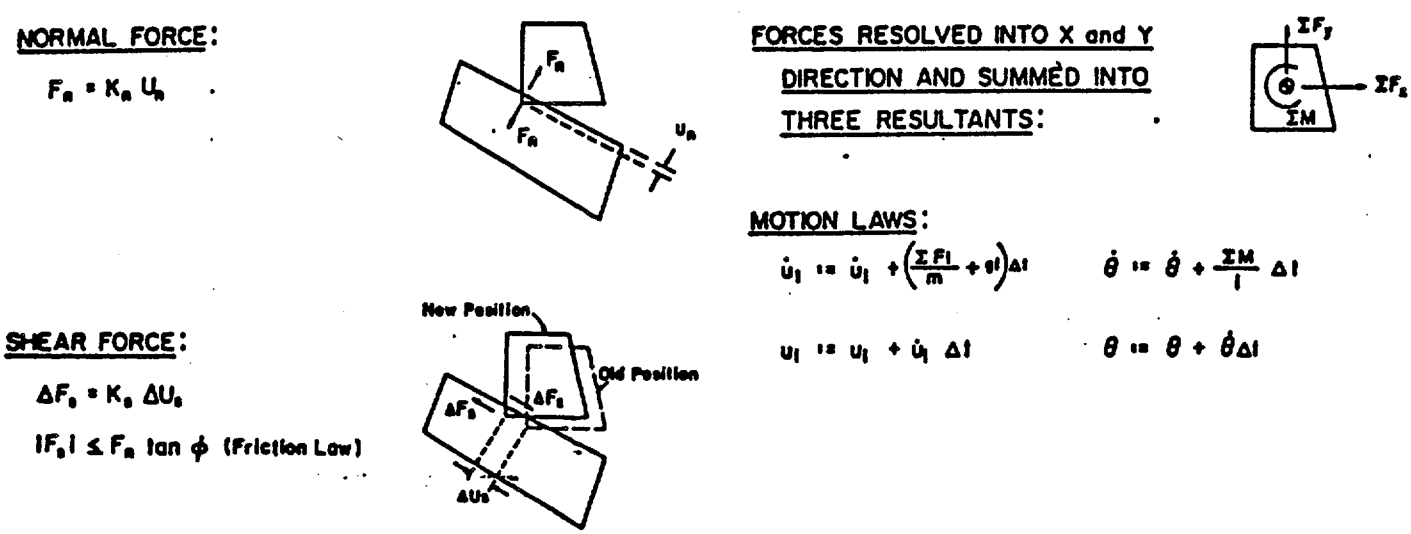


Fig. 12 Simplified Force-Displacement Relations and Motion Equations Used in the Distinct Element Method

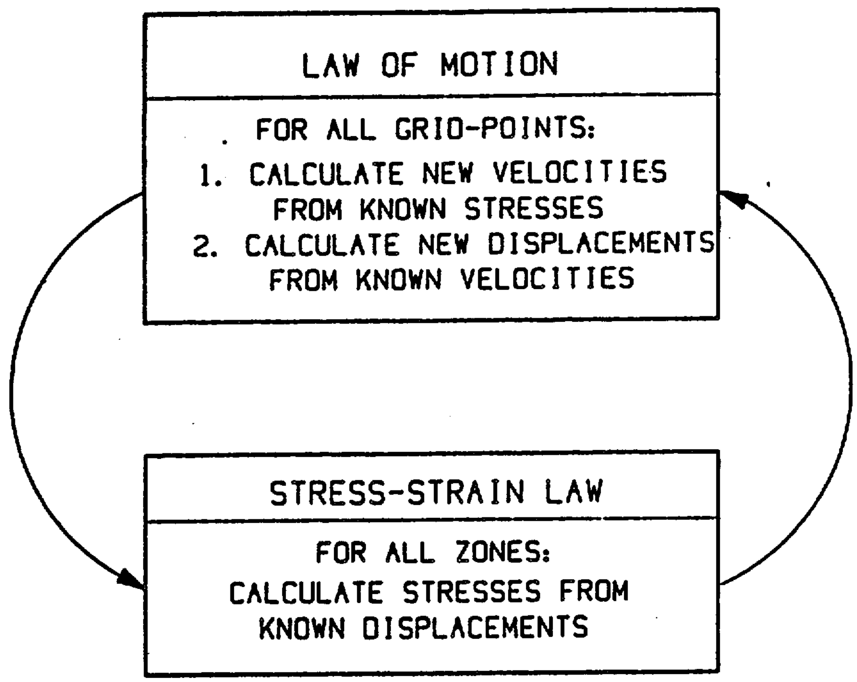


Fig. 13 Calculation Cycle for Explicit Codes

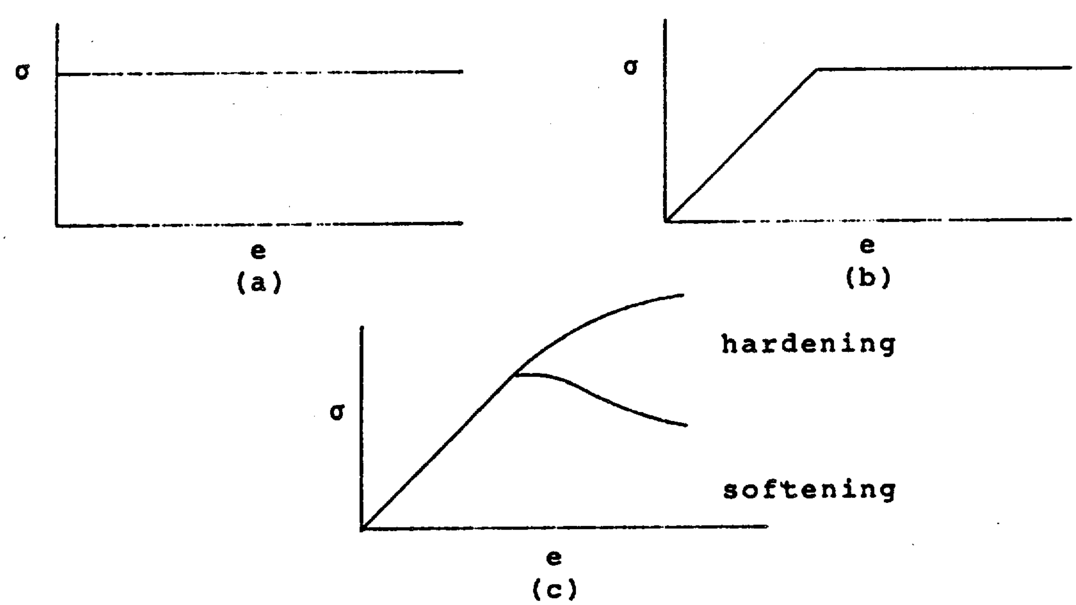
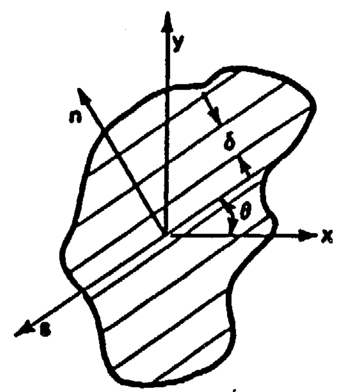
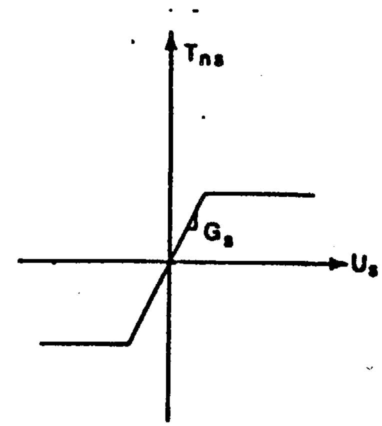


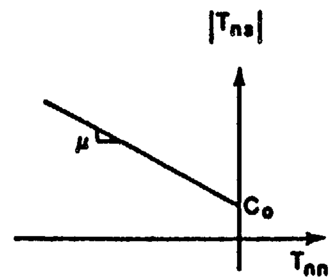
Fig. 14 Three Plasticity Models Typically Used to Represent Rock: (a) rigid perfectly plastic; (b) elastic perfectly plastic; (c) strain hardening/softening



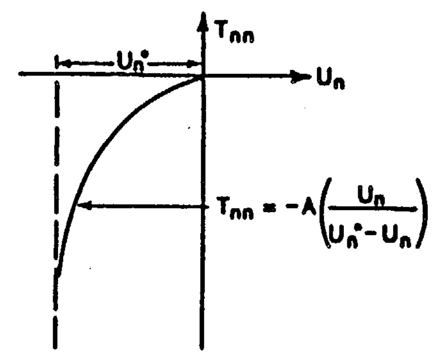
(a) jointed continuum



(b) shear stiffness

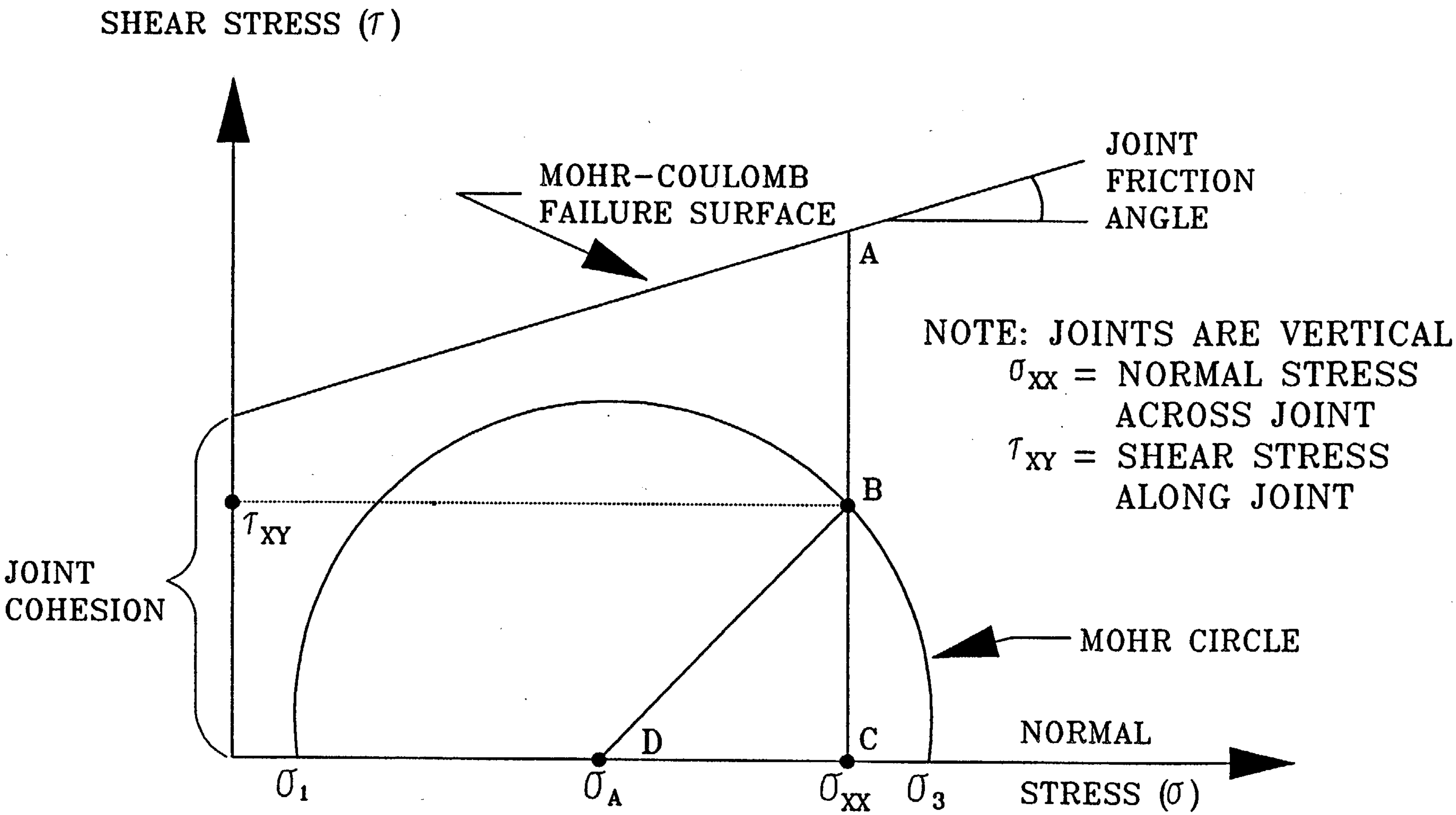


(c) slip criterion



(d) normal stiffness

Fig. 15 Compliant Joint Model Proposed by Thomas (1987) [(b) and (d) show the shear and normal joint behavior; (c) illustrates the standard Mohr-Coulomb slip criterion.]

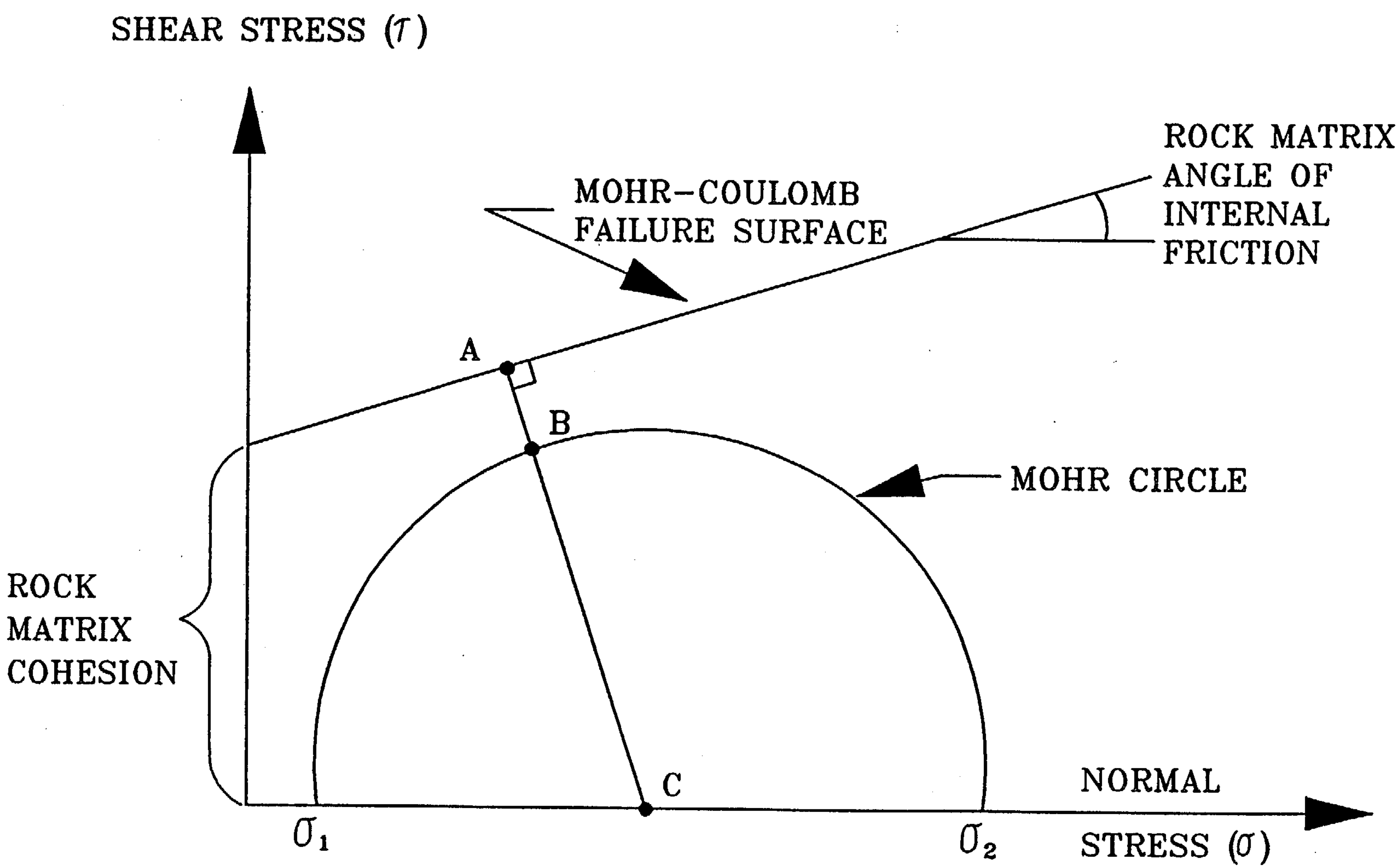


JFS = JOINT FACTOR-OF-SAFETY = $\frac{AC}{BC}$

IF JFS $\geq$ 1 (NO JOINT SLIP)

IF σ_{XX} = TENSILE THEN JFS = 0 (POTENTIAL JOINT OPENING)

Fig. 16 Mohr-Coulomb Criterion for Ubiquitous Joints in FLAC



MFS = MATRIX FACTOR-OF-SAFETY = $\frac{AC}{BC}$

IF MFS $\geq$ 1 (NO ROCK FRACTURING)

IF MFS < 1 (POTENTIAL ROCK FRACTURING)

Fig. 17 Mohr-Coulomb Criterion for Rock Matrix in FLAC

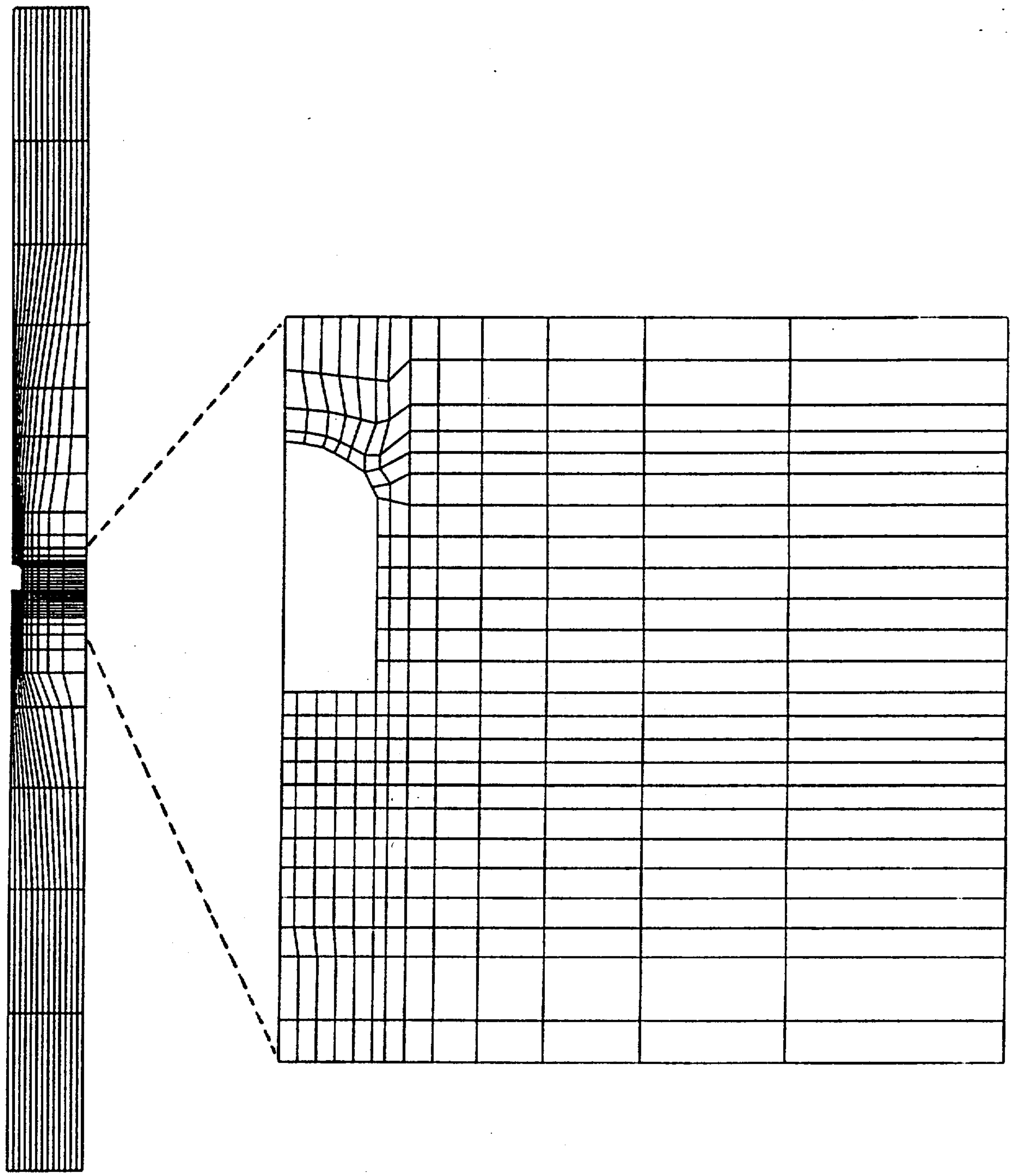


Fig. 18 FLAC Grid Used for Analyses (with blowup of drift area)

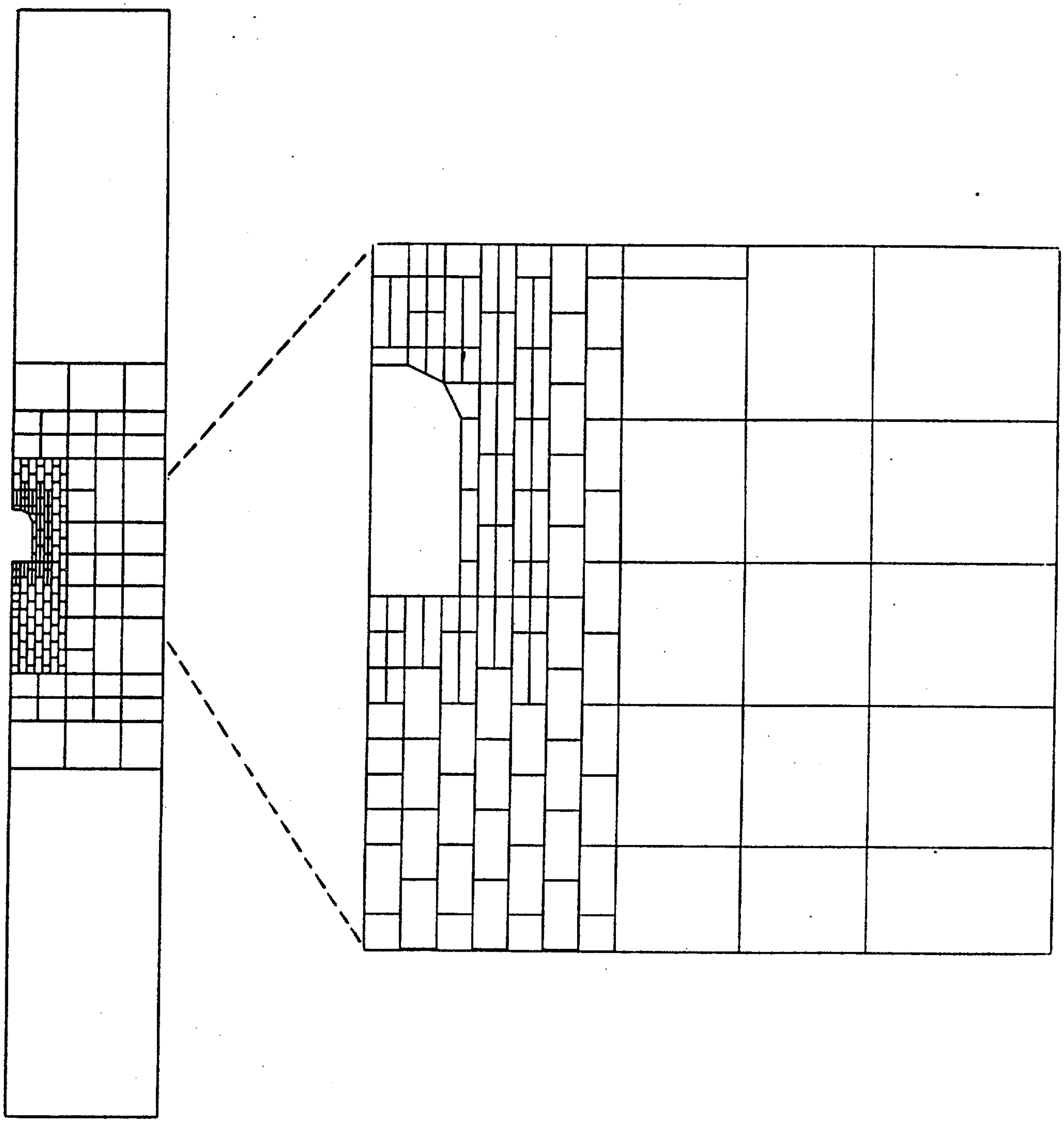


Fig. 19 UDEC Geometry Used for Analyses (with blowup of drift area)

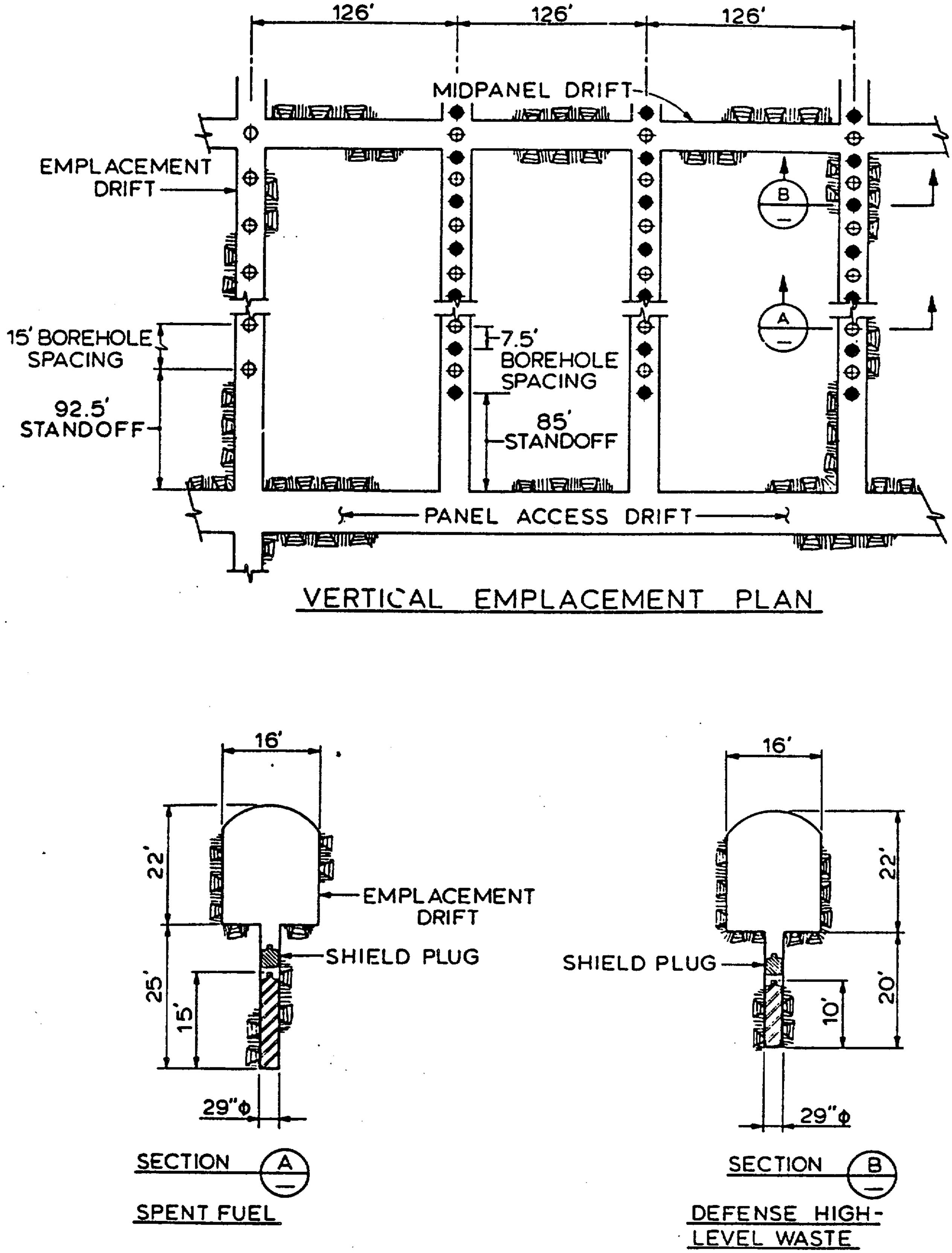


Fig. 20 Vertical Emplacement Concept (SCPCDR)

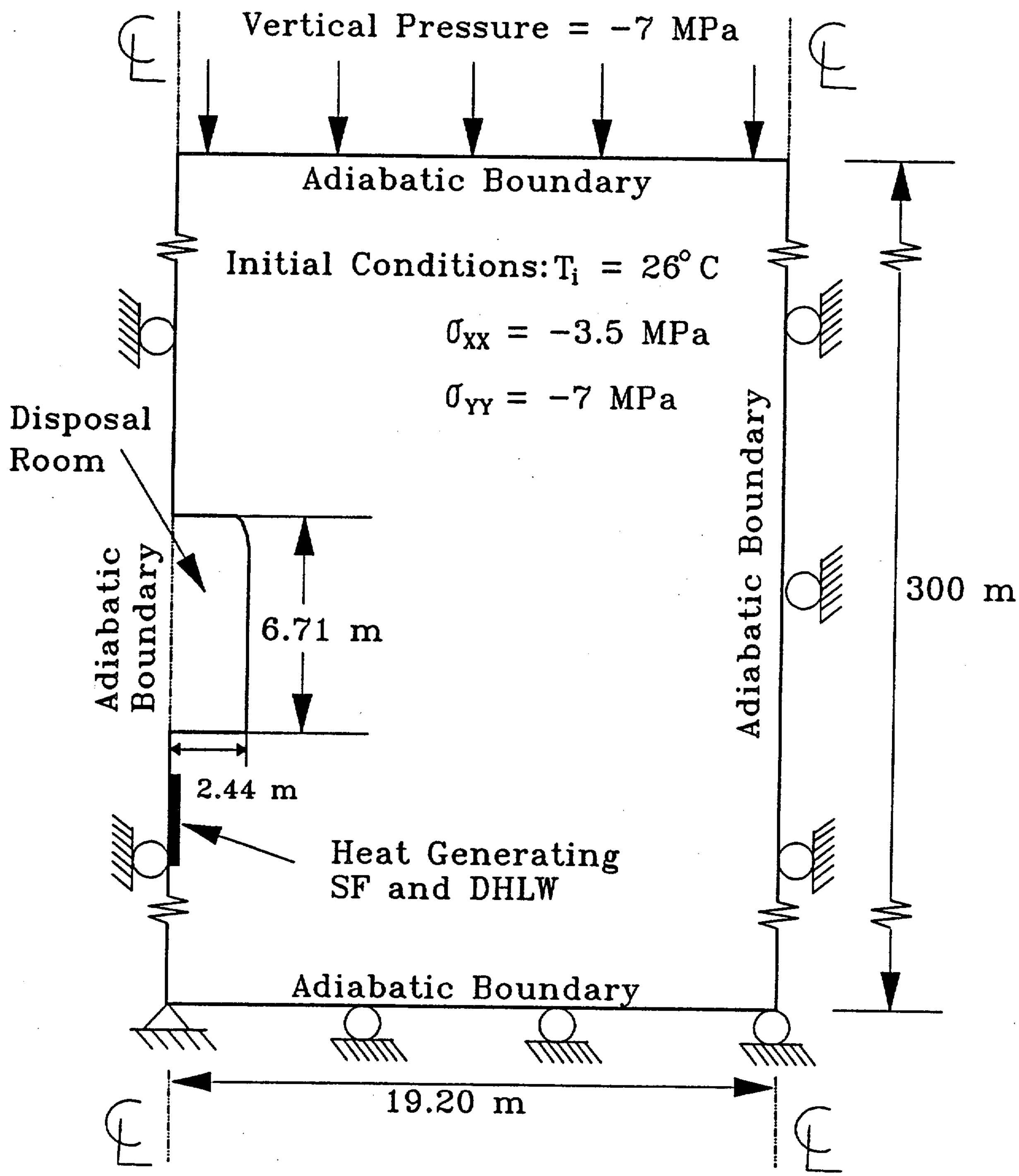


Fig. 21 Conceptual Model of Vertical Emplacement Concept (compressive stresses assumed negative)

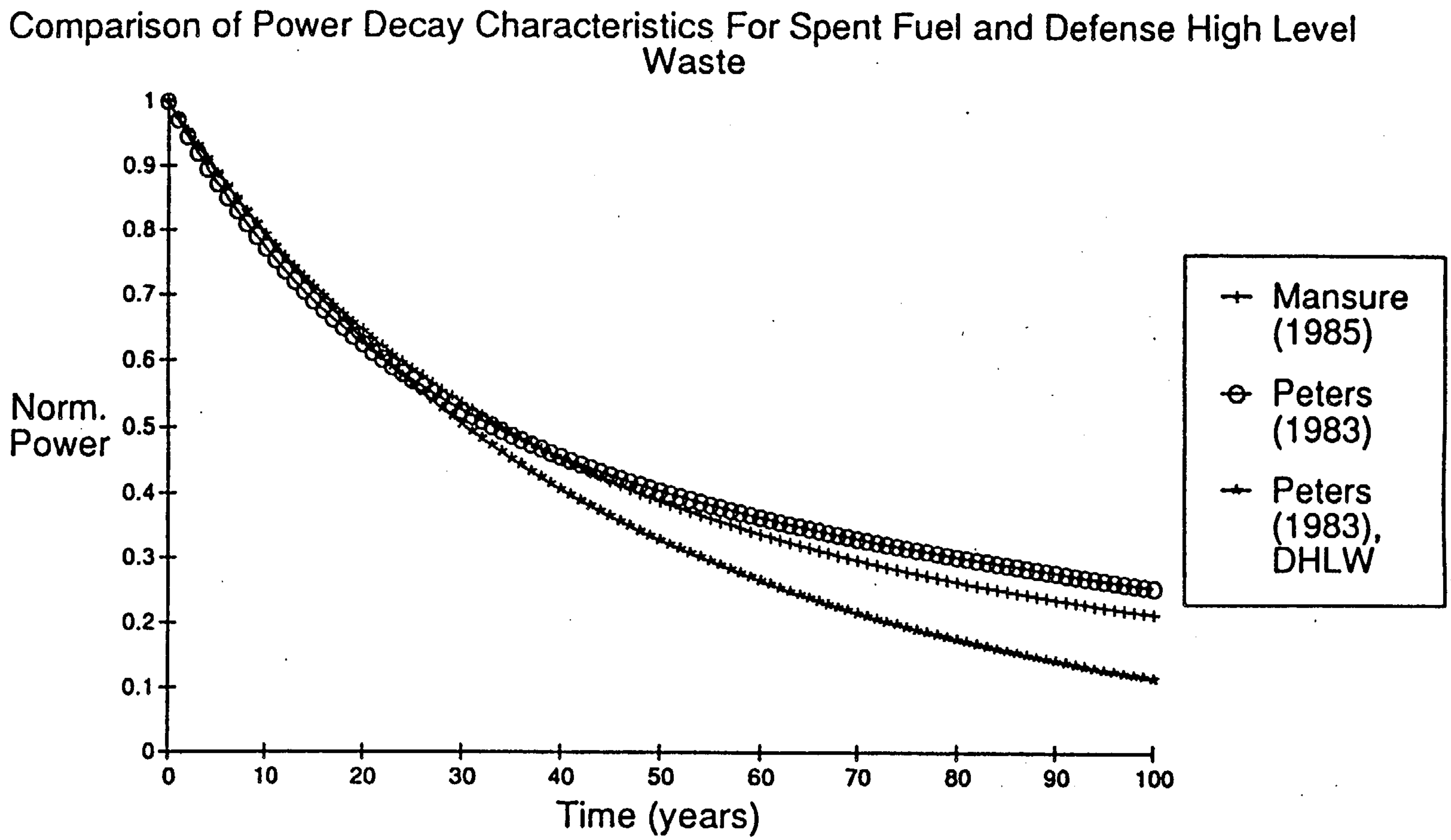


Fig. 22 Normalized Power as Function of Time

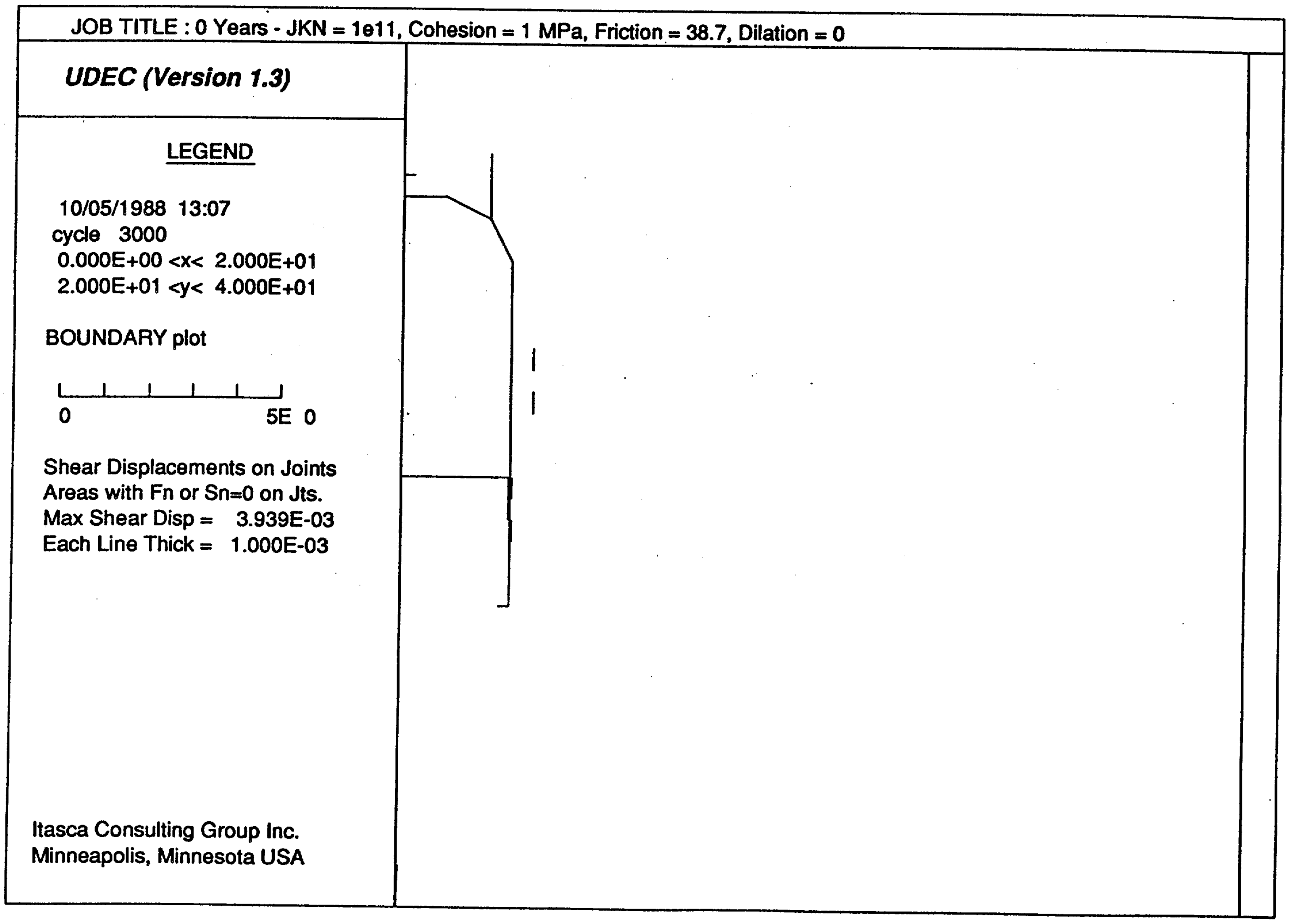


Fig. 23 UDEC Joint Displacements for 0 Years
(JKN = 1e11, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

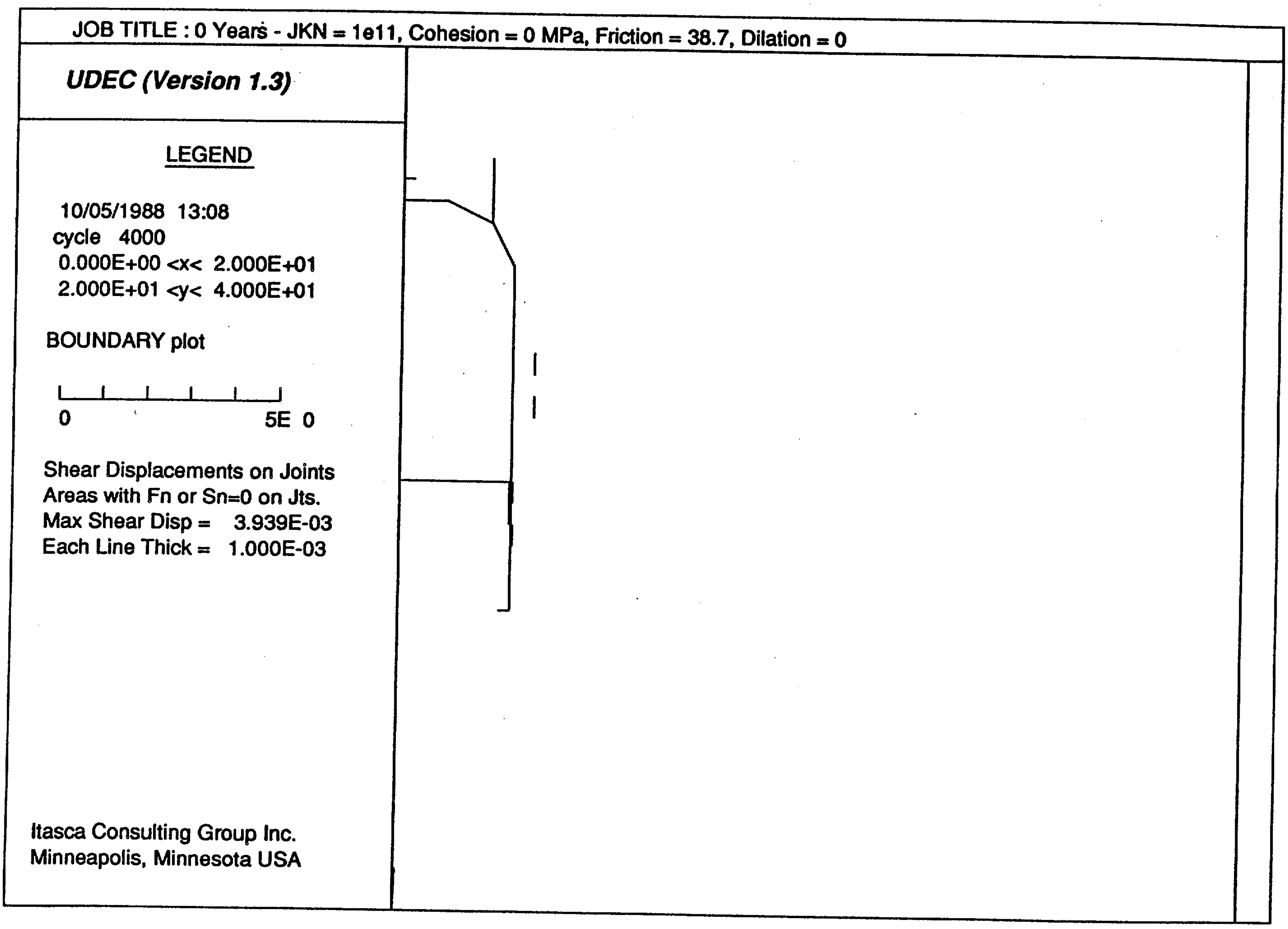


Fig. 24 UDEC Joint Displacements for 0 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

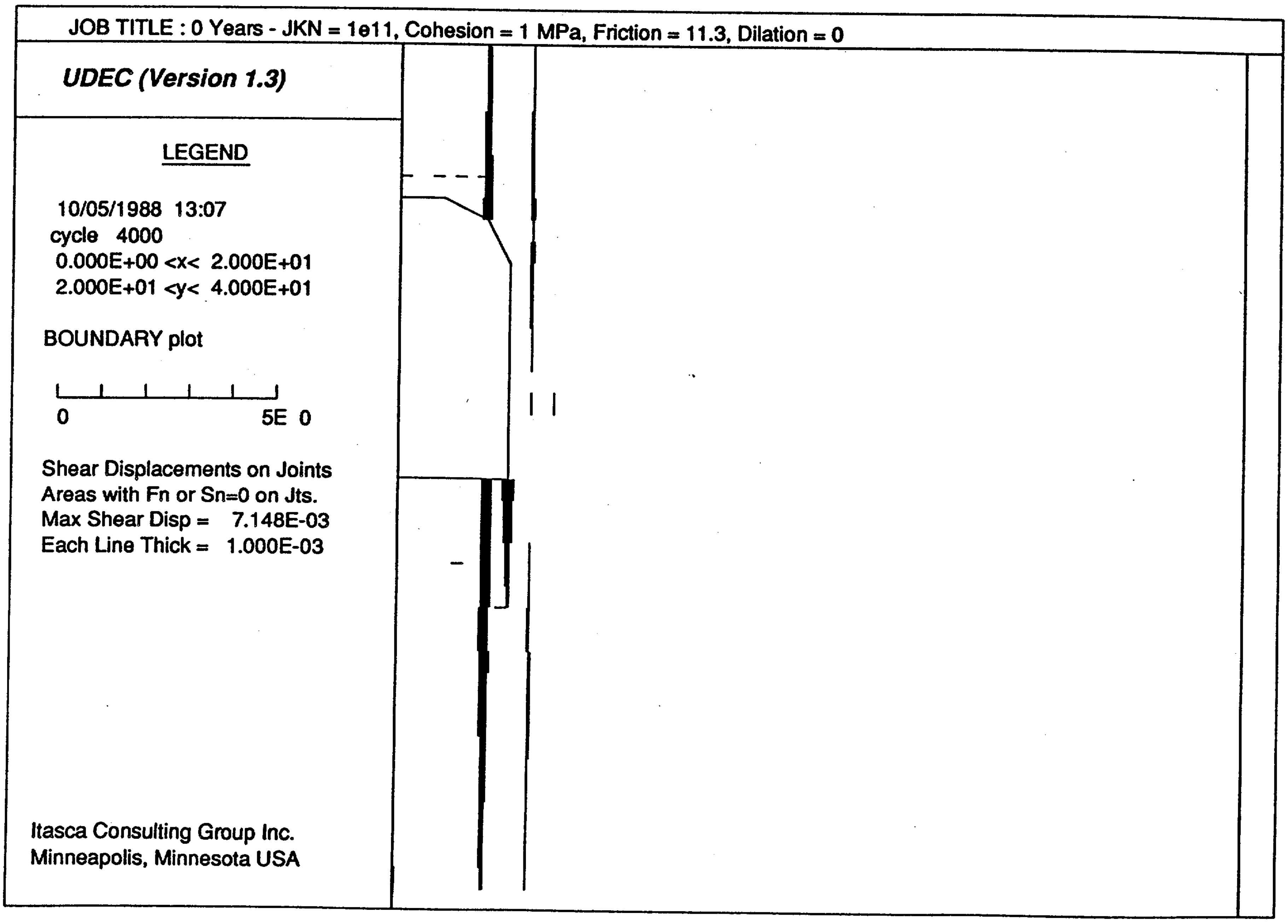


Fig. 25 UDEC Joint Displacements for 0 Years (JKN = 1e11, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

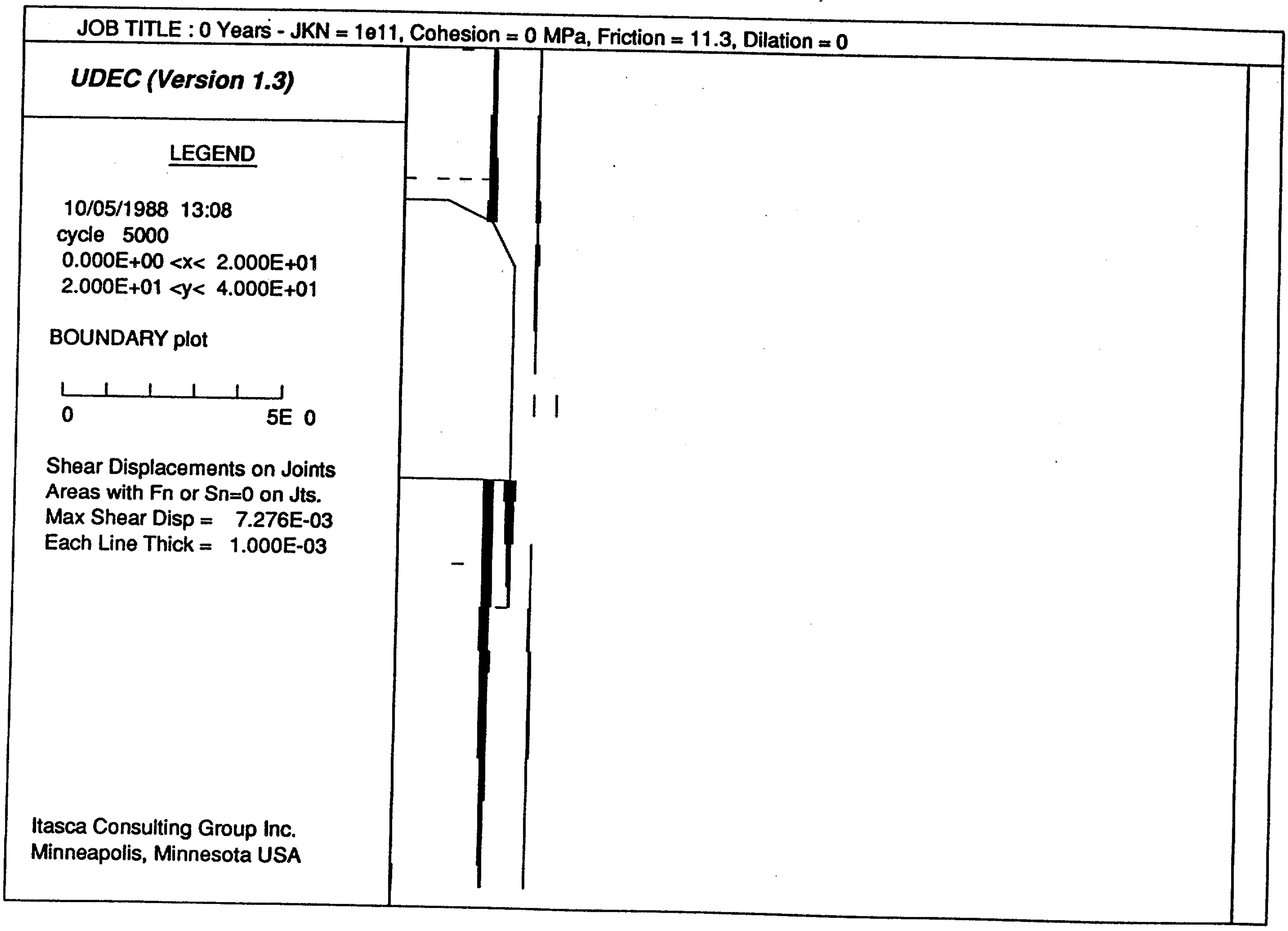


Fig. 26 UDEC Joint Displacements for 0 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

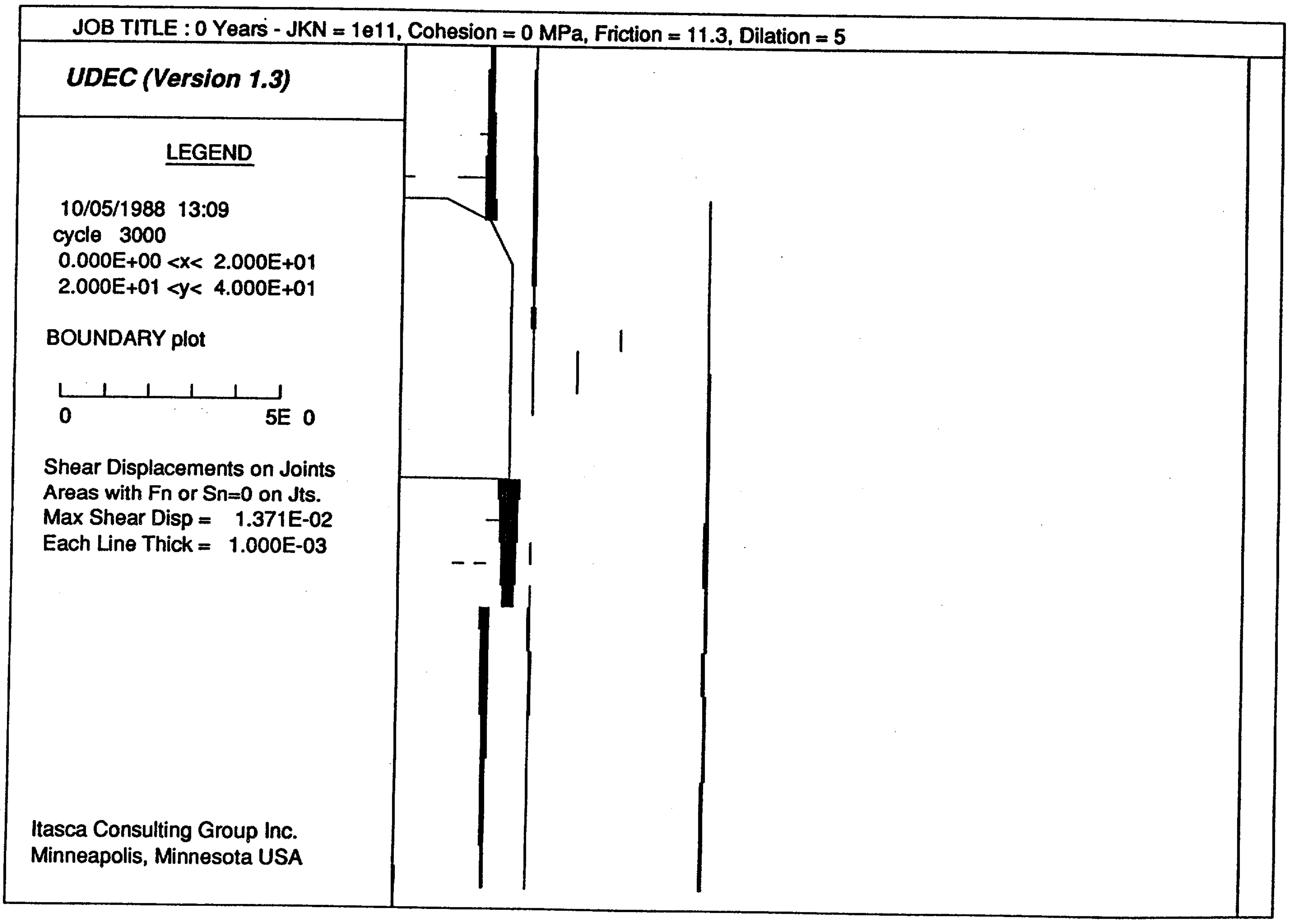


Fig. 27 UDEC Joint Displacements for 0 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 11.3, Dilation = 5.0)

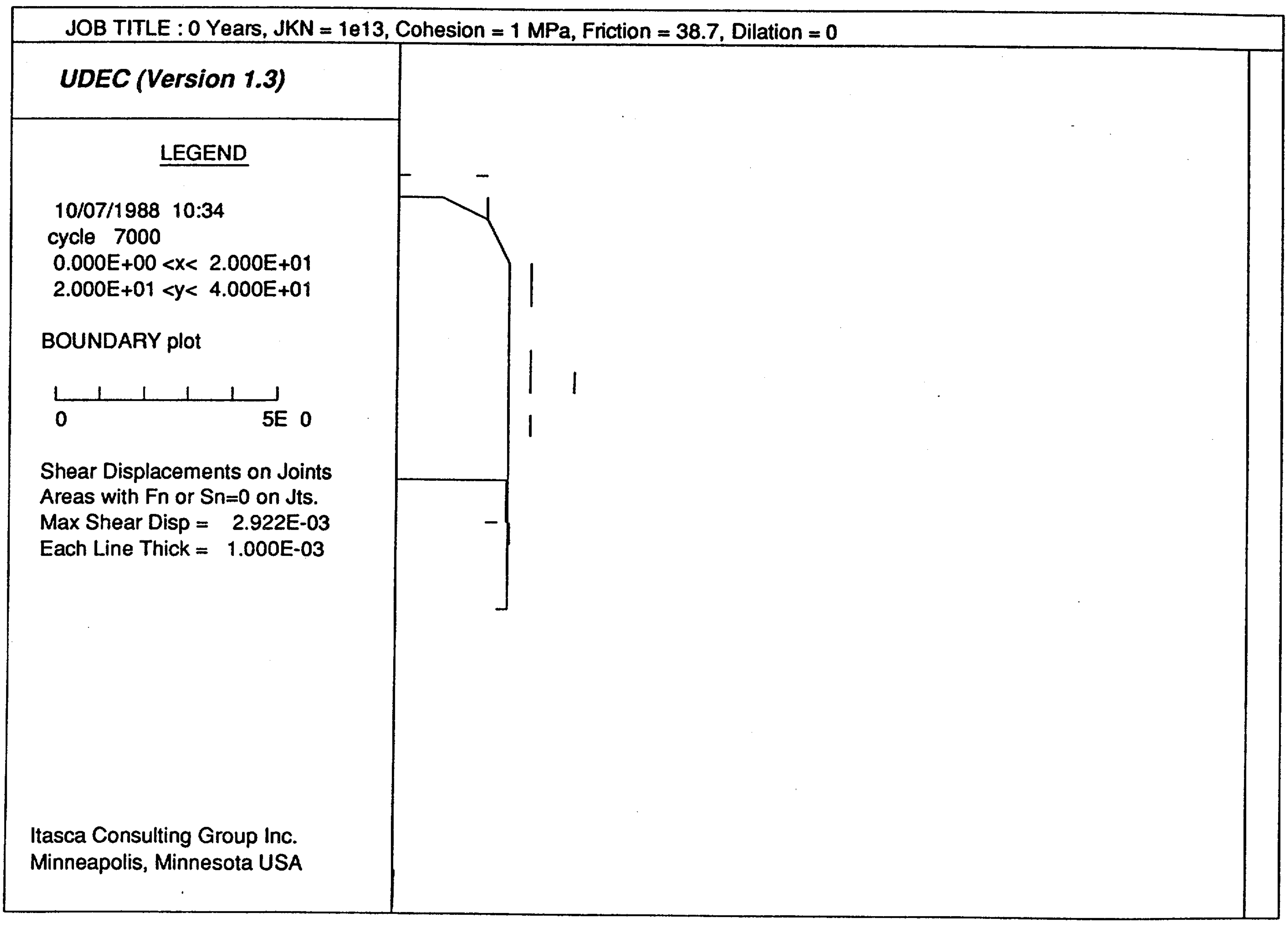


Fig. 28 UDEC Joint Displacements for 0 Years (JKN = 1e13, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

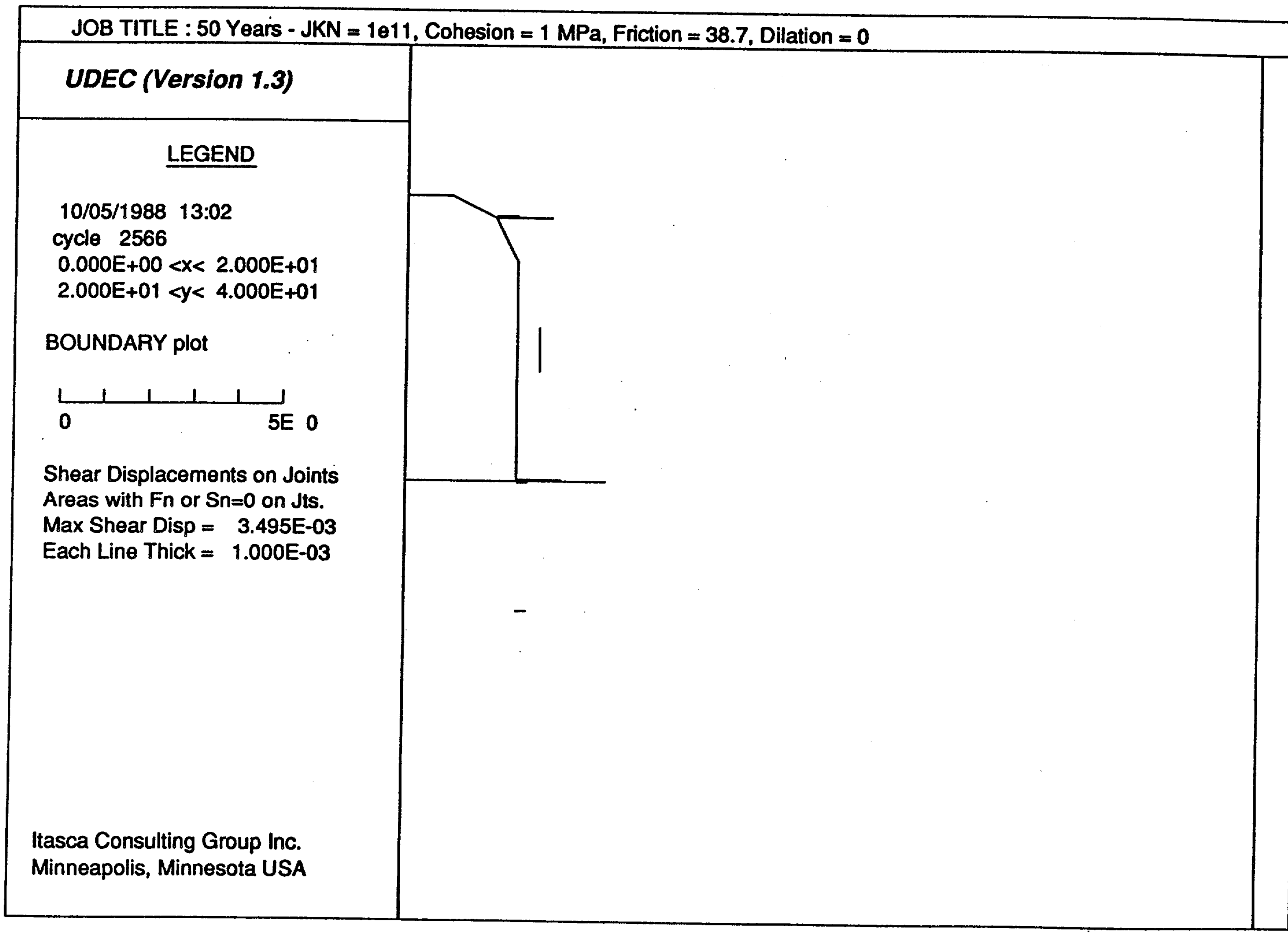


Fig. 29 UDEC Joint Displacements for 50 Years (JKN = 1e11, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

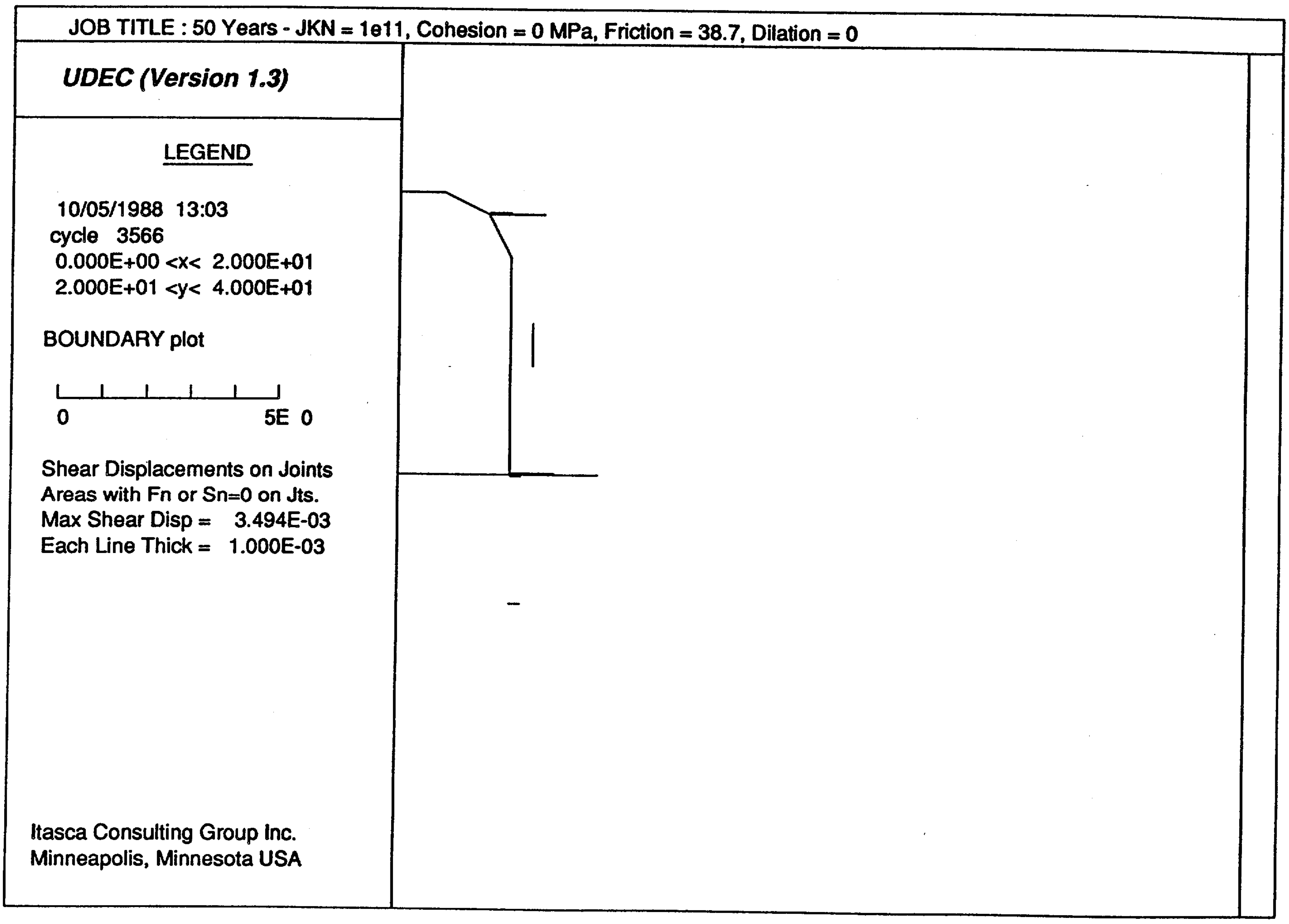


Fig. 30 UDEC Joint Displacements for 50 Years
(JKN = 1e11, Cohesion = 0 MPa, Friction = 38.7,
Dilation = 0)

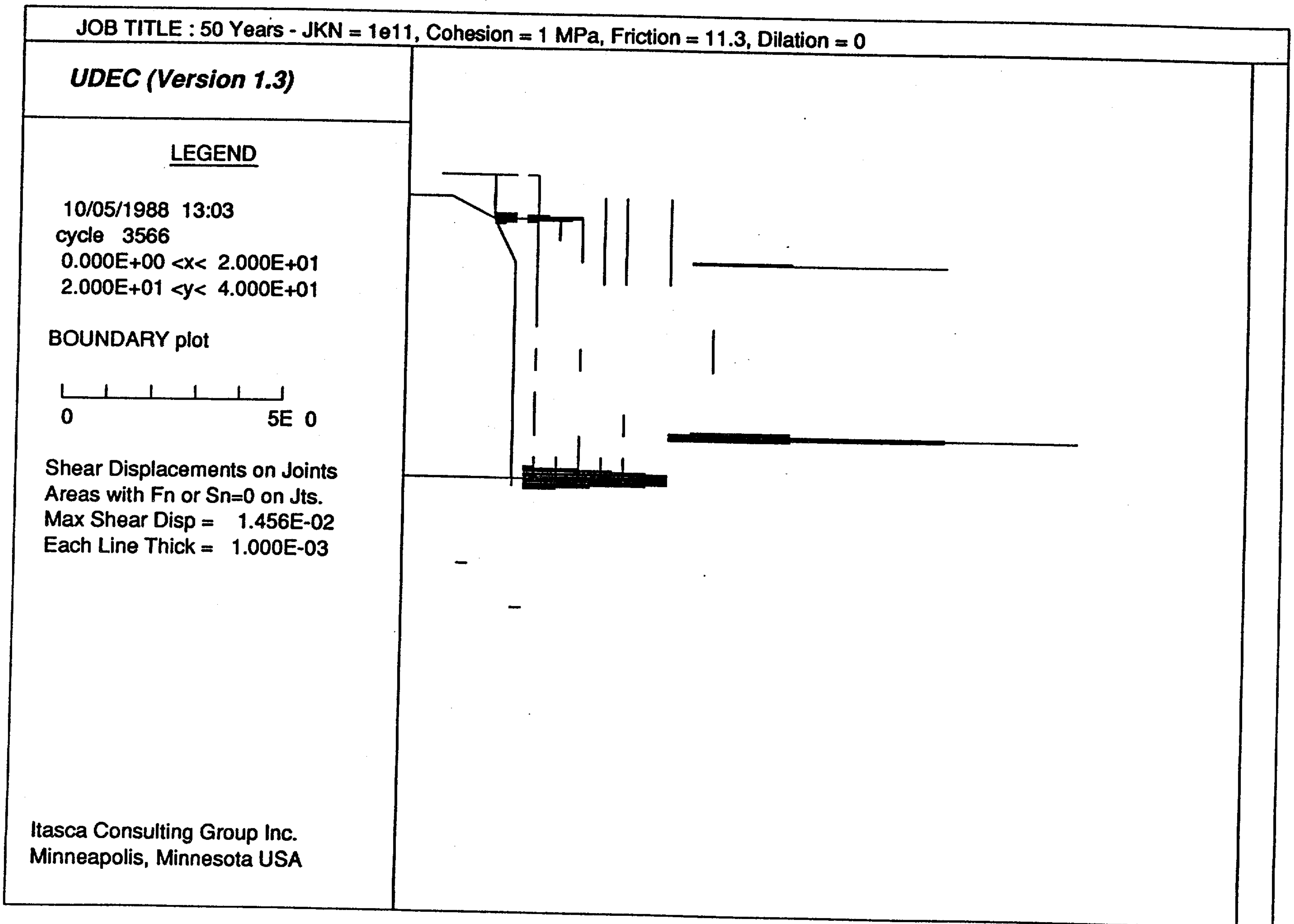


Fig. 31 UDEC Joint Displacements for 50 Years (JKN = 1e11, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

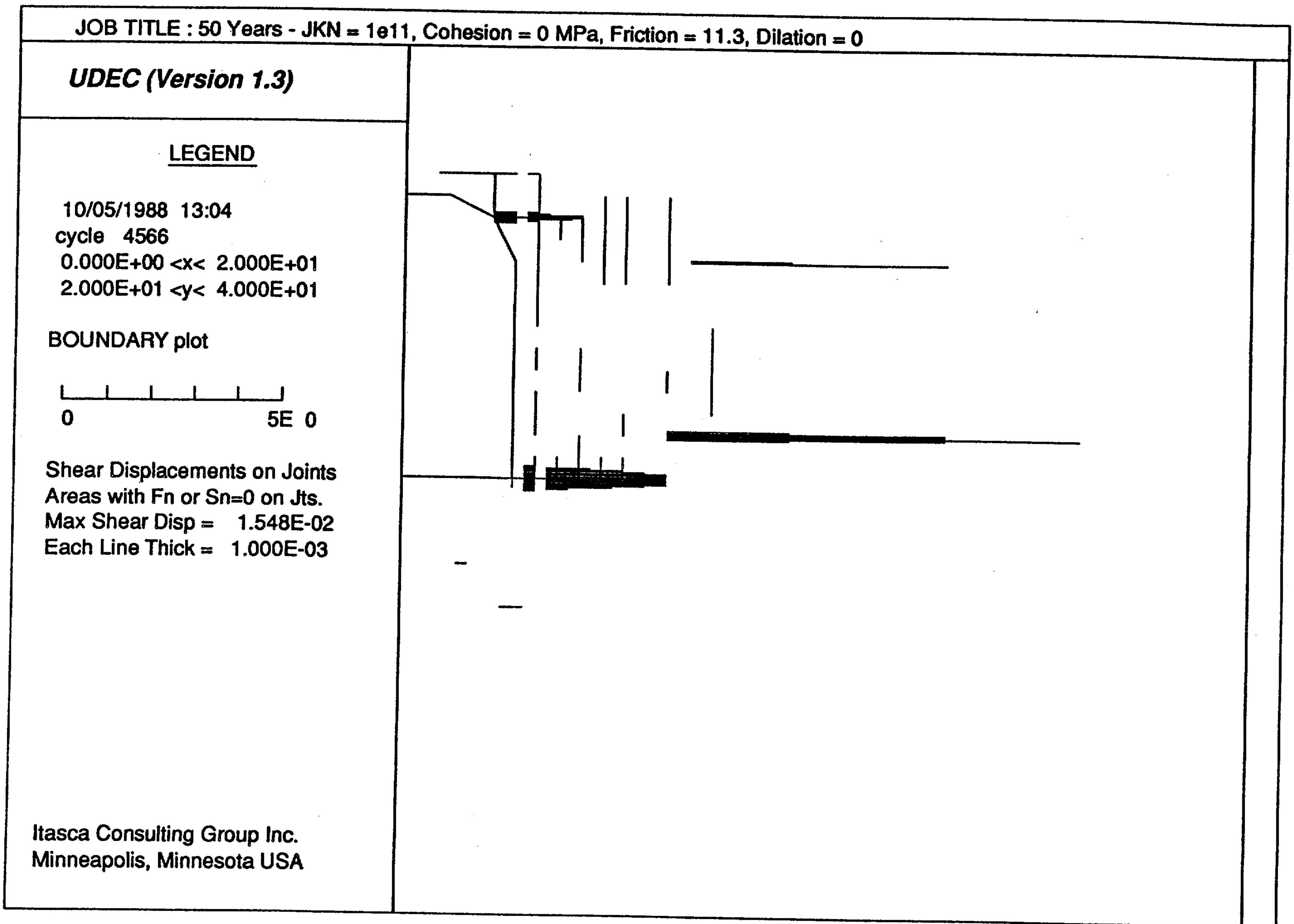


Fig. 32 UDEC Joint Displacements for 50 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

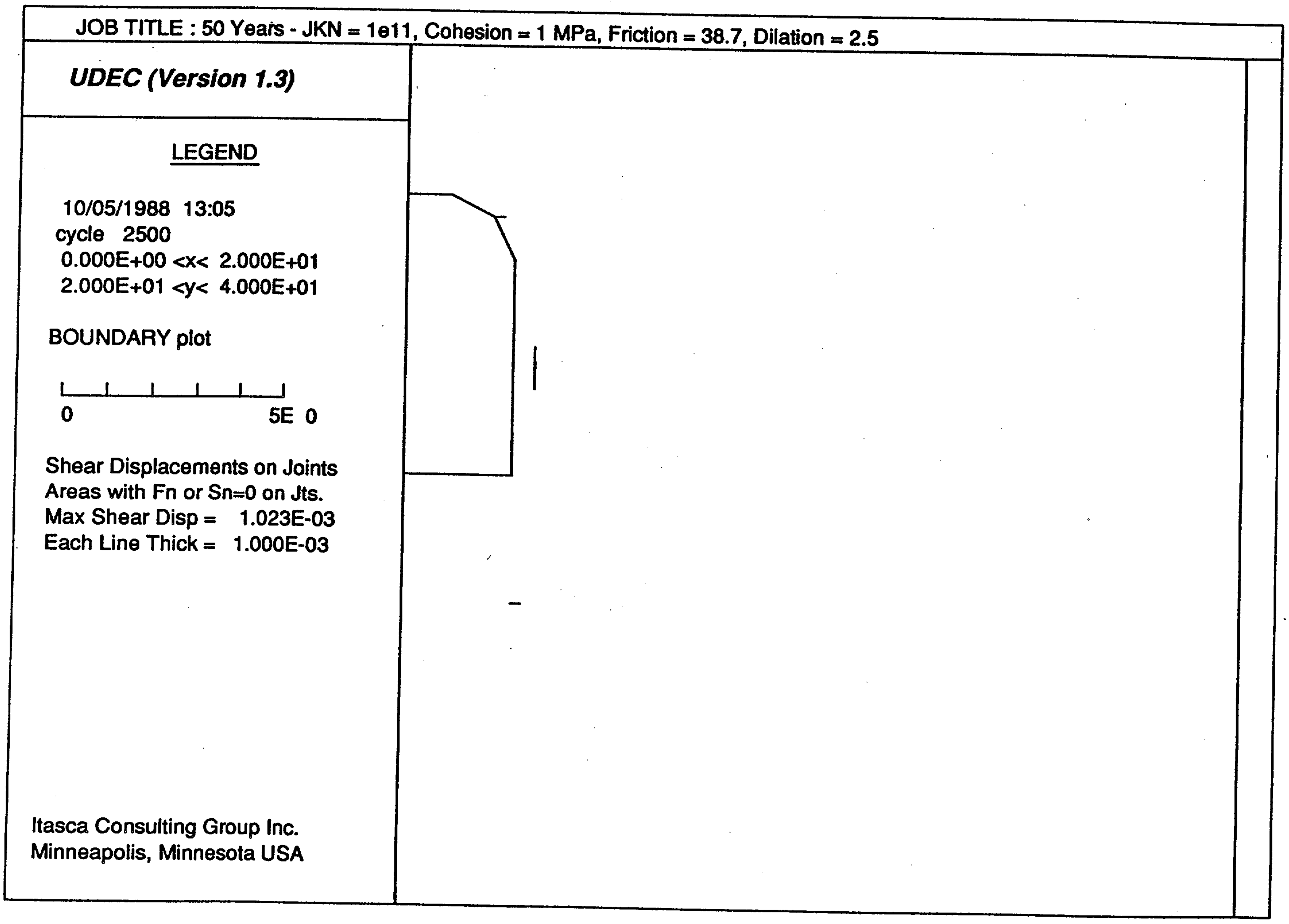


Fig. 33 UDEC Joint Displacements for 50 Years
JKN = 1e11, Cohesion = 1 MPa, Friction = 38.7,
Dilation = 2.5)

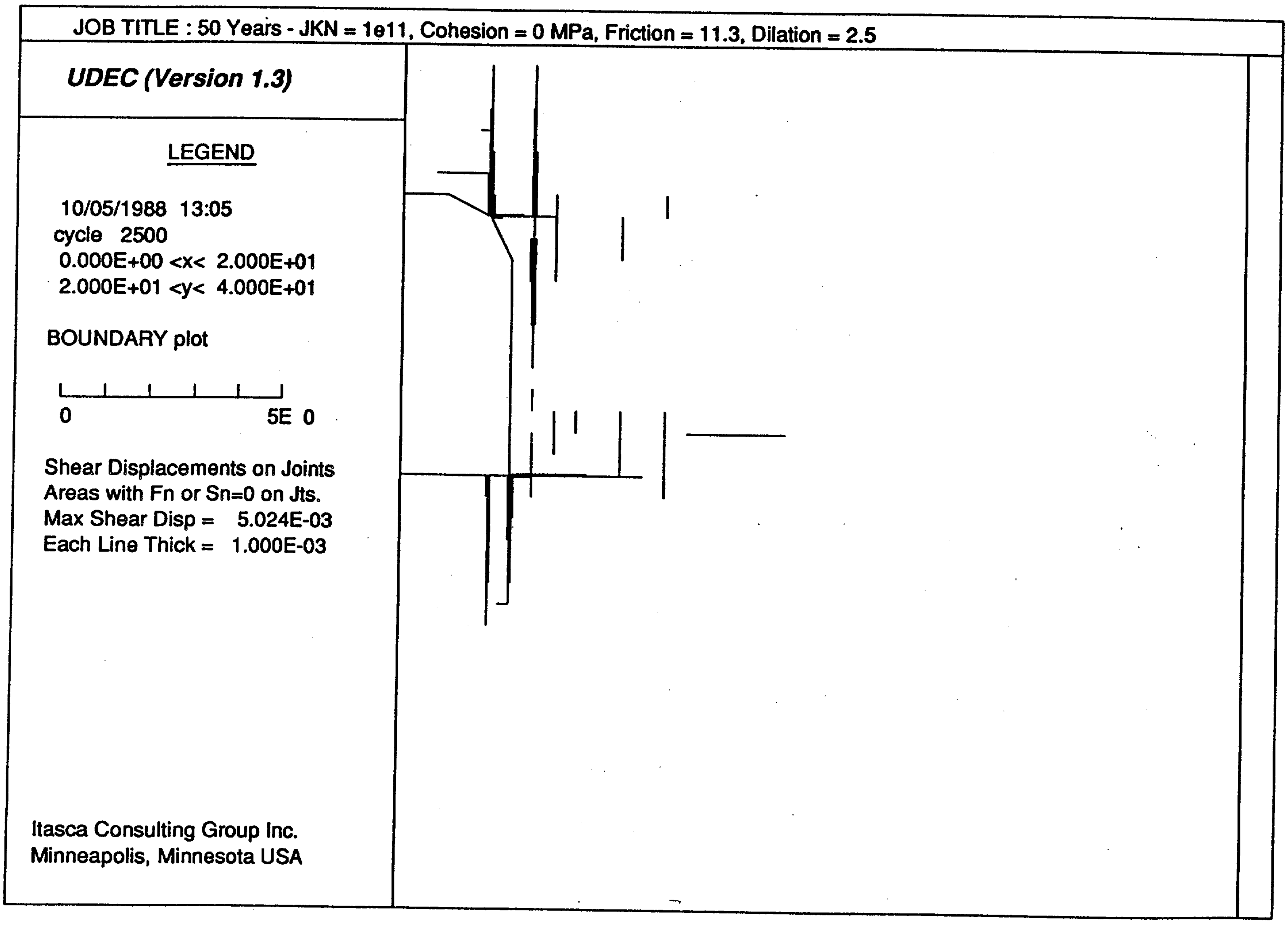


Fig. 34 UDEC Joint Displacements for 50 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 11.3, Dilation = 2.5)

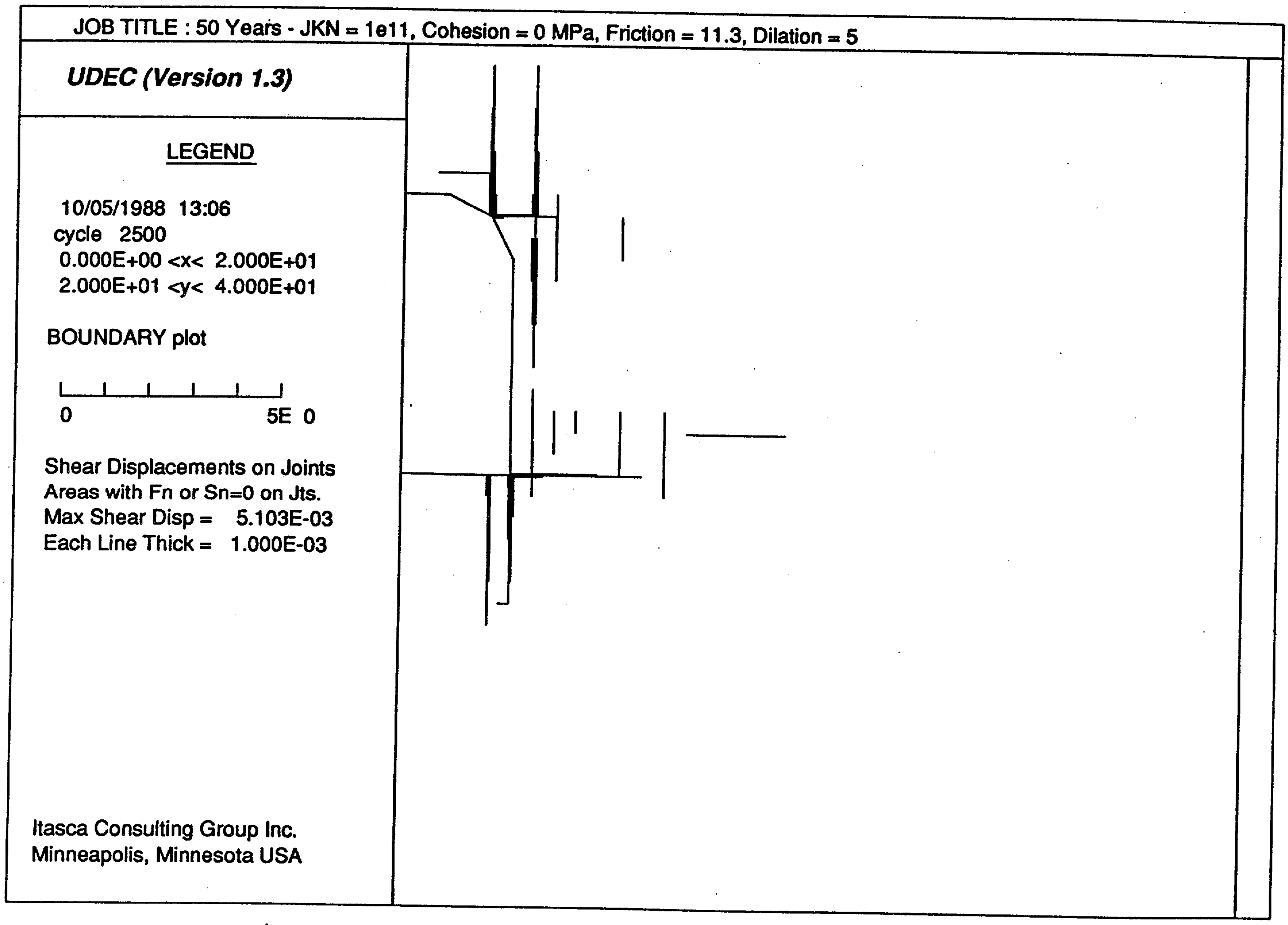


Fig. 35 UDEC Joint Displacements for 50 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 11.3, Dilation = 5.0)

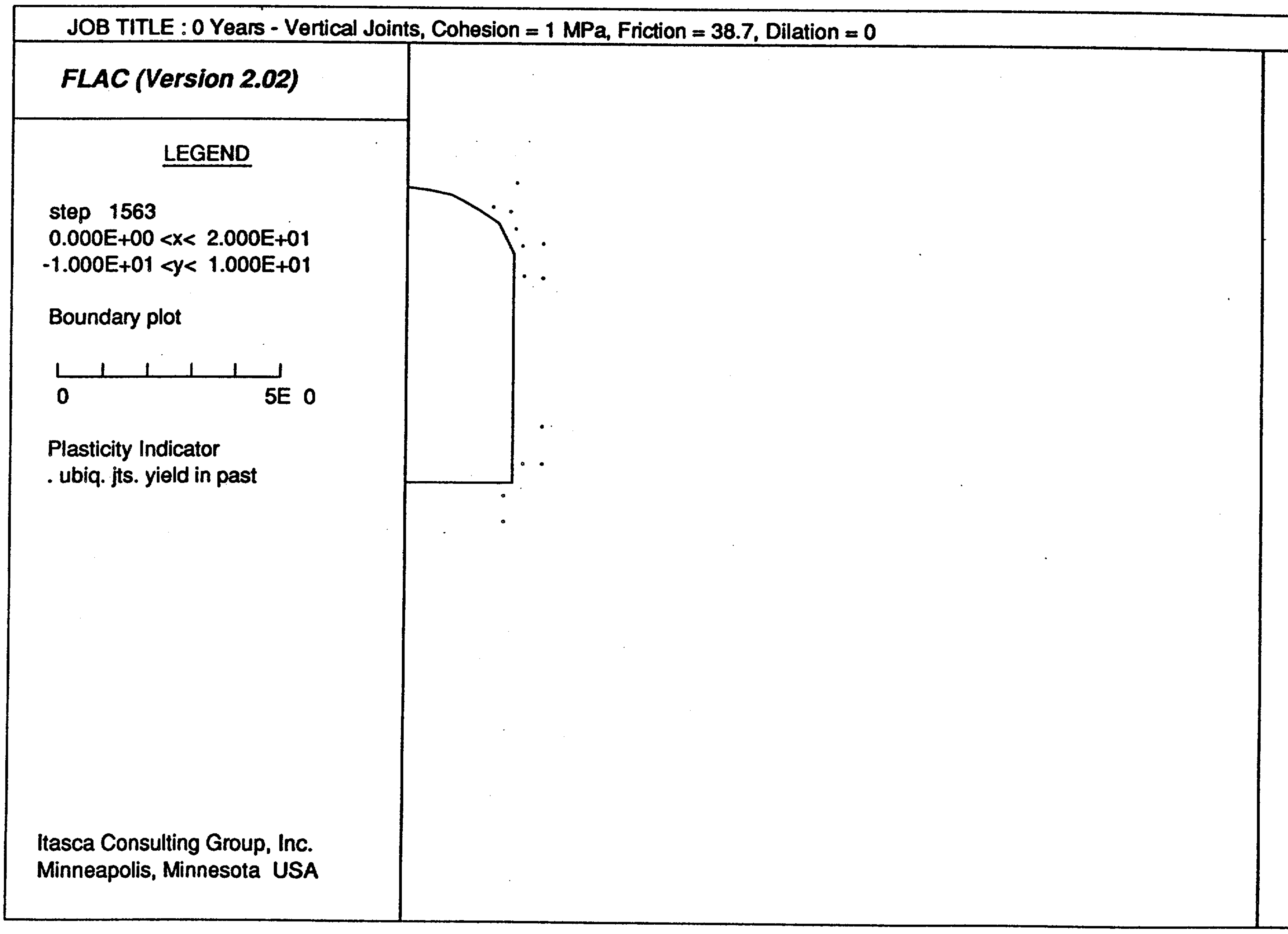


Fig. 36 FLAC Joint Displacements for 0 Years (Vertical Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

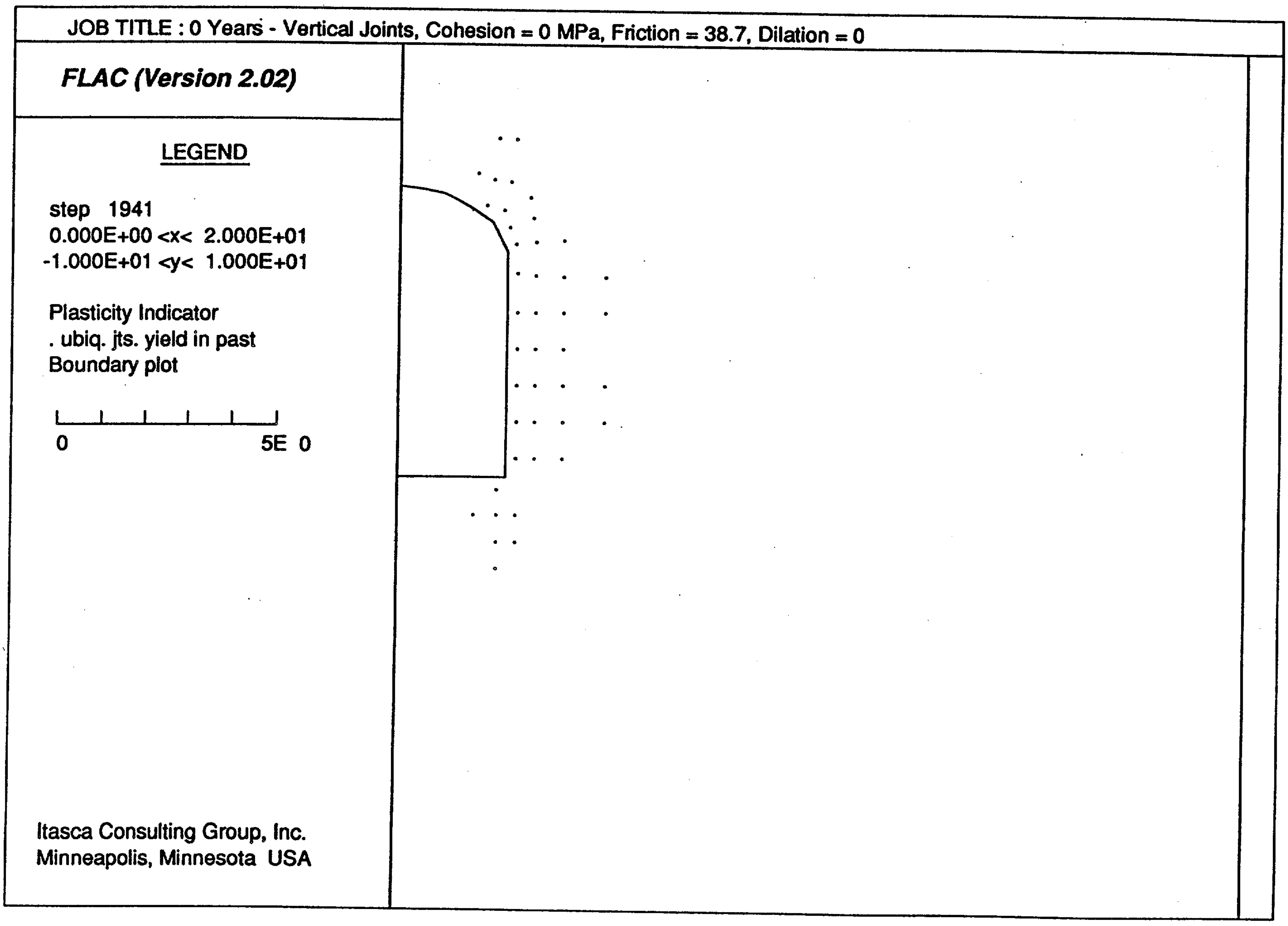


Fig. 37 FLAC Joint Displacements for 0 Years (Vertical Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

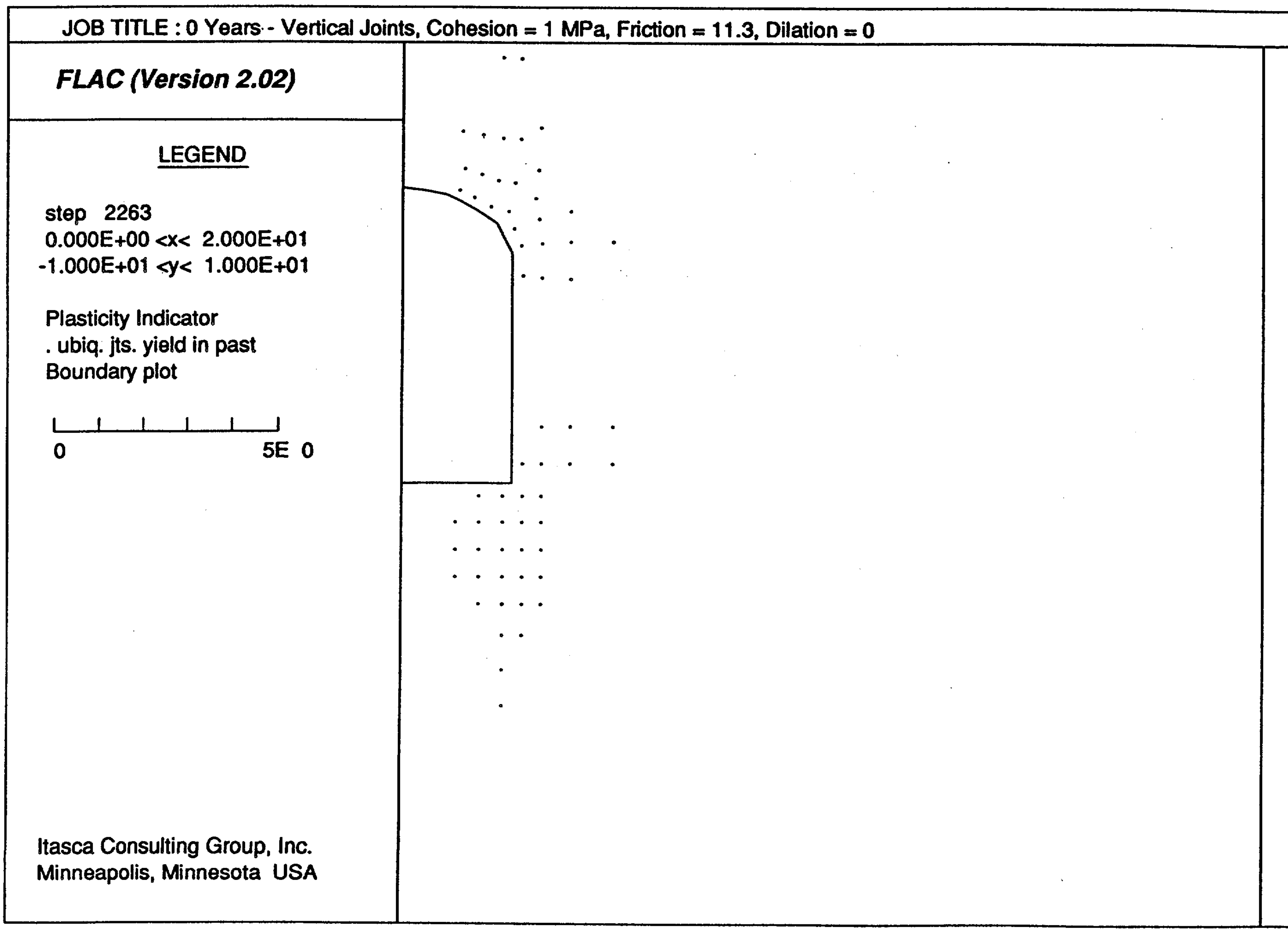


Fig. 38 FLAC Joint Displacements for 0 Years
Vertical Joints, Cohesion = 1 MPa, Friction = 11.3,
Dilation = 0)

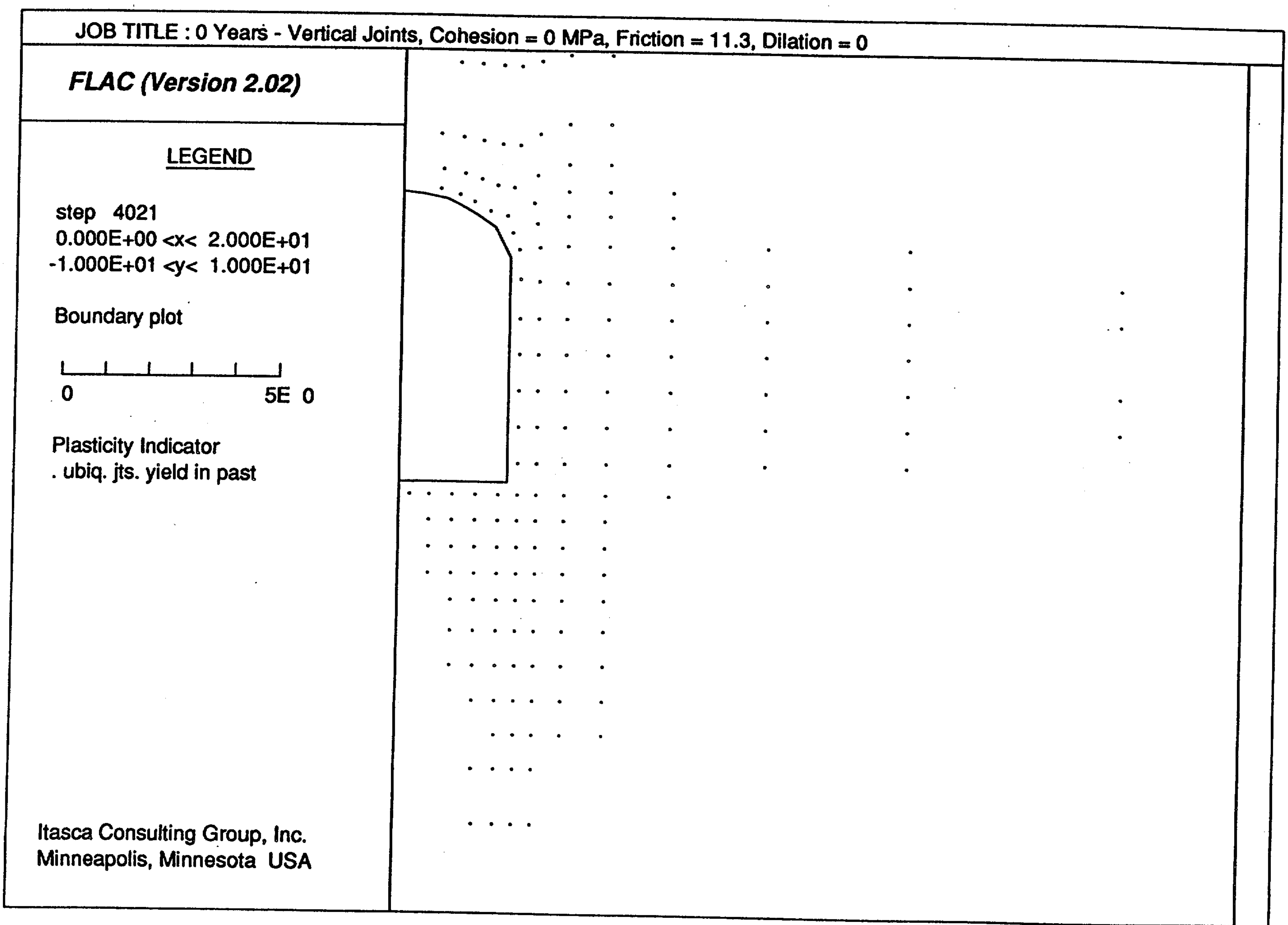


Fig. 39 FLAC Joint Displacements for 0 Years (Vertical Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

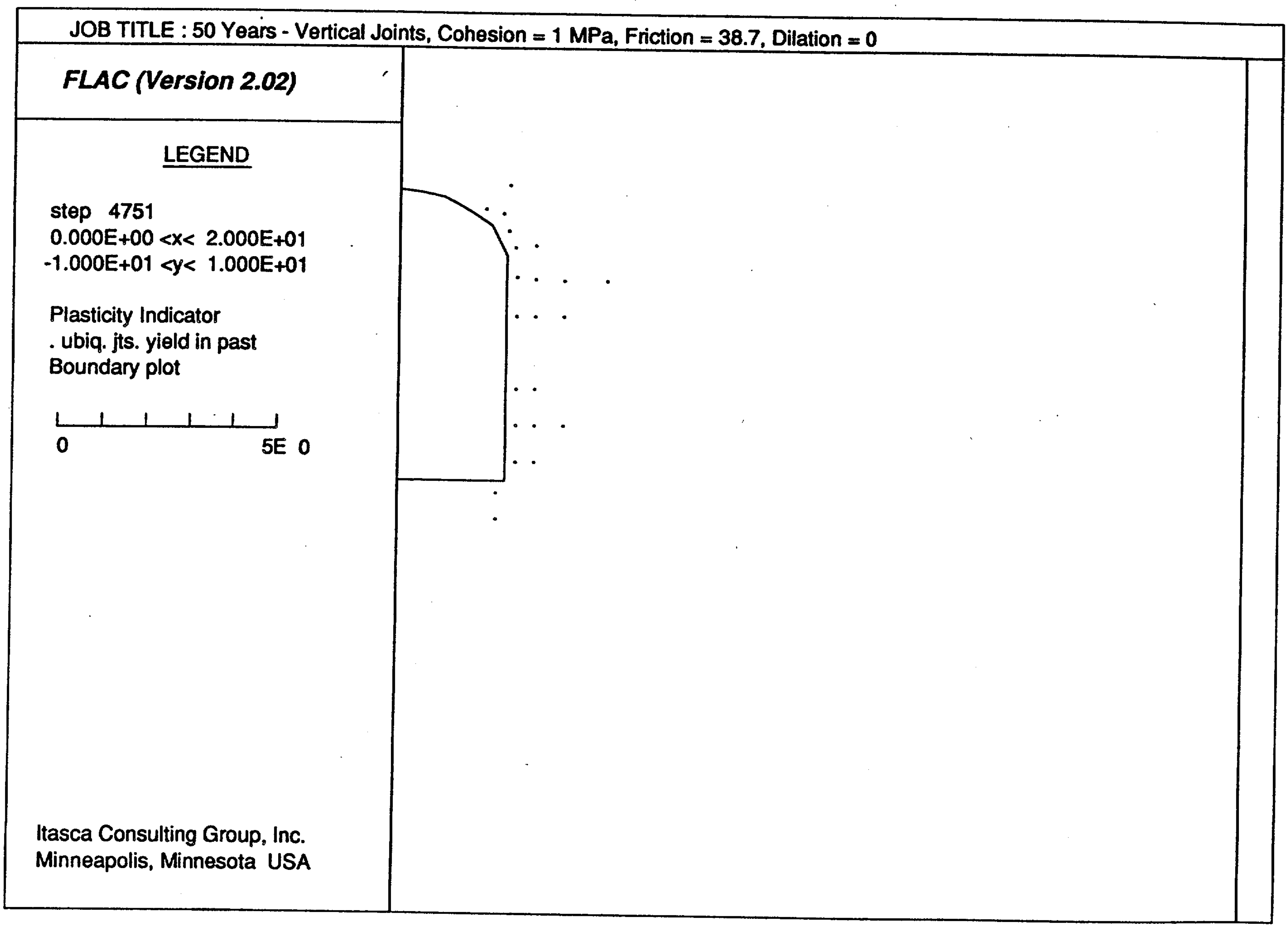


Fig. 40 FLAC Joint Displacements for 50 Years (Vertical Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

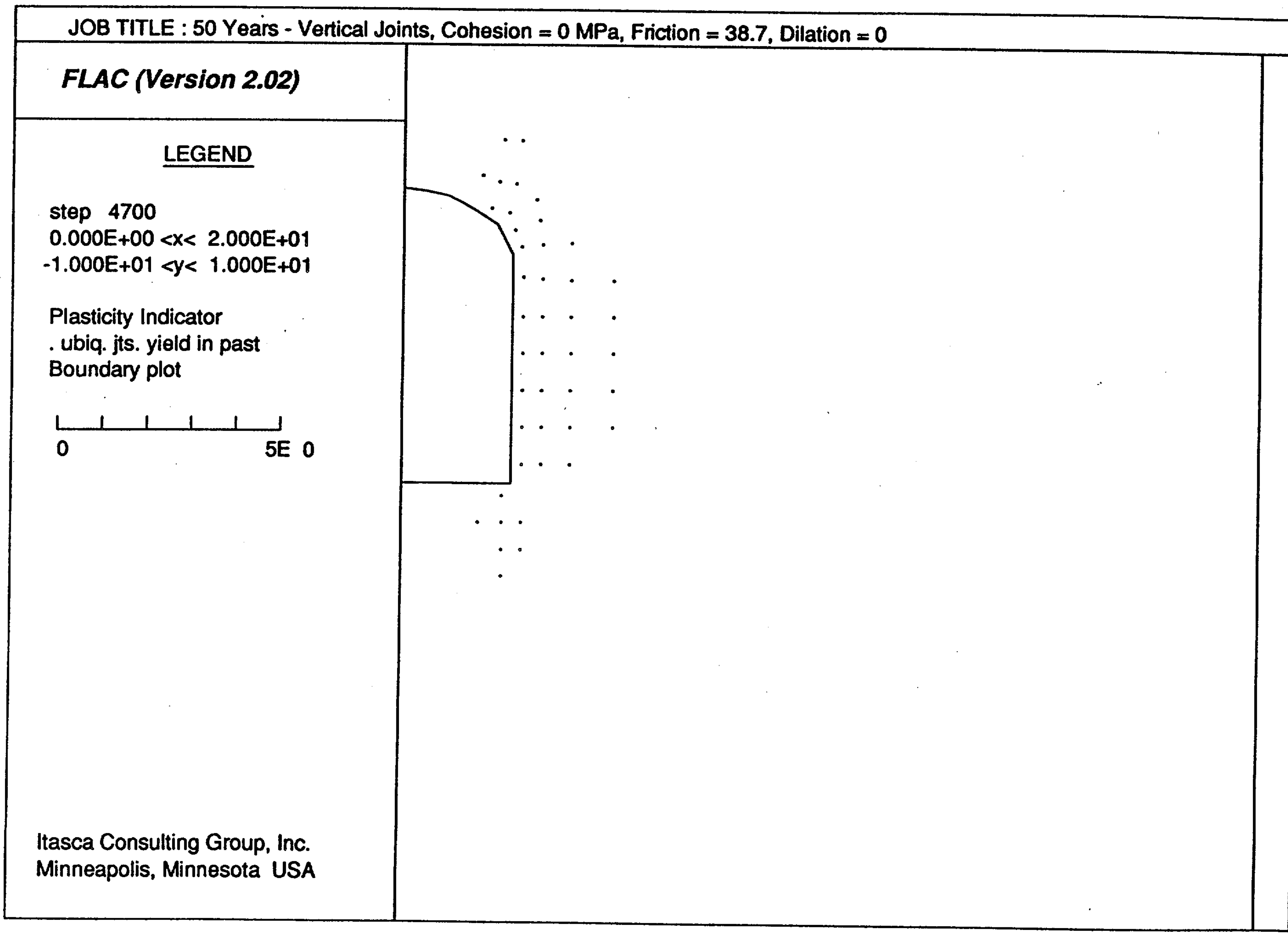


Fig. 41 FLAC Joint Displacements for 50 Years (Vertical Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

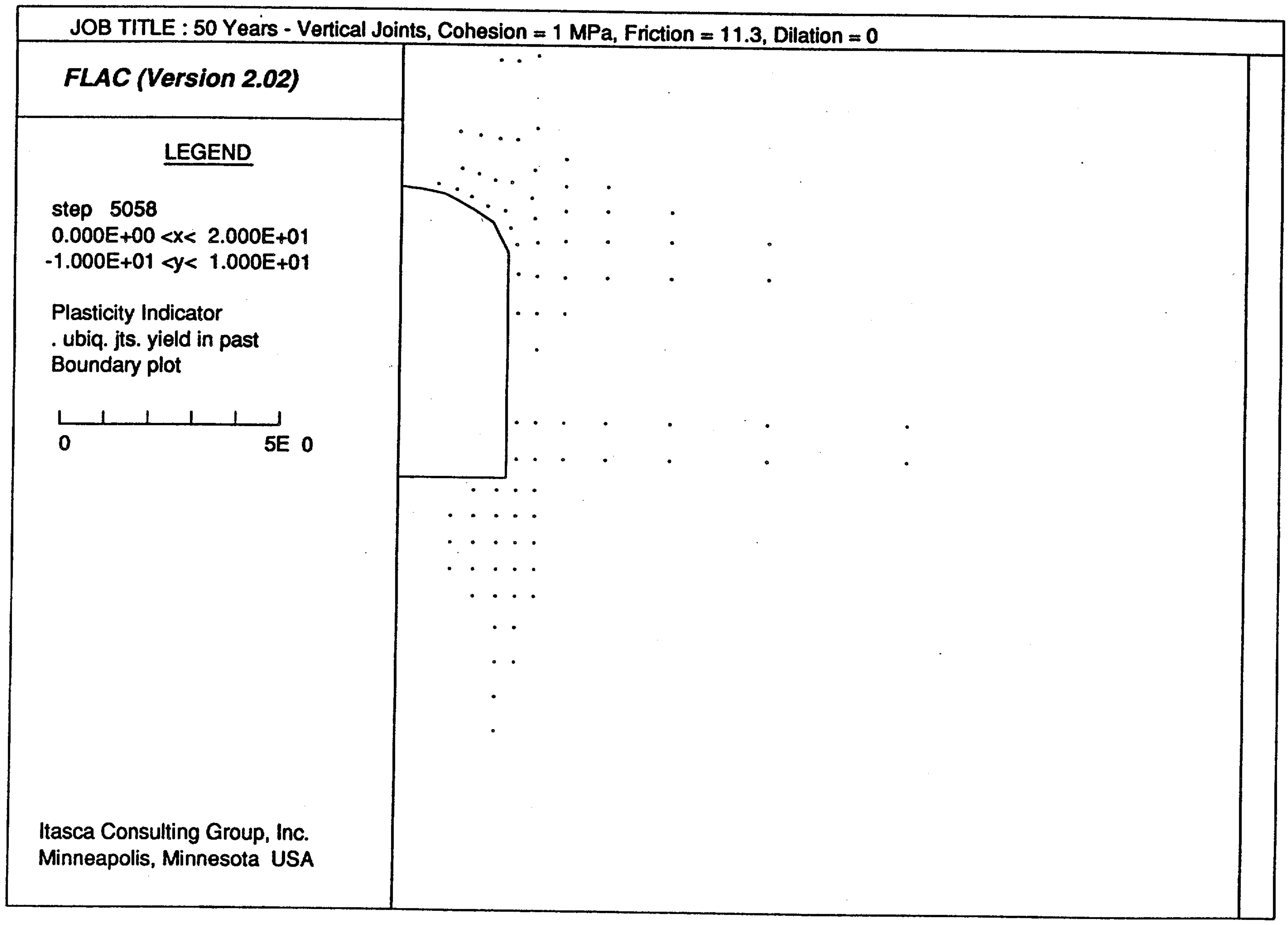


Fig. 42 FLAC Joint Displacements for 50 Years (Vertical Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

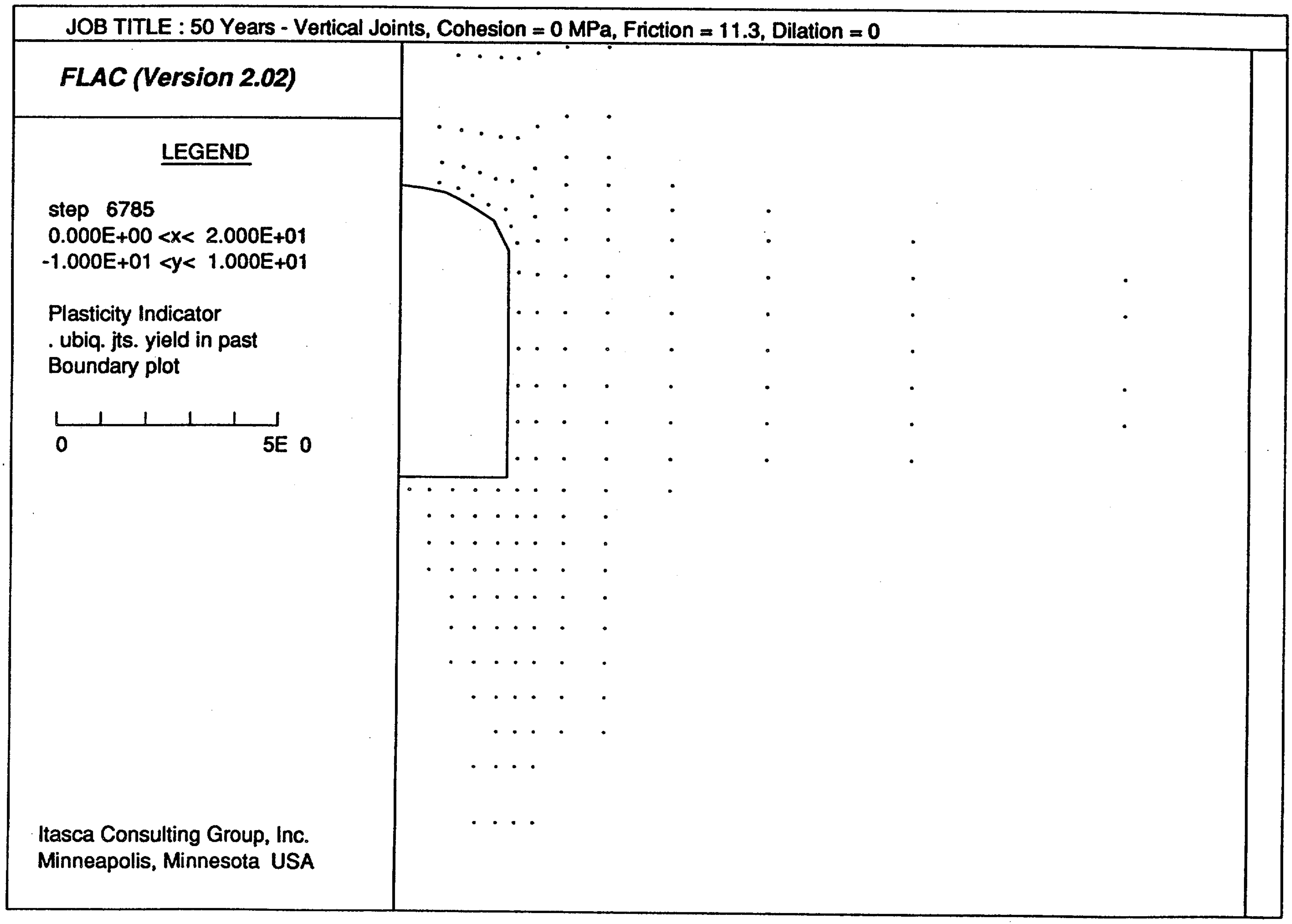


Fig. 43 FLAC Joint Displacements for 50 Years (Vertical Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

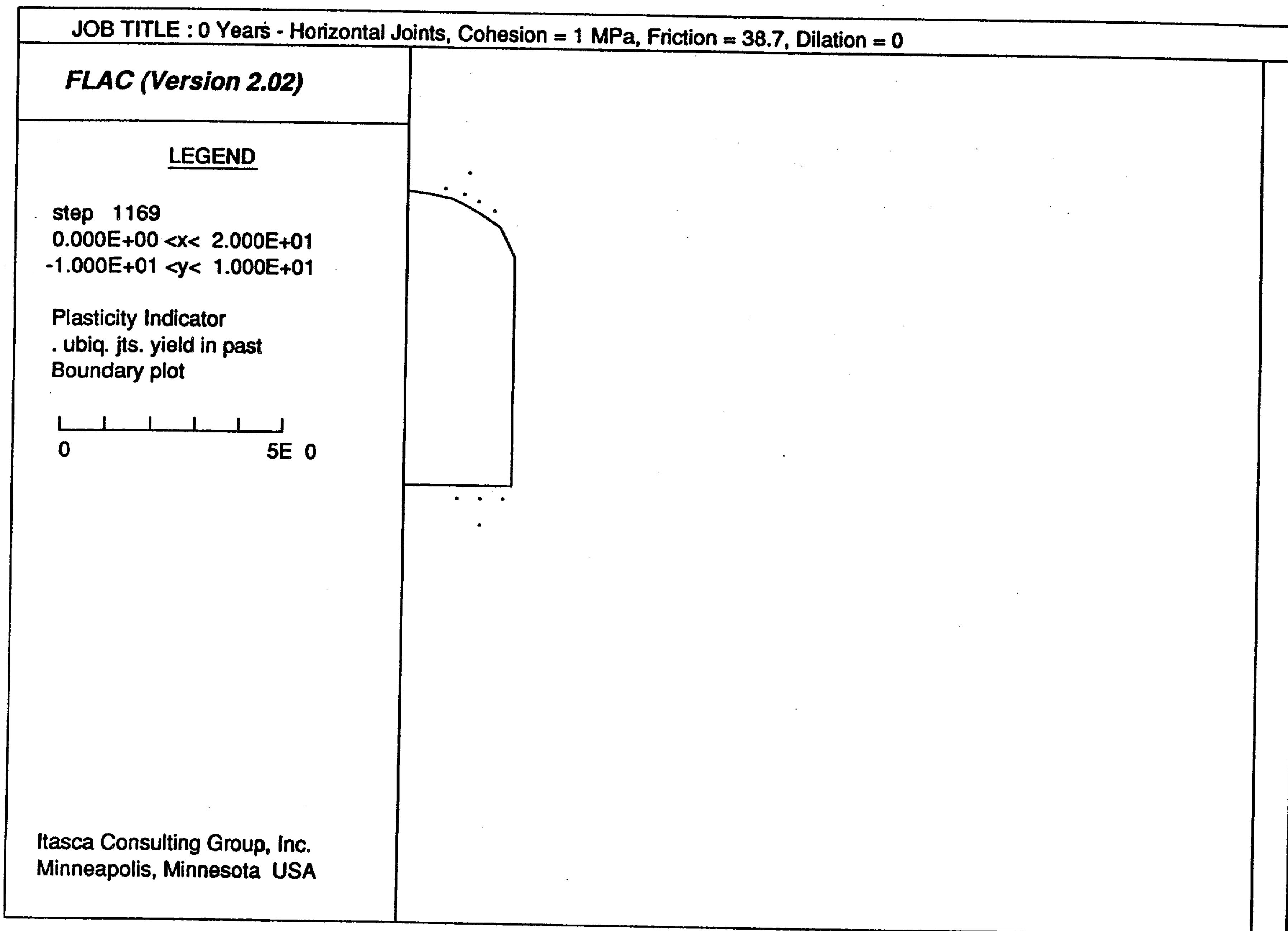


Fig. 44 FLAC Joint Displacements for 0 Years (Horizontal Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

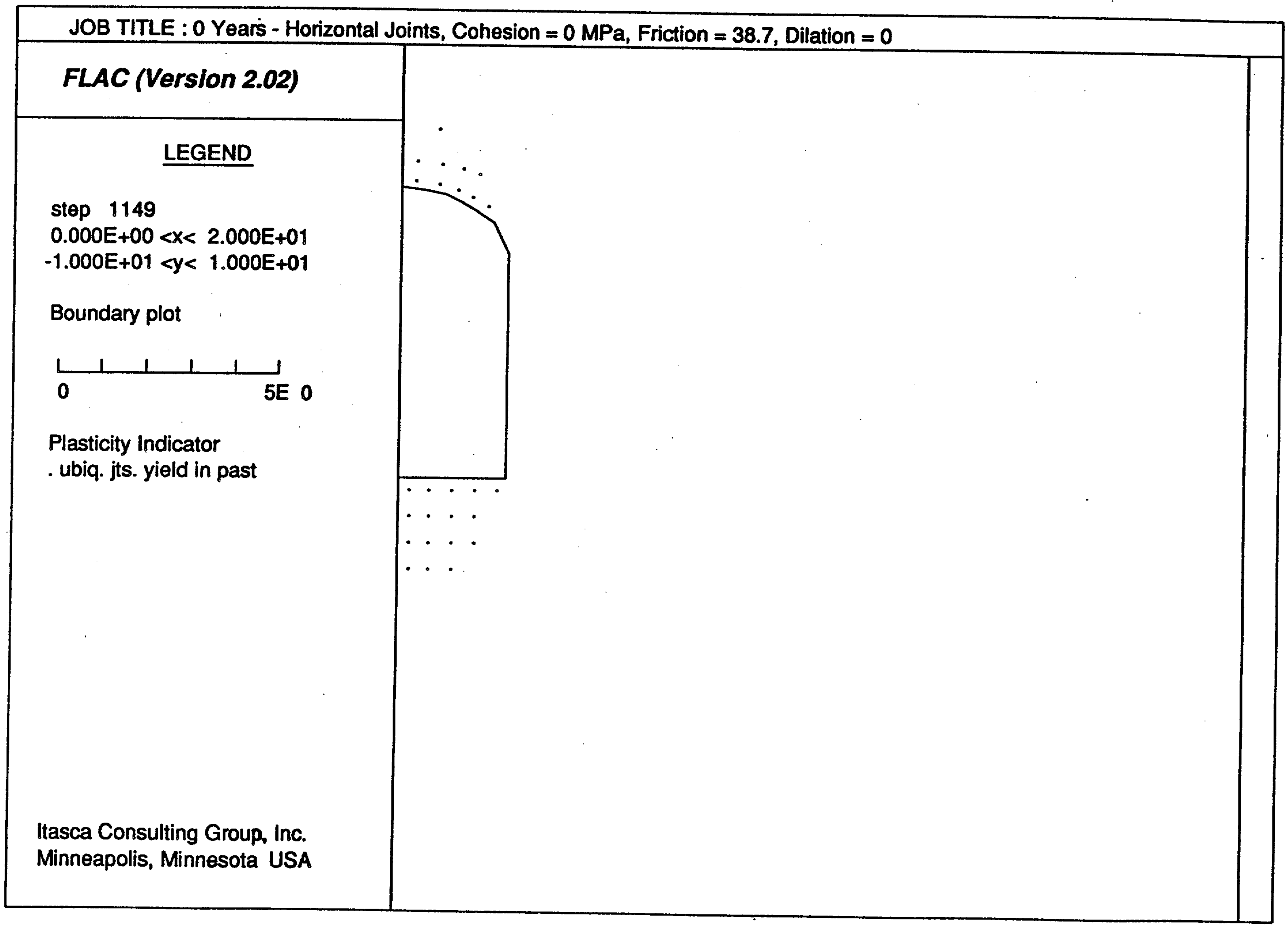


Fig. 45 FLAC Joint Displacements for 0 Years (Horizontal Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

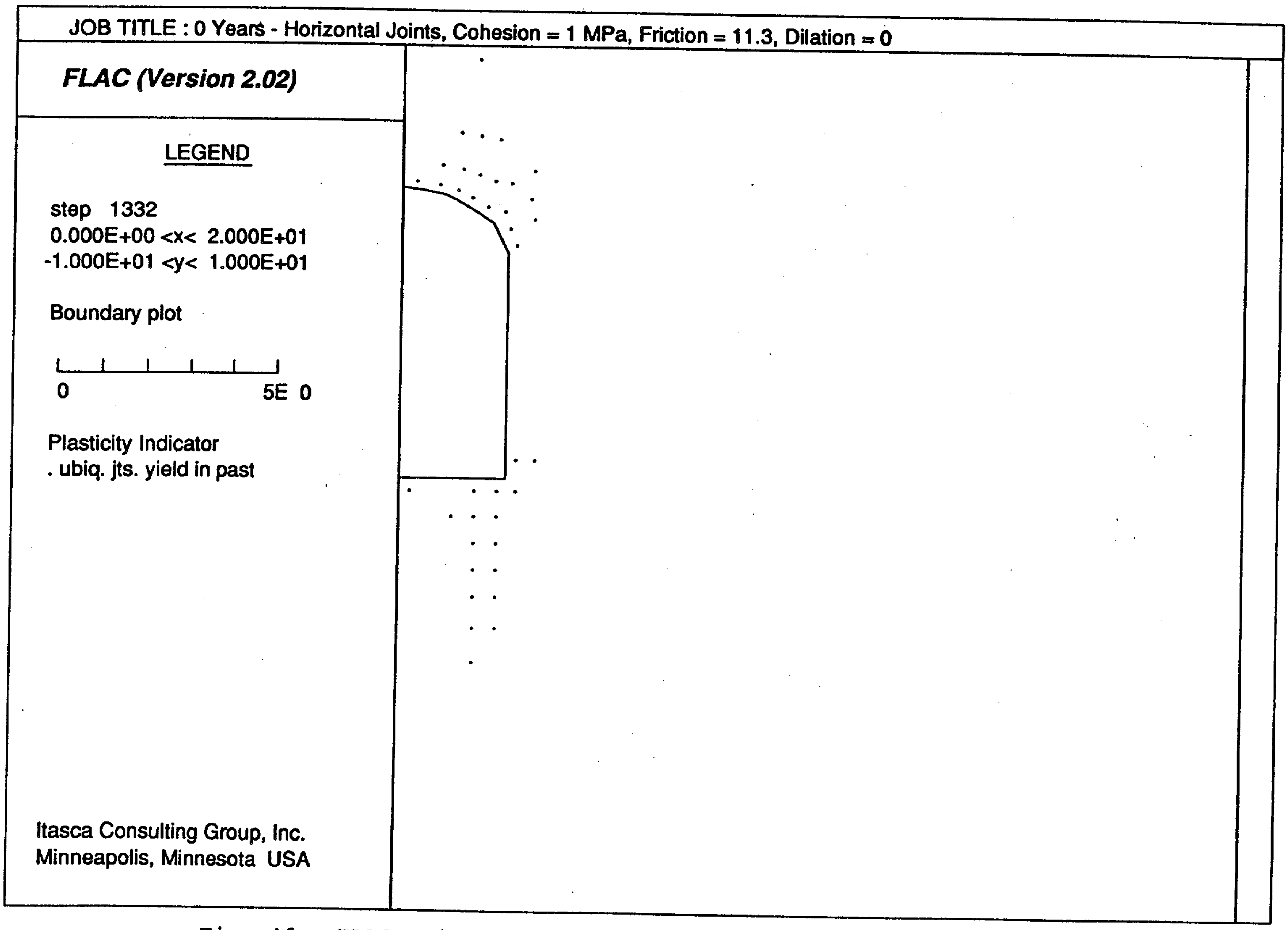


Fig. 46 FLAC Joint Displacements for 0 Years
(Horizontal Joints, Cohesion = 1 MPa, Friction = 11.3,
Dilation = 0)

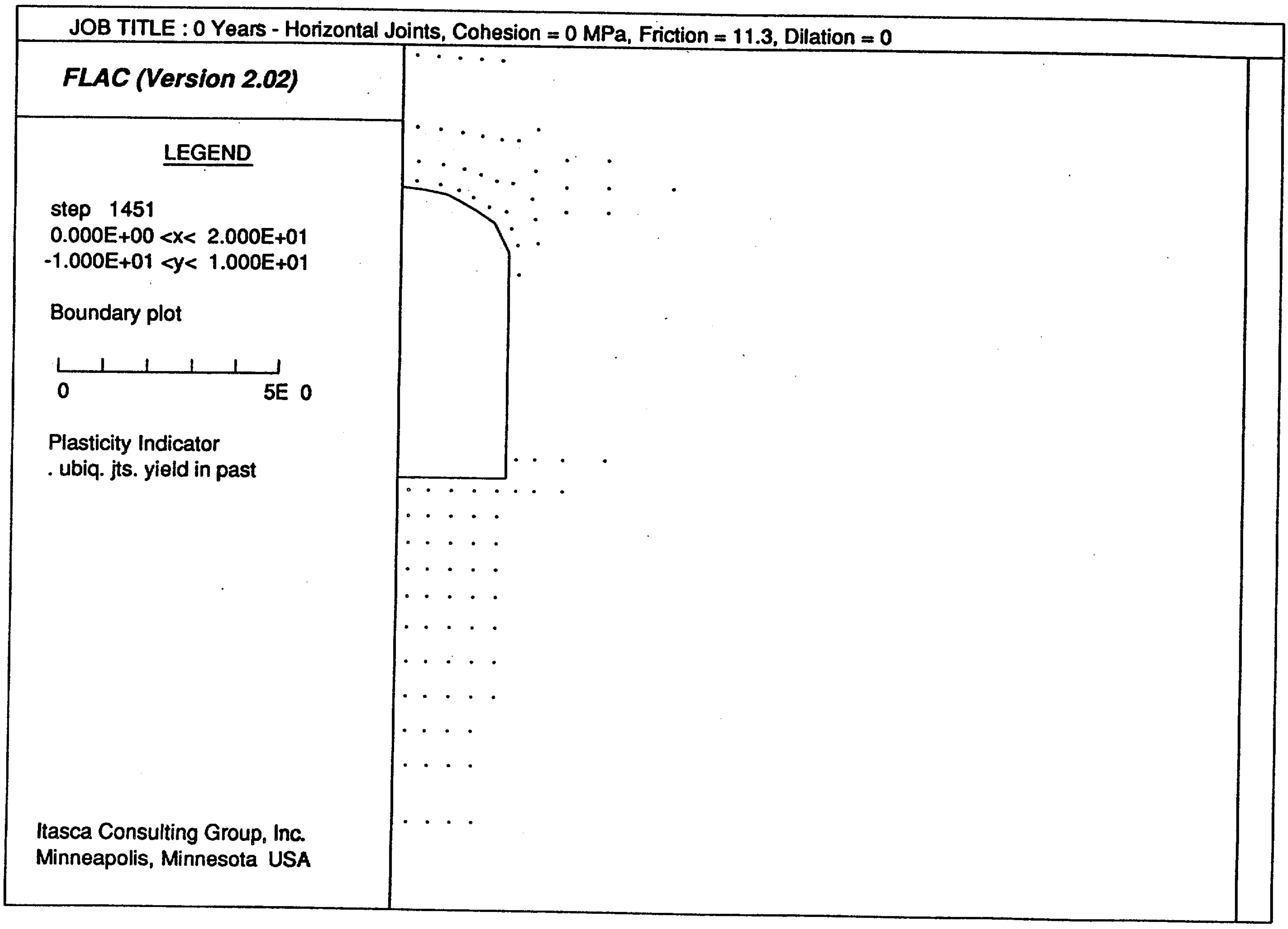


Fig. 47 FLAC Joint Displacements for 0 Years (Horizontal Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

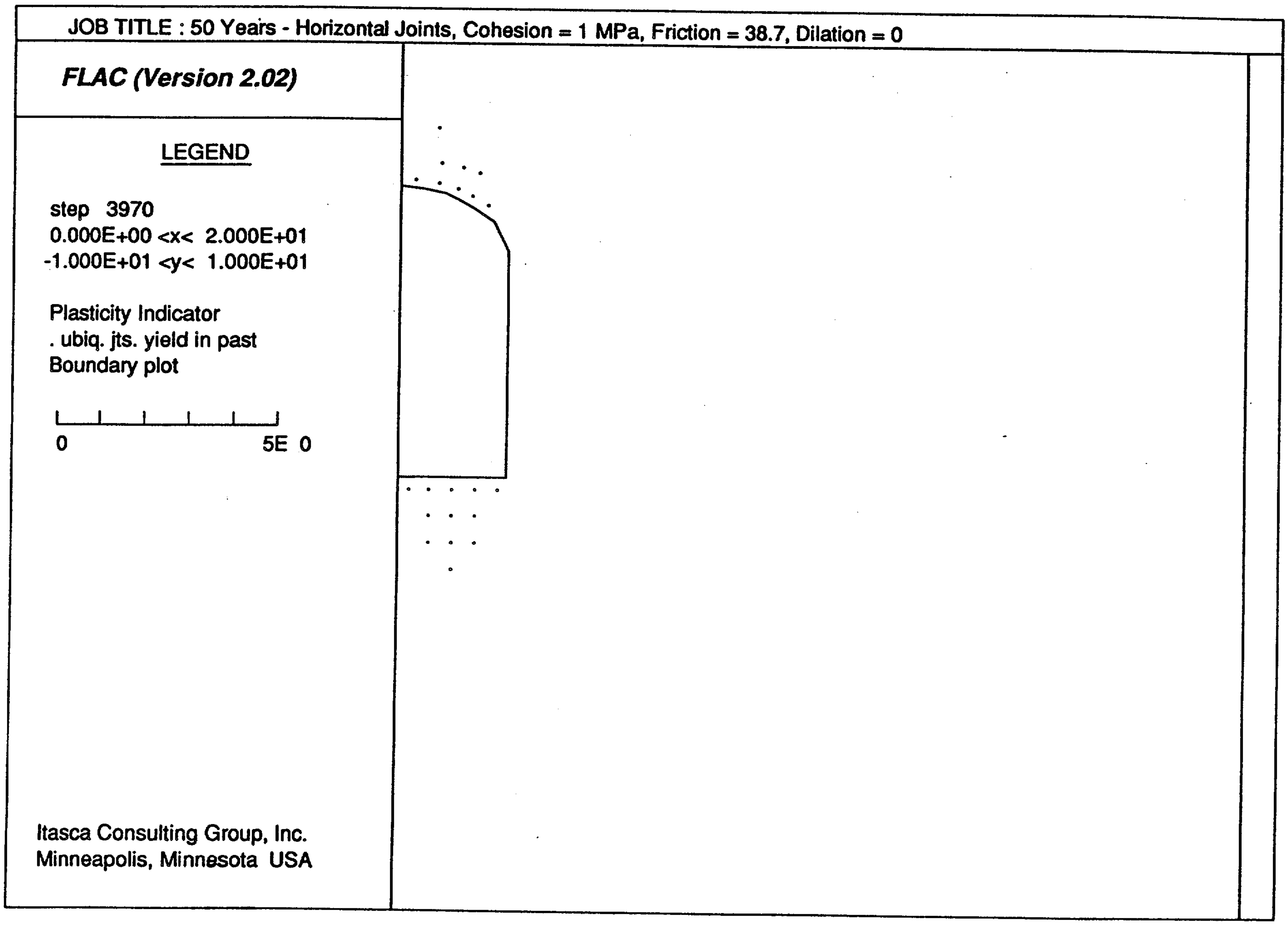


Fig. 48 FLAC Joint Displacements for 50 Years (Horizontal Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

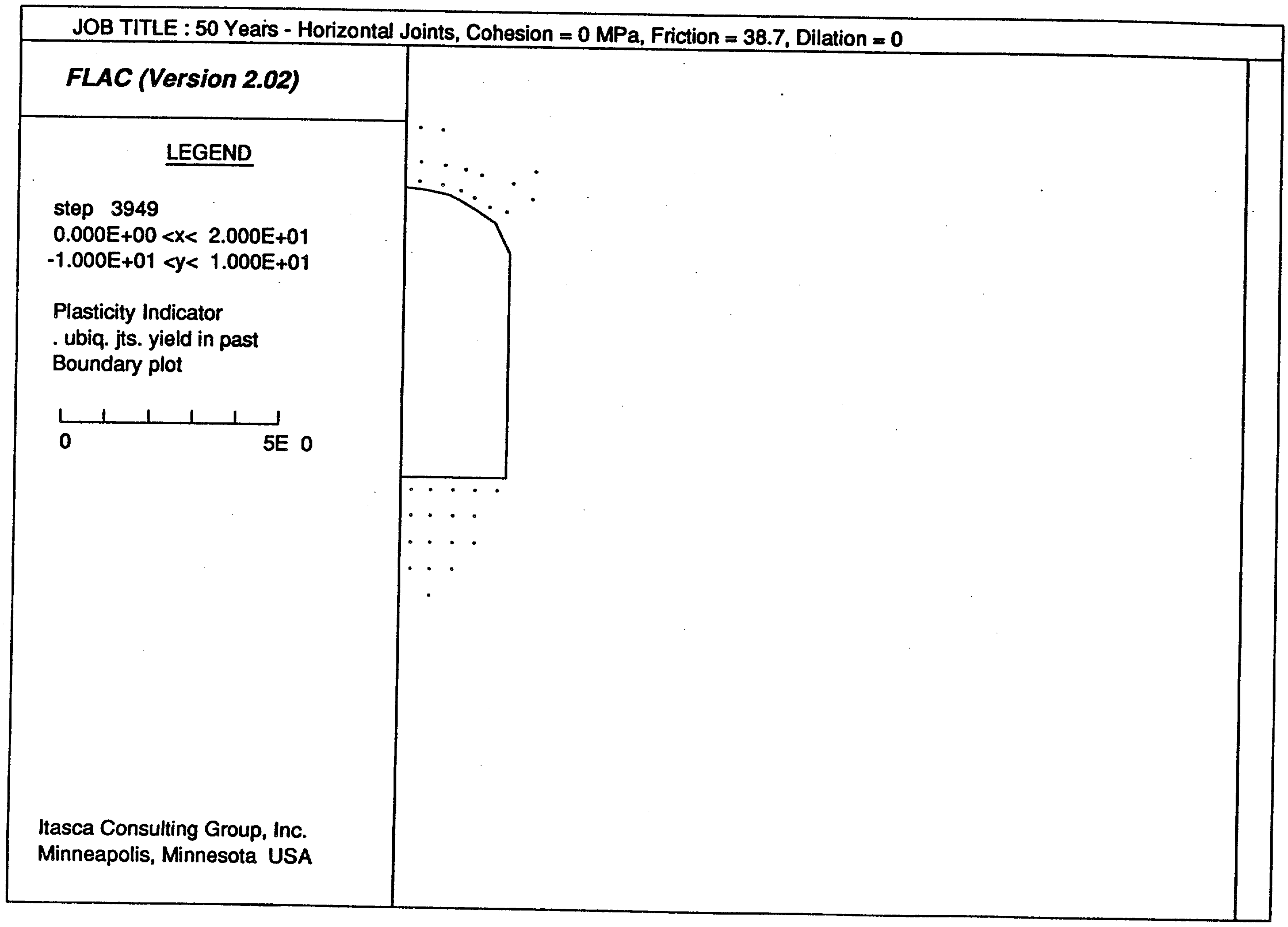


Fig. 49 FLAC Joint Displacements for 50 Years (Horizontal Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

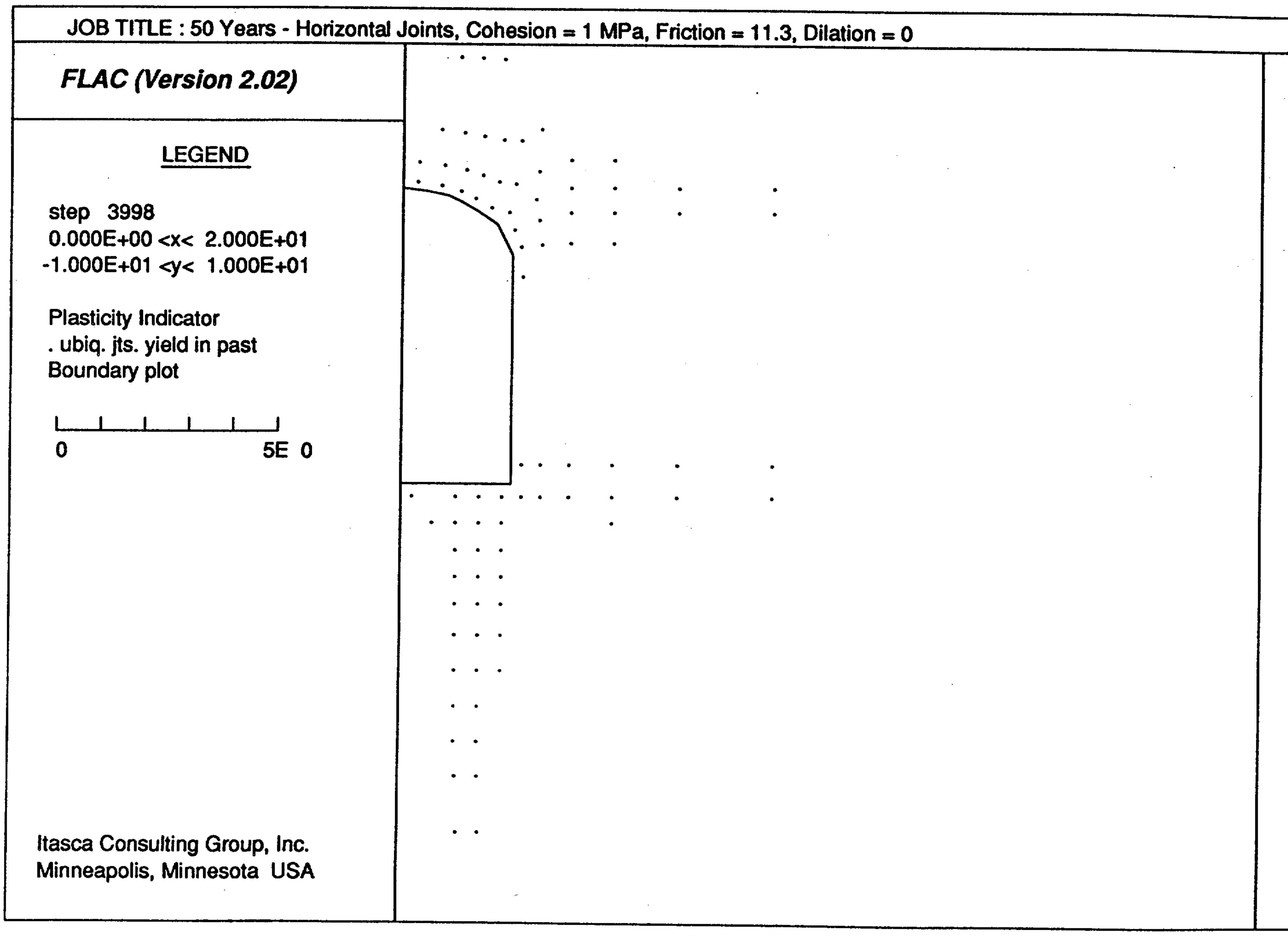


Fig. 50 FLAC Joint Displacements for 50 Years (Horizontal Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

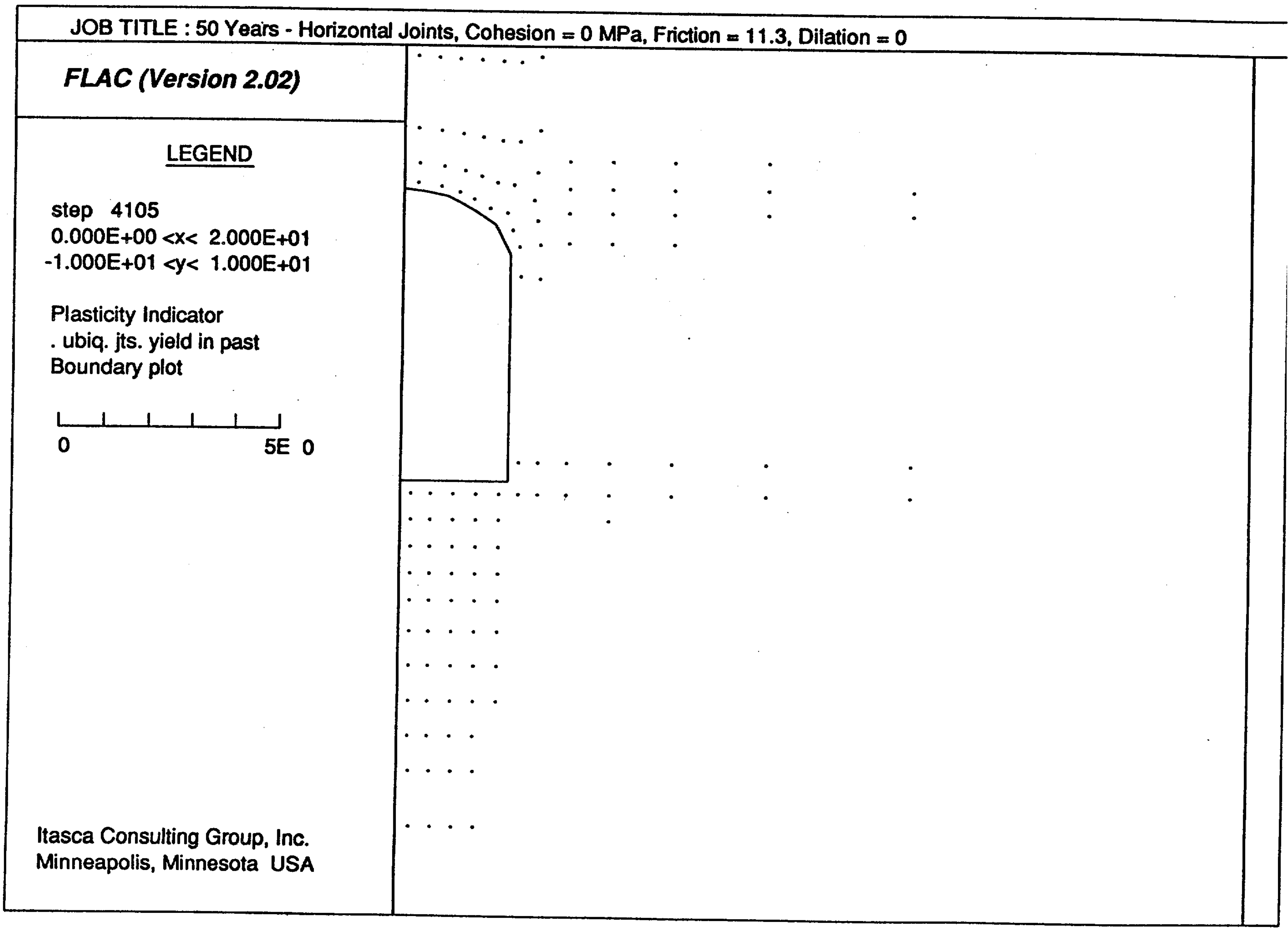


Fig. 51 FLAC Joint Displacements for 50 Years (Horizontal Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

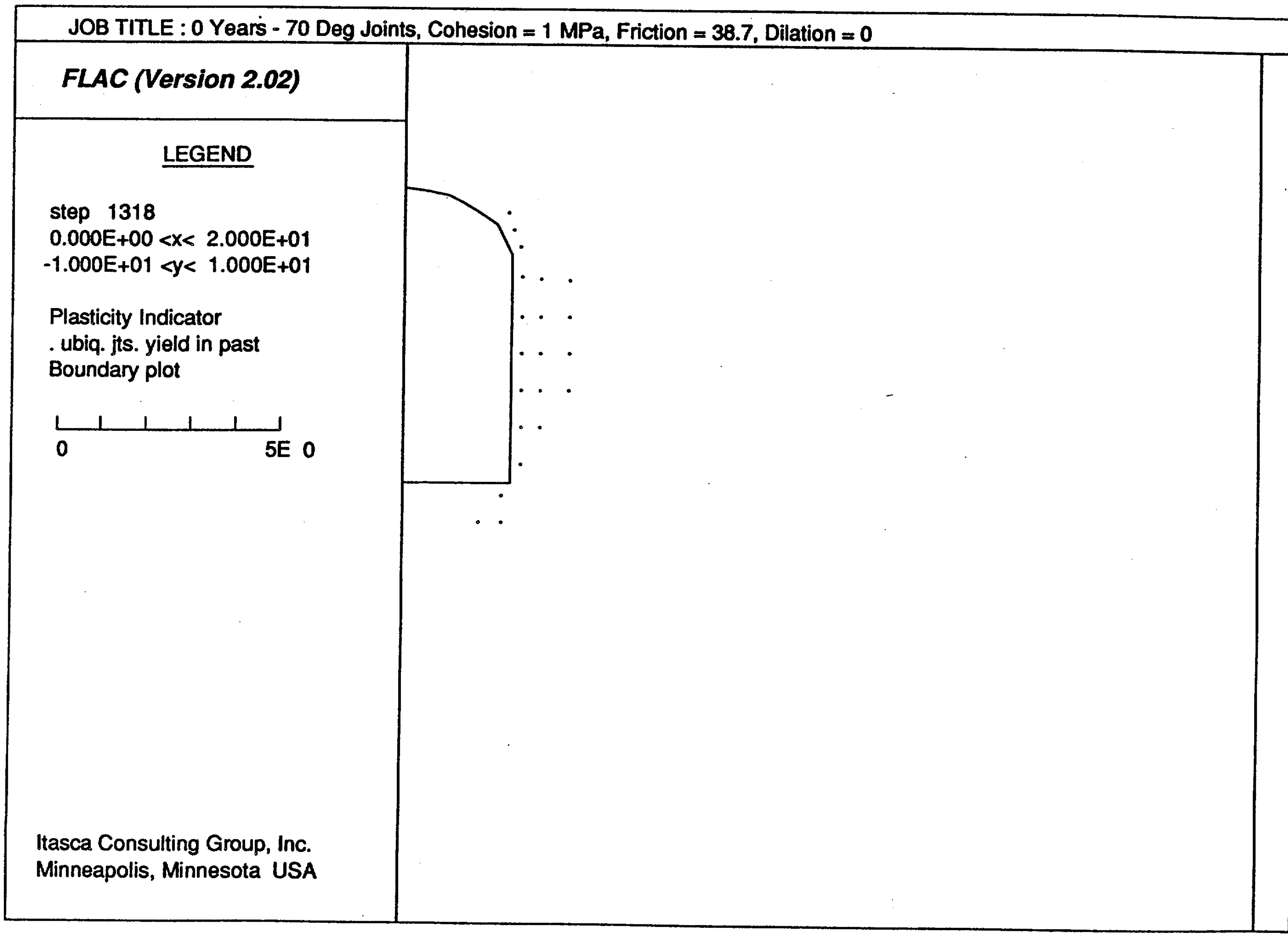


Fig. 52 FLAC Joint Displacements for 0 Years (70 Degree Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

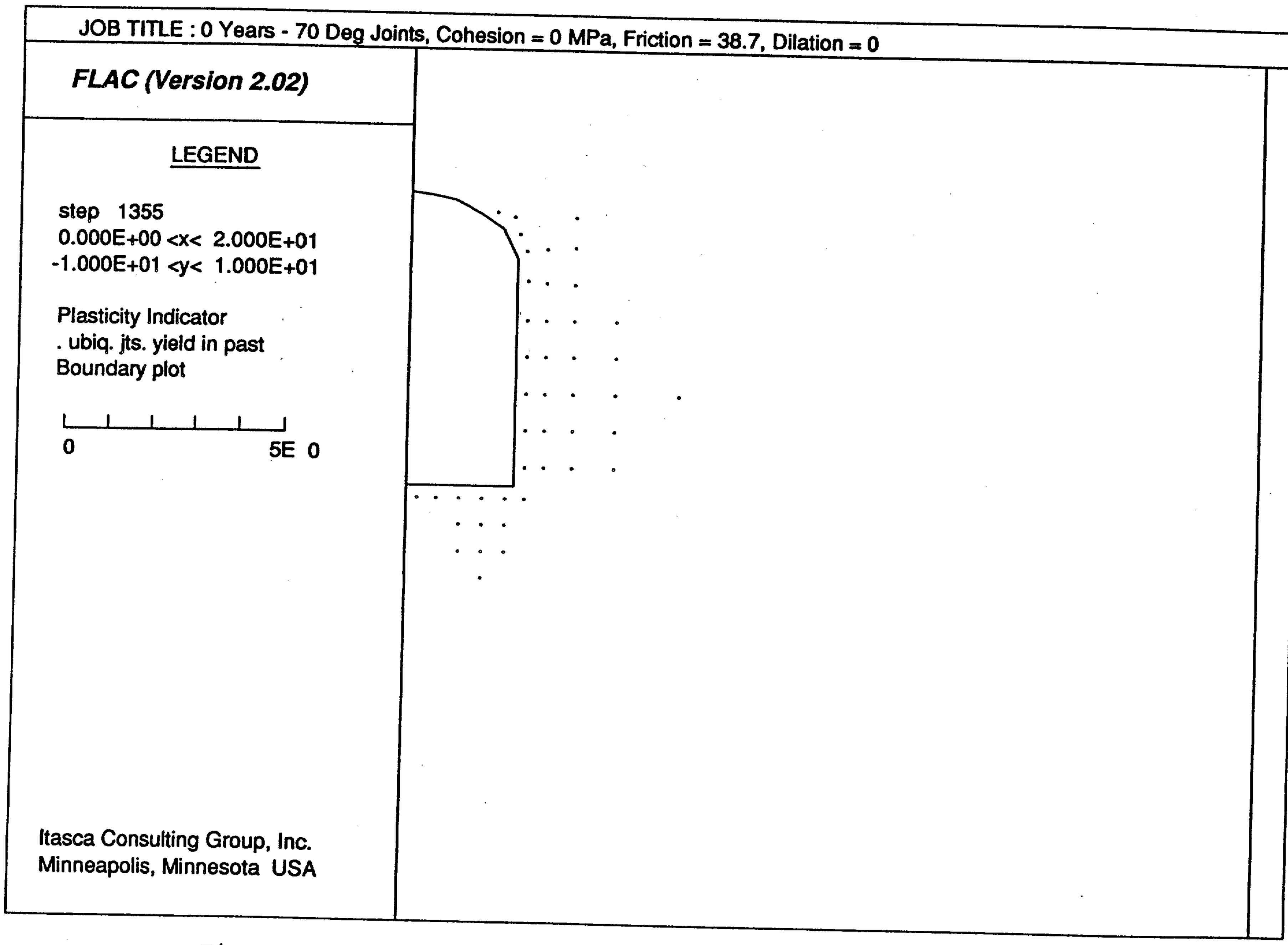


Fig. 53 FLAC Joint Displacements for 0 Years (70 Degree Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

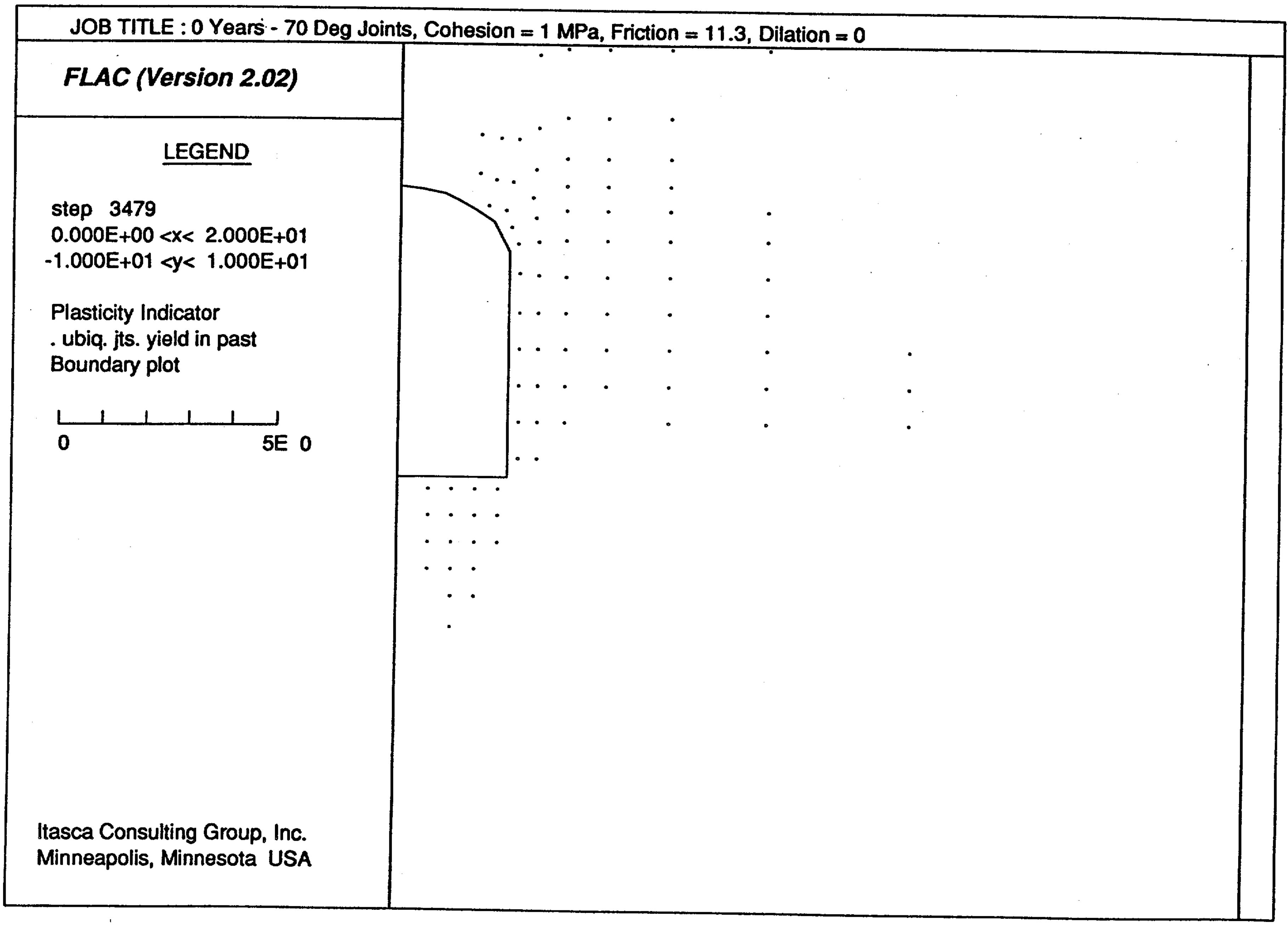


Fig. 54 FLAC Joint Displacements for 0 Years (70 Degree Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

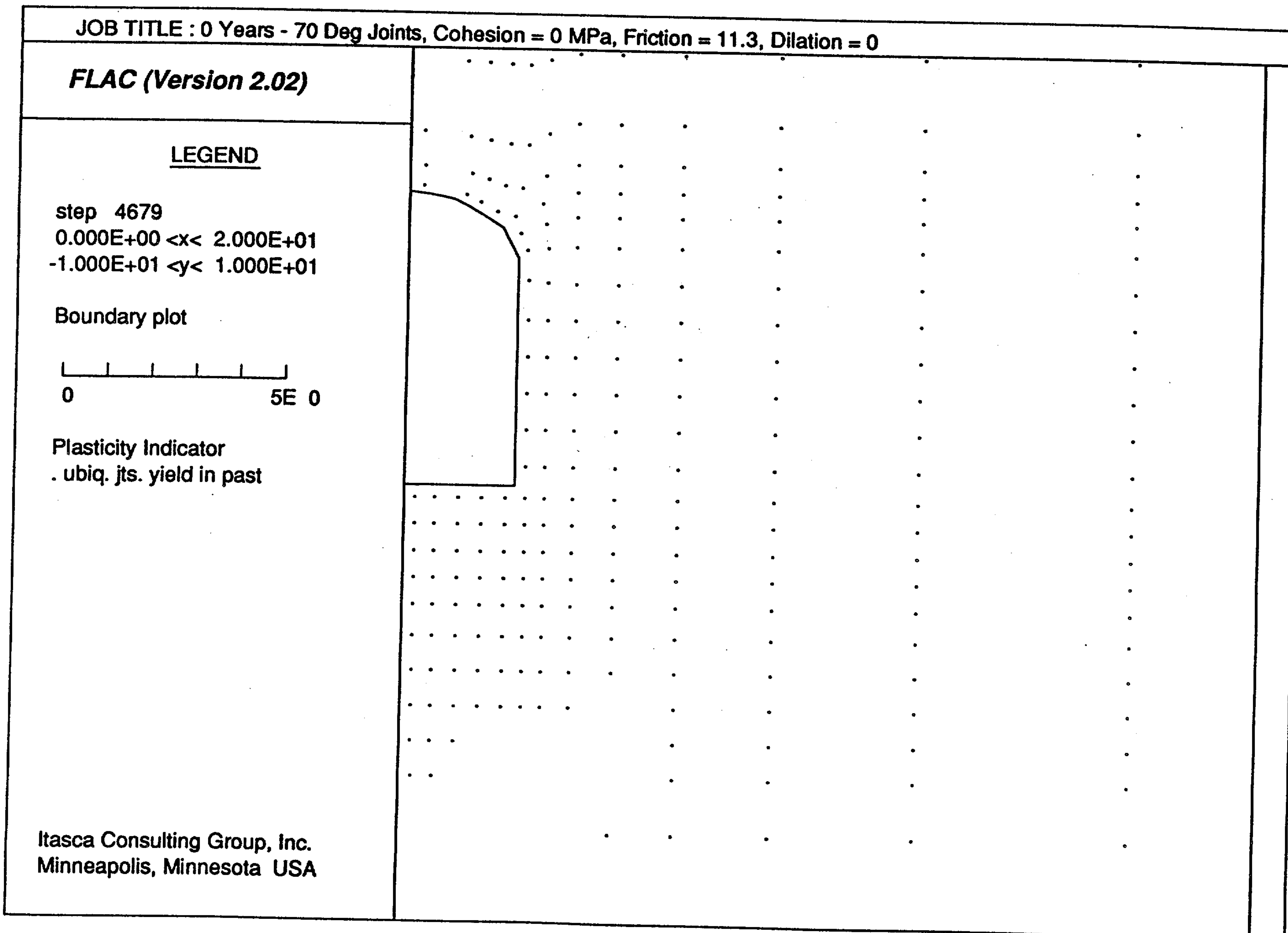


Fig. 55 FLAC Joint Displacements for 0 Years (70 Degree Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

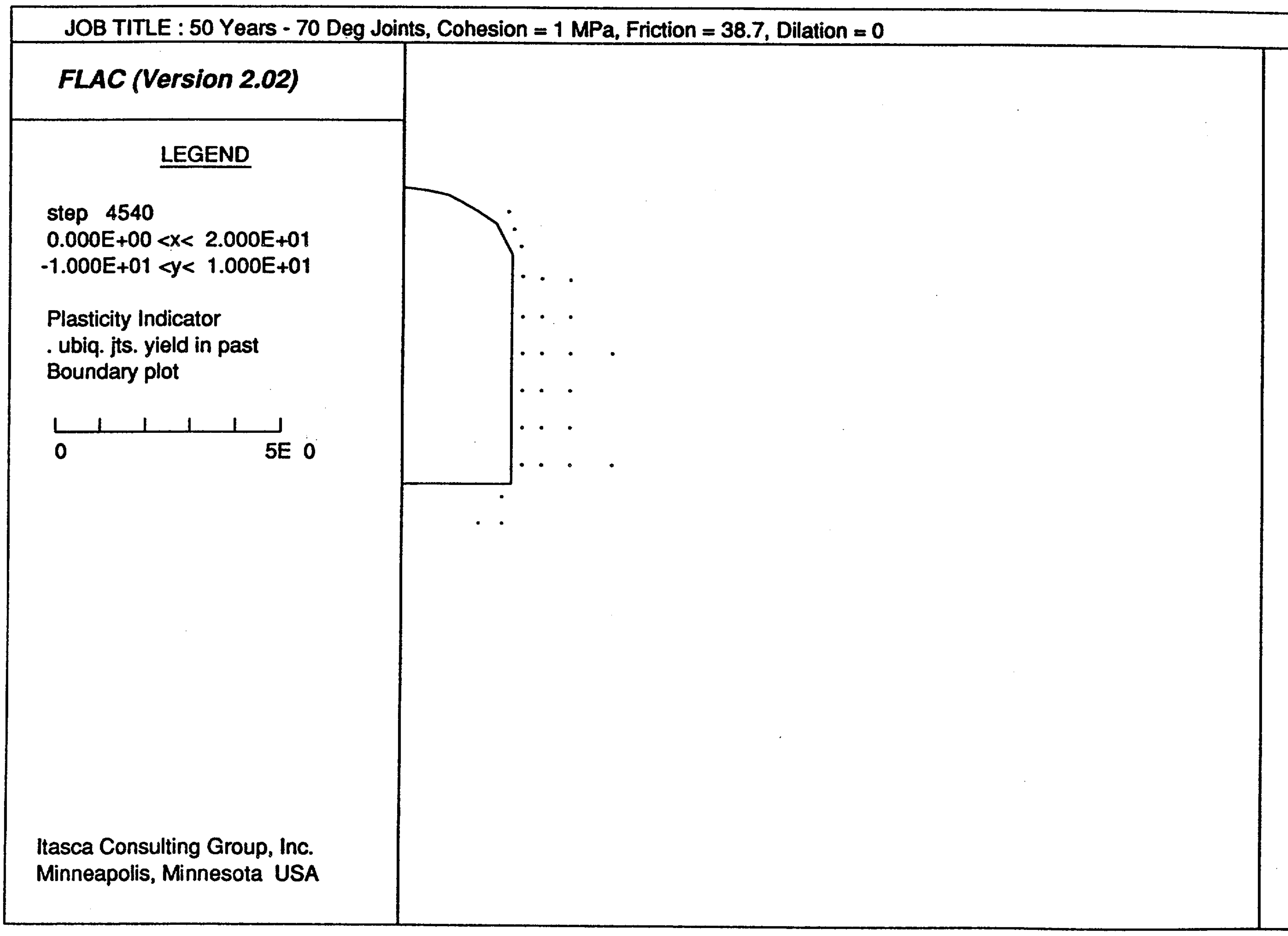


Fig. 56 FLAC Joint Displacements for 50 Years (70 Degree Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

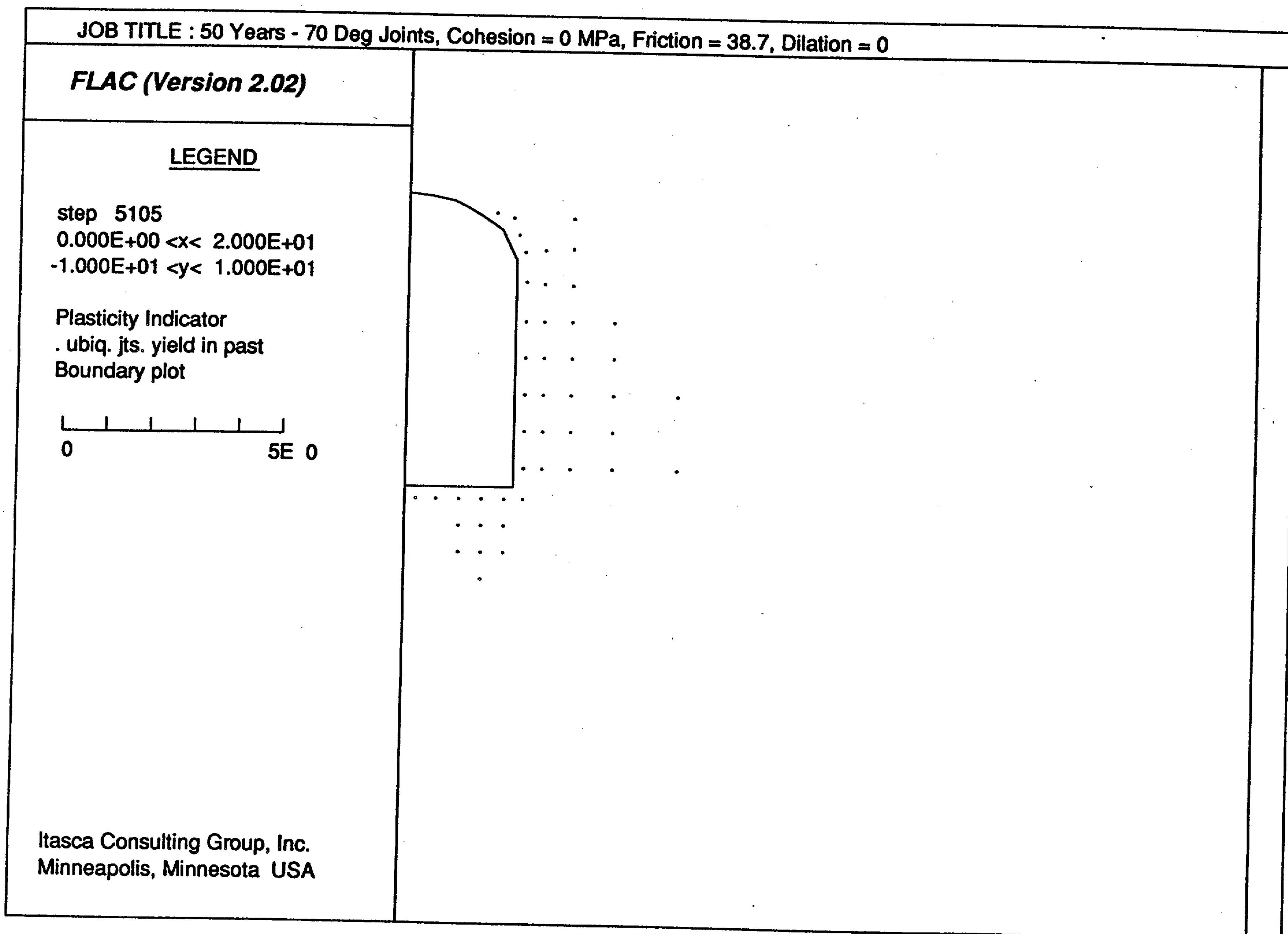


Fig. 57 FLAC Joint Displacements for 50 Years (70 Degree Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

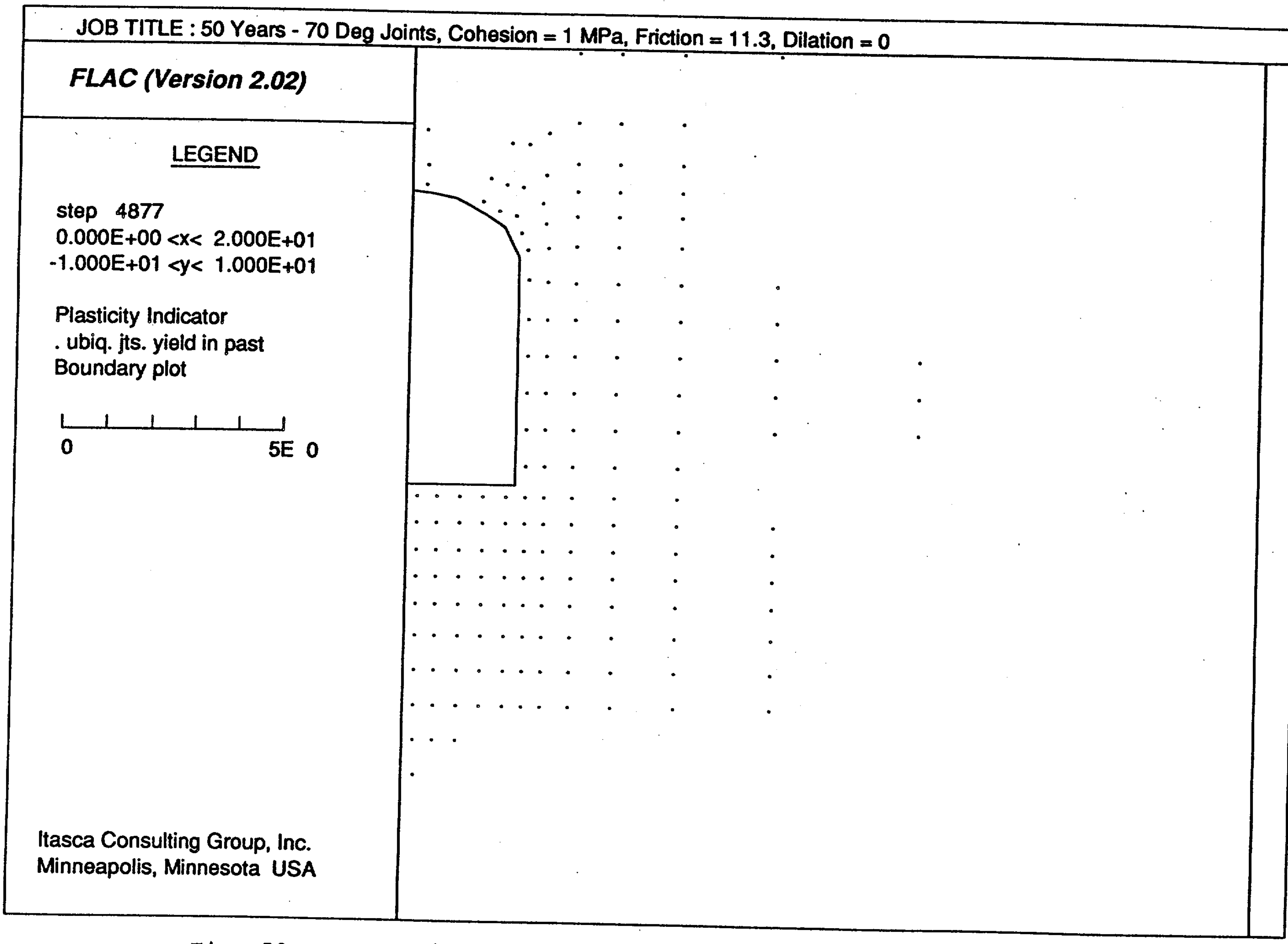


Fig. 58 FLAC Joint Displacements for 50 Years (70 Degree Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

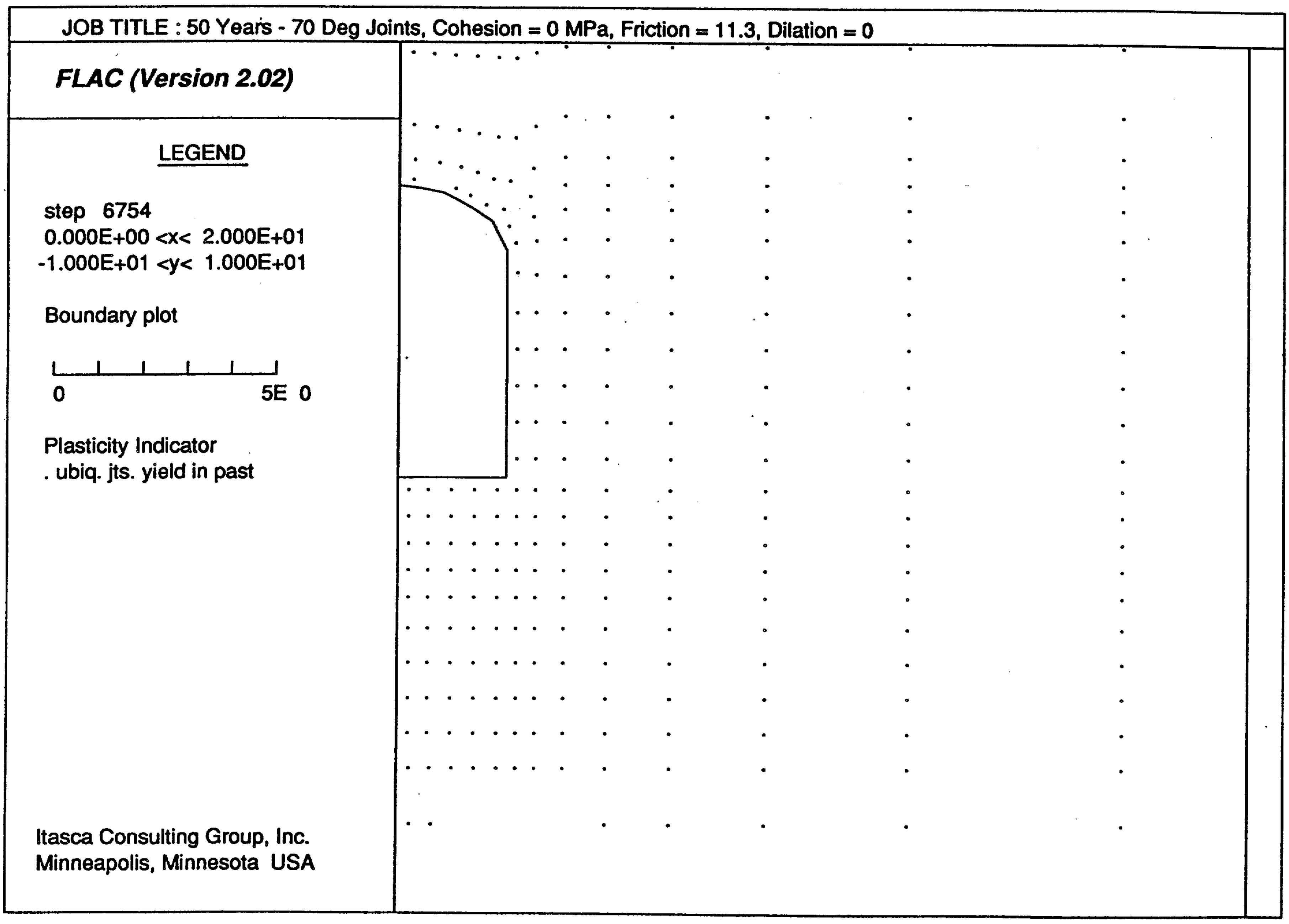


Fig. 59 FLAC Joint Displacements for 50 Years (70 Degree Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

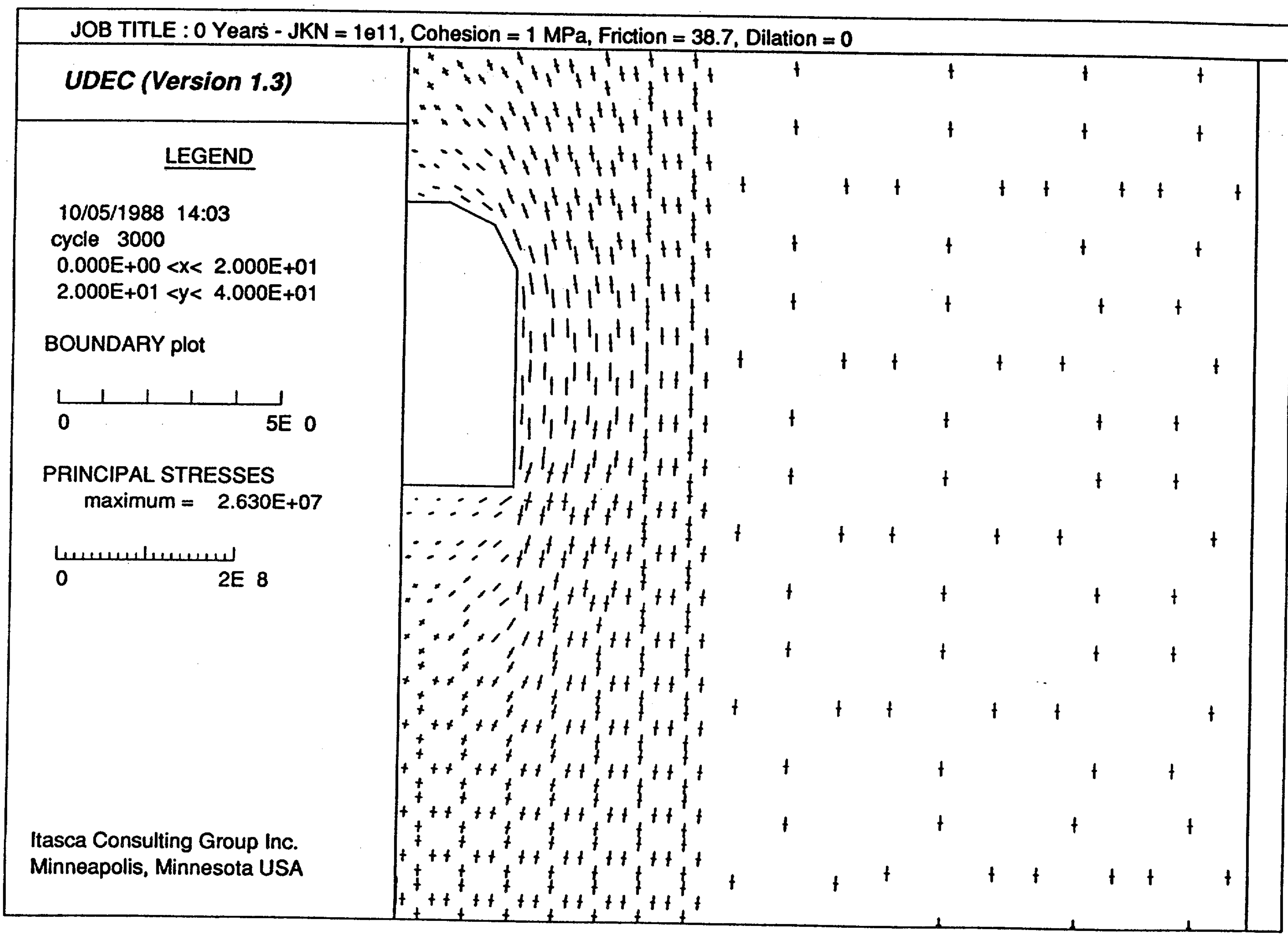


Fig. 60 UDEC Principal Stresses for 0 Years (JKN = 1e11, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

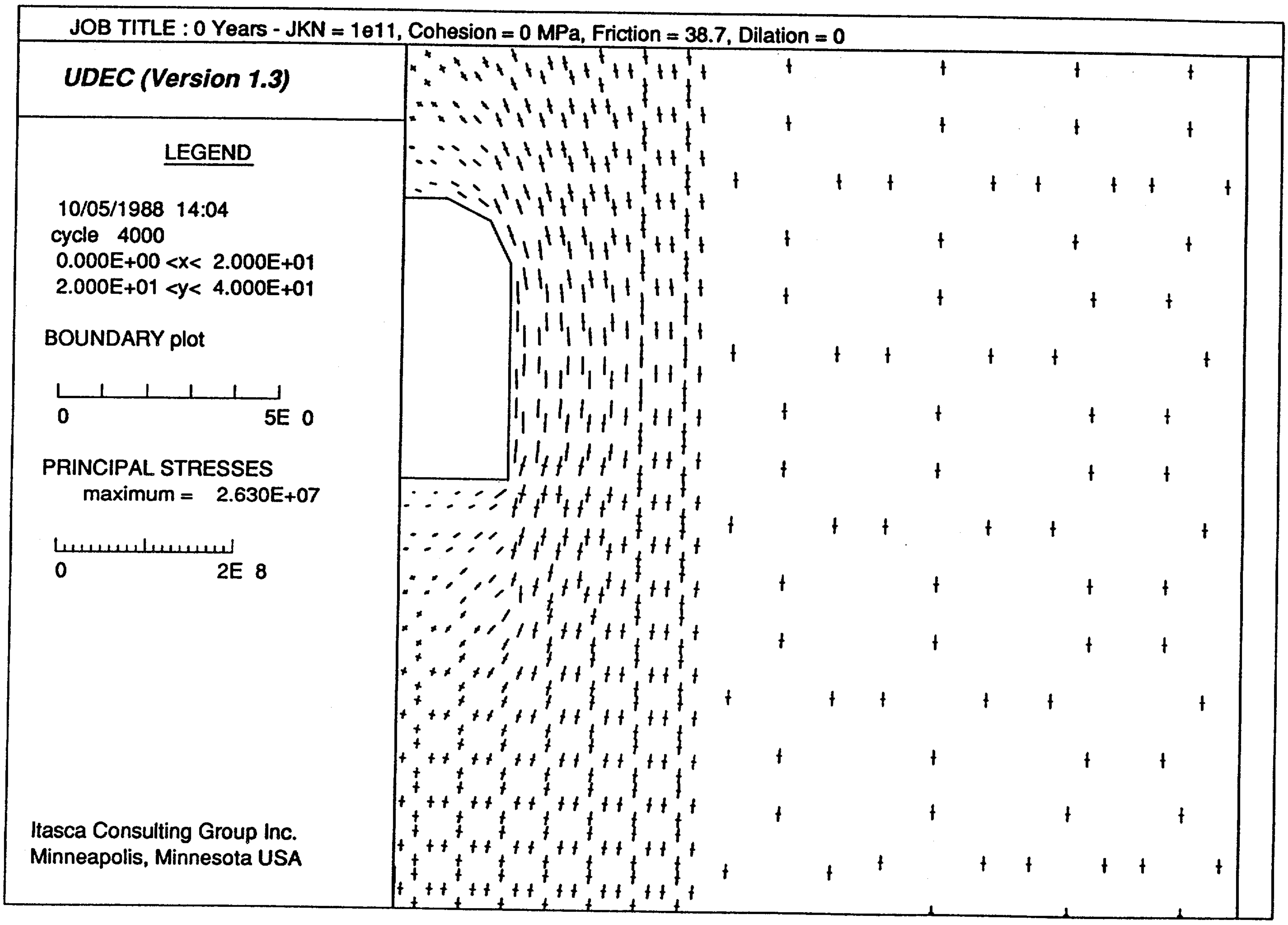


Fig. 61 UDEC Principal Stresses for 0 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

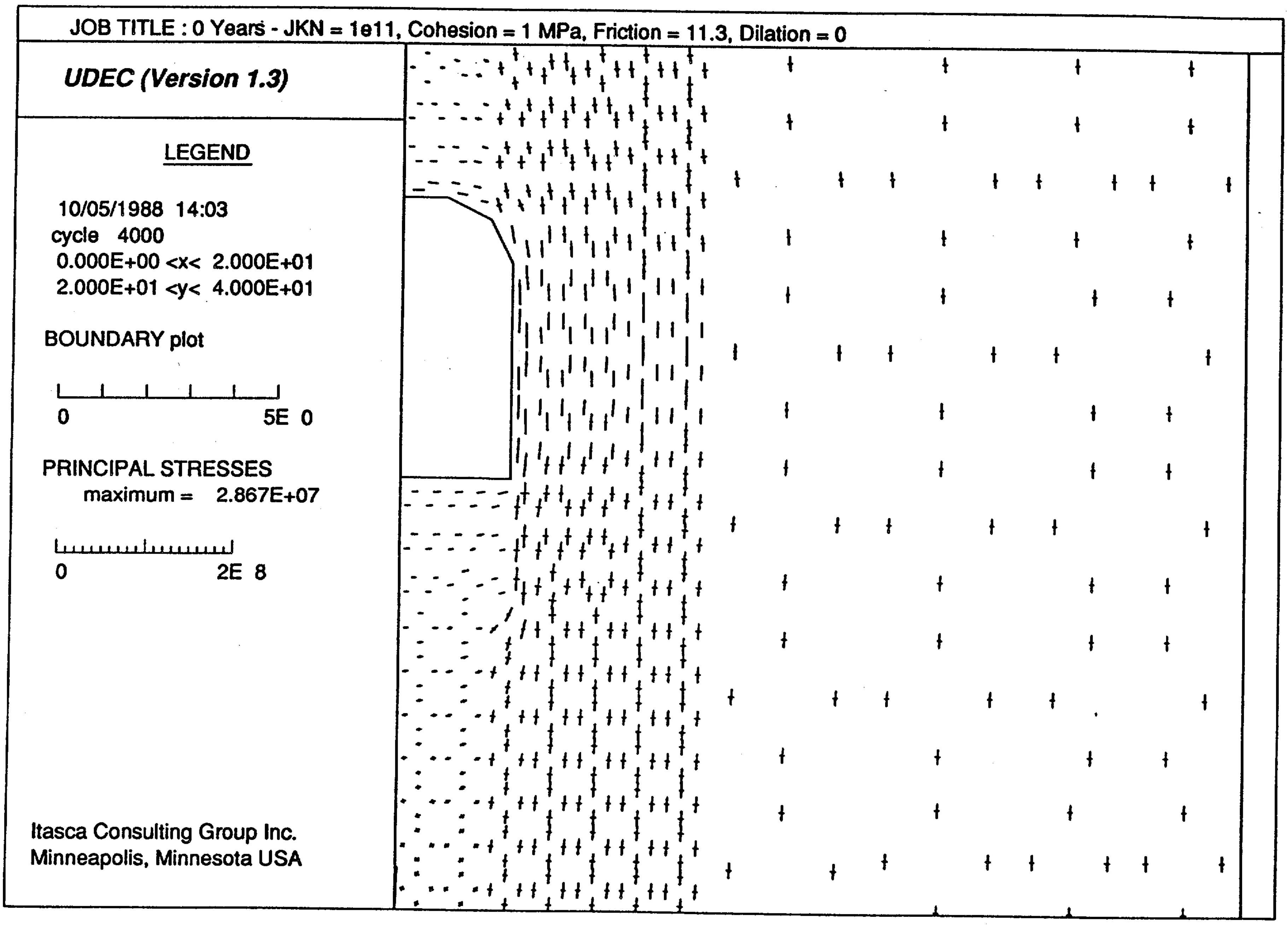


Fig. 62 UDEC Principal Stresses for 0 Years (JKN = 1e11, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

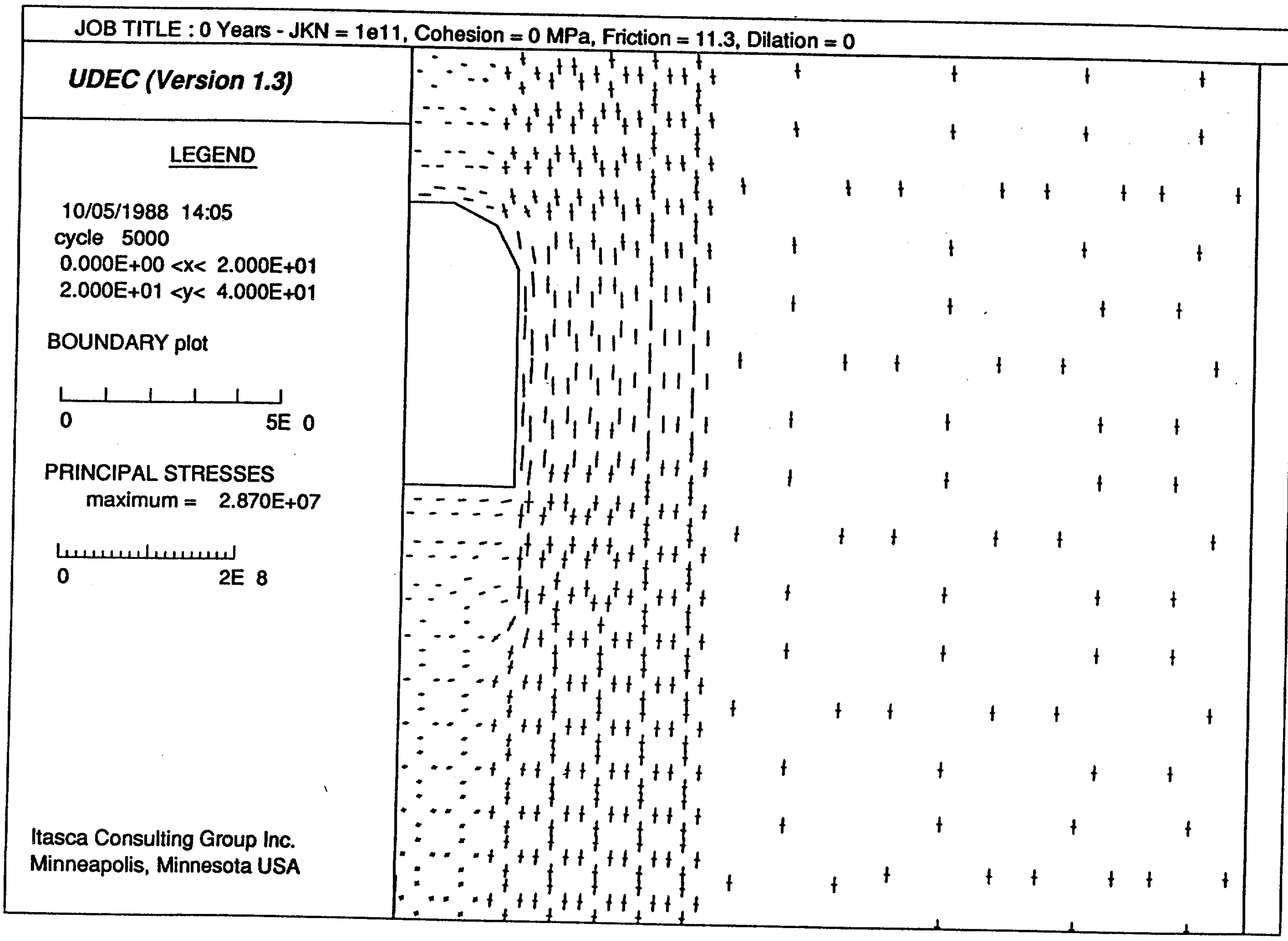


Fig. 63 UDEC Principal Stresses for 0 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

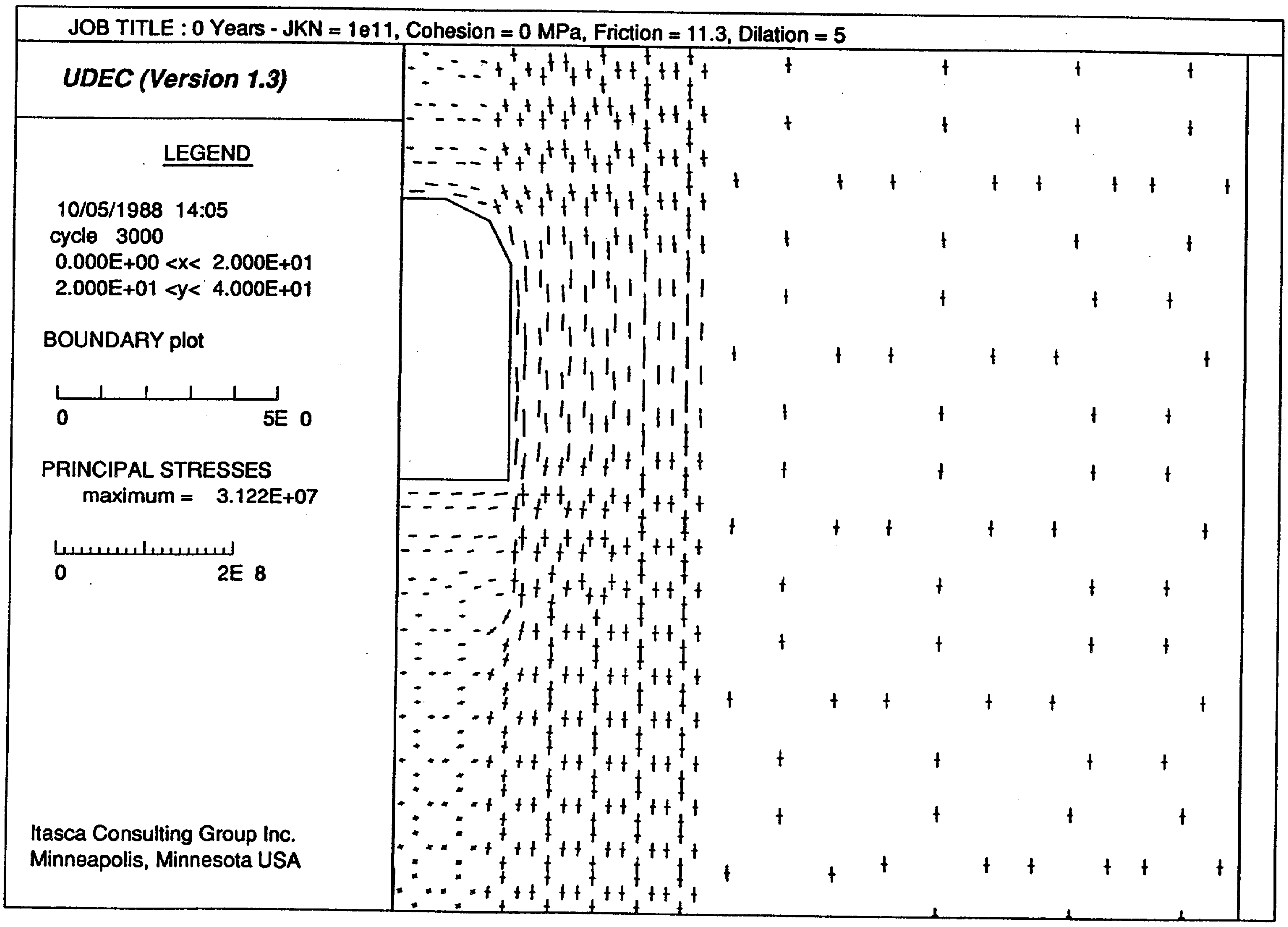


Fig. 64 UDEC Principal Stresses for 0 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 11.3, Dilation = 5)

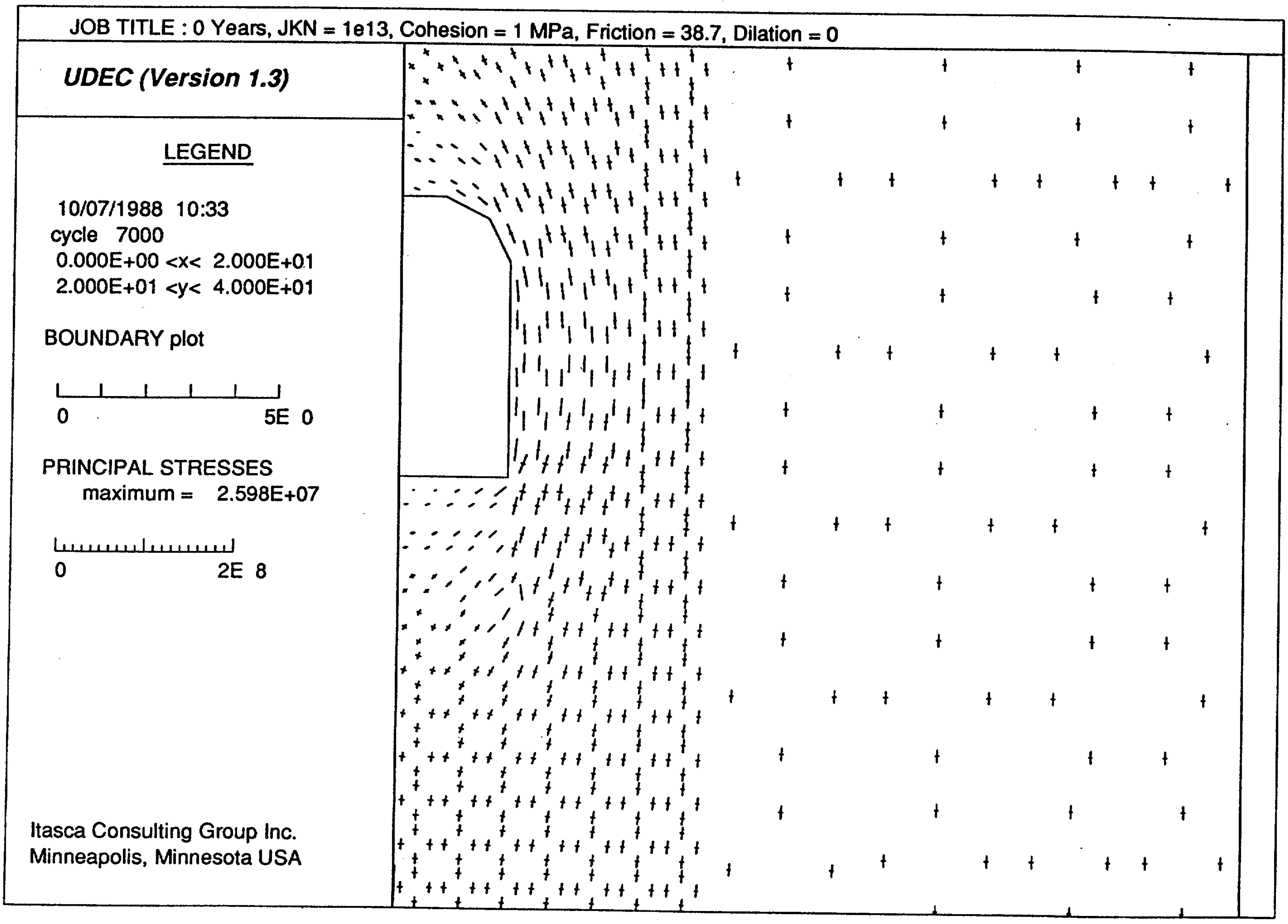


Fig. 65 UDEC Principal Stresses for 0 Years (JKN = 1e13, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

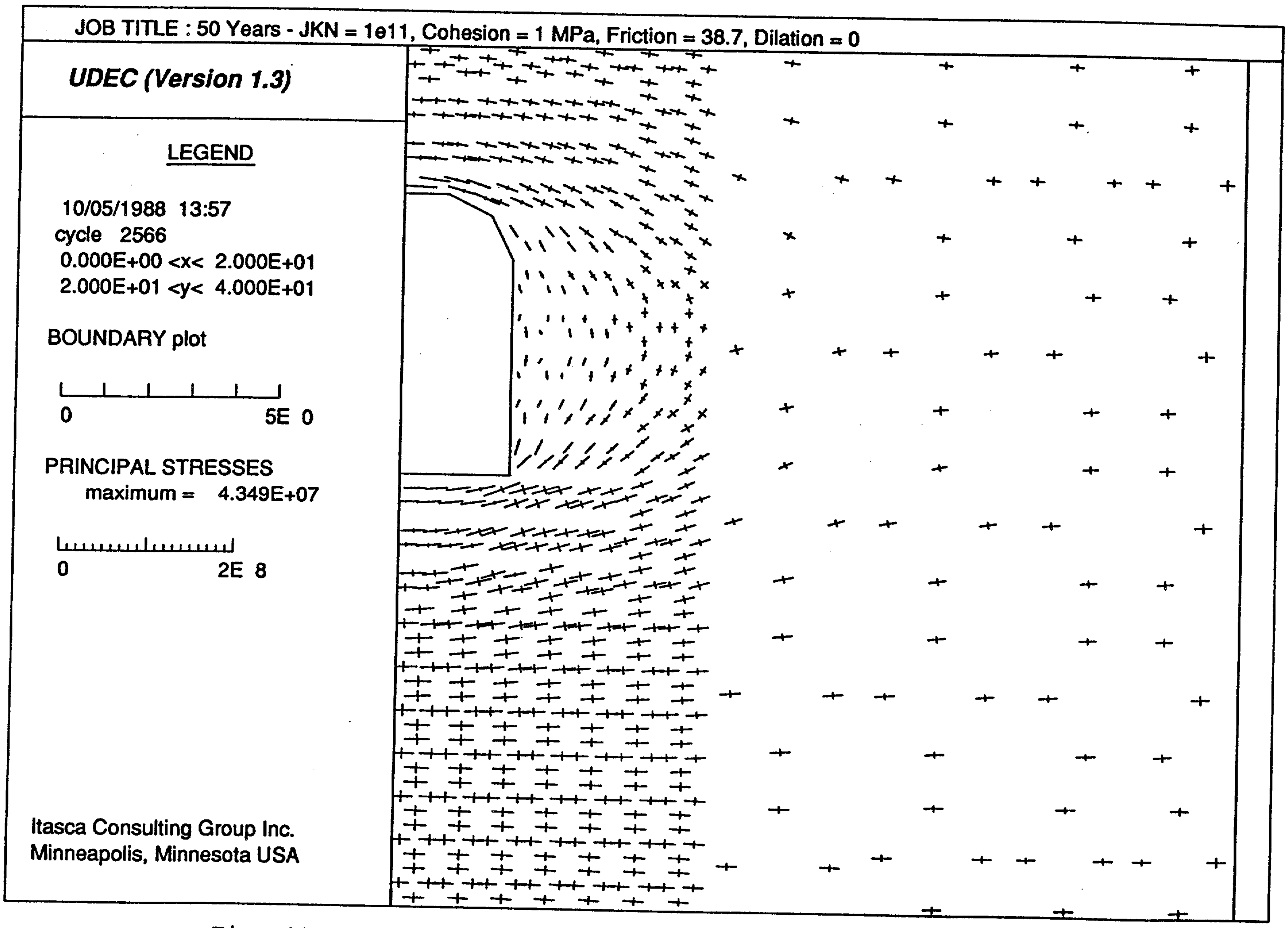


Fig. 66 UDEC Principal Stresses for 50 Years (JKN = 1e11, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

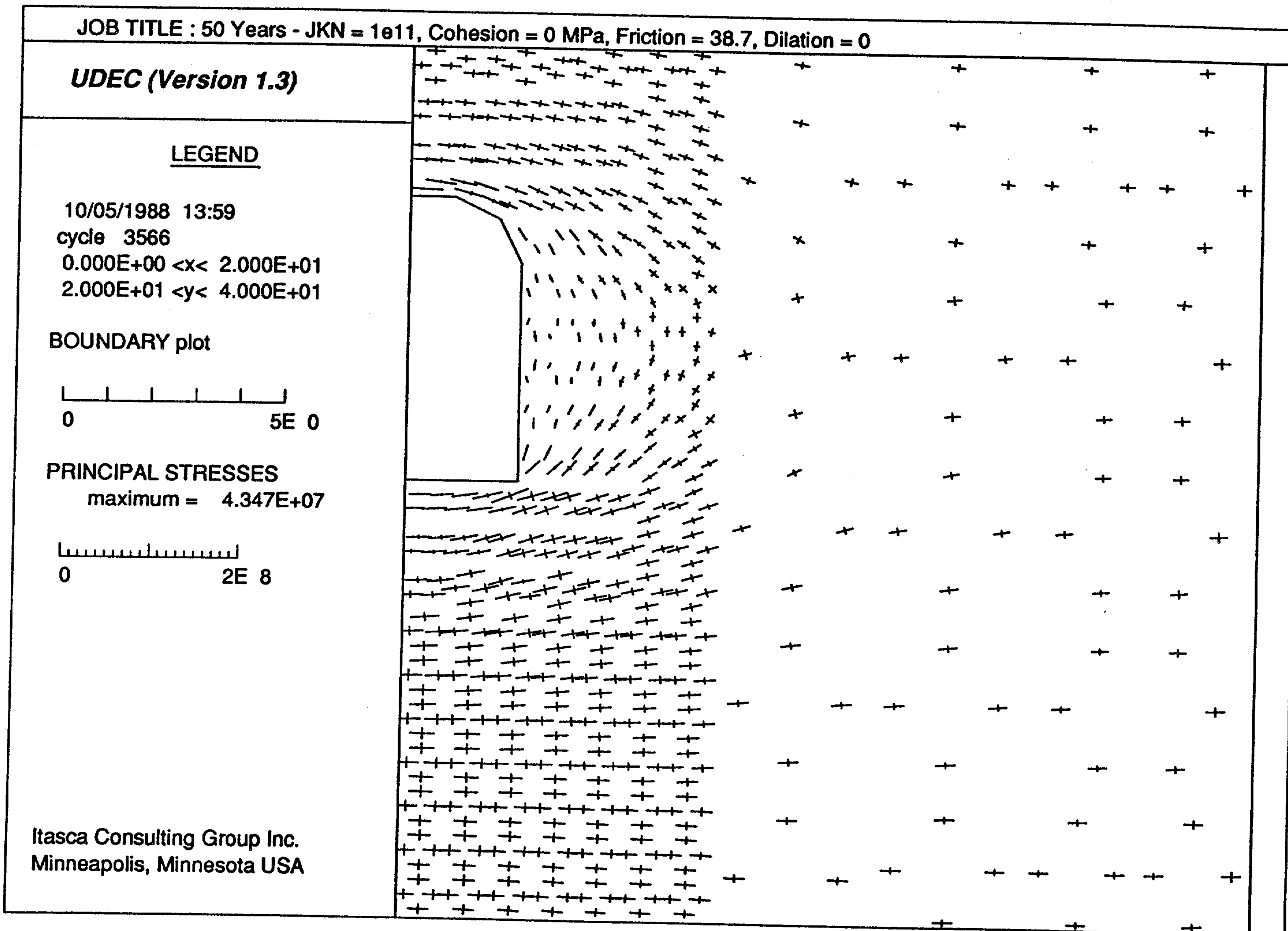


Fig. 67 UDEC Principal Stresses for 50 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

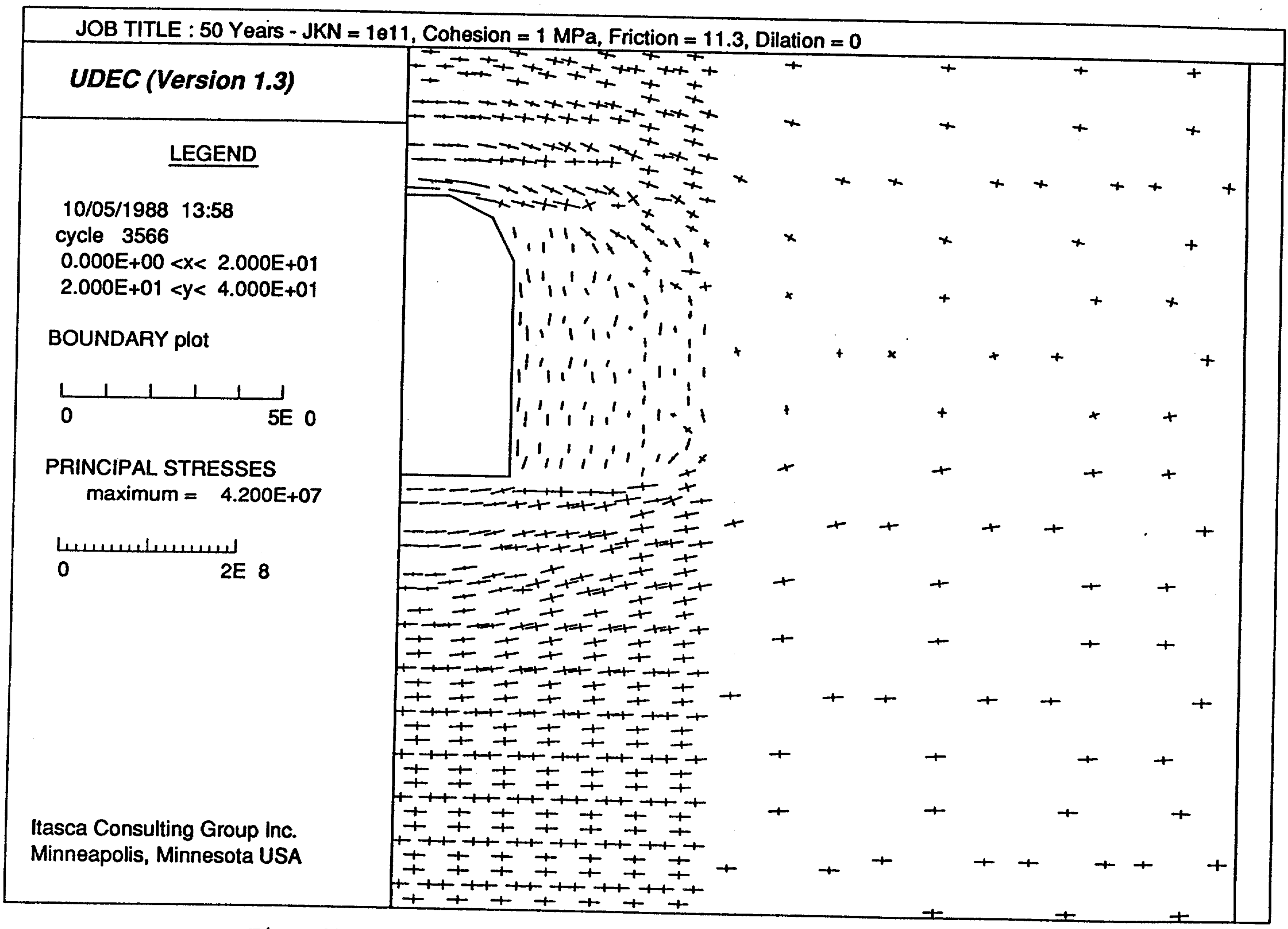


Fig. 68 UDEC Principal Stresses for 50 Years (JKN = 1e11, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

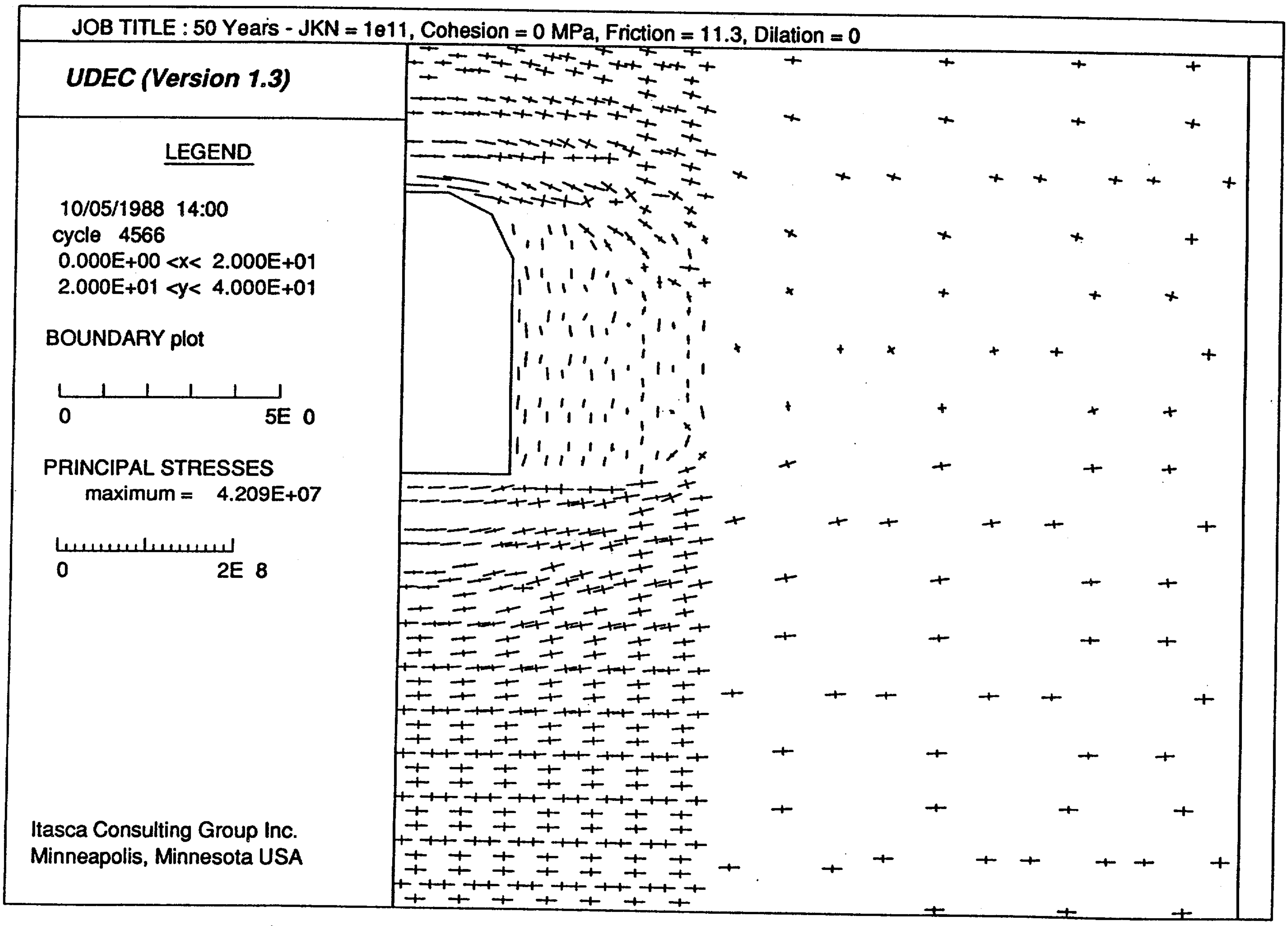


Fig. 69 UDEC Principal Stresses for 50 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

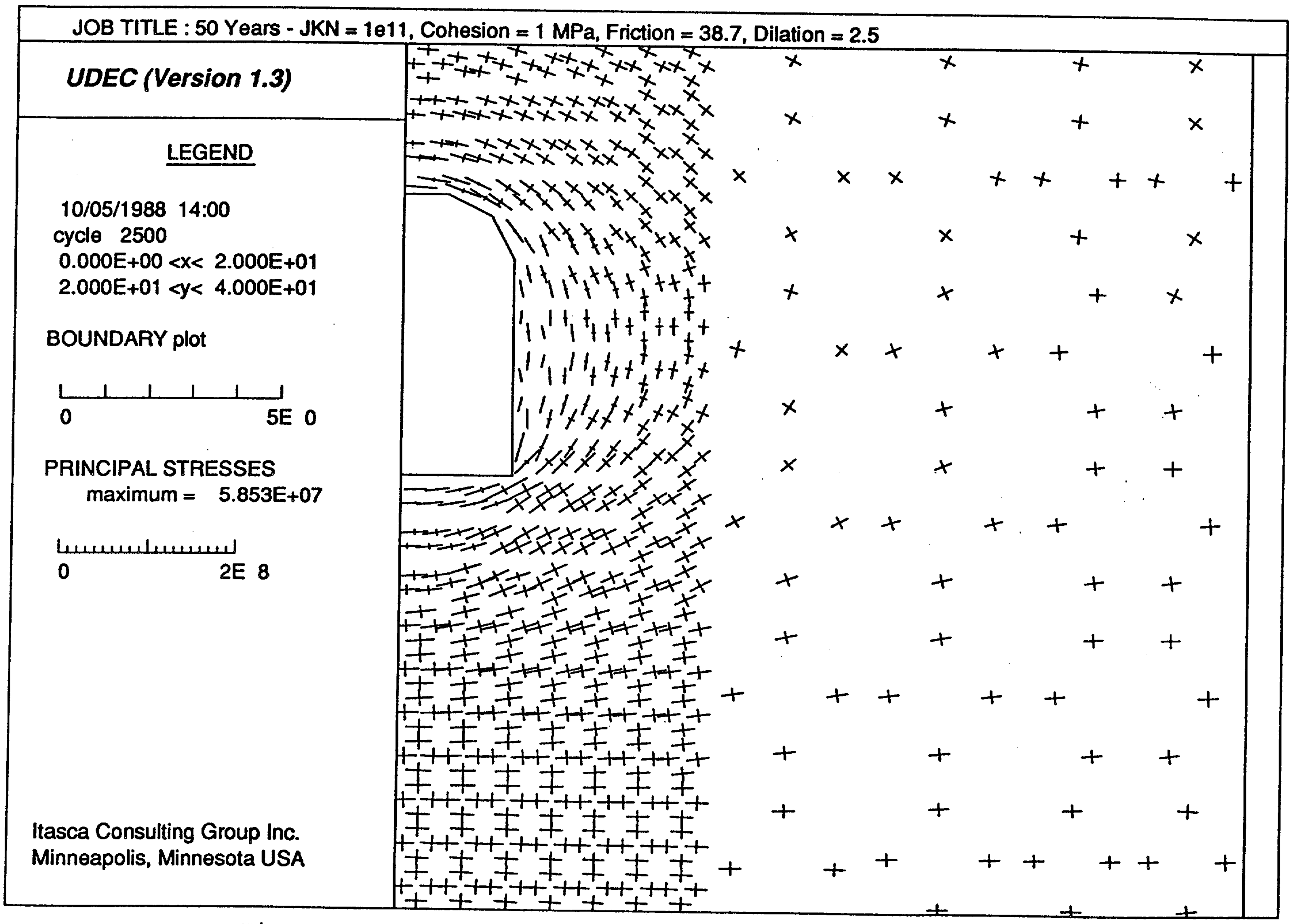


Fig. 70 UDEC Principal Stresses for 50 Years (JKN = 1e11, Cohesion 1 MPa, Friction = 37.7, Dilation = 2.5)

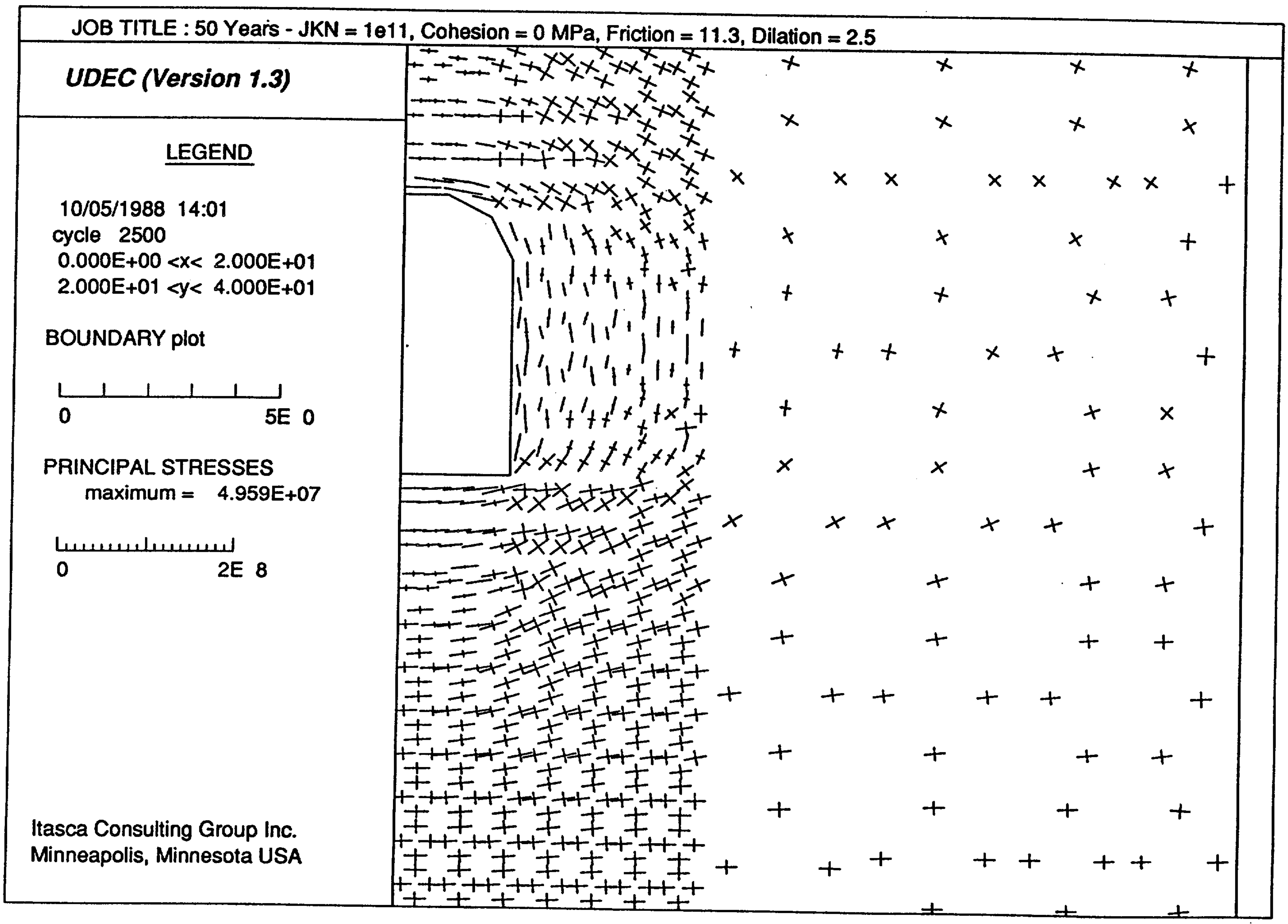


Fig. 71 UDEC Principal Stresses for 50 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 11.3, Dilation = 2.5)

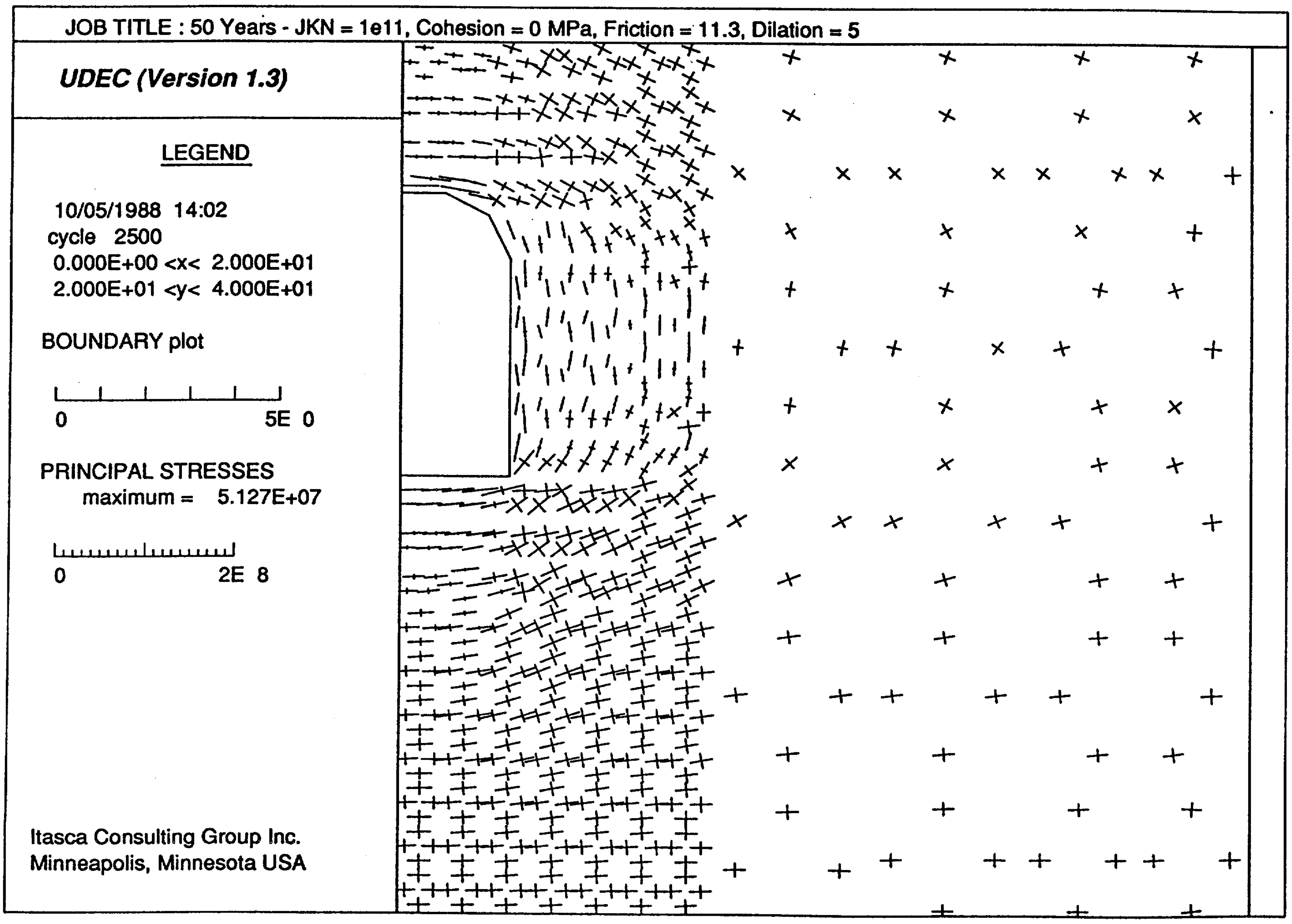


Fig. 72 UDEC Principal Stresses for 50 Years (JKN = 1e11, Cohesion = 0 MPa, Friction = 11.3, Dilation = 5)

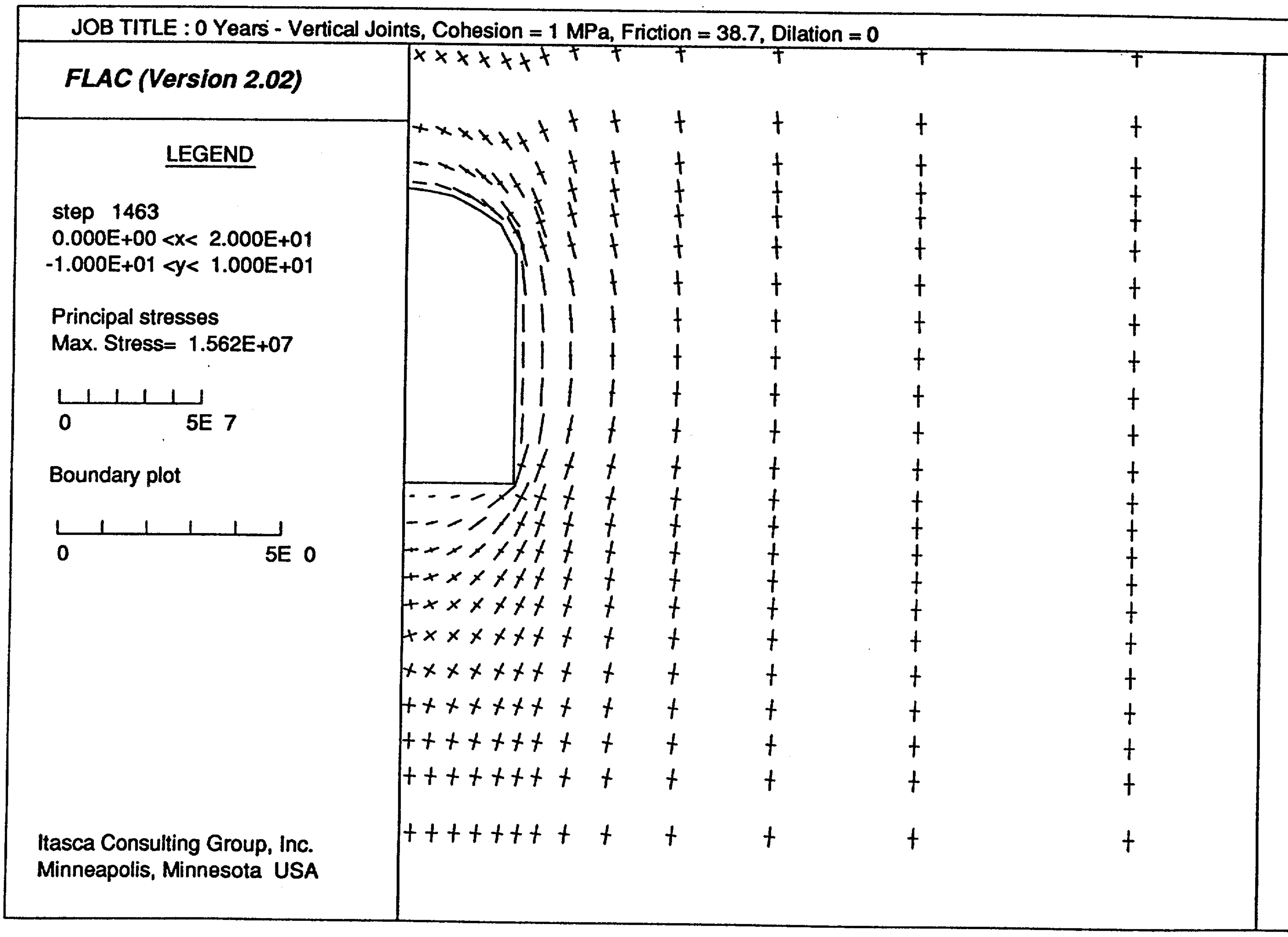


Fig. 73 FLAC Principal Stresses for 0 Years (Vertical Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

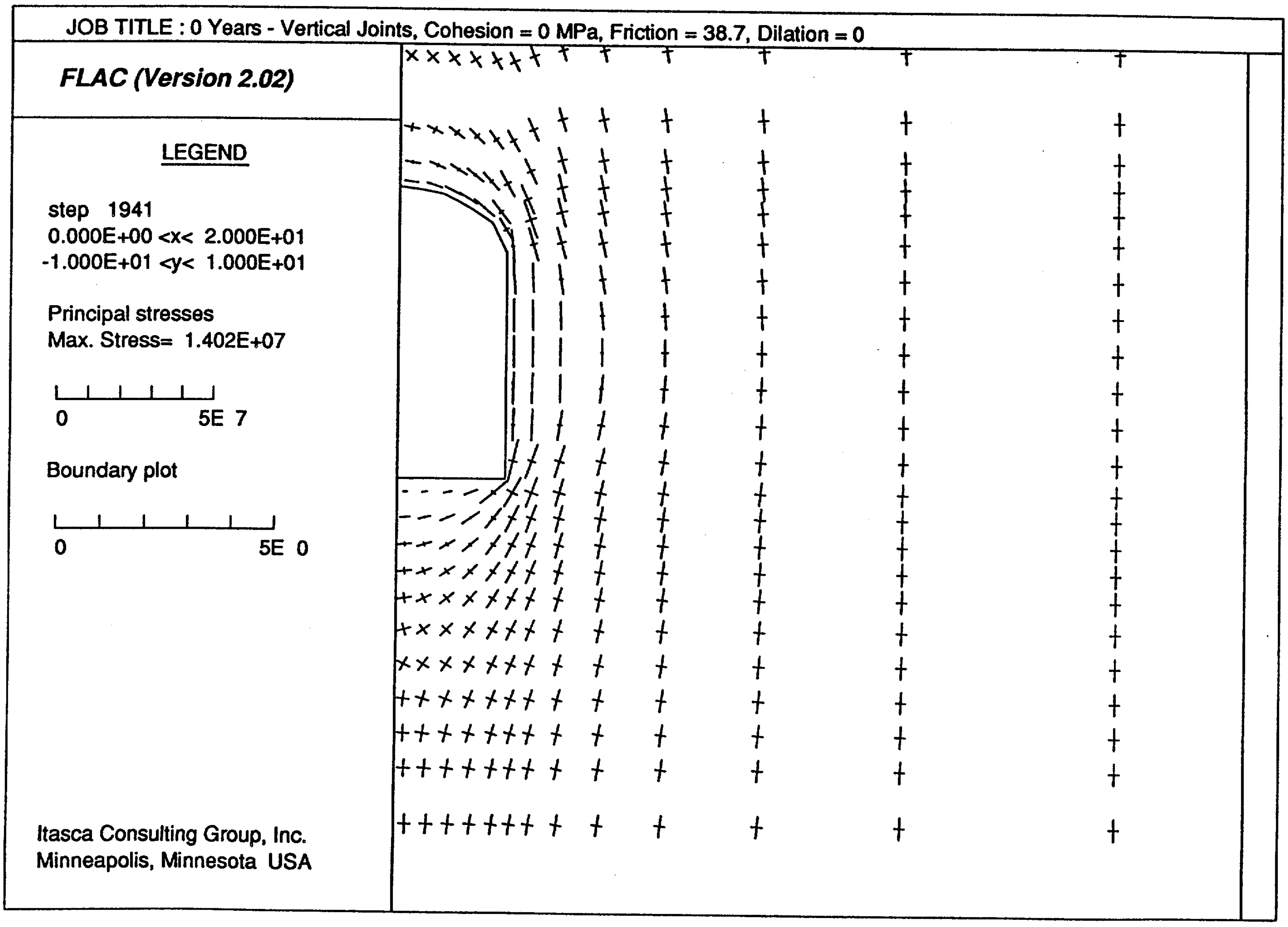


Fig. 74 FLAC Principal Stresses for 0 Years (Vertical Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

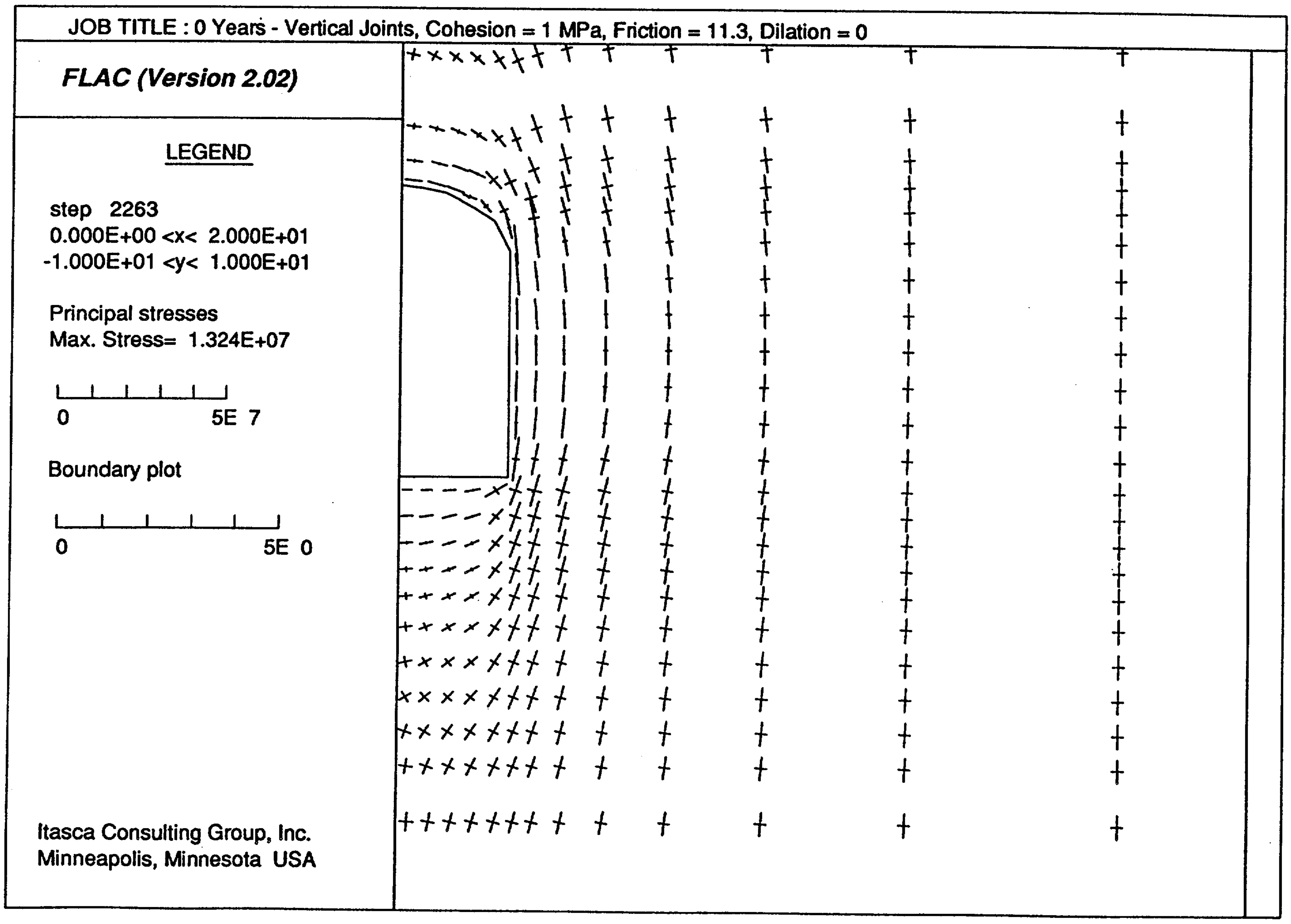


Fig. 75 FLAC Principal Stresses for 0 Years (Vertical Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

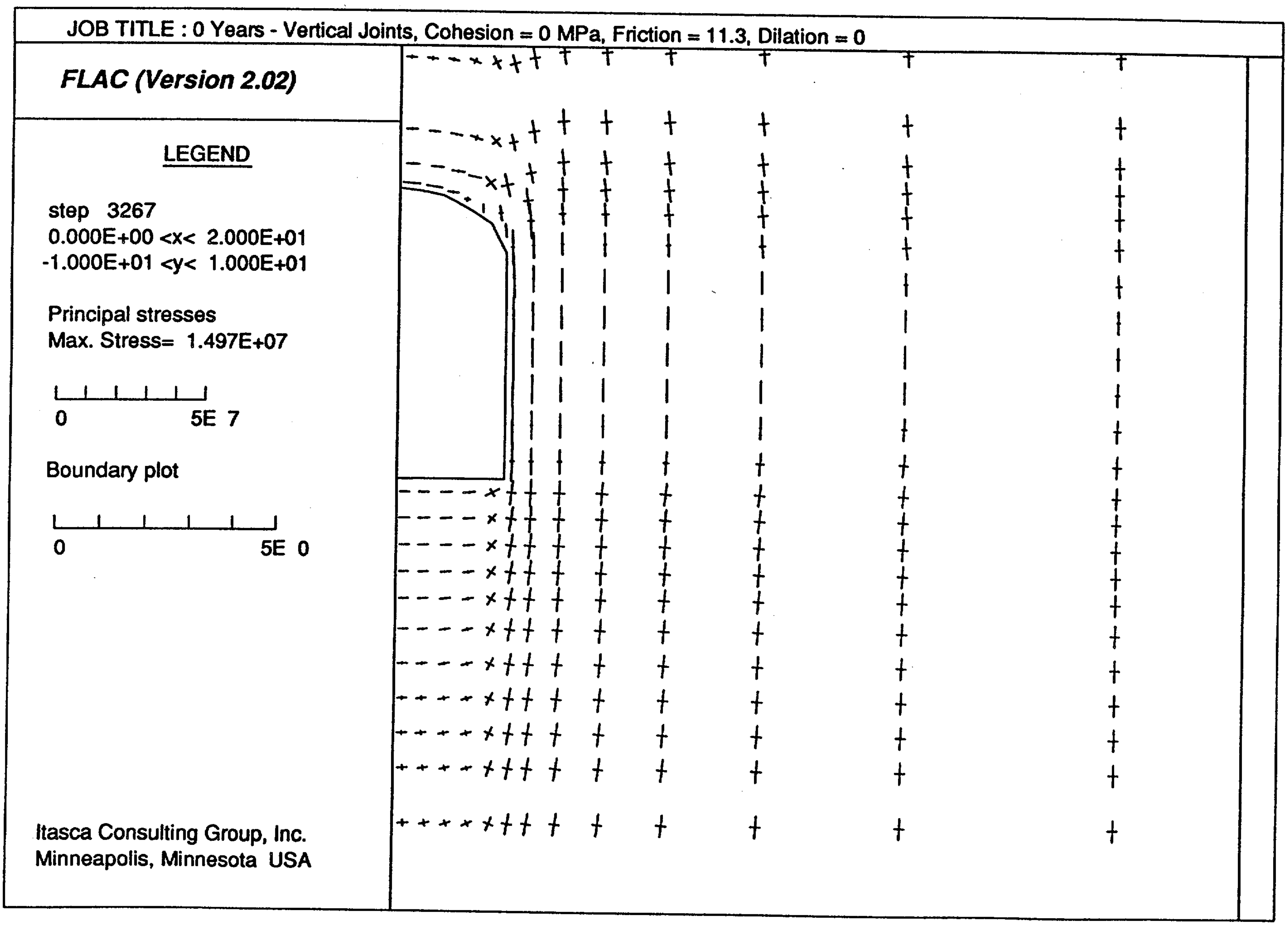


Fig. 76 FLAC Principal Stresses for 0 Years (Vertical Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

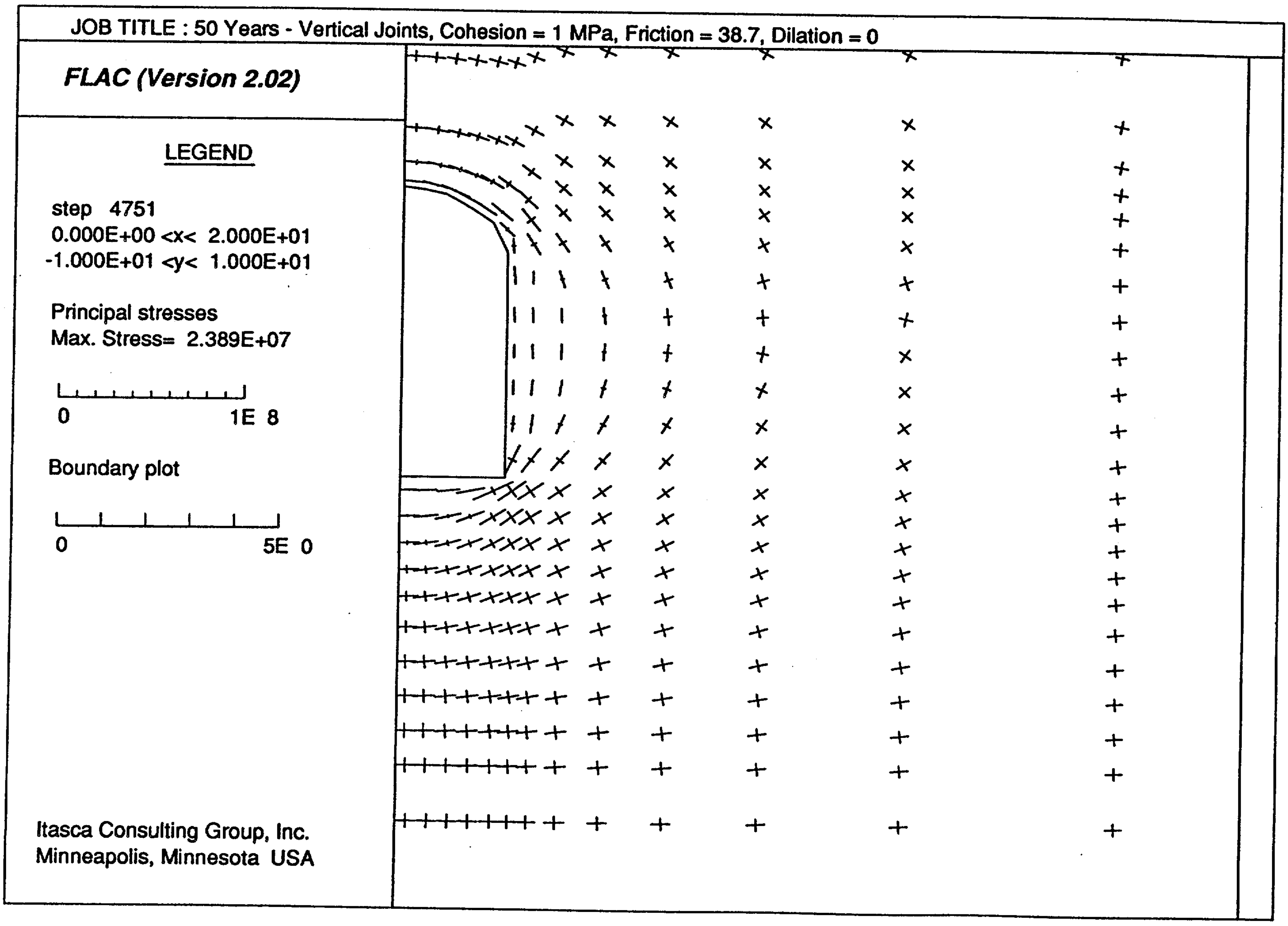


Fig. 77 FLAC Principal Stresses for 50 Years (Vertical Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

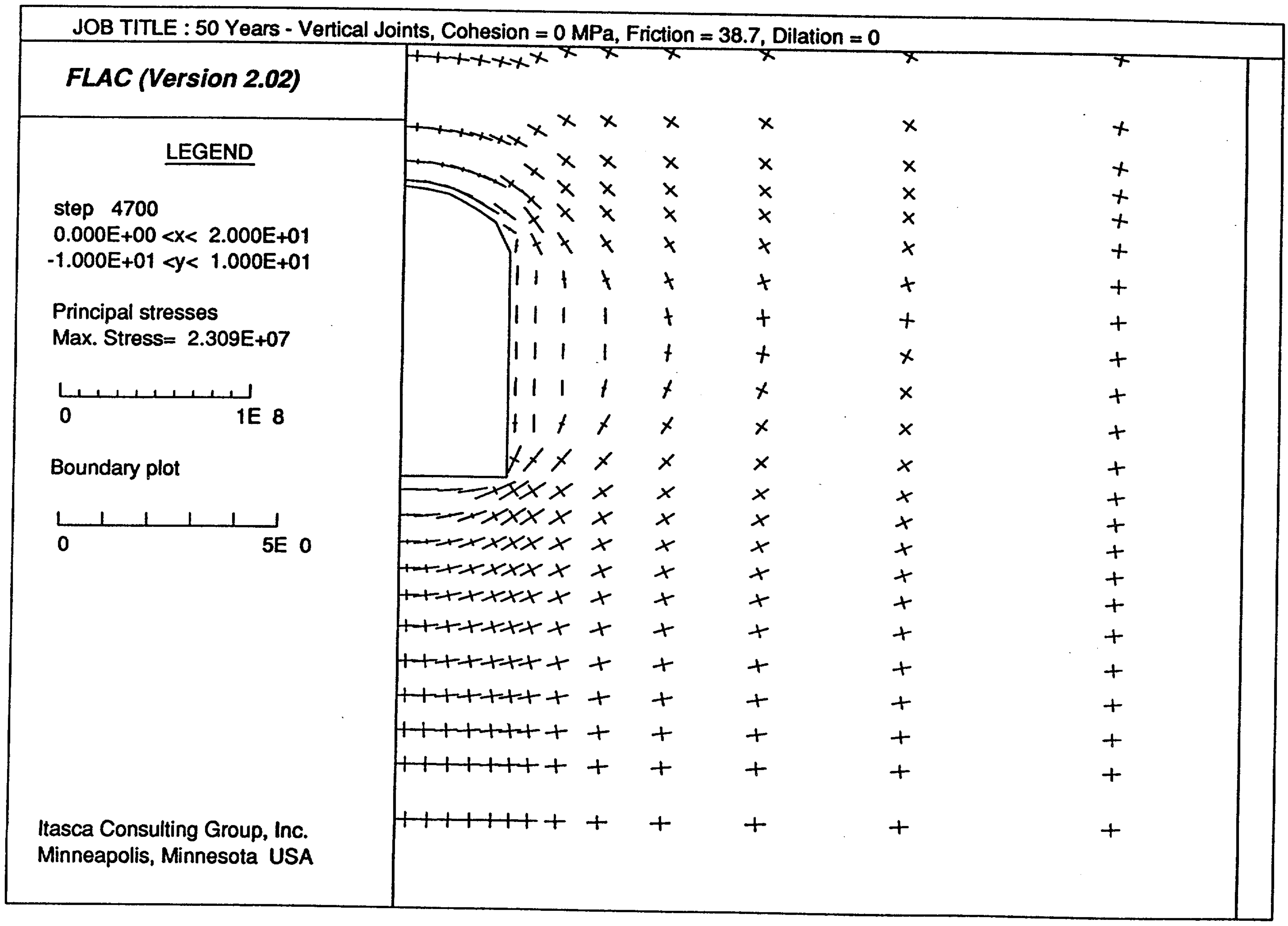


Fig. 78 FLAC Principal Stresses for 50 Years (Vertical Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

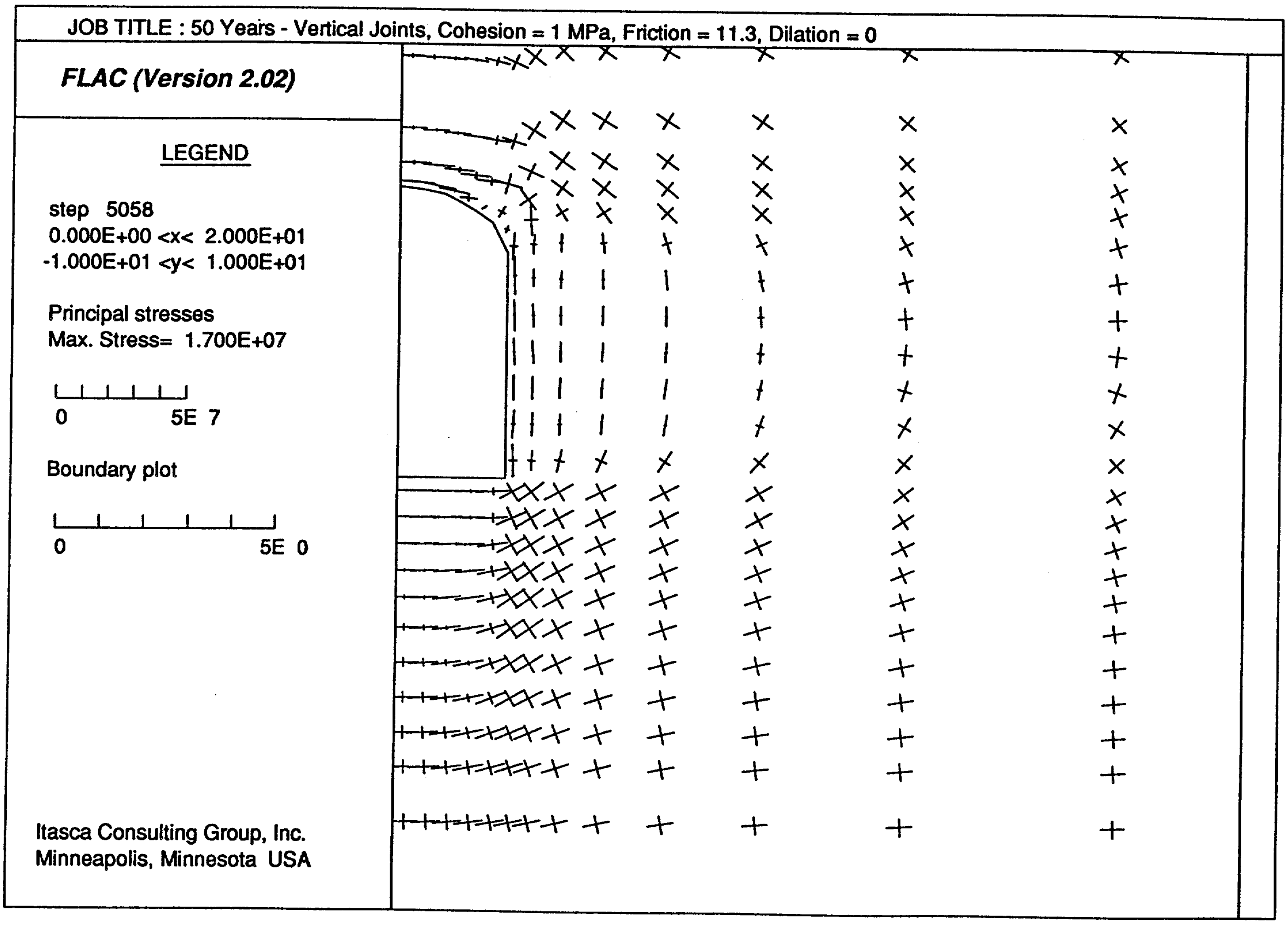


Fig. 79 FLAC Principal Stresses for 50 Years (Vertical Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

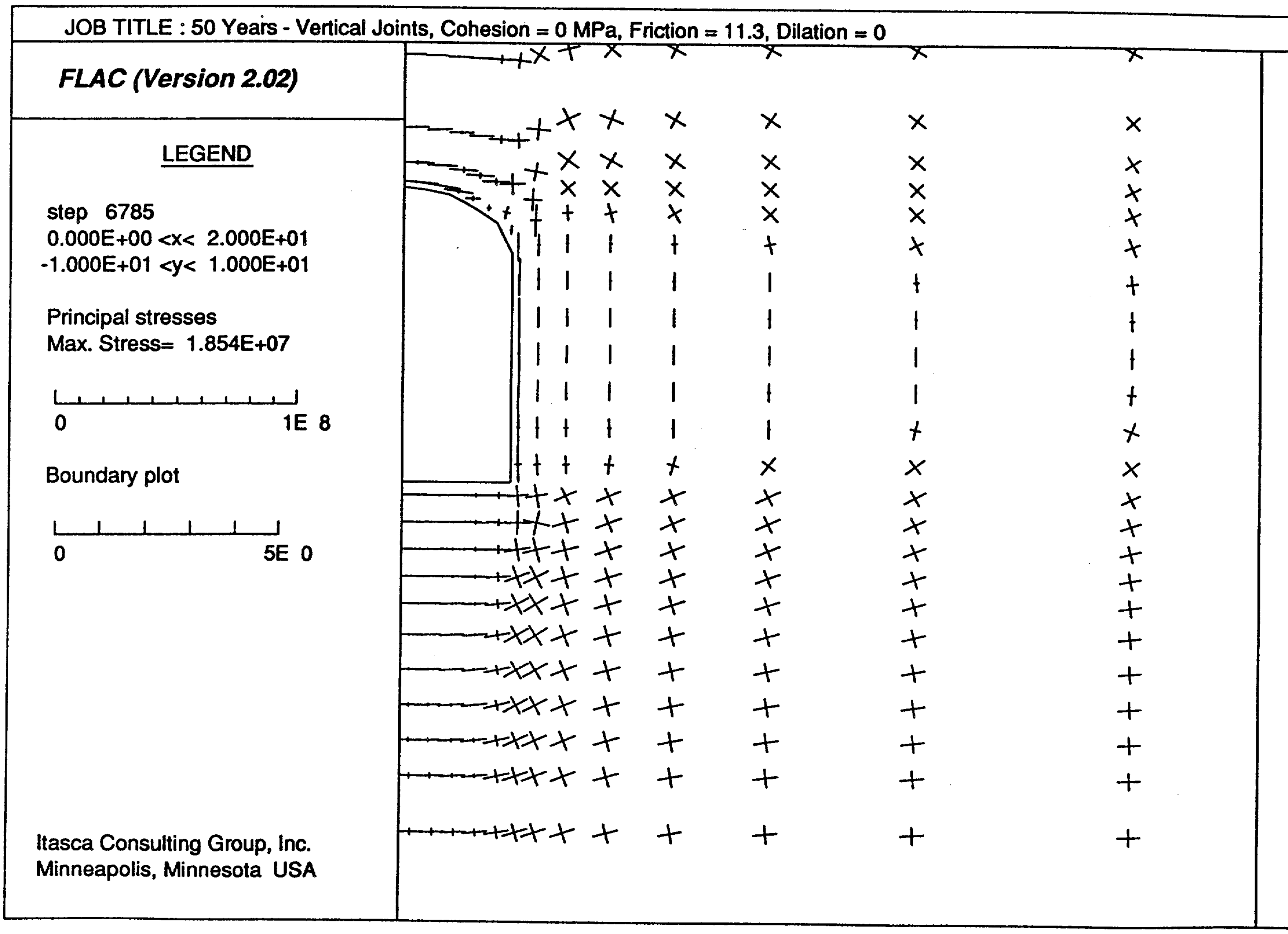


Fig. 80 FLAC Principal Stresses for 50 Years (Vertical Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

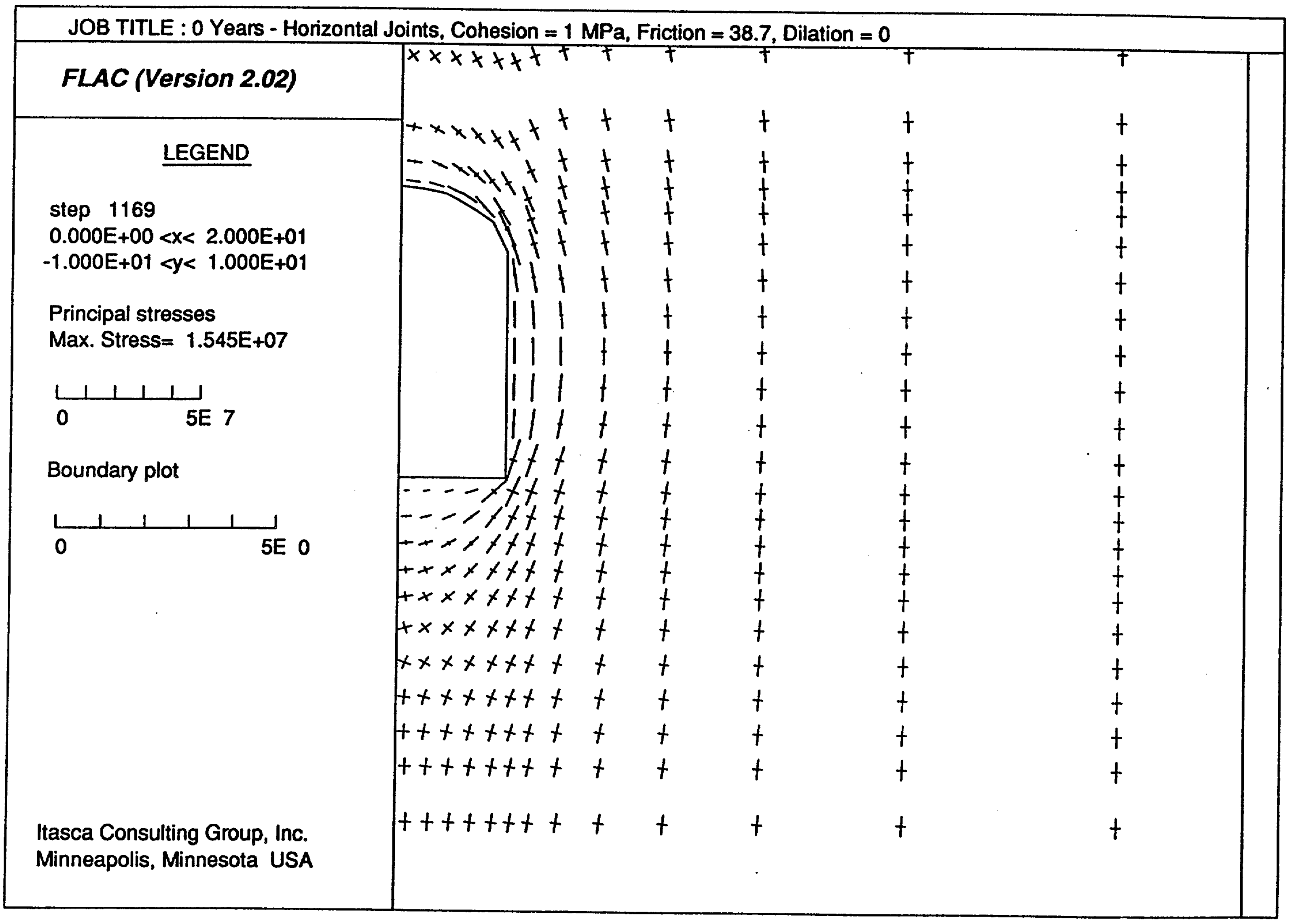


Fig. 81 FLAC Principal Stresses for 0 Years (Horizontal Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

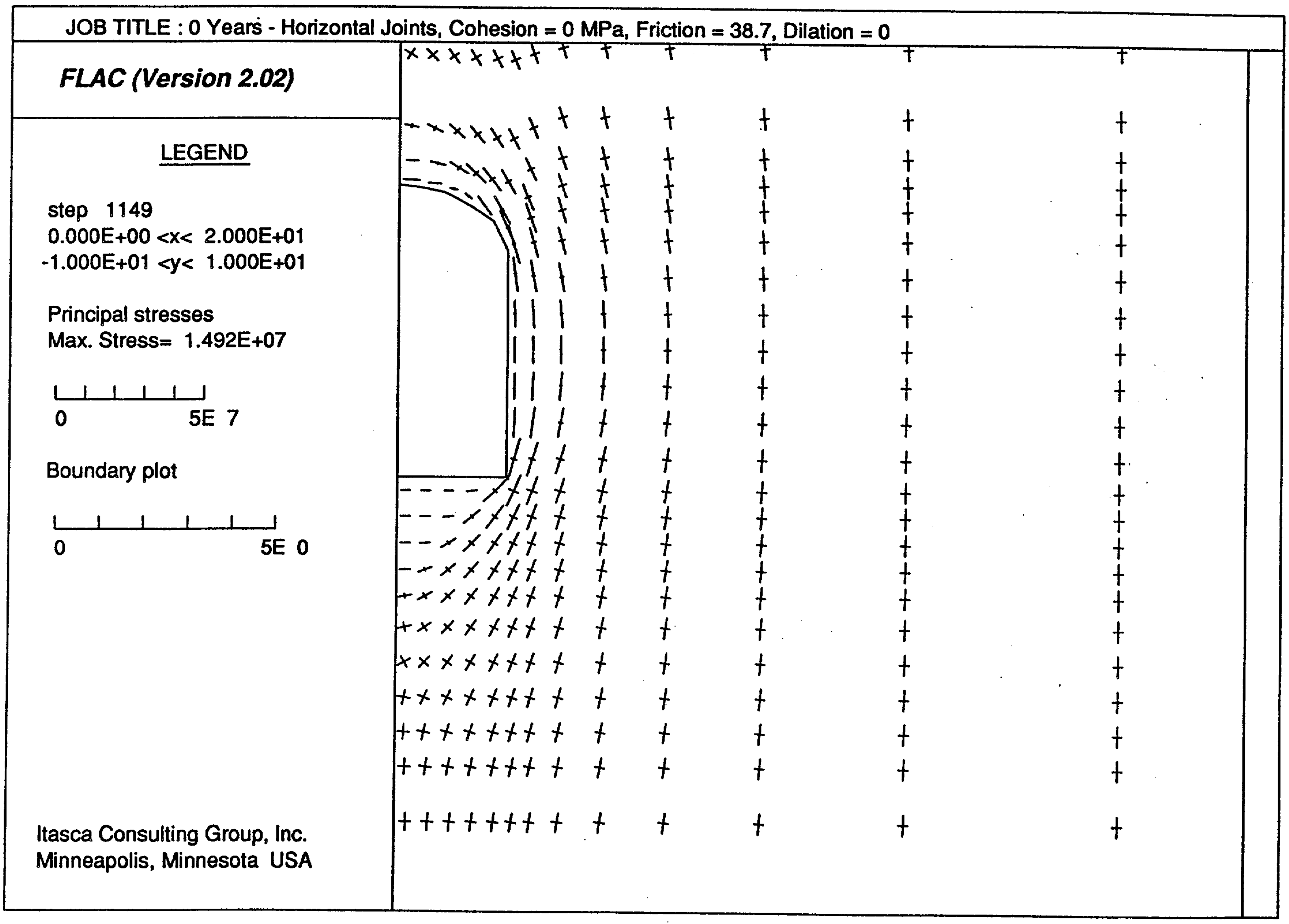


Fig. 82 FLAC Principal Stresses for 0 Years (Horizontal Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

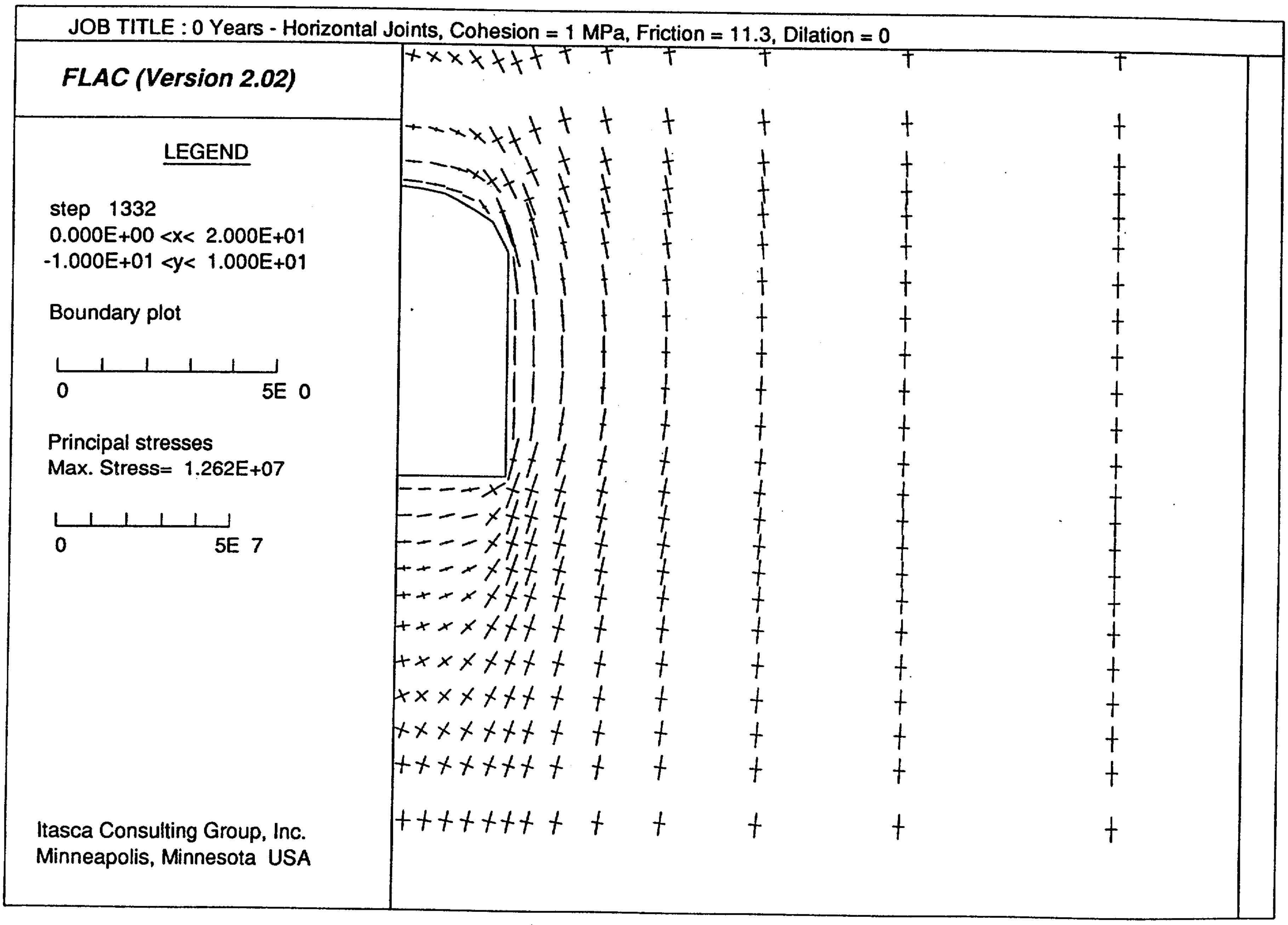


Fig. 83 FLAC Principal Stresses for 0 Years (Horizontal Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

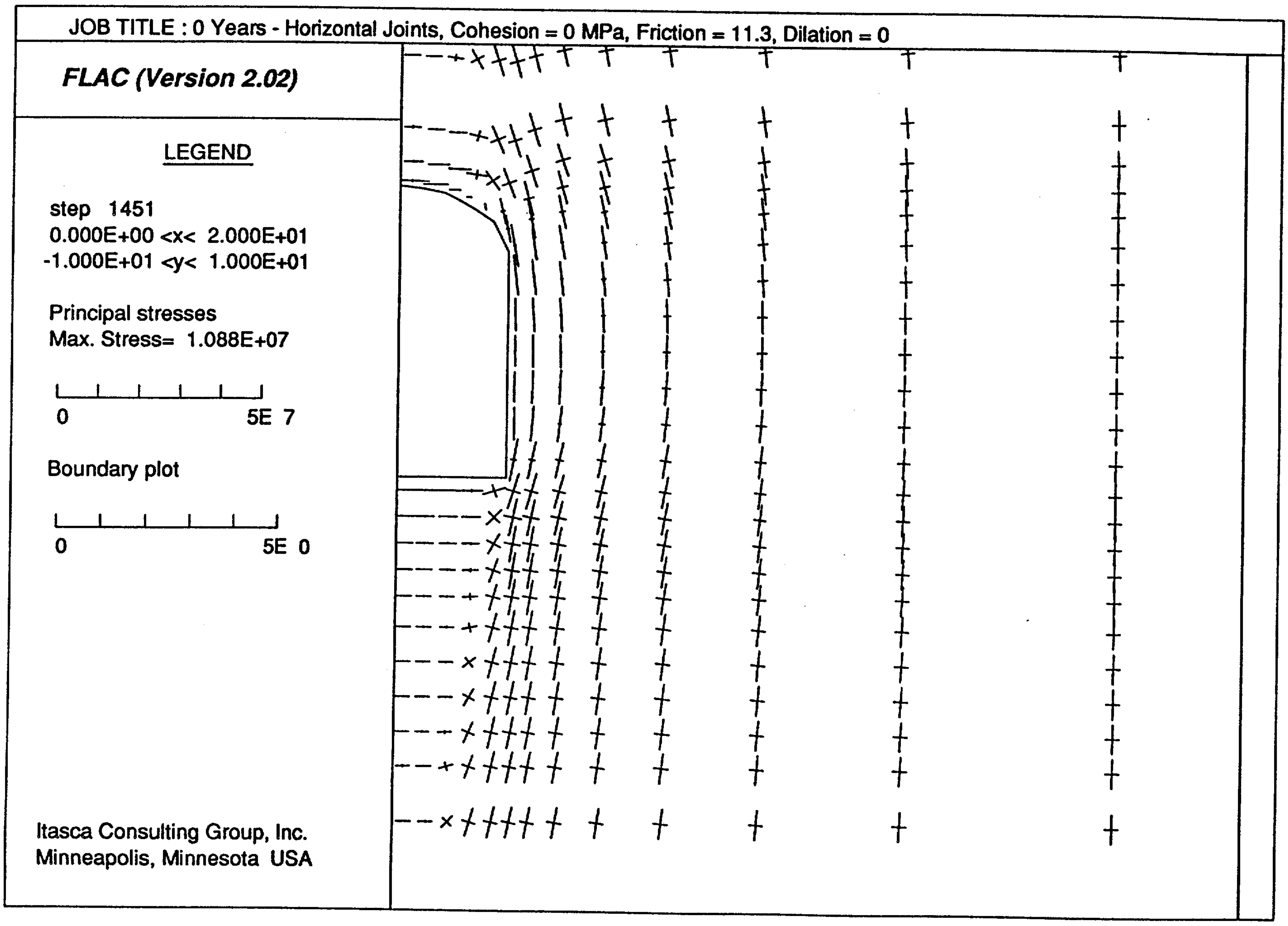


Fig. 84 FLAC Principal Stresses for 0 Years (Horizontal Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

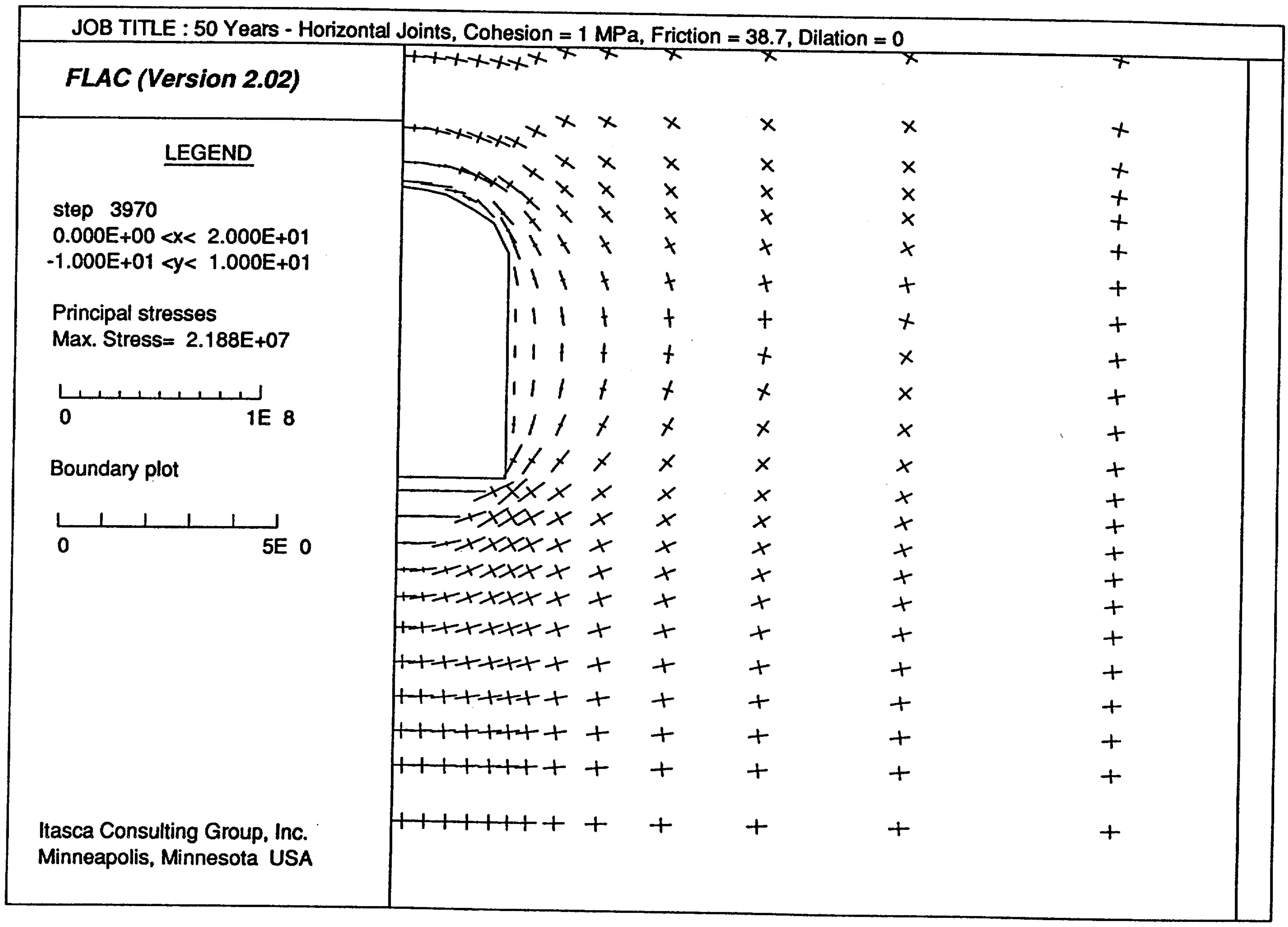


Fig. 85 FLAC Principal Stresses for 50 Years (Horizontal Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

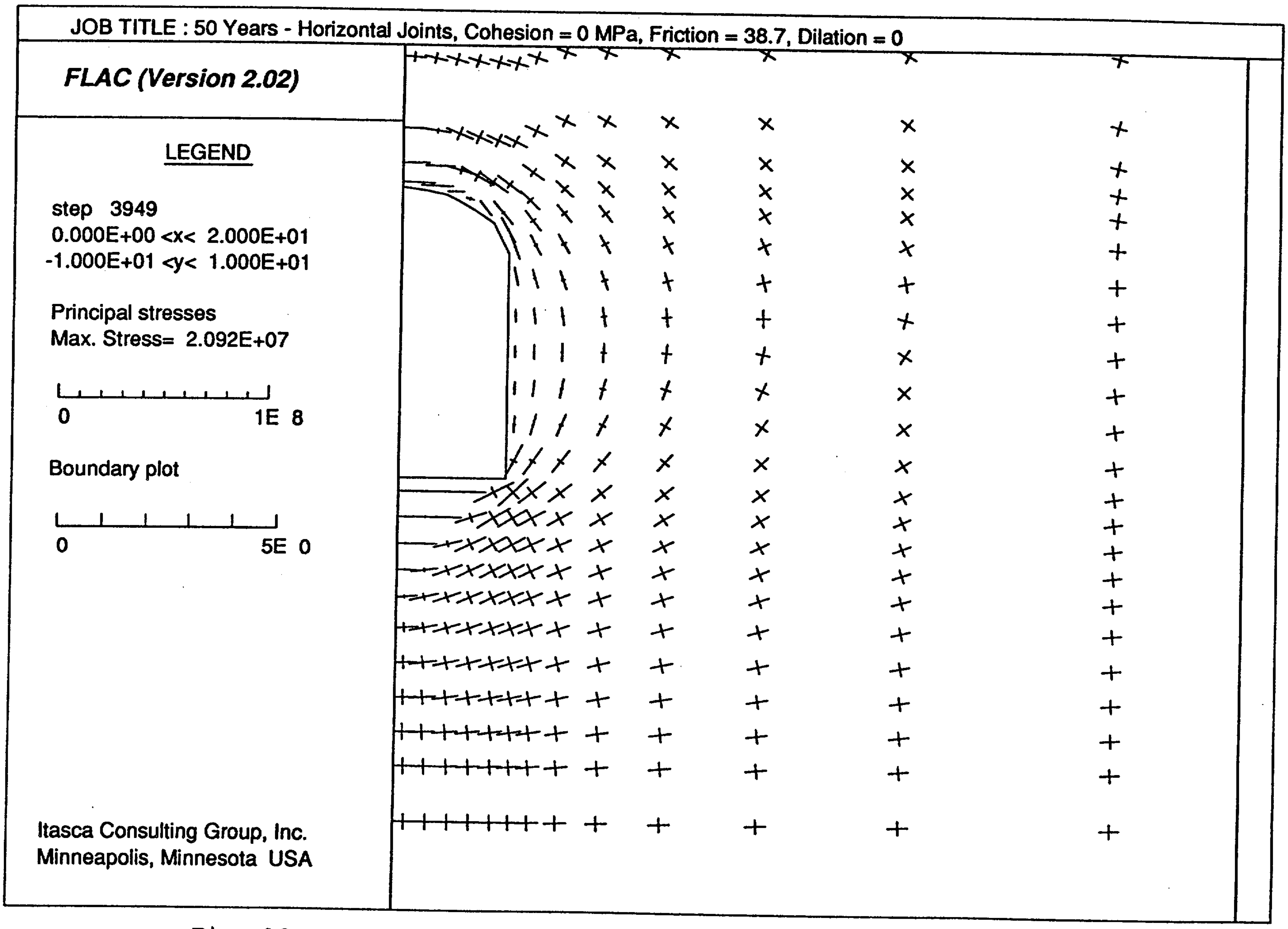


Fig. 86 FLAC Principal Stresses for 50 Years (Horizontal Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

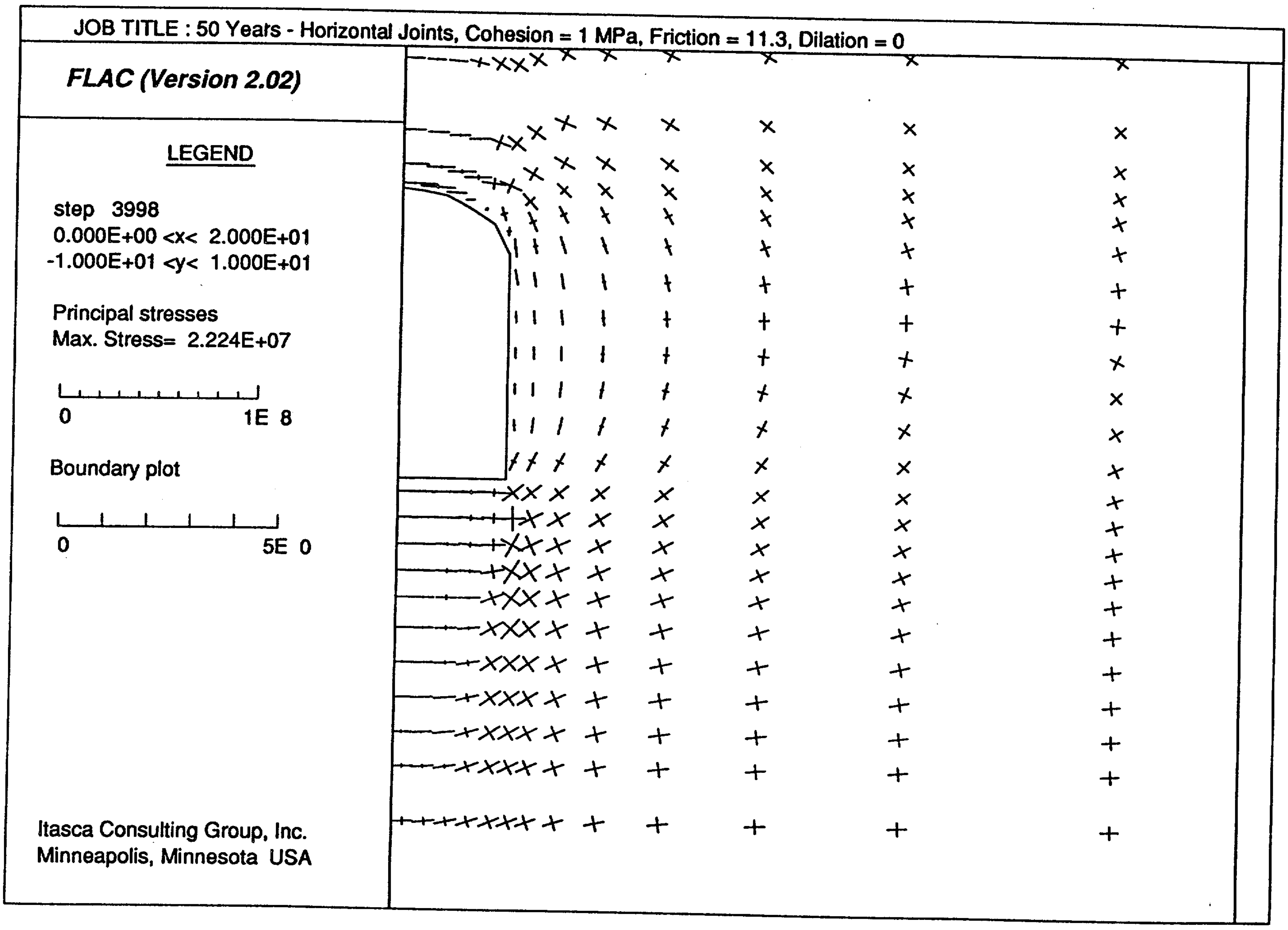


Fig. 87 FLAC Principal Stresses for 50 Years (Horizontal Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

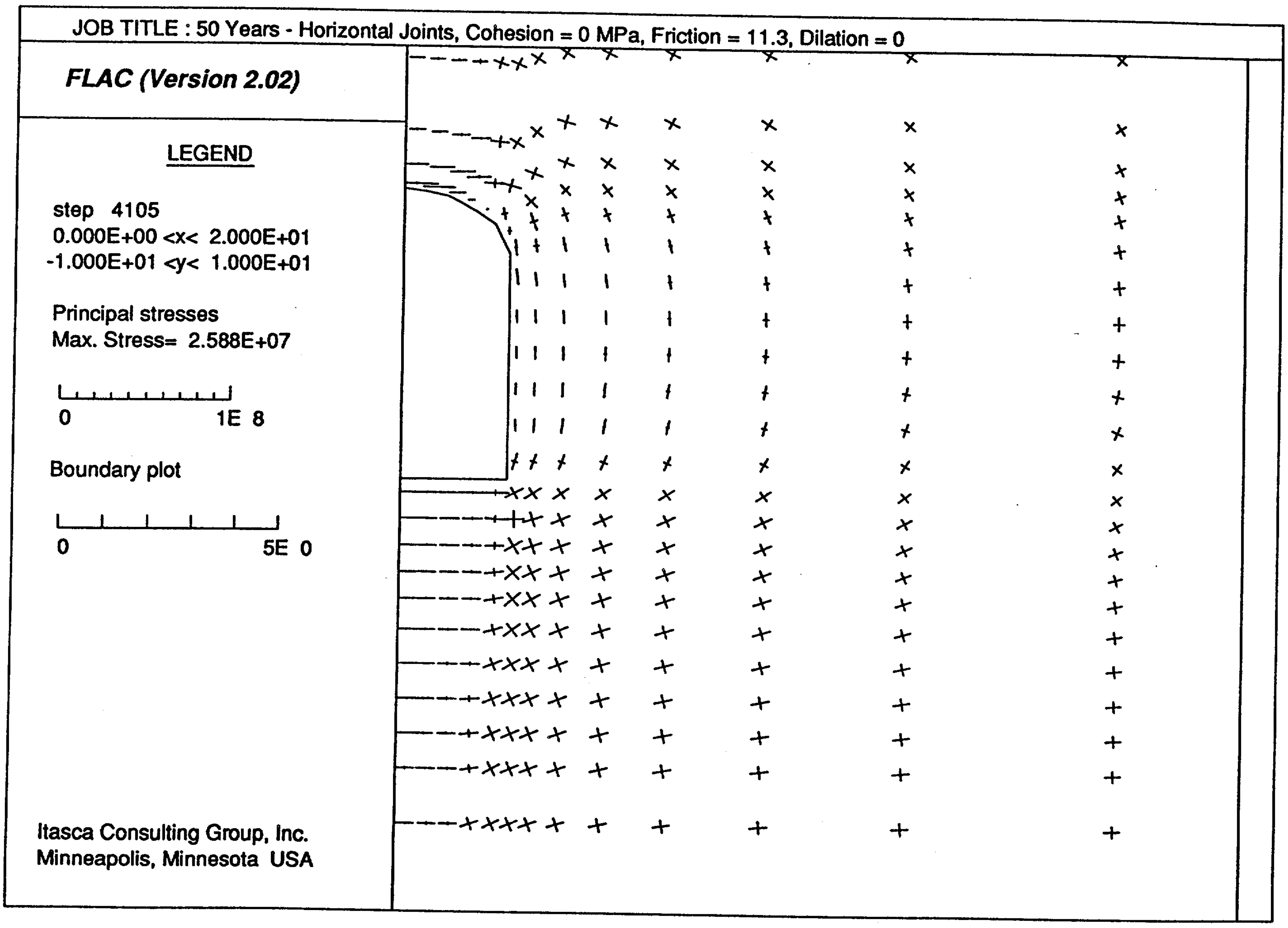


Fig. 88 FLAC Principal Stresses for 50 Years (Horizontal Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

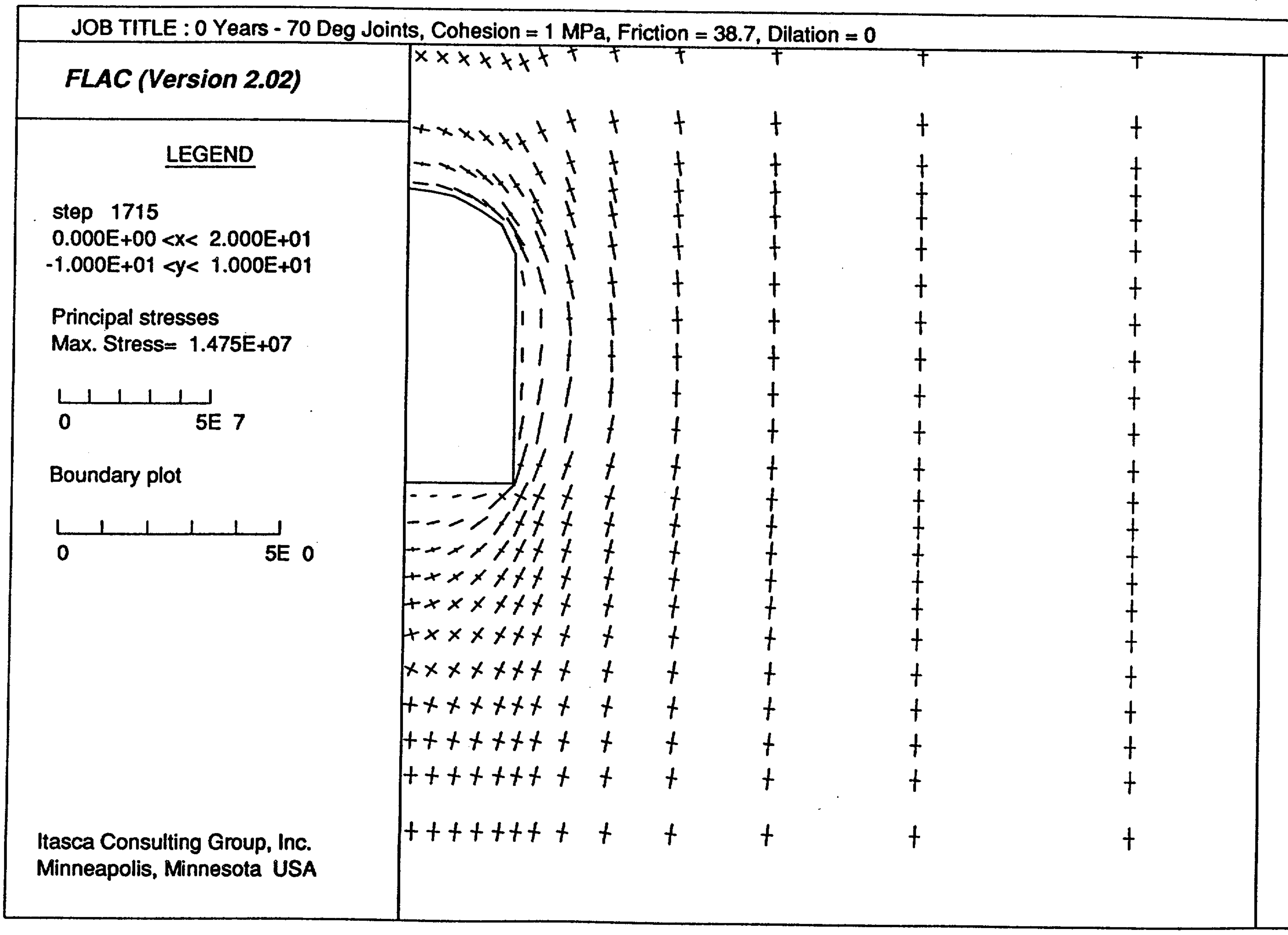


Fig. 89 FLAC Principal Stresses for 0 Years (70 Degree Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

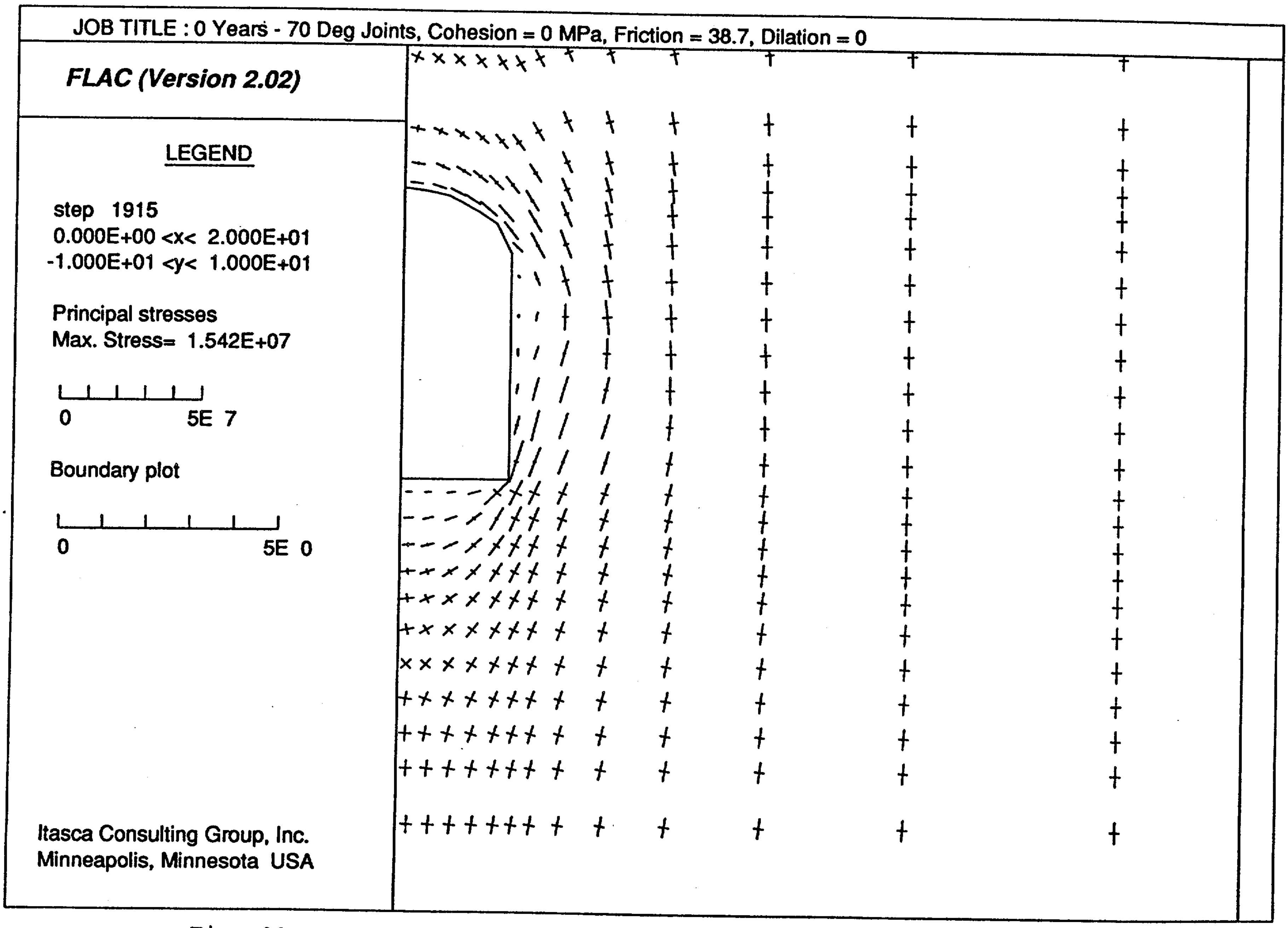


Fig. 90 FLAC Principal Stresses for 0 Years (70 Degree Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

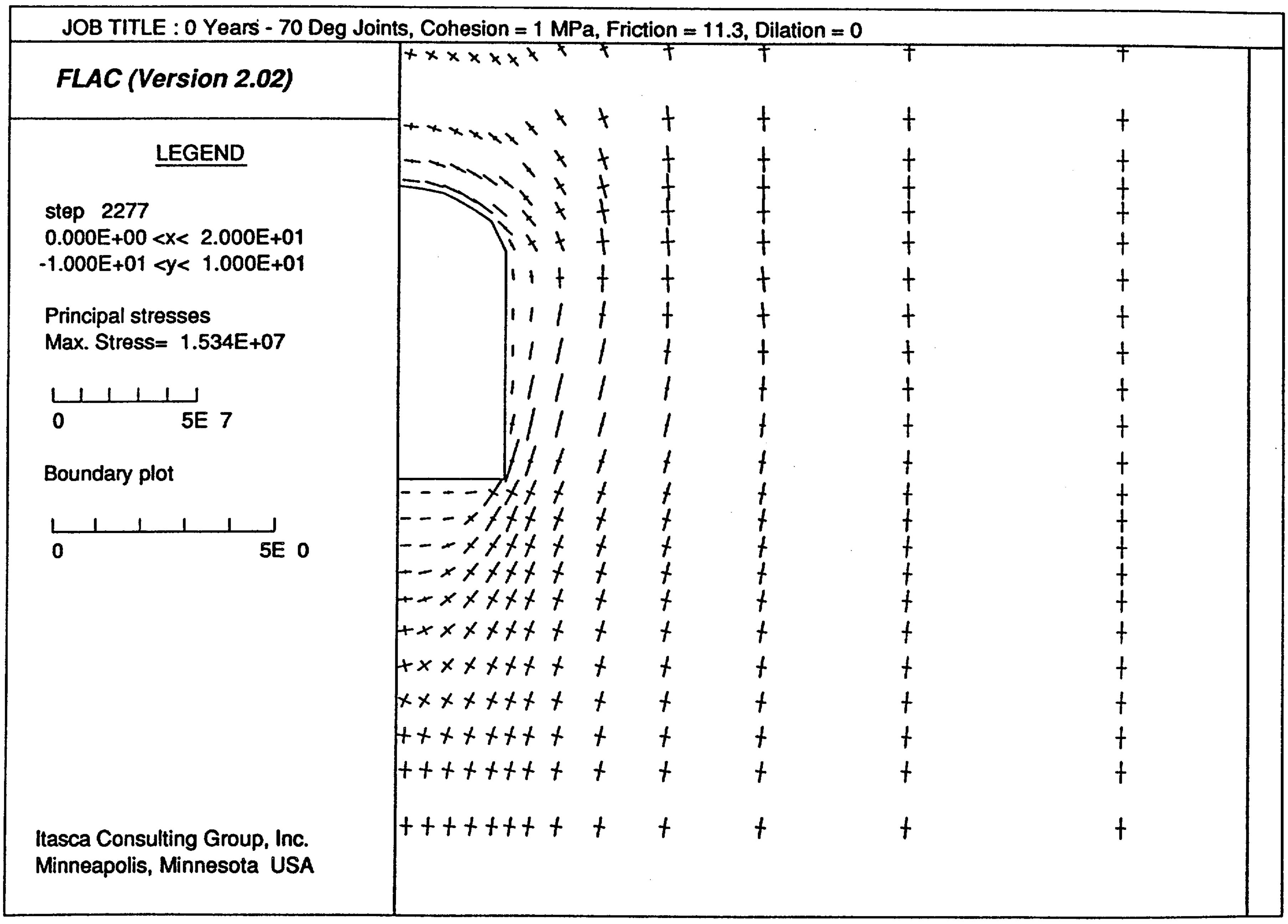


Fig. 91 FLAC Principal Stresses for 0 Years (70 Degree Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

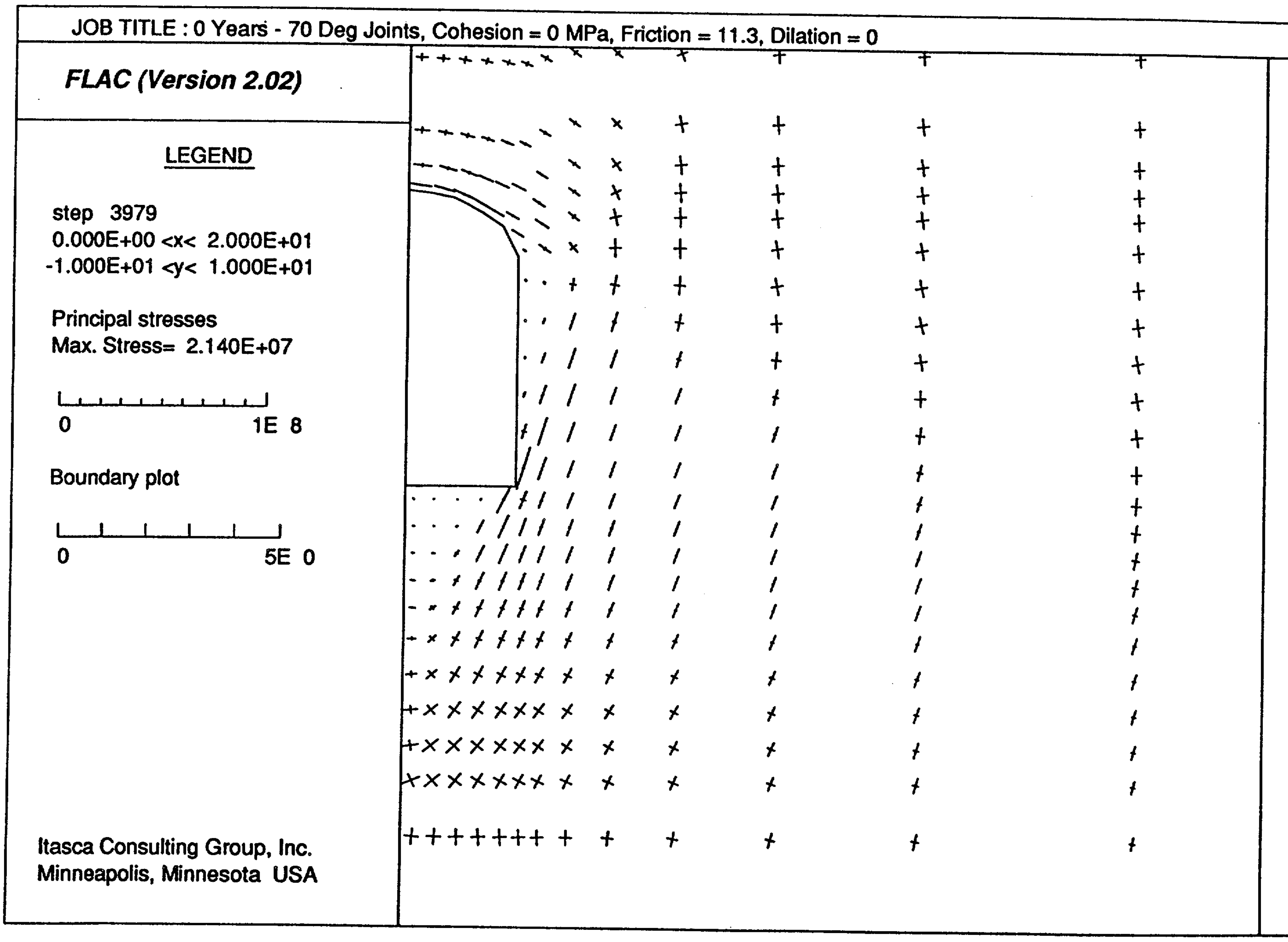


Fig. 92 FLAC Principal Stresses for 0 Years (70 Degree Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

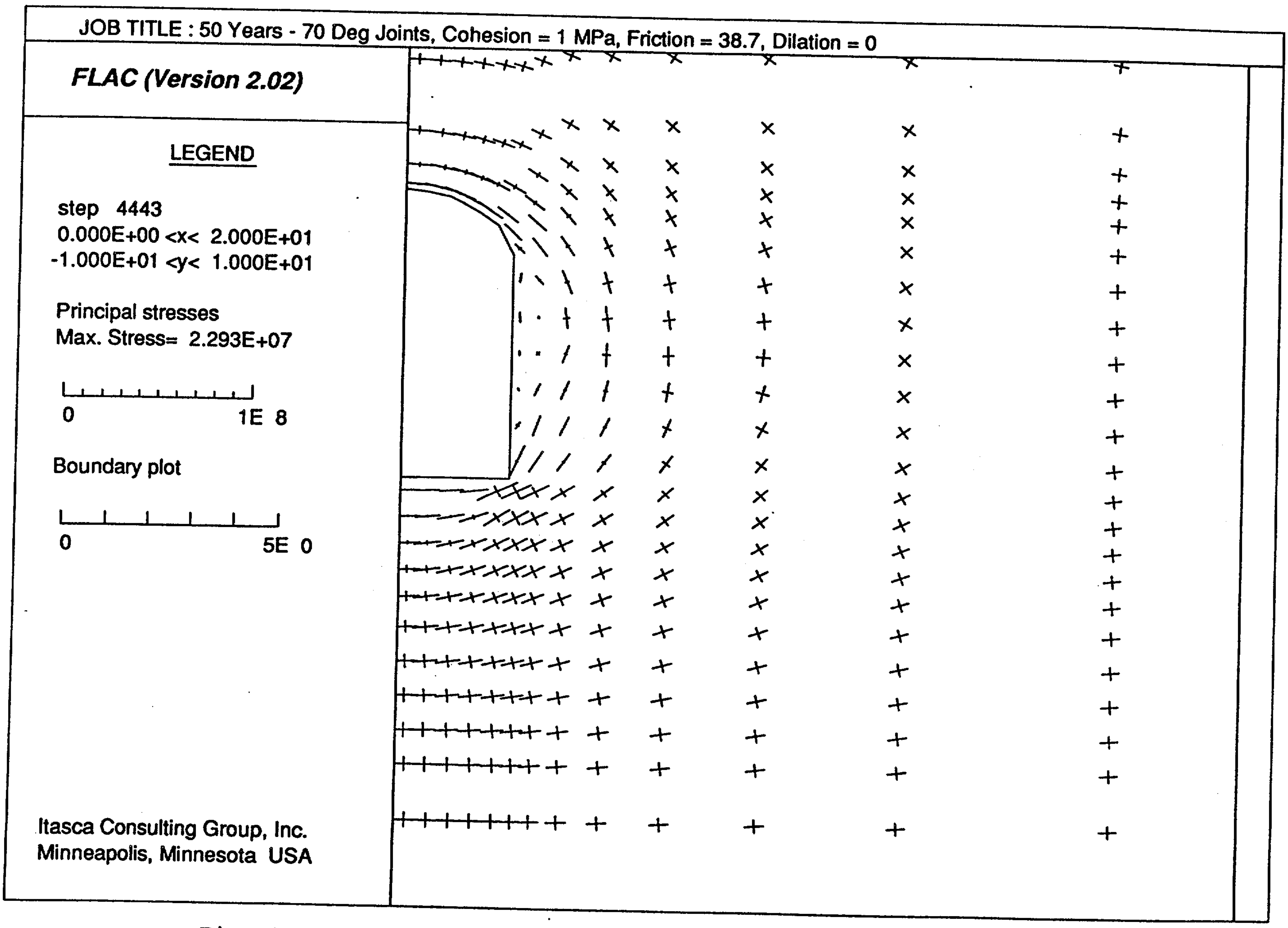


Fig. 93 FLAC Principal Stresses for 50 Years (70 Degree Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0)

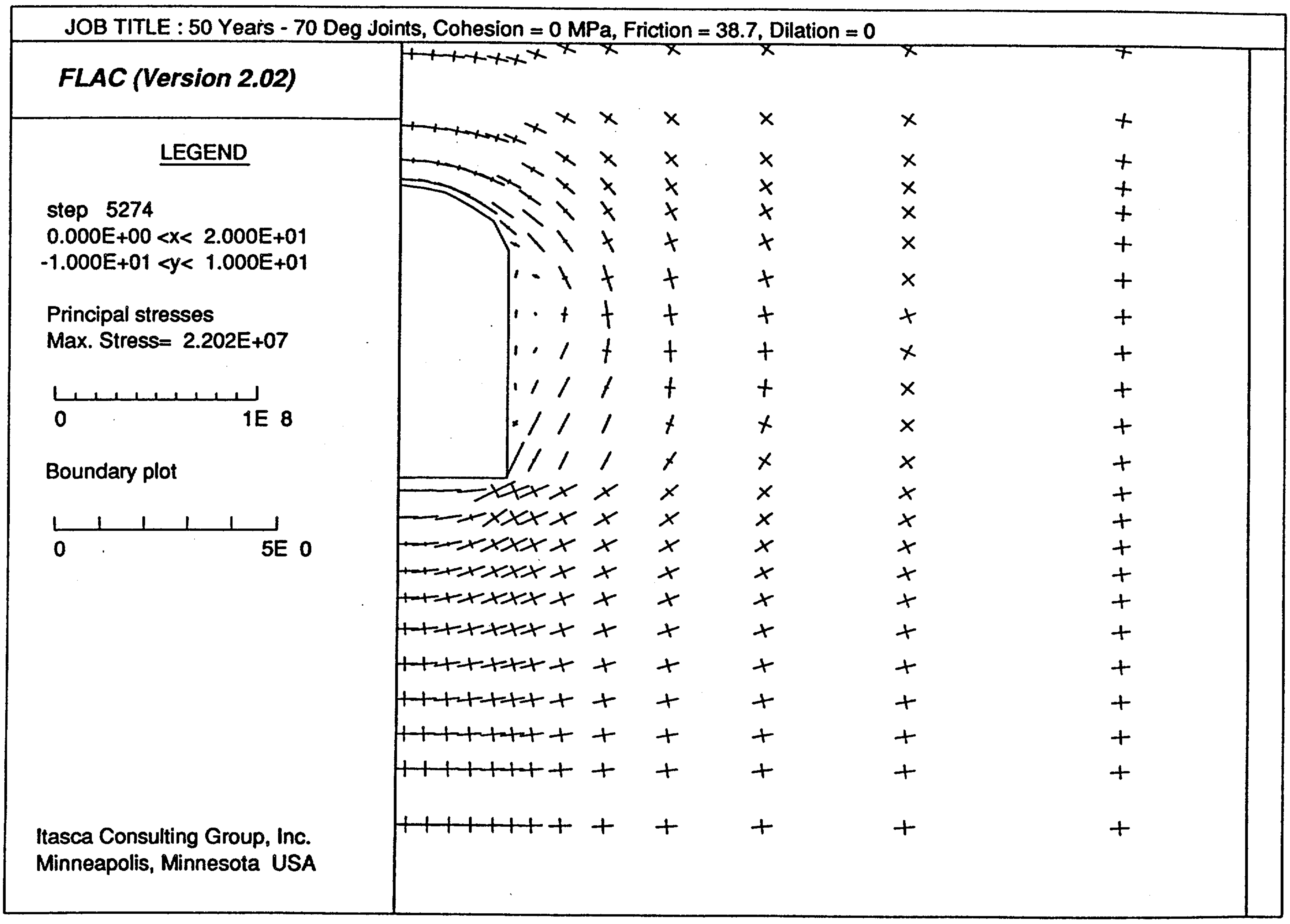


Fig. 94 FLAC Principal Stresses for 50 Years (70 Degree Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0)

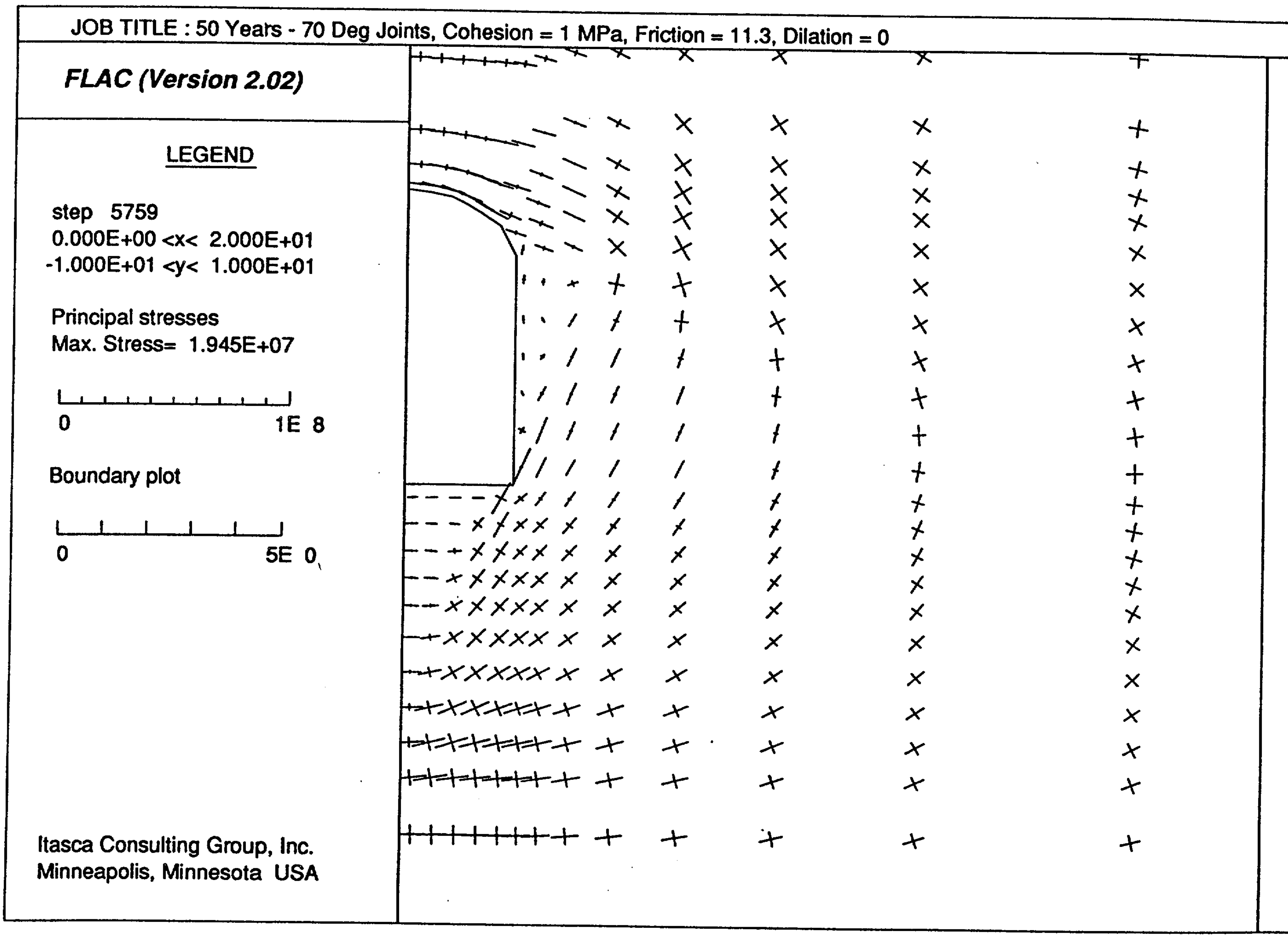


Fig. 95 FLAC Principal Stresses for 50 Years (70 Degree Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0)

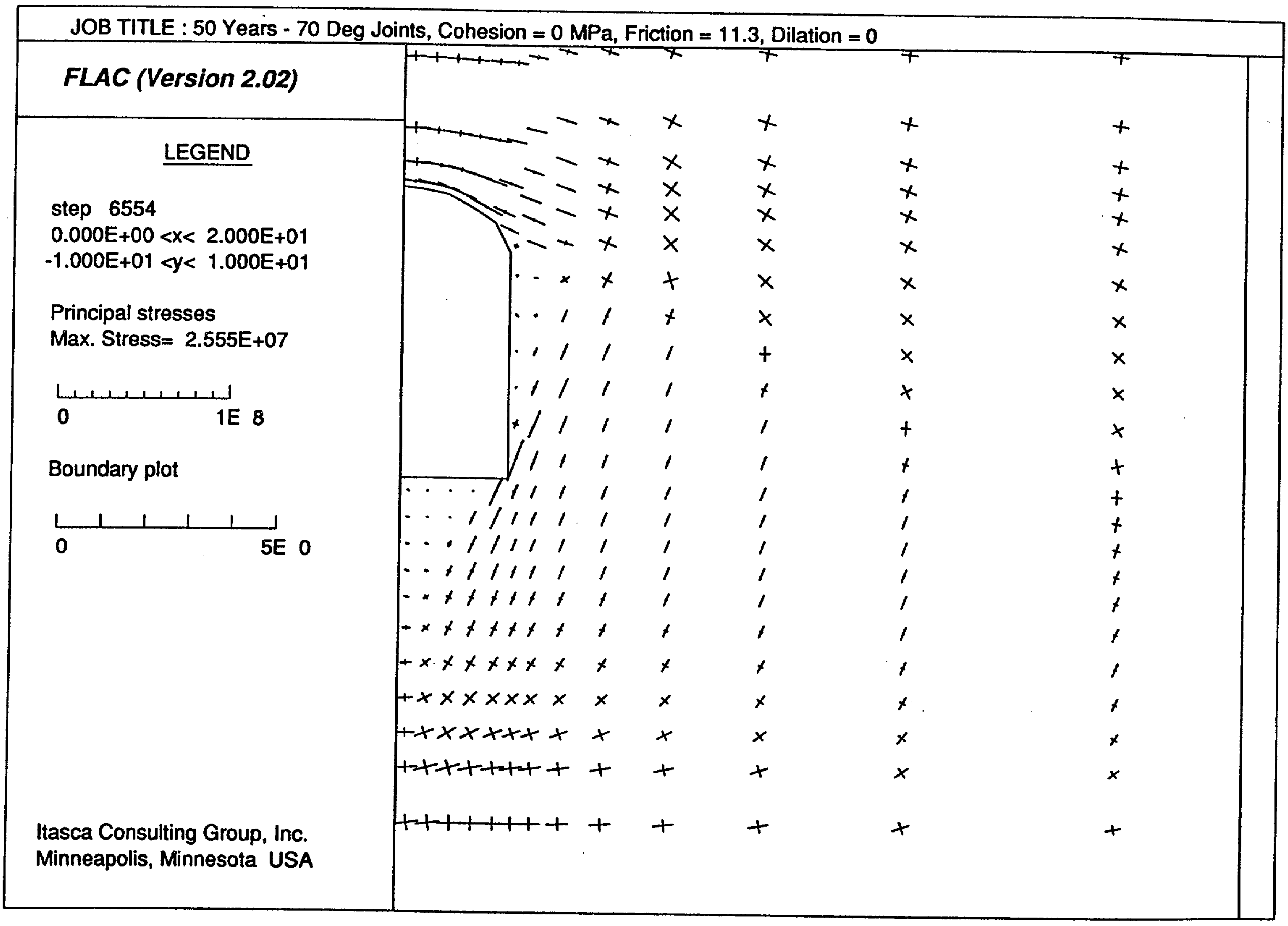


Fig. 96 FLAC Principal Stresses for 50 Years (70 Degree Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0)

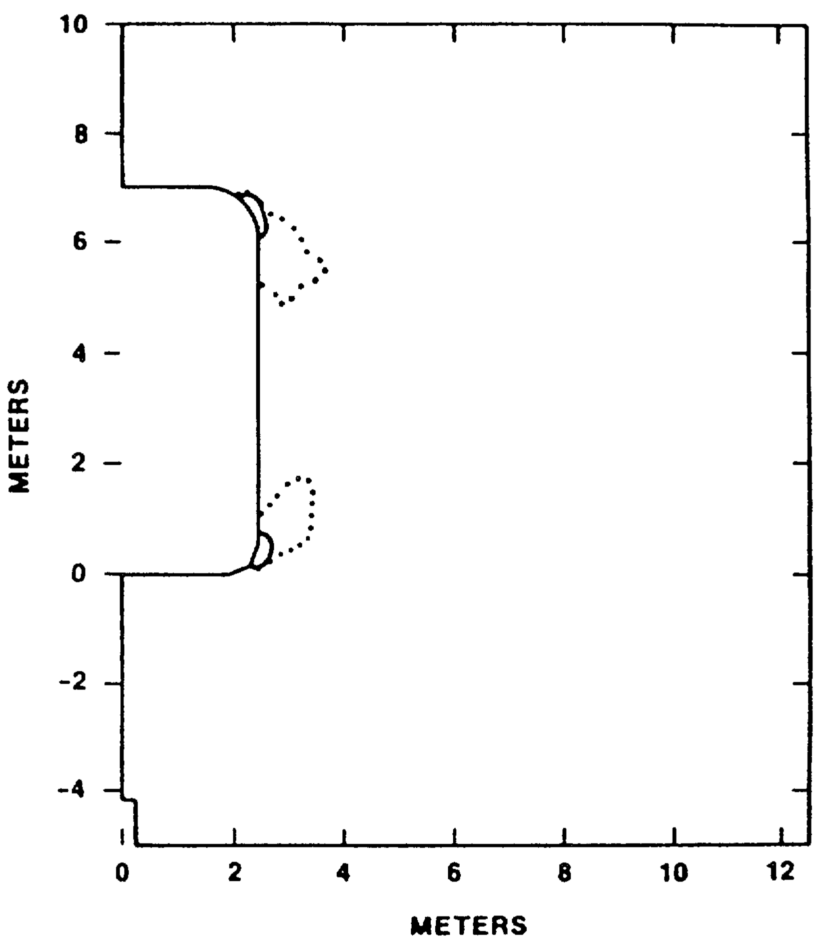


Fig. 97 Joint Movement for Topopah Spring at Excavation. (solid line = average properties; dotted line = limit properties) [Johnstone et al. 1984]

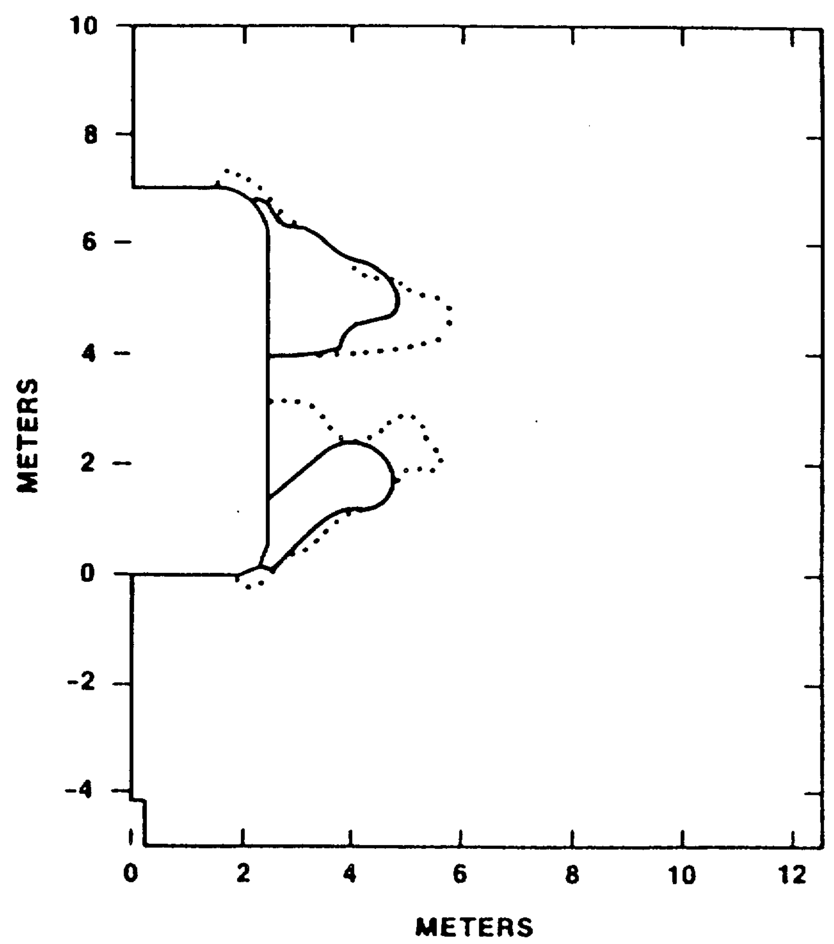


Fig. 98 Joint Movement for Topopah Spring to 100 Years. (solid line = average properties; dotted line = limit properties) [Johnstone et al. 1984]

APPENDIX A

CALCULATION OF APPLIED FLUX

APPENDIX A

CALCULATION OF APPLIED FLUX

From Fig. A-1:

Spent fuel	3.0m below drift 4.6m long
DHLW	3.0m below drift 3.0m long
For combined waste	3.0m below drift 4.0m long (assumed)
Emplacement Drift	38.4m centers 213.4m long 25.9m offset from end

$$38.4 \times 213.4 = 8194.5\text{m}^2 \text{ tributary area} \quad (1)$$

Average heat load 14.1 w/m^2

w/m of drift (corrected for offsets)

$$\frac{14.1\ w/m^2 \times 8194.5^2 m}{(213.4m - (2 \times 25.9m))} = 715\ w/m \quad (2)$$

Heat smeared over 4m length

$$715/4.0 = 178.4\ w \quad (3)$$

Splitting heat according to Peters (1980)

$$0.54 \times 178.4 = 96.34\ w \quad (4)$$

$$0.46 \times 178.4 = 41.03\ w \quad (5)$$

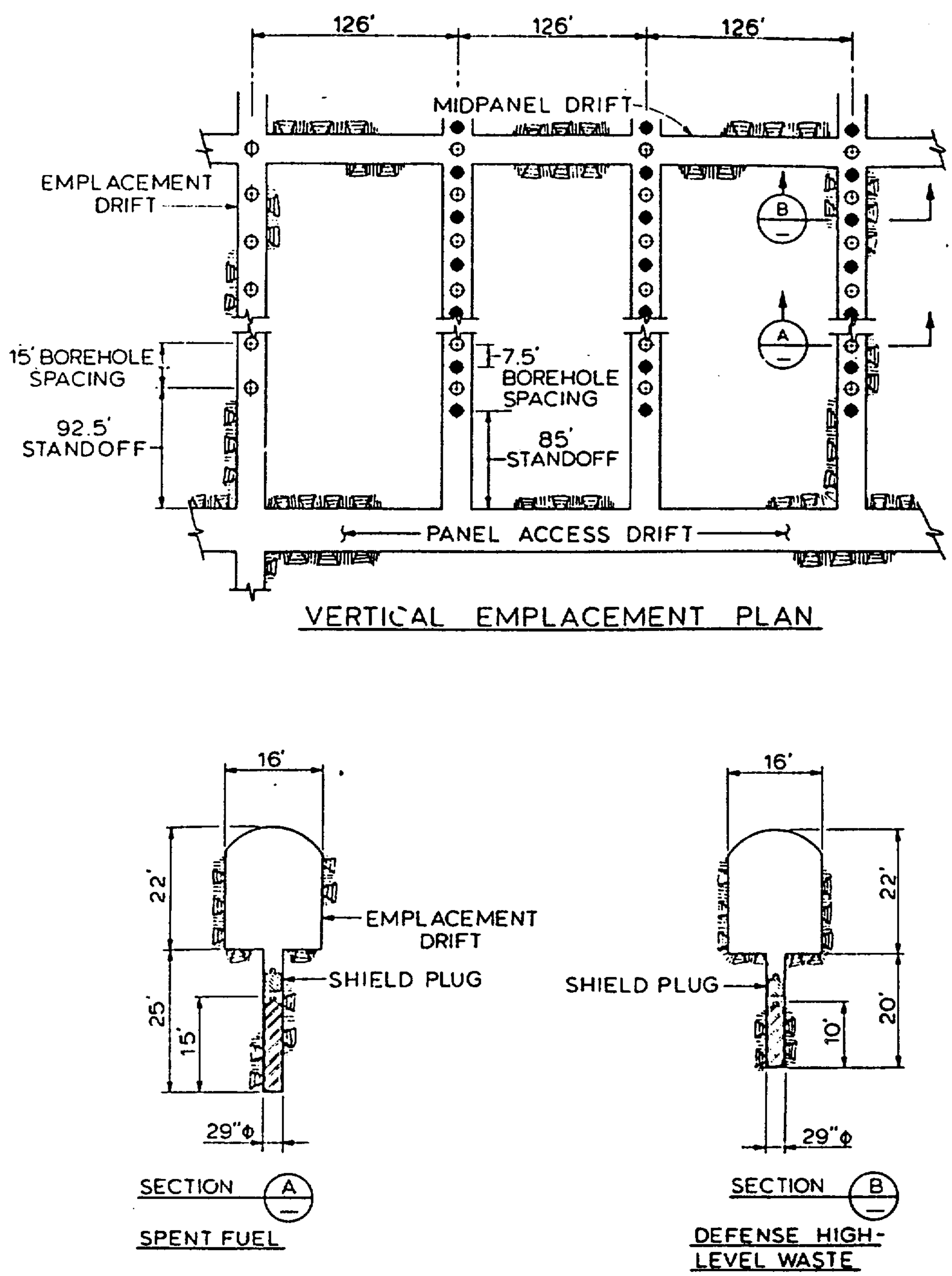


Fig. A-1 Vertical Emplacement Concept (SCP-CDR)

APPENDIX B

FLAC INPUT COMMANDS FOR JOINT SENSITIVITY ANALYSIS

```
***********************************************************************
*                                                                     *
*     T H E R M A L / M E C H A N I C A L   A N A L Y S I S           *
*                                                                     *
*  Input file to FLAC for determining the effect of joint parameters  *
*  on the ubiquitous modeling of disposal room stability.             *
*  Vertical emplacement scheme ...                                    *
*  NRC Contract 02-85-002, Task Order No. 005.                        *
*                                                                     *
*  File for generating general grid                                   *
*                                                                     *
*                                                                     *
***********************************************************************
*
*
GR 13,40
MOD UBIQUITOUS ;(ubiquitous joint model)
THMOD ISO      ;(isotropic thermal model)
*
*--- CONSTRUCT THE FINITE DIFFERENCE MESH BY VARIOUS
*--- GEOMETRIC ADJUSTMENTS
GEN 0.,-150. 0.,150. 19.2,150. 19.2,-150.
GEN 0.,0. 0.,6.71 2.44,6.71 2.44,0. I=1,6 J=20,28
GEN 2.44,0. 2.44,6.71 19.2,6.71 19.2,0. R 1.5,1. I=6,14 J=20,28
*
*--- The borehole above the waste container ...
GEN 0.,-3.1 0.,0. .37,0. .37,-3.1 I=1,2 J=15,20
*--- To the right of borehole and under floor ...
GEN .37,-3.1 .37,0. 2.44,0. 2.44,-3.1 I=2,6 J=15,20
*--- The container inside the borehole ...
GEN 0.,-7.10 0.,-3.1 .37,-3.1 .37,-7.10 I=1,2 J=10,15
*--- To the right of the container and under floor ......
GEN .37,-7.10 .37,-3.1 2.44,-3.1 2.44,-7.10 I=2,6 J=10,15
*--- To the right of borehole and under pillar ...
GEN 2.44,-3.10 2.44,0. 19.2,0. 19.2,-3.1 R 1.5,1. I=6,14 J=15,20
GEN 2.44,-7.10 2.44,-3.1 19.2,-3.1 19.2,-7.10 R 1.5,1. I=6,14 J=10,15
*--- Below the container and under pillar ...
GEN 0.,-30. 0.,-7.10 2.44,-7.10 2.44,-30. R 1.,.67 I=1,6 J=5,10
GEN 2.44,-30. 2.44,-7.10 19.2,-7.10 19.2,-30. R 1.5,.67 I=6,14 J=5,10
GEN 0.,-150. 0.,-30. 19.2,-30. 19.2,-150. R 1.,.80 I=1,14 J=1,5
*--- Adjusting the lower part of mesh to achieve better
*    element aspect ratios ...
GEN R 1.2,1. I=1,14 J=5
GEN R 1.05,1. I=1,14 J=4
GEN R 1.,1. I=1,8 J=6
*--- Adjusting the mesh above the disposal room ...
GEN 0.,7. 0.,30. 2.44,30. 2.44,7. R 1.,1.7 I=1,6 J=29,35
GEN 2.44,7. 2.44,30. 19.2,30 19.2,7. R 1.5 1.7 I=6,14 J=29,35
```

```
*--- Adjusting the mesh to the top of the model ...
GEN 0.,30. 0.,150. 19.2,150. 19.2,30. R 1.,1.3 I=1,14 J=35,41
GEN R 1.3,1. I=1,14 J=35
GEN R 1.25,1. I=1,14 J=36
GEN R 1.2,1. I=1,14 J=37
GEN R 1.1,1. I=1,14 J=38
*
*--- Constructing the crown of the room by individual nodal adjustments ...
INI X=2.44 I=6 J=26
INI Y=5.22 I=6 J=26
INI X=2.30 I=6 J=27
INI Y=5.50 I=6 J=27
INI X=2.10 I=6,J=28
INI Y=5.90 I=6 J=28
INI X=1.65 I=5 J=28
INI Y=6.20 I=5 J=28
INI X=1.30 I=4 J=28
INI Y=6.40 I=4 J=28
INI X=1.00 I=3 J=28
INI Y=6.55 I=3 J=28
INI X=0.50 I=2 J=28
INI Y=6.65 I=2 J=28
INI X=2.50 I=7 J=28
INI Y=6.00 I=7 J=28
INI Y=6.43 I=8 J=28
INI Y=5.60 I=7 J=27
INI Y=5.15 I=7 J=26
*
*--- Second row of nodal points above crown ...
INI X=0.55 I=2 J=29
INI Y=6.95 I=2 J=29
INI X=1.10 I=3 J=29
INI Y=6.85 I=3 J=29
INI X=1.45 I=4 J=29
INI Y=6.70 I=4,J=29
INI X=1.75 I=5 J=29
INI Y=6.55 I=5 J=29
INI X=2.10 I=6 J=29
INI Y=6.35 I=6 J=29
INI X=2.50 I=7 J=29
INI Y=6.35 I=7 J=29
*
```

```
*--- Third row of nodal points above crown ...
INI Y=7.60 I=1 J=30
INI X=0.60 I=2 J=30
INI Y=7.55 I=2,J=30
INI X=1.15 I=3 J=30
INI Y=7.50 I=3,J=30
INI X=1.60 I=4 J=30
INI Y=7.40 I=4 J=30
INI X=2.00 I=5 J=30
INI Y=7.30 I=5 J=30
INI X=2.40 I=6 J=30
INI Y=7.20 I=6 J=30
INI X=2.75 I=7 J=30
INI Y=7.30 I=7 J=30
*
*--- Forth row of nodal points above crown ...
GEN LINE 0.,8.6  2.78,8.3
*
*--- Some additional mesh adjustments ...
GEN LINE 3.291,6.43 19.2,6.43
*
*--- SET KINEMATIC BOUNDARY CONDITIONS ...
*    (The two vertical boundaries are symmetry planes, thus,
*     they are restricted from moving in the horizontal (x)
*     direction.  The bottom horizontal boundary is restricted
*     from moving in the vertical (y) direction.  The top
*     horizontal boundary is a free-to-move pressure boundary.
*     The pressure is acting downward, and is equal to the
*     initial vertical stress.)
FIX Y I=1,14 J=1
FIX X I=1 J=1,41
FIX X I=14 J=1,41
*
*--- DEFINE THE INITIAL STRESS FIELD (MPa)...
*--- REFERENCE:  SCP-CDR CHAP. 2, SEC. 2.3.1.9
*    (The initial vertical stress is about -7 MPa at
*     the disposal room horizon.  The horizontal stress
*     is determined as 0.5 x SYY.)
INI SXX=-3.5E6 ;(Pa)
INI SYY=-7.0E6 ;(Pa)
APPLY PRES=7.0E6 I=1,14 J=41 ;(MPa)
*
*--- SET THE INITIAL TEMPERATURE TO 26 DEG. CELSIUS ...
INI TEMP=26. ;(Degree Celsius)
*
```

```
*--- SET THERMAL BOUNDARY CONDITIONS ...
*--- THE BOUNDARIES ARE BY DEFAULT ADIABATIC (thermally insulated)
*
*--- SET THE CRITERIA FOR AUTOMATIC TERMINATION OF EXECUTION ...
SET F=1E4 ;Out-of-balance force (Newton)
SET CLOCK=120 ;Maximum execution time (minutes)
SET STEP=5000 ;Maximum number of time steps
*
*--- EXCAVATE THE DISPOSAL ROOM (save results) ...
*
*--- ASSIGN MATERIAL PROPERTIES (REF: SCP-CDR CHAP. 2, SEC. 2.3.1)
*--- USING THE JOINT PROPERTIES AND "ROCK MASS" PROPERTIES.
*--- ALSO USING THE 'DESIGN' VALUES,
*--- TABLES 2-4, 2-6, AND 2-7.
*--- THE ROCK IS CHARACTERIZED AS AN MOHR-COULOMB MATERIAL WITH
*--- UBIQUITOUS JOINTS.
*
*--- Rock Mass:
PROP SHEAR=6.29E9 BULK=8.39E9 COH=22.1E6 ;(Pa)
PROP DENS=2340. ;(Kg/m^3)
PROP FRIC=29.2  ;(degrees)
*
*
*--- THERMAL PROPERTIES OF THE ROCK ...
*    (Ref: SCP-CDR Chap. 2, Sec. 2.3.1.9, Table 2-9)
PROP CON=2.25 ;(W/mK)
PROP SPE=961. ;(J/kgK)
PROP THEX=10.7E-6 ;(1/K)
*
MOD NULL I=1,5 J=20,27
*
*
*--- ASSIGN THE DECAYING HEAT SOURCE WHICH SIMULATES THE
*--- COMMINGLED SF AND DHLW ...
*    (The thermal decay characteristics are from Peters, 1983,
*     SAND-2497.  The initial heat generating power per meter
*     of room length is 713.5 W.  Because of symmetry only half
*     of this power is applied.  Note that the decay coefficients
*     have dimension 1/sec and not 1/year, which is commonly
*     used in the literature ...
*     decay constants for SF are also used for the DHLW.
THAPP FLUX 48.17 -2.46E-10 I=1 J=10,15 ;(COMBINED WASTE FIRST TERM)
THAPP FLUX 41.03 -1.72E-9  I=1 J=10,15 ;(COMBINED WASTE SECOND TERM)
*
```

```
*--- DEFINE NODAL POINTS FOR WHICH TEMP. HISTORIES ARE RECORDED ...
*
THIS NSTEP=10 ;Record results every 10 time steps ...
THIS TEMP I=1 J=20 ;Location at the floor center ...
THIS TEMP I=6 J=23 ;Location at the rib center ...
THIS TEMP I=1 J=28 ;Location at the crown center ...
THIS TEMP I=1 J=12 ;Location at the waste container center ...
*
SAVE FJS_0.SAV
*
*
*
```

```
**********************************************************************
*                                                                    *
*      T H E R M A L / M E C H A N I C A L    A N A L Y S I S        *
*                                                                    *
*  Input file to FLAC for determining the effect of joint parameters *
*  on the ubiquitous modeling of disposal room stability.            *
*  Vertical emplacement scheme ...                                   *
*  NRC Contract 02-85-002, Task Order No. 005.                       *
*                                                                    *
*  File for Vertical jointing                                        *
*  Cohesion = 1 MPa, Friction = 38.7, Dilation = 0                   *
*                                                                    *
**********************************************************************
*
*
REST FJS_0.SAV
*
*--- Rock Joints:
PROP JCOH=1.0E6 ;(Pa)
PROP JFRIC=38.7 JANG=90. ;(degrees)
*
*
TITLE
0 Years - Vertical Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0
*
SOLVE
*
SAVE FJS_M0A.SAV
*
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
*--- SWITCH TO IMPLICIT SOLUTION
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time  step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
```

```
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TITLE
50 Years - Vertical Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0
*
*
SAVE FJS_M50A.SAV
*
*
```

```
***********************************************************************
*                                                                     *
*      T H E R M A L / M E C H A N I C A L    A N A L Y S I S        *
*                                                                     *
*  Input file to FLAC for determining the effect of joint parameters *
*  on the ubiquitous modeling of disposal room stability.            *
*  Vertical emplacement scheme ...                                    *
*  NRC Contract 02-85-002, Task Order No. 005.                       *
*                                                                     *
*  File for Vertical jointing                                         *
*  Cohesion = 1 MPa, Friction = 11.3, Dilation = 0                   *
*                                                                     *
***********************************************************************
*
*
REST FJS_0.SAV
*
*--- Rock Joints:
PROP JCOH=1.0E6 ;(Pa)
PROP JFRIC=11.3 JANG=90. ;(degrees)
*
TITLE
0 Years - Vertical Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0
*
*
SOLVE
*
SAVE FJS_M0D.SAV
*
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
*--- SWITCH TO IMPLICIT SOLUTION
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time  step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TITLE
50 Years - Vertical Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0
*
*
SAVE FJS_M50D.SAV
*
*
*
```

```
*********************************************************************
*                                                                   *
*     T H E R M A L / M E C H A N I C A L    A N A L Y S I S       *
*                                                                   *
*  Input file to FLAC for determining the effect of joint parameters *
*  on the ubiquitous modeling of disposal room stability.          *
*  Vertical emplacement scheme ...                                  *
*  NRC Contract 02-85-002, Task Order No. 005.                      *
*                                                                   *
*  File for Vertical jointing                                       *
*  Cohesion = 0 MPa, Friction = 38.7, Dilation = 0                  *
*                                                                   *
*********************************************************************
*
*
REST FJS_0.SAV
*
*--- Rock Joints:
PROP JCOH=0.0 ;(Pa)
PROP JFRIC=38.7 JANG=90. ;(degrees)
*
TITLE
0 Years - Vertical Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0
*
*
WIND 0,20 -10,10
*
SOLVE
SAVE FJS_M0E.SAV
*
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
*--- SWITCH TO IMPLICIT SOLUTION
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time  step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TITLE
50 Years - Vertical Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0
*
*
WIND 0,20 -10,10
*
SAVE FJS_M50E.SAV
*
*
*
```

```
***********************************************************************
*                                                                     *
*     T H E R M A L / M E C H A N I C A L   A N A L Y S I S          *
*                                                                     *
*  Input file to FLAC for determining the effect of joint parameters  *
*  on the ubiquitous modeling of disposal room stability.             *
*  Vertical emplacement scheme ...                                    *
*  NRC Contract 02-85-002, Task Order No. 005.                        *
*                                                                     *
*  File for Vertical jointing                                         *
*  Cohesion = 0 MPa, Friction = 11.3, Dilation = 0                    *
*                                                                     *
***********************************************************************
*
*
REST FJS_0.SAV
*
*--- Rock Joints:
PROP JCOH=0 ;(Pa)
PROP JFRIC=11.3 JANG=90. ;(degrees)
*
TITLE
0 Years - Vertical Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0
*
*
WIND 0,20 -10,10
*
SOLVE
SAVE FJS_M0F.SAV
*
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
*--- SWITCH TO IMPLICIT SOLUTION
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time  step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TITLE
50 Years - Vertical Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0
*
*
SAVE FJS_M50F.SAV
*
```

```
*********************************************************************
*                                                                   *
*     T H E R M A L / M E C H A N I C A L   A N A L Y S I S        *
*                                                                   *
*  Input file to FLAC for determining the effect of joint parameters *
*  on the ubiquitous modeling of disposal room stability.           *
*  Vertical emplacement scheme ...                                  *
*  NRC Contract 02-85-002, Task Order No. 005.                      *
*                                                                   *
*  File for horizontal jointing                                     *
*  Cohesion = 1 MPa, Friction = 38.7, Dilation = 0                  *
*                                                                   *
*********************************************************************
*
*
REST FJS_0.SAV
*
*--- Rock Joints:
PROP JCOH=1.0E6 ;(Pa)
PROP JFRIC=38.7 JANG=0. ;(degrees)
*
*
TITLE
0 Years - Horizontal Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0
*
SOLVE
*
SAVE FJS_M0J.SAV
*
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
*--- SWITCH TO IMPLICIT SOLUTION
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time  step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TITLE
50 Years - Horizontal Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0
*
*
SAVE FJS_M50J.SAV
*
*
```

```
************************************************************************
*                                                                      *
*     T H E R M A L / M E C H A N I C A L   A N A L Y S I S            *
*                                                                      *
*  Input file to FLAC for determining the effect of joint parameters   *
*  on the ubiquitous modeling of disposal room stability.              *
*  Vertical emplacement scheme ...                                     *
*  NRC Contract 02-85-002, Task Order No. 005.                         *
*                                                                      *
*  File for horizontal jointing                                        *
*  Cohesion = 1 MPa, Friction = 11.3, Dilation = 0                     *
*                                                                      *
************************************************************************
*
*
REST FJS_0.SAV
*
*--- Rock Joints:
PROP JCOH=1.0E6 ;(Pa)
PROP JFRIC=11.3 JANG=0. ;(degrees)
*
TITLE
0 Years - Horizontal Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0
*
*
SOLVE
*
SAVE FJS_M0K.SAV
*
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
*--- SWITCH TO IMPLICIT SOLUTION
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time  step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TITLE
50 Years - Horizontal Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0
*
*
SAVE FJS_M50K.SAV
*
*
*
```

```
***********************************************************************
*                                                                     *
*     T H E R M A L / M E C H A N I C A L     A N A L Y S I S         *
*                                                                     *
*  Input file to FLAC for determining the effect of joint parameters  *
*  on the ubiquitous modeling of disposal room stability.             *
*  Vertical emplacement scheme ...                                    *
*  NRC Contract 02-85-002, Task Order No. 005.                        *
*                                                                     *
*  File for horizontal jointing                                       *
*  Cohesion = 0 MPa, Friction = 38.7, Dilation = 0                    *
*                                                                     *
***********************************************************************
*
*
REST FJS_0.SAV
*
*--- Rock Joints:
PROP JCOH=0.0 ;(Pa)
PROP JFRIC=38.7 JANG=0. ;(degrees)
*
TITLE
0 Years - Horizontal Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0
*
*
WIND 0,20 -10,10
*
SOLVE
SAVE FJS_M0L.SAV
*
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
*--- SWITCH TO IMPLICIT SOLUTION
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time  step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TITLE
50 Years - Horizontal Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0
*
*
WIND 0,20 -10,10
*
SAVE FJS_M50L.SAV
*
*
*
```

```
**********************************************************************
*                                                                    *
*      T H E R M A L / M E C H A N I C A L    A N A L Y S I S        *
*                                                                    *
*  Input file to FLAC for determining the effect of joint parameters *
*  on the ubiquitous modeling of disposal room stability.            *
*  Vertical emplacement scheme ...                                   *
*  NRC Contract 02-85-002, Task Order No. 005.                       *
*                                                                    *
*  File for horizontal jointing                                      *
*  Cohesion = 0 MPa, Friction = 11.3, Dilation = 0                   *
*                                                                    *
**********************************************************************
*
*
REST FJS_0.SAV
*
*--- Rock Joints:
PROP JCOH=0 ;(Pa)
PROP JFRIC=11.3 JANG=0. ;(degrees)
*
TITLE
0 Years - Horizontal Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0
*
*
WIND 0,20 -10,10
*
SOLVE
SAVE FJS_M0M.SAV
*
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
*--- SWITCH TO IMPLICIT SOLUTION
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time  step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TITLE
50 Years - Horizontal Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0
*
*
SAVE FJS_M50M.SAV
*
*
*
```

```
************************************************************************
*                                                                      *
*     T H E R M A L / M E C H A N I C A L    A N A L Y S I S          *
*                                                                      *
*  Input file to FLAC for determining the effect of joint parameters  *
*  on the ubiquitous modeling of disposal room stability.             *
*  Vertical emplacement scheme ...                                    *
*  NRC Contract 02-85-002, Task Order No. 005.                        *
*                                                                      *
*  File for 70 degree jointing                                        *
*  Cohesion = 1 MPa, Friction = 38.7, Dilation = 0                    *
*                                                                      *
************************************************************************
*
*
REST FJS_0.SAV
*
*--- Rock Joints:
PROP JCOH=1.0E20 ;(Pa)
PROP JFRIC=38.7 JANG=70. ;(degrees)
*
TITLE
0 Years - 70 Deg Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0
*
SOLVE
PROP JCOH=1.0E6 ;(Pa)
SOLVE
*
WIND 0,20 -10,10
*
SAVE FJS_MON.SAV
*
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
*--- SWITCH TO IMPLICIT SOLUTION
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
```

```
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time  step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TITLE
50 Years - 70 Deg Joints, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0
*
SAVE FJS_M50N.SAV
*
*
*
```

```
***********************************************************************
*                                                                     *
*     T H E R M A L / M E C H A N I C A L   A N A L Y S I S           *
*                                                                     *
*  Input file to FLAC for determining the effect of joint parameters  *
*  on the ubiquitous modeling of disposal room stability.             *
*  Vertical emplacement scheme ...                                    *
*  NRC Contract 02-85-002, Task Order No. 005.                        *
*                                                                     *
*  File for 70 degree jointing                                        *
*  Cohesion = 1 MPa, Friction = 11.3, Dilation = 0                    *
*                                                                     *
***********************************************************************
*
*
REST FJS_0.SAV
*
*--- Rock Joints:
PROP JCOH=1.0E20 ;(Pa)
PROP JFRIC=11.3 JANG=70. ;(degrees)
*
TITLE
0 Years - 70 Deg Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0
*
SOLVE
PROP JCOH=1.0E6 ;(Pa)
SOLVE
*
*
SAVE FJS_M0O.SAV
*
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
*--- SWITCH TO IMPLICIT SOLUTION
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time  step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TITLE
50 Years - 70 Deg Joints, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0
*
*
SAVE FJS_M500.SAV
*
*
*
```

```
**********************************************************************
*                                                                    *
*     T H E R M A L / M E C H A N I C A L    A N A L Y S I S         *
*                                                                    *
*  Input file to FLAC for determining the effect of joint parameters *
*  on the ubiquitous modeling of disposal room stability.            *
*  Vertical emplacement scheme ...                                   *
*  NRC Contract 02-85-002, Task Order No. 005.                       *
*                                                                    *
*  File for 70 degree jointing                                       *
*  Cohesion = 0 MPa, Friction = 38.7, Dilation = 0                   *
*                                                                    *
**********************************************************************
*
*
REST FJS_0.SAV
*
*--- Rock Joints:
PROP JCOH=1.0E20 ;(Pa)
PROP JFRIC=38.7 JANG=70. ;(degrees)
*
TITLE
0 Years - 70 Deg Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0
*
SOLVE
PROP JCOH=0.0 ;(Pa)
SOLVE
*
*
SAVE FJS_M0P.SAV
*
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
*--- SWITCH TO IMPLICIT SOLUTION
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time  step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TITLE
50 Years - 70 Deg Joints, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0
*
*
SAVE FJS_M50P.SAV
*
*
*
```

```
**********************************************************************
*                                                                    *
*     T H E R M A L / M E C H A N I C A L   A N A L Y S I S          *
*                                                                    *
*  Input file to FLAC for determining the effect of joint parameters *
*  on the ubiquitous modeling of disposal room stability.            *
*  Vertical emplacement scheme ...                                   *
*  NRC Contract 02-85-002, Task Order No. 005.                       *
*                                                                    *
*  File for 70 degree jointing                                       *
*  Cohesion = 0 MPa, Friction = 11.3, Dilation = 0                   *
*                                                                    *
**********************************************************************
*
*
REST FJS_0.SAV
*
*--- Rock Joints:
PROP JCOH=1.0E20 ;(Pa)
PROP JFRIC=11.3 JANG=70. ;(degrees)
*
TITLE
0 Years - 70 Deg Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0
*
SOLVE
PROP JCOH=0.0 ;(Pa)
SOLVE
*
*
SAVE FJS_M0Q.SAV
*
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
*--- SWITCH TO IMPLICIT SOLUTION
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time  step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
*
```

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TITLE
50 Years - 70 Deg Joints, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0
*
*
SAVE FJS_M50Q.SAV
*
```

APPENDIX C

UDEC INPUT COMMANDS FOR JOINT SENSITIVITY ANALYSIS

```
**********************************************************************
*                                                                    *
*     T H E R M A L / M E C H A N I C A L   A N A L Y S I S          *
*      J O I N T   S E N S I T I V I T Y   A N A L Y S I S           *
*                                                                    *
*  Input file to UDEC1.3 for determining the effect of joint        *
*  parameters on emplacement room behavior.                          *
*  Vertical emplacement scheme ...                                   *
*  NRC Contract 02-85-002, Task Order No. 005                        *
*                                                                    *
*  Geometry generation data                                          *
*                                                                    *
**********************************************************************
*
*
THERMAL
SET ENH
HEAD
TUFF 90 DEGREE DIP - 140M MODEL
ROUND=.005
SET OVTOL=1.0
BLOCK 0,-40 0,100 19.2,100 19.2,-40
**********************
* LARGE BLOCK CRACKS
**********************
SPLIT 0,43 19.2,43
SPLIT 0,16 19.2,16
*
*************************
* EMPLACEMENT ROOM CRACKS
*************************
CRACK 0.0,36.5  1.0,36.5
CRACK 1.0,36.5  2.0,36.0
CRACK 2.0,36.0  2.5 35.0
CRACK 2.5,27.0  2.5,40.0
CRACK 0.0,30.0  6.0,30.0
*
*************************
* HEAVILY JOINTED REGION
*************************
JREG  0,16 0,43 7,43 7,16
JSET  0,0  1,0 1,0 2,0 1,0
JSET  0,0  1,0 1,0 2,0 0,1
JSET 90,0 30,0 0,0 1,0
SPLIT 7,16 7,43
*
```

```
*************************
* MAKE SPLIT FOR HEATERS
************************
SPLIT 0,28 1,28
SPLIT 0,26 1,26
SPLIT 0,24 1,24
*
*
*************************
* ADDITIONAL FINE CRACKS
*************************
SPLIT  0.5,27 0.5,30
SPLIT  0.5,37 0.5,40
SPLIT  1.5,27 1.5,30
SPLIT  1.5,36.1 1.5,40
SPLIT  2.5,27 2.5,30
SPLIT  2,27   3,27
SPLIT  3.5,27 3.5,40
SPLIT  4.5,27 4.5,40
SPLIT  1,37 2,37
SPLIT  1,39 2,39
SPLIT  2,36 3,36
SPLIT  2.5,35.9 2.5,40
*
************************
* BOTTOM REGION
************************
SPLIT 0,4 19.2,4
SPLIT 0,10 19.2,10
SPLIT 0,13 19.2,13
SPLIT 3.5,10 3.5 16
SPLIT 7,4 7,16
SPLIT 10.5,10 10.5,16
SPLIT 14,4 14,16
*
************************
* TOP REGION
************************
SPLIT 0,46 19.2,46
SPLIT 0,49 19.2,49
SPLIT 0,55 19.2,55
SPLIT 3.5,49 3.5 43
SPLIT 7,55 7,43
SPLIT 10.5,49 10.5,43
SPLIT 14,55 14,43
*
*
```

```
************************
* RIGHT SIDE
************************
SPLIT 10.5,16 10.5,43
SPLIT 14,16 14,43
SPLIT 7,19 10.5 19
SPLIT 7,23 19.2 23
SPLIT 7,27 19.2 27
SPLIT 7,31 19.2 31
SPLIT 7,35 19.2 35
SPLIT 7,39 10.5 39
*
JDEL
*
*
*
*--- EXCAVATE THE DISPOSAL ROOM ...
*
DELETE 0,2.5 30,35
DELETE 2,2.3 35,35.5
DELETE 0,1.55 35,36.2
*
* GENERATE ZONES
*
GEN  0,7    16,43  AUTO 1.4
GEN  7,20   16,43  AUTO 4.2
GEN  0,20    4,16  AUTO 4.2
GEN  0,20 -40,4    AUTO 14
GEN  0,20   43,55  AUTO 4.2
GEN  0,20   55,100 AUTO 14
*
* DEFINE MATERIAL PROPERTIES AND INITIAL CONDITIONS
*
CHANGE JCONS=5 MAT=1
CHANGE CONS=1 MAT=1
*
*--- ASSIGN MATERIAL PROPERTIES (REF: SCP-CDR CHAP. 2, SEC. 2.3.1)
*--- USING THE JOINT PROPERTIES AND "ROCK MASS" PROPERTIES.
*--- USING THE 'DESIGN' VALUES FROM
*--- TABLES 2-4, 2-6, AND 2-7.
*--- THE ROCK IS CHARACTERIZED AS AN ELASTIC/PLASTIC MATERIAL
*--- WITH VERTICAL AND HORIZONTAL.  A MOHR-COULOMB FAILURE CRITERION
*--- IS USED FOR THE JOINTS ...
*
*
*--- ROCK MASS:
PROP MAT=1 K   = 8.39E9  G     =  6.29E9  DENS = 2340
*
```

```
*--- ROCK JOINTS:
PROP MAT=1 JKN = 1.0E11  JKS   =  1.0E11  JCOH = 1.0E6 &
           JDIL=    .000 JFRIC =   0.800  JTENS=    0  &
           KN   =  1.0E3 KS    =   1.0E3
*
*--- THERMAL PROPERTIES OF THE ROCK ...
*    (REF: SCP-CDR CHAP. 2, SEC. 2.3.1.9, TABLE 2-9)
PROP MAT=1 CON =   2.07  THEXP =  1.07E-5 SPEC =  961
*
*--- DEFINE THE INITIAL STRESS FIELD (MPA)...
*--- REFERENCE:  SCP-CDR CHAP. 2, SEC. 2.3.1.9
*    (THE INITIAL VERTICAL STRESS IS ABOUT -7 MPA AT
*     THE DISPOSAL ROOM HORIZON.  THE HORIZONTAL STRESS
*     IS DETERMINED AS 0.5 X SYY.)
*
INSITU -.1 19.2 -40.1 100.1 STRESS -3.5E6 0 -7.0E6
*
*--- SET THE INITIAL TEMPERATURE TO 26 DEG. CELSIUS ...
INITEM 26 -1,19.2 -41,101
*
GRAV 0,-9.8
*
*--- SET KINEMATIC BOUNDARY CONDITIONS ...
*    (THE TWO VERTICAL BOUNDARIES ARE SYMMETRY PLANES, THUS,
*     THEY ARE RESTRICTED FROM MOVING IN THE HORIZONTAL (X)
*     DIRECTION.  THE BOTTOM HORIZONTAL BOUNDARY IS RESTRICTED
*     FROM MOVING IN THE VERTICAL (Y) DIRECTION.  THE TOP
*     HORIZONTAL BOUNDARY IS A FREE-TO-MOVE PRESSURE BOUNDARY.
*     THE PRESSURE IS ACTING DOWNWARD, AND IS EQUAL TO THE
*     INITIAL VERTICAL STRESS.)
*
BOUND -.1 .1 -40.1 100.1 XVEL 0
BOUND 17.9 19.3 -40.1 100.1 XVEL 0
BOUND -.1 19.3 -40.1 -39.9 YVEL 0
BOUND -.1 19.3  99.9 100.1 STR -3.5E6 0 -7E6
*
* SET HISTORY POINTS
*
*
*--- DEFINE POINTS FOR WHICH TEMP. HISTORIES ARE RECORDED ...
*
RESET HIST
THIS NTC=500 TYPE 1
THIS TEM 0.0 30   * FLOOR CENTER
THIS TEM 0.0 36.7 * CROWN CENTER
THIS TEM 2.5 30   * FLOOR RIB INTERSECTION
```

```
* HISTORIES ALONG A LINE OUT FROM HEATER CENTER
THIS TEM 1 25 TEM 2,25 TEM 3,25 TEM 5,25 TEM 9,25 TEM 18,25
*
*--- DEFINE POINTS FOR WHICH MECH HISTORIES ARE RECORDED ...
*
HIST NC=100
*
HIST YDIS 0.0, 36.5
HIST YDIS 0.0, 30.0
HIST XDIS 2.5, 33.0
HIST YDIS 1.5, 36.2
HIST SXX  0.0, 36.5
HIST SXX  0.0, 30.0
HIST SYY  2.5, 33.0
*
* RUN TIME PARAMETERS
*
DAMP AUTO
MSCALE ON
*--- ASSIGN THE DECAYING HEAT SOURCE WHICH SIMULATES THE
*--- COMMINGLED SF AND DHLW ...
*    (THE THERMAL DECAY CHARACTERISTICS ARE FROM PETERS, 1983,
*     SAND-2497.  THE INITIAL HEAT GENERATING POWER PER METER
*     OF ROOM LENGTH IS 713.5 W.  BECAUSE OF SYMMETRY ONLY HALF
*     OF THIS POWER IS APPLIED.  NOTE THAT THE DECAY COEFFICIENTS
*     HAVE DIMENSION 1/SEC AND NOT 1/YEAR, WHICH IS COMMONLY
*     USED IN THE LITERATURE ...
*     DECAY CONSTANTS FOR SF ARE ALSO USED FOR THE DHLW.
*
SAVE UJS_T0.SAV
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
*
THAPP -.1,.1 23,27 FLUX 48.17 -2.46079E-10
THAPP -.1,.1 23,27 FLUX 41.03 -1.716788E-9
*
RUN T=200 S=100000 AGE=1.58E9
SAVE UJS_T50.SAV
*
RET
```

```
**********************************************************************
*                                                                    *
*     T H E R M A L / M E C H A N I C A L   A N A L Y S I S          *
*      J O I N T   S E N S I T I V I T Y   A N A L Y S I S           *
*                                                                    *
*  Input file to UDEC1.3 for determining the effect of joint         *
*  parameters on emplacement room behavior.                          *
*  Vertical emplacement scheme ...                                   *
*  NRC Contract 02-85-002, Task Order No. 005                        *
*                                                                    *
*  JKN = 1E11, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0       *
*                                                                    *
**********************************************************************
*
*
REST UJS_T0.SAV

CYC 3000
*
HEAD
0 Years, JKN = 1e11, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0
*
SAVE UJS_M0A.SAV
*
**********************************************************************
*                                                                    *
*  JKN = 1E13, COHESION = 1 MPA, FRICTION = 38.7, DILATION = 0       *
*                                                                    *
**********************************************************************
*
*
REST UJS_T0.SAV
*
PROP MAT=1 JKN=1E13 JKS=1E13
CYC 7000
*
HEAD
0 Years, JKN = 1e13, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0
*
SAVE UJS_M0B.SAV
*
**********************************************************************
*                                                                    *
*  JKN = 1E11, COHESION = 1 MPA, FRICTION = 11.3, DILATION = 0       *
*                                                                    *
**********************************************************************
*
```

```
*
REST UJS_M0A.SAV
PROP MAT=1 JFRIC=.2
HIST NC=20
CYC 1000
*
HEAD
0 Years, JKN = 1e11, Cohesion = 1 MPa, Friction = 11.3, Dilation = 0
*
SAVE UJS_M0D.SAV
*                                                                     *
***********************************************************************
*                                                                     *
*  JKN = 1E11, COHESION = 0 MPA, FRICTION = 38.7, DILATION = 0        *
*                                                                     *
***********************************************************************
*
*
REST UJS_M0A.SAV
PROP MAT=1 JCOH=0.0
HIST NC=20
CYC 1000
*
HEAD
0 Years, JKN = 1e11, Cohesion = 0 MPa, Friction = 38.7, Dilation = 0
*
SAVE UJS_M0E.SAV
*
***********************************************************************
*                                                                     *
*  JKN = 1E11, COHESION = 0 MPA, FRICTION = 11.3, DILATION = 0        *
*                                                                     *
***********************************************************************
*
*
PROP MAT=1 JFRIC=.2
CYC 1000
*
HEAD
0 Years, JKN = 1e11, Cohesion = 0 MPa, Friction = 11.3, Dilation = 0
*
SAVE UJS_M0F.SAV
*
```

```
***********************************************************************
*                                                                     *
*  JKN = 1E11, COHESION = 0 MPA, FRICTION = 11.3, DILATION = 5        *
*                                                                     *
***********************************************************************
*
*
REST UJS_T0.SAV
*
PROP MAT=1 JCOH=0 JFRIC=.2 JDIL=.088
CYC 3000
*
HEAD
0 Years, JKN = 1e11, Cohesion = 0 MPa, Friction = 11.3  Dilation = 5
*
SAVE UJS_M0I.SAV
```

```
**********************************************************************
*                                                                    *
*     T H E R M A L / M E C H A N I C A L   A N A L Y S I S          *
*      J O I N T   S E N S I T I V I T Y   A N A L Y S I S           *
*                                                                    *
*  Input file to UDEC1.3 for determining the effect of joint         *
*  parameters on emplacement room behavior.                          *
*  Vertical emplacement scheme ...                                   *
*  NRC Contract 02-85-002, Task Order No. 005                        *
*                                                                    *
*  JKN = 1E11, Cohesion = 1 MPa, Friction = 38.7, Dilation = 0       *
*                                                                    *
**********************************************************************
*
*
REST UJS_T50.SAV
*
CYC 2500
*
HEAD
50 YEARS, JKN = 1E11, COHESION = 1 MPA, FRICTION = 38.7, DILATION = 0
*
SAV UJS_M50A.SAV
*
*
**********************************************************************
*                                                                    *
*  JKN = 1E11, COHESION = 1 MPA, FRICTION = 11.3, DILATION = 0       *
*                                                                    *
**********************************************************************
*
*
REST UJS_T50.SAV
*
PROP MAT=1 JFRIC = .2
*
CYC 1000
*
HEAD
50 YEARS, JKN = 1E11, COHESION = 1 MPA, FRICTION = 11.3, DILATION = 0
*
SAV UJS_M50D.SAV
*
*
```

```
***********************************************************************
*                                                                     *
*  JKN = 1E11, COHESION = 0 MPA, FRICTION = 38.7, DILATION = 0        *
*                                                                     *
***********************************************************************
*
*
REST UJS_T50.SAV
*
PROP MAT=1 JCOH = 0.0
*
CYC 1000
*
HEAD
50 YEARS, JKN = 1E11, COHESION = 0 MPA, FRICTION = 38.7, DILATION = 0
*
SAV UJS_M50E.SAV
*
*
***********************************************************************
*                                                                     *
*  JKN = 1E11, COHESION = 0 MPA, FRICTION = 11.3, DILATION = 0        *
*                                                                     *
***********************************************************************
*
*
REST UJS_T50.SAV
*
PROP MAT=1 JCOH = 0 JFRIC = .2
*
CYC 1000
*
HEAD
50 YEARS, JKN = 1E11, COHESION = 0 MPA, FRICTION = 11.3, DILATION = 0
*
SAV UJS_M50F.SAV
*
*
*
***********************************************************************
*                                                                     *
*  JKN = 1E11, COHESION = 1 MPA, FRICTION = 38.7, DILATION = 2.5      *
*                                                                     *
***********************************************************************
*
```

```
*
REST UJS_T50.SAV
*
PROP MAT=1 JDIL=.044
*
CYC 2500
*
HEAD
50 YEARS, JKN = 1E11, COHESION = 1 MPA, FRICTION = 38.7, DILATION = 2.5
*
SAV UJS_M50G.SAV
*
*
************************************************************************
*                                                                      *
*  JKN = 1E11, COHESION = 0 MPA, FRICTION = 11.3, DILATION = 2.5       *
*                                                                      *
************************************************************************
*
*
REST UJS_T50.SAV
*
PROP MAT=1 JDIL=.044
PROP MAT=1 JFRIC=.2, JCOH=0.0
*
CYC 2500
SAV UJS_M50H.SAV
*
*
************************************************************************
*                                                                      *
*  JKN = 1E11, COHESION = 0 MPA, FRICTION = 11.3, DILATION = 5         *
*                                                                      *
************************************************************************
*
*
REST UJS_T50.SAV
*
PROP MAT=1 JDIL=.087
PROP MAT=1 JFRIC=.2, JCOH=0.0
*
CYC 2500
SAV UJS_M50I.SAV
*
RET
```