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Computer-Aided Structural Engineering (CASE) Project

Procedure for Static Analysis of Gravity Dams Including Foundation Effects Using the Finite Element Method – Phase 1B

by Jerry Foster, U.S. Army Corps of Engineers
H. Wayne Jones, WES

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Prepared for Headquarters, U.S. Army Corps of Engineers

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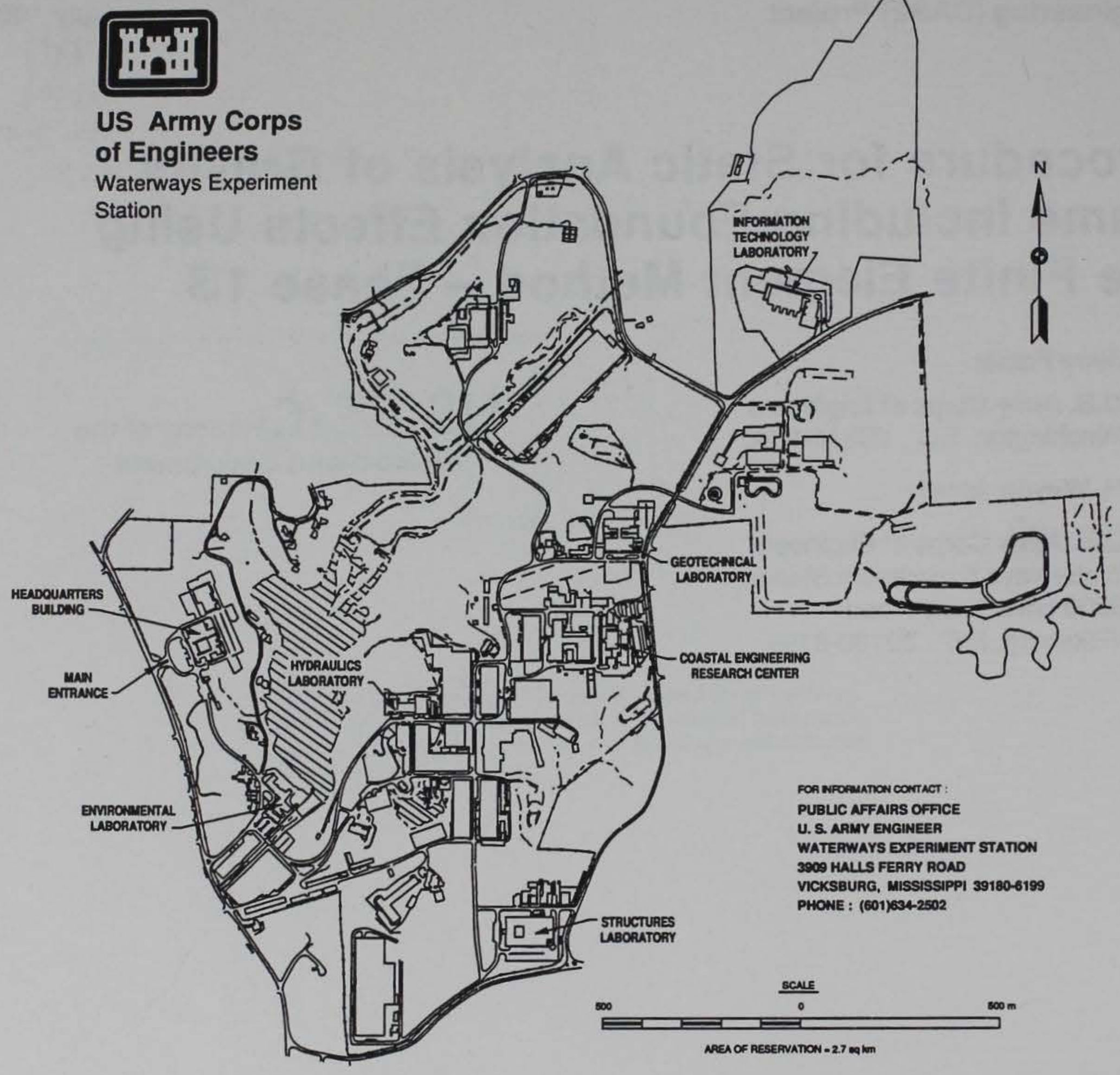

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Preface

This report is aimed at providing information for the use of the finite element method of analysis for the analysis of concrete gravity dams. The Phase Ia report will address only the static analysis of the gravity dam, while this Phase Ib report will address the effect of the foundation in the static analysis of concrete gravity dams. The Phase II report addressed the dynamic analysis of concrete gravity dams. The work was sponsored under funds provided to the U.S. Army Engineer Waterways Experiment Station (WES) by the Engineering Division of Headquarters of the U.S. Army Corps of Engineers (HQUSACE) as part of the Computer-Aided Structural Engineering (CASE) Project. Mr. Lucian Guthrie of the Structures Branch of the Engineering Division was the HQUSACE point of contact.

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At the time of the publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	2.54	centimeters
pounds (force) per square inch	6.894757	kilopascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter

1 Introduction

Purpose

The structural engineer has long been faced with the question of what effect does the foundation have on the structure and when should the foundation be included in the analysis of the structure. If it is necessary to include the foundation, similar questions arise as to what model should be used for the foundation and how much of the foundation is necessary. The objectives of this study are to determine the impact of foundation-structure interaction upon stresses within a gravity dam and to make recommendations concerning how and when to include the foundation in a finite element analysis.

This study is part of the continuing effort of the Computer-Aided Structural Engineering (CASE) Committee, Finite Element Task Group, to establish guidelines for the analysis of gravity dams using the finite element method. Previous work by the Task Group has been utilized within this study and is referenced where used. All of the analyses within this report use linear elastic models of the structure and foundation. Analyses using nonlinear foundation behavior will be examined in a later study.

Approach

Several numerical models for the foundation were examined and are summarized in Chapter 2 with recommendations on strengths and limitations of each. A finite element model of the foundation is selected from these models for use in the remainder of this study.

The foundation size required to obtain stress convergence within the foundation based on a uniformly applied loading is investigated in Chapter 3. The effect of the foundation on the stresses inside the structure is investigated in Chapter 4 by varying the size of the finite element foundation model while maintaining a constant finite element model for the gravity dam. The stresses within the dam are examined to determine what conclusions can be drawn concerning stress convergence as the foundation

size is varied. In Chapter 5, one finite element model of the foundation is selected, based on stress convergence, to study the impact upon the stresses in the dam for various ratios of foundation-to-dam elastic moduli.

2 Foundation Models to be Used for Finite Element Structures

Foundation Models

The finite element method (FEM) is a common method for determining the displacements and stresses within complex structures. The effects of the foundation often contribute an important part to the behavior of many structures and must be considered. However, the structural engineer may not be interested in the behavior within the foundation except to the extent that the structure and foundation interact and influence the behavior within the structure. Many models for the foundation are available to the engineer with the following being the most frequently used types:

a. Winkler Foundation.

b. Two-Parameter Foundation.

c. Boundary Element Method.

d. Elastic Half-Plane.

e. Finite Element Method.

This chapter gives a brief summary of these foundation models, along with the limitations and strengths of each.

Winkler Foundation

The Winkler foundation is based on Winkler's (1867) hypothesis: the displacement of a single point on the foundation is independent of the displacements at any other point on the foundation and is a function of the

stiffness of the foundation at that point. This model allows the foundation to be described as a series of one-dimensional (1-D) springs which can be coupled numerically with the structure stiffness as shown below:

$$\left[K_T\right]\{u\} = \{F\} \tag{1}$$

where

$[K_T]$ = $[K_S]$ + $[K_F]$

$[K_F]$ = stiffness matrix of Winkler foundation (diagonal matrix)

$[K_S]$ = stiffness matrix of structure

$[K_T]$ = stiffness matrix of coupled foundation-structure system

$\{u\}$ = displacements of system nodes

$\{F\}$ = forces acting on system

This procedure has been used to solve many soil-structure interaction problems (Dawkins 1982, Haliburton 1971, Reese and Matlock 1956). The basic weakness of this foundation model is that it does not give a coupled two-dimensional (2-D) representation of the foundation. This weakness can be demonstrated by placing a uniform load on a uniform beam which rests on a Winkler foundation. With a Winkler foundation model this analysis yields a constant displacement of the beam, i.e., rigid body deflection. Since all of the relative displacements within the beam are zero, all moments and shears within the beam are zero. This foundation model would not model the true behavior of such a problem. The stiffness matrix, $[K_T]$, given in Equation 1 is a function of the material and geometric properties of the foundation and structure, which makes an assumption of an overall stiffness of the foundation stiffness necessary. There is literature which contains tables with ranges of modulus values for the foundation, or they may be determined empirically. The Winkler foundation model should be used with extreme care keeping these limitations in mind.

Two-Parameter Model

Nogami and Lam (1986) developed a two-parameter model for analyzing a beam resting on the ground surface. The two parameters represent a vertical stiffness and a shearing stiffness. These two parameters give the 2-D coupling within the foundation not present in the Winkler model. Prior to Nogami, other two-parameter models for the soil-structure interaction (SSI) analysis were determined by known ground surface displacements or by using a variational method with an assumed ground surface displacement. Since the ground surface displacements are needed for

these models, the two parameters for these models are difficult to determine. The two parameters used in Nogami's model are calculated from Young's modulus (E) and Poisson's ratio (ν) of the foundation. Therefore, they are easy to determine once E and ν are known.

The following is a brief outline of Nogami's two-parameter model. A linearly elastic 2-D foundation can be represented with the following two-parameter model:

$$p(x,y) = Kw(x,y) - G\nabla^2 w(x,y) \tag{2}$$

where

$$\nabla^2 = \left(\frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2}\right)$$

p = pressure

K, G = soil parameters

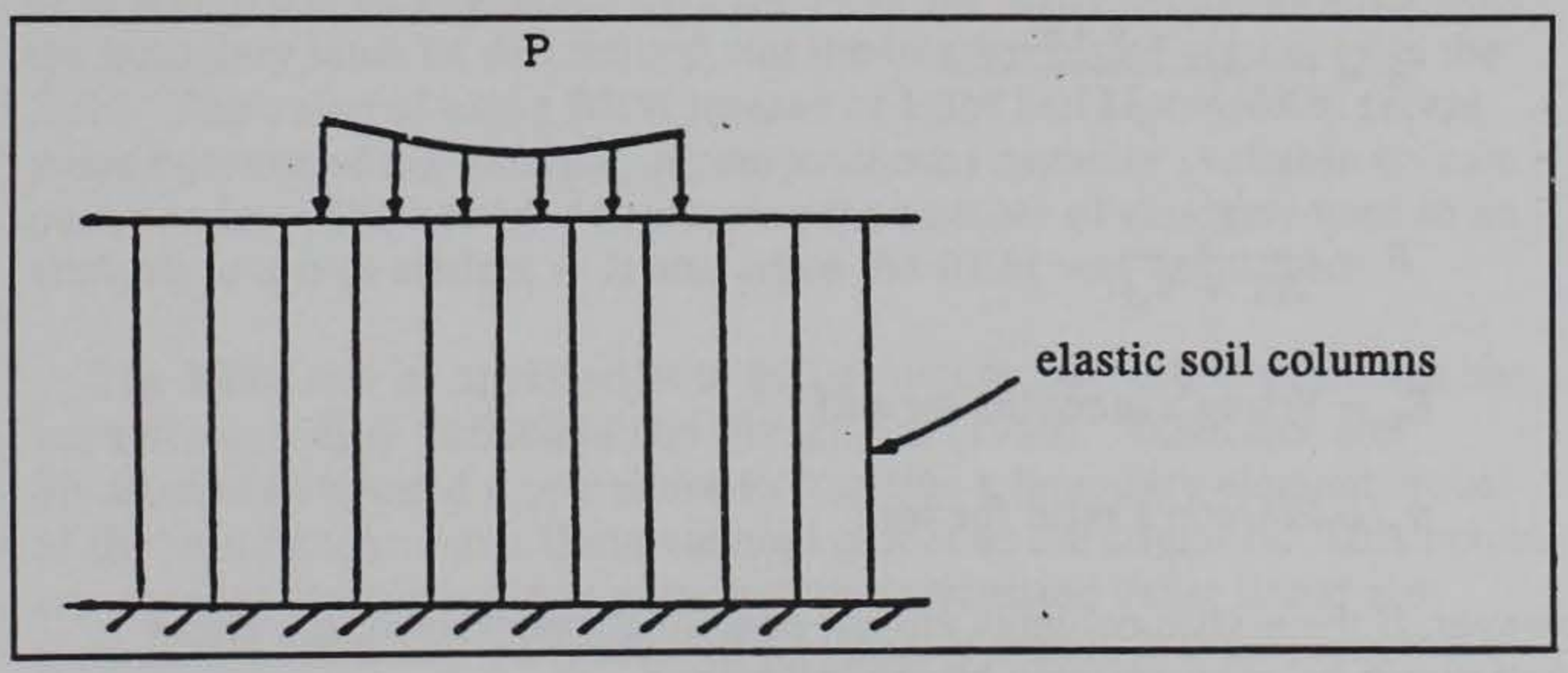
w = displacements

Nogami discretized the ground surface and used variational methods to arrive at the following equation:

$$[K]\{w(x)\} - [N]\{\nabla^2 w(x)\} = \{p(x)\} \tag{3}$$

where $[N]$ and $[K]$ are n by n matrices, and $w(x)$ represents the vertical displacements at the interface between the foundation and structure.

As seen in Equation 3, the effect of the foundation is represented by only the displacements at the ground surface. This representation is accomplished by assuming the entire foundation is made up of a series of elastic soil columns as illustrated below. The stresses in the foundation can then be described by the following equations:



Soil media idealized by a system of elastic columns

Axial normal stress:

$$\sigma(x,y) = E\frac{\partial w(x,y)}{\partial y}$$

Shear stress along sides:

$$\tau(x,y) = G\frac{\partial w(x,y)}{\partial x}$$

where

$$w(x,y) = \sum_{i=1} \varphi_i(y) w_i$$

The φ_i function is an assumed linear shape function. From these equations the stresses anywhere in the foundation can be determined if the surface displacements are known. The equation for a plate resting on a foundation is as follows:

$$[EI]\left\{\frac{\partial^3 w(x)}{\partial x^3}\right\} - [N]\left\{\frac{\partial^2 w(x)}{\partial x^2}\right\} + [K]\{w(x)\} = \{p(x)\}$$

For a continuous media model consisting of elastic columns with completely restrained lateral displacements, the stress can be written as follows:

$$\sigma(x,y) = A\frac{\partial w(x,y)}{\partial x}$$

$$\tau(x,y) = B\frac{\partial w(x,y)}{\partial x}$$

where

$$A = \frac{(1 - \nu_s) E_s}{2(1 + \nu_s)(1 - \nu_s)}$$

$$B = \frac{E_s}{2(1 + \nu_s)}$$

E_s = Young's modulus for soil

ν_s = Poisson's ratio for soil

However, if the elastic columns are not completely restrained, the stress equation can be approximated by the following:

$$\sigma(x,y) = F_e A \frac{\partial w(x,y)}{\partial y} \tag{4}$$

$$\tau(x,y) = F_a B \frac{\partial w(x,y)}{\partial x}$$

From finite element studies, the relationships were determined for F_e and F_a as a function of ν_s. The following are limits for ν_s values between 0.0 and 0.3 for F_e and F_a:

ν_s	0.0	0.3
F_e	0.95	0.99
F_a	0.475	0.495

Graphs for F_e and F_a as a function of ν_s are presented by Nogami and Lam (1986).

Therefore by determining the Young's modulus and Poisson's ratio of the foundation, an engineer can find the corresponding F_e and F_a. Using these values and applying the proper boundary conditions, the engineer can solve Equation 4 to determine the displacements in the structure which leads directly to the determination of the shear and moments. The major problem with this foundation model is that it can not be used to produce a stiffness matrix for the foundation to be later combined with the structure stiffness matrix.

Boundary Element Method

The boundary element method (BEM) is a numerical analysis procedure which has an advantage over the FEM for many problems since only the boundary must be discretized, not the interior of the system as in the FEM. The value of using BEM instead of FEM has decreased in recent years because of the increase in computational capacity available on computers today. The need for decreasing the number of elements used in an analysis is not as critical as it was when the BEM was developed.

The BEM and its application to soil-structure interaction problems has been discussed by Vallabhan and Sivakumar (1986). Vallabhan and Sivakumar developed a procedure to combine a boundary element model of the foundation with a finite element model of the structure. This boundary element foundation was numerically constructed using linear elements. The structure was modeled by linearly elastic 2-D isoparametric plate finite elements.

The BEM is typically stated as follows:

$$[H]\{\varphi\} = [G]\{q\}$$

For an elastic half-plane problem:

$\{\varphi\}$ = nodal displacements

$\{q\}$ = surface tractions

$[H]$, $[G]$ = n by n matrices

n = number of degrees of freedom

Since these matrices represent a well-posed boundary value problem, only the traction or displacement can be described at any given node. Therefore, the set of equations can be reordered as follows:

$$[A]\{X\} = \{B\}$$

where

$[A]$ = combination of $[H]$ and $[G]$ matrices

$\{X\}$ = unknown displacements or tractions

$\{B\}$ = specified displacements or tractions

The unknown boundary displacements and tractions can now be determined. The BEM does provide techniques for directly calculating tractions and displacements at internal points. However, results at internal points are not needed for this particular problem.

The SSI problem which we are interested in solving can be modeled by using a finite element model for the structure and a boundary element model for the foundation. The following is a summary of Vallabhan's procedure for combining a linear boundary element with linear finite elements. For the FEM model of the structure:

$$[K]\begin{Bmatrix} u_s \\ u_i \end{Bmatrix} = \begin{Bmatrix} F_s \\ F_i \end{Bmatrix}$$

where

u_s = displacements of the structure not in contact with the foundation

u_i = displacements at interface of structure and foundation

F_s = forces on structural nodes not in contact with the foundation

F_i = forces on interface nodes

$[K]$ = stiffness matrix of structure

For the BEM model of the foundation:

$$[H]\begin{Bmatrix} u_i \\ u_F \end{Bmatrix} = [G]\begin{Bmatrix} T_i \\ T_F \end{Bmatrix}$$

where

u_i = displacements at interface of structure and foundation

u_F = displacements of the foundation not in contact with the structure

T_i = interface tractions

T_F = foundation tractions

Assuming that the interface tractions and displacements are compatible between the finite element and boundary element models, the BEM equation reduces to:

$$[K_F]\{u_F\} = -\{F_B\} - \{f_B\}$$

$[K_F]$ = stiffness matrix of foundation

F_B = equivalent nodal forces from the known tractions

f_B = equivalent nodal forces from the known displacements

Although this method is useful for homogeneous problems, a major limitation is that general purpose computer software is not readily available which can combine a boundary element foundation with a finite element structure.

Elastic Half-Plane

Wilson and Turcotte (1986) present an exact solution of the equations of elasticity for an elastic half-plane subjected to an arbitrary set of surface loads. This solution leads to the calculation of flexibility and stiffness matrices which relate concentrated loads and the corresponding

displacements. The elasticity problem was solved using a complex variable formulation to calculate stresses and displacements within a half-plane subjected to several concentrated loads. Once the half-plane stiffness matrix is formed, it can be combined with the beam stiffness matrix using a procedure similar to that used by the BEM. These equations can then be solved to calculate the displacements, which lead to shears and moments within the beam.

This procedure gives an exact solution if it can be assumed that the foundation actually behaves as an elastic half-plane. However, the same limitations apply as for the BEM: (a) there is no readily available computer software to attach an elastic half-plane model of the foundation to a finite element model of the structure; and (b) this model is only valid for a homogeneous foundation.

Finite Element Method

In the FEM approach, both the foundation and the structure are modeled using finite elements. While these two stiffnesses can be combined using a procedure similar to the BEM, this combination is not necessary since the foundation can simply be modeled along with the structure. The finite element model can also be used for foundations with varying depths and with nonhomogeneous materials. The main limitation is that this study assumes the foundation to be linearly elastic; however, material models are available for nonlinear foundation models if desired.

Conclusion

Of the currently available procedures, the FEM is the most practical means for modeling the foundation effects on a structure since existing computer software is readily available and the method allows for modeling of a variety of foundations with different sizes, shapes, and materials.

3 Extent of Foundation Necessary in Finite Element Analysis

Background

The purpose of this study is to determine the extent of the foundation necessary to produce accurate results which must be included in the finite element models to accurately produce stresses within the foundation that match those obtained from theory of elasticity solutions. This size of the foundation which must be included in the analysis is relevant for any type of structure, (i.e., beam, mat, or dam) to be placed on an elastic media. However, the size of foundation determined in this study may be larger than that necessary to produce convergence of stresses within the structure itself.

This study addresses three loadings on an elastic half-plane for which closed form solutions are available. The first load case is a uniform normal pressure over a finite length of the foundation surface. The second load case is a uniform shear pressure over a finite length of the surface. The third load case is an antisymmetric uniform normal pressure load over a finite length of the foundation with one half of pressure acting in the negative direction, while the other half of the pressure acts in the positive direction.

The grids used for the uniform normal pressure loadings are shown in Figures 1-10. Table 1 gives the dimensions of the models in terms of the base width (BW) of the applied pressure loading. The BW of the applied pressure is equivalent to the BW of the structure sitting on the foundation. The grids used for the uniform shear loading and the antisymmetric normal pressure loading were generated by adding mirror images about the center line of each grid. This addition resulted in grids for these unsymmetric load cases which were twice the width of the grids shown in Figures 1-10.

All grids are restrained from displacing horizontally along all vertical boundaries. The bottom horizontal boundary is restrained from displacing vertically. The bottom corner nodes are therefore restrained from moving either horizontally or vertically. These boundary conditions allow for symmetrical behavior for the grids shown in Figures 1-10 and are also valid for the grids used for the unsymmetric load cases.

The finite element runs are all made using the general purpose finite element program, GTSTRUDL.[1] The element used is the "IPLQ" element which is a four-node isoparametric element that uses a linearly varying displacement function. The value of the modulus of elasticity for this problem is not important since the foundation is a homogeneous foundation and only stresses are being evaluated. A Poisson ratio of 0.499 was used for the finite element solution since the closed form solution assumed an incompressible media.

The nodes used for comparison lie on a diagonal line starting at the center of the load and running along an angle of 45 deg from the horizontal as shown in Figure 11. All grids have the same mesh density along this line used for comparison.

The equations and descriptions of angles used in the calculation of stresses by the closed form solution for the uniform load are shown in Figure 12. Figure 13 gives the equations and descriptions of angles used to calculate closed form stresses for the uniform shear loading. The antisymmetric normal pressure load case is calculated by applying a upward pressure on the left of the center line and a downward pressure on the right of the center line as shown in Figure 14. The closed form and finite element results are tabulated in Table 2 and plotted in Figures 15-17. The finite element results for horizontal stresses do not agree closely with the closed form values since the density of the mesh in the area of high stress gradients was not sufficient. The horizontal stresses tabulated on Table 2 and plotted in Figure 15 demonstrate these errors. However, the results for the shear and vertical stresses are predicted very accurately for the larger finite element grids. The finite element shear stresses at Point 11 for a uniform normal pressure are 26.9 percent in error for Model 3 and only 7.6 percent in error for Model 4. Similar magnitudes of error were obtained for the shear stresses from the other two load cases. The finite element vertical stresses at Point 11 are 4.5 percent in error for Model 3 and 1.4 percent in error for Model 4. The closed form and finite element results are tabulated in Table 3 and plotted in Figures 18-20 for the uniform shear load and in Table 4 and Figures 21-23 for the antisymmetric load case. Table 5 gives a list of the percentage of error for the vertical

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[1] GTSTRUDL is a general-purpose finite element program owned and maintained by the GTICES Systems Laboratory, School of Civil Engineering, Georgia Institute of Technology. Program runs used in this report were made on the Control Data Corporation, Cybernet Computer System.

stresses for all load cases for Models 3 and 4. In these analyses positive stresses are compressive, and negative stresses are tensile.

Conclusions

This study shows that a finite element grid must include a foundation depth of at least three times the BW of the structure in order to obtain foundations with vertical stresses with less than 10 percent difference from the theory of elasticity solution. This study has not addressed the problem of convergence of stresses within the structure.

4 Effect of Foundation Size on Stresses Within the Structure

Background

The results of Chapter 3 indicated that a foundation model of depth equal to at least three times the BW of the dam was necessary to achieve convergence of the vertical stresses in the foundation to within 10 percent of the stresses from the closed form solution. This study also indicated that a more shallow foundation depth may be sufficient to achieve convergence of stresses within the dam. Based upon this information, the maximum foundation depth studied herein is three times the BW of the dam.

The foundation-structure interaction is observed by varying the size of the foundation model while maintaining a constant gravity dam model. An examination of the stresses within the dam was then made to determine what conclusions could be drawn concerning stress convergence.

Dam Model

The general configuration of a typical dam (Figure 24) was used as the gravity dam in this study. The finite element mesh used to model the dam in the foundation size study that utilized 6 elements along the dam-foundation interface has a total of 102 elements and 365 nodes as shown in Figure 25.

Foundation Models

Three foundation models were considered in the analysis. The sizes of each foundation model presented in Table 6 are all a function of the BW

of the gravity dam and have six elements along the base of the dam model, as shown in Figure 25. The FEM meshes, node, and element numbering are shown in Figures 26, 27, and 28.

Material Properties

A Poisson's ratio of 0.2 for both the rock and concrete, a concrete modulus of elasticity (Ec) of 4.0×10^6 pounds per square inch (psi) and a foundation deformation modulus of elasticity (Er) of 4.0×10^6 psi were used in these analyses.

Boundary Conditions

The boundary nodes for all foundation models were input as rollers with the exception of the lower right and left corners, which were fixed.

Loads

Hydrostatic loading from the reservoir was applied to the foundation elements upstream of the dam and to the upstream face of the dam. These loads were input as uniform edge loads on the upstream foundation elements and as uniformly varying edge loads on the upstream face elements of the dam. The weight of the concrete dam was input as body forces for the elements within the dam equal to 150 pounds per cubic foot (pcf). The weight of the rock foundation was ignored in the analyses. Uplift on the base of the dam and pore pressure in the foundation was not considered in the analyses.

Analysis Procedure

All computer runs were made using the program GTSTRUDL. One run was made for each of the foundation models. The results of these analyses were examined for the effects of the foundation size on stresses within the dam.

Results of Model Size Study

The impact of varying the size of the foundation model upon stresses in the dam is illustrated in Tables 7, 8, and 9. These tables show the vertical, horizontal and shear stresses (Syy, Sxx and Sxy), respectively, for the lower two rows of nodes in the gravity dam. Examination of these tables indicates that there is not a significant change in the stresses in the lower portion of the dam, even when the foundation model size is changed by a factor of more than three.

In general, as foundation model size increases, vertical stresses in the heel and toe region become more compressive and are reduced in the center portion of the base. Shear and horizontal stresses were distributed more towards the toe as model size was increased. Stresses at the extreme heel of the dam-foundation interface changed more dramatically than in the interior. This change became less dramatic above the dam-foundation interface.

Vertical displacements were greatly effected by changes in model size, increasing by more than 20 percent between Models 1 and 2 and by more than 50 percent between Models 1 and 3. However, this variation of vertical displacement with foundation depth is as expected for a linear elastic foundation with a constant loading. Horizontal displacements decreased as model size increased. Table 10 shows the effects of model size on the horizontal and vertical displacements.

Stress contour plots of vertical, horizontal and shear stresses for foundation Model 1 (3×5 BW) are shown in Figures 29, 30, and 31, respectively.

Conclusions

A foundation model of depth and width equal to 1.5 and 3.0 times the BW of the dam, respectively, is sufficient to achieve accurate stress results within the dam.

5 Effect of Foundation Stiffness on Stresses Within a Gravity Dam

Scope

This section examines the impact upon dam stresses of varying the ratio of rock deformation modulus to concrete elastic modulus. The foundation-structure interaction was tested in Chapter 4 by varying the size of the foundation model while maintaining a constant gravity dam section as shown in Figure 24. An examination of the stresses within the dam was made to determine what conclusions can be drawn concerning stress convergence. The results of Chapter 3 indicated that a foundation model of depth equal to at least three times the BW of the dam was necessary to achieve convergence of foundation stresses to within 10 percent of a closed form solution. The results of Chapter 4 indicated that a more shallow depth may be sufficient to achieve convergence of stresses within the dam. Based upon these works, the maximum depth studied herein is three times the BW of the dam (Model 3).

The gravity dam mesh that was used in this study is finer than the mesh used in the size studies in Chapter 4 in order to determine the effect of mesh density upon stresses at the heel and toe of the dam. This finer mesh shown in Figure 32 has 10 elements along the dam-foundation interface.

Material Properties

A Poisson's ratio of 0.2 for both rock and concrete and a concrete modulus of elasticity of 4.0×10^6 psi were used throughout the analyses. The foundation deformation modulus of elasticity was varied from 0.2×10^5 to 12×10^6 psi as shown in Table 11, with an additional run with the base of the dam fixed to simulate an infinitely rigid foundation. These runs utilized

the 10 base-element gravity dam and foundation model as shown in Figure 32.

Boundary Conditions

The boundary nodes for all foundation models were input as rollers with the exception of the lower right and left corners, which were fixed.

Loads

Hydrostatic loading from the reservoir was applied to the foundation elements upstream of the dam and to the upstream face of the dam. These loads were input as uniform edge loads on the upstream foundation elements and as uniformly varying edge loads on the upstream face elements of the dam. The weight of the concrete dam was input as body forces on the elements within the dam equal to 150 pcf. The weight of the rock foundation was ignored in the analysis. Uplift on the base of the dam and pore pressure in the foundation was not considered in these analyses.

Analysis Procedure

All computer runs were made using the program GTSTRUDL. The analysis results from Model 3 (material property condition C from Table 11) of the Chapter 4 study were used in this study also. Four additional runs using Model 3 and material property conditions A, B, D, and E and one run with the fixed base model (F) were made for this part of the study. Table 12 summarizes the additional GTSTRUDL runs analyzed.

Results of Foundation Stiffness Study

The effect of foundation stiffness on dam stresses was studied by varying the modulus of elasticity of the foundation elements in Model 3. The results summarized in Tables 13, 14, and 15 indicate that foundation stiffness has a significant impact upon stresses in the dam. It should be noted that the Model 3 used for this study differs from the same size foundation model used in the Chapter 4 study. The Chapter 4 model used 6 elements at the dam-foundation interface. In this study, the dam-foundation model used 10 elements above the base, as shown in Figure 33. This refinement was made in order to gain a better understanding of the stresses which occur at reentrant corners in FEM analyses.

Figure 34 shows the effect on the vertical stress distribution of using the finer heel and toe mesh. This figure shows that as the mesh was refined, the magnitude of the extreme heel and toe stress was increased, but the length of base over which the high stresses occurred was decreased. The use of an even finer mesh would probably show that the zone of high stress concentration can be reduced significantly.

Table 13 shows the vertical stresses for the various Er/Ec ratios studied. The distribution of vertical (Syy) stresses at the interface between the dam and the foundation shifted from the extreme nodes towards the center nodes as the foundation stiffness increased. Figure 35 shows this stress shift for selected nodes and also indicates that the stresses are approaching an asymptotic value as the Er/Ec ratio approaches 3.0. Figure 36 shows that the stresses become more compressive at the interior nodes and become less compressive at the end nodes as the foundation stiffness increased. Horizontal stresses shown in Table 14 were distributed more evenly across the plane of the nodes, and more of the horizontal load was resisted by the interface nodes as foundation stiffness increased. Accordingly, shear stresses also increased with increasing foundation stiffness.

Both horizontal and vertical displacements at the interface were reduced rapidly as foundation stiffness increased. Tables 16 and 17 show the effect of foundation stiffness on displacements. Figure 37 demonstrates graphically that, as expected, displacements follow the same patterns as stresses, i.e., they converge as the Er/Ec ratio approaches 3.0.

Relative displacements are shown in Tables 18 and 19. Table 19 shows that the relative vertical displacements above the interface do not change appreciably for Er/Ec ratios greater than 1.0. At Er/Ec=1.0, the displacements are within 57 percent of those for Er/Ec equal to infinity. Relative horizontal movements near the interface followed a similar pattern and are within 10 percent of the Er/Ec ratio of 1.0. In the upper portions of the dam, relative movements reduced as foundation stiffness increased.

Stresses at the plane approximately two thirds of the height of the dam above the interface were not significantly affected by changes in the foundation stiffness.

Plots of Results

Vertical, horizontal, and shear stresses for modulus ratios of 0.05, 0.25, 1.0, 1.75, and 3.00 are given in Figures 38-52, respectively. The CASE program for plotting of shears, moments, and thrust (CSMT) was used to plot the results of the stiffness study along a plane through the foundation structure interface. These plots are shown in Figures 53-57 for modulus ratios of 0.05, 0.25, 1.0, 1.75, and 3.0, respectively.

Relative vertical displacements, although small in magnitude, more than doubled when the foundation size ratio increased from 1.78 to 3.33. Relative horizontal displacements decreased when the model size ratio increased to 1.78; however, they decreased when the size ratio increased to 3.33.

Conclusions

Foundation stiffness has a significant effect upon the distribution of stresses in the dam, especially with Er/Ec ratios approaching 1.00, and therefore should be selected carefully.

As foundation stiffness increases, the effect of foundation stresses upon stresses within the dam is decreased. Dam stresses for Er/Ec ratios of greater than 3.0 did not yield significantly different results than for Er/Ec = 3.0 and were not much greater than the results for Er/Ec = 1.0.

As the Er/Ec ratio increases, vertical stresses near the rock-concrete interface become more compressive near the center line of the base and less compressive at the heel and toe of the structure.

The dam-foundation interface resists more of the driving forces on the dam as the foundation stiffness increases; i.e., shear and horizontal stresses at the interface increased with increased foundation stiffness.

A fine mesh should be used to model the structure foundation interface, especially, at reentrant corners such as the heel and toe of the dam.

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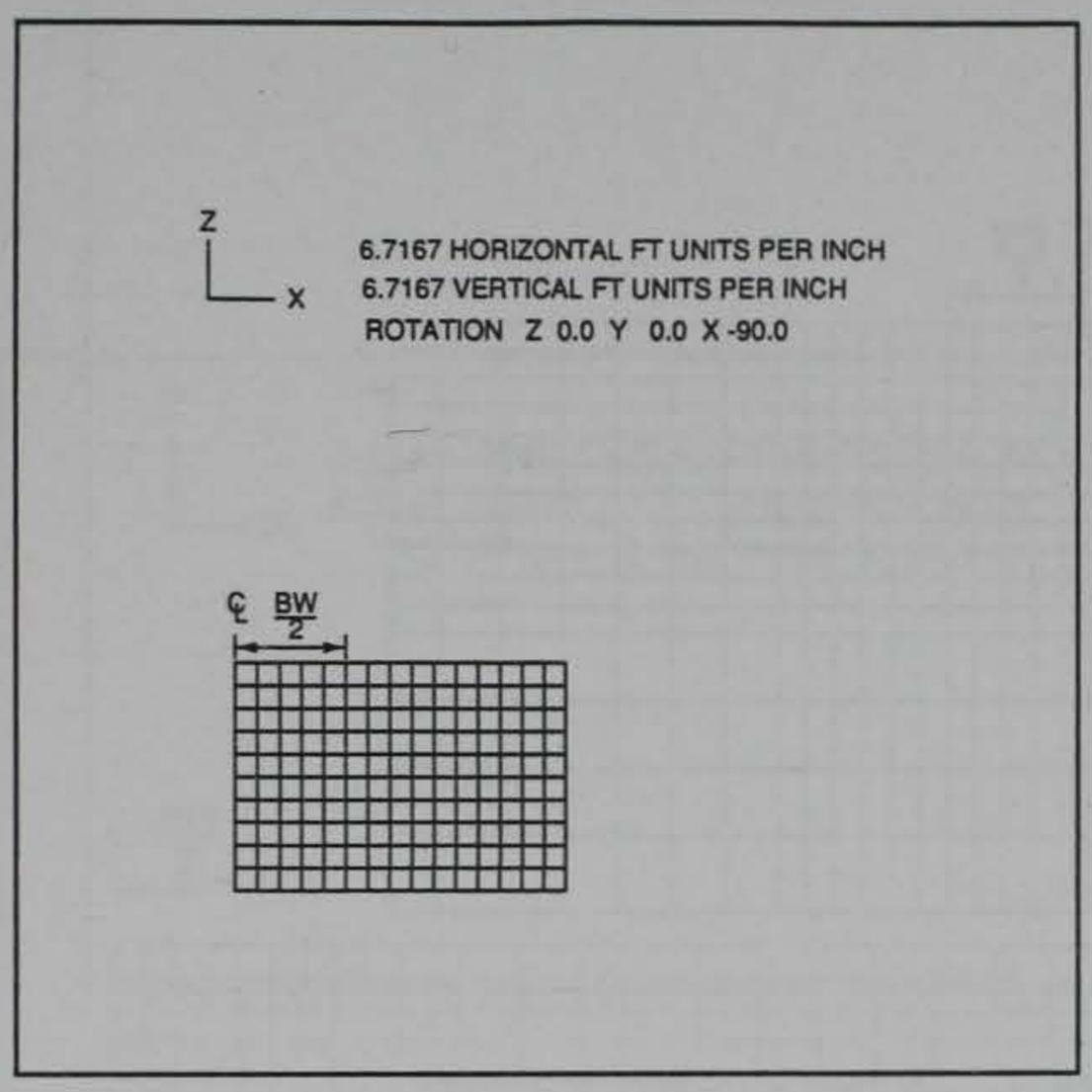


Figure 1. Model 1 (3 BW x 1 BW)

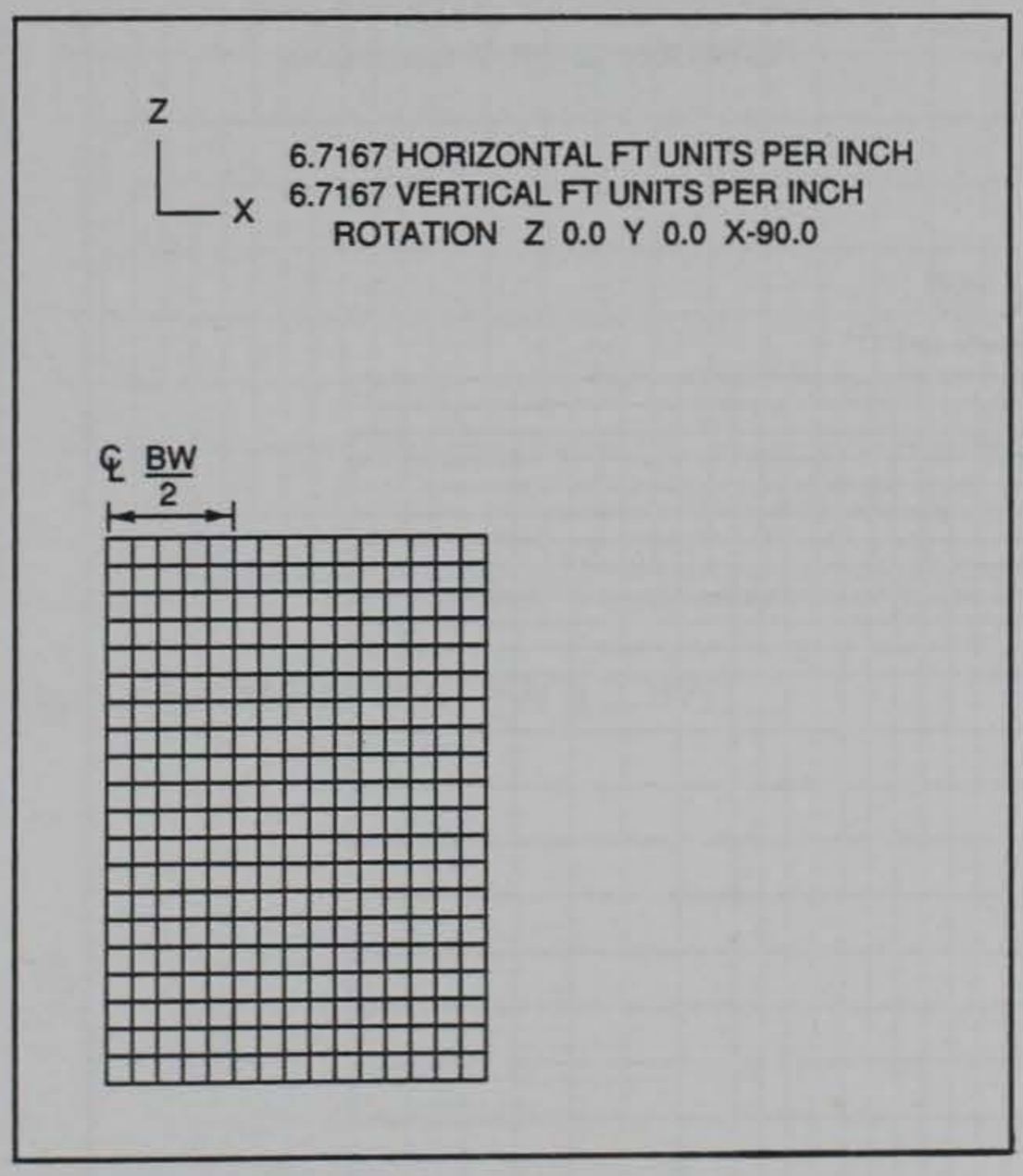


Figure 2. Model 2 (3 BW x 2 BW)

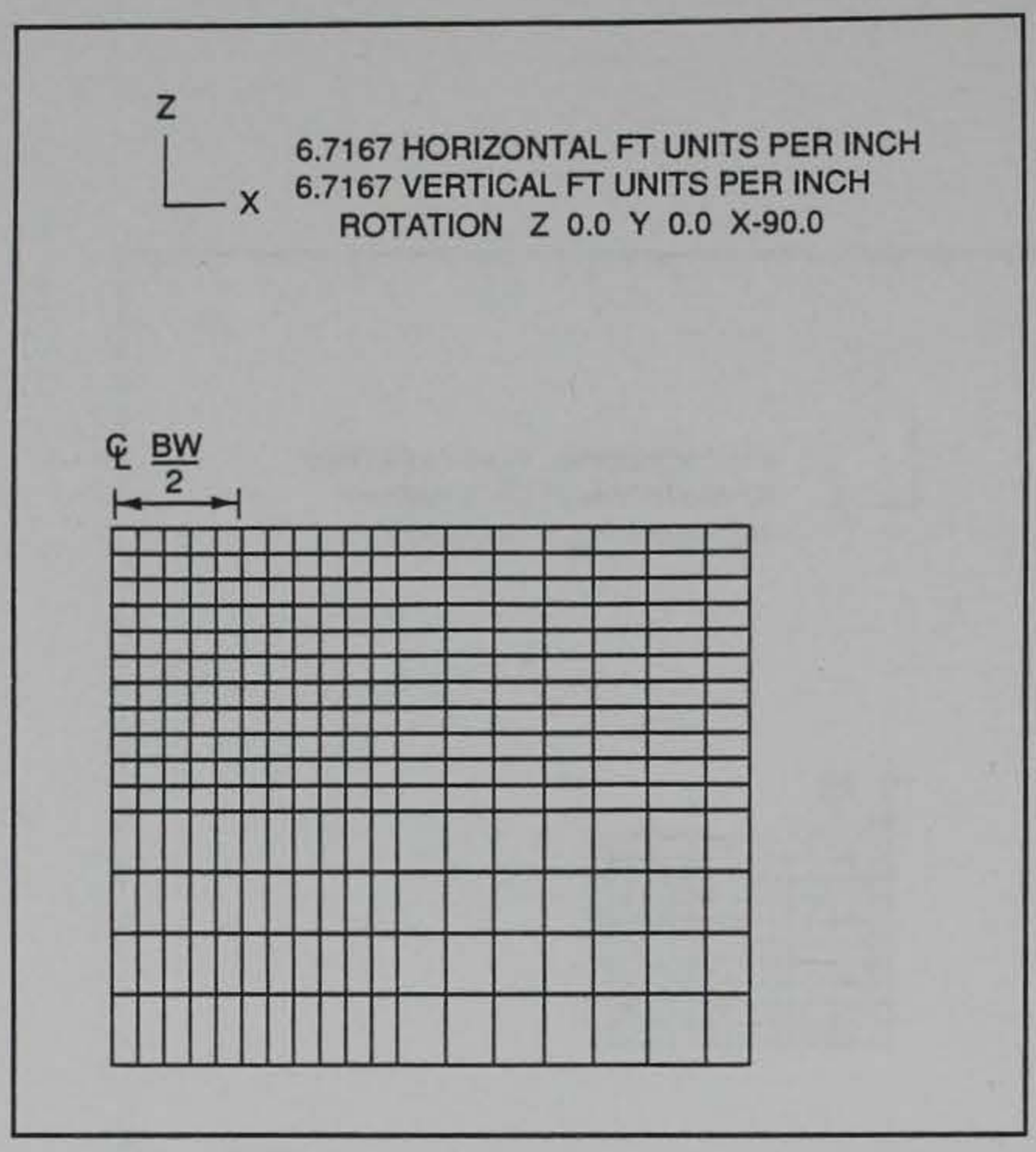


Figure 3. Model 3 (5 BW x 2 BW)

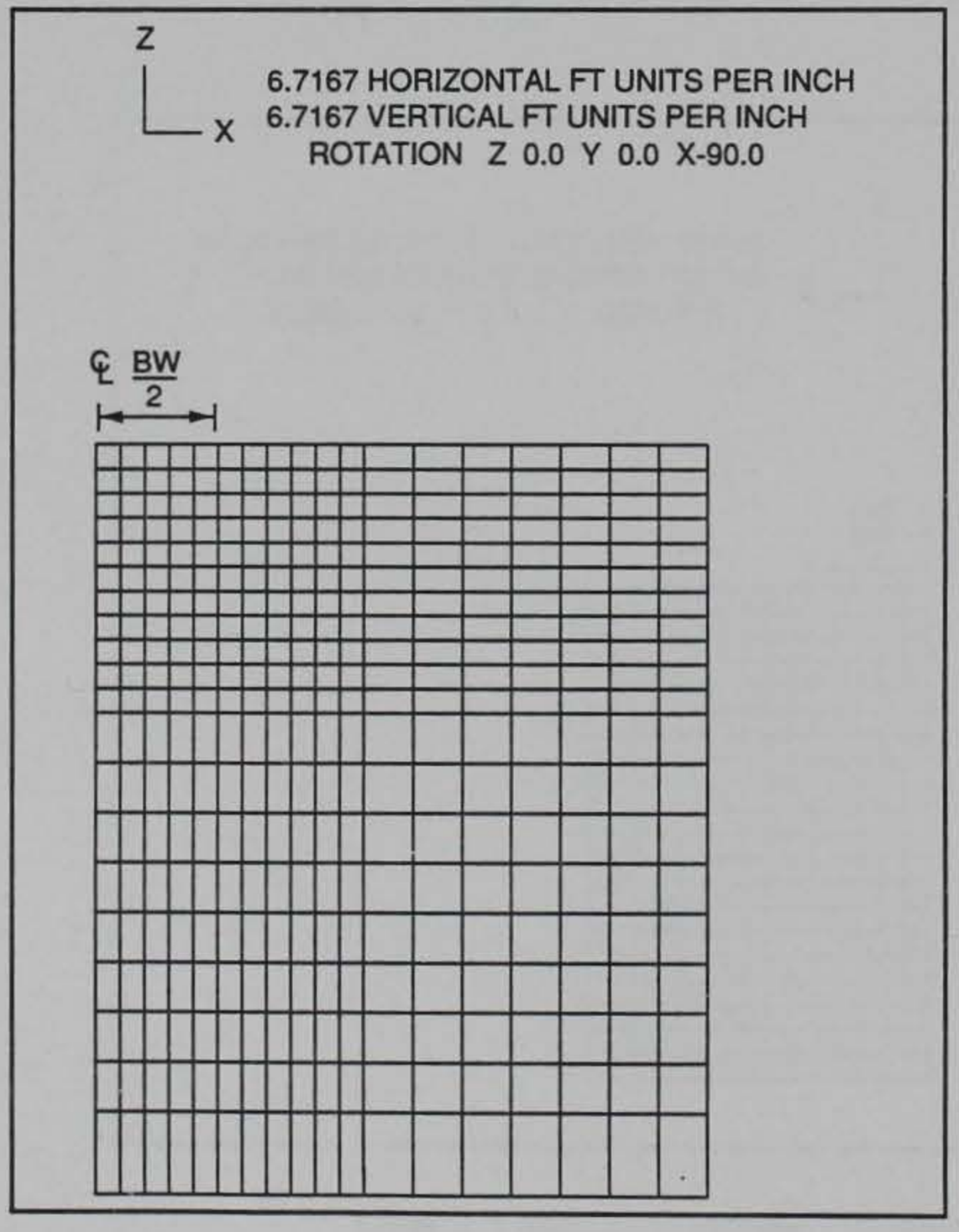


Figure 4. Model 4 (5 BW x 3 BW)

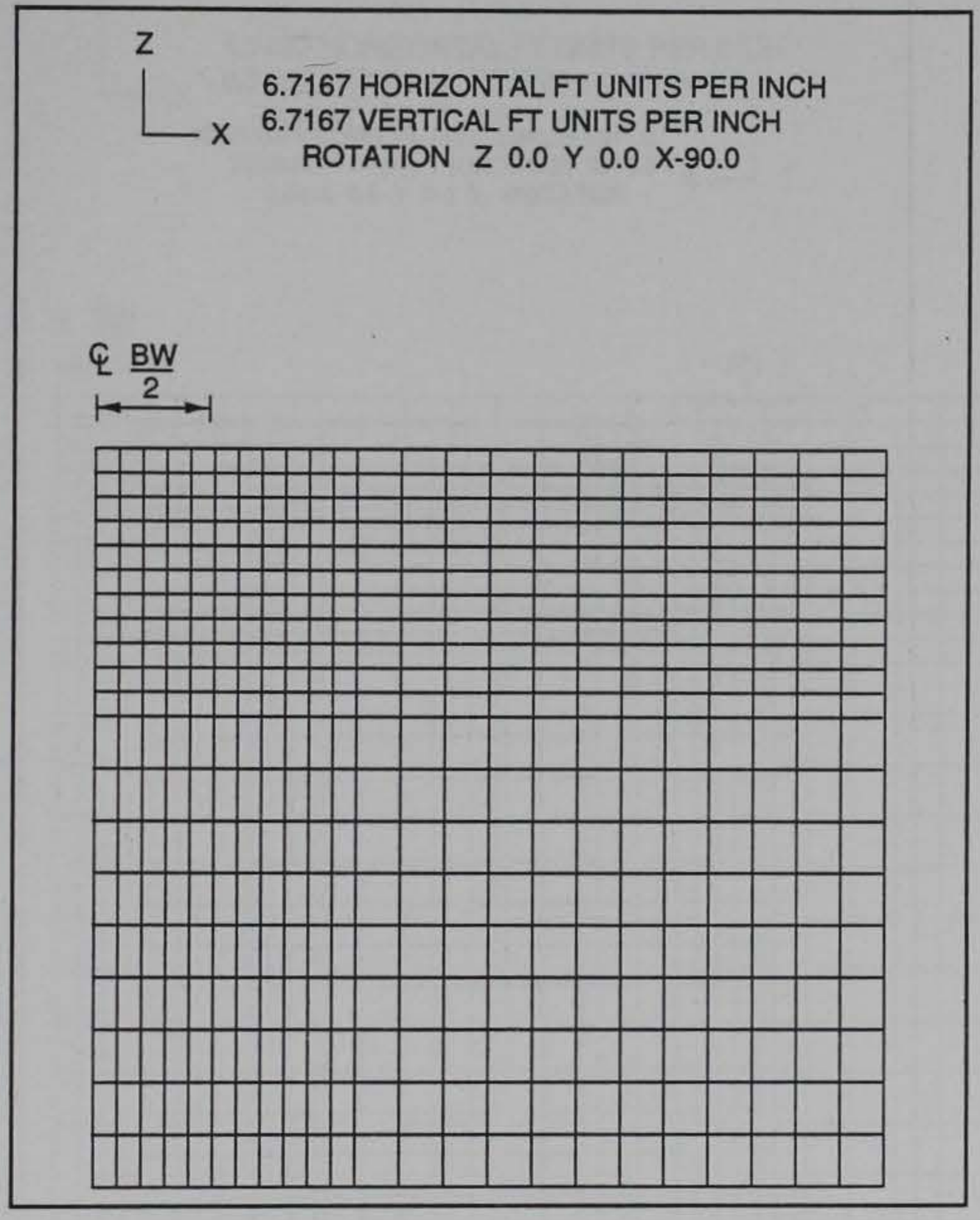


Figure 5. Model 5 (7 BW x 3 BW)

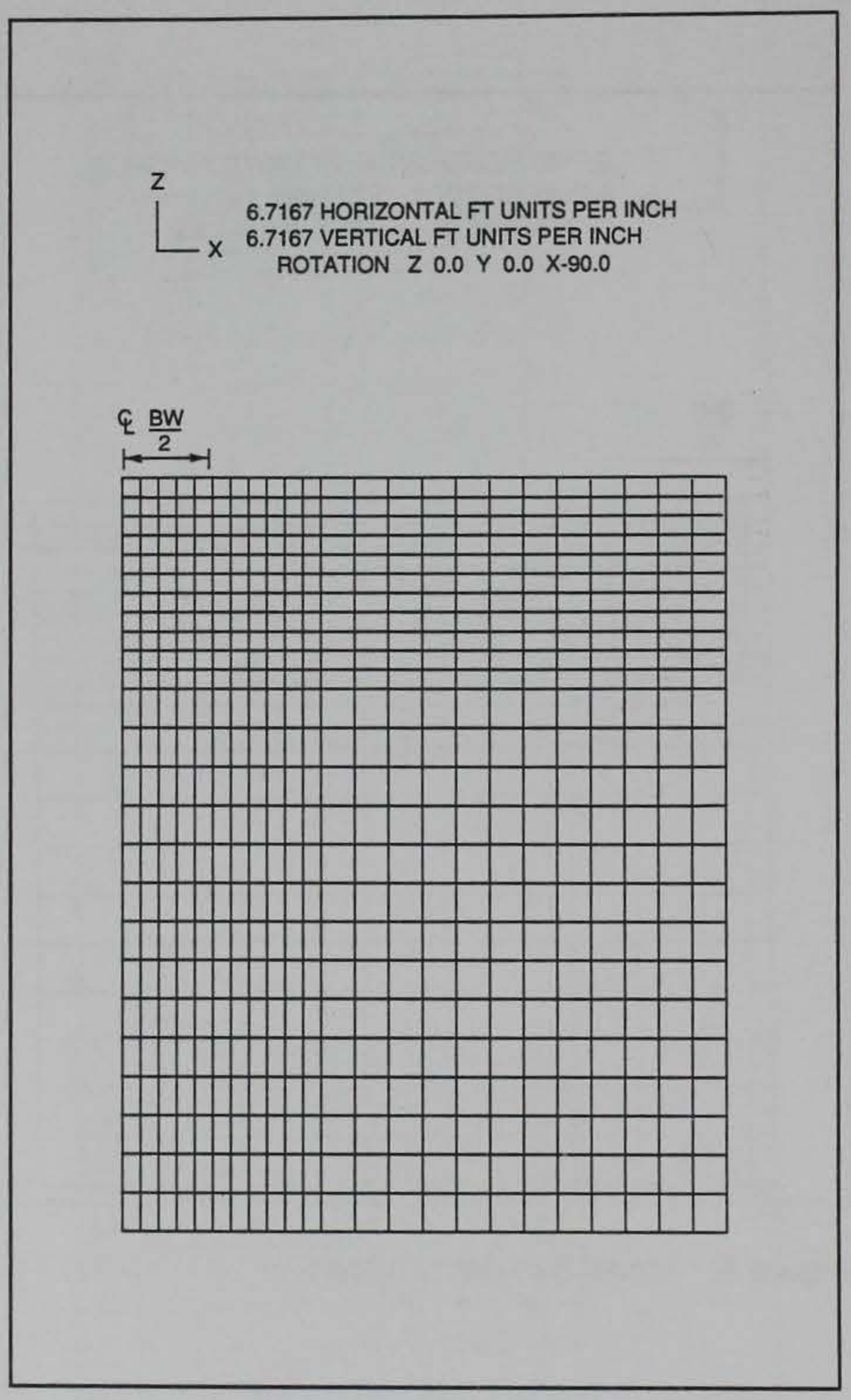


Figure 6. Model 6 (7 BW x 4 BW)

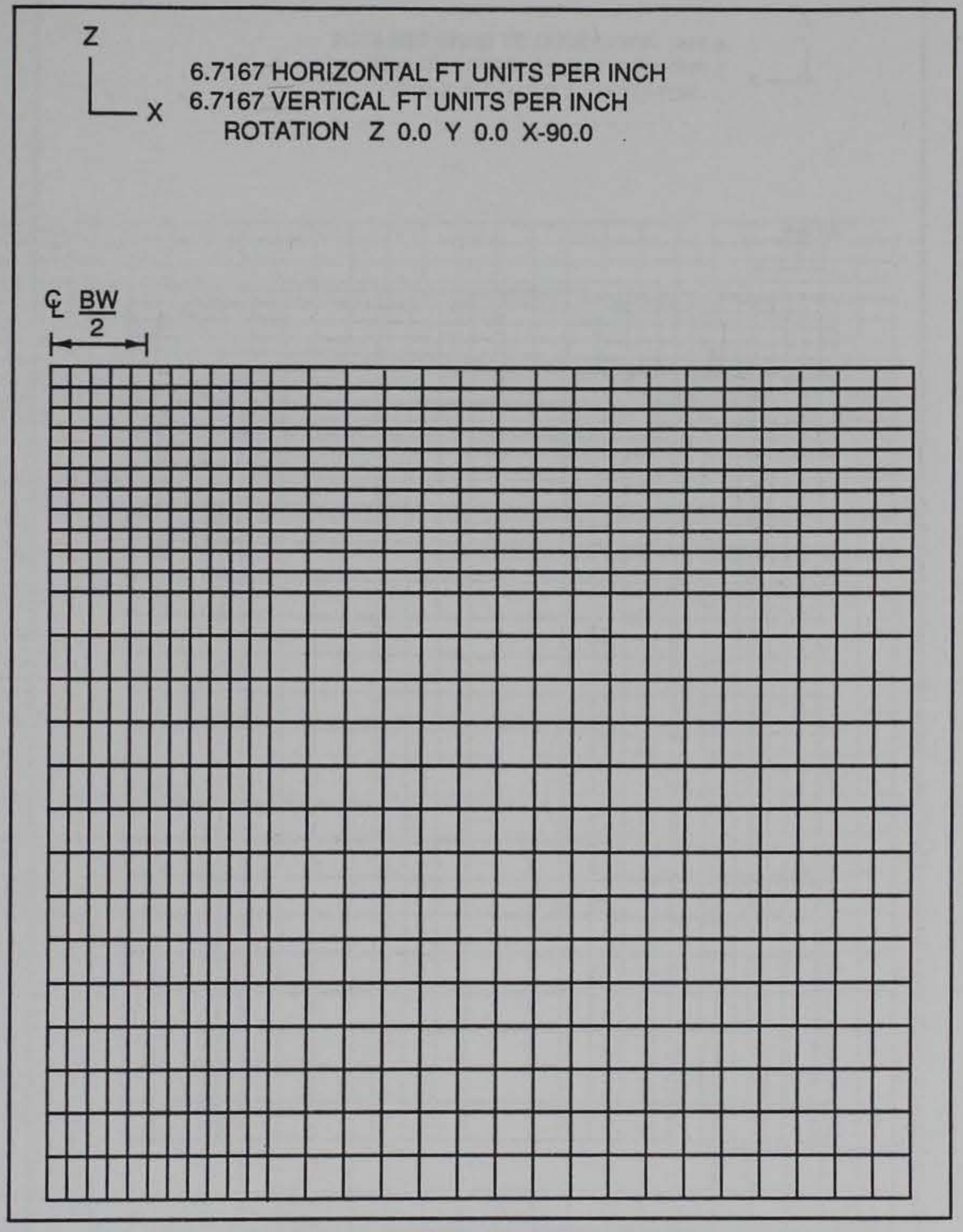


Figure 7. Model 7 (9 BW x 4 BW)

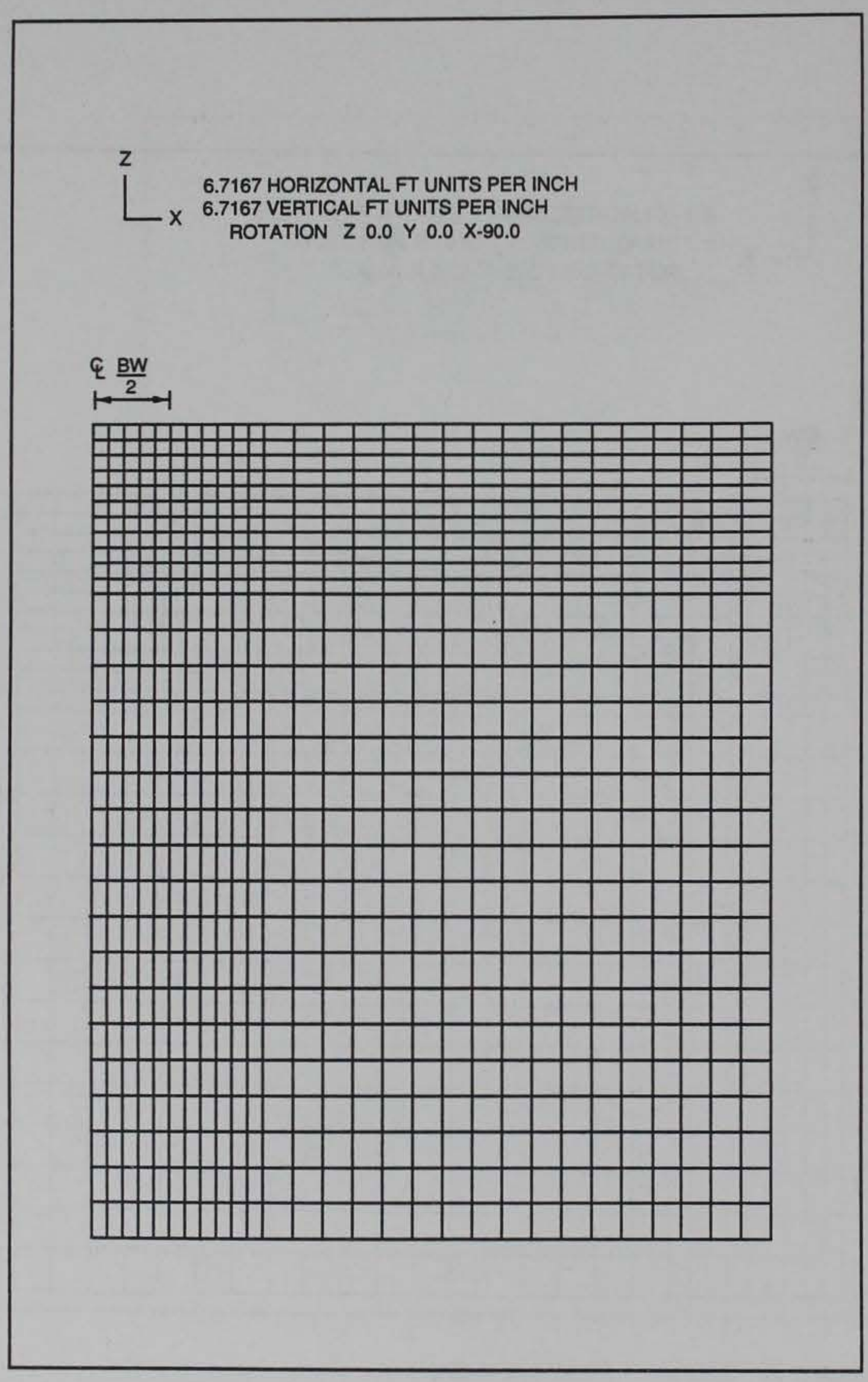


Figure 8. Model 8 (9 BW x 5 BW)

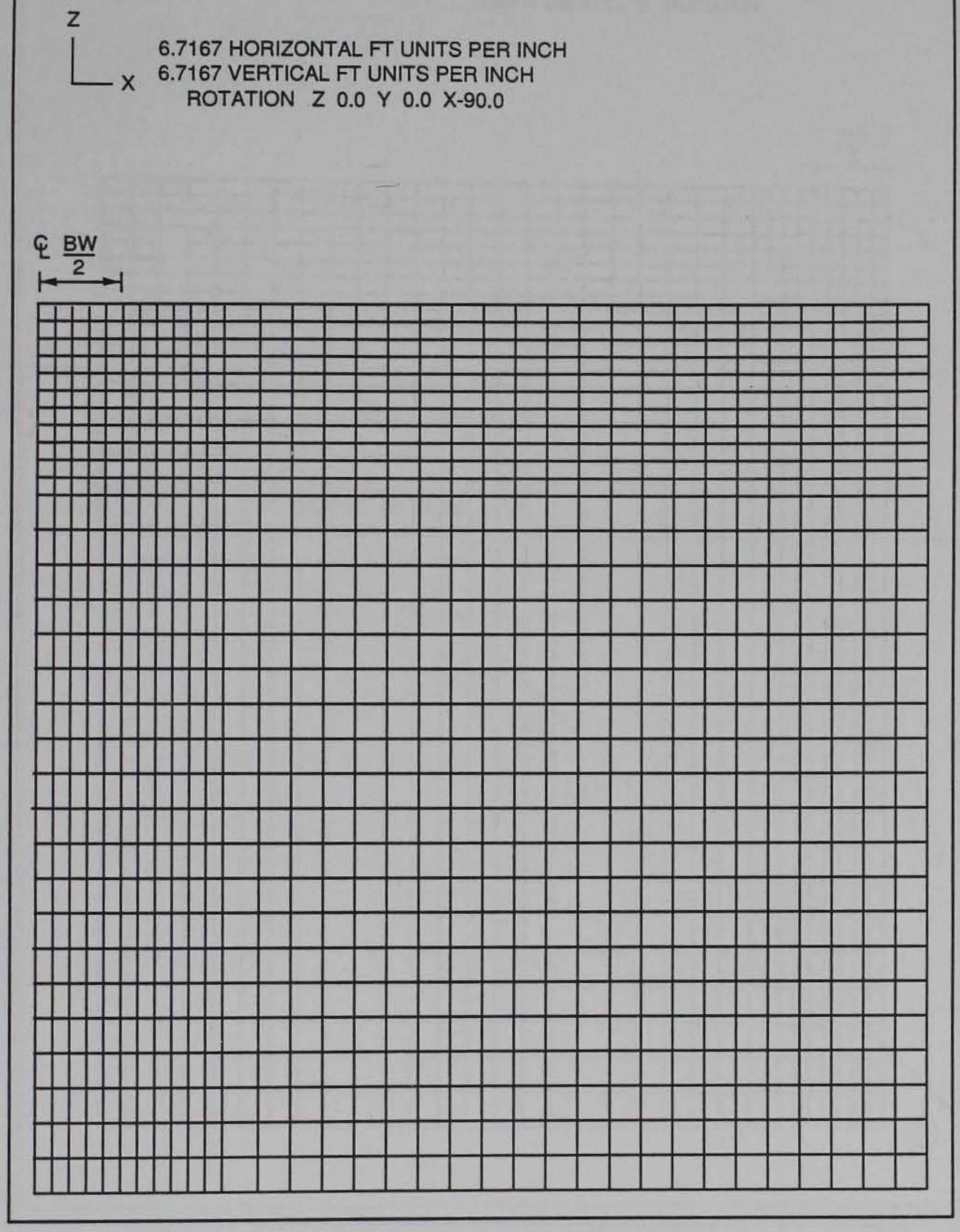


Figure 9. Model 9 (11 BW x 5 BW)

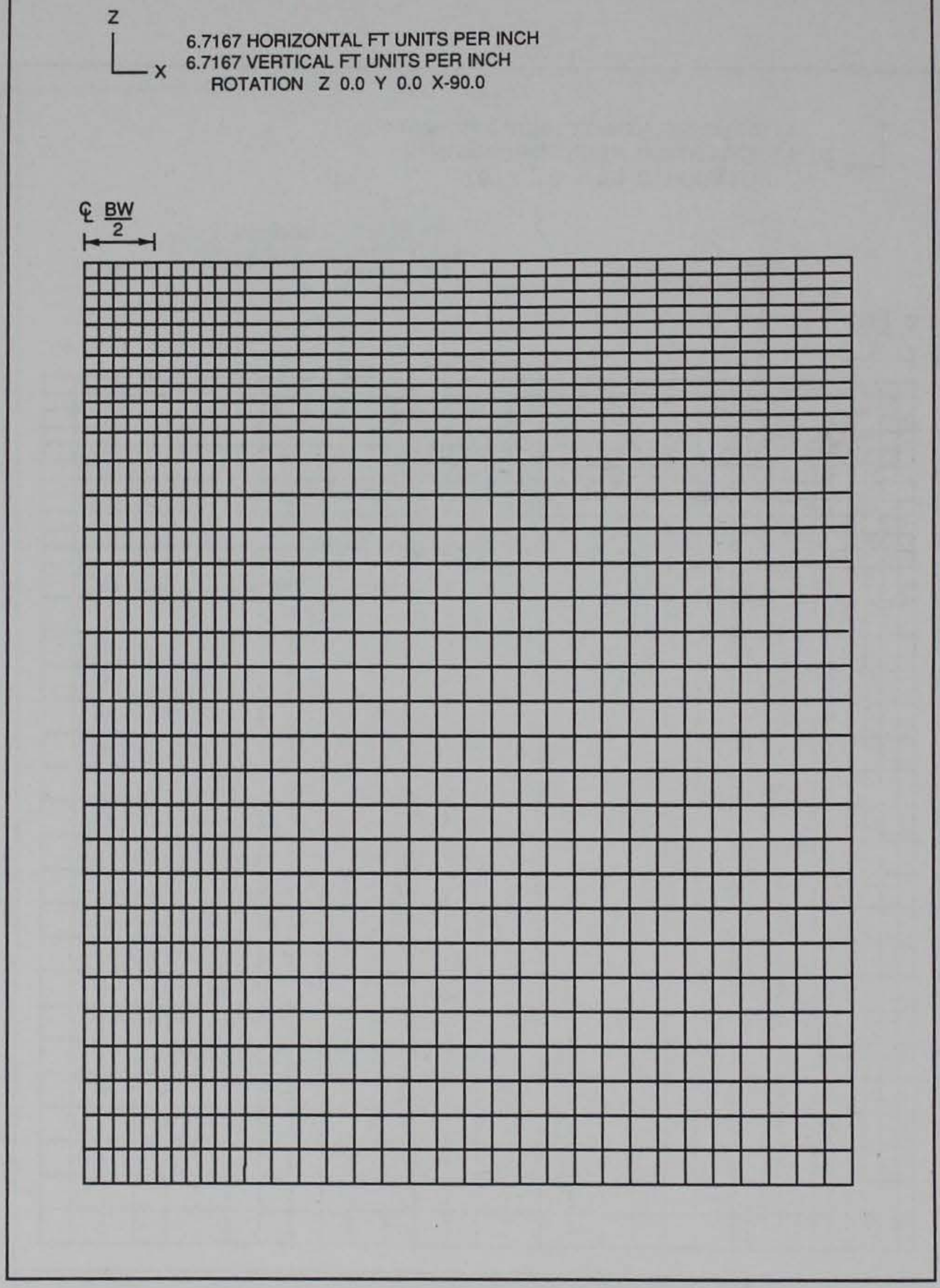


Figure 10. Model 10 (11 BW x 6 BW)

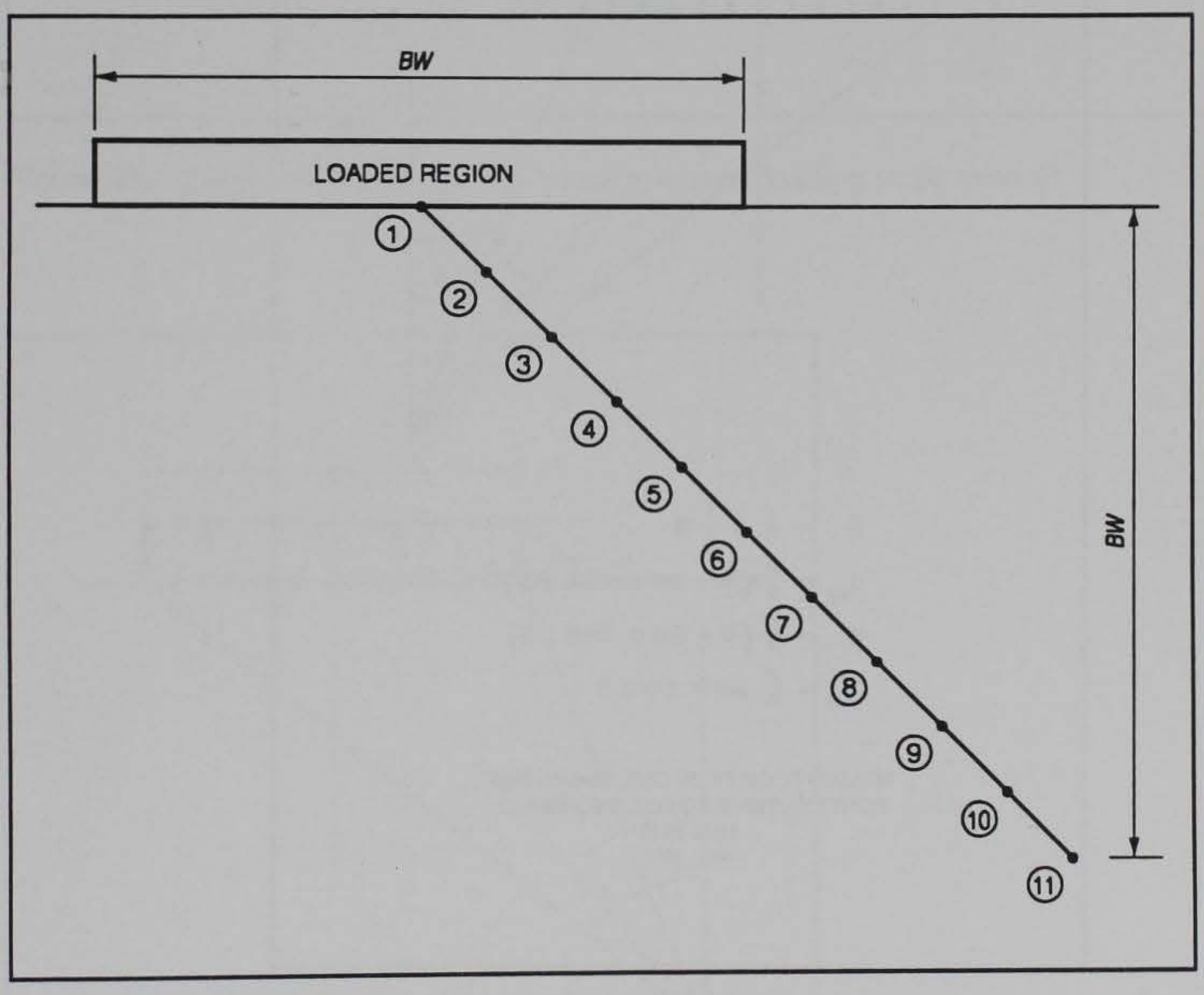
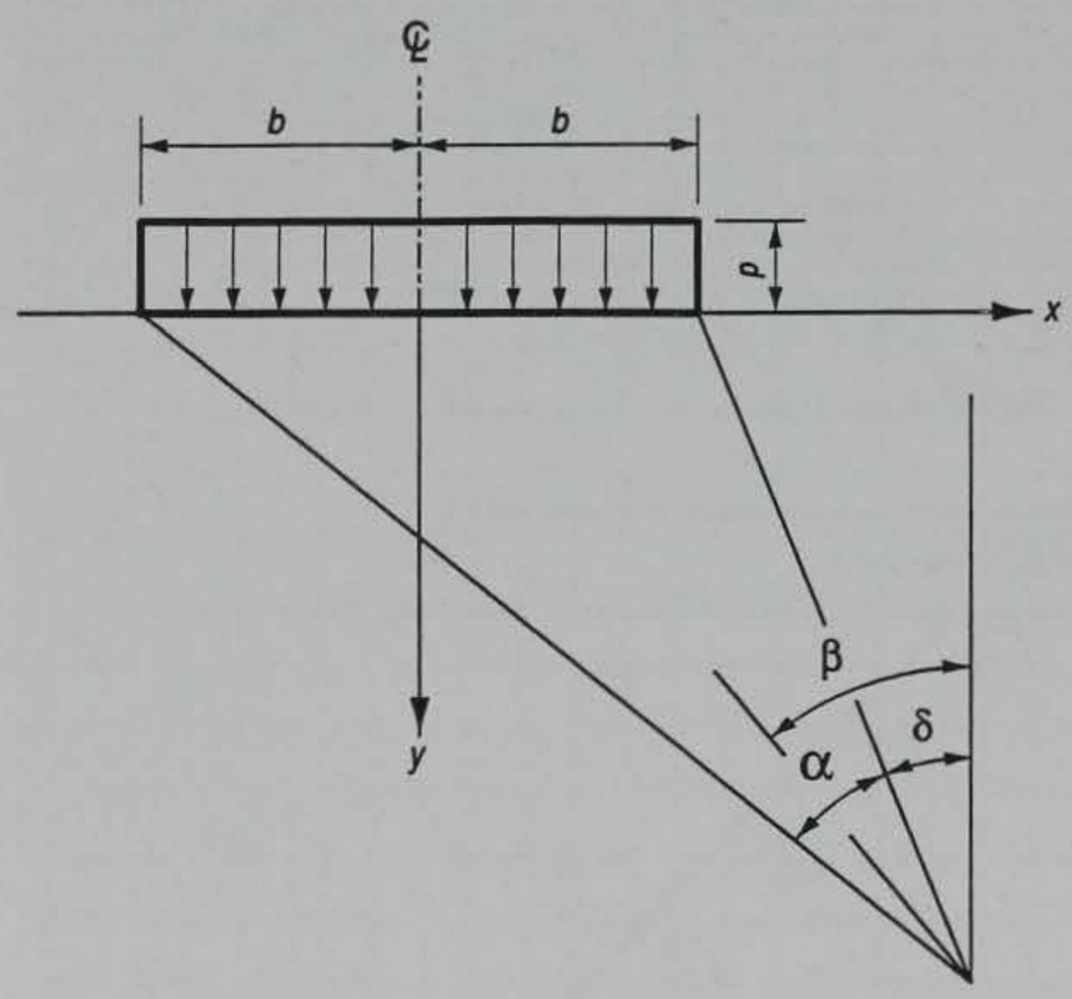


Figure 11. Nodes used for comparison



$$\beta = \delta + \frac{1}{2}\alpha$$

$$\sigma_{xx} = \frac{P}{\pi}\left(\alpha - \text{SIN}\,\alpha \;\; \text{COS}\; 2\,\beta\right)$$

$$\sigma_{yy} = \frac{P}{\pi}\left(\alpha + \text{SIN}\,\alpha \;\; \text{COS}\; 2\,\beta\right)$$

$$\tau_{xy} = \frac{P}{\pi}\;\text{SIN}\,\alpha \;\; \text{SIN}\; 2\,\beta$$

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Figure 12. Closed form stresses for normal pressure loading (load case 1)

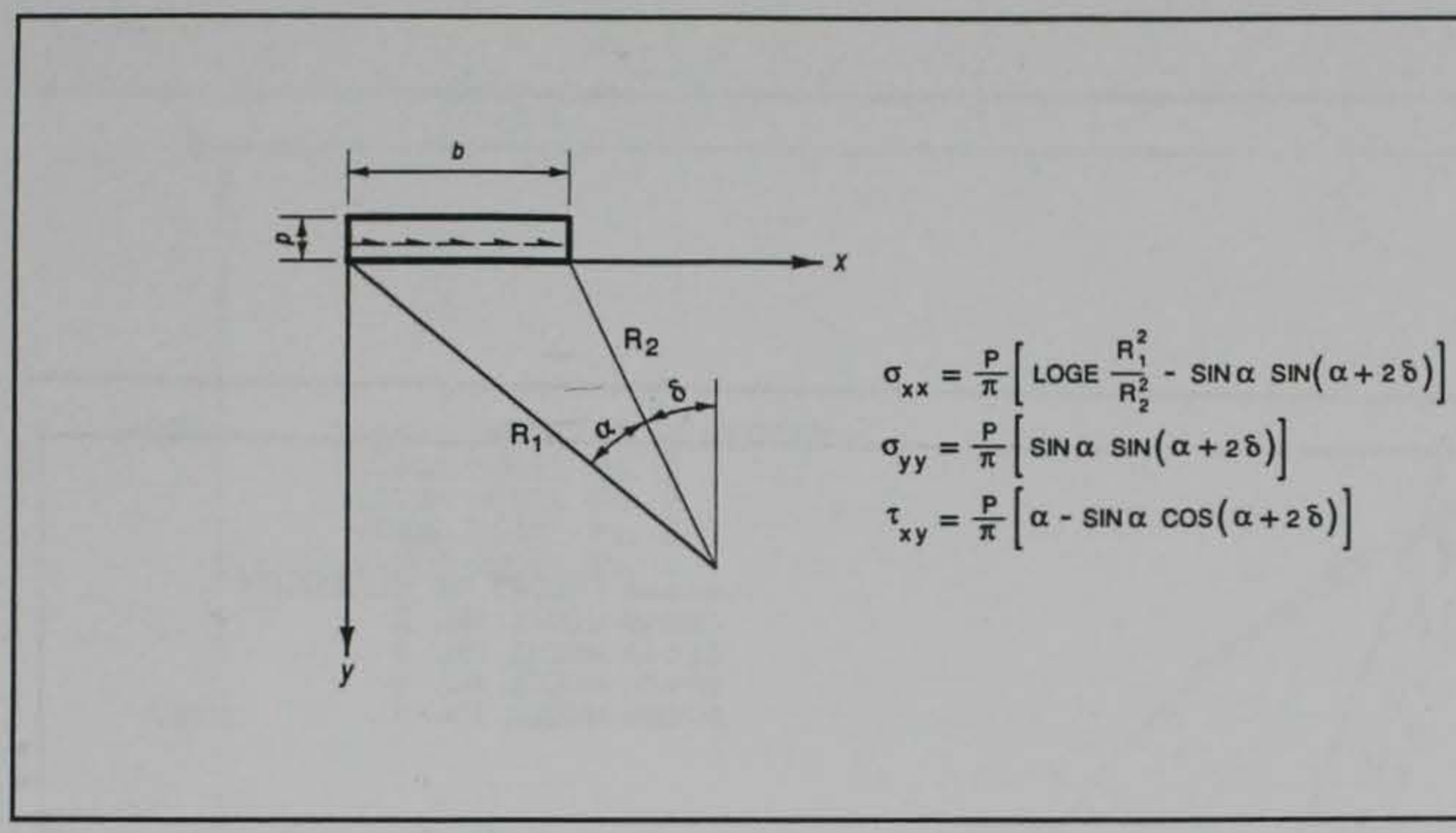


Figure 13. Closed form stresses for shear pressure loading (load case 2)

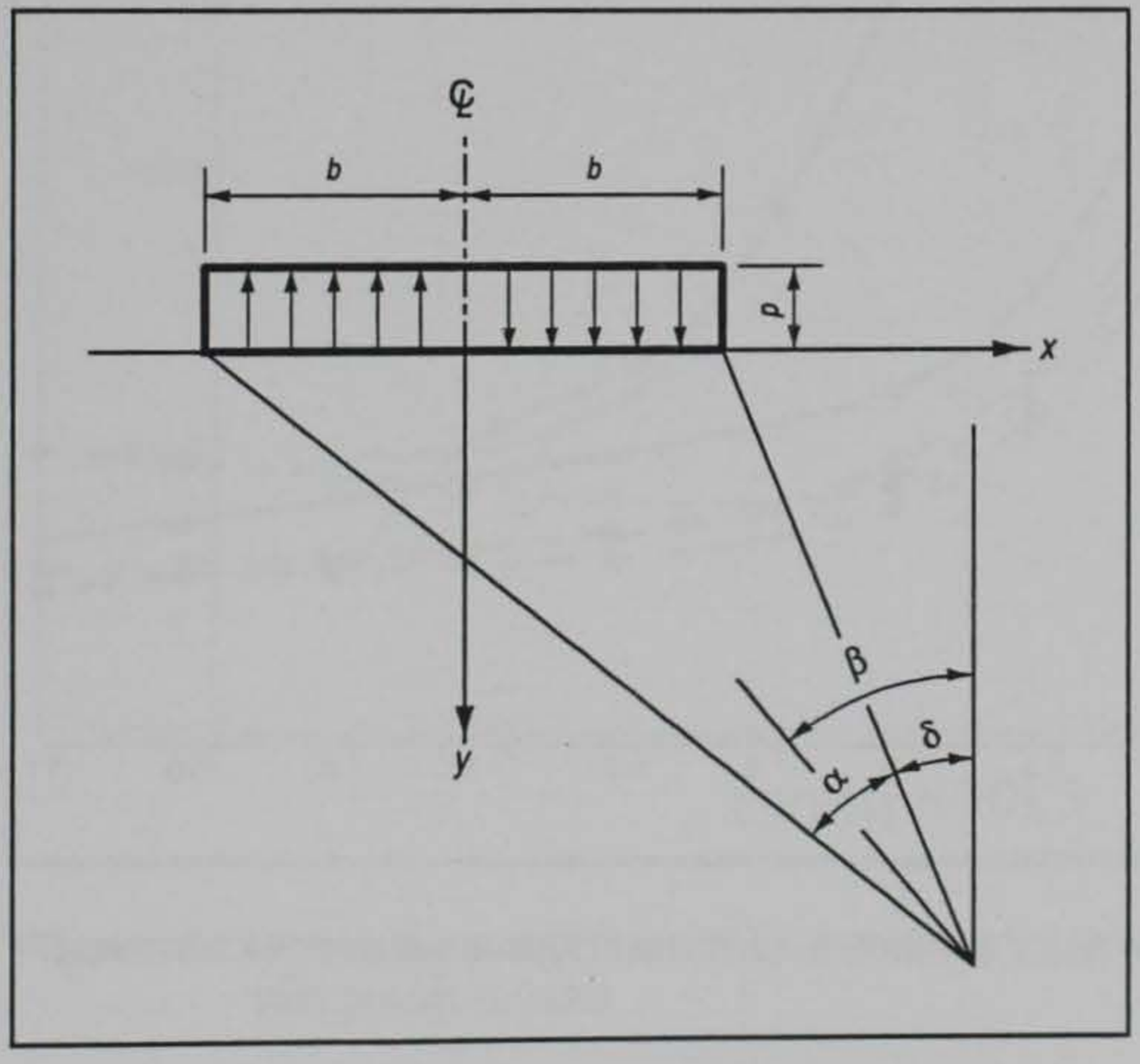


Figure 14. Closed form stresses for antisymmetric normal pressure loading (load case 3)

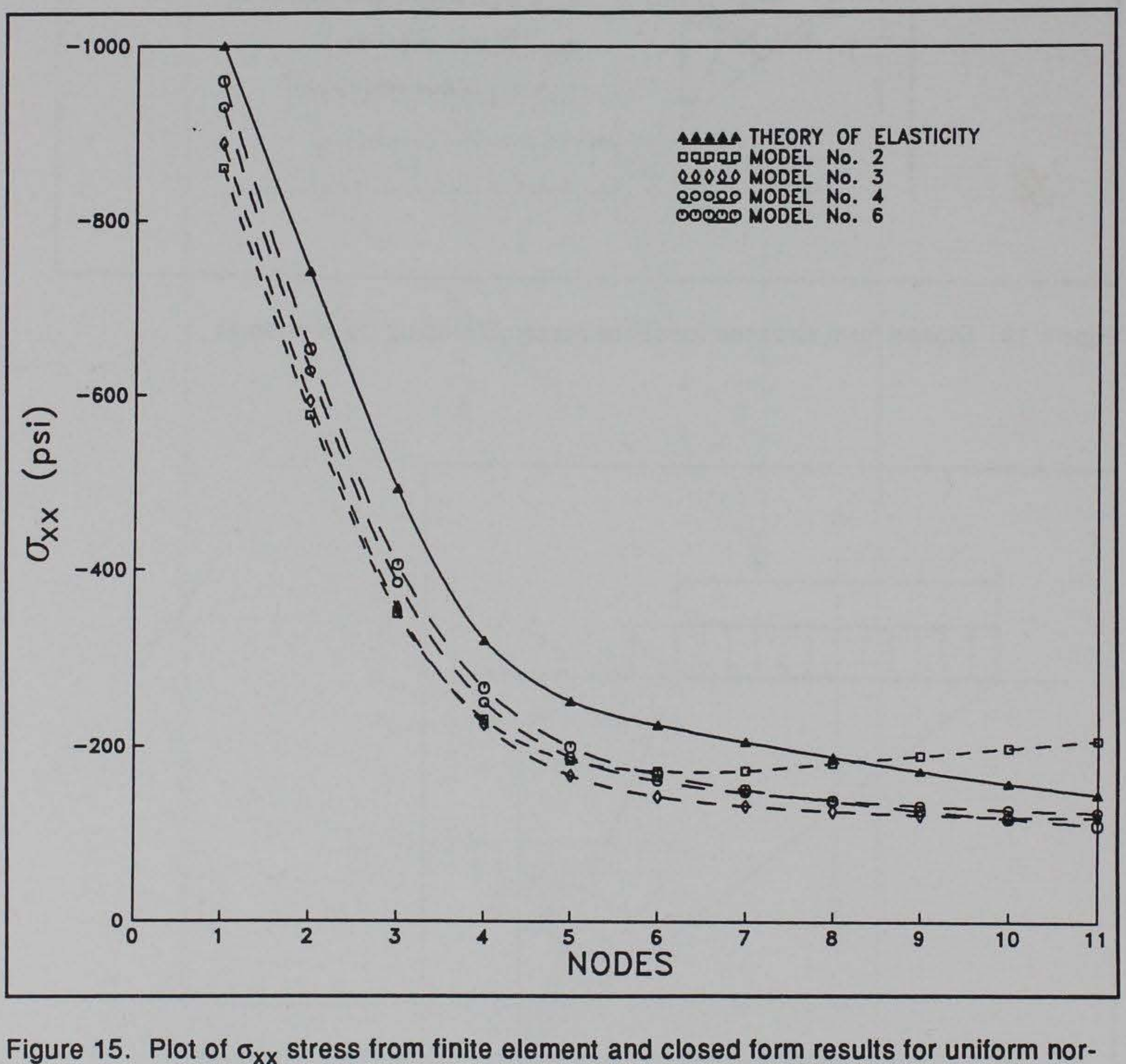


Figure 15. Plot of σ_{xx} stress from finite element and closed form results for uniform normal pressure load

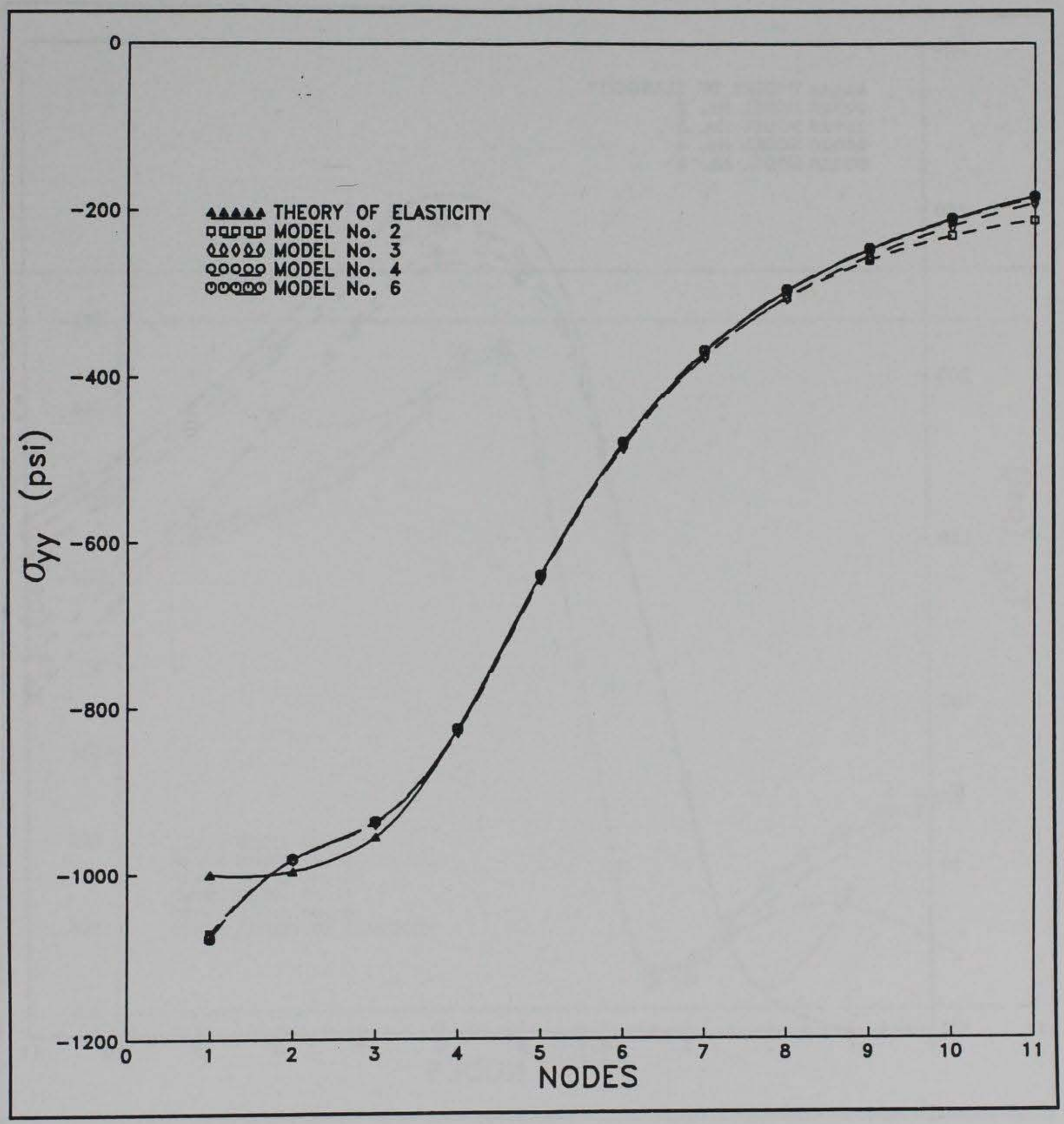


Figure 16. Plot of σ_{yy} stress from finite element and closed form results for uniform normal pressure load

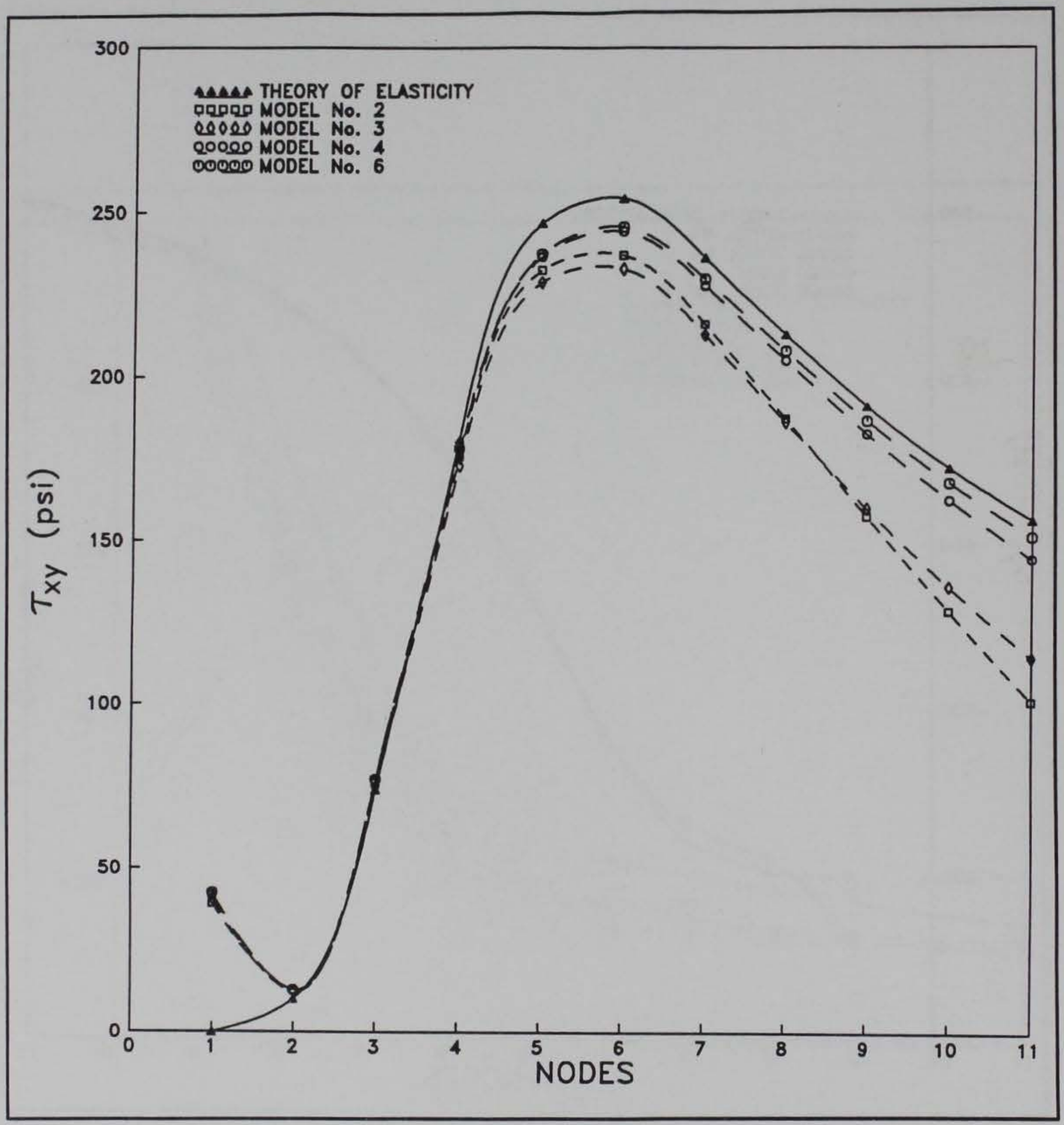


Figure 17. Plot of τ_{xy} stress from finite element and closed form results for uniform normal pressure load

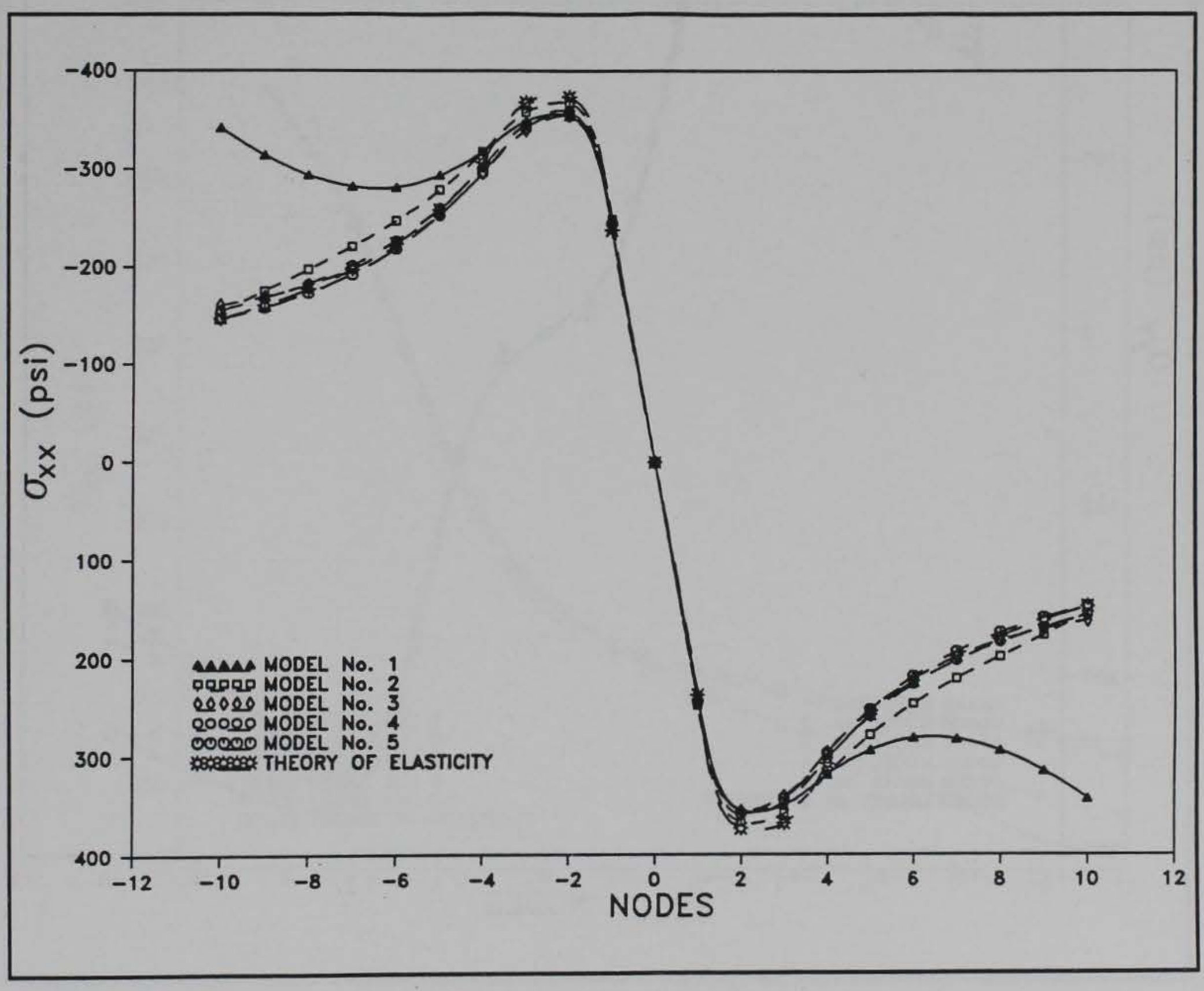


Figure 18. Plot of σ_{xx} stress from finite element and closed form results for uniform shear load

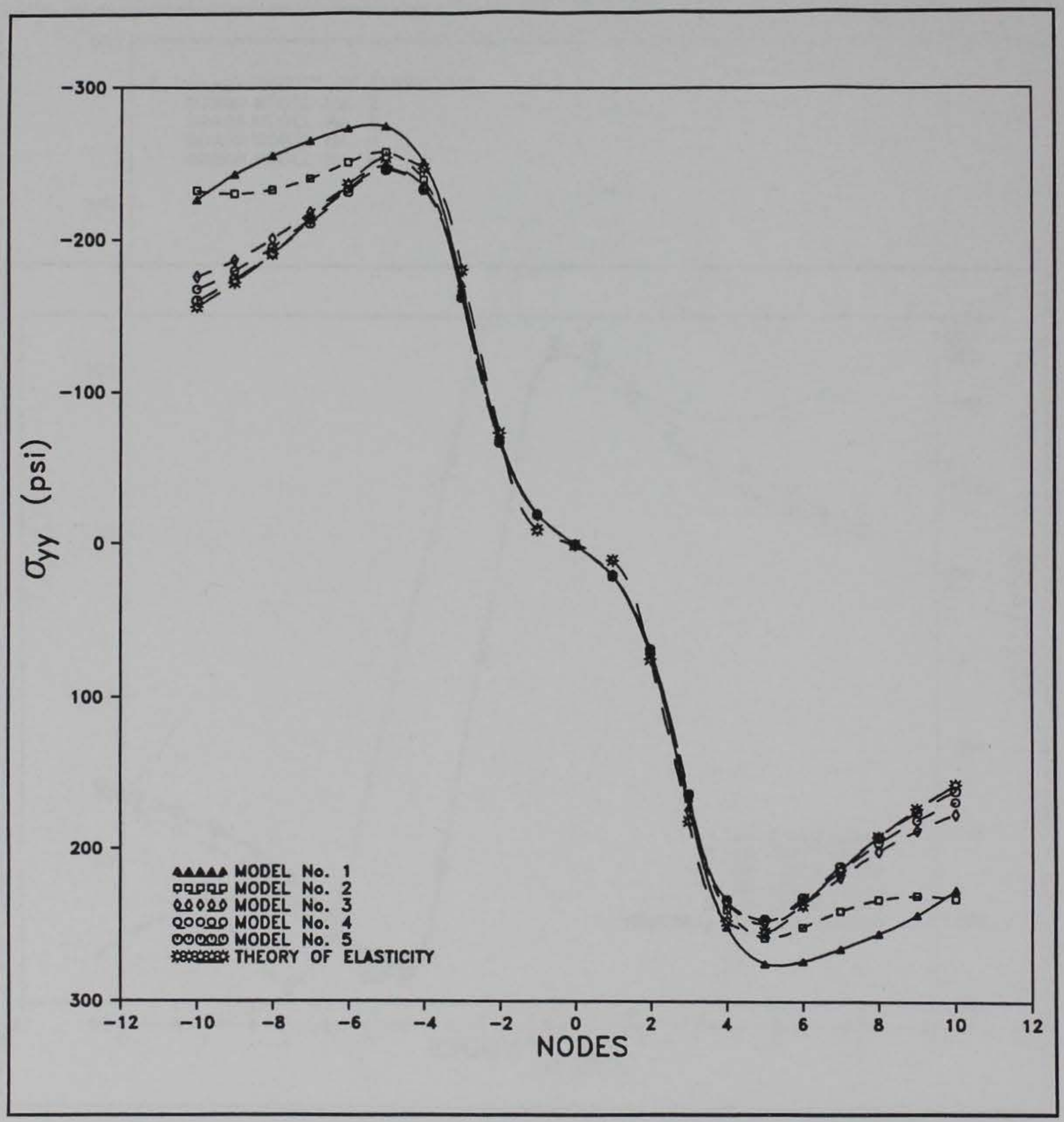


Figure 19. Plot of σ_{yy} stress from finite element and closed form results for uniform shear load

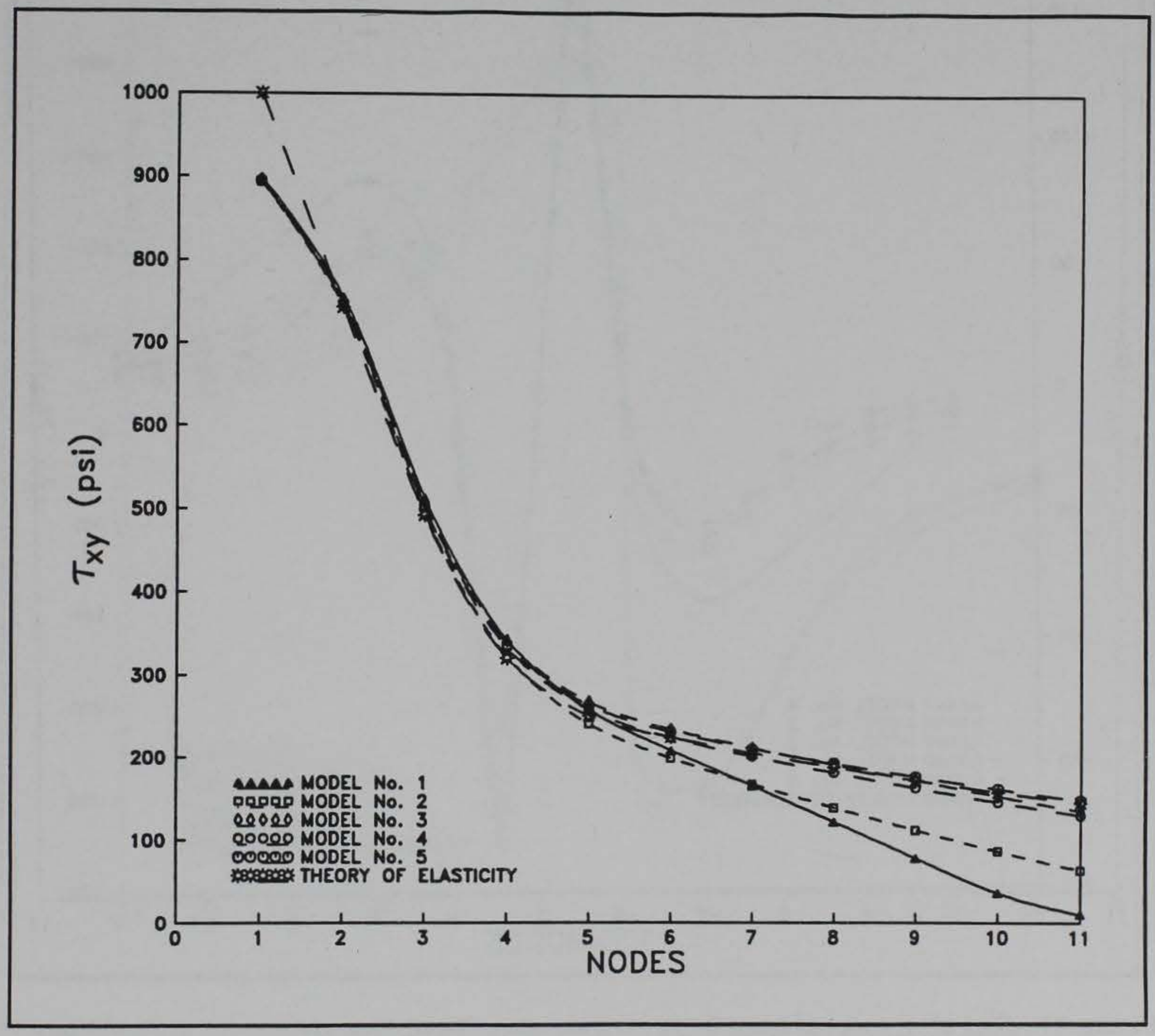


Figure 20. Plot of τ_{xy} stress from finite element and closed form results for uniform shear load

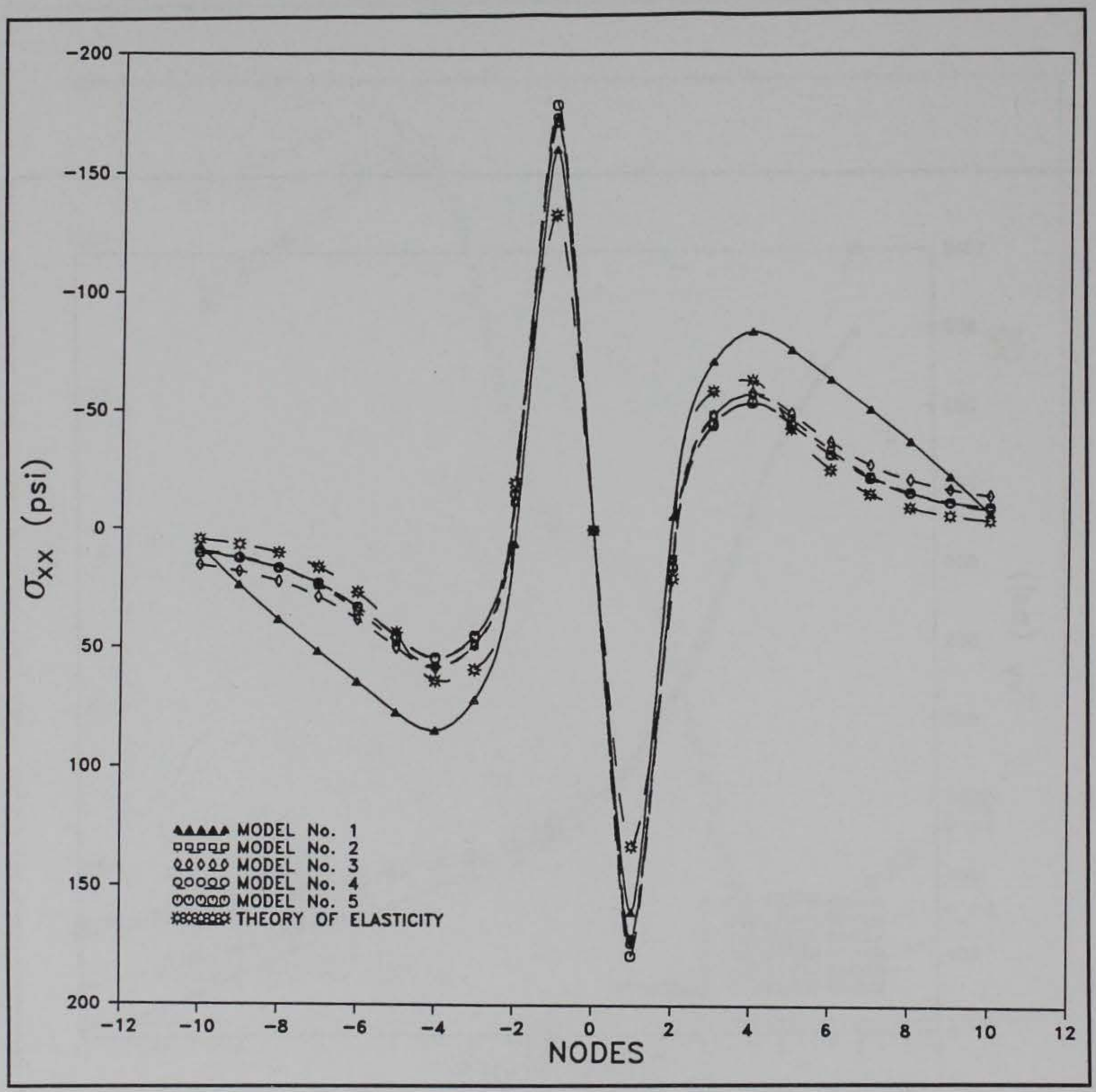


Figure 21. Plot of σ_{xx} stress from finite element and closed form results for antisymmetric normal pressure

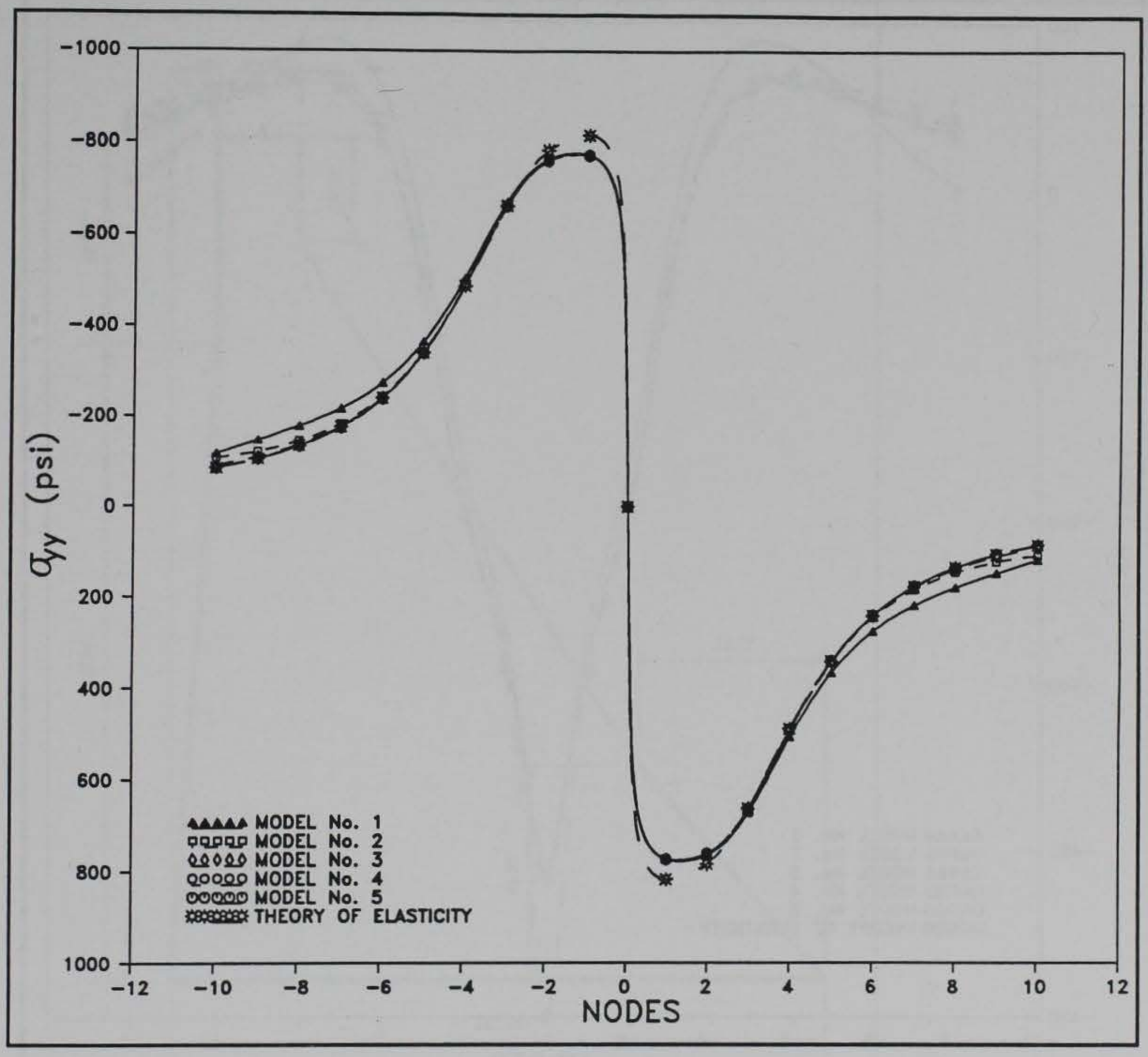


Figure 22. Plot of σ_{yy} stress from finite element and closed form results for antisymmetric normal pressure

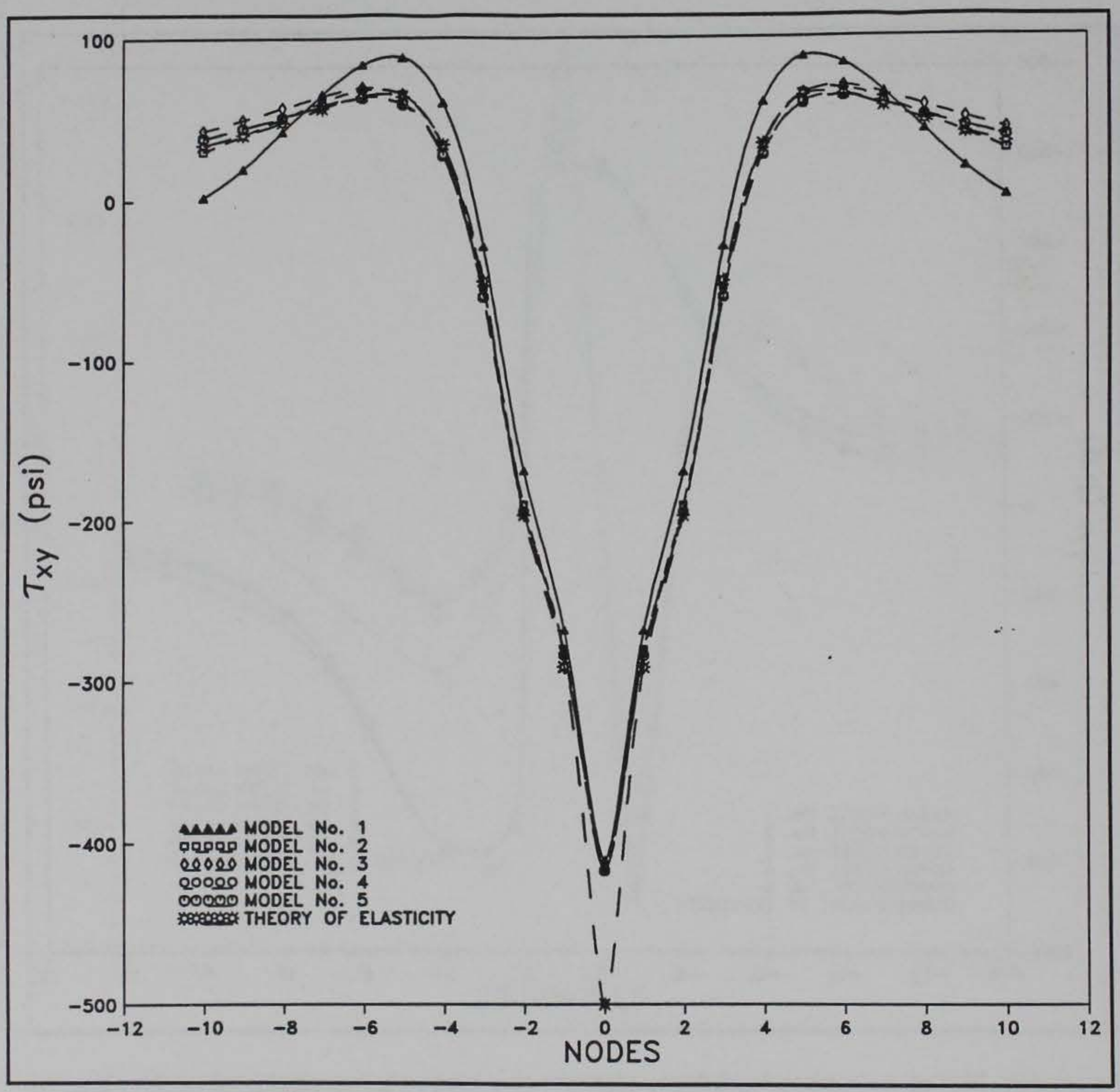


Figure 23. Plot of τ_{xy} stress from finite element and closed form results for antisymmetric normal pressure

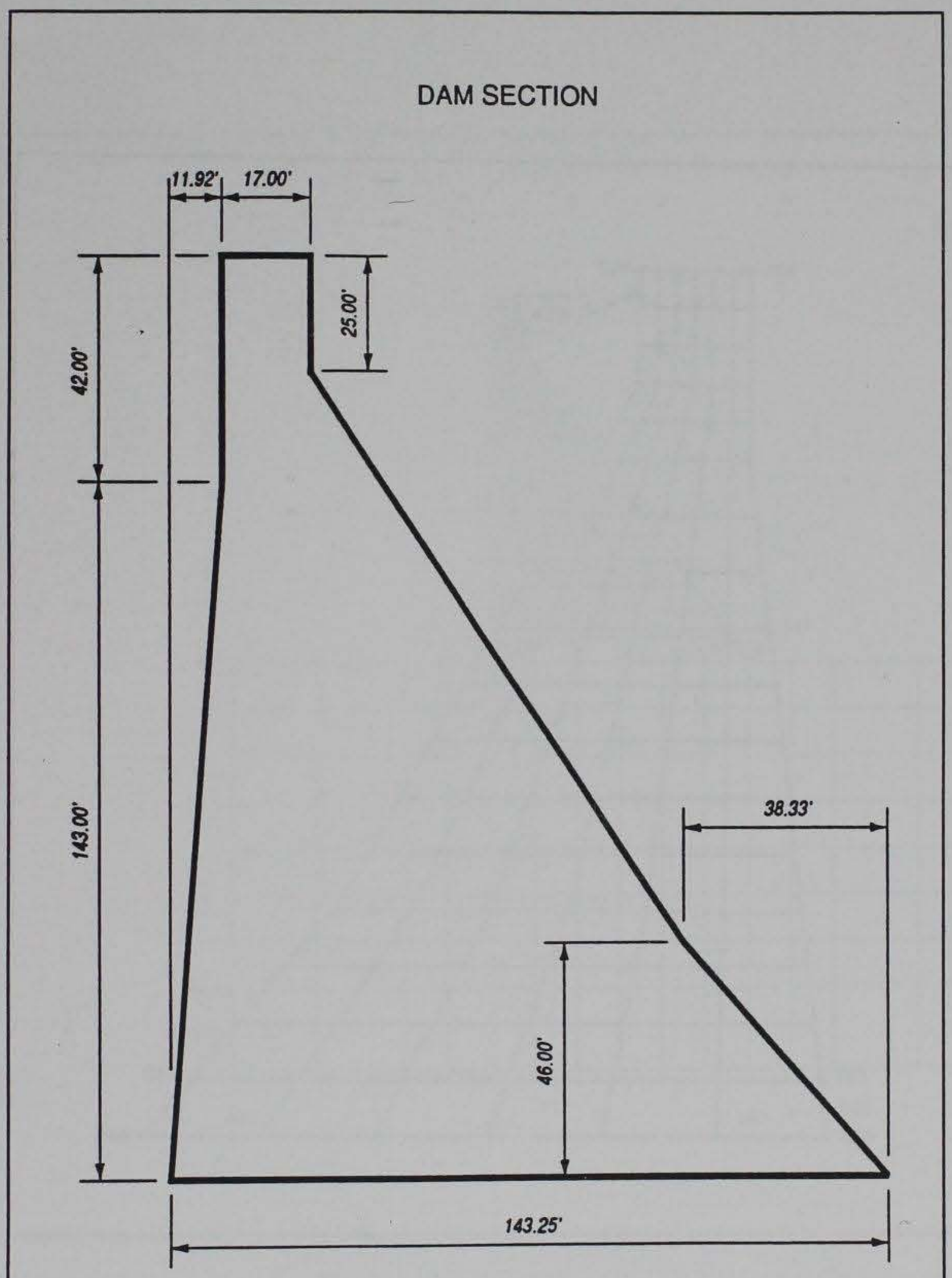


Figure 24. Gravity dam section

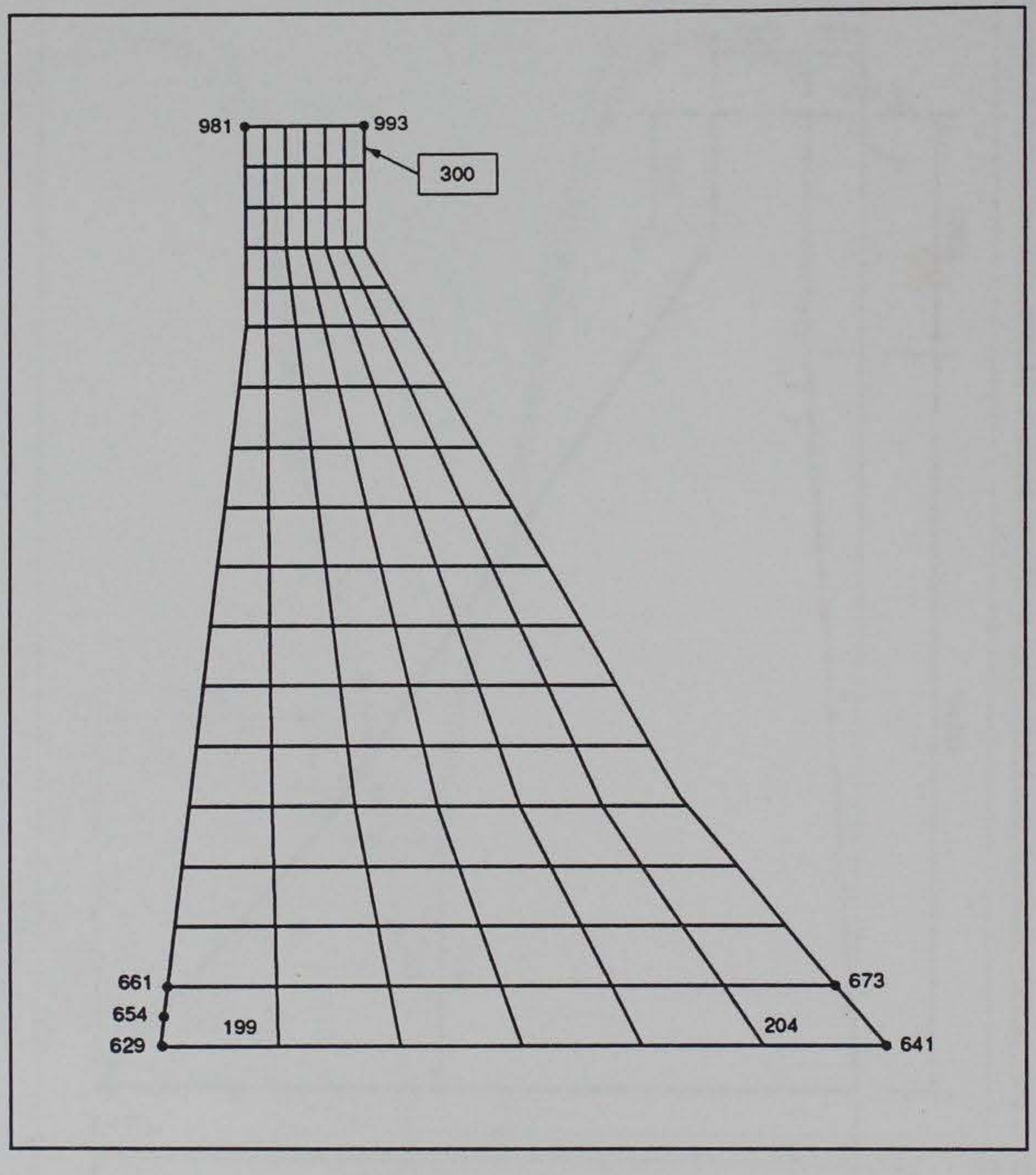


Figure 25. Six base-element model

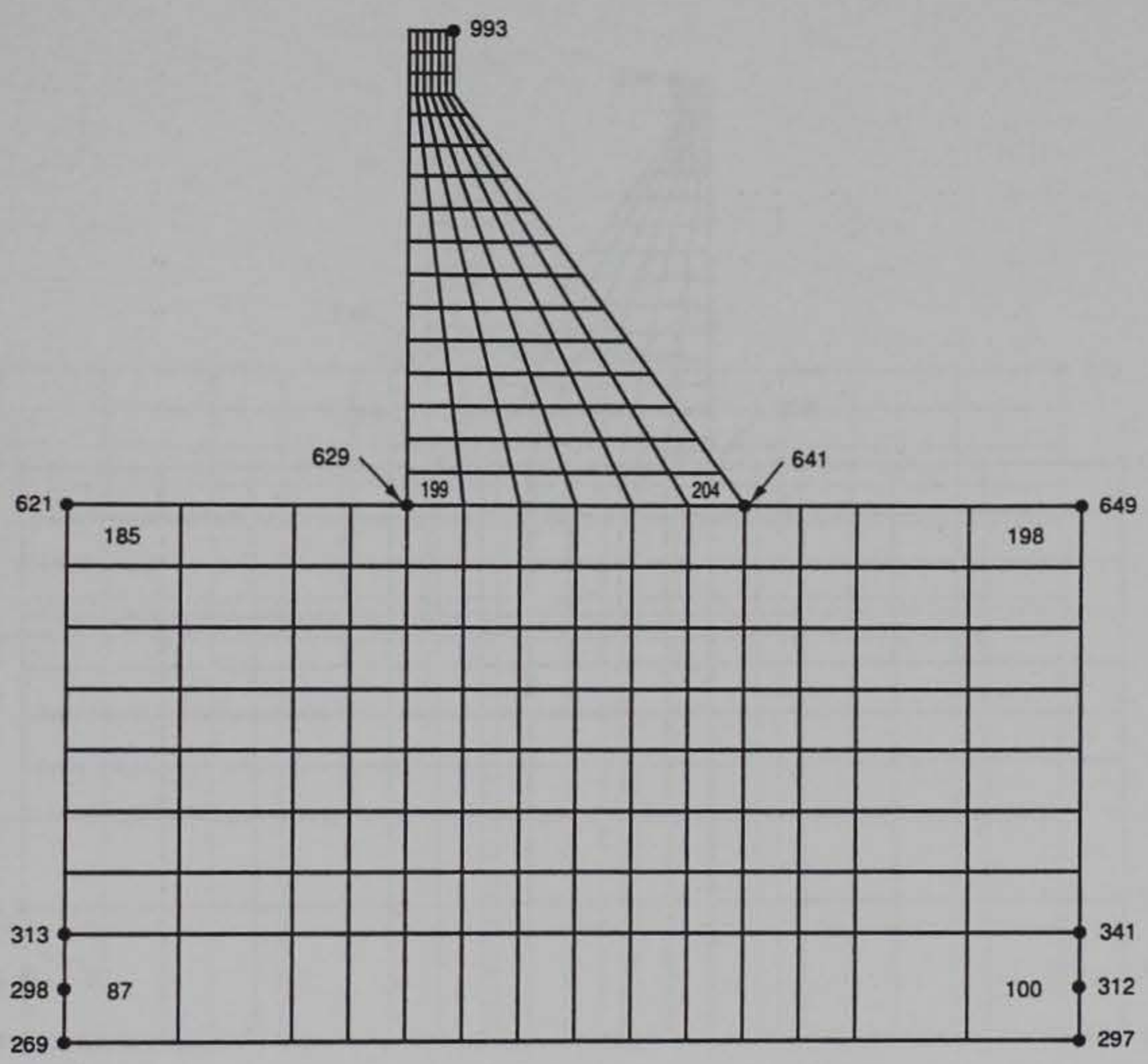


Figure 26. Model 1 (1.5-BW x 3-BW foundation model)

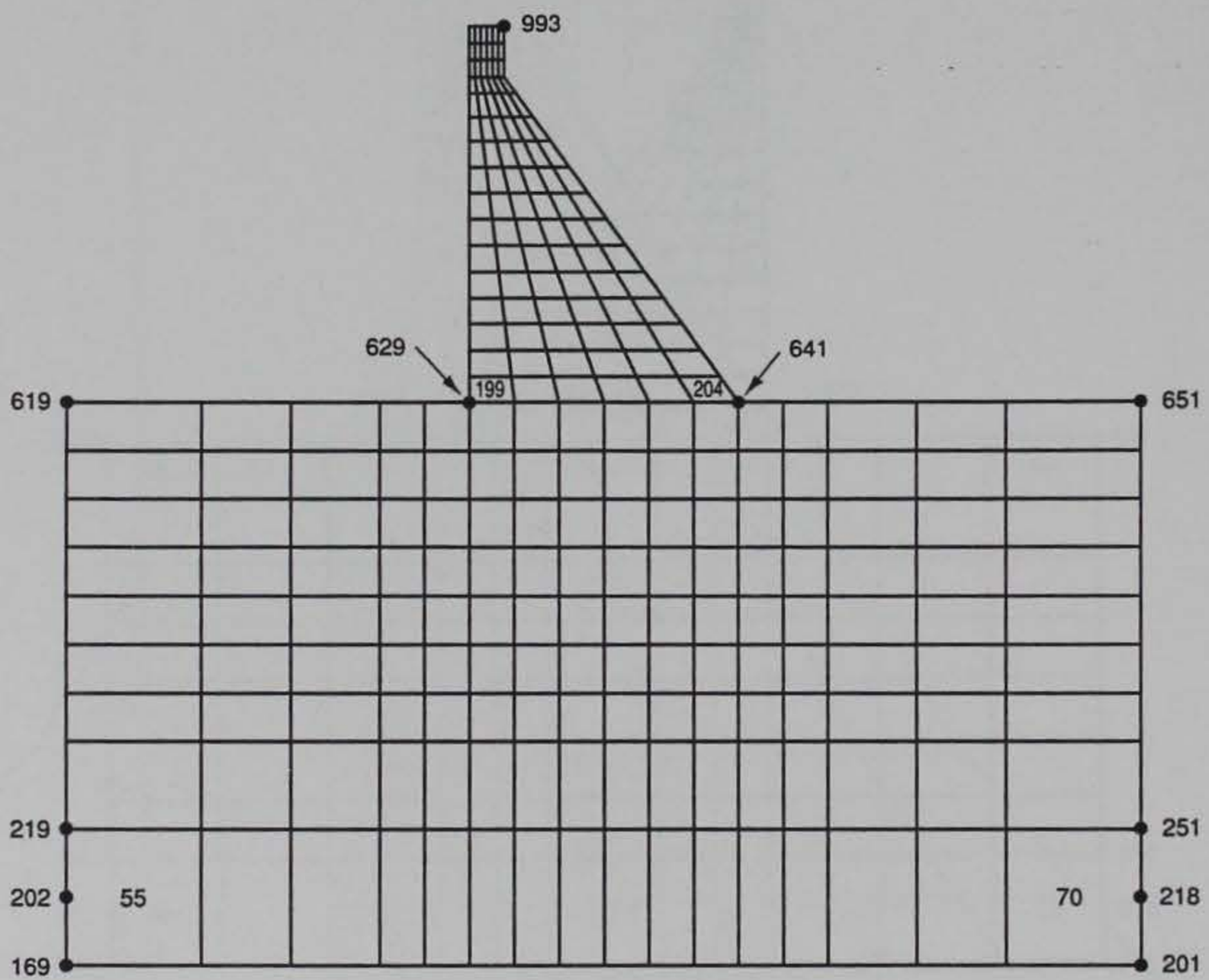


Figure 27. Model 2 (2-BW x 4-BW foundation model)

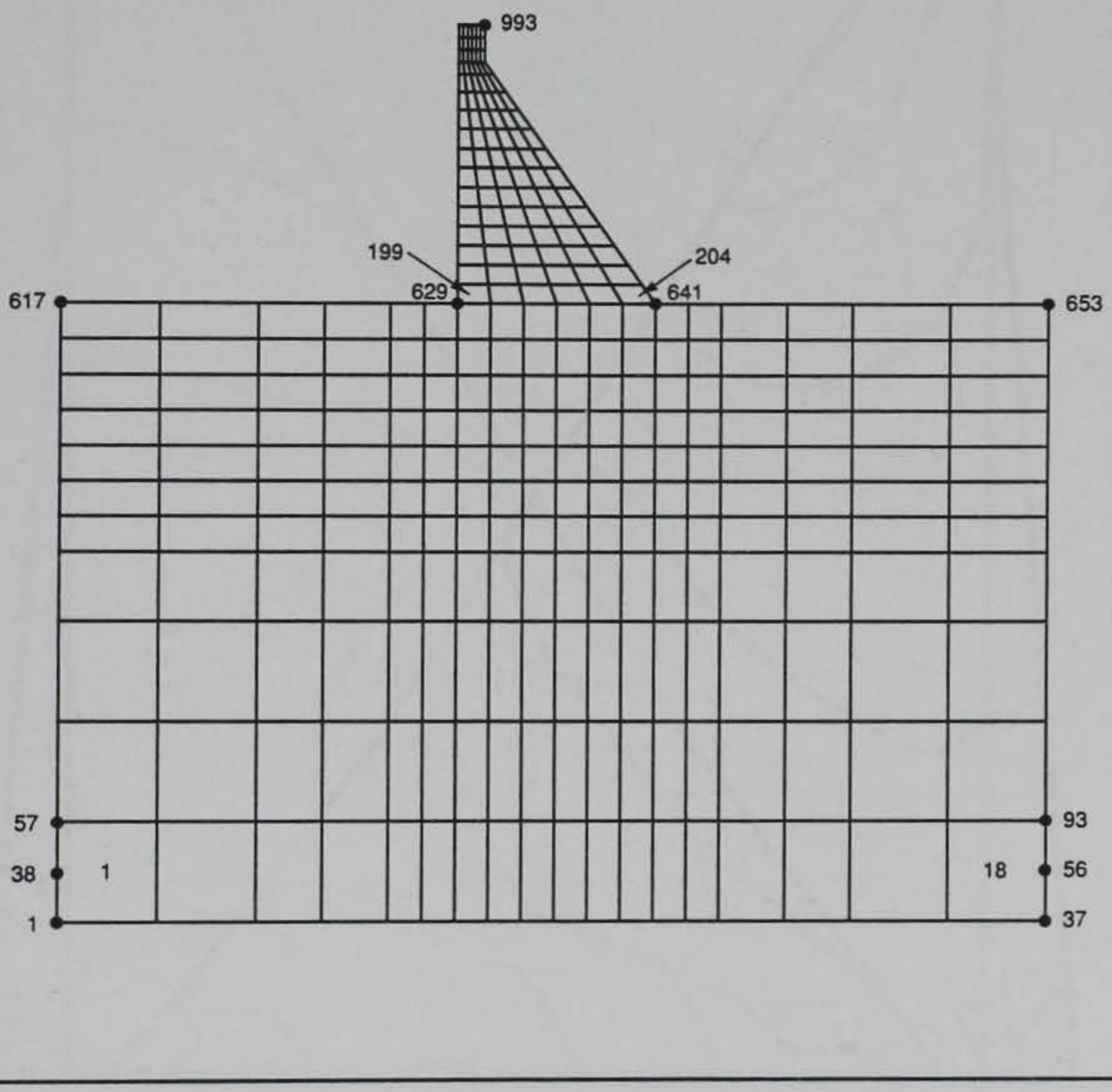


Figure 28. Model 3 (3-BW x 5-BW foundation model)

Figure 29. Vertical stresses (Syy), 3-BW x 5-BW foundation model

Figure 30. Horizontal stresses (Sxx), 3-BW x 5-BW foundation model

Figure 31. Shear stresses (Sxy), 3-BW x 5-BW foundation model

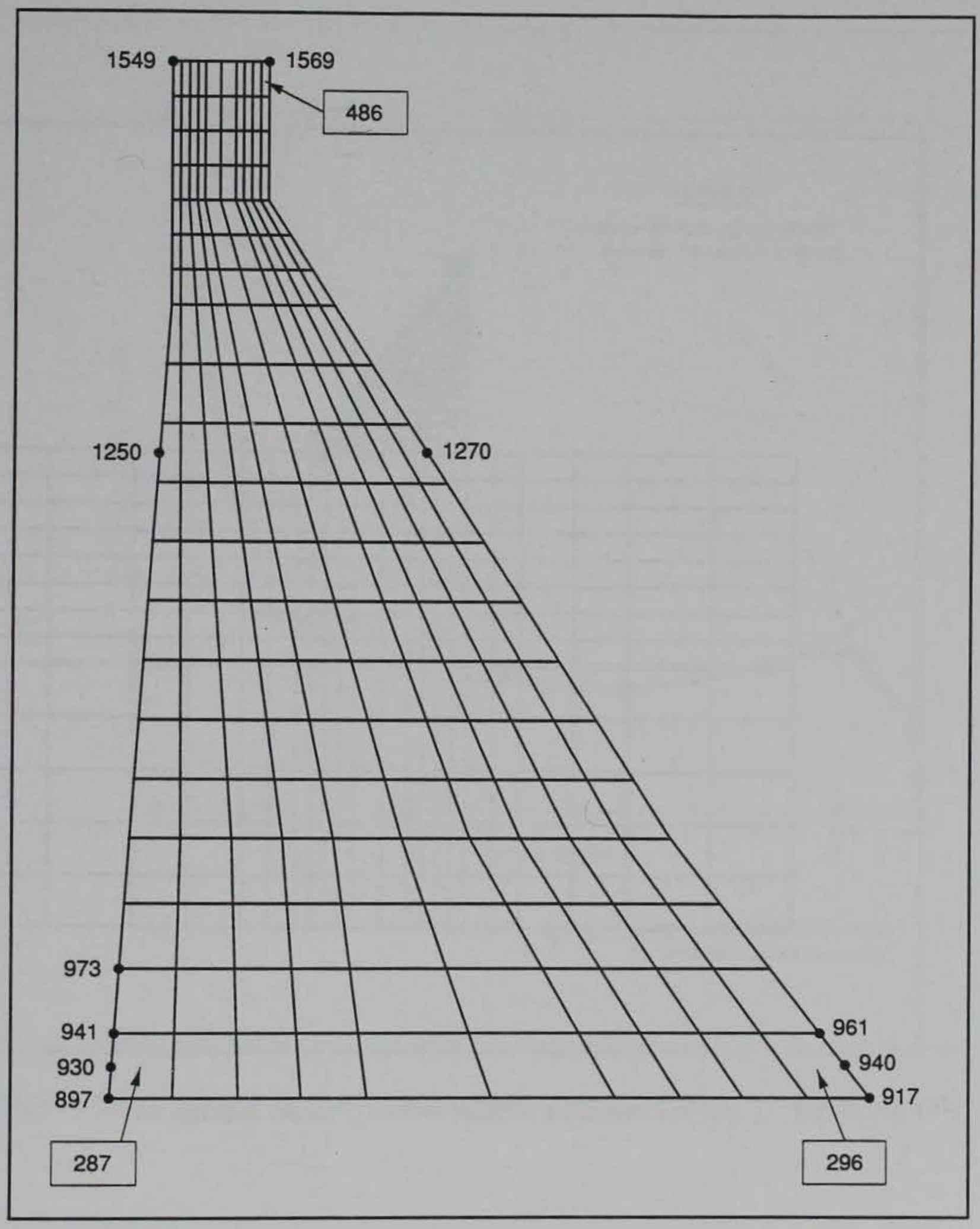


Figure 32. Ten base-element gravity dam model

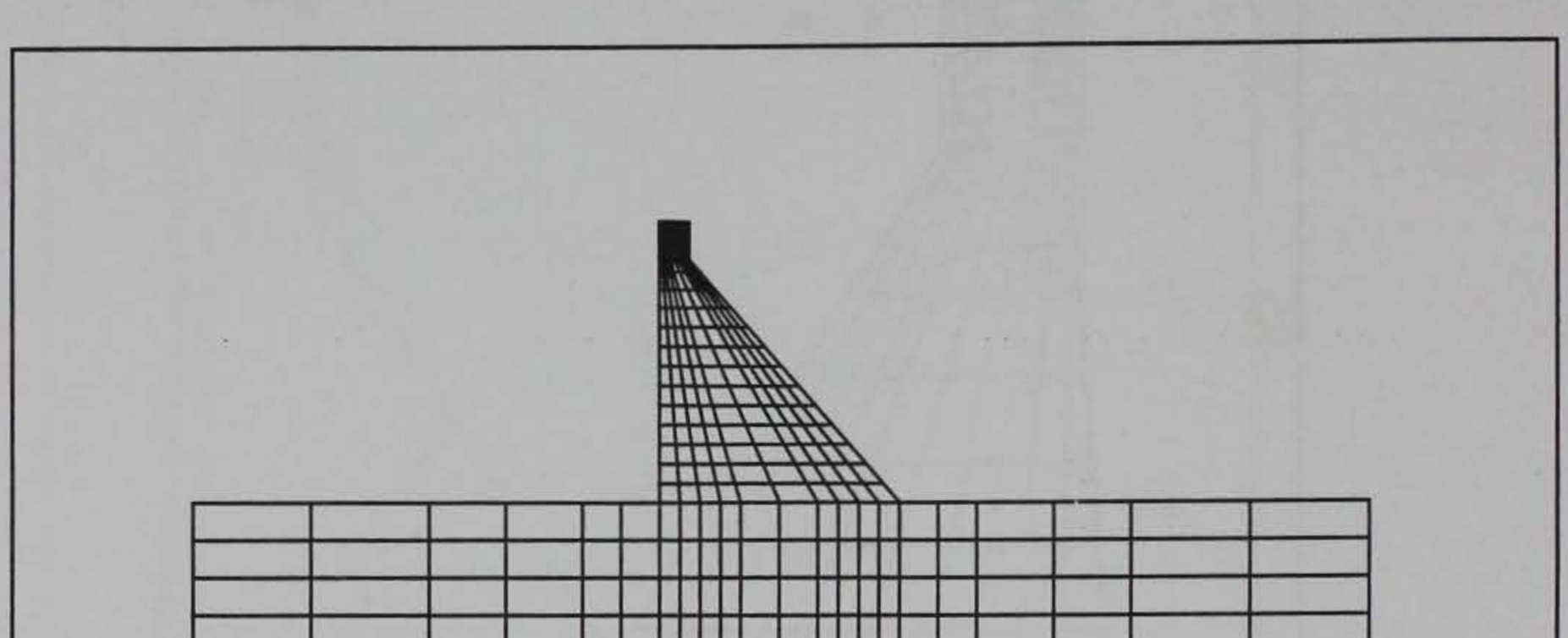


Figure 33. Dam-foundation model with 10 base elements

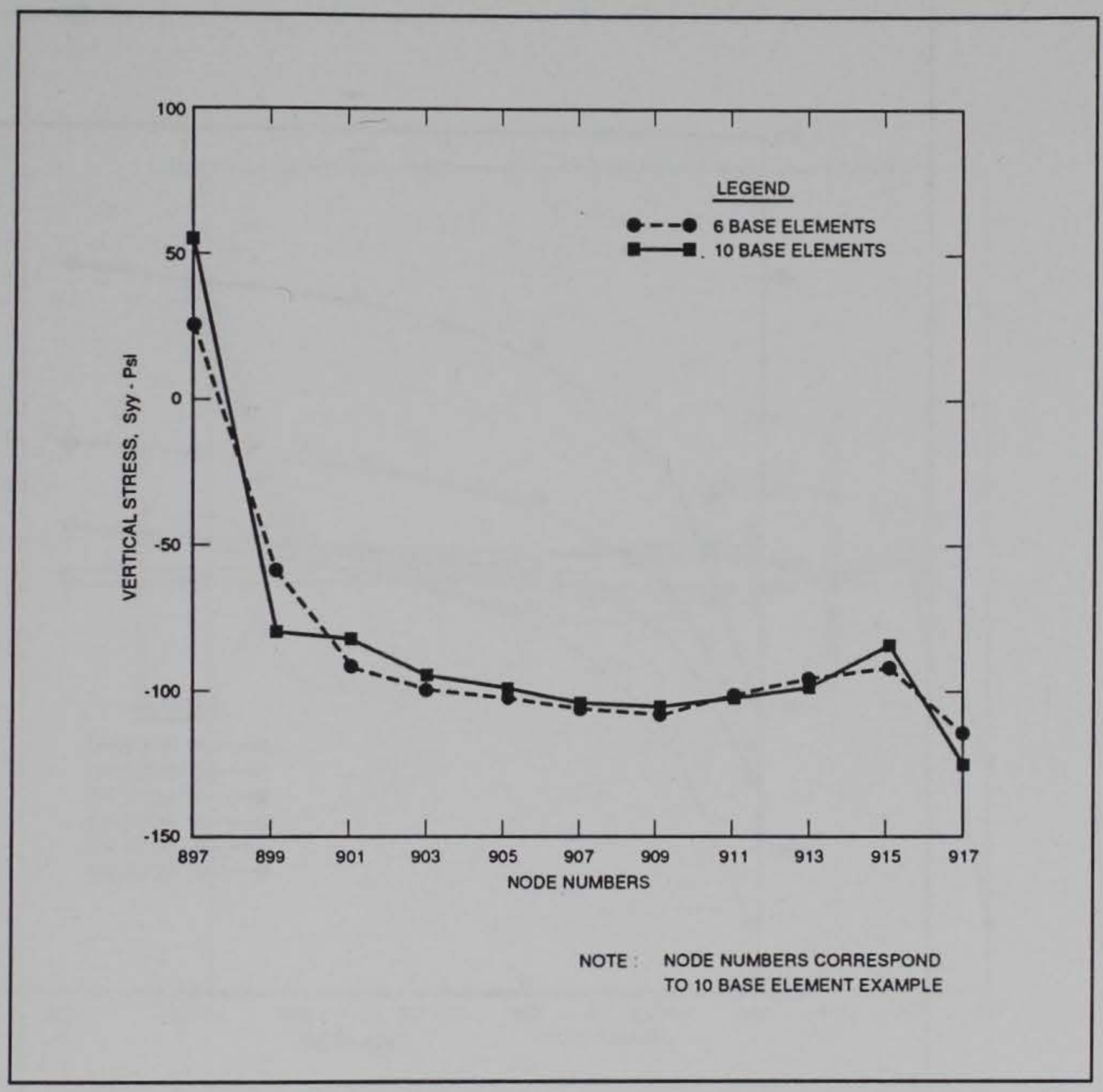


Figure 34. Change in vertical stresses versus change in mesh density

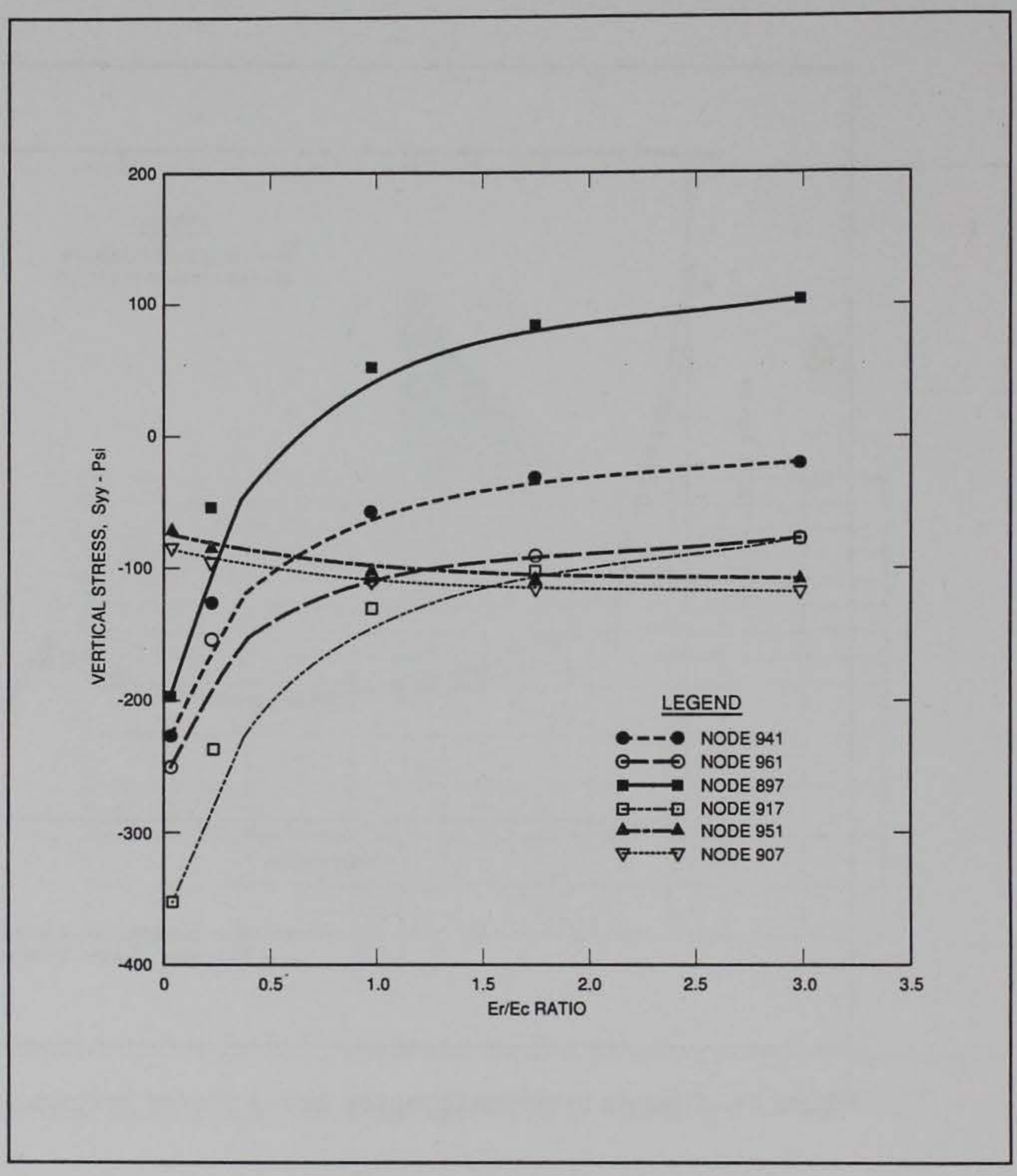


Figure 35. Foundation stiffness versus vertical stresses

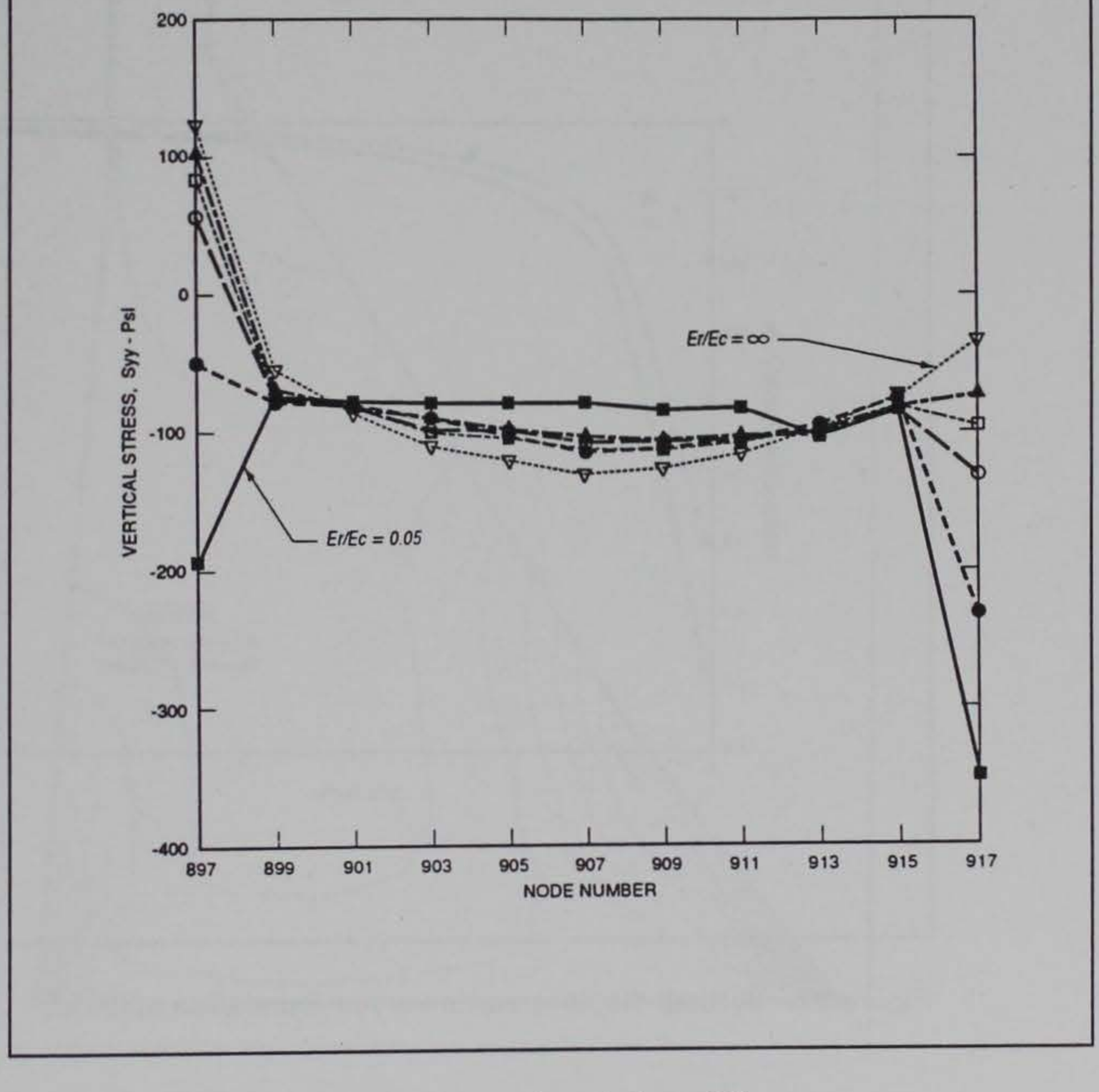


Figure 36. Vertical stresses versus foundation stiffness

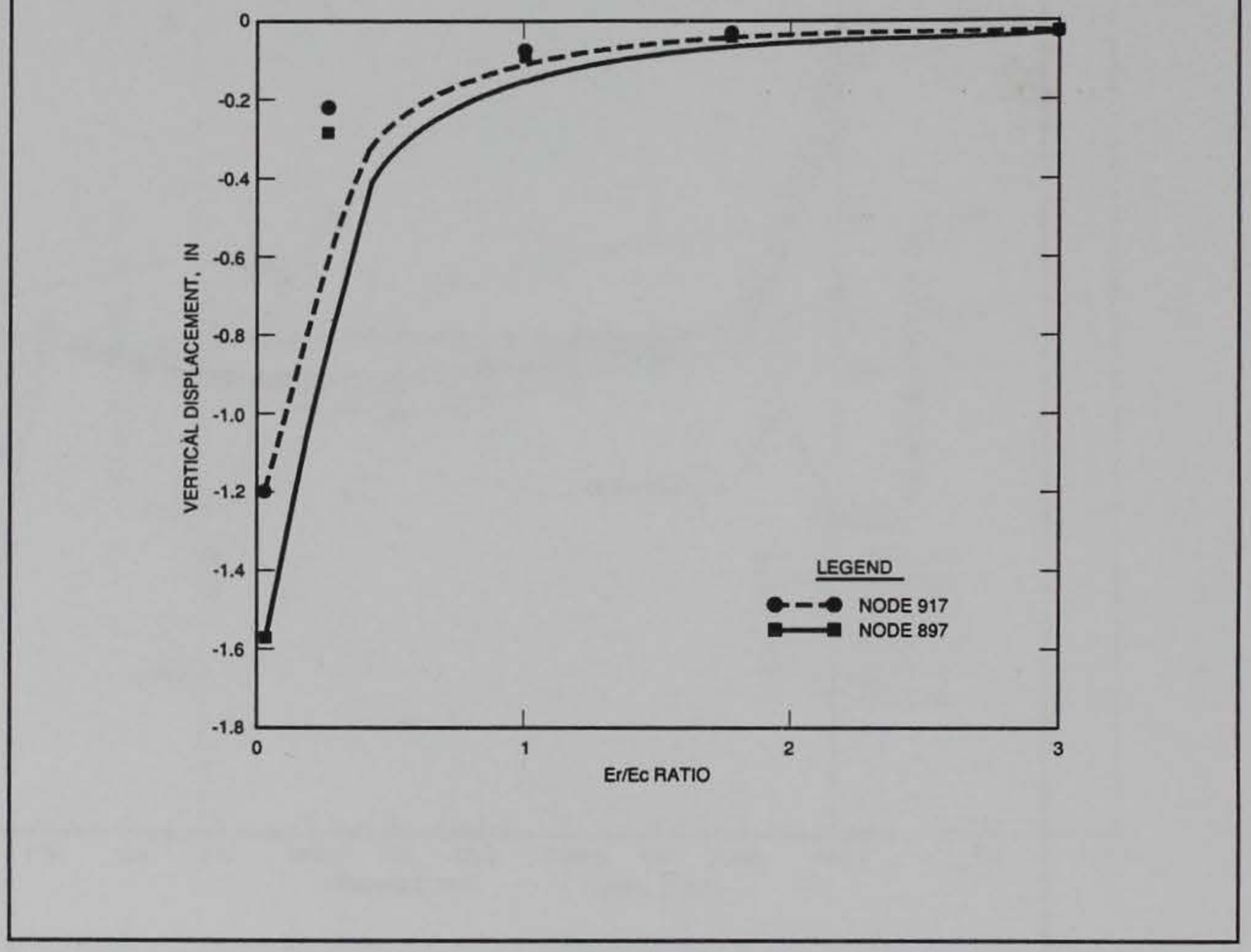


Figure 37. Vertical displacements versus foundation stiffness

Figure 38. Er/Ec = 0.05, vertical stress contours

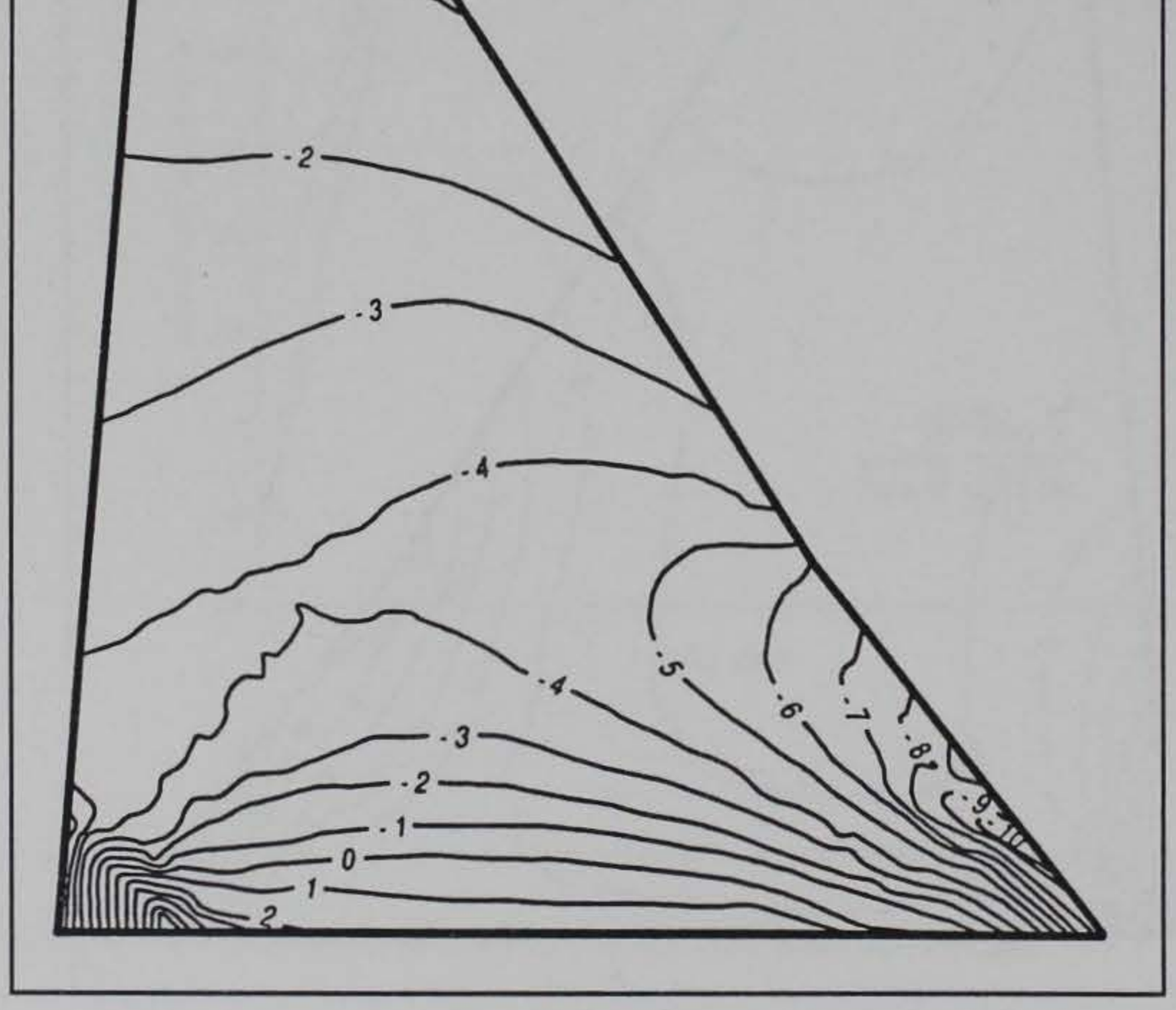


Figure 39. Er/Ec = 0.05, horizontal stress contours

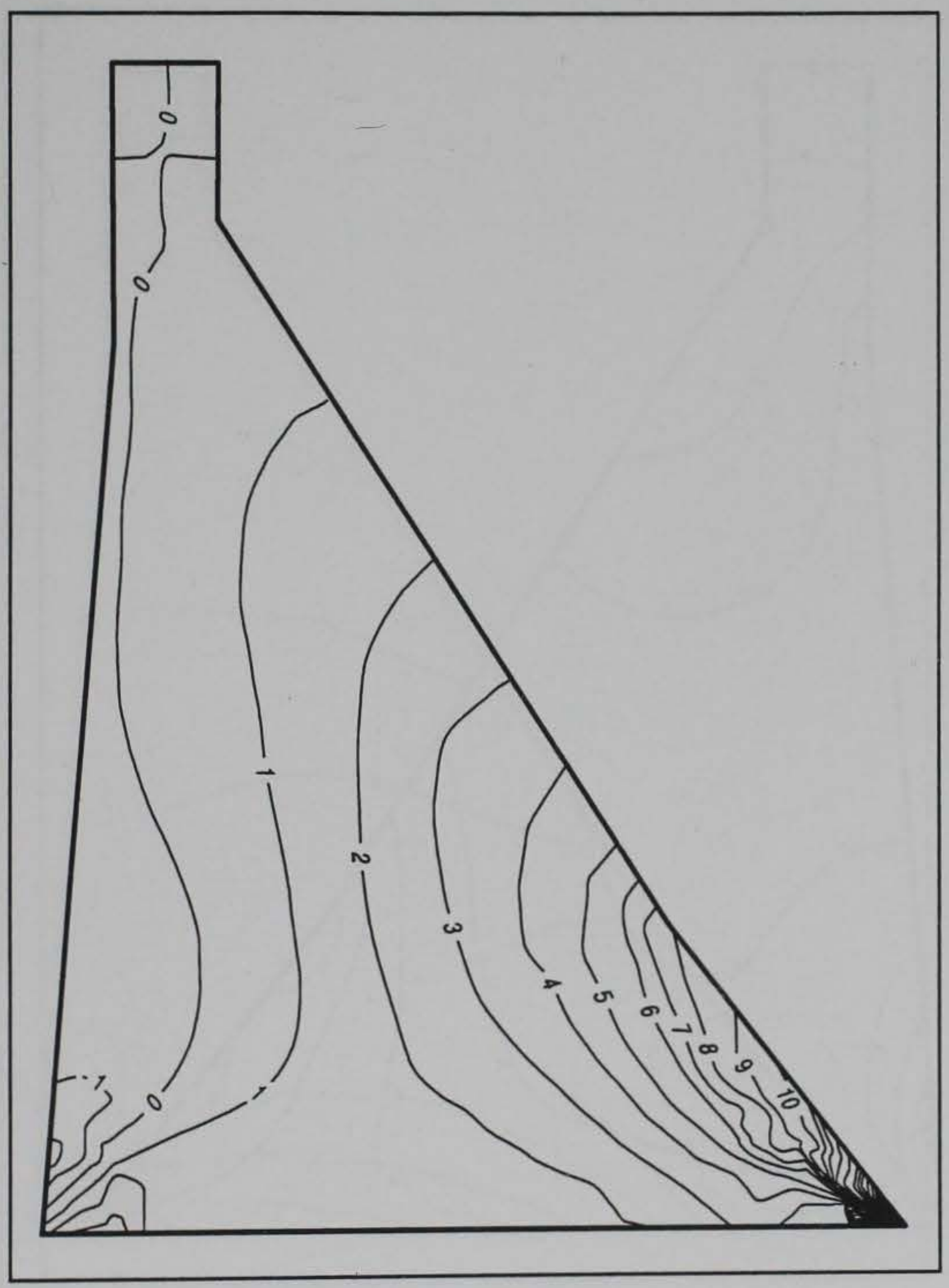


Figure 40. Er/Ec = 0.05, shear stress contours

Figure 41. Er/Ec = 0.25, vertical stress contours

Figure 42. Er/Ec = 0.25, horizontal stress contours

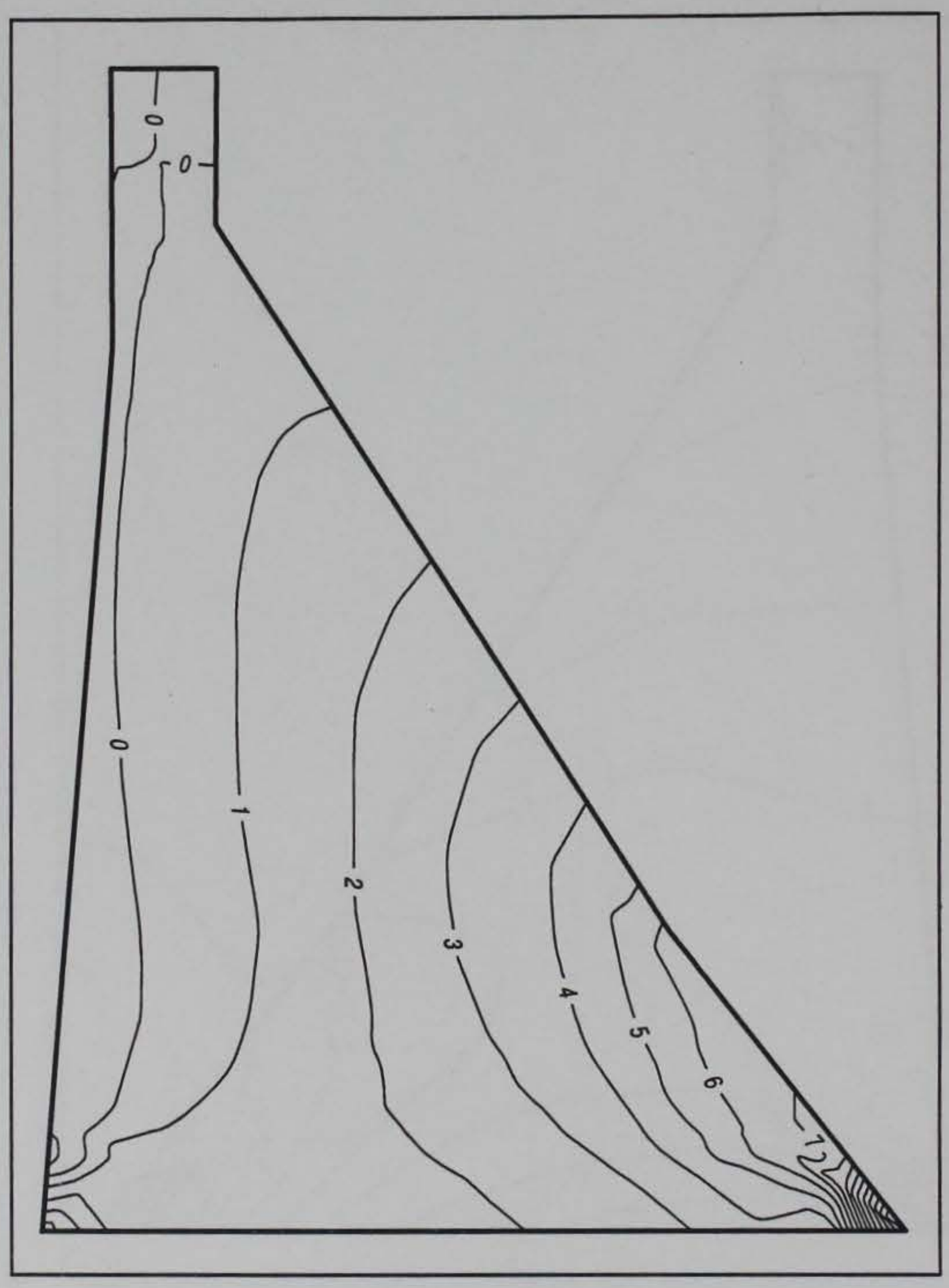


Figure 43. Er/Ec = 0.25, shear stress contours

Figure 44. Er/Ec = 1.00, vertical stress contours

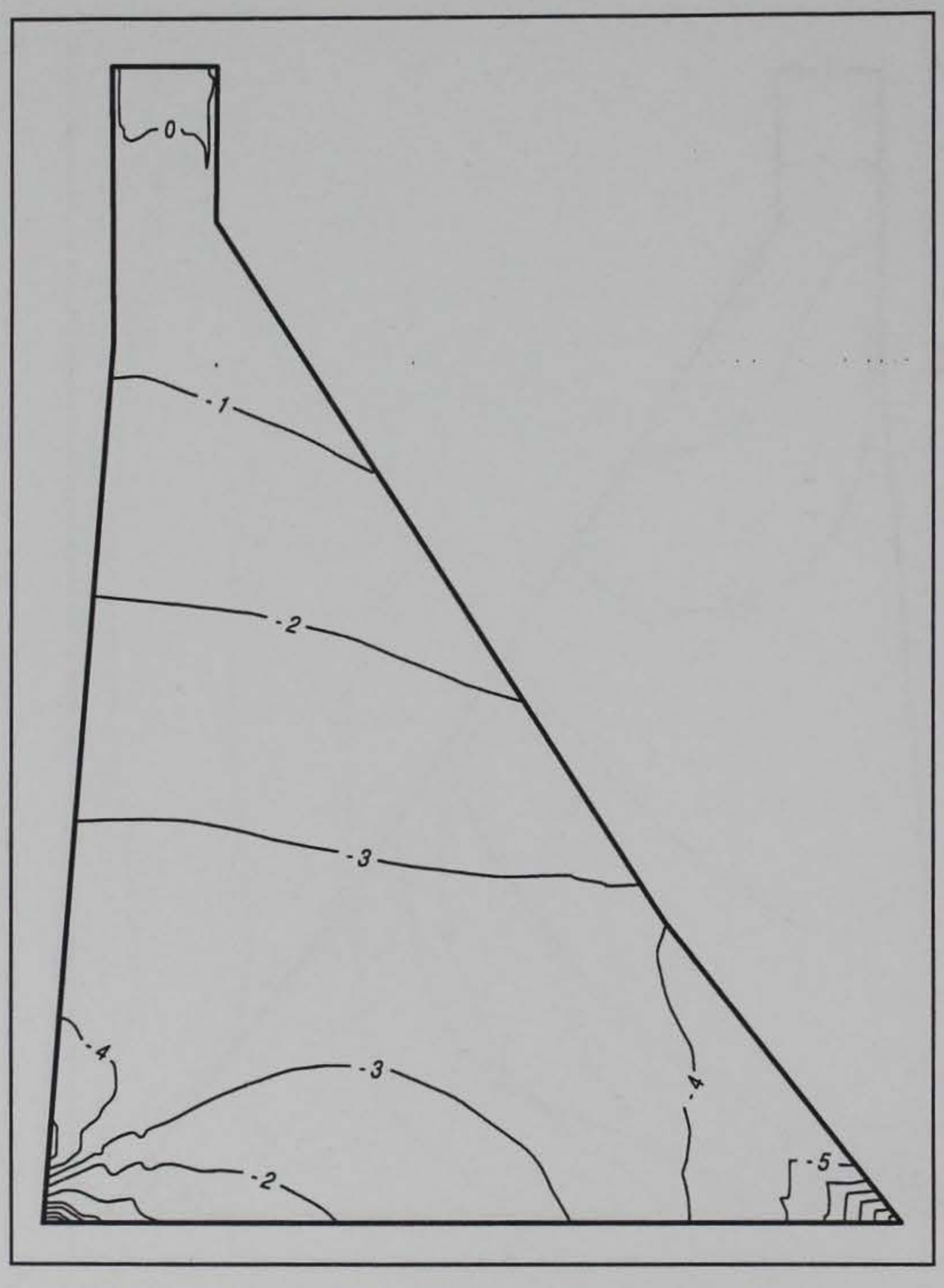


Figure 45. Er/Ec = 1.00, horizontal stress contours

Figure 46. Er/Ec = 1.00, shear stress contours

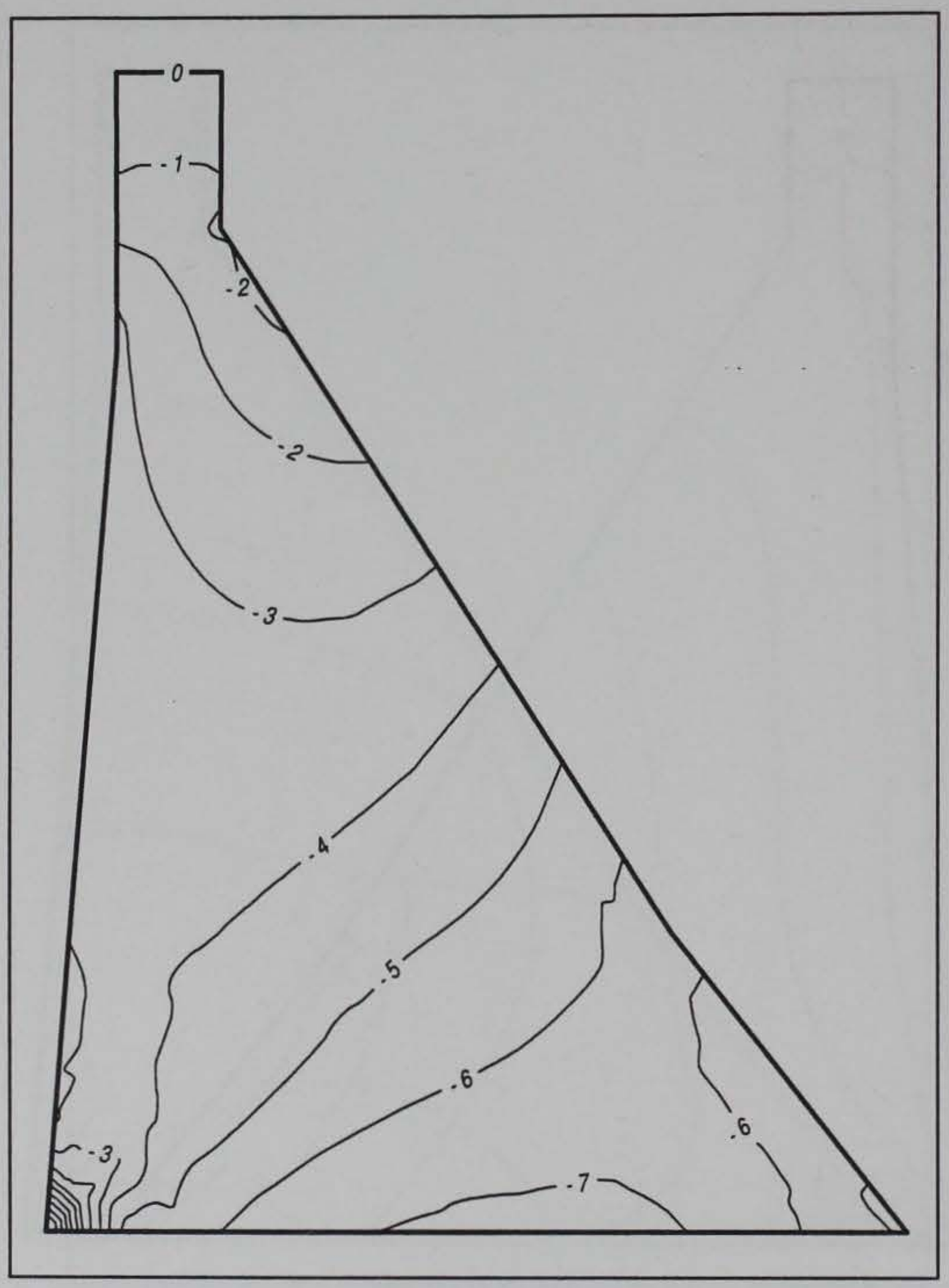


Figure 47. Er/Ec = 1.75, vertical stress contours

Figure 48. Er/Ec = 1.75, horizontal stress contours

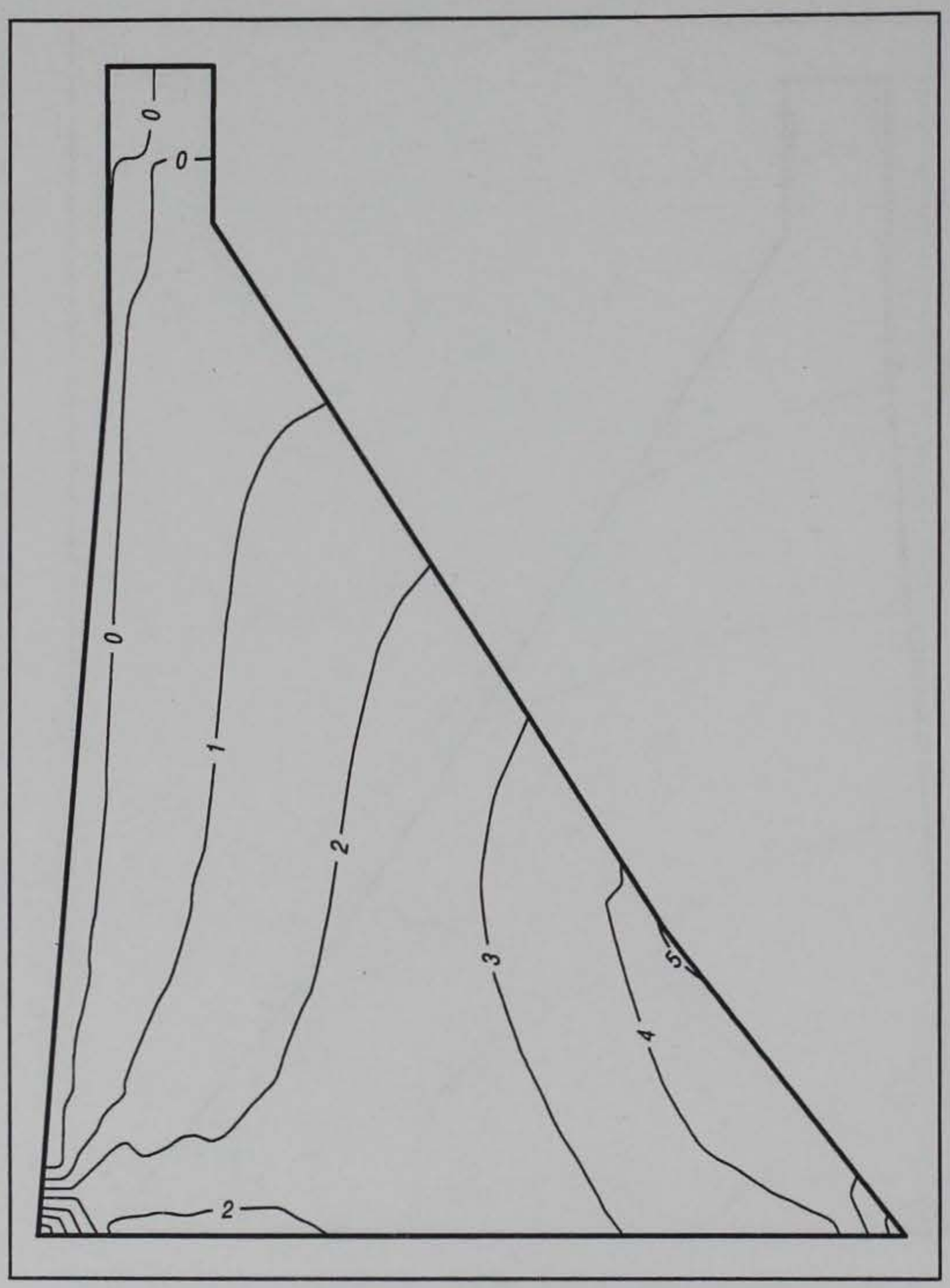


Figure 49. Er/Ec = 1.75, shear stress contours

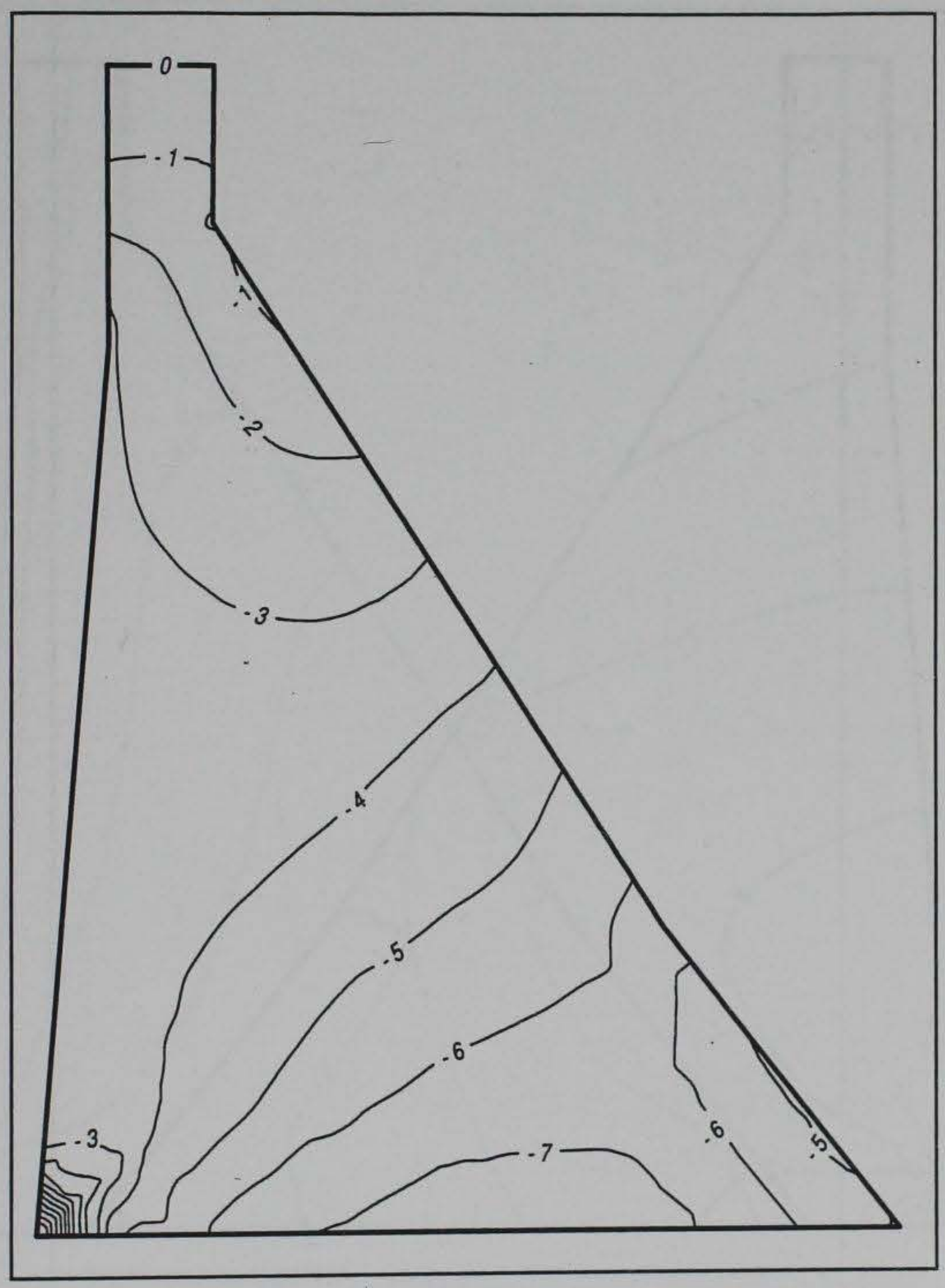


Figure 50. Er/Ec = 3.00, vertical stress contours

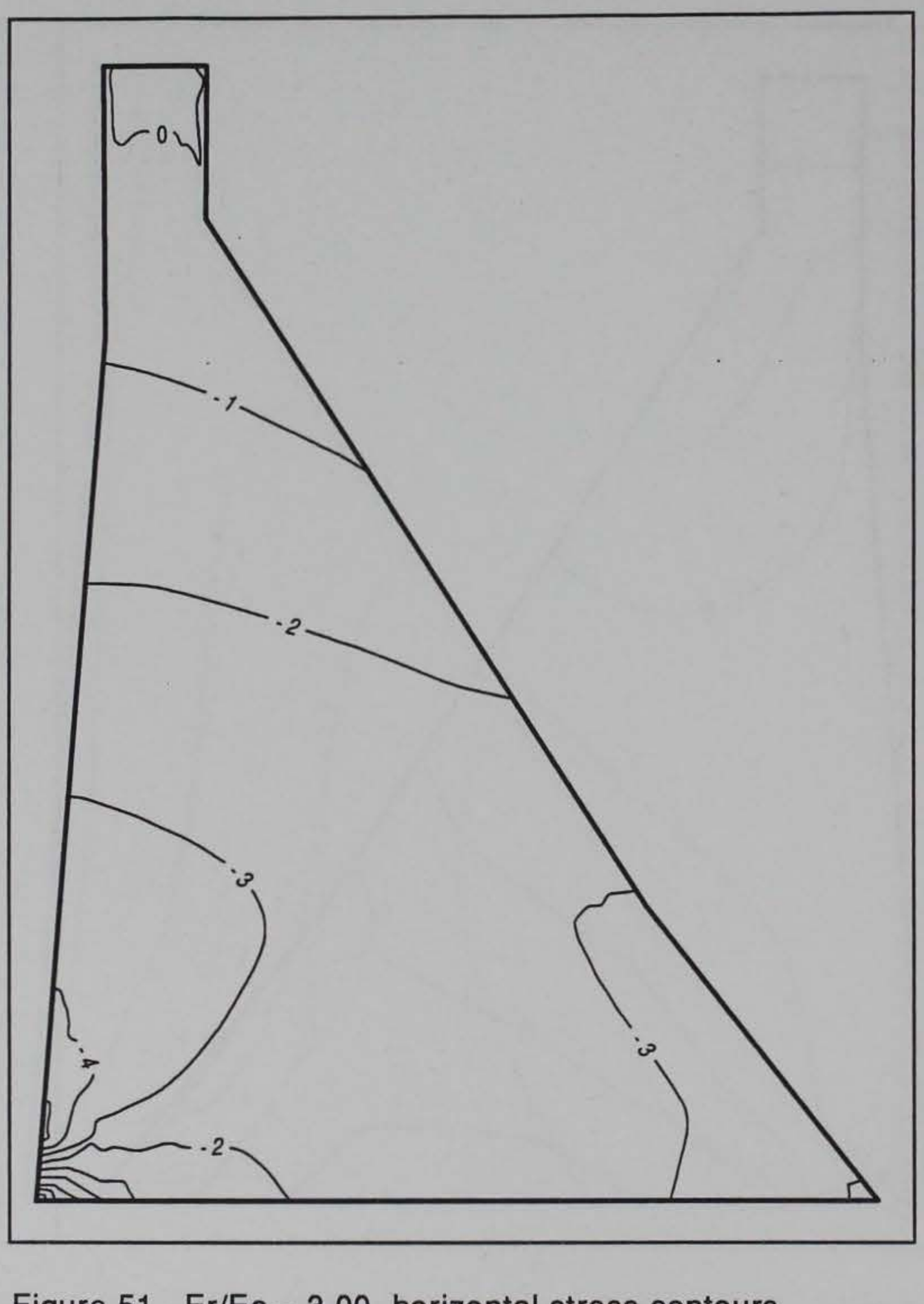


Figure 51. Er/Ec = 3.00, horizontal stress contours

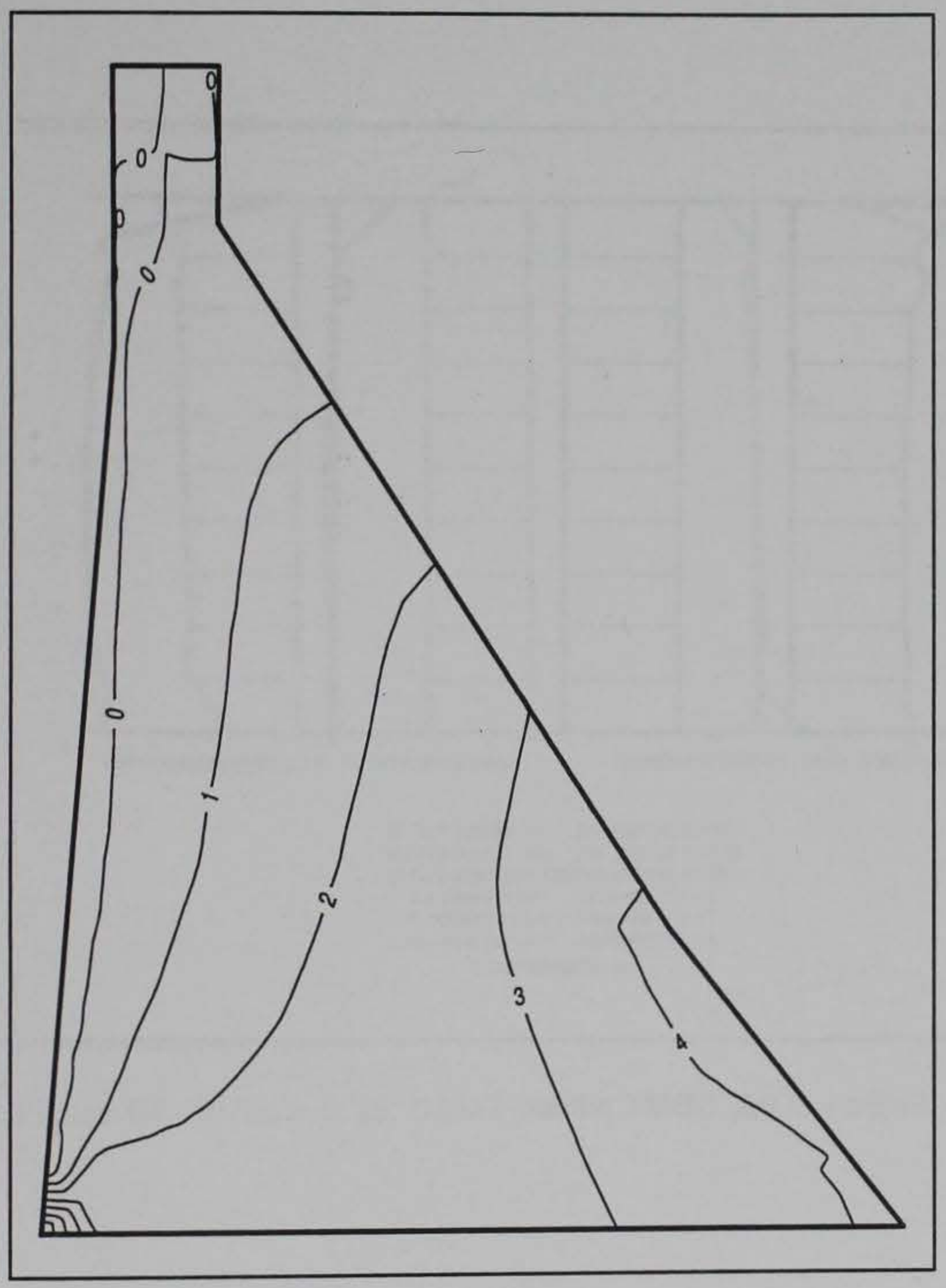


Figure 52. Er/Ec = 3.00, shear stress contours

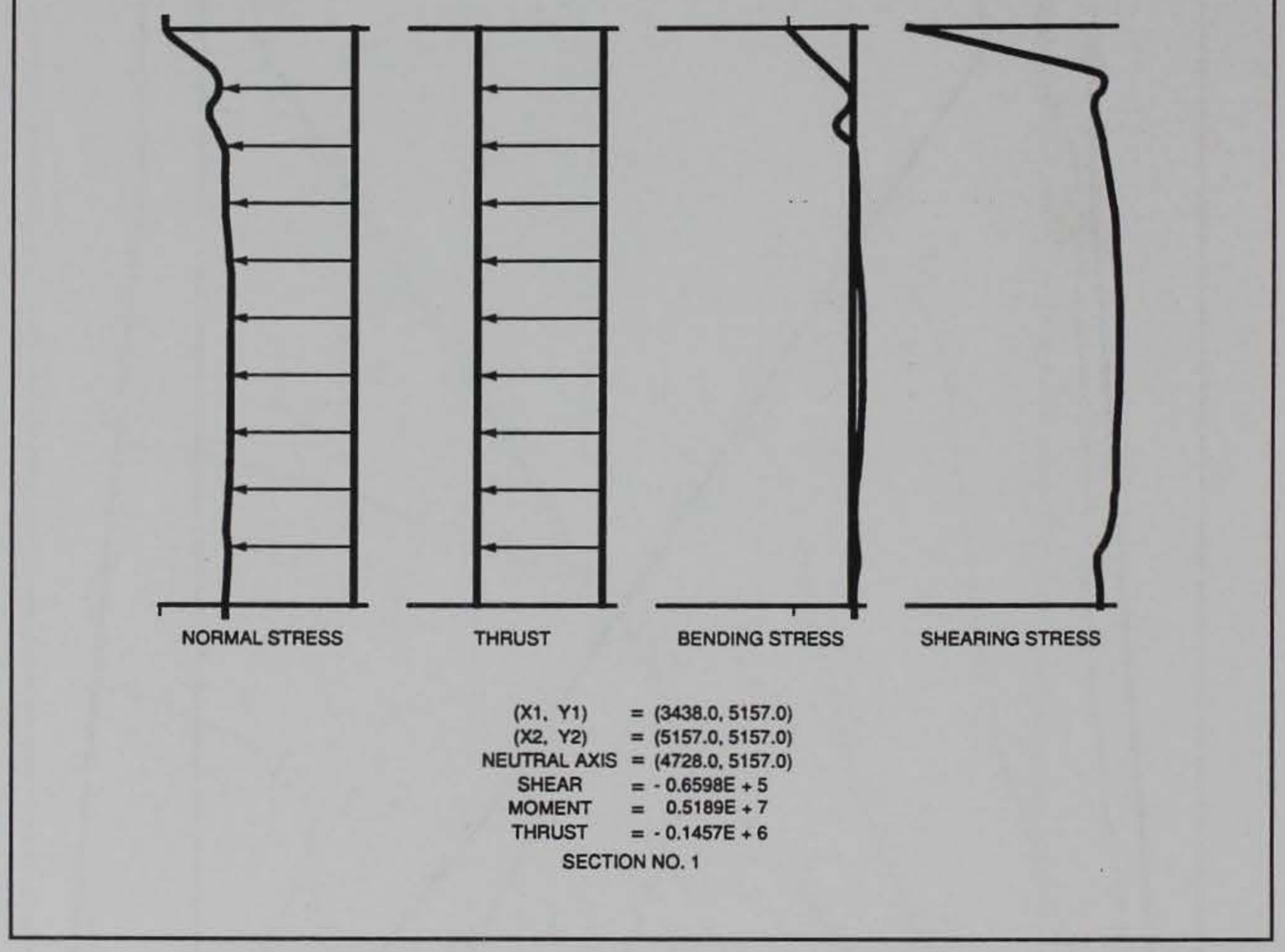


Figure 53. Er/Ec = 0.05, CSMT plots

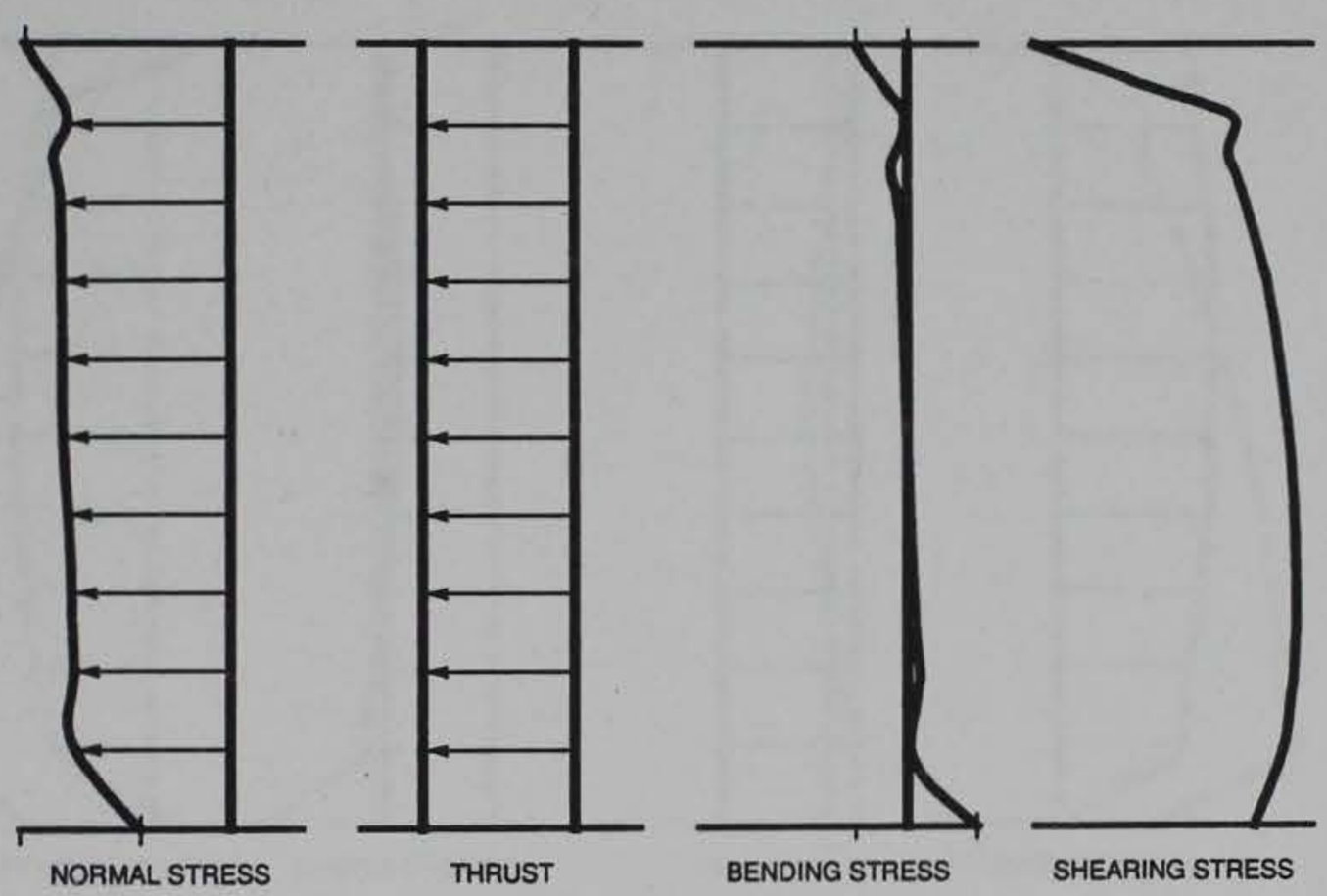
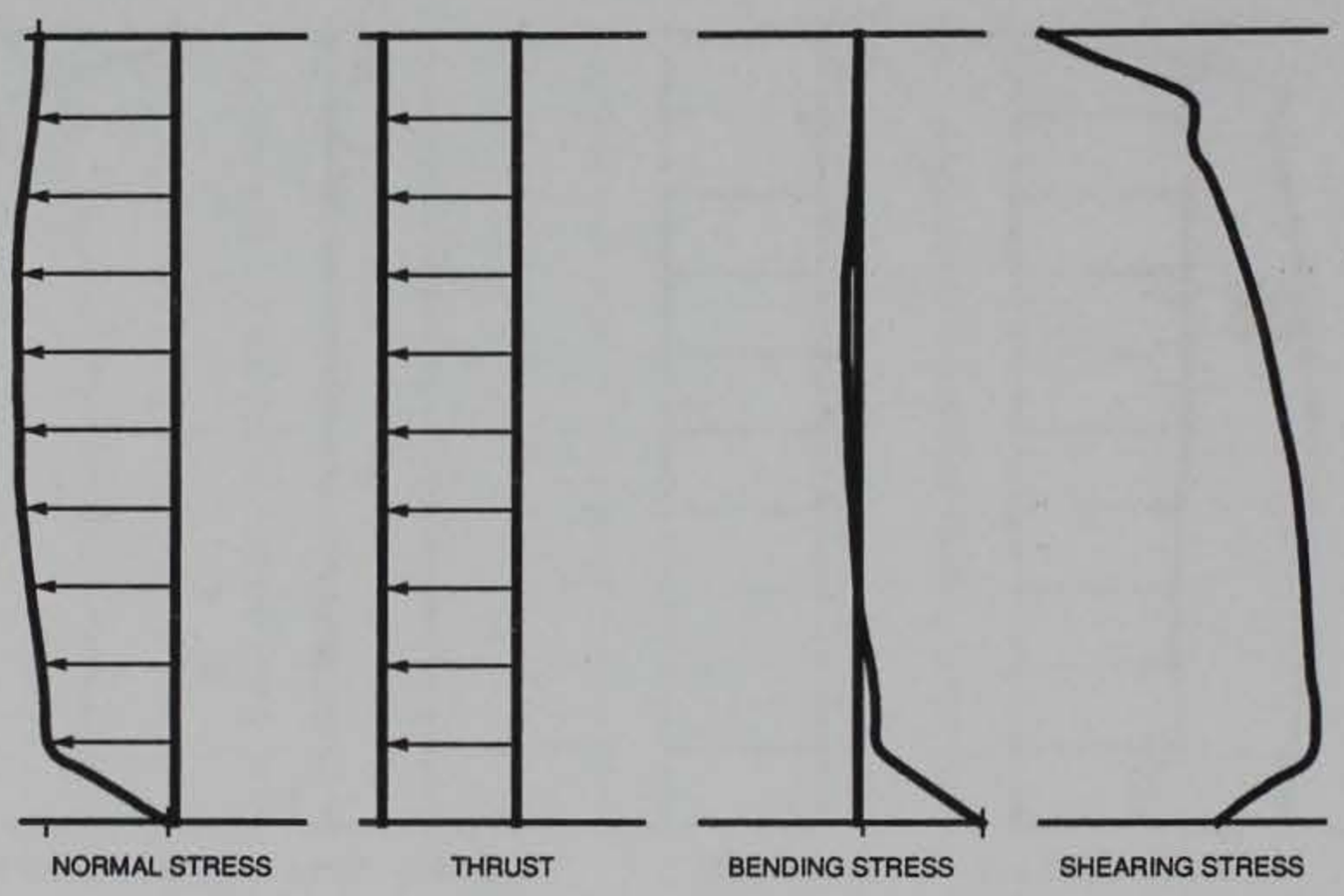
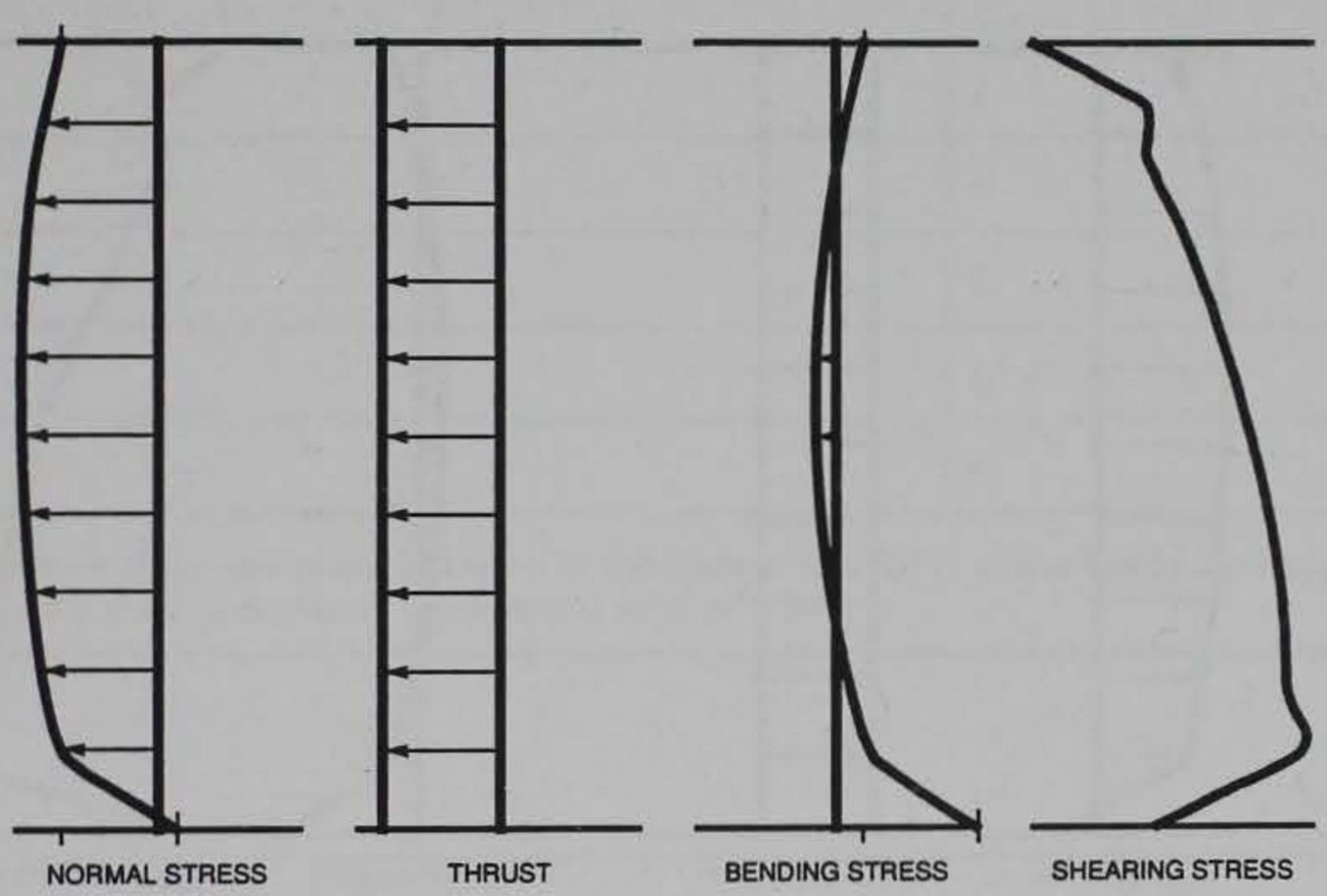


Figure 54. Er/Ec = 0.25, CSMT plots



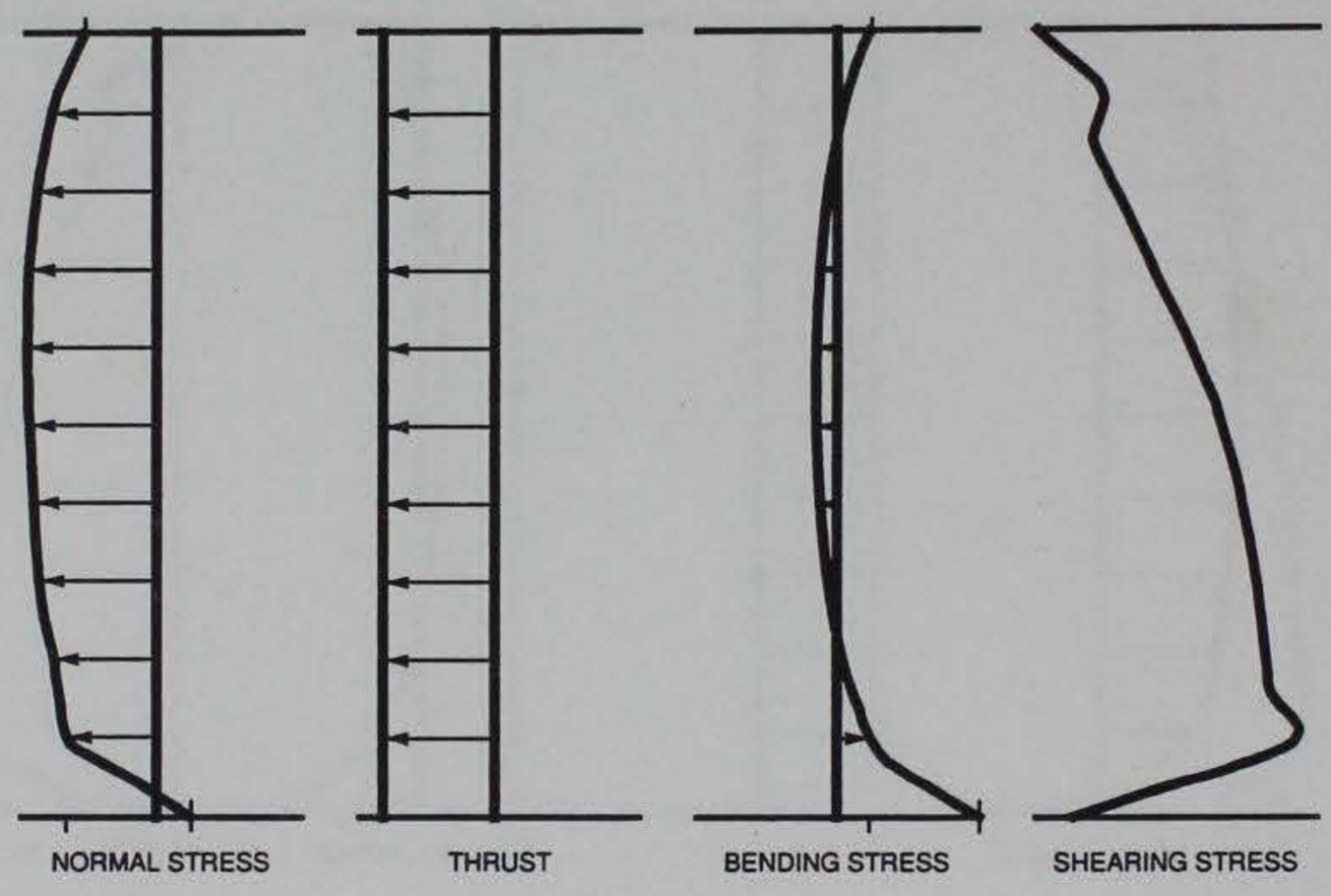
(X1, Y1) = (3438.0, 5157.0)
(X2, Y2) = (5157.0, 5157.0)
NEUTRAL AXIS = (4979.0, 5157.0)
SHEAR = - 0.6885E + 5
MOMENT = 0.7937E + 7
THRUST = - 0.1586E + 6
SECTION NO. 1

Figure 55. Er/Ec = 1.00, CSMT plots



(X1, Y1) = (3438.0, 5157.0)
(X2, Y2) = (5157.0, 5157.0)
NEUTRAL AXIS = (4934.0, 5157.0)
SHEAR = - 0.6958E + 5
MOMENT = 0.8458E + 7
THRUST = - 0.1598E + 6
SECTION NO. 1

Figure 56. Er/Ec = 1.75, CSMT plots



(X1, Y1) = (3438.0, 5157.0)
(X2, Y2) = (5157.0, 5157.0)
NEUTRAL AXIS = (4913.0, 5157.0)
SHEAR = - 0.7010E + 5
MOMENT = 0.8863E + 7
THRUST = - 0.1605E + 6
SECTION NO. 2

Figure 57. Er/Ec = 3.00, CSMT plots

Table 1
Dimensions of Models

Model Number	Width of Foundation Model (BW)	Depth of Foundation Model (BW)
1	3	1
2	3	2
3	5	2
4	5	3
5	7	3
6	7	4
7	9	4
8	9	5
9	11	5
10	11	6

Note: All dimensions are given in terms of the base width (BW) of the applied pressure load. Model 1 would have a depth of 1 BW and a total of 3 BW.

Table 2
Tabulations of Finite Element and Closed Form Stress Results for Uniform Normal Pressure Load

Point	T.O.E.	MD2	MD3	MD4	MD5	MD6	MD7	MD8
				σ_{xx}				
1	-1000.0	-861.1	-888.3	-929.4	-938.8	-959.1	-963.8	-975.9
2	-742.9	-577.8	-594.0	-628.3	-635.1	-653.0	-656.7	-667.7
3	-493.2	-350.9	-356.8	-386.0	-390.4	-406.4	-409.2	-419.3
4	-321.4	-230.9	-225.8	-250.6	-252.4	-266.8	-268.6	-277.8
5	-251.8	-184.2	-167.2	-188.3	-187.4	-200.1	-200.9	-209.4
6	-225.0	-172.4	-143.0	-160.9	-157.1	-168.4	-168.2	-175.9
7	-206.2	-172.9	-132.6	-147.8	-140.8	-150.9	-149.5	-156.6
8	-188.9	-181.9	-126.7	-139.3	-129.2	-138.2	-135.6	-142.1
9	-172.8	-190.3	-122.8	-133.1	-119.6	-127.6	-123.9	-129.8
10	-158.4	-199.1	-120.6	-128.5	-111.6	-118.7	-113.6	-119.1
11	-145.7	-207.5	-119.9	-125.4	-105.0	-111.3	-103.2	-108.4

(Continued)

Table 2 (Concluded)

Point	T.O.E.	MD2	MD3	MD4	MD5	MD6	MD7	MD8
				σ_{yy}				
1	-1000.0	-1072.0	-1075.4	-1076.9	-1077.8	-1078.3	-1079.1	-1079.2
2	-996.0	-981.7	-982.3	-981.5	-981.7	-981.5	-981.5	-981.5
3	-955.2	-937.6	-938.7	-937.2	-937.4	-937.0	-937.1	-936.9
4	-824.5	-826.1	-827.8	-825.1	-825.6	-824.9	-825.1	-824.8
5	-637.8	-641.4	-643.6	-639.6	-640.4	-639.2	-639.5	-639.0
6	-479.7	-482.1	-484.3	-478.9	-480.0	-478.4	-478.8	-478.1
7	-370.6	-374.7	-376.1	-369.5	-370.8	-368.7	-369.2	-368.3
8	-297.8	-305.4	-304.8	-297.3	-298.9	-296.2	-296.9	-295.8
9	-247.6	-260.5	-255.8	-248.2	-249.9	-246.8	-247.6	-246.2
10	-211.7	-231.4	-220.4	-213.2	-214.9	-211.5	-212.4	-210.8
11	-184.8	-213.5	-193.2	-187.4	-188.9	-185.2	-223.1	-221.2
				τ_{xy}				
1	0	39.2	40.7	41.8	42.1	42.5	42.6	42.8
2	10.1	12.9	12.4	13.0	12.9	13.0	13.0	13.7
3	73.9	76.3	74.8	77.0	76.6	77.2	77.1	77.3
4	191.1	175.9	173.1	177.8	177.0	178.3	177.9	178.5
5	247.0	232.9	229.2	236.9	235.6	237.7	237.2	238.0
6	254.6	237.4	233.3	244.5	242.3	245.9	245.2	246.4
7	236.7	216.6	213.4	228.3	225.9	230.3	229.4	231.0
8	213.5	187.9	186.7	205.6	202.9	208.5	207.4	209.5
9	191.6	158.0	160.4	183.2	180.3	187.2	185.8	188.6
10	172.7	128.9	136.3	162.9	159.9	168.2	166.7	169.9
11	156.7	101.2	114.5	144.8	141.9	151.6	158.6	162.2

Table 3
Tabulations of Finite Element and Closed Form Stress Results for Uniform Shear Load

Point	T.O.E.	MDC1	MDC2	MDC3	MDC4	MDC5
			σ_{xx}			
1	0	0	0	0	0	0.0
2	-237.4	-238.2	-367.2	-355.0	-360.2	-357.5
3	-373.4	-354.7	-367.2	-355.0	-360.2	-357.5
4	-368.1	-349.6	-358.3	-340.4	-346.7	-342.6
5	-307.3	-318.4	-318.2	-295.9	-302.5	-296.9
6	-257.7	-293.8	-278.3	-253.3	-259.5	-252.7
7	-233.3	-281.1	-246.4	-221.3	-226.5	-218.5
8	-197.9	-282.2	-220.8	-198.6	-202.1	-193.2
9	-177.8	-293.9	-198.1	-182.2	183.4	-174.0
10	-161.3	-314.6	-176.2	-170.3	-168.6	-158.9
11	-147.4	-342.7	-154.1	-161.6	-156.1	-146.8
			σ_{yy}			
1	0	0	0	0	0	0.0
2	-10.1	-20.7	-20.1	-19.9	-19.9	-19.9
3	-73.9	-71.2	-68.9	-68.1	-67.9	-67.8
4	-181.1	-171.9	-166.1	-163.9	-163.4	-163.1
5	-247.1	-251.3	-239.9	-235.2	-234.2	-233.6
6	-254.6	-275.0	-258.0	-249.2	-247.4	-246.3
7	-236.7	-273.6	-251.3	-236.7	-233.9	-232.1
8	-213.5	-265.4	-240.6	-218.3	-214.2	-211.4
9	-191.6	-255.5	-233.1	-201.1	-195.7	-191.7
10	-172.7	-243.1	-230.5	-187.1	-180.3	-174.7
11	-156.7	-226.5	-232.3	-176.2	-168.1	-160.6

(Continued)

Table 3 (Concluded)

Point	T.O.E.	MDC1	MDC2	MDC3	MDC4	MDC5
			τ_{xy}			
1	1000	898.2	892.8	895.2	893.7	894.2
2	742.9	754.9	743.4	749.3	745.9	747.2
3	493.2	514.2	495.7	507.9	501.8	504.4
4	321.4	343.2	322.9	342.1	333.9	337.9
5	251.8	258.7	241.5	268.4	258.8	264.5
6	225.1	209.4	200.0	235.2	224.8	232.2
7	206.3	166.5	168.8	212.6	202.1	211.4
8	188.9	122.6	139.9	192.2	182.2	193.6
9	172.8	78.3	112.5	172.7	163.7	177.3
10	158.4	36.2	86.9	153.8	146.5	162.3
11	145.7	10.3	63.9	135.6	130.4	148.6

Table 4
Tabulation of Finite Element and Closed Form Stress Results for Antisymmetric Normal Pressure

Point	T.O.E.	MDB1	MDB2	MDB3	MDB4	MDB5
			σ_{xx}			
1	0.0	0.0	0.0	0.0	0.0	0.0
2	-133.0	-160.6	-171.6	-172.4	-173.8	-179.0
3	-20.3	6.1	-11.9	-12.8	-15.3	-15.7
4	59.2	71.9	48.9	48.6	45.3	44.8
5	63.9	84.8	57.9	58.7	54.7	54.3
6	43.4	77.2	47.9	49.9	45.3	45.0
7	26.5	64.4	34.4	37.9	32.8	32.6
8	16.2	51.5	23.7	28.4	22.9	22.9
9	10.2	38.0	16.6	22.1	16.2	16.6
10	6.65	23.6	12.5	18.0	11.9	12.5
11	4.49	7.5	10.7	15.4	9.2	10.0

(Continued)

Table 4 (Concluded)

Point	T.O.E.	MDB1	MDB2	MDB3	MDB4	MDB5
			σ_{yy}			
1	0.0	0.0	0.0	0.0	0.0	0.0
2	-816.2	-772.9	-772.2	-772.2	-772.0	-772.2
3	-782.6	-763.5	-760.5	-760.9	-760.3	-760.3
4	-661.9	-670.2	-662.7	662.3	-662.1	-662.0
5	-486.2	-503.9	-439.6	-488.7	488.1	-488.1
6	-338.6	-363.1	-340.8	-339.1	-338.1	-337.9
7	-239.3	-272.6	-242.7	-239.7	238.1	-238.1
8	-175.2	-216.2	-181.8	-176.7	-174.4	-174.0
9	-132.9	-177.5	-143.9	-135.9	-132.8	-132.3
10	-104.1	-146.0	-120.5	-108.5	104.6	-103.9
11	-83.7	-116.6	-106.5	-89.7	-84.9	-83.9
			τ_{yy}			
1	-500.0	-410.4	-415.9	-416.3	-416.9	-417.1
2	-291.0	-268.0	-280.1	-281.1	-282.5	-283.8
3	-196.3	-168.7	-189.5	-190.9	-193.8	-194.2
4	-58.7	-29.1	-54.7	56.2	-60.1	-60.7
5	33.8	59.8	33.5	32.4	27.8	27.1
6	63.7	87.9	65.0	64.9	59.7	58.9
7	64.4	83.6	68.0	69.5	63.9	63.2
8	56.8	65.5	60.8	64.4	58.8	58.2
9	48.2	42.5	50.7	57.1	51.6	51.1
10	40.6	19.4	40.3	49.8	44.7	44.5
11	34.3	2.1	30.5	43.1	38.1	38.7

Table 5
Percentage of Error in σ_{xx} Stress

Node	Stresses for Indicated Load Cases					
	1		2		3	
	Model 3	Model 4	Model 3	Model 4	Model 3	Model 4
1	11.2	7.1	0.0	0.0	0.0	0.0
3	27.6	21.7	4.9	3.5	36.9	24.6
5	33.6	25.2	3.7	1.6	8.1	14.3
7	35.7	28.4	0.9	1.4	43.0	11.4
9	28.9	22.9	5.5	5.5	117.0	58.8
11	17.7	13.7	9.6	5.9	242.0	107.0

Table 6
Foundation Size Models

Size Model	Depth[1]	Width[1]	No. of Nodes[2]	No. of Elements[2]	Size Ratio[3]
1	1.5 BW	3 BW	492	112	1.00
2	2.0 BW	4 BW	626	144	1.78
3	3.0 BW	5 BW	850	198	3.33

[1] Depth and width in terms of BW of dam.
[2] The numbers of nodes and elements do not include the dam model.
[3] Size ratio with respect to (w.r.t.) Model 1, based on ratios of foundation model area.

Table 7
Effect of Model Size on Vertical Stresses (Syy) (Stresses in psi)

Node[2]	Foundation Size Model[1]		
	1 (1.5 BW x 3 BW)	2 (2 BW x 4 BW)	3 (3 BW x 5 BW)
629	26.32	22.85	20.00
630	-58.82	-59.51	-60.03
631	-91.41	-91.03	-90.62
632	-98.06	-97.53	-97.05
633	-96.73	-96.32	-96.01
634	-100.99	-100.48	-100.12
635	-104.83	-104.24	-103.82
636	-106.62	-106.10	-105.75
637	-107.33	-106.94	-106.70
638	-101.00	-100.70	-100.55
639	-96.27	-96.29	-96.39
640	-91.88	-92.49	-92.90
641	-116.00	-118.34	-119.72
661	-39.48	-40.44	-40.95
662	-60.53	-60.97	-61.29
663	-65.85	-66.20	-66.51
664	-80.30	-80.21	-80.16
665	-88.04	-87.74	-87.52
666	-92.33	-91.95	-91.69
667	-95.50	-95.09	-94.82
668	-97.86	-97.43	-97.14
669	-99.75	-99.37	-99.11
670	-101.05	-100.84	-100.70
671	-100.11	-100.19	-100.25
672	-92.34	-92.72	-92.97
673	-103.20	-104.70	-105.66

[1] Er/Ec = 1.00 for all models.
[2] See Figure 25.

Table 8
Effect of Model Size on Horizontal Stresses (Sxx)
(Stresses in psi)

Node[2]	Foundation Size Model[1]		
	1 (1.5 BW x 3 BW)	2 (2 BW x 4 BW)	3 (3 BW x 5 BW)
629	51.63	46.80	41.84
630	14.52	11.20	7.74
631	-11.30	-13.52	-15.80
632	-21.29	-23.14	-25.03
633	-25.91	-27.57	-29.20
634	-29.72	-31.31	-32.78
635	-34.68	-36.14	-37.40
636	-40.89	-42.33	-43.45
637	-45.85	-47.26	-48.24
638	-53.46	-54.91	-55.79
639	-63.64	-65.22	-66.07
640	-102.35	-104.85	-105.99
641	-147.23	-150.93	-152.54
661	-73.32	-73.12	-72.87
662	-46.17	-47.00	-47.80
663	-23.69	-25.33	-26.93
664	-33.04	-34.35	-35.60
665	-32.06	-33.42	-34.71
666	-35.10	-36.42	-37.60
667	-38.15	-39.43	-40.52
668	-42.33	-43.58	-44.57
669	-45.63	-46.86	-47.77
670	-52.31	-53.54	-54.38
671	-63.02	-64.42	-65.26
672	-66.72	-67.90	-68.62
673	-66.72	-67.90	-68.62

[1] Er/Ec = 1.00 for all models.
[2] See Figure 25.

Table 9
Effect of Model Size on Shear Stresses (Sxy) (Stresses in psi)

Node[2]	Foundation Size Model[1]		
	1 (1.5 BW x 3 BW)	2 (2 BW x 4 BW)	3 (3 BW x 5 BW)
629	87.21	83.80	80.48
630	44.06	42.53	41.11
631	19.86	19.46	19.18
632	22.52	22.27	22.19
633	28.20	27.95	27.89
634	29.71	29.66	29.77
635	31.96	32.06	32.31
636	36.99	37.23	37.58
637	43.19	43.57	43.98
638	46.77	47.19	47.62
639	48.87	49.31	49.71
640	75.42	76.67	77.44
641	117.73	102.03	121.65
661	5.15	4.78	4.50
662	20.36	19.69	19.13
663	36.27	35.23	34.30
664	29.65	29.10	28.66
665	30.42	30.08	29.86
666	32.17	32.02	31.98
667	35.19	35.19	35.27
668	39.24	39.38	39.57
669	44.27	44.54	44.81
670	52.51	52.96	53.32
671	61.49	62.13	62.56
672	69.56	70.37	70.92
673	85.18	86.41	87.20

[1] Er/Ec = 1.00 for all models.
[2] See Figure 25.

Table 10
Effect of Model Size Upon Vertical and Horizontal Displacements

Node[2]	X-Displacements (in.) Foundation Size Model[1]			Y-Displacements (in.) Foundation Size Model[1]		
	1	2	3	1	2	3
629	0.01572	0.01679	0.01406	-0.03902	-0.05184	-0.07437
630	0.01700	0.01794	0.01508	-0.04185	-0.05434	-0.07632
631	0.01774	0.01858	0.01562	-0.04405	-0.05621	-0.07772
632	0.01796	0.01873	0.01570	-0.04557	-0.05743	-0.07846
633	0.01796	0.01867	-0.01557	-0.04656	-0.05811	-0.07867
634	0.01788	0.01852	0.01537	-0.04704	-0.05827	-0.07838
635	0.01765	0.01824	0.01504	-0.04698	-0.05790	-0.07754
636	0.01727	0.01780	0.01455	-0.04636	-0.05696	-0.07614
637	0.01667	0.01715	0.01387	-0.04510	-0.05538	-0.07409
638	0.01588	0.01631	0.01299	-0.04316	-0.05312	-0.07136
639	0.01473	0.01511	0.01176	-0.04050	-0.05012	-0.06789
640	0.01267	0.01298	0.00960	-0.03686	-0.04613	-0.06342
641	0.00930	0.00940	0.00610	-0.03128	-0.04016	-0.05694
661	0.02392	0.02446	0.02105	-0.03925	-0.05210	-0.07459
662	0.02242	0.02295	0.01954	-0.04380	-0.05628	-0.07825
663	0.02194	0.02243	0.01898	-0.04620	-0.05837	-0.07990
664	0.02148	0.02193	0.01844	-0.04802	-0.05990	-0.08098
665	0.02112	0.02152	0.01799	-0.04917	-0.06076	-0.08140
666	0.02077	0.02112	0.01755	-0.04982	-0.06112	-0.08134
667	0.02035	0.02067	0.01706	-0.05000	-0.06101	-0.08079
668	0.01984	0.02011	0.01616	-0.04967	-0.06039	-0.07975
669	0.01921	0.01944	0.01576	-0.04879	-0.05921	-0.07814
670	0.01846	0.01865	0.01494	-0.04728	-0.05711	-0.07591
671	0.01719	0.01761	0.01390	-0.04508	-0.05490	-0.07297
672	0.01613	0.01623	0.01247	-0.04208	-0.05160	-0.06924
673	0.01471	0.01479	0.01101	-0.03842	-0.04765	-0.06485

[1] Er/Ec = 1.00 for all models.
[2] See Figure 25.

Table 11
Foundation Material Properties

Property Model	Poisson's Ratio	Modulus of Elasticity		Er/Ec
		Rock (Er) x 10^6 psi	Concrete (Ec) x 10^6 psi	
A	0.20	12.0	4.0	3.0
B	0.20	7.0	4.00	1.75
C	0.20	4.0	4.0	1.00
D	0.20	1.0	4.0	0.25
E	0.20	0.20	4.0	0.05
F	0.20	∞	4.0	∞

Table 12
GTSTRUDL Computer Runs

Run	Model[1]	Er/Ec[2]
1	3A	3.00
2	3B	1.75
3	3D	0.25
4	3E	0.05
5	F	∞

[1] Foundation modeled with infinite stiffness fixed supports at base of dam.
[2] See Table 11 for definition.

Table 13
Effect of Foundation Stiffness on Vertical (Syy) Stresses (Stresses in psi)

Node[1]	Er/Ec Ratio					
	0.05	0.25	1.00	1.75	3.00	∞
897	-196.25	-50.83	+56.91	+84.29	+101.93	+127.66
899	-75.94	-84.01	-81.77	-77.36	-72.20	-55.43
901	-80.73	-82.05	-83.16	-83.49	-83.68	83.70
903	-78.62	-85.27	-93.42	-96.44	98.88	-104.56
905	-78.21	-86.57	-97.80	-102.35	-106.20	-115.71
907	-79.32	-90.20	-103.97	-109.57	-114.36	-126.31
909	-83.64	-94.11	-105.06	-109.32	-112.91	-121.63
911	-83.60	-93.98	-101.92	-104.55	-106.59	-111.29
913	-102.30	-103.21	-98.93	-97.60	-96.60	-94.76
915	-84.00	-84.97	-85.32	-83.75	-81.27	-72.76
917	-347.48	-231.01	-128.47	-96.89	-74.55	-36.86
941	-220.94	-122.54	-53.38	-35.11	-22.26	-0.31
943	-74.15	-62.82	-47.44	-41.71	-37.17	-27.57
945	-65.54	-70.80	-72.68	-72.33	-71.69	-69.09
947	-65.11	-72.87	-80.59	-83.06	-84.91	-88.53
949	-65.79	-75.59	-86.85	-90.89	-94.11	-99.15
951	-68.89	-81.03	-94.95	-100.11	-104.32	-113.88
953	-76.32	-88.52	-99.75	-103.64	-106.77	-113.70
955	-83.00	-93.37	-99.96	-101.95	-103.50	-106.85
957	-90.27	-97.54	-97.38	-96.55	-95.71	-93.71
959	-132.36	-117.83	-96.62	-89.66	-84.37	-73.93
961	-246.37	-153.97	-100.40	-84.56	-72.64	-49.76

(Continued)

[1] See Figure 32.

Table 13 (Concluded)

Node	Er/Ec Ratio					
	0.05	0.25	1.00	1.75	3.00	∞
1250	-48.40	-48.68	-48.90	-48.98	-49.03	-49.22
1252	-45.12	-45.14	-45.18	-45.19	-45.20	-45.28
1254	-41.53	-41.44	-41.37	-41.35	-41.33	-41.29
1256	-36.15	-36.10	-36.03	-36.00	-35.98	-35.78
1258	-35.36	-35.40	-35.43	-35.44	-35.45	-35.24
1260	-35.94	-36.17	-36.43	-36.53	-36.61	-36.48
1262	-47.32	-47.47	-47.60	-47.63	-47.66	-47.78
1264	-45.22	-45.30	-45.36	-45.38	-45.40	-45.47
1266	-43.08	-43.08	-43.10	-43.10	-43.11	-43.15
1268	-40.95	-40.90	-40.87	-40.86	-40.85	-40.85
1270	-37.92	-37.82	-37.74	-37.71		-37.63

Table 14
Effect of Foundation Stiffness on Horizontal (Sxx) Stresses (Stresses in psi)

Node[1]	Er/Ec Ratio					
	0.05	0.25	1.00	1.75	3.00	∞
897	114.50	73.59	62.55	57.69	51.87	31.91
899	87.03	29.27	4.83	0.13	-3.57	-13.86
901	34.08	0.17	-16.52	-18.57	-19.47	-20.92
903	26.45	-5.20	-23.70	-26.43	-27.34	-26.14
905	23.49	-9.09	-28.66	-31.36	-31.97	-28.93
907	25.06	-16.41	-37.52	-39.24	-38.61	-31.58
909	24.77	-31.24	-48.39	-46.67	-43.16	-30.41
911	17.97	-47.07	-56.67	-51.29	-45.07	-27.82
913	1.53	-75.35	-69.61	-58.07	-47.51	-23.69
915	-50.12	-137.38	-94.81	-70.67	-51.85	-18.19
917	-722.18	-462.15	-176.77	-106.03	-163.89	-9.22

(Continued)

[1] See Figure 32.

Table 14 (Concluded)

Node	Er/Ec Ratio					
	0.05	0.25	1.00	1.75	3.00	∞
941	-92.66	-83.28	-79.82	-78.64	-78.28	-77.97
943	-54.35	-45.53	-37.70	-35.96	-35.17	-36.17
945	-23.68	-32.81	-34.49	-33.62	-32.64	-30.60
947	-13.44	-28.42	-33.64	-33.14	-32.08	-28.37
949	-9.92	-27.95	-35.17	-34.79	-33.52	-28.20
951	-11.33	-33.32	-40.50	-39.19	-36.86	-28.15
953	-25.57	-47.27	-48.47	-44.55	-40.18	-27.43
955	-42.67	-59.72	-54.19	-48.11	-42.25	-27.16
957	-67.14	-75.17	-61.14	-52.63	-45.16	-27.68
959	-153.92	-116.34	-74.69	-60.48	-49.84	-28.94
961	-120.89	-83.04	-67.00	-59.25	-52.22	-35.51
1250	-23.78	-23.78	-23.78	-23.78	-23.78	-23.79
1252	-23.28	-23.27	-23.28	-23.28	-23.29	-23.31
1254	-22.89	-22.83	-22.81	-22.82	-22.83	-22.86
1256	-20.93	-20.79	-20.75	-20.77	-20.79	-20.86
1258	-18.79	-18.73	-18.74	-18.77	-18.80	-18.89
1260	-15.79	-15.90	-16.02	-16.06	-16.10	-16.20
1262	-21.29	-21.30	-21.30	-21.31	-21.31	-21.31
1264	-21.03	-21.04	-21.05	-21.05	-21.06	-21.07
1266	-20.79	-20.80	-20.82	-20.83	-20.83	-20.85
1268	-20.54	-20.54	-20.56	-20.57	-20.58	-20.61
1270	-20.03	-20.02	-20.04	-20.06		-20.12

Table 15
Effect of Foundation Stiffness on Shear (Sxy) Stresses (Stresses in psi)

Node[1]	Er/Ec Ratio					
	0.05	0.25	1.00	1.75	3.00	∞
897	28.35	70.67	100.30	103.89	103.52	92.58
899	48.82	27.91	24.65	28.44	33.03	67.00
901	28.63	23.69	25.14	28.06	31.46	42.78
903	24.22	22.54	25.44	28.23	31.25	40.85
905	22.86	22.84	26.86	29.60	32.36	40.41
907	23.38	26.73	32.78	35.26	37.27	41.62
909	28.86	35.94	42.94	44.49	45.16	44.40
911	33.91	43.08	49.57	50.07	49.58	45.35
913	50.69	57.29	57.65	55.68	53.19	44.43
915	28.04	51.41	60.81	58.74	54.73	40.14
917	415.34	271.71	138.45	97.40	69.61	26.98
941	-40.63	-23.20	-12.49	-9.49	-7.18	2.68
943	10.48	20.39	33.04	37.53	40.93	47.31
945	24.54	23.54	29.28	32.89	36.27	45.12
947	23.79	23.71	28.63	31.71	34.67	42.84
949	22.95	24.89	29.85	32.52	35.01	41.82
951	24.14	30.09	35.22	36.97	38.35	41.49
953	34.42	42.42	45.16	45.11	44.72	42.73
955	48.31	54.38	52.92	51.12	49.27	43.81
957	70.30	70.31	62.03	57.78	53.97	44.31
959	127.15	101.43	75.08	65.72	58.40	43.00
961	191.87	114.83	79.83	69.22	60.69	41.92

(Continued)

[1] See Figure 32.

Table 15 (Concluded)

Node	Er/Ec Ratio					
	0.05	0.25	1.00	1.75	3.00	∞
1250	-4.04	-4.06	-4.08	-4.09	-4.09	-4.10
1252	3.59	3.55	3.49	3.47	3.45	3.36
1254	9.74	9.73	9.69	9.67	9.65	9.55
1256	18.40	18.39	18.39	18.39	18.40	18.34
1258	21.39	21.39	21.43	21.46	21.48	21.45
1260	23.78	23.93	24.09	24.15	24.20	24.24
1262	-2.00	2.04	-2.08	-2.09	-2.10	-2.13
1264	1.59	1.53	1.47	1.45	1.43	1.37
1266	4.76	4.70	4.64	4.61	4.59	4.45
1268	7.57	7.52	7.46	7.44	7.42	7.33
1270	11.12	11.09	11.05	11.04		10.94

Table 16
Effect of Foundation Stiffness on Horizontal (x) Displacements (Displacements in inches)

Node[1]	Er/Ec Ratio					
	0.05	0.25	1.00	1.75	3.00	∞
897	0.2421	0.0492	0.0138	0.0083	0.0051	0
899	0.2472	0.0518	0.0152	0.0094	0.0059	0
901	0.2495	0.0527	0.0156	0.0097	0.0060	0
903	0.2412	0.0534	0.0157	0.0097	0.0060	0
905	0.2528	0.0539	0.0156	0.0095	0.0059	0
907	0.2557	0.0545	0.0150	0.0089	0.0053	0
909	0.2588	0.0545	0.0139	0.0079	0.0045	0
911	0.2603	0.0539	0.0130	0.0071	0.0039	0
913	0.2612	0.0526	0.0117	0.0061	0.0032	0
915	0.2615	0.0501	0.0098	0.0047	0.0023	0
917	0.2500	0.0409	0.0059	0.0024	0.0009	0

(Continued)

[1] See Figure 32.

Table 16 (Concluded)

Node	Er/Ec Ratio					
	0.05	0.25	1.00	1.75	3.00	∞
941	0.2327	0.0558	0.0211	0.0154	0.0119	0.0064
943	0.2316	0.0546	0.0197	0.0141	0.0105	0.0048
945	0.2309	0.0538	0.0189	0.0132	0.0097	0.0040
947	0.2308	0.0534	0.0185	0.0128	0.0093	0.0037
949	0.2310	0.0531	0.0180	0.0124	0.0090	0.0036
951	0.2313	0.0524	0.0171	0.0115	0.0083	0.0035
953	0.2313	0.0512	0.0158	0.0105	0.0075	0.0035
955	0.2309	0.0502	0.0149	0.0098	0.0071	0.0035
957	0.2297	0.0488	0.0139	0.0090	0.0065	0.0035
959	0.2277	0.0469	0.0126	0.0080	0.0057	0.0032
961	0.2243	0.0441	0.0110	0.0067	0.0047	0.0027
1250	0.0307	0.0502	0.0466	0.0447	0.0433	0.0402
1252	0.0305	0.0500	0.0463	0.0444	0.0430	0.0399
1254	0.0302	0.0497	0.0460	0.0442	0.0427	0.0397
1256	0.0297	0.0491	0.0454	0.0436	0.0421	0.0391
1258	0.0295	0.0489	0.0451	0.0433	0.0419	0.0388
1260	0.0293	0.0487	0.0449	0.0431	0.0417	0.0386
1262	0.0199	0.0496	0.0476	0.0459	0.0446	0.0416
1264	0.0199	0.0495	0.0475	0.0458	0.0444	0.0415
1266	0.0198	0.0494	0.0473	0.0457	0.0444	0.0414
1268	0.0197	0.0493	0.0472	0.0456	0.0442	0.0413
1270	0.0195	0.0492	0.0471	0.0454	0.0441	0.0412

Table 17
Effect of Foundation Stiffness on Vertical (y) Displacements (Displacements in Inches)

Node[1]	Er/Ec Ratio					
	0.05	0.25	1.00	1.75	3.00	∞
897	-1.5715	-0.3056	-0.0742	-0.0419	-0.0242	0
899	-1.5683	-0.3089	-0.0761	-0.0432	-0.0250	0
901	-1.5393	-0.3087	-0.0776	-0.0444	-0.0259	0
903	-1.5165	-0.3072	-0.0783	-0.0451	-0.0265	0
905	-1.4921	-0.3046	-0.0786	-0.0455	-0.0269	0
907	-1.4391	-0.2966	-0.0774	-0.0451	-0.0267	0
909	-1.3792	-0.2841	-0.0740	-0.0430	-0.0255	0
911	-1.3452	-0.2757	-0.0712	-0.0413	-0.0243	0
913	-1.3071	-0.2652	-0.0677	-0.0390	-0.0229	0
915	-1.2626	-0.2526	-0.0634	-0.0362	-0.0211	0
917	-1.1991	-0.2332	-0.0568	-0.0321	-0.0185	0
941	-1.5782	-0.3089	-0.0743	-0.0412	-0.0230	-0.0022
943	-1.5623	-0.3111	-0.0780	-0.0448	-0.0265	-0.0000
945	-1.5432	-0.3111	-0.0798	-0.0467	-0.0282	-0.0018
947	-1.5222	-0.3099	-0.0808	-0.0477	-0.0292	-0.0027
949	-1.4998	-0.3077	-0.0813	-0.0483	-0.0298	-0.0032
951	-1.4516	-0.3009	-0.0807	-0.0483	-0.0300	-0.0036
953	-1.3978	-0.2904	-0.0780	-0.0468	-0.0291	-0.0038
955	-1.3679	-0.2834	-0.0758	-0.0453	-0.0281	-0.0036
957	-1.3352	-0.2749	-0.0728	-0.0433	-0.0267	-0.0033
959	-1.2986	-0.2646	-0.0691	-0.0108	-0.0249	-0.0028
961	-1.2566	-0.2527	-0.0648	-0.0378	-0.0227	-0.0021

(Continued)

[1] See Figure 32.

Table 17 (Concluded)

Node	Er/Ec Ratio					
	0.05	0.25	1.00	1.75	3.00	∞
1250	-1.5837	-0.3263	-0.0909	-0.0572	-0.0384	-0.0122
1252	-1.5677	-0.3256	-0.0926	-0.0591	-0.0405	-0.0145
1254	-1.5515	-0.3216	-0.0939	-0.0607	-0.0423	-0.0164
1256	-1.5182	-0.3218	-0.0960	-0.0634	-0.0452	-0.0195
1258	-1.5014	-0.3202	-0.0967	-0.0641	-0.0463	-0.0208
1260	-1.1844	-0.3185	-0.0974	-0.0654	-0.0474	-0.0220
1262	-1.5799	-0.3267	-0.0921	-0.0584	-0.0397	-0.0136
1264	-1.5725	-0.3264	-0.0928	-0.0593	-0.0407	-0.0145
1266	-1.5651	-0.3260	-0.0935	-0.0601	-0.0514	-0.0155
1268	-1.5576	-0.3255	-0.0941	-0.0608	-0.0423	-0.0163
1270	-1.5463	-0.3247	-0.0949	-0.0618	-0.0431	-0.0175

Table 18
Effect of Foundation Stiffness on Relative Horiontal Displacement[1]

Node[2]	Relative Displacement w.r.t. Er/Ec = 0.05					
	Er/Ec Ratio					
	Er/Ec = 0.05	0.25	1.00	1.75	3.00	∞
897	0.2421	-0.1929	-0.2283	-0.2334	-0.2370	NA[3]
899	0.2472	-0.1954	-0.2320	-0.2378	-0.2413	NA
901	0.2495	-0.1968	-0.2339	-0.2398	-0.2435	NA
903	0.2412	-0.1878	-0.2255	-0.2315	-0.2352	NA
905	0.2528	-0.1999	-0.2372	-0.2433	-0.2469	NA
907	0.2557	-0.2012	-0.2407	-0.2468	-0.2504	NA
909	0.2588	-0.2043	-0.2449	-0.2509	-0.2543	NA
911	0.2603	-0.2064	-0.2473	-0.2532	-0.2564	NA
913	0.2612	-0.2086	-0.2495	-0.2551	-0.2580	NA
915	0.2615	-0.2114	-0.2517	-0.2568	-0.2592	NA
917	0.2500	-0.2091	-0.2441	-0.2476	-0.2491	NA

(Continued)

[1] All displacement in inches.
[2] See Figure 32.
[3] NA = not applicable since nodes are supported in fixed base case.

Table 18 (Concluded)

Node	Relative Displacement w.r.t. Er/Ec = 0.05					
	Er/Ec Ratio					
	Er/Ec = 0.05	0.25	1.00	1.75	3.00	∞
941	0.2327	-0.1769	-0.2116	-0.2173	-0.2208	-0.2263
943	0.2326	-0.1770	-0.2119	-0.2175	-0.2211	-0.2268
945	0.2309	-0.1771	-0.2120	-0.2177	-0.2212	-0.2269
947	0.2308	-0.1774	-0.2123	-0.2180	-0.2215	-0.2271
949	0.2310	-0.1779	-0.2130	-0.2186	-0.2220	-0.2274
951	0.2313	-0.1789	-0.2142	-0.2198	-0.2230	-0.2278
953	0.2313	-0.1801	-0.2155	-0.2208	-0.2238	-0.2278
955	0.2309	-0.1807	-0.2160	-0.2211	-0.2238	-0.2274
957	0.2297	-0.1795	-0.2140	-0.2189	-0.2214	-0.2262
959	0.2277	-0.1808	-0.2151	-0.2197	-0.2220	-0.2245
961	0.2243	-0.1798	-0.2133	-0.2176	-0.2196	-0.2216
1250	0.0307	0.0195	0.0159	0.0140	0.0126	0.0095
1252	0.0305	0.0195	0.0158	0.0139	0.0125	0.0094
1254	0.0302	0.-195	0.0158	0.0140	0.0125	0.0095
1256	0.0297	0.0194	0.0157	0.0139	0.0124	0.0094
1258	0.0295	0.0194	0.0156	0.0138	0.0124	0.0093
1260	0.0293	0.0194	0.0156	0.0138	0.0124	0.0093
1262	0.0199	0.0297	0.0277	0.0260	0.0247	0.0217
1264	0.0199	0.0296	0.0276	0.0259	0.0245	0.0216
1266	0.0198	0.0296	0.0275	0.0259	0.0246	0.0216
1268	0.0197	0.0296	0.0215	0.0259	0.0245	0.0216
1270	0.0195	0.0297	0.0276	0.0259	0.0246	0.0217

Table 19
Effect of Foundation Stiffness on Relative Vertical Displacement[1]

Node[2]	Relative Displacement w.r.t. Er/Ec = 0.05					
	Er/Ec Ratio					
	Er/Ec = 0.05	0.25	1.00	1.75	3.00	∞
897	-0.5715	1.2659	1.4973	1.5296	1.5473	NA[3]
899	-1.5683	1.2594	1.4922	1.5251	1.5433	NA
901	-1.5393	1.2306	1.4617	1.4949	1.5134	NA
903	-1.5165	1.2093	1.4382	1.4714	1.4900	NA
905	-1.4921	1.1875	1.4135	1.4466	1.4652	NA
907	-1.4391	1.1425	1.3617	1.3940	1.4124	NA
909	-1.3791	1.0950	1.3051	1.3361	1.3536	NA
911	-1.3452	1.0695	1.2740	1.3039	1.3209	NA
913	-1.3071	1.4019	1.2394	1.2681	1.2842	NA
915	-1.2626	1.0100	1.1992	1.2264	1.2415	NA
917	-1.1991	0.9659	1.1423	1.1670	1.1806	NA
941	-1.5782	1.2693	1.5039	1.5370	1.5552	1.5760
943	-1.5623	1.2513	1.4843	1.5175	1.5358	1.5623
945	-1.5432	1.2321	1.4634	1.4965	1.5150	1.5414
947	-1.5222	1.2123	1.4414	1.4745	1.4930	1.5195
949	-1.4998	1.1921	1.4185	1.4515	1.4700	1.4966
951	-1.4516	1.1507	1.3709	1.4033	1.4216	1.4480
953	-1.3978	1.1074	1.3198	1.3510	1.3687	1.3940
955	-1.3679	1.0845	1.2921	1.3226	1.3398	1.3643
957	-1.3352	1.0603	1.2624	1.2919	1.3085	1.3319
959	-1.2986	1.0340	1.2295	1.2578	1.2737	1.2958
961	-1.2566	1.0039	1.1918	1.2188	1.2339	1.2545

(Continued)

[1] All displacements in inches.
[2] See Figure 32.
[3] NA = not applicable since nodes are supports in fixed base case.

Table 19 (Concluded)

Node	Relative Displacement w.r.t. Er/Ec = 0.05					
	Er/Ec Ratio					
	Er/Ec = 0.05	0.25	1.00	1.75	3.00	∞
1250	-1.5837	1.2574	1.4928	1.5265	1.5453	1.5715
1252	-1.5677	1.2421	1.4751	1.5086	1.5272	1.5532
1254	-1.5515	1.2269	1.4576	1.4908	1.5092	1.5351
1256	-1.5182	1.1964	1.4222	1.4548	1.4730	1.4987
1258	-1.5014	1.1812	1.4047	1.4370	1.4551	1.4806
1260	-1.4844	1.1659	1.3870	1.4190	1.4370	1.4624
1262	-1.5799	1.2532	1.4878	1.5215	1.5402	1.5663
1264	-1.5725	1.2461	1.4797	1.5132	1.5318	1.5580
1266	-1.5651	1.2391	1.4716	1.5050	1.5236	1.5496
1268	-1.5576	1.2321	1.4635	1.4968	1.5153	1.5413
1270	-1.5463	1.2216	1.4514	1.4845	1.5029	1.5288

Appendix A
Data Files

```
STRUDL '6 BASE ELEMENTS,3 BU X 6 BU,ER/EC=1.0'
TYPE PLANE STRAIN
UNITS FT LBS
GENE 993 JOI ID 1 1 X 0 0
CHANGES
JOINT COORDINATES
1 0 0
37 716.25 0
617 0 429.75
653 716.25 429.75
661 287.45 441
673 429.17 441
721 290.33 476.5
733 391.417 475.6
881 298.416 572.5
893 326.749 572.5
921 298.416 589.5
933 315.416 589.5
981 298.416 614.5
993 315.416 614.5
GEN 8 1 37 653 617
XD 18 P 3 3 2 2 1 1 1 1 1 1 1 1 1 1 2 2 3 3
YD 11 P 3 3 3 2 1 1 1 1 1 1 1
GEN 8 661 673 733 721
XD 6 P EQ
YD 3 P EQ
GEN 8 721 733 893 881
XD 6 P EQ
YD 8 P EQ
GEN 8 881 893 933 921
XD 6 P EQ
YD 2 P EQ
GEN 8 921 933 993 981
XD 6 P EQ
YD 3 P EQ
ADDITIONS
GEN 18 ELE ID 1 1 F 1 2 T 3 2 T 59 2 T 57 2 T 2 2 T 39 1 T 58 2 T 38 1
REPEAT 10 ID 18 F 56
GEN 6 ELE ID 205 1 F 661 2 T 663 2 T 683 2 T 681 2 T 662 2 -
T 675 1 T 682 2 T 674 1
REPEAT 15 ID 6 F 20
GENE 6 ELE ID 199 1 F 629 2 T 631 2 T 663 2 T 661 2 T 630 2 -
T 655 1 T 662 2 T 654 1
ELEMENT PROPERTIES
1 TO 300 TYPE 'IPOQ' THICK 1.0
CON E 576000000 1 TO 300
POI .2 ALL
STATUS SUPPORTS 1 TO 37 38 57 94 113 150 169 206 225 262 281 318 337
STATUS SUPPORTS 374 393 430 449 486 505 542 561 598 617 56 112 149 168
STATUS SUPPORTS 205 224 261 280 317 336 373 392 429 448 485 504 541 560
STATUS SUPPORTS 597 616 653
JOINT RELEASES
2 TO 36 FORCE X
38 57 94 113 150 169 206 225 262 281 318 337 374 393 FORCE Y
430 449 486 505 542 561 598 617 56 112 149 168 205 FORCE Y
224 261 280 317 336 373 392 429 448 485 504 541 560 FORCE Y
597 616 653 FORCE Y
LOADING 1
ELEMENT LOADS
283 EDGE FOR EDGE 4 GLO VAR UX 104.21 363.8 624.
277 EDGE FOR EDGE 4 GLO VAR UX 624. 889.2 1154.4
271 EDGE FOR EDGE 4 GLO VAR UX 1154.4 1419.6 1684.8
265 EDGE FOR EDGE 4 GLO VAR UX 1684.8 2062.9 2441.4
259 EDGE FOR EDGE 4 GLO VAR UX 2441.4 2819.9 3198.
253 EDGE FOR EDGE 4 GLO VAR UX 3198. 3576.1 3954.6
247 EDGE FOR EDGE 4 GLO VAR UX 3954.6 4333.1 4711.2
241 EDGE FOR EDGE 4 GLO VAR UX 4711.2 5089.3 5467.8
235 EDGE FOR EDGE 4 GLO VAR UX 5467.8 5848.1 6224.4
229 EDGE FOR EDGE 4 GLO VAR UX 6224.4 6602.7 6981.
223 EDGE FOR EDGE 4 GLO VAR UX 6981. 7359.3 7737.6
217 EDGE FOR EDGE 4 GLO VAR UX 7737.6 8096.4 8455.2
211 EDGE FOR EDGE 4 GLO VAR UX 8456.2 8814. 9172.8
205 EDGE FOR EDGE 4 GLO VAR UX 9178.8 9531.6 9890.4
199 EDGE FOR EDGE 4 GLO VAR UX 9890.4 10249.2 10608.
199 TO 300 BODY FOR GLO BY -150.0
181 TO 198 EDGE FOR EDGE 3 GLO UNIF LY -10608.
UNITS INCHES
STIFFNESS ANALYSIS REDUCE BAND
LIST REACTIONS
LIST DISPLACEMENTS
CALCULATE AVERAGE STRESSES FOR 199 TO 300
CALCULATE AVERAGE STRESSES FOR 1 TO 198
SAVE DIRECT 'MODGP'
FINISH
/
```

Model 7

```
STPUDL '10 BASE ELEMENTS,3 BU X 5 BU FOUNDATION ,ER=1.0EC
TYPE PLANE STRAIN
UNITS FT LBS
GENE 1569 JOI ID 1 1 X 0 0
CHANGES
JOINT COORDINATES
1 0 0
45 716.25 0
885 0 429.75
929 716.25 429.75
941 297.45 441
961 420.17 441
1037 298.33 475.5
1057 391.417 475.0
1325 298.416 572.5
1345 326.749 572.5
1421 298.416 589.6
1441 315.416 589.5
1549 298.416 614.5
1569 315.416 614.5
GEN 8 1 45 929 885
XD 22 P 3 3 2 2 1 1 .5 .5 .5 .5 1 1 .5 .5 .5 .5 1 1 2 2 3 3
YD 13 P 2 2 2 2 2 1 1 1 1 1 1 1 1
GEN 8 941 961 1057 1037
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 3 P EQ
GEN 8 1037 1057 1345 1325
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 8 P EQ
GEN 8 1325 1345 1441 1421
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 3 P EQ
GEN 8 1421 1441 1569 1549
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 4 P EQ
ADDITIONS
GEN 22 ELE ID 1 1 F 1 2 T 3 2 T 71 2 T 69 2 T 2 2 T 47 1 T 70 2 -
T 46 1
REPEAT 12 ID 22 F 68
GEN 10 ELE ID 287 1 F 897 2 T 899 2 T 943 2 T 941 2 T 898 2 -
T 931 1 T 942 2 T 930 1
GEN 10 ELE ID 297 1 F 941 2 T 943 2 T 975 2 T 973 2 T 942 2 -
T 963 1 T 974 2 T 962 1
REPEAT 18 ID 10 F 32
 ELEMENT PROPERTIES
 1 TO 486 TYPE 'IPQQ' THICK 1.0
CON E 576000000 287 TO 486
CON E 144000000 1 TO 286
POI .2 ALL
STATUS SUPPORTS 1 TO 45 68 69 114 113 136 137 181 182 204 205 -
249 250 272 273 317 318 340 341 385 386 408 409 453 454 476 477 521 -
522 544 545 589 590 612 613 657 658 680 681 726 726 748 749 793 794 -
816 817 861 862 884 885 929 46
JOINT RELEASES
2 TO 44 FORCE X
46 68 69 113 114 136 137 181 182 204 205 249 250 -
272 273 317 318 340 341 385 386 408 409 453 454 476 477 521 522 -
544 545 589 590 612 613 657 658 680 681 725 726 748 749 793 794 -
816 817 861 862 884 885 929 FORCE Y
 LOADING 1 'HYDROSTATIC USING EDGE LOADS'
 ELEMENT LOADS
447 EDGE FOR EDGE 4 GLO VAR UX 234. 429. 624.
437 EDGE FOR EDGE 4 GLO VAR UX 624. 800.01 977.81
427 EDGE FOR EDGE 4 GLO VAR UX 977.81 1154.72 1331.62
417 EDGE FOR EDGE 4 GLO VAR UX 1331.62 1508.21 1684.8
407 EDGE FOR EDGE 4 GLO VAR UX 1684.8 2021.14 2357.47
397 EDGE FOR EDGE 4 GLO VAR UX 2357.47 2693.81 3030.14
387 EDGE FOR EDGE 4 GLO VAR UX 3030.14 3366.17 3702.19
377 EDGE FOR EDGE 4 GLO VAR UX 3702.19 4038.53 4374.86
367 EDGE FOR EDGE 4 GLO VAR UX 4374.86 4711.2 5047.54
357 EDGE FOR EDGE 4 GLO VAR UX 5047.54 5383.88 5720.21
347 EDGE FOR EDGE 4 GLO VAR UX 5720.21 6056.24 6392.26
337 EDGE FOR EDGE 4 GLO VAR UX 6392.26 6728.6 7064.93
327 EDGE FOR EDGE 4 GLO VAR UX 7064.93 7401.27 7737.6
317 EDGE FOR EDGE 4 GLO VAR UX 7737.6 8096.4 8455.2
307 EDGE FOR EDGE 4 GLO VAR UX 8455.2 8814.0 9172.8
297 EDGE FOR EDGE 4 GLO VAR UX 9172.8 9531.6 9890.4
287 EDGE FOR EDGE 4 GLO VAR UX 9890.4 10249.2 10608.
 287 TO 486 BODY FORCE GLOBAL BY -150.0
265 TO 270 EDGE FOR EDGE 3 GLO UNIF LV -10608.
PRINT JOINT COORDINATES
UNITS INCHES
STIFFNESS ANALYSIS REDUCE BAND
LIST REACTIONS
LIST SUM REACTIONS
LIST DISPLACEMENTS
CALCULATE AVERAGE STRESSES FOR 287 TO 486
CALCULATE AVERAGE STRESSES FOR 1 TO 286
LIST STRESSES
SAVE DIRECT 'MOD8P'
FINISH
/
```

```
STRUDL '10 BASE ELEMENTS,3 BU X 6 BU FOUNDATION ,ER-3.0EC
TYPE PLANE STRAIN
UNITS FT LBS
GENE 1569 JOI ID 1 1 X 0 0,
CHANGES
JOINT COORDINATES
1 0 0
45 716.25 0
885 0 429.75
929 716.25 429.75
941 287.45 441
961 420.17 441
1037 290.33 475.5
1057 391.417 475.0
1325 298.416 572.5
1345 326.749 572.5
1421 298.416 589.5
1441 315.416 589.5
1549 298.416 614.5
1569 315.416 614.5
GEN B 1 45 929 885
XD 22 P 3 3 2 2 1 1 .5 .5 .5 .5 1 1 .6 .5 .5 .5 1 1 2 2 3 3
YD 13 P 2 2 2 2 2 1 1 1 1 1 1 1 1
GEN B 941 961 1057 1037
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 3 P EQ
GEN B 1037 1057 1345 1325
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 9 P EQ
GEN B 1325 1345 1441 1421
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 3 P EQ
GEN B 1421 1441 1569 1549
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 4 P EQ
ADDITIONS
GEN 22 ELE ID 1 1 F 1 2 T 3 2 T 71 2 T 69 2 T 2 2 T 47 1 T 70 2 -
T 46 1
REPEAT 12 ID 22 F 68
GEN 10 ELE ID 287 1 F 897 2 T 899 2 T 943 2 T 941 2 T 898 2 -
T 931 1 T 942 2 T 930 1
GEN 10 ELE ID 297 1 F 941 2 T 943 2 T 975 2 T 973 2 T 942 2 -
T 963 1 T 974 2 T 962 1
REPEAT 18 ID 10 F 32
 ELEMENT PROPERTIES
 1 TO 486 TYPE 'IPQQ' THICK 1.0
CON E 576000000 287 TO 486
CON E 1728000000 1 TO 286
POI .2 ALL
STATUS SUPPORTS 1 TO 45 68 69 114 113 136 137 181 182 204 205 -
249 250 272 273 317 318 340 341 385 386 408 409 453 454 476 477 521 -
522 544 545 589 590 612 613 657 658 680 681 725 726 748 749 793 794 -
816 817 861 862 884 885 929 46
JOINT RELEASES
2 TO 44 FORCE X
46 68 69 113 114 136 137 181 182 204 205 249 250 -
272 273 317 318 340 341 385 386 408 409 453 454 476 477 521 522 -
544 545 589 590 612 613 657 658 680 681 725 726 748 749 793 794 -
816 817 861 862 884 885 929 FORCE Y
 LOADING 1 'HYDROSTATIC USING EDGE LOADS'
 ELEMENT LOADS
447 EDGE FOR EDGE 4 GLO VAR UX 234. 429. 624.
437 EDGE FOR EDGE 4 GLO VAR UX 624. 800.91 977.81
427 EDGE FOR EDGE 4 GLO VAR UX 977.81 1154.72 1331.62
417 EDGE FOR EDGE 4 GLO VAR UX 1331.62 1508.21 1684.8
407 EDGE FOR EDGE 4 GLO VAR UX 1684.8 2021.14 2357.47
397 EDGE FOR EDGE 4 GLO VAR UX 2357.47 2693.81 3030.14
387 EDGE FOR EDGE 4 GLO VAR UX 3030.14 3366.17 3702.19
377 EDGE FOR EDGE 4 GLO VAR UX 3702.19 4038.53 4374.86
367 EDGE FOR EDGE 4 GLO VAR UX 4374.86 4711.2 5047.54
357 EDGE FOR EDGE 4 GLO VAR UX 5047.54 5383.88 5720.21
347 EDGE FOR EDGE 4 GLO VAR UX 5720.21 6056.24 6392.26
337 EDGE FOR EDGE 4 GLO VAR UX 6392.26 6728.6 7064.93
327 EDGE FOR EDGE 4 GLO VAR UX 7064.93 7401.27 7737.6
317 EDGE FOR EDGE 4 GLO VAR UX 7737.6 8096.4 8455.2
307 EDGE FOR EDGE 4 GLO VAR UX 8455.2 8814.0 9172.8
297 EDGE FOR EDGE 4 GLO VAR UX 9172.8 9531.6 9890.4
287 EDGE FOR EDGE 4 GLO VAR UX 9890.4 10249.2 10608.
 287 TO 486 BODY FORCE GLOBAL BY -150.0
265 TO 270 EDGE FOR EDGE 3 GLO UNIF LY -10608.
PRINT JOINT COORDINATES
UNITS INCHES
STIFFNESS ANALYSIS REDUCE BAND
LIST REACTIONS
LIST SUM REACTIONS
LIST DISPLACEMENTS
CALCULATE AVERAGE STRESSES FOR 287 TO 486
CALCULATE AVERAGE STRESSES FOR 1 TO 286
LIST STRESSES
SAVE DIRECT 'MOD11P'
FINISH
/
```

Model 9

```
STRUDL '10 BASE ELEMENTS,3 BU X 5 BU FOUNDATION ,ER=1.0EC
TYPE PLANE STRAIN
UNITS FT LBS
GENE 1569 JOI ID 1 1 X 0 0\
CHANGES
JOINT COORDINATES
1 0 0
45 716.25 0
885 0 429.75
929 716.25 429.75
941 287.45 441
961 420.17 441
1037 290.33 475.5
1057 391.417 475.0
1325 298.416 572.5
1345 326.749 572.5
1421 298.416 589.5
1441 315.416 589.5
1549 298.416 614.5
1569 315.416 614.5
GEN 8 1 45 929 885
XD 22 P 3 3 2 2 1 1 .6 .6 .6 .5 1 1 .5 .6 .5 .6 1 1 2 2 3 3
YD 13 P 2 2 2 2 2 2 1 1 1 1 1 1 1 1
GEN 8 941 961 1057 1037
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 3 P EQ
GEN 8 1037 1057 1345 1325
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 9 P EQ
GEN 8 1325 1345 1441 1421
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 3 P EQ
GEN 8 1421 1441 1569 1549
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 4 P EQ
ADDITIONS
GEN 22 ELE ID 1 1 F 1 2 T 3 2 T 71 2 T 69 2 T 2 2 T 47 1 T 70 2 -
T 46 1
REPEAT 12 ID 22 F 68
GEN 10 ELE ID 287 1 F 897 2 T 899 2 T 943 2 T 941 2 T 898 2 -
T 931 1 T 942 2 T 930 1
GEN 10 ELE ID 297 1 F 941 2 T 943 2 T 976 2 T 973 2 T 942 2 -
T 963 1 T 974 2 T 962 1
REPEAT 18 ID 10 F 32
 ELEMENT PROPERTIES
 1 TO 486 TYPE 'IPQQ' THICK 1.0
CON E 576000000 287 TO 486
E 576000000 1 TO 286
POI .2 ALL
STATUS SUPPORTS 1 TO 45 68 69 114 113 136 137 181 182 204 205 -
249 250 272 273 317 318 340 341 385 386 408 409 453 454 476 477 521 -
522 544 545 589 590 612 613 657 658 680 681 725 726 748 749 793 794 -
816 817 861 862 884 885 929 46
JOINT RELEASES
2 TO 44 FORCE X
46 68 69 113 114 136 137 181 182 204 205 249 250 -
272 273 317 318 340 341 385 386 408 409 453 454 476 477 521 522 -
544 545 589 590 612 613 657 658 680 681 725 726 748 749 793 794 -
816 817 861 862 885 884 FORCE Y
 LOADING 1 'HYDROSTATIC USING EDGE LOADS'
 ELEMENT LOADS
447 EDGE FOR EDGE 4 GLO VAR UX 234. 429. 624.
437 EDGE FOR EDGE 4 GLO VAR UX 624. 800.81 977.81
427 EDGE FOR EDGE 4 GLO VAR UX 977.8; 1154.72 1331.62
417 EDGE FOR EDGE 4 GLO VAR UX 1331.62 1508.21 1684.8
407 EDGE FOR EDGE 4 GLO VAR UX 1684.8 2021.14 2357.47
397 EDGE FOR EDGE 4 GLO VAR UX 2357.47 2693.81 3030.14
387 EDGE FOR EDGE 4 GLO VAR UX 3030.14 3366.17 3702.19
377 EDGE FOR EDGE 4 GLO VAR UX 3702.19 4038.53 4374.86
367 EDGE FOR EDGE 4 GLO VAR UX 4374.86 4711.2 5047.54
357 EDGE FOR EDGE 4 GLO VAR UX 5047.54 5383.88 5720.21
347 EDGE FOR EDGE 4 GLO VAR UX 5720.21 6056.24 6392.26
337 EDGE FOR EDGE 4 GLO VAR UX 6392.26 6728.6 7064.93
327 EDGE FOR EDGE 4 GLO VAR UX 7064.93 7401.27 7737.6
317 EDGE FOR EDGE 4 GLO VAR UX 7737.6 8096.4 8455.2
307 EDGE FOR EDGE 4 GLO VAR UX 8455.2 8814.0 9172.8
297 EDGE FOR EDGE 4 GLO VAR UX 9172.8 9531.6 9890.4
287 EDGE FOR EDGE 4 GLO VAR UX 9890.4 10249.2 10608.
 287 TO 486 BODY FORCE GLOBAL BY -150.0
265 TO 270 EDGE FOR EDGE 3 GLO UNIF LY -10608.
UNITS INCHES
STIFFNESS ANALYSIS REDUCE BAND
LIST REACTIONS
 LIST SUM REACTIONS
LIST DISPLACEMENTS
 CALCULATE AVERAGE STRESSES FOR 287 TO 486
CALCULATE AVERAGE STRESSES FOR 1 TO 286
SAVE DIRECT 'MODDP'
 FINISH
/
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REPORT DOCUMENTATION PAGE

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Jerry Foster, H. Wayne Jones

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13. ABSTRACT *(Maximum 200 words)*

This study is a continuation of an on-going project by the Computer-Aided Structural Engineering (CASE) Committee on finite element analysis. This method of analysis, though in use for many years, is becoming more widely acclaimed as a viable method of solution available to engineers for structural analyses.

Phase Ib of this study, discussed herein, describes the use of foundations in finite element modeling using a typical Corps structure, a gravity dam. Included in the report are discussions of the various types of foundation models which can be used in a finite element analysis, the size of the foundation finite element model, the effect of the foundation size used in the analysis on stresses in the structure, and the effect of foundation stiffness on the stresses in the structure.

14. SUBJECT TERMS
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Gravity dams

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Washington, DC 20314-1000;
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

WATERWAYS EXPERIMENT STATION REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

	Title	Date
Technical Report K-78-1	List of Computer Programs for Computer-Aided Structural Engineering	Feb 1978
Instruction Report O-79-2	User's Guide: Computer Program with Interactive Graphics for Analysis of Plane Frame Structures (CFRAME)	Mar 1979
Technical Report K-80-1	Survey of Bridge-Oriented Design Software	Jan 1980
Technical Report K-80-2	Evaluation of Computer Programs for the Design/Analysis of Highway and Railway Bridges	Jan 1980
Instruction Report K-80-1	User's Guide: Computer Program for Design/Review of Curvilinear Conduits/Culverts (CURCON)	Feb 1980
Instruction Report K-80-3	A Three-Dimensional Finite Element Data Edit Program	Mar 1980
Instruction Report K-80-4	A Three-Dimensional Stability Analysis/Design Program (3DSAD)	
	Report 1: General Geometry Module	Jun 1980
	Report 3: General Analysis Module (CGAM)	Jun 1982
	Report 4: Special-Purpose Modules for Dams (CDAMS)	Aug 1983
Instruction Report K-80-6	Basic User's Guide: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA)	Dec 1980
Instruction Report K-80-7	User's Reference Manual: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA)	Dec 1980
Technical Report K-80-4	Documentation of Finite Element Analyses	
	Report 1: Longview Outlet Works Conduit	Dec 1980
	Report 2: Anchored Wall Monolith, Bay Springs Lock	Dec 1980
Technical Report K-80-5	Basic Pile Group Behavior	Dec 1980
Instruction Report K-81-2	User's Guide: Computer Program for Design and Analysis of Sheet Pile Walls by Classical Methods (CSHTWAL)	
	Report 1: Computational Processes	Feb 1981
	Report 2: Interactive Graphics Options	Mar 1981
Instruction Report K-81-3	Validation Report: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA)	Feb 1981
Instruction Report K-81-4	User's Guide: Computer Program for Design and Analysis of Cast-in-Place Tunnel Linings (NEWTUN)	Mar 1981
Instruction Report K-81-6	User's Guide: Computer Program for Optimum Nonlinear Dynamic Design of Reinforced Concrete Slabs Under Blast Loading (CBARCS)	Mar 1981
Instruction Report K-81-7	User's Guide: Computer Program for Design or Investigation of Orthogonal Culverts (CORTCUL)	Mar 1981
Instruction Report K-81-9	User's Guide: Computer Program for Three-Dimensional Analysis of Building Systems (CTABS80)	Aug 1981
Technical Report K-81-2	Theoretical Basis for CTABS80: A Computer Program for Three-Dimensional Analysis of Building Systems	Sep 1981
Instruction Report K-82-6	User's Guide: Computer Program for Analysis of Beam-Column Structures with Nonlinear Supports (CBEAMC)	Jun 1982

(Continued)

WATERWAYS EXPERIMENT STATION REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

(Continued)

	Title	Date
Instruction Report K-82-7	User's Guide: Computer Program for Bearing Capacity Analysis of Shallow Foundations (CBEAR)	Jun 1982
Instruction Report K-83-1	User's Guide: Computer Program with Interactive Graphics for Analysis of Plane Frame Structures (CFRAME)	Jan 1983
Instruction Report K-83-2	User's Guide: Computer Program for Generation of Engineering Geometry (SKETCH)	Jun 1983
Instruction Report K-83-5	User's Guide: Computer Program to Calculate Shear, Moment, and Thrust (CSMT) from Stress Results of a Two-Dimensional Finite Element Analysis	Jul 1983
Technical Report K-83-1	Basic Pile Group Behavior	Sep 1983
Technical Report K-83-3	Reference Manual: Computer Graphics Program for Generation of Engineering Geometry (SKETCH)	Sep 1983
Technical Report K-83-4	Case Study of Six Major General-Purpose Finite Element Programs	Oct 1983
Instruction Report K-84-2	User's Guide: Computer Program for Optimum Dynamic Design of Nonlinear Metal Plates Under Blast Loading (CSDOOR)	Jan 1984
Instruction Report K-84-7	User's Guide: Computer Program for Determining Induced Stresses and Consolidation Settlements (CSETT)	Aug 1984
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