FEASIBILITY OF CONCRETE GRAVITY DAMS IN HIMALAYAS

A DISSERTATION

Submitted in partial fulfilment of the requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
WATER RESOURCES DEVELOPMENT (CIVIL)

By

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CANDIDATE'S DECLARATION

I hereby certify that the work, which is being presented in the dissertation entitled **"FEASIBILITY OF CONCRETE GRAVITY DAMS IN HIMALAYAS"** in partial fulfillment of the requirement for the award of the Degree of Master in Technology in Water Resources Development (Civil) submitted in the Department of Water Resources Development Training Centre of Indian Institute of Technology Roorkee is an authentic record of my own work carried out during a period from July 2001 to February 2002 under the supervision of **Dr. B. N. Asthana,** Emeritus Fellow Water Resources Development Training Centre and **Dr. R. P. Singh** Professor, Water Resources Development Training Centre, Indian Institute of Technology Roorkee, Roorkee, India.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree.

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SYNOPSIS

Concrete gravity dam is a solid concrete structure with its cross-section approximately triangular in shape, so proportioned that the external forces exerted on it are resisted by its own weight. The pattern of stress distribution and deformations in the dam foundation system are of great concern for safety and economy case of a high concrete gravity dam founded on a weak rock. Any variation in foundation properties and dam height would largely affect the safe design of the foundation and dam.

In this dissertation, the stresses and deformations have been studied by using 2-D Finite Element Method. Four cases have been studied in this dissertation work. Dams of height 125m (Case 1), 150m (Case 2), 175m (Case 3) and 200m (Case 4) have been considered. Each case has been analyzed with varying modulus of foundation i.e. 0.2, 0.4, 0.6, 1.0 and 2.0 times of concrete. For each case constant foundation extent of 1.5H (H = Height of dam) on both laterals the depth is considered. Rigid boundary condition at bottom and both lateral vertical sides of foundation has been considered in the analysis of all cases. Each case has been analyzed for the loading combination of self weight of the dam + reservoir water pressure + normal uplift pressure + earthquake force.

Results of these case studies, in respect of distribution of stresses and deformations, have been analyzed and discussed in this dissertation.

The study has shown that variation in foundation elasticity and the dam heights affect the distribution of stresses and deformations in dam foundation system. Maximum tensile stresses are found concentrated around the heel and compressive stresses around the toe of the dam. Modulus deformation of foundation less than 0.6 times of concrete has been found to result in sharp increase of stresses and displacements in the dam foundation system. The effect of dam height on displacements is more pronounced than that on stresses. Foundation elasticity does not have that much influence on stresses as compare to that on displacements. Therefore, it is concluded that a high concrete gravity dam needs a rock modulus of deformation greater than 0.6 times of concrete. The data has shown that generally this value of rock modulus is not available in Himalayas. Hence a high conventional concrete gravity dam is not feasible in Himalayas.

INTRODUCTION

The choice of a concrete gravity dam for a perticular dam site depends on consideration of foundation type, valley shape, geology, availability of construction material, access to site etc. Gravity dams can be built at both narrow and wide valleys. Some times they are constructed at sites where rock fromations are not for arch dams (11).

Gravity dams are most commonly designed by gravity method of stress analysis, in which the vertical normal stresses on a horizontal plane are assumed to a linearly. Based on the analyses of several dams by refined analysis techniques it has been observed that the vertical normal stress distribution is non-linear in the lower third height of the dam. The gravity analysis can not take into account the foundation elasticity and thus, is not capable of predicting the stresses in the dam and foundation adequately.

All these drawbacks of gravity method are effectively removed in finite element analysis of the dam section. For wide valleys where the transverse joints are provided, the dam acts as a two-dimensional structure and therefore, a two dimensional finite element analysis of the dam section gives correct picture of the stress and strains in the dam and the foundation. However if the transverse joints are grouted the dam acts as a monolith and the structure essentially becomes a three-dimensional one to be analysed by 3-D FEM (12).

1.1 OBJECTIVE OF THE STUDY

The objective of the present study is to determine the limiting ratio of foundation elasticity (EF) to the elasticity of concrete dam (ED) beyond which the foundation is suitable for a concrete gravity dam.

To achieve the above objective, following analysis of dam-foundation system has been made in the present study.

- Stresses in the dam-foundation system and
- Deformations in the dam-foundation system due to applied loads.

1.2 METHODOLOGY

In the present study analysis has been carried out for 125m, 150m, 175m and 200m high concrete gravity dam sections with varying rock modules of foundation (0.2, 0.4, 0.6, 1.0 and 2.0 times of concrete) and constant foundation extent of 1.5H on both lateral and vertical direction in the foundation. A rigid boundary condition is assumed at bottom and both vertical sides in the foundation for the analyses of all heights of dam. Above studies have been done by using 2-Dimensional finite element technique for the evaluation of stresses and deformations in the dam foundation system.

1.3 SCOPE OF THE STUDY

A brief review of the 2-D Finite Element Method for analysis of dams has been presented in chapter–2.

In Chapter-3, the results of analysis of 125m, 150m, 175m and 200m high dams with varying rock modules of foundation have been presented. The discussion of results is also given in this chapter.

Conclusions of the study have been given in Chapter-4 along with suggestions for further study and recommendations.

FINITE ELEMENT METHOD IN ANALYSIS OF DAMS

2.1 GENERAL

The Finite Element Method is a numerical analysis technique for obtaining solutions to a wide variety of engineering problems. Although originally developed to study the stresses in complex air frame structures, it has since been extended and applied to the broad field of continuum mechanics. Because of its diversity and flexibility as an analysis tool, it is receiving much attention in engineering and in industry (7).

2.2 GENERAL DESCRIPTION OF THE METHOD

In a continuum problem of any dimension, the field variable possesses infinitely many values because it is a function of each generic point in the body or solution region. The finite element discretization procedure reduces the problem to one of a finite number of unknowns by dividing the solution region into elements and by expressing the unknown field variable in terms of assumed approximating functions within each element. The approximating functions are defined in terms of the values of the field variables at specified points called nodes or nodal points. Nodes usually lie on the element boundaries, where adjacent elements are considered to be connected. The nodal values of the field variables and the interpolation functions for the element completely define the behaviour of the field variable within the elements (5 and 6).

The approximating functions (or interpolation functions) have to satisfy certain compatibility conditions. Often the functions are so chosen that the field variables or its derivatives are continuous across adjoining element boundaries.

2.3 ANALYSIS PROCEDURE

The solution of a continuum problem by the finite element method always follows an orderly step by step process. The various steps are briefly described below (3 & 10).

2.3.1 Discretization of the Continuum

Discretization may be described as the process in which the given body is sub-divided into an equivalent system of finite elements. Many types of finite elements have been developed. Figure 2.1 shows a number of well proven elements for dealing with two-dimensional problems. As with all properly designed elements a convergent solution of any desired accuracy can be achieved using successively finer sub-divisions, the choice between them is strictly a matter of economy. Most of the elements shown in Fig. 2.1 & 2.2 are well known and described in standard books like C. S. Desai (1979) and C. S. Desai and J. F. Abael (1987).

The isoparametric elements (Fig. 2.2) are most efficient for the analysis of dams both in two and three-dimensional analysis. In this study an 8-noded parabolic isoparametric brick element has been used for two-dimensional analysis (10).

2.3.2 Selection of Displacement Models

The next step is to assign nodes to each element and choose the type of interpolation function to represent the variation of the field variable over the element. The displacement is modeled by means of shape functions of the element.

2.3.3 Determination of the Element Properties

Once the finite element model has been established and the interpolation functions selected the matrix equations expressing the properties of the individual element can be determined. This aspect is being dealt with in detail in para 2.6.

2.3.4 Assembly of the Algebric Equations for the Overall Discretized Continuum

To find the properties of the overall system modeled by the network of elements, all the matrix equations expressing the behaviour of the elements have to be assembled to form a global stiffness matrix. The assembled stiffness matrix is obtained by directly adding the individual stiffness coefficients in the appropriate locations in the global stiffness matrix. Thus for an assembled structure relations of the form given below is obtained

$$[K]\{r\} = \{R\} \tag{2.1}$$

Where $\{r\}$ is the displacement vector and $\{R\}$, the loads vector for the entire system.

The resultant load vector for the system is also obtained by adding individual element loads at the appropriate locations in the column matrix of resultant nodal loads.

The mathematical statement of the assembly procedure is

$$[K] = \sum_{e=1}^{E} [K]^e$$

$$\{R\} = \sum_{e=1}^{E} \{F\}^e \tag{2.2}$$

Where E is the total number of elements in the assemblage.

2.3.5 Solution of System Equations

The assembly process of the proceeding step gives a set of simultaneous equations, which can be solved to obtain the unknown nodal values of the field variables. As the element stiffness matrices and the assembled stiffness matrix are always singular, the equation (2.1) can not be solved for the nodal displacements unless modified to account for the boundary conditions, to render [K] non-singular. The boundary conditions can be applied in two ways, described below.

1. If i is the subscript of a prescribed nodal variable, the ith row and ith column of [K] are set equal to zero and k_{ii} is set equal to unity. The term R_i of the column vector {R} is replaced by the known value of r_i. Each of the remaining n-1 terms of {R} is modified by subtracting from it the entire value of the prescribed nodal variable multiplied by the appropriate column term from the original [K] matrix. This procedure is repeated for each prescribed r_i until all of them have been included.

2. The diagonal term of [K] associated with a specified nodal variable is multiplied by a large number, say, 1×10^{30} while the corresponding term {R} is replaced by the specified nodal variable multiplied by the same large factor times the corresponding diagonal term. This procedure is repeated until all prescribed nodal variables have been treated.

   Both these methods preserve the sparse, banded and usually symmetric properties of the original master matrix.

2.3.6 Making Additional Computations if desired

Sometimes the solutions of equations is desired to be used to calculate other important parameters. For example, in a dam, after the nodal displacements have been computed, other quantities derived from the primary unknowns such as strains and stresses must be computed.

2.4 DIRECT FORMULATIONS OF FINITE ELEMENT CHARACTERISTICS

The 'prescriptions' for deriving the characteristics of a 'finite element' of a continuum are presented in mathematical forms in the following paragraphs.

2.4.1 Displacement Function

A typical finite element, e, is defined by nodes i, j, m, etc. and straight line boundaries. The displacement vector

$$\{f\} = [N]\{\delta\}^e = [N_i, N_j, N_m ..] \begin{Bmatrix} \delta_i \\ \delta_j \\ \delta_m \\ \vdots \end{Bmatrix} \qquad (2.3)$$

in which the components of [N] are in general functions of position and $\{\delta\}^e$ represents a listing of nodal displacements for a particular element.

In the case of plane stress for instance

$$\{f\} = \begin{Bmatrix} u \\ v \end{Bmatrix}$$

Represents horizontal and vertical movements of a typical point within the element and

$$\{\delta_i\} = \begin{Bmatrix} u_i \\ v_i \end{Bmatrix}$$

the corresponding displacements of a node i.

The functions [N] are known as shape functions.

2.4.2 Strains

With displacements known at all points within the element the strains at any point can be determined. These will always result in a relationship which can be written in matrix notation as

$$\{\varepsilon\} = [B]\,\{\delta\}^e \qquad (2.4)$$

2.4.3 Stresses

The stresses will be related to the strains in the matrix notation as

$$\{\sigma\} = [D]\,(\{\varepsilon\} - \{\varepsilon_0\}) + \{\sigma_0\} \qquad (2.5)$$

Where [D] is an elasticity matrix containing the appropriate material properties, $\{\varepsilon_0\}$ is the initial strain vector and $\{\sigma_0\}$ is the initial stress vector.

2.4.4 Stiffness Matrix

Let a virtual displacement $\{\delta^*\}$ be given to an element acted on by the force system $\{F\}^e$, then the external work done is equal to $\{\delta^*\}^T\,\{F\}^e$.

If the virtual strains, caused by this virtual displacement is $\{\varepsilon^*\}$, then

$$\{\varepsilon^*\} = [B]\,\{\delta^*\}$$

Internal work done/volume

$$= \{\varepsilon^*\}^T\,\{\sigma\} = ([B]\,\{\delta^*\})^T\,[D]\,\{\varepsilon\}$$

$$= \{\delta^*\}^T\,[B]^T\,[D]\,[B]\,\{\delta\}$$

Equating external work to total internal work obtained by integrating over the volume of the element.

$$\{\delta^*\}^T\,\{F\}^e = \int_v \{\delta^*\}^T\,[B]^T\,[D]\,[B]\,\{\delta\}\,dv$$

$$= \{\delta^*\}^T\,\left(\int_v [B]^T\,[D]\,[B]\,dv\right)\{\delta\}$$

since $\{\delta^*\}^T$ and $\{\delta\}$ being constant can be taken out of integration constant.

$$\{F\}^e = (\int_v [B]^T [D] [B] \, dv) \{\delta\}$$

or $\{F\} = [K]^e \{\delta\}$ (2.6)

Where,

$$[K]^e = \int_v [B]^T [D] [B] \, dv \qquad (2.7)$$

is the stiffness matrix of the element.

2.4.5 Equivalent Nodal Forces

Let the equilibrium of an element be considered which, in addition to forces applied at the nodes, is also subjected to distributed body forces. In practice these may be, for example, gravity loading or centrifugal effects. Consider a single element acted upon by nodal loads $\{F\}^e$ and body forces $\{P\}$ which result in an equilibrating stress field $\{\sigma\}$. Suppose that this element is subjected to an arbitrary virtual nodal displacement pattern $\{\delta^*\}$ which results in compatible internal displacement and strain distribution $\{f^*)$ and (ε^*) respectively. Then the principle of virtual work requires that

$$\{\delta^*\}^T \{F\}^e + \int_v \{f^*\}^T \{P\} \, dv = \int_v \{\varepsilon_o^*\}^T \{\sigma\} \, dv \qquad (2.8)$$

Where integration is over the element volume.

Expanding Eq. 2.8.

$$\{\delta^*\}^T \{F\}^e + \int_v \{\delta^*\}^T [N]^T \{P\} \, dv = \int_v \{\delta^*\}^T [B]^T \{\sigma\} \, dv \qquad (2.9)$$

or $\{\delta^*\}^T (\{F\}^e + \int_v [N]^T \{P\} \, dv = \{\delta^*\}^T \int_v [B]^T \{\sigma\} \, dv$ (2.9)

Since the virtual nodal displacement system is arbitrary, the above expression must hold for all values of $\{\delta^*\}$. Hence

$$\{F\}^e + \int_v [N]^T \{p\}\, dv = \int_v [B]^T \{\sigma\}\, dv \tag{2.10}$$

Substituting for $\{\sigma\}$ from Eq. 2.5

$$\{F\}^e + \int_v [N]^T \{p\}\, dv = (\int_v [B]^T [D] [B]\, dv)\, \{\delta\}$$

$$- \int_v [B]^T [D] \{\varepsilon_0\}\, dv + \int_v [B]^T \{\sigma_0\}\, dv \tag{2.11}$$

or $$\{F\}^e + \{F\}_p^e + \{F\}_{\varepsilon_o}^e + \{F\}_{\sigma_o}^e = [K]^e \{\delta\} \tag{2.11}$$

or $$\{K\}^e = \int_v [B]^T [D] [B]\, dv$$

$$\{F\}_p^e = \int_v [N]^T \{p\}\, dv \tag{2.12}$$

$$\{F\}_{\varepsilon_o}^e = \int_v [B]^T [D] \{\varepsilon_0\}\, dv \tag{2.13}$$

$$\{F\}_{\sigma_o}^e = -\int_v [B]^T \{\sigma_0\}\, dv \tag{2.14}$$

Equation (2.12) to (2.14) define respectively the equivalent nodal forces for body force, initial strain and initial stress loadings.

2.5 SHAPE FUNCTIONS

The efficiency of any particular element type used will depend on how well the shape functions are capable of representing the time displacement field. The choice of the appropriate shape functions is however not arbitrary and there are two minimum conditions which must be satisfied in order to ensure convergence of the solution to the correct result as the finite element mesh is refined.

Shape functions must guarantee continuity of the function between elements.

In the limits as the element size is reduced to infinitesimal dimensions, the shape functions must be able to reproduce a constant strain condition through the element.

In the isoparametric family, the shape functions are used to define the geometry as well as the displacement field, i.e.

$$\left.\begin{aligned} x &= \sum_{i=1}^{n} N_i x_i \\ y &= \sum_{i=1}^{n} N_i y_i \end{aligned}\right\} \tag{2.15}$$

$$\left.\begin{aligned} u &= \sum_{i=1}^{n} N_i u_i \\ v &= \sum_{i=1}^{n} N_i v_i \end{aligned}\right\} \tag{2.16}$$

For isoparametric elements, the shape functions are defined in terms of the natural coordinate system, in which each coordinate axis is associated with a pair of opposing faces which are given the coordinates ± 1. In Fig. 2.2 the natural coordinates are shown for two dimensional parabolic isoparametric element.

The shape functions for an 8-node parabolic isoparametric two-dimensional element are given as follows.

At corner nodes

$$N_i = \frac{1}{4}(1+\varepsilon_o)(1+\eta_o)(-1+\varepsilon_o+\eta_o)$$

At mid side nodes

$$N_i = \frac{1}{2}(1-\varepsilon^2)(1+n_0) \quad at \quad \varepsilon_i = 0 \tag{2.17}$$

$$N_i = \frac{1}{2}(1-\eta^2)(1+\varepsilon_0) \quad at \quad \eta_i = 0$$

Where $\varepsilon_0 = \varepsilon\ \varepsilon_i$

and $\eta_0 = \eta\ \eta_i$

ε_i and η_i are respectively the ε and η coordinates of the node.

2.6 TWO-DIMENSIONAL EMEMENTS PROPERTIES

2.6.1 Strain Matrix

The total strain at any point with in the element can be defined by its three components. The strain matrix can now be defined as,

$$\{\in\} = \begin{Bmatrix} \in_x \\ \in_y \\ \tau_{xy} \end{Bmatrix} = \begin{Bmatrix} \partial u/\partial x \\ \partial v/\partial y \\ \dfrac{\partial u}{\partial y} + \dfrac{\partial v}{\partial x} \end{Bmatrix} \tag{2.18}$$

Substitution of displacements from equation (2.16), results in

$$\{\varepsilon\} = [B]\ \{\delta\}^e = \sum_{i=1}^{n} [B_i]\ \{\delta_i\} \tag{2.19}$$

Where n is the total no. of nodes in the element.

$$[B_i] = \begin{bmatrix} \frac{\partial N_i}{\partial x} & 0 \\ 0 & \frac{\partial N_i}{\partial y} \\ \frac{\partial N_i}{\partial y} & \frac{\partial N_i}{\partial x} \end{bmatrix} \tag{2.20}$$

2.6.2 Elasticity Matrix

For plane stress situation the strains can be expressed in terms of the stress components as follows:

$$\varepsilon_x = \frac{1}{\mathrm{E}}\sigma_x - \frac{\nu}{E}\sigma_y$$

$$\varepsilon_y = -\frac{\nu}{E}\sigma_x + \frac{1}{E}\sigma_y \tag{2.21}$$

$$\gamma_{xy} = \frac{\tau_{\mathrm{xy}}}{G} = \frac{2(1+\nu)}{\mathrm{E}}\tau_{\mathrm{xy}}$$

Where σ_x, σ_y and τ_{xy} are the stress components and E and ν are the elastic modulus and poison's ratio respectively. Writing equation (2.21) in matrix form.

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \tau_{xy} \end{Bmatrix} = \frac{1}{E}\begin{bmatrix} 1 & -\nu & 0 \\ -\nu & 1 & 0 \\ 0 & 0 & 2(1+\nu \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}$$

Therefore, {σ} = [D] {ε}, in which

$$D = \frac{E}{(1-\nu^2)}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \quad (2.22)$$

For the plains strain case, since a normal stresses σ_z exists in addition to the three others stress components,

$$\varepsilon_x = \frac{1}{E}\sigma_x - \frac{\nu}{E}(\sigma_x + \sigma_y)$$

$$\varepsilon_y = \frac{1}{E}\sigma_y - \frac{\nu}{E}(\sigma_x + \sigma_z) \quad (2.23)$$

$$\nu_{xy} = \frac{2(1+\nu)}{E}\tau_{xy}$$

and in addition

$$\varepsilon_z = 0 = \frac{\sigma_z}{E} - \frac{\nu}{E}(\sigma_x + \sigma_y)$$

giving $\sigma_z = \nu(\sigma_x + \sigma_y)$ (2.24)

Substituting equation (2.24) in equation (2.23) and writing in matrix notations.

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{Bmatrix} = \frac{1-\nu^2}{E}\begin{bmatrix} 1 & \frac{-\nu}{1-\nu} & 0 & \sigma_x \\ \frac{-\nu}{1-\nu} & 1 & 0 & \sigma_y \\ 0 & 0 & \frac{2}{1-\nu} & \tau_{xy} \end{bmatrix}$$

Solving we get $\{\sigma\} = \{D\}\{\varepsilon\}$

$$\text{Where } [D] = \frac{\varepsilon(1-\nu)}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1 & \frac{\nu}{1-\nu} & 0 \\ \frac{\nu}{1-\nu} & 1 & 0 \\ 0 & 0 & \frac{1-2\nu}{2(1-\nu)} \end{bmatrix} \tag{2.25}$$

2.7 TRANSFORMATION IN ε, η CO-ORDINATES

The stiffness matrix from equation (2.7) is given by

$$\{K\}^e = \int_v [B]^T [D] [B] \; dv$$

in which the matrix [B] depends on N or its derivatives with respect to global coordinates. Similarly, in the relationship for distributed load vector given by $\int_v [N]^T [p] dv$, the shape functions N and the integration over the entire volume of figure.

To evaluate such matrices two transformations are necessary. In the first place as N_i is defined in terms of local coordinates it is necessary to devise some means of expressing the global derivatives in terms of local derivatives.

In the second place the volume (or surface) of element over which the integration has to be carried out needs to be expressed in terms of the local coordinates with an appropriate change of limits of integration.

The natural coordinates ε, η are functions of global coordinates x, y. Using the chain rule of partial differentiation.

$$\frac{\partial N_i}{\partial \varepsilon} = \frac{\partial N_i}{\partial x}\frac{\partial x}{\partial \varepsilon} + \frac{\partial N_i}{\partial y}\frac{\partial y}{\partial \varepsilon} \tag{2.26}$$

Performing the same differentiation with reference to the other two co-ordinates and writing in matrix form

$$\begin{Bmatrix} \frac{\partial N_i}{\partial \varepsilon} \\ \frac{\partial N_i}{\partial \eta} \end{Bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial \varepsilon} & \frac{\partial y}{\partial \varepsilon} \\ \frac{\partial x}{\partial \eta} & \frac{\partial y}{\partial \eta} \end{bmatrix} \begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \end{Bmatrix} = [J] \begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \end{Bmatrix} \tag{2.27}$$

where the square matrix [J] is called the Jacobean matrix. From equation (2.27) the global derivatives can be found by inverting [J].

$$\begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \end{Bmatrix} = [J]^{-1} \begin{Bmatrix} \frac{\partial N_i}{\partial \varepsilon} \\ \frac{\partial N_i}{\partial \eta} \end{Bmatrix} \tag{2.28}$$

Substituting equations (2.15) in equation (2.28)

$$[J] = \begin{bmatrix} \Sigma \frac{\partial N_i}{\partial \varepsilon} x_i & \Sigma \frac{\partial N_i}{\partial \varepsilon} y_i \\ \Sigma \frac{\partial N_i}{\partial \eta} x_i & \Sigma \frac{\partial N_i}{\partial \eta} y_i \end{bmatrix}$$

$$\text{or} \quad \begin{bmatrix} \frac{\partial N_i}{\partial \varepsilon} & \frac{\partial N_2}{\partial \varepsilon} & \cdots \\ \frac{\partial N_i}{\partial \eta} & \frac{\partial N_2}{\partial \eta} & \cdots \end{bmatrix} \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \\ . & . \\ . & . \\ . & . \end{bmatrix} \tag{2.29}$$

To transform the variables and the region with respect to which the integration is made, the relationship dx dy = det [J] dε, dη shall be made use of.

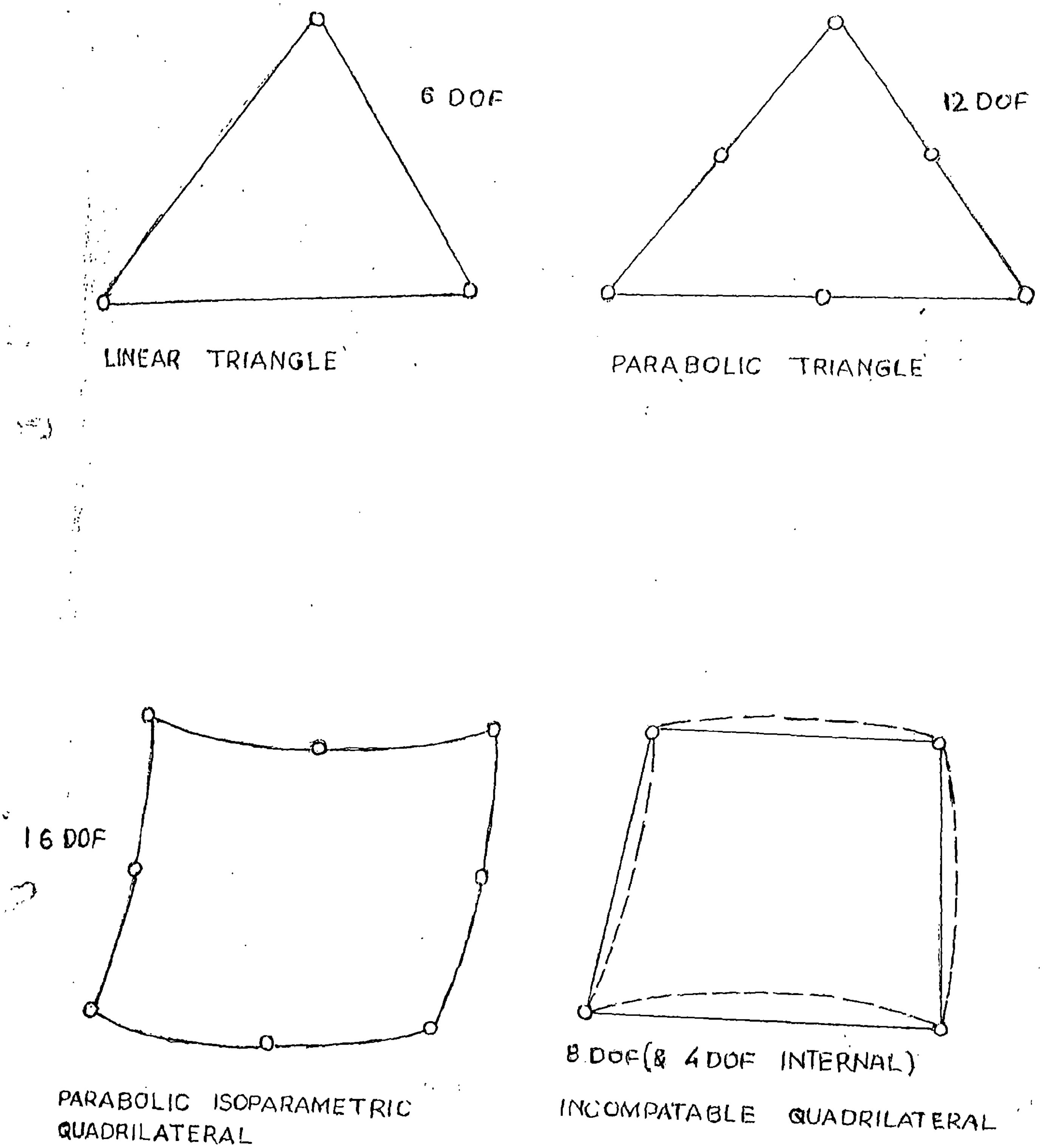


FIG. 2.1. USEFUL TWO DIMENSIONAL ELEMENTS

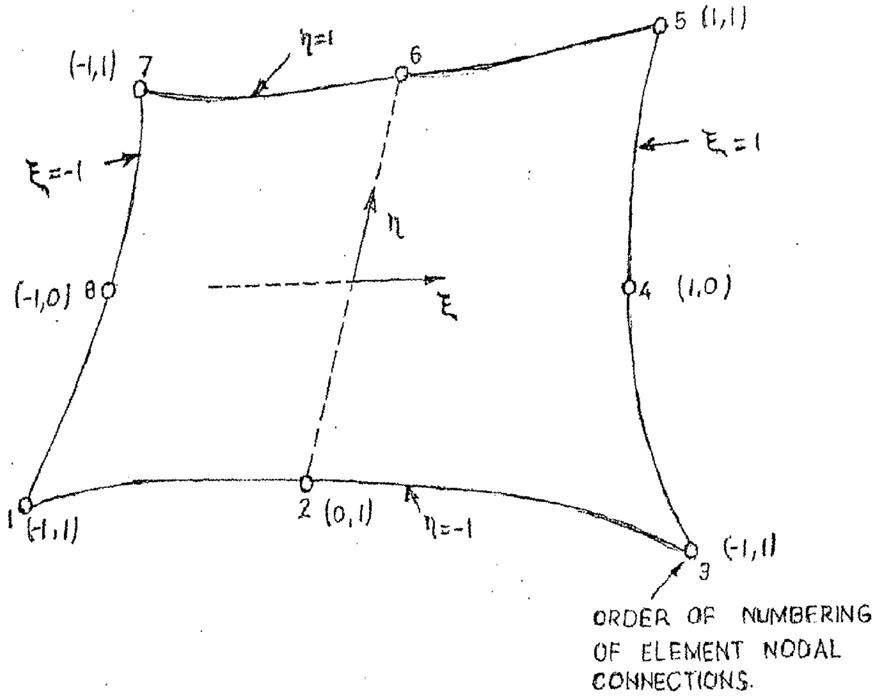


FIG. 2.2 ORIENTATION OF LOCAL AXIS FOR TWO DIMENSIONAL PARABOLIC ISOPARAMETRIC ELEMENT

RESULTS AND DISCUSSION

3.1 GENERAL

A section of the dam is assumed for 2-D analysis for four heights of the dam. The elasticity of foundation is known to have a bearing on the stresses and displacements in the dam. Therefore, the effect of variation of foundation elasticity on stresses and displacements in dam is studied. 2-D Finite Element Method is used for determining the normal stresses (Horizontal and Vertical) and deformations (Horizontal and Vertical) at 4 (four) gaussian points of each element of the Discretized dam and foundation system. The section analysed, the loading conditions, assumptions for analysis, the results of analyses and the discussion of results are given in this chapter.

3.2 DATA AND ASSUMPTIONS OF ANALYSIS

3.2.1 Dam Section:

A dam section with vertical upstream face and downstream slope of 0.8H: 1.0V is considered for analysis. The downstream slope has been fixed on the basis of the slopes of the existing high gravity dams. The upstream face of dam is considered vertical for ease of analysis. Details of dam section of some high dams are given in Table 3.1(8). Top width of the dam is taken as 8m. Base width of each dam section is taken as 0.8 times the dam height (H). A constant foundation extent of 1.5H on both laterals and the depth of foundation has been considered for the analysis of all the cases.

Table 3.1: Profile of some existing dams

SL No.	Name of dam	Height (m)	Upstream Slope	Downstream Slope
1.	Detroit Dam (USA)	92	Vertical for top 1/3rd and 1/10th for rest	0.75:1
2.	Fontana Dam (USA)	134	Vertical with fillets at bottom	0.76:1
3.	Grand Coulee Dam (USA)	167	Upper half vertical, bottom half 1:6.66	0.8:1
4.	Bhakra Dam (India)	226	Vertical for top 110 m and 1:2.9 for fillets	0.8:1
5.	Shasta Dam (USA)	137	Vertical with fillets	0.8:1
6.	Karjan Dam (India)	100	Vertical for top 2/3rd and 1:2 for rest	0.8:1
7.	Narmada Dam (India)	155	Vertical for top 3/5th and rest 1:4	0.75:1

Rigid boundary condition at bottom and in both vertical sides in the foundation has been considered in the analysis i.e. both horizontal and vertical displacements at the boundary are zero. In this study four dam heights of 125m, 150m, 175m and 200m have been considered. A typical discretized dam foundation system for 125m high concrete gravity dam is shown in Fig. 3.1. The details of discretization are as follows.

Number of elements in the dam = 35

Number of elements in the foundation = 75

Total number of elements in the mesh = 110

Total number of nodes in the mesh = 385

Total number of boundary nodes in the mesh = 51

The same mesh has been adopted for the analysis of all the four cases. Only the coordinates of the mesh have been changed depending upon the height. In all cases normal drainage condition is considered. Drainage gallery is assumed at a distance of 0.1 B (where B = base width of dam) on dam base from heel.

3.2.2 Material Characteristics of Dam and Foundation

In this study, the system has two distinctly different sub-systems of dam and foundation, ignoring presence of interface between dam and foundation at dam base. Hence, dam and foundation have been considered totally integrated as a monolithic structure. The effect of different elasticity of the foundation rock and dam heights on stresses and displacements in both the dam and the foundation has been studied.

The characteristics of dam material which are taken in this study are

(i) Elasticity (E) = 2×10^6 t/m^2

(ii) Poisson's Ratio (ν) = 0.2

(iii) Density of Concrete (γ) = 2.4 t/m^3

In this analysis, the following values of foundation rock properties have been considered.

(i) The Poisson's ratio is taken as 0.2 in all cases for the foundation rock.

(ii) The modulus of elasticity ranges from 0.2 to 2 times of that of concrete for various analyses.

(iii) The foundation rocks are initially stresses under its weight and other tectonic activities before the construction of the dam. In this study we are working out the additional stresses and displacements due to the loads coming due to the dam construction. Hence, the dead weight of the foundation has not been taken while calculating the forces acting on the dam. The stresses due to dam construction should be superimposed on the initial stresses in the foundation to get the total stress distribution in the foundation.

3.2.3 Loads:

The loads, which usually act on a gravity dam, are as follows (1)

(i) Self weight of the dam

(ii) Reservoir water pressure

(iii) Normal uplift pressure

(iv) Silt pressure

(v) Wave pressure

(vi) Wind load

(vii) Ice pressure (in cold climate only)

(viii) Seismic loads (if located in an earthquake prone region).

In this study, however, only following main loads have been considered:

- Self weight of the dam
- Reservoir water pressure
- Normal uplift pressure
- Earthquake force

And for simplification, it is assumed that there is no tail water in the downstream. Reservoir water level has been taken 10 m below the top of the dam. Horizontal seismic coefficient α_h has been taken as 0.15 in all cases. The vertical seismic coefficient α_v is taken as half of α_h (2).

3.2.4 Sign Convention:

The following sign conventions are considered in the study.

The horizontal displacement is positive acting right and negative if acting in the left direction. Vertical displacement is positive in the upward direction and negative in the downward direction. The compressive stresses are negative and tensile stresses are positive.

3.2.5 Cases Analyzed:

The study comprises the analysis for 4 dam heights namely, 125m(case 1), 150m(case 2), 175m(case 3) and 200m(case 4). For each dam height five ratios of foundation elasticity to that of concrete elasticity (namely 0.2, 0.4, 0.6, 1.0 and 2.0) have been considered.

3.3 SELECTION OF CRITICAL SEISMIC LOADING CONDITION:

For selecting the critical direction of vertical earthquake force, analysis has been done only for a dam height of 125m with EF/ED=0.2 with both the upward and downward direction of this force along with other main loads namely self weight of the dam, reservoir water pressure and normal uplift pressure. The direction of the horizontal earthquake force has been taken acting in downstream direction in both the cases of vertical earthquake forces. The values of displacements and stresses for analysis with upward and downward directions of vertical earthquake force, along the base and upstream and downstream faces of the dam are given in Tables 3.2 to 3.9 and plotted in Figures 3.2 to 3.5.

From the results of horizontal displacements given in Tables 3.2 and 3.3 it is clear that the magnitudes of horizontal displacement obtained from the two directions of earthquake forces are not substantially different from each other. The upward acting earthquake force has given slightly higher values. But the difference in magnitude has been found from 1% at base of dam to about 7% at the top of dam. The results are plotted in Figure 3.2.

The values of vertical displacements (Tables 3.4 and 3.5 and Figure 3.3) with earthquake force acting upward and downward are found significantly different. The difference is more near the base than at the top. The downward direction of earthquake force has given higher values as compared to that for the upward acting force. The difference is of the order of about 10% at the base where maximum settlement has occurred.

From the study of results of horizontal stresses given in Tables 3.6 to 3.7 and Figure 3.4 along the dam base, upstream and downstream faces it is seen that the stresses obtained from the two directions of vertical earthquake force are not significantly different, in the region of higher stress values. However the difference in the values is perceptible at the heel and the toe.

Study of results of vertical stress along the three planes namely the base and the two faces of the dam given in Tables 3.8 to 3.9 and Figure 3.5 has revealed a trend similar to that of horizontal stress. There is perceptible difference in values at the heel.

It can, therefore, be inferred that the direction of vertical earthquake forces acting downward is critical for the study of stresses and displacements. Therefore, for further study only vertical earthquake force acting downward has been considered in the analysis.

3.4 RESULTS OF ANALYSIS AND DISCUSSION

3.4.1 Displacement

Horizontal displacement:

The variation of the horizontal displacements at the dam base for different EF/ED ratios for a dam of height 125m is shown in Fig 3.6(a). It is seen that for each EF/ED ratio the horizontal displacement is almost constant all along the dam base from upstream to downstream. The results also show that the magnitude of the horizontal displacement increases as the EF/ED ratio decreases. It is also evident that the foundation elasticity affects the horizontal displacements significantly. As the EF/ED ratio decreases from 2.0 to 0.2, the horizontal displacement at the dam base increases by 10 times.

The horizontal displacements at the upstream and downstream faces of the 125m high dam are shown in Fig 3.6(b) and 3.6(c). It is seen that on both the faces the displacements for a constant value of EF/ED increases almost linearly from the base to the top being maximum at the top. The magnitudes of the displacements for both the upstream and downstream faces are almost same for a given EF/ED ratio. It is also seen that the magnitude of horizontal displacements increases as the EF/ED ratio decreases. The value of maximum horizontal movement at the crest increases from 25.9mm to 92mm as the EF/ED ratio decreases from 2.0 to 0.2 respectively.

The variation of horizontal displacements along the dam base and the upstream and downstream faces for dams of height 150m, 175m, and 200m are shown in Figures 3.7 to 3.9. It is seen that the effect of foundation elasticity on the horizontal displacements on these heights is similar to that observed in case of dam of height 125m. It is seen that the value of displacement increases as the dam height increases. The value of the horizontal displacement along the dam base and on upstream and downstream faces for four dams of height 125m, 150m, 175m, and 200m are given in Tables 3.10 to 3.12 for different EF/ED ratios. For a EF/ED ratio of 2.0 the maximum horizontal displacement is 25.9mm for a dam height of 125m where as it is 39.8, 56.9 and 77mm for 150m, 175m, and 200m high dams respectively for the same EF/ED=2.0. For a EF/ED ratio of 0.2 the maximum horizontal displacements at crest are 92, 139.7, 195.3, and 262.5mm for dams of height 125m, 150m, 175m, and 200m respectively.

The variation in magnitude of horizontal displacement at crest and heel for different dam heights and EF/ED ratio is shown in Fig 3.10. It is seen from this figure that the effect of foundation elasticity on horizontal displacement is very significant for EF/ED ratios less than 0.6. For EF/ED values greater than 0.6 the variation is marginal and for value beyond 1.0 the variation is negligible for all dam heights. It can thus be concluded that founding a dam on soft foundation with EF/ED less than 0.6 would result in excessive horizontal displacement. The magnitude of horizontal displacements at crest and heel for different dam heights with varying ratio of EF/ED are also given in Table 3.13.

Ratio R_u of maximum horizontal displacement for a given EF/ED ratio to that with EF/ED=1, for the dam base and upstream face are shown in Fig 3.11 for different heights of dam analyzed. It is seen from this figure that the variation for the four heights is almost same and it can thus be concluded that the effect of foundation elasticity is same for all dam heights. It is also evident from this figure that the displacement increases steeply as the EF/ED ratio decreases below 0.6. The values of these of displacement ratio R_u for different dam heights with the corresponding values with Ef/ED=1.0 is given in Table 3.14 along the dam base and upstream face respectively. It is seen that this ratio R_u is constant at 4.57 for EF/ED ratio of 0.2 and 0.52 for a EF/ED ratio=2.0 at the dam base where the displacements are minimum. For the crest where the displacements are maximum the corresponding value varies from 2.64 to 2.71 for EF/ED=0.2 and 0.76 for EF/ED=2.0.

Horizontal displacement contours of 125m high dam for EF/ED=0.6 are shown in Fig 3.12. From the figure it is seen that the variation of horizontal displacements are almost constant along different horizontal planes in the dam body whereas in the foundation the variation is not constant along the horizontal planes. It is also seen that the horizontal displacements are maximum at the crest and minimum at the dam base and sharply reduce in the foundation. Horizontal displacements at the crest and the dam base are 44mm and 11mm respectively. Analyses were also carried out for other dam heights namely 150m, 175m and 200m for EF/ED=0.6 and found that the variation of horizontal displacements on these heights is similar in variation as seen for a dam height of 125m. The maximum displacements at crest are 67.44, 94.96 and 127.71mm for 150m, 175m and 200m dams respectively.

Vertical displacement (Settlements):

The variation of the vertical displacements at the dam base for different EF/ED ratios for a dam of height of 125m is shown in Fig 3.13(a). It is seen that for each EF/ED ratio the vertical displacements are minimum at the heel and maximum near the toe. The settlement varies from 15.09mm at heel to 39.64mm at toe for EF/ED=0.2 and from 1.02mm to 3.71mm for EF/ED=2. The magnitude of the vertical displacement thus increases as the EF/ED ratio decreases. It is also evident that the foundation elasticity affects the vertical displacements significantly. As the EF/ED ratio decreases from 2.0 to 0.2, the maximum vertical displacement at the dam base increases by about 10 times. It can be seen that for EF/ED ratio of 2, 1 and 0.6 the displacement curves are closely spaced while these are progressively distant for EF/ED less than 0.6.

The vertical displacements at the upstream and downstream faces of the 125m high dam are shown in Fig 3.13(b) and 3.13(c). It is seen that on upstream face the vertical displacements for a constant value of EF/ED are maximum at the top and minimum at the base where as on downstream face vertical displacements are maximum at a point below mid height near the toe. The location of the maximum displacement on downstream face has shifted from about 20% of the height above base to about 40% for EF/ED=0.2 and 2 respectively. It is also seen that the magnitude of vertical displacement increases as the EF/ED ratio decreases. The value of maximum vertical displacement on the downstream face of dam increases from about 7.95mm to 43.45mm as the EF/ED ratio decreases from 2.0 to 0.2 respectively.

The variation of vertical displacement along the dam base and along the upstream and downstream faces for dams of height 150m, 175m, and 200m are shown in figures

3.14 to 3.16. It is seen that the effect of foundation elasticity on the vertical displacements on these heights is similar in variation as seen for a dam of height 125m. The value of displacement increases as the dam height increases. The value of the vertical displacement along the dam base and on upstream and downstream faces for the four heights of dam namely 125m, 150m, 175m, and 200m are given in Tables 3.15 to 3.17 for different EF/ED ratios. For a EF/ED ratio of 2.0 the maximum vertical movement on the downstream face is 7.95mm for a dam height of 125m whereas it is 13.11, 15.91,and 20.92mm for 150m, 175m, and 200m high dams respectively for the same EF/ED=2.0. For a EF/ED ratio of 0.2 the maximum vertical displacements on downstream face are 43.45, 64.55, 86.75, and 114.04mm for dam heights of 125m, 150m, 175m, and 200m respectively.

The variation in magnitude of vertical displacement at crest and toe for different dam heights and EF/ED ratio is shown in Fig 3.17. It is seen from this figure that the effect of foundation elasticity on vertical displacement is very significant for EF/ED ratios less than 0.6. For EF/ED values more than of 0.6 the variation is marginal and for a value of EF/ED beyond 1.0 the variation is negligible for all dam heights. It can thus be inferred that founding a dam on soft foundation with EF/ED less than 0.6 would result in sharp excessive settlement. The magnitudes of vertical displacements at crest and toe for different dam heights with varying ratio of EF/ED are given in Table 3.18.

The ratio R_v of maximum vertical displacement for a given EF/ED ratio to that for the maximum displacement with EF/ED=1, is shown in Fig 3.18 for different heights of dams. It is seen from this figure that the variation of R_v for the four heights are almost same and it can thus be concluded that the effect of foundation elasticity on settlement values is same for all dam heights. It is also evident from this figure that the displacement increases steeply as the EF/ED ratio decreases below 0.6. The values of these displacement ratios for different dam heights with the corresponding value with Ef/ED=1.0 are given in Table 3.19 along the dam base and upstream and downstream faces. It is seen that this ratio R_v is around 4.71 for the dam base, varies from 3.74 to 4.46 for upstream face and from 3.61 to 3.92 for downstream face in all the four cases for EF/ED ratio of 0.2. This ratio of R_v for EF/ED=2.0 are 0.51 for the dam base, varies from 0.58 to 0.66 for upstream face and from 0.61 to 0.65 for the downstream face.

Vertical displacement contours of 125m high dam for EF/ED=0.6 are shown in Fig 3.19. From the figure it is seen that the variation of vertical displacements is almost constant along vertical sections in the dam body whereas in the foundation the settlement has occurred below the toe and gradually reduced with depth. It is also seen that the vertical displacements are maximum at the lower half of the height on downstream face and minimum at the heel and the crest. The maximum vertical displacement on the downstream face is 16.85mm in this case (case 1 for EF/ED=0.6).

Analyses were also carried out for other dam heights namely 150m, 175m and 200m for EF/ED=0.6 and found that the variation of vertical displacements on these heights is similar to that observed for a dam of height 125m. The maximum displacements on downstream face are 25.47, 33.60 and 44.15mm (from table 3.17) for 150m, 175m and 200m dams respectively. It is also seen that the vertical displacements increase with increase in dam height.

3.4.2 Stresses

Horizontal normal stress:

The variation of the horizontal normal stresses at the dam base for different EF/ED ratios for a dam of height 125m is shown in Fig 3.20(a). It is seen that for all EF/ED values the horizontal normal stresses are tensile at heel and compressive at toe. The tensile zone extends to about 1/5th of the dam base width in the heel region. The stresses in rest of the base width are compressive with maximum at toe. These compressive stresses increase considerably from 232.36 to 422.62 t/sq m as the EF/ED ratio decreases from 2.0 to 0.2. It is thus evident that the foundation elasticity affects the maximum horizontal compressive stress at toe significantly. As the EF/ED ratio decreases from 2.0 to 0.2, the horizontal tensile stresses at heel decreases from 132.72 to 117.63 t/sq m. Thus effect of foundation elasticity on the tensile stresses at heel is marginal.

The horizontal stresses at the upstream and downstream faces of the 125m high dam are shown in Fig 3.20(b) and 3.20(c). It is seen that the horizontal compressive stress on upstream face is maximum at a height of about 15.0% of dam height above the base and is maximum on downstream face at toe. These stresses reduce to zero at the top of both the faces. It is seen that along the upstream face the horizontal stress is tensile up to a small height above the base. Along upstream face the maximum horizontal stress increases slightly from 144.16 to 155.25 t/sq m as the EF/ED ratio decreases from 2.0 to 0.2. It is also seen that on upstream and downstream faces the stresses for any value of EF/ED vary non-linearly up to about one third height from the base and almost linearly for the remaining height of dam. The variation in horizontal normal stresses in the upper two third height is only marginal for different EF/ED ratio.

The variation of horizontal stresses along the dam base and the upstream and downstream faces for dams of height 150m, 175m, and 200m are shown in Figures 3.21 to 3.23. It is seen that the effect of foundation elasticity on the horizontal normal stresses on these dams is similar to that for the dam of height 125m. The values of these stresses increase as the dam height increases. The value of the horizontal normal stresses along the dam base and on upstream and downstream faces for the four heights viz.125m, 150m, 175m, and 200m are given in Tables 3.20 to 3.22 for different EF/ED ratio. For a EF/ED ratio of 2.0 the maximum horizontal normal stress is 232.36 t/sq m (compressive) for a dam of height 125m whereas it is 287.62, 338.61 and 391.97 t/sq m (compressive) for 150m, 175m, and 200m high dams respectively. For a EF/ED ratio of 0.2 the maximum horizontal normal stresses are 422.62, 521.58, 609.93, and 703.35 t/sq m (compressive) for dam heights of 125m, 150m, 175m, and 200m respectively.

The variation in horizontal normal stresses at heel and toe for different dam heights with EF/ED ratio is shown in Fig 3.24. These are also given in table 3.23. It is seen that the effect of foundation elasticity on horizontal normal stress at toe is large for EF/ED ratios less than 0.6. For EF/ED values above 0.6, the variation is marginal and for a value beyond 1.0 the variation is negligible for all dam heights. It can thus be concluded that founding a dam on soft foundation with EF/ED less than 0.6 would result in sharp increase of horizontal normal stresses at the toe and above it on the downstream face. The effect of foundation elasticity on stress at heel is linear for all heights of the dam.

The ratio R_h, of maximum horizontal normal stress for any EF/ED ratio to that for the maximum horizontal normal stress with EF/ED=1.0, is shown in Fig 3.25 for different heights of dam. The values of these stress ratio R_h for different dam heights with the corresponding value with Ef/ED=1.0 are shown in Table 3.24 along the dam base (at toe) and upstream face (at maximum stress location). It is seen that this ratio R_h is almost constant at 1.50 at toe and it is 1.06 on upstream face for EF/ED ratio of 0.2 whereas 0.82 at toe and almost 1.0 on upstream face for a EF/ED ratio=2.0, for all the four heights. It is also evident from this figure that the stresses increase considerably as the EF/ED ratio decreases below 0.6.

Horizontal normal stress contours of 125m high dam for EF/ED=0.6 are shown in Fig 3.26. From the figure it is seen that the tensile stresses are concentrating around the heel and compressive around toe. It is also seen that the horizontal normal stresses are naximum at the toe and minimum at the heel and reduces towards the crest and the foundation base. Horizontal normal stress at the heel and toe in this case are 123.56(tensile) and 326.86(compressive) respectively.

Analyses has been carried out for other dam heights viz. 150m, 175m and 200m for EF/ED=0.6 and found that the variation of horizontal normal stresses on these heights is found similar to that observed in case of dam of height 125m. The maximum tensile stresses at heel are 155.15, 190.82 and 223.56 (t/sq m) and the maximum compressive stresses at toe are 403.75, 473.7 and 547.42 (t/sq m) for 150m, 175m and 200m high dams respectively. Horizontal normal stresses increase with increase in dam height.

Vertical normal stress:

The variation of the vertical normal stresses at the dam base for different EF/ED ratios for a dam of height 125m is shown in Fig 3.27(a). It is seen that for EF/ED ratio=0.2, the vertical normal stresses are compressive all along the dam base whereas for EF/ED ratio 0.4, 0.6 1.0 and 2.0 vertical normal stresses at heel are tensile and compressive at toe. The tensile zone extends only up to a distance of about 5% of base width from heel. The tensile stress at heel decreases and compressive stress at toe increases considerably as the EF/ED ratio decreases from 2.0 to 0.2. It is also evident that the foundation elasticity affects the maximum vertical normal stresses significantly. As the EF/ED ratio decreases from 2.0 to 0.2, the vertical normal stresses along the dam base decreases from 119.26(tensile) to 88.17 t/sq m(compressive) at heel and at toe vertical normal stresses increase from 128.44(compressive) to 247.84 t/sq m(compressive).

The vertical normal stresses at the upstream and downstream faces of the 125m high dam are shown in Fig 3.27(b) and 3.27(c). It is seen that the vertical normal stresses are maximum at a height of about 15% and 8% of dam height from base on upstream and downstream faces respectively. The upstream face is subjected to tensile stresses in about $1/10^{th}$ of the dam height from base for all EF/ED ratios except 0.2. Along upstream face the maximum vertical normal stress increases from 125.16 to 244.32 t/sq m, whereas along downstream face the maximum vertical normal stress increases from 189.85 to 345.68 t/sq m, as the EF/ED ratio decreases from 2.0 to 0.2. It is seen that on upstream and downstream faces the vertical normal stresses for all values of EF/ED ratio vary non-linearly being maximum near the base and minimum (nominal values) at the top.

The variation of vertical normal stresses along the dam base and upstream and downstream faces for dam heights of 150m, 175m, and 200m are shown in Figures 3.28 to 3.30. It is seen that the effect of foundation elasticity on the vertical normal stresses on these heights is similar in variation as seen for dam of height 125m. The values of vertical normal stresses increase as the dam height increases. The values of the vertical normal stresses along the dam base and on upstream and downstream faces for the four heights of dam viz. 125m, 150m, 175m, and 200m are given in Tables 3.25 to 3.27 for different EF/ED ratios. For a EF/ED ratio of 2.0 the maximum vertical normal stress in the dam at the base is 194.29 t/sq m(compression) for a dam of height 125m whereas the maximum vertical normal stresses are 243.01, 282.71 and 326.77 t/sq m (compression) occurred along the dam base for dams of height 150m, 175m, and 200m respectively. For a EF/ED ratio of 0.2 the maximum vertical normal stresses on downstream face are 345.68, 433.57, 518.38, and 600.98 t/sq m (compression) for dams of height 125m, 150m, 175m, and 200m respectively.

The variation in vertical normal stresses at heel and toe for different dam heights and EF/ED ratio is shown in Fig 3.31. Then stresses are also given in Table 3.28. It is seen from this figure that the effect of foundation elasticity on vertical stress is significant for EF/ED ratios less than 0.6. For EF/ED values greater than 0.6, the variation is marginal and for a value beyond 1.0 the variation is negligible for all dam heights. It can thus be concluded that founding a dam on soft foundation with EF/ED less than 0.6 would result in sharp increase in vertical normal stresses.

The ratio $R_{vs,}$ of maximum vertical normal stress for a given EF/ED ratio to that for the maximum vertical normal stress with EF/ED=1.0, is shown in Fig 3.32 for different heights of dam. It is also evident from this figure that the vertical normal stresses increase steeply as the EF/ED ratio decreases below 0.6. The values of these stress ratio R_{vs} for different dam heights with the corresponding value with EF/ED=1.0 are given in Table 3.29 along the dam base and upstream and downstream faces respectively. It is seen that this ratio R_{vs} is constant at 1.19 along the dam base, varies from 1.51 to 1.56 on upstream face and 1.5 to 1.56 on the downstream face for EF/ED ratio of 0.2. The values of R_{vs} are 0.92 along dam base, varies from 0.84 to 0.86 along upstream face and from 0.8 to 0.83 on the downstream face for EF/ED=2.

Vertical normal stress contours of 125m high dam for EF/ED=0.6 are shown in Fig 3.33. From the figure it is seen that the tensile stresses are concentrated around the heel and compressive stresses around toe. It is also seen that the vertical normal stresses are maximum at the toe and minimum at the heel and reduce to nominal values at the crest. These stresses go deep in the foundation with reducing values. Vertical normal stress in this case at the heel and toe are 59.16(tensile) and 188.19(compressive) respectively.

Analyses has also been carried out for other dam heights viz. 150m, 175m and 200m for EF/ED=0.6 and found that the variation of vertical normal stresses on these heights is similar in variation as seen for a dam of height 125m. The maximum tensile stresses at heel are 85.23, 115.38 and 142.37 (t/sq m) and the maximum compressive stresses at toe 239.9, 273.41 and 316.09 (t/sq m) for 150m, 175m and 200m dams respectively.

3.5 PRINCIPAL STRESS

Maximum principal stresses around heel and toe for different EF/ED ratios and dam heights are given in Table 3.32. From the table it is seen that around heel principal stresses are tensile and around toe these are compressive for all EF/ED ratio and dam heights. Tensile stress around heel decreases with decrease in EF/ED ratio and compressive stress around toe increases with decrease in EF/ED ratio for all dam heights. It is also seen that the maximum principal stresses on downstream face occur at a height of about 8% of the dam height above the base. Tensile stresses around the heel in all cases can be taken care of by providing fillets. Theses are generally provided (Table 3.1). For EF/ED=0.6 the principal stresses (compressive) around toe are 468.88, 579.43, 680.33 and 787.02 (t/sq m) for 125m, 150m, 175m and 200m high dams respectively. For emergency loading condition with seismic forces the 33% increase in permissible stress in concrete (700 t/sq m) is allowed (2). It can be seen from the results that the maximum stresses in the dam foundation system are within the permissible limit for all EF/ED ratios and dam heights. Thus it can be concluded that the stresses are not the governing factor in deciding the feasibility of a concrete gravity dam at a site.

3.6 EFFECT OF DAM HEIGHT AND FOUNDATION ELASTICITY ON STRESSES AND DISPLACEMENTS:

The maximum displacements and stresses in the dam of a given height have been compared in terms of the displacements and stresses for the dam of 125m height. It is found that the displacement and stress ratios are found to be same for all EF/ED ratios. These ratios R_{dh}, R_{dv}, R_{sh} and R_{sv} i.e. the ratio of maximum horizontal displacement, maximum vertical displacement, maximum horizontal normal stress and maximum vertical normal stress to the corresponding values for 125m high dam are given in Table 3.30 and plotted in fig 3.34. It is seen from the Table 3.30 and Figure 3.34 that the effect of dam height on maximum stresses is same for both horizontal and vertical stresses. Effect of height on displacements is more pronounced than that on stresses. The variation of maximum horizontal displacements with height is more than that for the vertical displacements. The horizontal displacements increase more rapidly as the dam height increases than the corresponding increase in vertical displacements.

Table 3.31 shows the values of maximum horizontal displacement, maximum vertical displacement, maximum horizontal normal stress and maximum vertical normal stress for different EF/ED ratio interms of the corresponding values of EF/ED=1. These ratios are plotted in Figure 3.35.

It is seen that the foundation elasticity does not have that much influence on stress as on displacement. It is also seen that the effect of foundation elasticity on both horizontal and vertical normal stresses is almost same. The effect of foundation elasticity is more on vertical displacements than on horizontal displacements. It is also seen from this curve that for EF/ED ratio less than 0.6 the displacements increase sharply.

3.6.1 Use of Figures 3.34 and 3.35

The above figures can be used to find out the normal stresses (horizontal and vertical) and displacements (horizontal and vertical) for different dam heights by knowing the dam height and EF/ED ratio.

Fig 3.34 gives the displacement and stress ratio against the height of dam expressed as a multiple of 125m. Fig 3.35 gives the displacement and stress ratios verses foundation elasticity ratio EF/ED.

To find out the maximum stresses and displacements for a dam of any height say h, for a EF/ED ratio say E_r, the ratios of stresses and displacements are read for height ratio=h/125, from Fig 3.34. After that the stress and displacement ratios are read for the given E_r = EF/ED, from the Fig 3.35. The two ratios read from Fig 3.34 and 3.35 respectively are then multiplied to get a new ratio, R_{hc}, incorporating the effects of both the height and foundation elasticity. The ratio R_{hc}, multiplied with the corresponding stress and displacements for a 125m high dam with EF/ED=1.0 gives the maximum stresses and displacements for a dam of height h and a given EF/ED ratio.

For example, we have to find out the maximum stresses and displacements for a 200m high dam with EF/ED ratio=0.6. The procedure for obtaining these values using the analysis for a 125m high dam with EF/ED=1.0 is explained as follows.

Calculation of maximum stresses and displacement for 200m high dam.

Sl No	**Particulars**	**R_u**	**R_{du}**	**R_{hc}**	**Displacement / stresses for a 125m high dam with EF/ED=1.0**	**Predicted displacement and stresses for the dam with 200m height and EF/ED=0.6**	**Values from actual analysis**
Col (1)	Col (2)	Col (3)	Col (4)	Col (5) =(3) X (4)	Col (6)	Col (7) = (5) X (6)	Col (8)
1	Horizontal Displacement (mm)	2.95	1.3	3.835	33.9	130.0	127.7
2	Vertical Displacement (mm)	2.63	1.48	3.8924	11.02	42.89	44.15
3	Horizontal stresses (t/sq m)	1.68	1.16	1.9488	282	549.56	547.42
4	Vertical stresses (t/sq m)	1.68	1.16	1.948	229.6	447.44	446.86

It is seen from the Table no 3.32 that the predicted values for the 200m high dam using the ratios of Fig 3.34 and Fig 3.35 are very nearly the same as obtained from actual analysis. The predicted displacements are within 4% of the actual value while the predicted stress values are within 0.5% of the actual value. The maximum stresses and displacements thus can be predicted with an accuracy of 98% to 99% which is acceptable for a massive structure like dam.

Table 3.2: Horizontal displacement at the dam base for 125m dam height (EF/ED= 0.2)

Distance from heel (m)	Horizontal displacement (mm) for earthquake force acting	
	Upward	Downward
0	31.05	30.94
5	31.78	31.58
10	32.47	32.18
22.5	33.05	32.75
35	33.37	33.09
47.5	33.56	33.28
60	33.54	33.26
72.5	33.53	33.25
85	33.11	32.83
92.5	31.81	31.51
100	29.61	29.25

Table 3.3: Horizontal displacement on dam faces for 125m dam height (EF/ED =0.2)

Height from base (m)	Horizontal displacement (mm) on upstream face for earthquake force acting		Horizontal displacement (mm) on downstream face for earthquake force acting	
	Upward	Downward	Upward	Downward
0	31.05	30.94	29.61	29.25
9.59	38.35	37.74	35.18	34.48
19.17	42.92	41.93	39.52	38.46
28.75	47.68	46.24	44.34	42.91
38.34	51.96	50.12	49.09	47.29
47.92	56.41	54.15	54.15	51.94
57.51	60.79	58.09	59.19	56.55
67.09	65.27	62.11	64.18	61.07
76.68	69.74	66.1	69.06	65.46
86.26	74.24	70.1	73.85	69.74
95.85	78.7	74.04	78.52	73.88
105.43	83.1	77.9	83.05	77.86
115	87.44	81.67	87.45	81.68
120	89.74	83.68	89.76	83.69
125	92.04	85.68	92.03	85.66

Table 3.4 Vertical displacement at the dam base for 125m dam height (EF/ED = 0.2)

Distance from heel (m)	Vertical displacement (mm) for earthquake force acting	
	Upward	Downward
0	-8.46	-15.09
5	-11.65	-18.36
10	-14.26	-20.96
22.5	-19.84	-26.26
35	-24.67	-30.66
47.5	-29	-34.53
60	-32.75	-37.78
72.5	-35.82	-40.31
85	-37.84	-41.75
92.5	-37.92	-41.44
100	-36.55	-39.64

Table 3.5 Vertical displacement on dam faces for 125m dam height (EF/ED = 0.2)

Height from base (m)	Vertical displacement (mm) on upstream face for earthquake force acting		Vertical displacement (mm) on downstream face for earthquake force acting	
	Upward	Downward	Upward	Downward
0	-8.46	-15.09	-36.55	-39.64
9.59	-9.16	-16.28	-38.9	-42.47
19.17	-9.97	-17.39	-39.44	-43.44
28.75	-10.41	-18.02	-38.78	-43.18
38.34	-10.71	-18.47	-37.6	-42.36
47.92	-10.94	-18.84	-35.93	-41.05
57.51	-11.11	-19.14	-33.77	-39.25
67.09	-11.27	-19.4	-31.23	-37.06
76.68	-11.42	-19.65	-28.43	-34.66
86.26	-11.59	-19.89	-25.42	-32.06
95.85	-11.76	-20.13	-22.24	-29.31
105.43	-11.92	-20.33	-18.95	-26.45
115	-12.03	-20.47	-15.64	-23.61
120	-12.05	-20.5	-15.71	-23.69
125	-12.06	-20.51	-15.71	-23.68

Table 3.6 Horizontal stresses at the dam base for 125m dam height EF/ED = 0.2)

Distance from heel (m)	Horizontal stresses (t/sq m) for earthquake force acting	
	Upward	Downward
0	117.63	89.21
5	79.95	56.91
10	63.19	48.76
22.5	27.32	19.46
35	2.17	-2.14
47.5	-19.24	-23.48
60	-37.99	-41.66
72.5	-74.17	-77.96
85	-115.01	-118.88
92.5	-283.23	-291.44
100	-411.65	-422.62

Table 3.7 Horizontal stresses on dam faces for 125m dam height (EF/ED=0.2)

Height from base (m)	Horizontal stresses (t/sq m) on upstream face for earthquake force acting		Horizontal stresses (t/sq m) on downstream face for earthquake force acting	
	Upward	Downward	Upward	Downward
0	117.63	89.21	-411.65	-422.62
9.59	-72.31	-86.86	-383.45	-395.11
19.17	-165.1	-155.25	-77.27	-80.87
28.75	-91.26	-89.35	-132.28	-136.02
38.34	-93.74	-93.49	-145.44	-148.41
47.92	-76.47	-77.55	-116.97	-118.43
57.51	-69.48	-68.78	-78.73	-78.65
67.09	-56.62	-56.4	-64.34	-64.1
76.68	-47.05	-47.11	-49.9	-49.98
86.26	-35.53	-35.69	-36.91	-36.74
95.85	-25.09	-25.11	-21.86	-21.6
105.43	-12.81	-12.74	-12.92	-12.96
115	-0.4	-0.17	-4.15	-4.54
120	0.17	0.3	-0.86	-0.92
125	-0.12	-0.05	1.53	1.76

Table 3.8 Vertical stresses at the dam base for 125m dam height (EF/ED = 0.2)

Height from heel (m)	Vertical stresses (t/sq m) for earthquake force acting	
	Upward	Downward
0	-20.59	-88.17
5	-51.19	-107.76
10	-60.87	-88.72
22.5	-80.09	-103.31
35	-94.08	-114.31
47.5	-113.89	-131.84
60	-131.72	-146.15
72.5	-140.44	-152.99
85	-152.07	-162.65
92.5	-219	-229.42
100	-239.37	-247.84

Table 3.9 Vertical stresses on dam faces for 125m dam height (EF/ED =0.2)

Height from base (m)	Vertical stresses (t/sq m) on upstream face for earthquake force acting		Vertical stresses (t/sq m) on downstream face for earthquake force acting	
	Upward	Downward	Upward	Downward
0	-20.59	-88.17	-299.97	-247.84
9.59	-161.13	-244.52	-345.68	-350.65
19.17	-180.58	-220.88	-277.04	-286.92
28.75	-106.2	-145.18	-243.97	-250.57
38.34	-77.94	-109.29	-197.2	-200.79
47.92	-62.77	-91.84	-165.33	-166.99
57.51	-50.3	-74.85	-132.64	-132.62
67.09	-47.83	-69.45	-109.74	-109.43
76.68	-45.95	-64.5	-74.65	-74.04
86.26	-45.61	-61.03	-55.87	-55.55
95.85	-45.16	-57.42	-32.59	-32.07
105.43	-32.34	-40.67	-22.27	-22.43
115	-15.31	-19.38	-92.02	-95.04
120	-6.71	-8.49	-14.25	-16.12
125	-1.84	-1.56	19.77	20.84

Table 3.10 Horizontal displacements along the dam base for case 1,2,3 & 4 and for different EF/ED ratio.

		Horizontal displacement(mm) for distance of nodal points from heel/base width										
Case No.	EF/ED Ratio	0	0.05	0.1	0.225	0.350	0.476	0.599	0.725	0.847	0.925	1
1 (125m)	0.2	31.05	31.78	32.47	33.05	33.37	33.53	33.54	33.56	33.11	31.81	29.61
	0.4	15.72	16.25	16.77	17.16	17.31	17.34	17.19	16.96	16.39	15.28	13.60
	0.6	10.61	11.05	11.49	11.78	11.86	11.83	11.64	11.34	10.78	9.83	8.51
	1.0	6.47	6.82	7.16	7.36	7.38	7.31	7.1	6.79	6.29	5.58	4.66
	2.0	3.31	3.54	3.77	3.88	3.87	3.79	3.61	3.35	2.99	2.57	2.06
2 (150m)	0.2	45.87	46.95	47.96	48.83	49.33	49.69	49.77	49.82	49.24	47.29	44
	0.4	23.21	24.01	24.78	25.34	25.59	25.69	25.53	25.22	24.40	22.72	20.22
	0.6	15.66	16.32	16.97	17.4	17.54	17.53	17.29	16.83	16.05	14.63	12.64
	1.0	9.55	10.07	10.58	10.87	10.92	10.83	10.55	10.11	9.36	8.31	6.93
	2.0	4.88	5.23	5.58	5.75	5.74	5.62	5.36	4.99	4.46	3.83	3.06
3 (175m)	0.2	63.23	64.75	66.2	67.37	68.05	68.47	68.46	68.48	67.68	65.04	60.59
	0.4	31.95	33.08	34.18	34.97	35.30	35.40	35.13	34.68	33.56	31.28	27.88
	0.6	21.53	22.46	23.39	23.99	24.18	24.15	23.79	23.2	22.08	20.15	17.45
	1.0	13.12	13.84	14.57	14.99	15.05	14.93	14.52	13.91	12.9	11.46	9.57
	2.0	6.69	7.18	7.67	7.92	7.91	7.79	7.39	6.88	6.15	5.29	4.25
4 (200m)	0.2	83.6	85.63	87.57	89.13	90.03	90.6	90.61	90.68	89.62	86.11	80.29
	0.4	42.22	43.73	45.20	46.26	46.71	46.85	46.50	45.93	44.45	41.43	36.97
	0.6	28.42	29.67	30.9	31.71	31.97	31.84	31.46	30.71	29.22	26.67	23.12
	1.0	17.31	18.28	19.25	19.81	19.91	19.75	19.23	18.42	17.08	15.18	12.7
	2.0	8.82	9.48	10.13	10.45	10.46	10.25	9.79	9.11	8.15	7.01	5.63

Table 3.11 Horizontal displacements along the upstream face of the dam for cases 1, 2, 3 & 4 and for different EF/ED ratio.

		Horizontal displacement (mm) for height of nodal points/height of dam														
Cells No.	EF/ED Ratio	0	0.076	0.153	0.229	0.307	0.385	0.461	0.538	0.613	0.689	0.769	0.847	0.926	0.962	1
1 (125m)	0.2	31.05	38.35	42.92	47.68	51.96	56.41	60.79	65.27	69.74	74.24	78.7	83.1	87.44	89.74	92.04
	0.4	15.72	20.83	23.88	27.10	29.90	32.85	35.75	38.72	41.68	44.66	47.61	50.49	53.32	54.83	56.33
	0.6	10.61	14.87	17.41	20.08	22.38	24.81	27.19	29.64	32.08	34.55	36.97	39.35	41.67	42.92	44.16
	1.0	6.47	9.97	12.07	14.3	16.17	18.16	20.11	22.11	24.11	26.12	28.1	30.02	31.89	32.9	33.9
	2.0	3.31	6.14	7.91	9.78	11.34	12.98	14.59	16.24	17.88	19.54	21.16	22.73	24.25	25.07	25.89
2 (150m)	0.2	45.87	56.98	64.03	71.48	78.17	85.23	92.15	99.22	106.19	113.2	120.11	127.03	133.85	136.82	139.77
	0.4	23.21	30.96	35.67	40.71	45.12	49.84	54.44	59.16	63.50	68.46	73.02	77.58	82.05	84.0	85.92
	0.6	15.66	22.11	26	30.2	33.82	37.72	41.53	45.43	49.25	53.08	56.83	60.58	64.25	65.85	67.44
	1.0	9.55	14.84	18.06	21.54	24.51	27.72	30.85	34.05	37.18	40.31	43.35	46.39	49.34	50.64	51.91
	2.0	4.88	9.16	11.86	14.78	17.25	19.92	22.52	25.17	27.75	30.33	32.85	35.31	37.72	38.78	39.82
3 (175m)	0.2	63.23	78.77	88.58	99.1	108.36	118.29	127.93	137.97	147.92	158.11	168.15	178.23	188.06	191.73	195.27
	0.4	31.95	42.82	49.33	56.44	62.48	69.1	75.48	82.21	88.87	95.75	102.50	109.30	115.85	118.33	120.68
	0.6	21.53	30.58	35.95	41.86	46.79	52.25	57.5	63.07	68.58	74.29	79.89	85.53	90.96	93.01	94.96
	1.0	13.12	20.53	24.97	29.86	33.89	38.37	42.68	47.27	51.81	56.54	61.17	65.82	70.28	71.96	73.56
	2.0	6.69	12.68	16.41	20.48	23.83	27.54	31.11	34.92	38.71	42.65	46.53	50.4	54.11	55.52	56.86
4 (200m)	0.2	83.6	104.47	117.71	131.9	144.48	157.92	171.06	184.72	198.33	212.28	226.12	240.05	253.76	258.18	262.49
	0.4	42.22	56.79	65.57	75.14	83.36	92.31	101.03	110.19	119.34	128.78	138.14	147.58	156.78	159.77	162.63
	0.6	28.42	40.53	47.75	55.68	62.38	69.74	76.9	84.47	92.02	99.84	107.58	115.37	122.91	125.37	127.71
	1.0	17.31	27.24	33.2	39.76	45.24	51.3	57.19	63.45	69.7	76.21	82.66	89.16	95.42	97.47	99.41
	2.0	8.82	16.83	21.83	27.3	31.84	36.85	41.74	46.94	52.16	57.59	63.00	68.42	73.63	75.33	76.95

Table 3.12 Horizontal displacements along the downstream face of the dam for cases 1,2,3 & 4 and for different EF/ED ratio.

		Horizontal displacement (mm) for height of nodal points/height of dam														
Case No.	EF/ED Ratio	0	0.076	0.153	0.229	0.307	0.385	0.461	0.538	0.613	0.689	0.769	0.847	0.926	0.962	1
1 (125m)	0.2	29.61	35.18	39.52	44.34	49.09	54.15	59.19	64.18	69.09	73.85	78.52	83.05	87.45	89.76	92.03
	0.4	13.60	17.76	20.77	24.06	27.28	30.74	34.21	37.64	41.0	44.27	47.43	50.45	53.33	54.84	56.32
	0.6	8.51	11.97	14.5	17.22	19.9	22.78	25.69	28.58	31.4	34.15	36.79	39.3	41.67	42.93	44.15
	1.0	4.66	7.36	9.44	11.64	13.84	16.22	18.64	21.06	23.43	25.73	27.92	29.97	31.89	32.91	33.89
	2.0	2.06	3.98	5.64	7.38	9.18	11.13	13.15	15.2	17.21	19.15	20.98	22.68	24.25	25.08	25.88
2 (150m)	0.2	44	52.4	58.91	66.26	73.9	81.98	90.06	97.97	105.24	112.45	119.79	126.97	133.83	136.85	139.73
	0.4	20.22	26.50	30.99	35.98	41.20	46.50	52.44	57.94	62.86	67.70	72.70	77.52	82.03	84.02	85.89
	0.6	12.64	17.87	21.64	25.76	30.11	34.8	39.57	44.22	48.31	52.32	56.5	60.52	64.22	65.88	67.41
	1.0	6.93	11.01	14.1	17.43	21.02	24.92	28.94	32.86	36.24	39.55	43.03	46.33	49.32	50.66	51.88
	2.0	3.06	5.97	8.44	11.06	14.02	17.24	20.66	24	26.82	29.57	32.5	35.25	37.69	38.8	39.79
3 (175m)	0.2	60.59	72.4	81.79	92.26	102.65	113.73	124.74	135.76	146.58	157.3	167.82	178.12	188.09	191.73	195.31
	0.4	27.88	36.66	43.10	50.22	57.24	64.82	72.42	80.05	87.54	94.95	102.17	109.18	115.18	118.32	120.71
	0.6	17.45	24.75	30.12	35.99	41.8	48.12	54.49	60.92	67.24	73.48	79.55	85.42	90.98	93.01	94.98
	1.0	9.57	15.26	19.68	24.41	29.19	34.4	39.73	45.13	50.48	55.73	60.83	65.71	70.3	71.97	73.59
	2.0	4.25	8.29	11.8	15.54	19.45	23.74	28.22	32.8	37.37	41.84	46.18	50.29	54.13	55.52	56.87
4 (200m)	0.2	80.29	96.1	108.65	122.9	136.9	151.92	166.86	181.82	196.57	211.21	225.66	239.9	253.79	258.18	262.5
	0.4	36.97	48.69	57.27	66.94	76.39	86.67	96.98	107.34	117.57	127.72	137.69	147.42	156.82	159.77	162.67
	0.6	23.12	32.85	40.01	47.95	55.76	64.3	72.93	81.64	90.26	98.78	107.13	115.22	122.95	125.37	127.75
	1.0	12.7	20.29	26.17	32.58	39	46.06	53.29	60.64	67.94	75.15	82.2	89.01	95.46	97.47	99.44
	2.0	5.63	11.04	15.72	20.76	26.03	31.83	37.91	44.15	50.39	56.54	62.54	68.27	73.66	75.33	76.96

Table 3.13: Horizontal displacements at crest and heel with different EF/ED ratio and cases

Case No.	EF/ED Ratio	Horizontal displacement (mm)	
		Crest	Heel
1 (125m)	0.2	92.04	31.05
	0.4	56.33	15.75
	0.6	44.16	10.61
	1.0	33.9	6.47
	2.0	25.89	3.31
2 (150m)	0.2	139.77	45.87
	0.4	85.92	23.21
	0.6	67.44	15.66
	1.0	51.91	9.55
	2.0	39.82	4.88
3 (175m)	0.2	195.27	63.23
	0.4	120.68	31.95
	0.6	94.96	21.53
	1.0	73.56	13.12
	2.0	56.86	6.69
4 (200m)	0.2	262.49	83.6
	0.4	162.63	42.22
	0.6	127.71	28.42
	1.0	99.41	17.31
	2.0	76.95	8.82

Table 3.14 Ratio of R_u and maximum horizontal displacements along the dam base and upstream face for cases 1, 2, 3, and 4.

Location	EF/ED Ratio	Ratio of R_u and maximum displacement values for							
		Case 1 (125m)		Case 2 (150m)		Case 3 (175m)		Case 4 (200m)	
		u	R_u	u	R_u	u	R_u	u	R_u
Dam Base	0.2	33.53	4.57	49.69	4.58	68.47	4.58	90.6	4.58
	0.4	17.34	2.37	25.69	2.37	35.4	2.37	46.85	2.37
	0.6	11.83	1.62	17.53	1.62	24.15	1.62	31.84	1.61
	1.0	**7.31**	1.0	**10.83**	1.0	**14.93**	1.0	**19.75**	1.0
	2.0	3.79	0.52	5.62	0.52	7.74	0.52	10.25	0.52
Upstream Face	0.2	92.04	2.71	139.77	2.69	195.27	2.65	262.49	2.64
	0.4	56.32	1.66	85.92	1.66	120.68	1.64	162.63	1.64
	0.6	44.16	1.30	67.44	1.30	94.96	1.29	127.71	1.29
	1.0	**33.9**	1.0	**51.91**	1.0	**73.56**	1.0	**99.41**	1.0
	2.0	25.89	0.76	39.82	0.76	56.86	0.77	76.95	0.77

Where u = Maximum Horizontal displacement for different EF/ED ratio.
R_u = Ratio of u / maximum horizontal displacement for EF/ED=1.

Table 3.15 vertical displacements along the dam base for cases 1,2,3 & 4 and for different EF/ED ratio.

		Vertical displacement (mm) for distance of nodal points from heel/base width										
Case No.	EF/ED Ratio	0	0.05	0.1	0.225	0.350	0.476	0.599	0.725	0.847	0.925	1
1 (125m)	0.2	15.09	18.36	20.96	26.26	30.66	34.53	37.78	40.31	41.75	41.44	39.64
	0.4	6.77	8.70	10.30	13.50	16.06	18.18	19.81	20.94	21.39	20.88	19.43
	0.6	4.2	5.58	6.76	9.16	11.03	12.53	13.63	14.32	14.49	14	12.81
	1.0	2.3	3.17	3.97	5.62	6.88	7.85	8.51	8.86	8.87	8.44	7.57
	2.0	1.02	1.46	1.91	2.88	3.61	4.41	4.48	4.61	4.52	4.23	3.71
2 (150m)	0.2	21.47	26.32	30.24	38.38	45.23	51.24	56.2	59.97	62.09	61.6	58.93
	0.4	9.57	12.42	14.81	19.73	23.70	27.01	29.52	31.16	31.79	31.02	28.88
	0.6	5.91	7.94	9.71	13.38	16.29	18.63	20.31	21.3	21.52	20.79	19.03
	1.0	3.22	4.5	5.68	8.2	10.17	11.68	12.69	13.19	13.15	12.54	11.24
	2.0	1.41	2.06	2.73	4.21	5.34	6.17	6.63	6.86	6.71	6.29	5.51
3 (175m)	0.2	26.07	32.62	37.99	49.21	58.7	67.11	74.24	79.9	83.29	82.88	79.44
	0.4	11.47	15.31	18.55	25.29	30.76	35.38	39.0	41.57	42.70	41.78	38.95
	0.6	7.03	9.76	12.14	17.15	21.15	24.41	26.85	28.43	28.93	28.01	25.66
	1.0	3.77	5.49	7.09	10.51	13.2	15.31	16.79	17.62	17.7	16.91	15.16
	2.0	1.62	2.49	3.38	5.39	6.94	8.1	8.84	9.18	9.04	8.48	7.43
4 (200m)	0.2	32.57	41.25	48.37	63.38	76.15	87.49	97.15	104.84	109.45	108.98	104.66
	0.4	14.24	19.30	23.59	32.58	39.94	46.16	51.07	54.57	56.13	54.94	51.30
	0.6	8.71	12.3	15.45	22.11	27.47	31.85	35.15	37.31	38.01	36.81	33.77
	1.0	4.64	6.89	8.99	13.54	17.15	19.98	21.99	23.14	23.27	22.23	19.96
	2.0	1.97	3.11	4.28	6.94	9.02	10.57	11.59	12.05	11.88	11.16	9.78

Table 3.16 Vertical displacements along the upstream face of the dam for cases 1,2,3 and 4 and for different EF/ED ratio

		Vertical displacement (mm) for heights of nodal points / height of dam														
Case No.	EF/ED Ratio	0	0.076	0.153	0.229	0.307	0.385	0.461	0.538	0.613	0.689	0.769	0.847	0.926	0.962	1
1 (125m)	0.2	15.09	16.28	17.39	18.02	18.47	18.84	19.14	19.4	19.65	19.89	20.13	20.33	20.47	20.5	20.51
	0.4	6.77	7.41	8.17	8.69	9.10	9.44	9.73	9.99	10.24	10.49	10.72	10.93	11.07	11.10	11.11
	0.6	4.2	4.54	3.13	5.59	5.98	6.3	6.58	6.84	7.09	7.33	7.57	7.77	7.91	7.94	7.95
	1.0	2.3	2.34	2.74	3.15	3.51	3.82	4.1	4.34	4.61	4.86	5.09	5.3	5.43	5.46	5.48
	2.0	1.02	0.75	0.98	1.32	1.66	1.95	2.23	2.49	2.75	2.99	3.23	3.43	3.57	3.6	3.61
2 (150m)	0.2	21.47	23.1	24.63	25.48	26.06	26.54	26.95	27.34	27.72	28.07	28.38	28.63	28.81	28.84	28.85
	0.4	9.57	10.38	11.40	12.08	12.60	13.04	13.43	13.82	14.20	14.56	14.87	15.12	15.31	15.34	15.35
	0.6	5.91	6.29	7.07	7.66	8.14	8.55	8.94	9.33	9.71	10.06	10.37	10.62	10.79	10.82	10.84
	1.0	3.22	3.16	3.67	4.16	4.62	5.01	5.39	5.78	6.17	6.52	6.83	7.09	7.27	7.3	7.31
	2.0	1.41	0.9	1.15	1.55	1.97	2.34	2.72	3.11	3.5	3.85	4.16	4.42	4.6	4.63	4.64
3 (175m)	0.2	26.07	28.08	30.08	31.17	31.92	32.5	32.93	33.3	33.65	34	34.37	34.7	34.94	34.96	34.98
	0.4	11.47	12.39	13.73	14.60	15.26	15.77	16.18	16.55	16.90	17.25	17.61	17.93	18.17	18.19	18.22
	0.6	7.03	7.39	8.39	9.14	9.76	10.24	10.64	11.01	11.36	11.71	12.06	12.38	12.61	12.63	12.65
	1.0	3.77	3.55	4.2	4.83	5.4	5.85	6.25	6.62	6.97	7.32	7.67	7.99	8.22	8.25	8.27
	2.0	1.62	0.81	1.12	1.61	2.13	2.56	2.95	3.32	3.68	4.03	4.37	4.69	4.92	4.94	4.96
4 (200m)	0.2	32.57	35.08	37.62	38.97	39.87	40.55	41.03	41.44	41.81	42.2	42.59	42.94	43.2	43.22	43.24
	0.4	14.24	15.32	16.99	18.05	18.84	19.44	19.90	20.31	20.89	21.07	21.46	21.82	22.09	22.11	22.14
	0.6	8.71	9.07	10.31	11.23	11.97	12.53	12.99	13.41	13.8	14.2	14.6	14.97	15.25	15.27	15.3
	1.0	4.64	4.22	5	5.75	6.43	6.95	7.4	7.82	8.21	8.61	9	9.37	9.65	9.67	9.69
	2.0	1.97	0.79	1.12	1.7	2.33	2.82	3.27	3.69	4.09	4.49	4.89	5.26	5.53	5.56	5.58

Table 3.17 Vertical displacements along downstream face of the dam for all cases 1, 2, 3 and 4 and for different EF / ED ratio

		Vertical displacement (mm) for height of nodal points / height of dam														
Case No.	EF / ED Ratio	0	0.076	0.153	0.229	0.307	0.385	0.461	0.538	0.613	0.689	0.769	0.847	0.926	0.962	1
1 (125m)	0.2	39.64	42.47	43.45	43.18	42.36	41.05	39.25	37.08	34.66	32.06	29.31	26.45	23.61	23.69	23.68
	0.4	19.43	21.80	22.96	23.34	23.35	22.99	22.23	21.14	19.81	18.29	16.62	14.84	13.07	13.16	13.15
	0.6	12.81	14.87	16.01	16.57	16.85	16.81	16.41	15.71	14.76	13.62	12.33	10.93	9.53	8.61	9.61
	1.0	7.57	9.25	10.33	11.02	11.51	11.73	11.64	11.26	10.65	9.83	8.86	7.79	6.72	6.8	6.8
	2.0	3.71	4.96	5.93	6.72	7.36	7.79	7.95	7.83	7.48	6.93	6.22	5.4	4.58	4.67	4.66
2 (150m)	0.2	58.93	63.16	64.55	63.94	62.64	61.15	58.87	58.06	56.47	49.17	42.07	37.51	32.9	33	32.97
	0.4	28.88	32.41	34.09	34.60	34.75	34.58	33.76	33.60	32.69	28.12	23.74	20.86	17.94	18.03	18.01
	0.6	19.03	22.09	23.75	24.58	25.19	25.47	25.16	25.25	24.58	20.97	17.55	15.27	12.93	13.03	13.01
	1.0	11.24	13.74	15.3	16.37	17.33	17.98	18.11	18.4	17.94	15.16	12.55	10.78	8.96	9.05	9.03
	2.0	5.51	7.36	8.77	10	11.22	12.16	12.66	13.11	12.81	10.69	8.73	7.37	5.95	6.04	6.02
3 (175m)	0.2	79.44	85.07	86.75	85.82	83.73	80.56	76.35	71.37	65.81	59.82	53.44	46.75	39.97	40.06	40.05
	0.4	38.95	43.74	45.98	46.58	46.40	45.38	43.49	40.91	37.77	34.18	30.19	25.89	21.48	21.56	21.56
	0.6	25.66	29.86	32.12	33.17	33.6	33.32	32.26	30.52	28.24	25.5	22.36	18.9	15.33	15.41	15.4
	1.0	15.16	18.61	20.78	22.17	23.1	23.41	23.04	22.04	20.48	18.46	16.02	13.28	10.42	10.5	10.5
	2.0	7.43	10.01	12.01	13.62	14.92	15.71	15.91	15.48	14.51	13.06	11.2	9.02	6.72	6.8	6.8
4 (200m)	0.2	104.66	111.91	114.04	112.67	109.75	105.36	99.56	92.72	85.1	76.87	68.08	58.82	49.33	49.42	49.41
	0.4	51.30	57.58	60.5	61.23	60.92	59.46	56.83	53.25	48.92	43.95	38.40	32.4	26.15	26.24	26.23
	0.6	33.77	39.29	42.26	43.61	44.15	43.69	42.18	39.77	36.61	32.81	28.43	23.59	18.54	18.63	18.63
	1.0	19.96	24.51	27.39	29.21	30.41	30.78	30.21	28.78	26.59	23.76	20.34	16.45	12.35	12.43	12.43
	2.0	9.78	13.2	15.86	18	19.7	20.72	20.92	20.28	18.89	16.82	14.18	11.07	7.74	7.83	7.82

Table 3.18 :Vertical Displacement at crest and toe with different EF/ED ratio and cases

Case No.	EF/ED Ratio	Vertical displacement (mm)	
		Crest	Toe
1 (125m)	0.2	20.51	39.64
	0.4	11.11	19.43
	0.6	7.95	12.81
	1.0	5.48	7.57
	2.0	3.61	3.71
2 (150m)	0.2	28.85	58.93
	0.4	15.37	28.88
	0.6	10.84	19.03
	1.0	7.31	11.24
	2.0	4.64	5.51
3 (175m)	0.2	34.98	79.44
	0.4	18.22	38.95
	0.6	12.65	25.66
	1.0	8.27	15.16
	2.0	4.96	7.43
4 (200m)	0.2	43.24	104.66
	0.4	22.14	51.30
	0.6	15.3	33.77
	1.0	9.69	19.96
	2.0	5.58	9.78

Table 3.19 Ratio of R_v and maximum vertical displacements along the dam base, upstream and downstream face for cases 1, 2, 3, and 4.

Location	EF/ED Ratio	Ratio R_v and maximum vertical displacement values for							
		Case 1 (125m)		Case 2 (150m)		Case 3 (175m)		Case 4 (200m)	
		v	R_v	v	R_v	v	R_v	v	R_v
Dam Base	0.2	41.75	4.71	62.09	4.72	83.29	4.71	109.45	4.7
	0.4	21.39	2.41	31.79	2.41	42.7	2.41	56.13	2.41
	0.6	14.49	1.63	21.52	1.63	28.93	1.63	38.01	1.63
	1.0	**8.87**	1.0	**13.15**	1.0	**17.7**	1.0	**23.27**	1.0
	2.0	4.52	0.51	6.71	0.51	9.04	0.51	11.88	0.51
Upstream face	0.2	20.51	3.74	28.85	3.94	34.98	4.23	43.24	4.46
	0.4	11.11	2.03	15.35	2.09	18.22	2.2	22.14	2.28
	0.6	7.95	1.45	10.84	1.48	12.65	1.53	15.3	1.58
	1.0	**5.48**	1.0	**7.31**	1.0	**8.27**	1.0	**9.69**	1.0
	2.0	3.61	0.66	4.64	0.63	4.96	0.6	5.58	0.58
Downstream face	0.2	43.18	3.92	62.64	3.61	85.82	3.87	112.67	3.86
	0.4	23.34	2.12	34.75	2.0	46.58	2.10	61.23	2.09
	0.6	16.57	1.50	25.19	1.45	33.17	1.50	43.61	1.49
	1.0	**11.02**	1.0	**17.33**	1.0	**22.17**	1.0	**29.21**	1.0
	2.0	6.72	0.61	11.22	0.65	13.62	0.61	18	0.62

Where v = Maximum vertical displacement for different EF/ED ratio.
R_v= Ratio of v / maximum vertical displacement for EF/ED=1.

Table 3.20: Horizontal stresses along the dam base for cases 1, 2, 3 & 4 and for different EF / ED ratio.

		Horizontal stresses (t/sq m) for distance of nodal points from heel / base width										
Case No.	EF / ED Ratio	0	0.05	0.1	0.225	0.350	0.476	0.599	0.725	0.847	0.925	1
1 (125m)	0.2	117.63	79.95	63.19	27.32	2.17	-23.48	-41.66	-77.96	-118.88	-291.44	-422.62
	0.4	119.81	73.07	51.81	14.19	-20.1	-42.29	-64.03	-100.46	-143.80	-268.64	-363.82
	0.6	123.56	72.11	47.89	8.27	-29.48	-52.01	-75.07	-109.78	-152.01	-250.28	-326.86
	1.0	129.36	73.07	45.52	2.65	-39.86	-62.75	-86.82	-118.82	-156.79	-225.48	-282.12
	2.0	132.72	76.87	46.02	-14.21	-51.08	-74.5	-99.38	-124.79	-156.85	-195.35	-232.36
2 (150m)	0.2	147.82	100.79	78.52	35.71	7.25	-21.99	-43.35	-91.34	-145.18	-358.85	-521.58
	0.4	150.64	92.82	65.34	19.45	-21.11	-47.36	-73.65	-121.15	-177.22	-331.35	-449.28
	0.6	155.15	91.75	60.91	12.14	-33.29	-60.46	-88.6	-133.55	-187.77	-308.91	-403.75
	1.0	162.27	93.11	58.49	5.32	-46.66	-74.83	-104.46	-144.55	-194.04	-278.83	-348.77
	2.0	172.54	97.96	59.63	-15.12	-61.01	-90.41	-121.3	-153.62	-194.38	-241.77	-287.62
3 (175m)	0.2	184.11	127.18	97.84	43.79	7.39	-30.04	-56.72	-109.77	-170.49	-419.75	-609.93
	0.4	186.43	117.44	82.89	25.71	-24.29	-57.29	-89.44	-143.06	-207.18	-387.99	-526.54
	0.6	190.82	115.56	77.66	17.56	-37.72	-71.46	-105.7	-156.98	-219.37	-361.94	-473.7
	1.0	198.2	116.4	74.68	10.03	-52.41	-87.02	-123.02	-169.4	-226.81	-326.85	-409.89
	2.0	208.99	121.07	75.69	4.01	-68.21	-104.05	-141.58	-179.75	-227.51	-283.98	-338.61
4 (200m)	0.2	216.57	149.82	115.07	51.91	9.56	-33.24	-63.02	-126.68	-202.2	-487.43	-703.35
	0.4	219.08	138.53	97.90	31.23	-26.78	-64.87	-101.65	-165.37	-242.79	-450.36	-608.45
	0.6	223.56	135.95	91.66	21.76	-42.29	-81.37	-120.81	-181.38	-255.76	-419.61	-547.42
	1.0	232.69	137.1	88.51	13.32	-59.06	-99.37	-141.13	-195.71	-263.53	-378.89	-474.3
	2.0	244.13	142.33	89.78	6.51	-77.17	-119.05	-162.79	-207.52	-263.54	-328.9	-391.97

Table 3.21: Horizontal stresses along upstream face of the dam for all cases 1, 2, 3 & 4 and for different EF / ED ratio

		Horizontal stresses (t/sq m) for height of nodal points / height of dam														
Case No.	EF / ED Ratio	0	0.076	0.153	0.229	0.307	0.385	0.461	0.538	0.613	0.689	0.769	0.847	0.926	0.962	1
1 (125m)	0.2	117.63	-86.86	-155.25	-89.35	-93.49	-77.55	-68.78	-56.4	-47.11	-35.69	-25.11	-12.74	-0.17	0.3	-0.05
	0.4	119.81	-81.98	-149.21	-94.40	-92.08	-76.56	-69.04	-56.89	-46.81	-35.59	-25.08	-12.79	-0.52	0.8	0.03
	0.6	123.56	-78.9	-147.27	-95.89	-91.34	-76.06	-69.24	-57.13	-46.71	-35.53	-25.08	-12.86	-0.44	0.07	-0.08
	1.0	129.36	-75.85	-145.7	-99.41	-90.52	-75.57	-69.43	-57.43	-46.57	-35.46	-25.11	-12.84	-0.2	0.11	-0.21
	2.0	137.72	-73.78	-144.16	-101.79	-89.16	-75.19	-69.54	-57.56	-46.46	-35.44	-25.1	-12.86	-0.25	0.11	-0.15
2 (150m)	0.2	147.82	-104.66	-189.27	-108.64	-114.53	-94.24	-84.33	-68.57	-57.59	-43.25	-30.75	-15.57	-0.08	0.2	-1.25
	0.4	150.64	-98.82	-192.56	-116.45	-112.85	-93.02	-84.52	-69.21	-57.34	-43.18	-30.69	-15.51	-0.45	0.18	-0.43
	0.6	155.15	-82.03	-189.12	-119.23	-111.73	-91.37	-85.42	-69.69	-57.17	-43.02	-30.83	-15.63	-0.37	0.23	-0.39
	1.0	162.27	-91.53	-177.96	-120.62	-110.44	-91.78	-84.93	-69.8	-57.02	-43.03	-30.68	-15.6	-0.35	0.17	-0.25
	2.0	172.54	-89.09	-176.03	-123.49	-109.18	-91.3	-85.04	-70.1	-56.82	-43	-30.73	-15.65	-0.26	0.15	-0.38
3 (175m)	0.2	184.11	-120.41	-223.97	-127.37	-137.2	-110.38	-100.37	-80.53	-68.5	-50.86	-36.04	-18.25	-0.72	0.54	-1.35
	0.4	186.43	-114.69	-216	-134.19	-134.52	-109.13	-100.53	-81.15	-68.03	-50.71	-36.30	-18.38	0.11	0.81	-0.81
	0.6	190.82	-111.07	-213.12	-137.64	-133.09	-108.5	-100.62	-81.53	-67.67	-50.61	-36.05	-18.36	-0.3	0.56	-0.91
	1.0	198.2	-107.38	-210.67	-141.19	-131.46	-107.85	-100.7	-81.93	-67.52	-50.64	-36.23	-18.45	0.02	0.62	-0.91
	2.0	208.99	-105.04	-208.08	-144.59	-129.68	-107.38	-100.71	-82.3	-67.17	-50.63	-36.23	-18.44	0.11	0.56	-1
4 (200m)	0.2	216.57	-135.99	-260.17	-147.02	-157.81	-126.97	-115.47	-92.78	-78.49	-58.7	-41.74	-20.86	1.27	1.35	-2.61
	0.4	219.08	-129.57	-250.74	-154.87	-154.69	-125.58	-115.62	-93.59	-78.05	-58.46	-41.65	-21.25	0.13	1.1	-0.7
	0.6	223.56	-109.36	-258.96	-160.59	-153.45	-123.56	-116.63	-94.12	-77.73	-58.24	-41.81	-21.18	1.03	1.16	-2.92
	1.0	232.09	-121.83	-244.15	-162.84	-151.29	-124.18	-115.82	-94.38	-77.51	-58.35	-41.66	-21.25	0.49	0.68	-1.54
	2.0	244.13	-109.6	-248.37	-167.78	-149.42	-122.93	-116.32	-94.9	-77.13	-58.23	-41.69	-21.23	0.66	0.74	-1.75

Table 3.22: Horizontal stresses along downstream face of the dam for all cases 1, 2, 3 & 4 and for different EF / ED ratio.

		Horizontal stresses (t/sq m) for height of nodal points / height of dam														
Case No.	EF / ED Ratio	0	0.076	0.153	0.229	0.307	0.385	0.461	0.538	0.613	0.689	0.769	0.847	0.926	0.962	1
1 (125m)	0.2	-422.62	-395.11	-80.87	-136.02	-148.41	-118.43	-78.65	-64.1	-49.58	-36.74	-21.6	-12.96	-4.54	-0.92	1.76
	0.4	-363.82	-304.57	-85.35	-124.68	-130.12	-108.03	-78.18	-63.77	-49.28	-36.46	-21.78	-12.96	-4.56	-0.88	1.92
	0.6	-326.86	-254.19	-91.12	-119.12	-121.06	-102.89	-78.35	-63.94	-49.48	-36.66	-22.24	-13.37	-4.79	-0.91	1.9
	1.0	-282.12	-196.09	-97.29	-112.67	-111.53	-97.31	-78.37	-63.84	-49.31	-36.45	-22.28	-13.28	-4.66	-0.9	1.83
	2.0	-232.36	-141.15	-100.74	-105.09	-102.58	-92.02	-78.5	-63.88	-49.35	-36.39	-22.41	-13.32	-4.66	-0.9	1.79
2 (150m)	0.2	-521.58	-489.28	-113.1	-199.24	-219.84	-145.21	-55.28	-19.56	-15.72	-50.8	-47.85	-17.07	-0.2	-0.02	-0.22
	0.4	-449.28	-377.13	-115.41	-181.25	-195.11	-133.03	-57.27	-20.59	-15.44	-50.63	-48.67	-17.18	0.35	0.36	-0.19
	0.6	-403.75	-314.8	-120.85	-172.33	-182.71	-126.88	-58.58	-21.24	-15.34	-50.77	-49.38	-17.63	0.4	0.34	-0.82
	1.0	-348.77	-245.85	-126.82	-162.29	-169.67	-120.26	-59.93	-21.81	-15.18	-50.48	-49.43	-17.43	0.63	0.46	-0.73
	2.0	-287.62	-175.57	-129.47	-150.96	-157.45	-114.09	-61.35	-22.41	-15.13	-50.61	-50.02	-17.67	0.69	0.51	-0.88
3 (175m)	0.2	-609.93	-569.26	-118.48	-196.06	-216.44	-173.55	-113.93	-94.33	-74.19	-54.79	-31.41	-16.45	-3.58	-1.18	2.52
	0.4	-526.54	-439.8	-124.71	-181.15	-191.13	-159.24	-114.52	-94.69	-74.26	-54.69	-32.24	-17.07	-3.57	-0.95	2.41
	0.6	-437.7	-367.48	-132.92	-173.73	-178.3	-151.87	-115.19	-94.99	-74.32	-54.65	-32.79	-17.57	-3.65	-0.92	2.07
	1.0	-409.89	-287.17	-142.1	-165.35	-165.06	-144.15	-116.02	-95.22	-74.27	-54.46	-33.06	-17.69	-3.71	-0.97	1.93
	2.0	-338.61	-205.48	-147.63	-155.39	-152.6	-136.91	-116.98	-95.56	-74.49	-54.45	-33.4	-18.02	-3.76	-0.89	1.68
4 (200m)	0.2	-703.35	-657.48	-138.45	-227.97	-251.72	-201.48	-132.38	-110.84	-87.48	-65.3	-38.92	-20.64	-4.86	-1.92	3
	0.4	-608.45	-508.77	-144.36	-210.67	-222.43	-185.11	-133.21	-111.08	-87.45	-64.94	-39.47	-20.65	-4.39	-1.58	3.20
	0.6	-547.42	-425.01	-153.26	-201.71	-207.26	-176.31	-133.73	-110.87	-86.88	-64.15	-38.97	-20	-4.26	-1.59	3.42
	1.0	-474.3	-332.6	-164.04	-192.14	-192.2	-167.69	-134.99	-111.36	-87.05	-64.19	-39.57	-20.4	-4.02	-1.37	2.87
	2.0	-391.97	-238.15	-170.92	-180.59	-177.85	-159.31	-136.12	-111.12	-87.03	-63.93	-39.7	-20.31	-3.61	-1.26	2.43

Table 3.23 :Horizontal Stresses at heel and toe with different EF/ED ratio and cases

Case No.	EF/ED Ratio	Horizontal Stresses (t/m^2)	
		Heel	Toe
1 (125m)	0.2	117.63	-422.62
	0.4	119.81	-363.82
	0.6	123.56	-326.86
	1.0	129.36	-282.12
	2.0	137.72	-232.36
2 (150m)	0.2	147.82	-521.58
	0.4	150.64	-449.28
	0.6	155.15	-403.75
	1.0	162.27	-348.75
	2.0	172.54	-287.62
3 (175m)	0.2	184.11	-609.93
	0.4	186.43	-526.54
	0.6	190.82	-473.7
	1.0	198.2	-409.89
	2.0	208.99	-338.61
4 (200m)	0.2	216.57	-703.35
	0.4	219.08	-608.45
	0.6	223.56	-547.42
	1.0	232.09	-474.30
	2.0	244.13	-391.97

Table 3.24 Ratio of R_h and maximum horizontal stresses along the dam base and upstream face for cases 1, 2, 3, and 4.

Location	EF/ED Ratio	Ratio R_h and maximum horizontal stress values for							
		Case 1 (125m)		Case 2 (150m)		Case 3 (175m)		Case 4 (200m)	
		h	R_h	**h**	R_h	**h**	R_h	**h**	R_h
Dam Base (At toe)	0.2	-422.62	1.50	-521.58	1.50	-609.93	1.49	-703.35	1.48
	0.4	-363.82	1.29	-449.28	1.29	-526.54	1.29	-608.45	1.28
	0.6	-326.86	1.16	-403.75	1.16	-473.7	1.16	-547.42	1.15
	1.0	**-282.12**	1.0	**-348.77**	1.0	**-409.89**	1.0	**-474.3**	1.0
	2.0	-232.36	0.82	-287.62	0.82	-338.61	0.82	-391.97	0.82
Upstream face (Maximum)	0.2	-155.25	1.07	-189.27	1.06	- 223.97	1.06	-260.17	1.06
	0.4	-157.87	1.08	-192.56	1.08	-216	1.03	-263.95	1.08.
	0.6	-147.27	1.01	- 189.12	1.06	-213.12	1.01	-258.96	1.06
	1.0	**-145.7**	1.0	**- 177.98**	1.0	**-210.67**	0.99	**-244.15**	1.0
	2.0	-144.16	0.99	-177.03	0.99	-208.08		-248.37	1.01

Where h= Maximum Horizontal stress for different EF/ED ratio.
R_h= Ratio of h / maximum horizontal stress for EF/ED=1.

Table 3.25: Vertical stresses along the dam base for cases 1, 2, 3 & 4 and for different EF / ED ratio.

		Vertical stresses (t/sq m) for distance of nodal points from heel / base width										
Case No.	EF / ED Ratio	0	0.05	0.1	0.225	0.350	0.476	0.599	0.725	0.847	0.925	1
1 (125m)	0.2	-88.17	-107.76	-88.72	-103.31	-114.31	-131.84	-146.15	-152.99	-162.65	-229.42	-247.84
	0.4	31.16	-75.0	-97.69	-113.96	-127.58	-143.76	-158.93	-165.24	-173.88	-213.56	-210.44
	0.6	59.16	-55.1	-99.63	-119.56	-136.52	-151.67	-166.86	-172.48	-180.58	-204.34	-188.19
	1.0	88.85	17.3	-98.53	-125.51	-148.52	-162.15	-176.99	-181.06	-187.85	-192.43	-160.77
	2.0	119.26	42.69	-91.2	-130.87	-164.54	-176.4	-190.76	-191.28	-194.29	-176.88	-128.44
2 (150m)	0.2	-95.29	-122.37	-104.55	-124.53	-141.29	-164.7	-184.28	-190.82	-199.51	-283.96	-308.71
	0.4	51.12	-80.78	-113.69	-137.32	-158.33	-180.48	-201.27	-206.06	-212.98	-263.81	-261.72
	0.6	85.23	6.84	-115.05	-143.96	-169.75	-190.8	-211.69	-214.95	-220.84	-252.1	-239.9
	1.0	121.38	33.22	-112.33	-150.87	-184.96	-204.43	-225	-225.53	-229.36	-237.18	-199.86
	2.0	158.21	64.92	-101.6	-156.84	-205.16	-222.81	-243.01	-238.18	-236.74	-217.8	-159.87
3 (175m)	0.2	-90.35	-126.64	-113.59	-136.61	-158	-185.47	-208.01	-219.85	-235.72	-332.98	-360.1
	0.4	76.82	-78.47	-123.47	-151.25	-176.90	-202.68	-226.99	-238.08	-252.46	-310.10	-305.80
	0.6	115.38	21.94	-124.81	-158.82	-189.62	-214.06	-238.65	-248.69	-262.22	-296.66	-273.41
	1.0	156.38	52.27	-121.18	-166.48	-206.61	-229.23	-253.72	-261.44	-273.05	-279.62	-233.76
	2.0	197.49	88.31	-108.21	-172.88	-229.24	-249.81	-274.13	-276.63	-282.71	-257.33	-186.97
4 (200m)	0.2	16.72	-134.61	-125.75	-154.22	-179.51	-212.25	-239.22	-252.43	-273.9	-386.97	-416.68
	0.4	99.62	5.65	-136.52	-170.59	-201.24	-232.18	-261.49	-273.99	-292.77	-359.93	-353.89
	0.6	142.37	33.97	-137.98	-179.16	-215.9	-245.24	-274.87	-286.24	-303.48	-343.72	-316.09
	1.0	189.13	68.99	-132.99	-187.47	-235.42	-262.81	-292.46	-301.38	-315.92	-323.87	-270.44
	2.0	235.12	109.92	-117.46	-194.44	-261.44	-286.54	-316.01	-319.1	-326.77	-297.75	-216.35

Table 3.26 Vertical stresses along upstream face of the dam for all cases 1, 2, 3 & 4 and for different EF / ED ratio.

		Vertical stresses (t/sq m) for height of nodal points / height of dam														
Case No.	EF / ED Ratio	0	0.076	0.153	0.229	0.307	0.385	0.461	0.538	0.613	0.689	0.769	0.847	0.926	0.962	1
	0.2	-88.17	-244.52	-220.88	-145.18	-109.29	-91.84	-74.85	-69.45	-64.5	-61.03	-57.42	-40.67	-19.98	-8.49	-1.56
	0.4	31.16	-160.95	-184.71	-126.09	-101.35	-87.33	-75.24	-69.97	-65.16	-61.36	-57.67	-40.98	-20.18	-8.96	-1.2
1	0.6	59.16	-116.49	-165.75	-115.73	-97.2	-84.7	-74.92	-69.54	-64.67	-60.59	-57.67	-40.15	-19.67	-8.73	-1.16
(125m)	1.0	88.85	-69.48	-145.96	-105.29	-99.89	-82.99	-75.54	-70.09	-65.29	-60.98	-57.08	-40.41	-19.44	-8.58	-1.32
	2.0	119.26	34.7	-125.16	-94.36	-90.85	-81.29	-76.12	-70.45	-65.49	-61.02	-57.04	-40.4	-19.54	-8.6	-1.11
	0.2	-95.29	-279.38	-252.64	-160.45	-118.99	-102.6	-89.48	-85.82	-80.21	-70	-59.86	-42.47	-19.9	-7.82	-2.6
	0.4	51.12	-176.80	-208.7	-136.96	-108.97	-97.27	-90.06	-86.29	-80.85	-70.12	-59.93	-42.95	-20.86	-8.84	-2.10
2	0.6	85.23	-122.8	-185.96	-124.6	-104.09	-94.51	-90.2	-86.21	-80.72	-69.52	-59.05	-41.95	-19.92	-8.4	-1.86
(150m)	1.0	121.38	11.01	-162.17	-112.05	-100.1	-92.57	-81.15	-86.97	-81.43	-70.06	-59.72	-42.68	-20.32	-8.72	-2.29
	2.0	158.21	60.66	-196.9	-98.85	-96.95	-90.64	-91.83	-87.31	-81.6	-69.91	-59.48	-42.49	-20.8	-8.69	-1.06
	0.2	3.77	-306.09	-286.58	-176.82	190.86	-103.36	-80.87	-74.38	-69.52	-67.13	-64.9	-47.88	-19.82	-8.88	-11.51
	0.4	76.82	-189.26	-237.67	-150.26	-118.98	-97.23	-81.31	-74.83	-69.24	-66.24	-63.63	-47.10	-19.47	-9.91	-11.53
3	0.6	115.38	-128.1	-212.52	-136.63	-113.52	-94.38	-81.63	-74.81	-68.97	-65.63	-62.74	-46.12	-19.91	-.9.17	-10.91
(175m)	1.0	156.36	24.24	-185.73	-122.45	-108.65	-92.03	-82.49	-75.28	-69.36	-65.76	-62.96	-46.39	-19.66	-9.46	-10.45
	2.0	197.49	80.32	-157.35	-107.85	-104.96	-89.91	-83.24	-75.52	-69.3	-65.33	-62.35	-45.74	-20.12	-9.07	-7.42
	0.2	16.72	-333.81	-319.03	-191.45	-138.1	-107.36	-82.14	-74.91	-69.32	-65.39	-62.23	-45.8	-18.17	-7.32	-11.08
	0.4	99.62	-201.08	-263.26	-161.57	-125.37	-100.91	-83.08	-75.45	-68.77	-65.45	-62.39	-46.67	-19.35	-9.88	-11.94
4	0.6	142.37	-132.34	-235.36	-147.1	-120.42	-98.35	-84.72	-76.37	-70.36	-67	-64.47	-48.25	-19.21	-9.66	-13.92
(200m)	1.0	189.13	40.57	-204.35	-130.62	-114.7	-95.89	-85.16	-76.37	-70.07	-66.38	-63.66	-47.71	-20.1	-9.75	-11.7
	2.0	295.12	109.48	-172.16	-114.36	-110.37	-94	-86.49	-77.85	-70.69	-66.79	64.15	-48.04	-21.28	-9.02	-7.37

Table 3.27 Vertical stresses along downstream face of the dam for all cases 1, 2, 3 & 4 and for different EF / ED ratio.

		Vertical stresses (t/sq m) for height of nodal points / height of dam														
Case No.	EF / ED Ratio	0	0.076	0.153	0.229	0.307	0.385	0.461	0.538	0.613	0.689	0.769	0.847	0.926	0.962	1
1 (125m)	0.2	-299.37	-345.68	-277.04	-243.97	-197.2	-165.33	-132.64	-103.74	-74.65	-55.87	-32.59	-22.27	-32.02	-14.25	19.77
	0.4	-210.44	-298.16	-243.04	-220.17	-184.57	-156.77	-128.74	-101.80	-74.64	-55.6	-32.09	-22.28	-34.44	-16.37	19.48
	0.6	-188.19	-266.27	-222.37	-204.89	-176.55	-152.04	-127.25	-101.44	-75.45	-56.19	-32.67	-22.94	-34.99	-16.56	19.29
	1.0	-160.77	-229.66	-200.25	-188	-167.81	-146.83	-125.37	-100.61	-75.78	-56.13	-32.48	-22.65	-35.19	-16.64	20
	2.0	-128.41	-189.85	-176.91	-170.21	-159.29	-141.24	-123.87	-100.02	-76.35	-56.32	-32.48	-22.63	-35.09	-16.59	19.88
2 (150m)	0.2	-308.71	-433.57	-322.94	-313.56	-285.88	-266.78	-260.42	-131.58	-19.31	-38.56	-96.82	-21.01	-41.75	-16.37	35.29
	0.4	-261.72	-360.19	-271.95	-275.59	-262.97	-253.69	-256.77	-130.71	-14.85	-38.91	-36.87	-20.81	-40.06	-15.48	34.12
	0.6	-233.9	-320.99	-247.65	-256.34	-251.41	-247.52	-255.5	-130.67	-15.74	-39.27	-97.29	-21.29	-41.24	-15.89	35.07
	1.0	-199.86	-276.36	-221.95	-235.23	-239.01	-240.89	-253.87	-130.22	-16.56	-39.37	-98.86	-20.77	-40.5	-15.78	34.25
	2.0	-153.87	-227.09	-194.92	-213.11	-226.97	-235.04	-253.23	-130.31	-17.59	-39.81	-96.95	-20.55	-40.28	-15.65	33.76
3 (175m)	0.2	-360.1	-518.38	-412.55	-365.12	-295.99	-243.66	-195.54	-154.16	-110.59	-82.9	-49.58	-27.4	-32.24	-16.88	20.96
	0.4	-305.80	-432.53	-351.75	-322.27	-272.45	-230.16	-191.06	-152.56	-112.24	-83.61	-50.36	-28.29	-31.91	-16.04	21.25
	0.6	-273.41	-386.38	-322.42	-300.43	-260.74	-223.57	-189	-151.87	-113.14	-84.05	-50.82	-28.84	-32.97	-15.39	22.7
	1.0	-233.76	-333.91	-291.65	-276.65	-248.42	-216.79	-186.89	-150.37	-113.98	-84.29	-50.77	-28.79	-32.29	-16.69	19.85
	2.0	-186.97	-275.79	-259.02	-251.58	-236.38	-210.55	-185.17	-150.3	-115.09	-84.81	-51.01	-29.19	-32.47	-16.28	20.38
4 (200m)	0.2	-416.68	-600.98	-486.59	-427.45	-399.1	282.69	-227.1	-179.5	-131.45	-99.17	-61.11	-33.92	-91.11	-17.14	27.99
	0.4	-353.89	-501.01	-412.74	-376.57	-314.01	-267.62	-222.34	-177.70	-132.93	-99.48	-61.30	-33.70	-34.03	-16.95	24.56
	0.6	-316.09	-446.86	-376.91	-350.17	-300.72	-259.68	-219.5	-176.15	-132.99	-99.5	-60.09	-32.48	-99.9	-17.82	22.29
	1.0	-270.44	-386.32	-340.05	-322.26	-287.71	-252.54	-217.55	-175.61	-134.13	-99.45	-60.67	-32.89	-99.99	-16.97	23.86
	2.0	-216.95	-319.11	-301.14	-292.53	-274.71	-245.53	-215.59	-174.73	-134.93	-99.63	-60.28	-32.64	-99.17	-16.91	29.97

Table 3.28 : Vertical stresses at heel and toe with different EF/ED ratio and cases

Case No.	EF/ED Ratio	Vertical Stresses (t/m^2)	
		Heel	Toe
1 (125m)	0.2	-88.17	-247.84
	0.4	31.16	-210.44
	0.6	59.16	-188.19
	1.0	88.85	-160.77
	2.0	119.26	-128.41
2 (150m)	0.2	-95.29	-308.71
	0.4	51.12	-261.72
	0.6	85.23	-239.9
	1.0	121.36	-199.86
	2.0	158.21	-159.87
3 (175m)	0.2	-90.35	-360.10
	0.4	76.82	-305.80
	0.6	115.38	-273.41
	1.0	156.36	-233.76
	2.0	197.49	-186.97
4 (200m)	0.2	16.72	-416.68
	0.4	99.62	-353.89
	0.6	142.37	-316.09
	1.0	189.13	-270.44
	2.0	295.12	-216.35

Table 3.29 Ratio of R_{vs} and maximum vertical stresses along the dam base, upstream face and downstream face for cases 1, 2, 3, and 4.

Location	EF/ED Ratio	Ratio R_{vs} and maximum vertical stress values for							
		Case 1 (125m)		Case 2 (150m)		Case 3 (175m)		Case 4 (200m)	
		vs	R_{vs}	vs	R_{vs}	vs	R_{vs}	vs	R_{vs}
Dam Base	0.2	-229.42	1.19	-283.96	1.19	-332.98	1.19	-386.97	1.19
	0.4	-213.56	1.11	-263.81	1.11	-310.1	1.11	-359.93	1.11
	0.6	204.34	1.06	-252.1	1.06	-296.66	1.06	-343.72	1.06
	1.0	**-192.43**	1.0	**-237.18**	1.0	**-279.62**	1.0	**-323.87**	1.0
	2.0	-176.88	0.92	-217.8	0.92	-257..33	0.92	-297.75	0.92
Upstream Face	0.2	-220.88	1.51	-252.64	1.55	-286.58	1.54	-319.03	1.56
	0.4	-184.71	1.27	-208.70	1.28	-237.67	1.28	-263.26	1.28
	0.6	-165.75	1.14	-185.96	1.14	-212.52	1.14	-235.36	1.15
	1.0	**145.96**	1.0	**-162.17**	1.0	**-185.73**	1.0	**-204.35**	1.0
	2.0	-145.96	0.86	-137.84	0.85	157.35	0.85	-172.16	0.84
Downstream Face	0.2	-345.68	1.50	-433.57	1.56	-518.38	1.55	-600.98	1.55
	0.4	-298.16	1.30	-360.19	1.30	-432.53	1.30	-501.01	1.30
	0.6	-266.27	1.16	-320.99	1.16	-386.38	1.16	-446.86	1.16
	1.0	**-229.66**	1.0	**-276.36**	1.0	**-333.91**	1.0	**-386.32**	1.0
	2.0	-189.85	0.8	-227.09	0.82	-275.79	0.83	-319.11	0.83

Where vs= Maximum vertical stress for different EF/ED ratio
R_{vs}= Ratio of vs / maximum vertical stress for EF/ED=1

Table 3.30 Ratio of different dam heights, maximum displacements and maximum stresses in the dam.

Ratio of dam heights	Ratio of maximum horizontal displacement (R_{dh})	Ratio of maximum vertical displacement (R_{dv})	Ratio of maximum horizontal stress (R_{sh})	Ratio of maximum vertical stress (R_{sh})
1	1	1	1	1
1.2	1.53	1.5	1.2	1.2
1.4	2.17	2	1.45	1.45
1.6	2.95	2.63	1.68	1.68

Where R_{dh} = Ratio of maximum horizontal displacement for dam / maximum horizontal displacement for 125m .

R_{dv} = Ratio of maximum vertical displacement for dam / maximum vertical displacement for 125m .

R_{sh} = Ratio of maximum horizontal normal stress for dam / maximum horizontal normal stress for 125m .

R_{sv} = Ratio of maximum vertical normal stress for dam / maximum vertical normal stress for 125m .

Table 3.31 Ratio of maximum displacements and maximum stresses for different EF/ED ratios.

EF/ED Ratio	Ratio of maximum horizontal displacement (R_u)	Ratio of maximum vertical displacement (R_v)	Ratio of maximum horizontal normal stress (R_h)	Ratio of maximum vertical normal stress (R_{vs})
0.2	2.67	3.8	1.49	1.55
0.4	1.65	2.07	1.29	1.3
0.6	1.3	1.48	1.16	1.16
1	1	1	1	1
2	0.77	0.62	0.82	0.82

Where R_u = Ratio of maximum horizontal displacement for EF/ED / maximum horizontal displacement for EF/ED=1.

R_v = Ratio of maximum vertical displacement for EF/ED / maximum vertical displacement for EF/ED=1.

R_h = Ratio of maximum horizontal normal stress for EF/ED / maximum horizontal normal stress for EF/ED=1.

R_{vs} = Ratio of maximum vertical normal stress for EF/ED / maximum vertical normal stress for EF/ED=1.

Table 3.32 Maximum principal stresses around heel and toe for different EF/ED ratios and dam heights

EF/ED Ratio	Case 1 (125m)		Case 2 (150m)		Case 3 (175m)		Case 4 (200m)	
	Principle stress (t/sq m)		Principle stress (t/sq m)		Principle stress (t/sq m)		Principle stress (t/sq m)	
	Around heel	Around toe	Around heel	Around toe	Around heel	Around toe	Around heel	Around toe
0.2	153.95	-619.19	197.11	-765.58	251.8	-896.41	300.23	-1036.33
	112.90	-696.34	143.30	-855.79	183.81	-1007.23	218.21	-1166.49
	85.50	-59	105.28	-70.52	132.22	-85.23	154.69	-99.56
0.4	173.82	-526.62	222.89	-650.93	281.40	-763.64	334.71	-883.85
	112.1	-565.92	143.56	-694.93	184.45	-819.95	219.20	-949.69
	70.33	-62.68	87.69	-74.42	112.57	-90.09	132.24	-104.44
0.6	189.2	-468.88	242.08	-579.43	302.54	-680.33	357.93	-787.02
	116.27	-385.91	149.21	-476.87	190.65	-559.83	225.81	-649.97
	65.89	-63.06	82.77	-74.84	107.02	-90.80	125.74	-104.93
1.0	207.86	-398.18	265.25	-492.24	328.09	-578.8	387.35	-670.22
	124.47	-350.64	160.03	-433.49	202.75	-509.52	240.22	-591.28
	64.76	-63.25	82.11	-75	106.46	-91.33	125.56	-105.49
2.0	228.58	-318.07	290.68	-393.57	355.35	-463.47	417.53	-536.72
	138.37	-306.67	177.93	-379.37	222.5	-446.55	262.78	-517.44
	69.90	-63.98	89.39	-75.91	115.08	-92.67	135.9	-107.03

1st row –values at the base.
2nd row –Values at first nodal point along the dam base and downstream face from heel and toe respectively.
3rd row - values at second nodal point along the dam base and downstream face from heel and toe respectively.

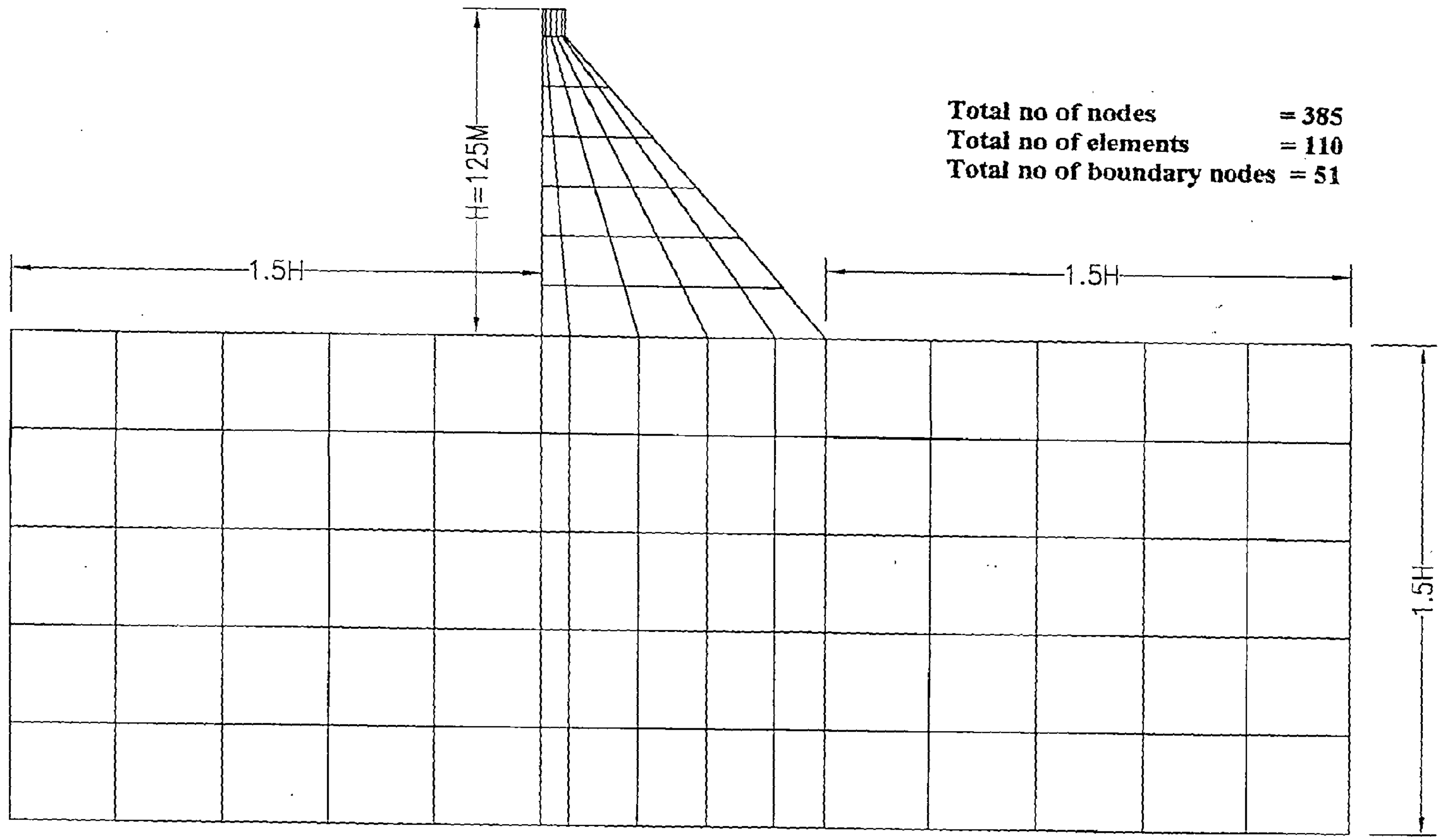
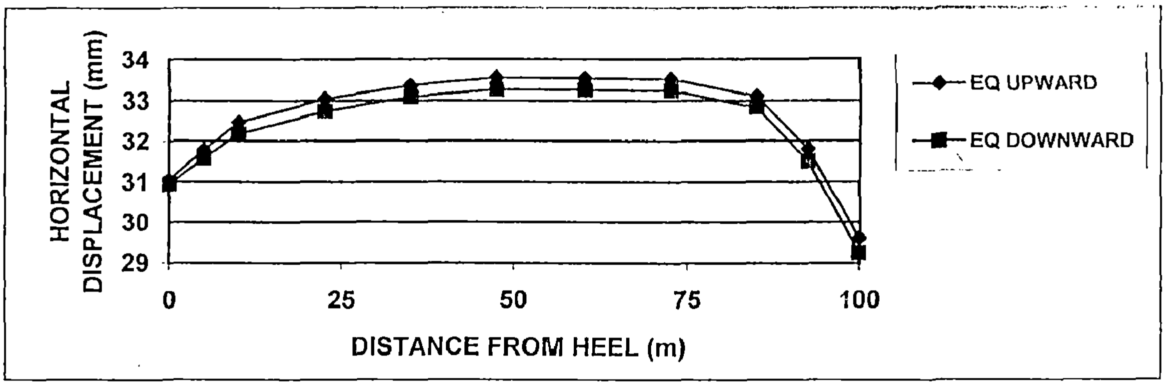
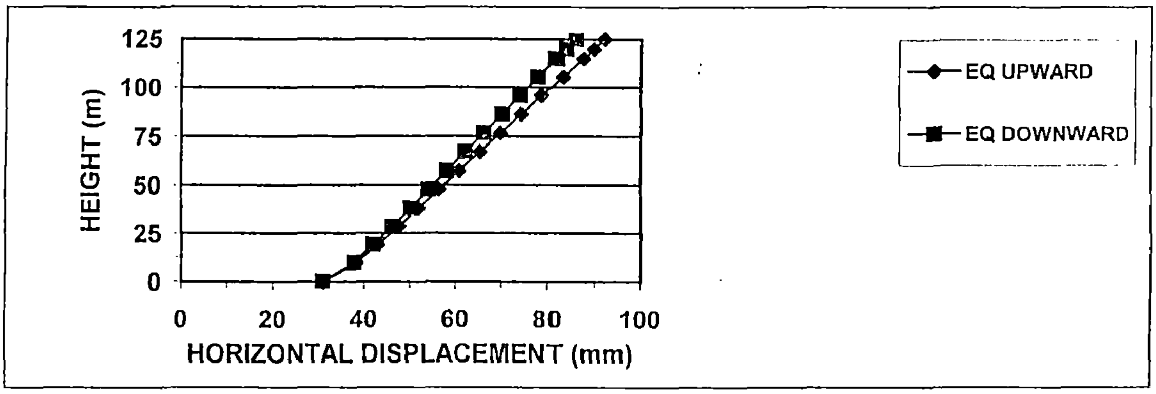


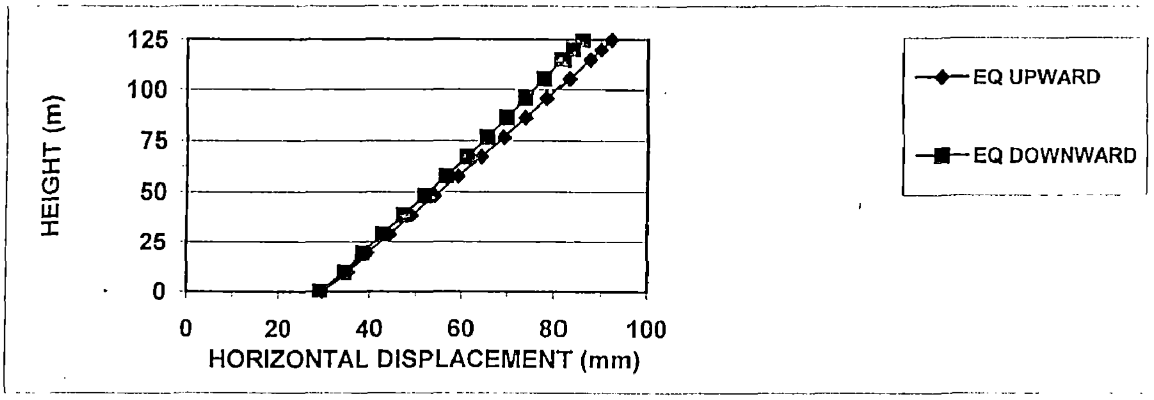
Fig 3.1 FEM MESH GENERATION FOR 125M DAM HEIGHT (CASE 1)



a. ALONG THE DAM BASE.

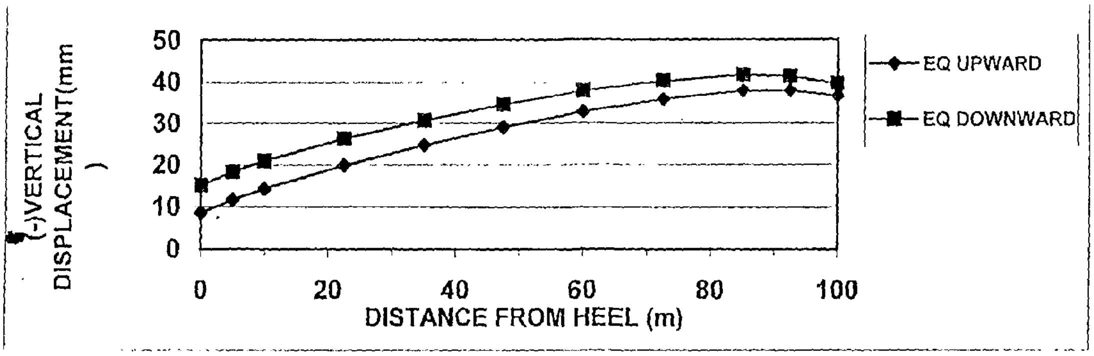


b. ALONG THE U/S FACE.

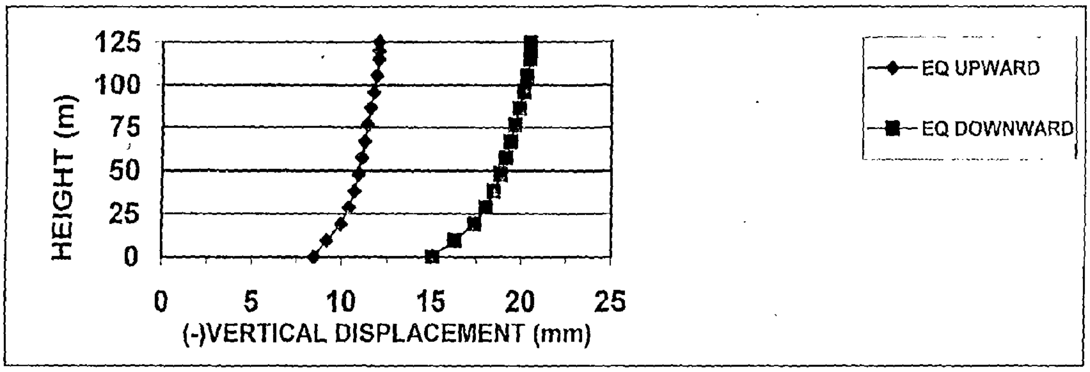


c. ALONG THE D/S FACE.

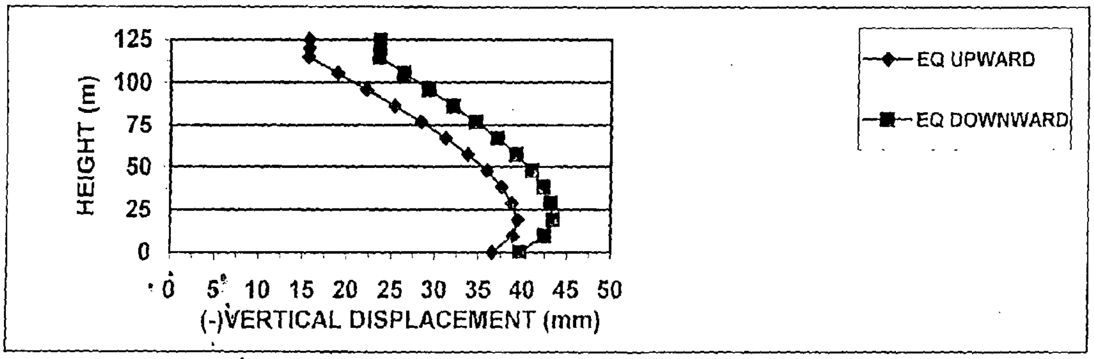
FIG 3.2 HORIZONTAL DISPLACEMENTS ALONG DIFFERENT LOCATIONS IN DAM FOR EF/ED=0.2(HEIGHT=125M).



a. ALONG THE DAM BASE.

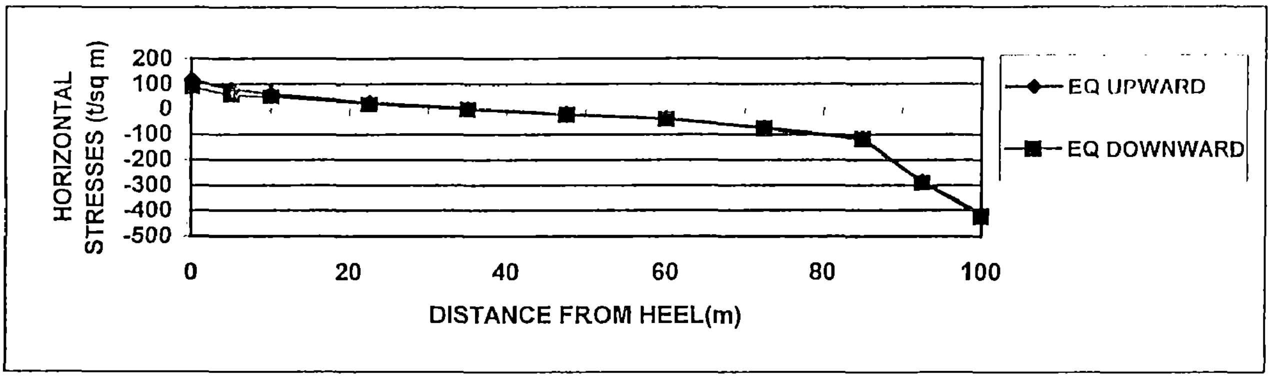


b. ALONG THE U/S FACE.

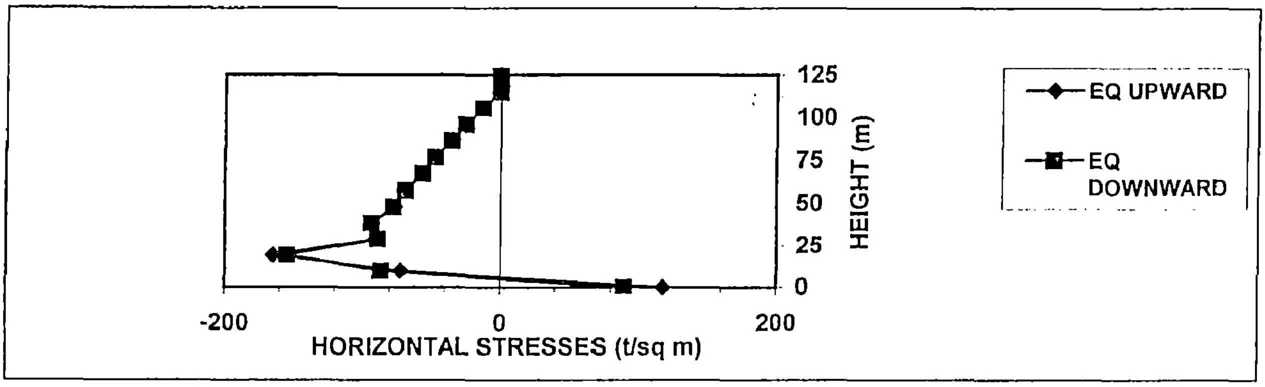


c. ALONG THE D/S FACE.

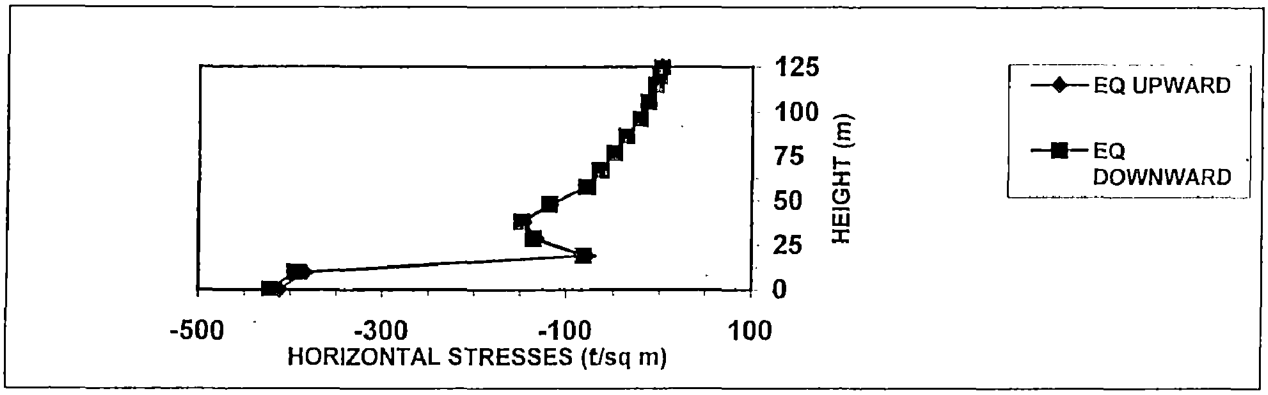
FIG 3.3 VERTICAL DISPLACEMENTS ALONG DIFFERENT LOCATIONS IN DAM FOR EF/ED=0.2(HEIGHT=125M).



a. ALONG THE DAM BASE.

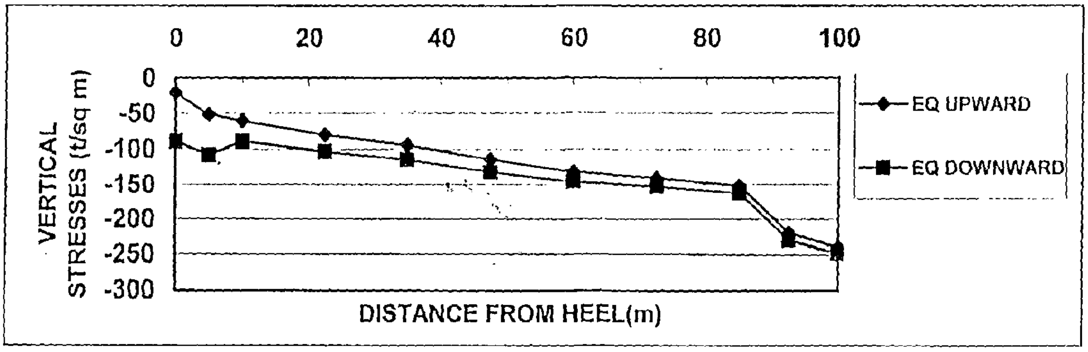


b. ALONG THE U/S FACE.

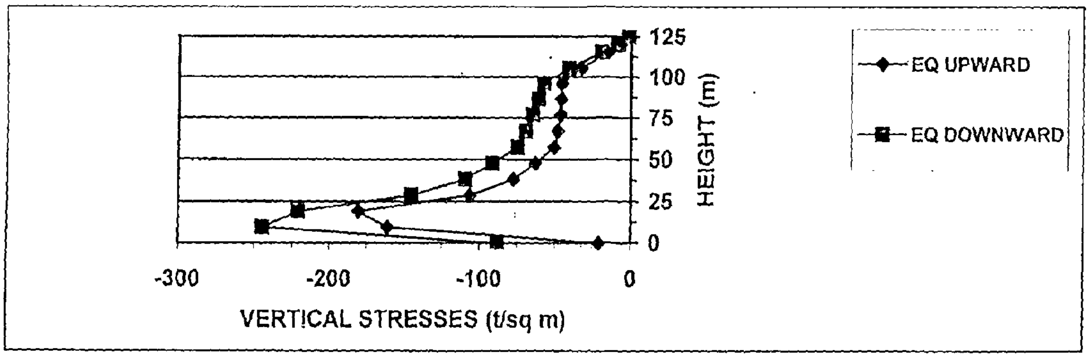


c. ALONG THE D/S FACE.

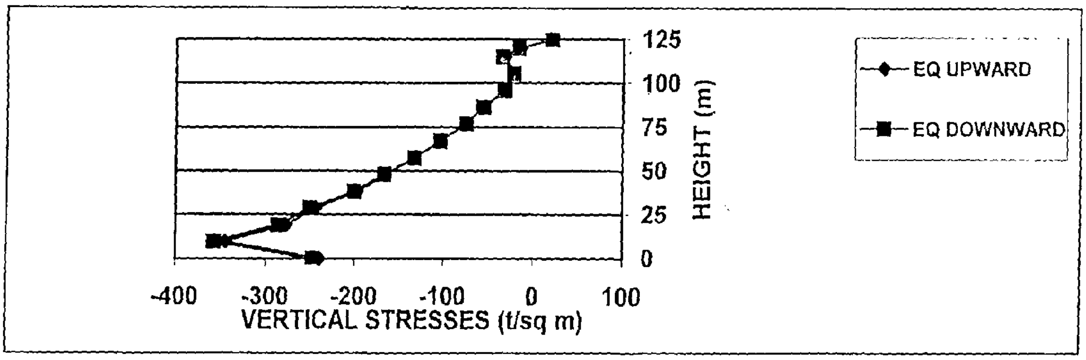
FIG 3.4 HORIZONTAL STRESSES ALONG DIFFERENT LOCATIONS IN DAM FOR EF/ED=0.2(HEIGHT=125M).



a. ALONG THE DAM BASE.

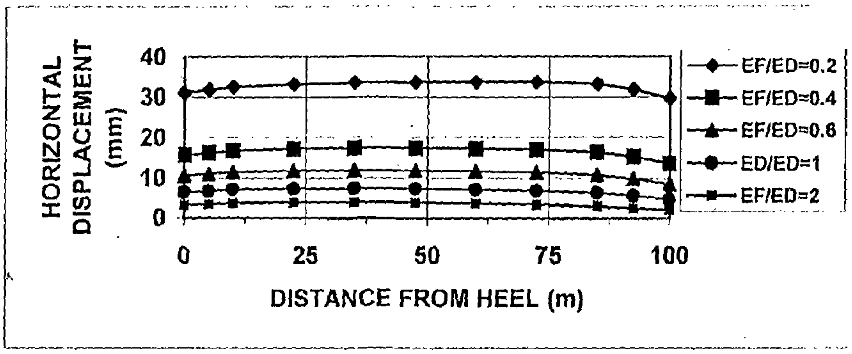


b. ALONG THE U/S FACE.

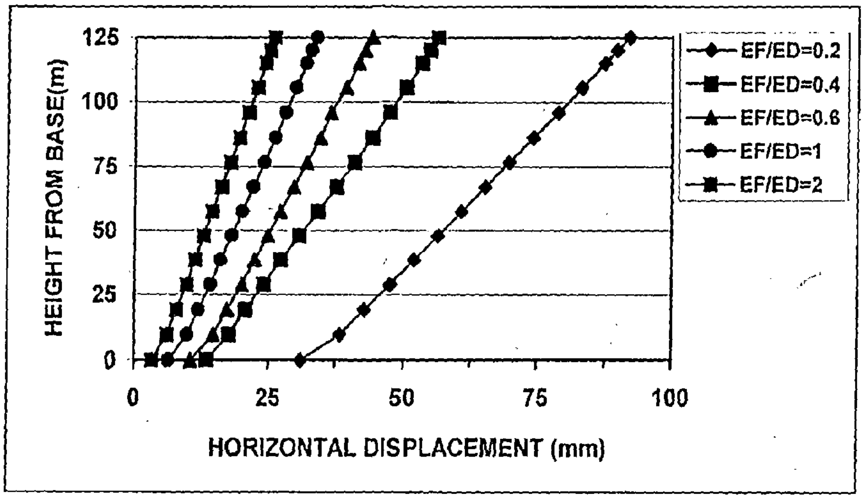


c. ALONG THE D/S FACE.

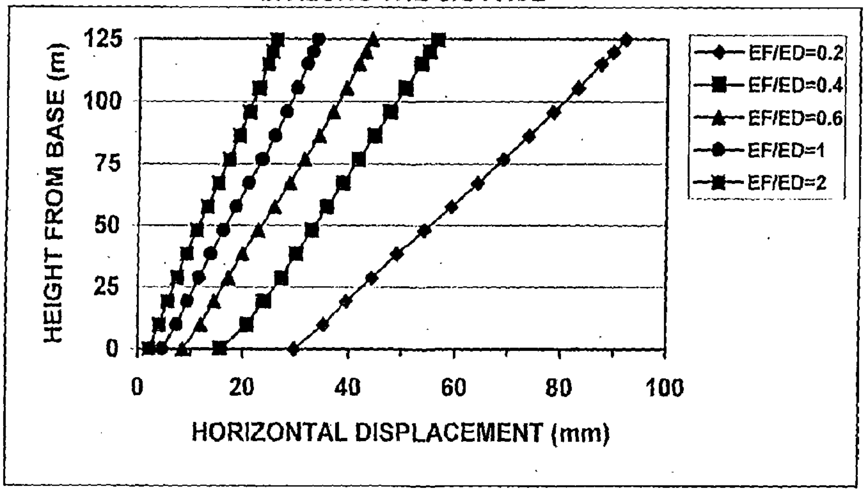
FIG 3.5 VERTICAL STRESSES ALONG DIFFERENT LOCATIONS IN DAM FOR EF/ED=0.2(HEIGHT=125M).



a. ALONG THE DAM BASE

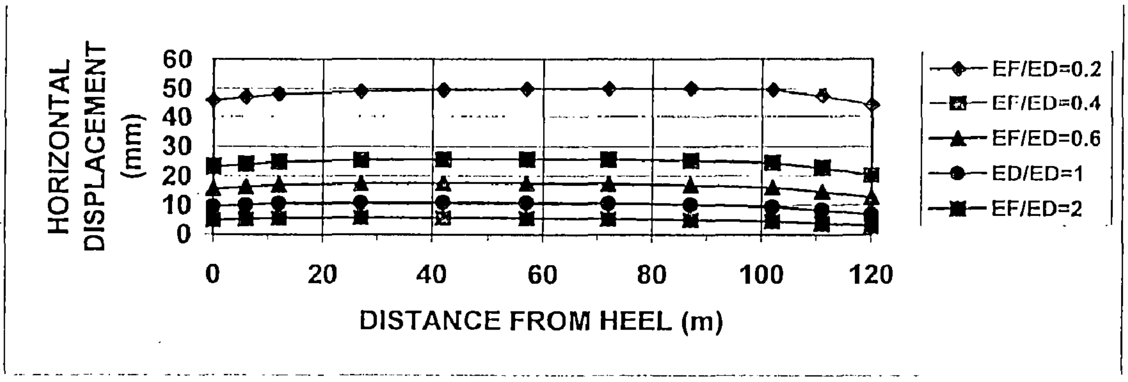


b. ALONG THE U/S FACE

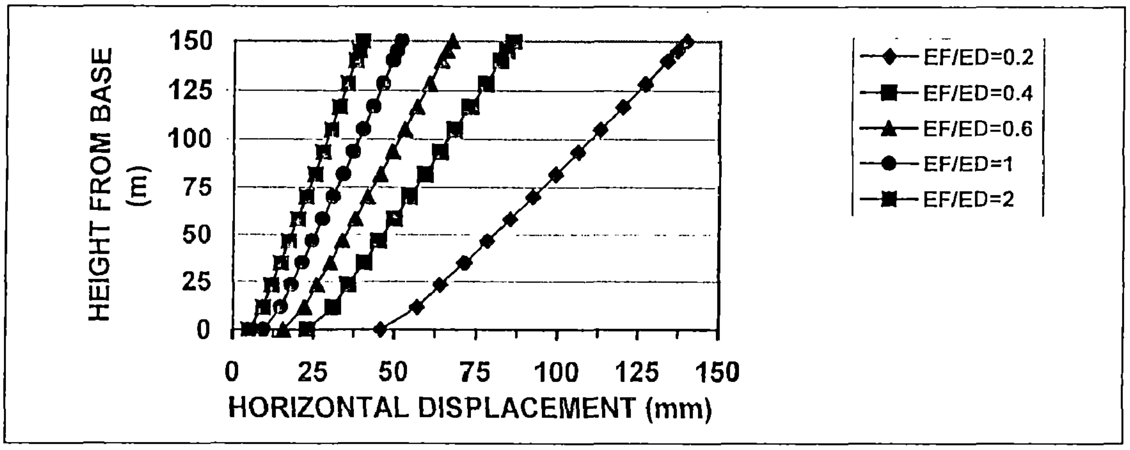


c. ALONG THE D/S FACE

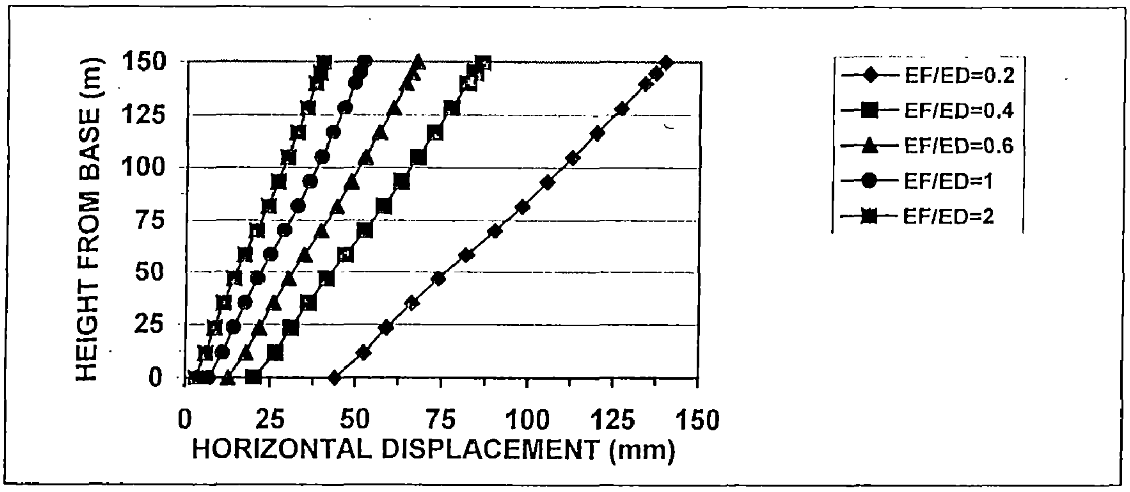
FIG 3.6 HORIZONTAL DISPLACEMENTS ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=125M)



a. ALONG THE DAM BASE

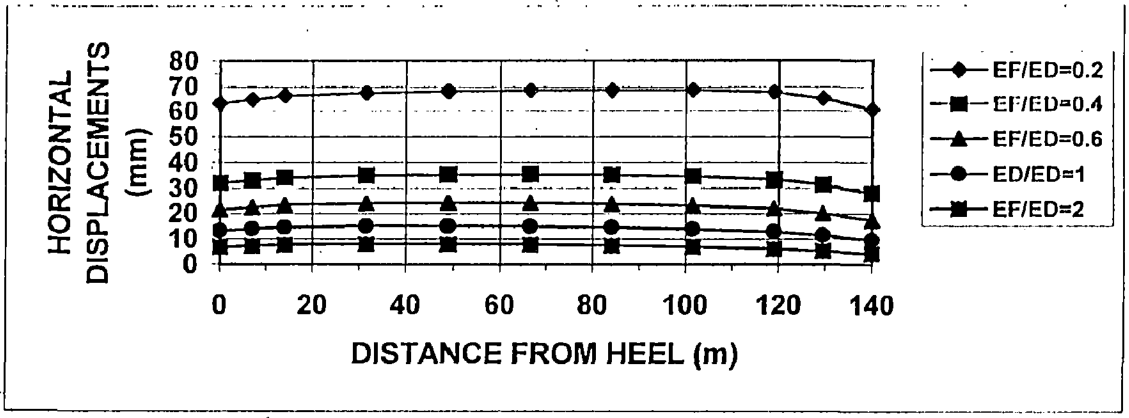


b. ALONG THE U/S FACE

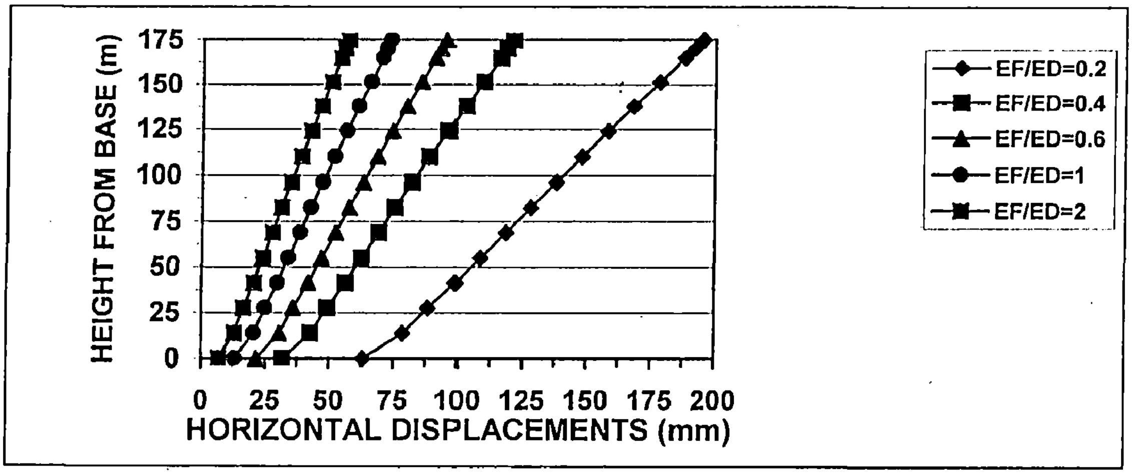


c. ALONG THE D/S FACE

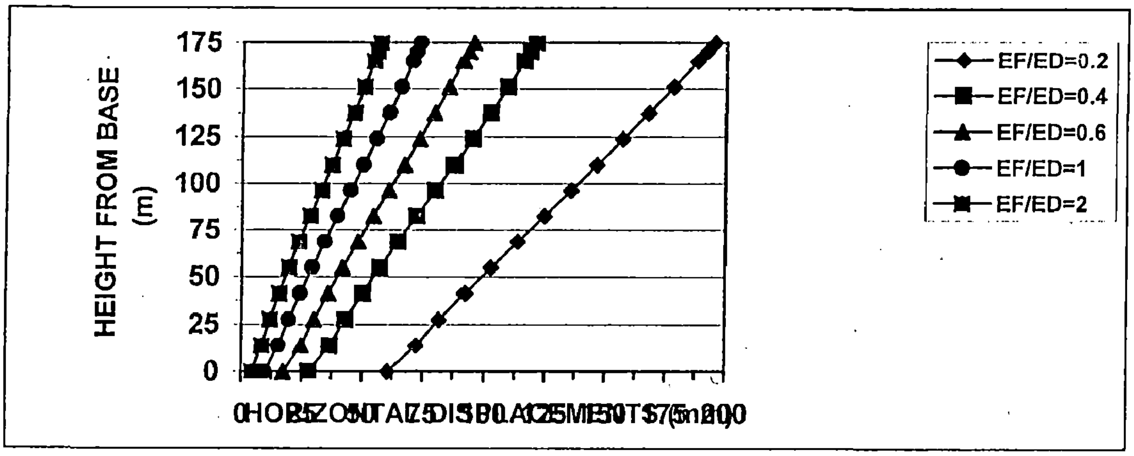
FIG 3.7 HORIZONTAL DISPLACEMENTS ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=150M).



a. ALONG THE DAM BASE

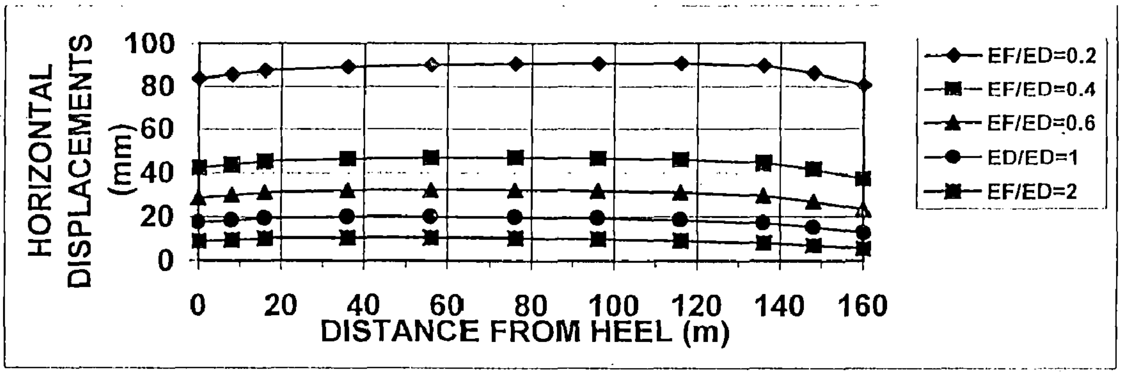


b. ALONG THE U/S FACE

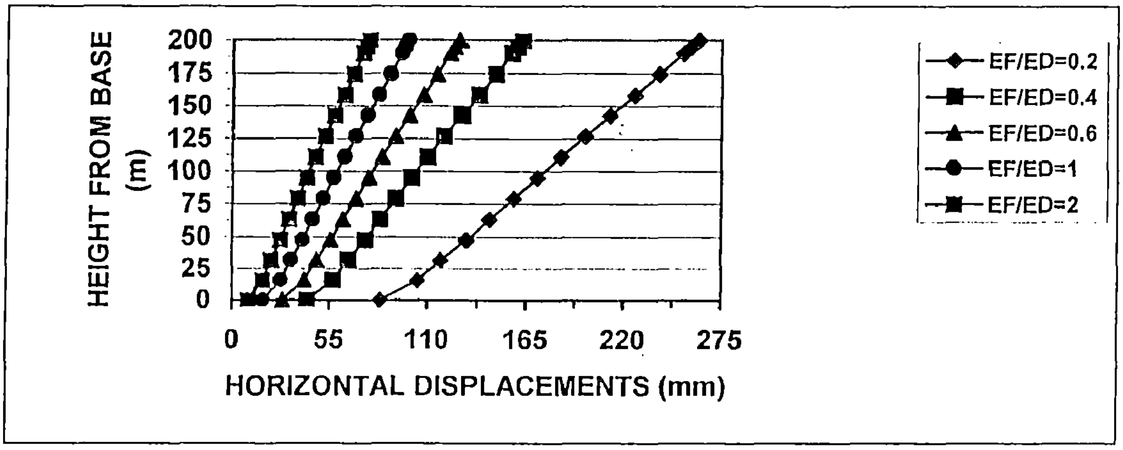


c. ALONG THE D/S FACE

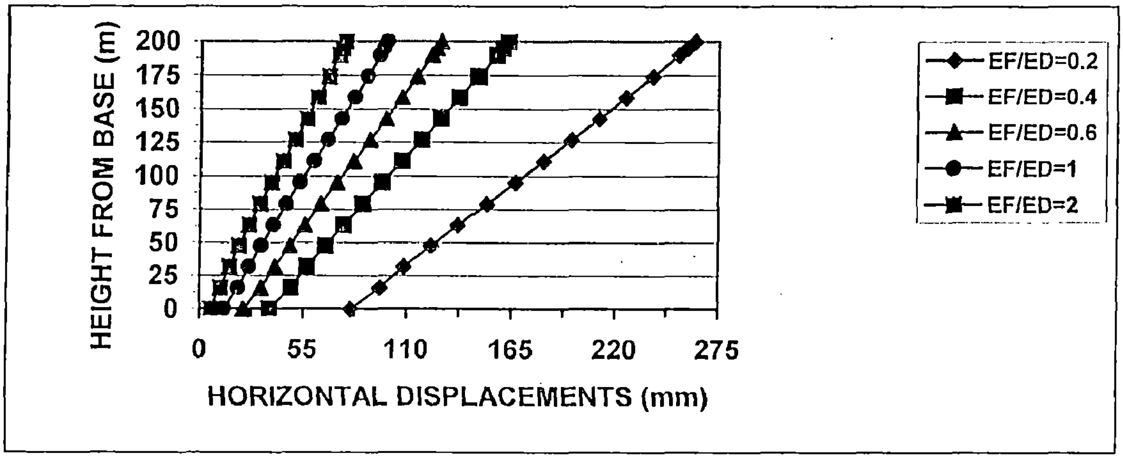
FIG 3.8 HORIZONTAL DISPLACEMENTS ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=175M).



a. ALONG THE DAM BASE

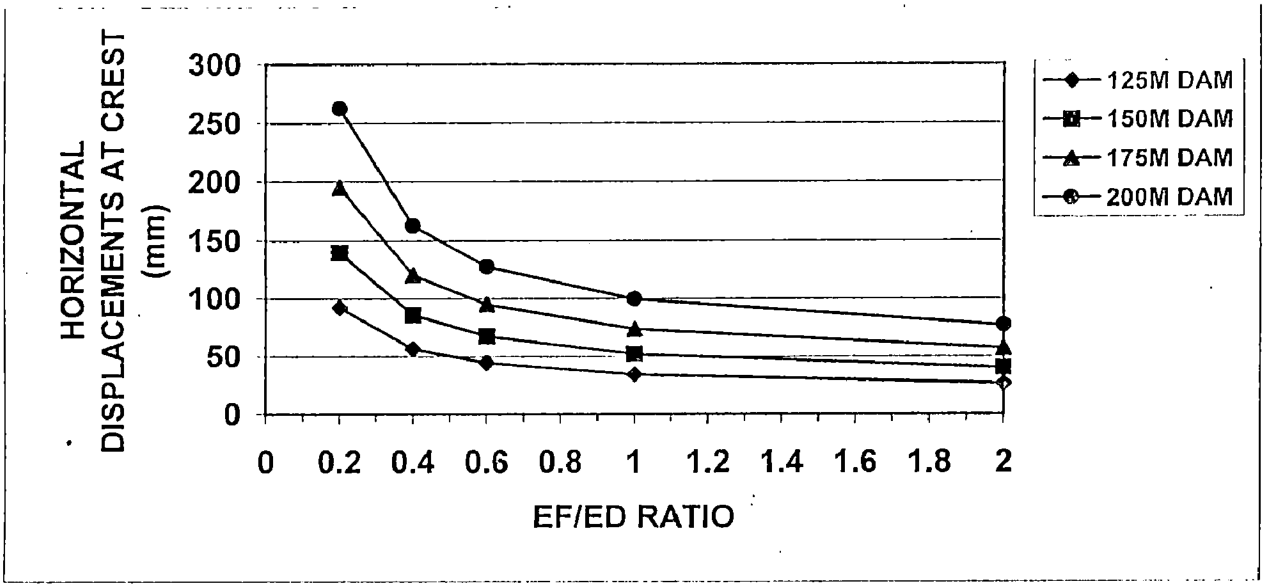


b. ALONG THE U/S FACE

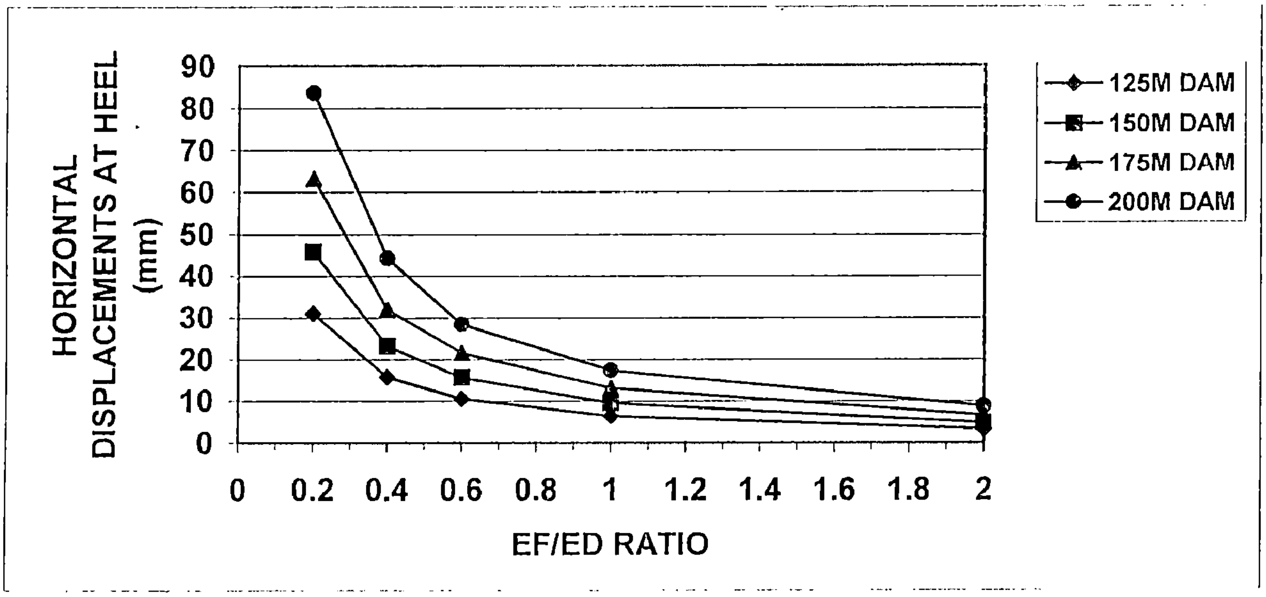


c. ALONG THE D/S FACE

FIG 3.9 HORIZONTAL DISPLACEMENTS ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=200M).

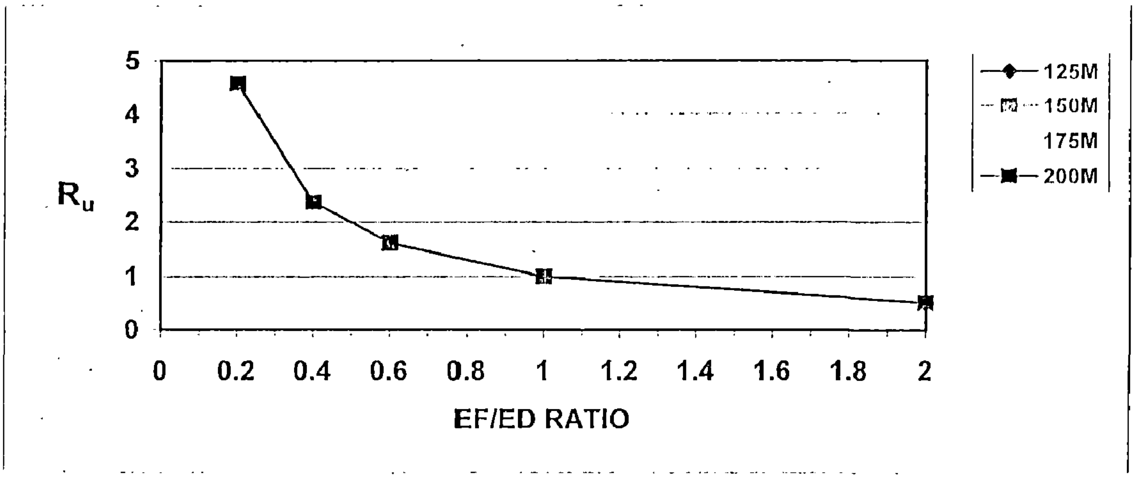


a. AT CREST LEVEL

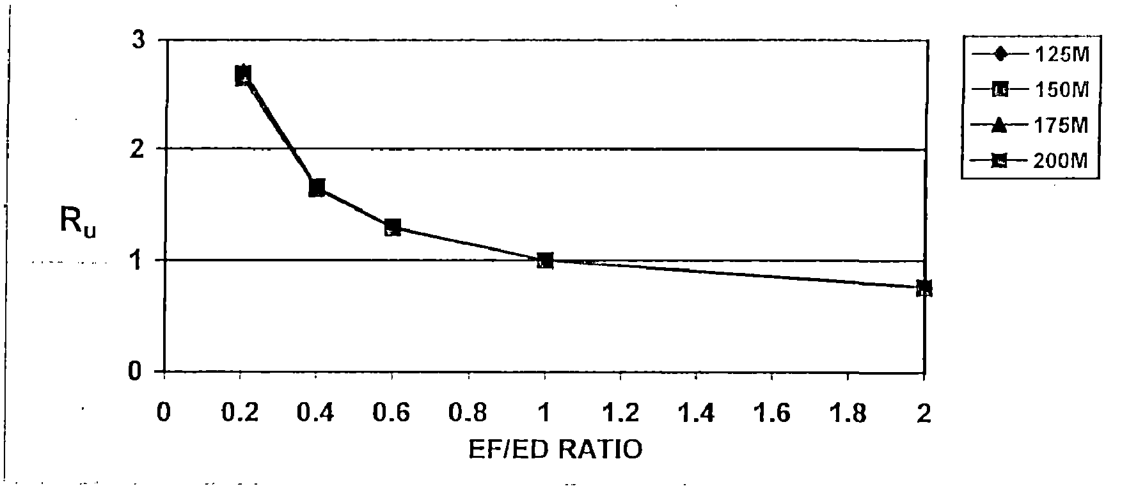


b. AT HEEL

FIG 3.10 VARIATION OF HORIZONTAL DISPLACEMENT WITH EF/ED RATIO FOR DIFFERENT DAM HEIGHTS.



a. ALONG THE DAM BASE



b. ALONG THE U/S FACE

FIG 3.11 VARIATION OF R_u WITH EF/ED RATIO ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT DAM HEIGHTS.

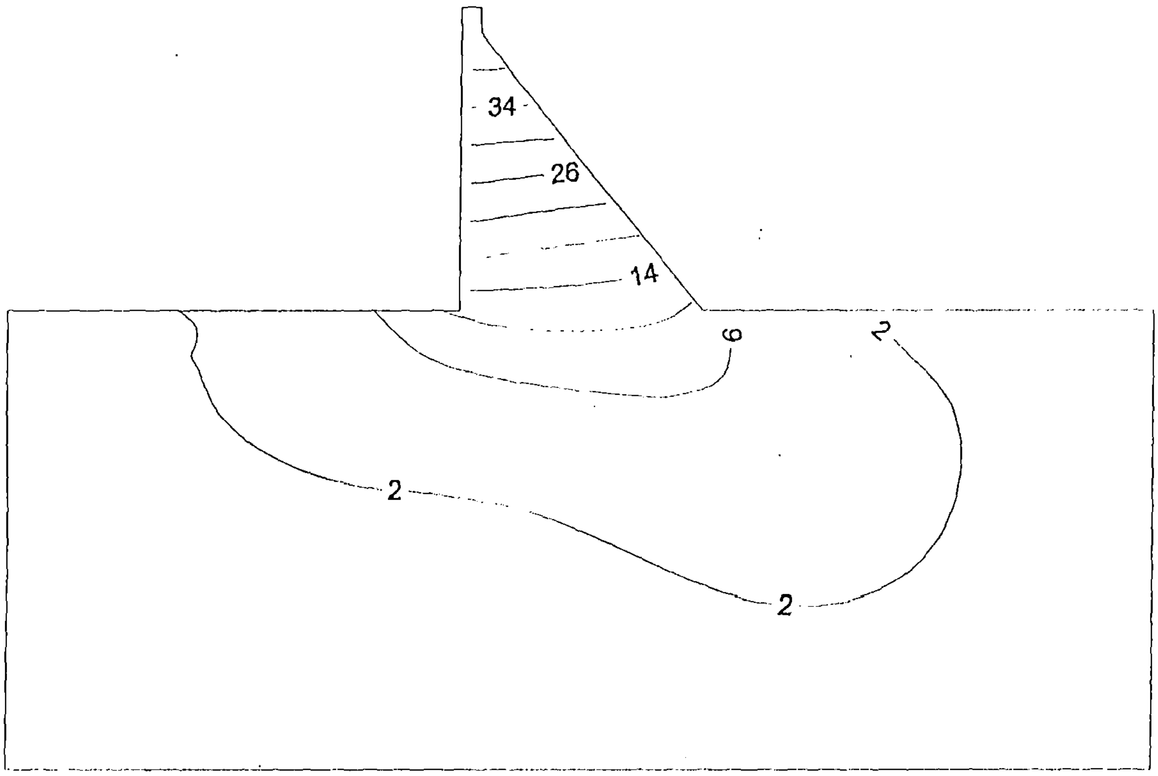
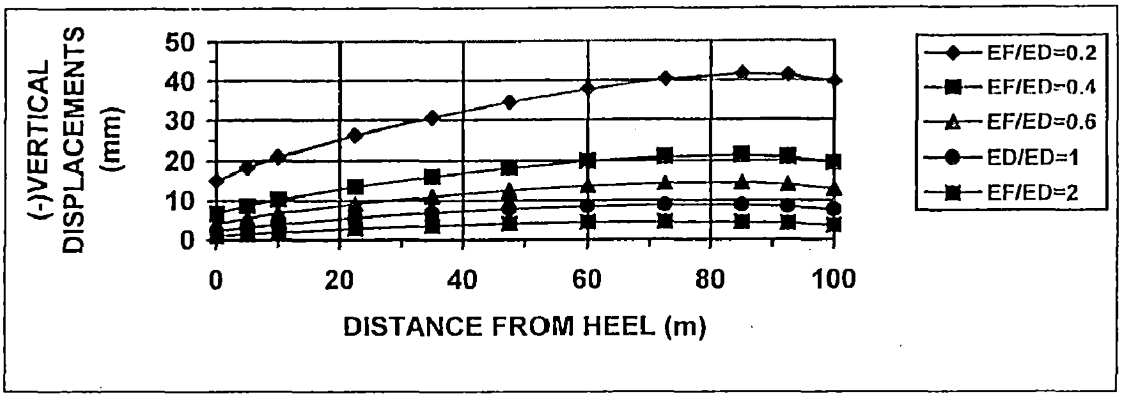
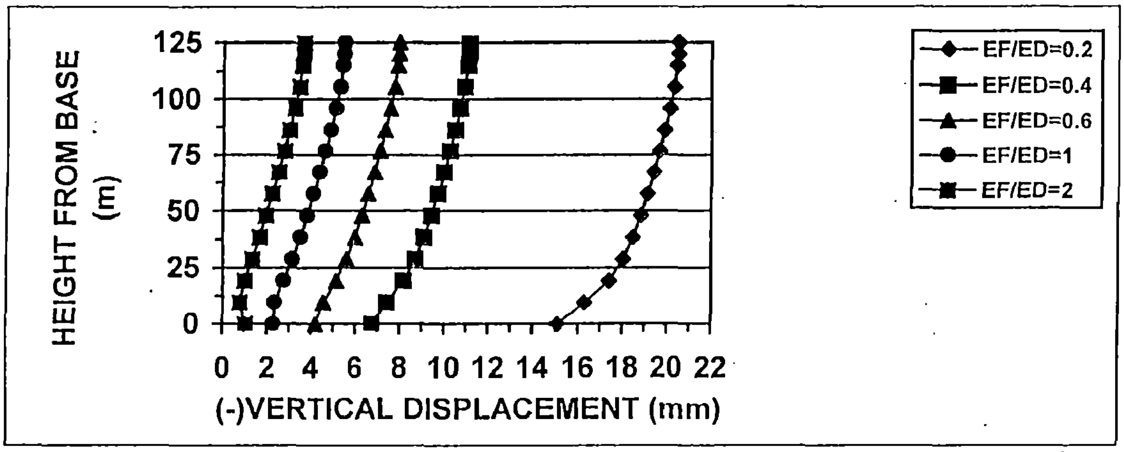


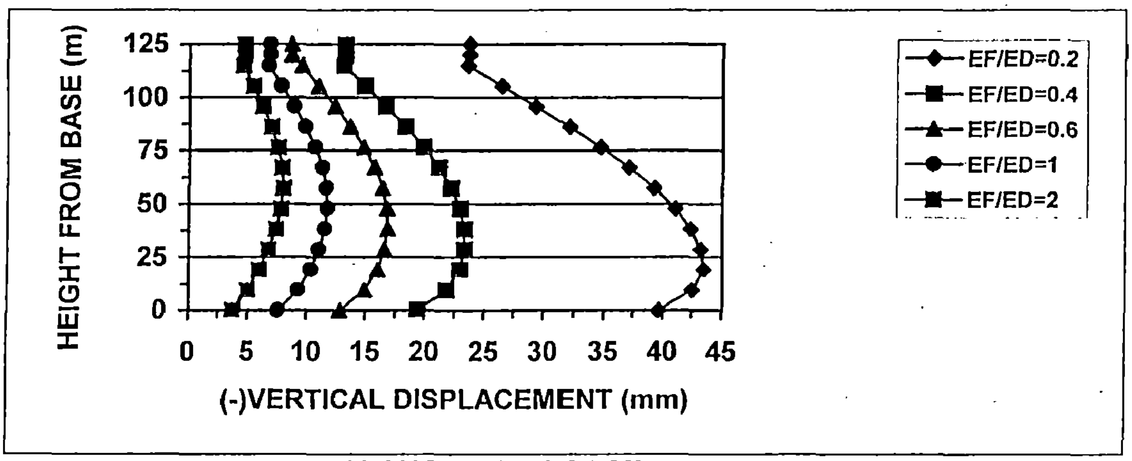
FIG 3.12 HORIZONTAL DISPLACEMENT(mm) CONTOURS OF 125M(CASE 1) FOR EF/ED=0.6



a. ALONG THE DAM BASE

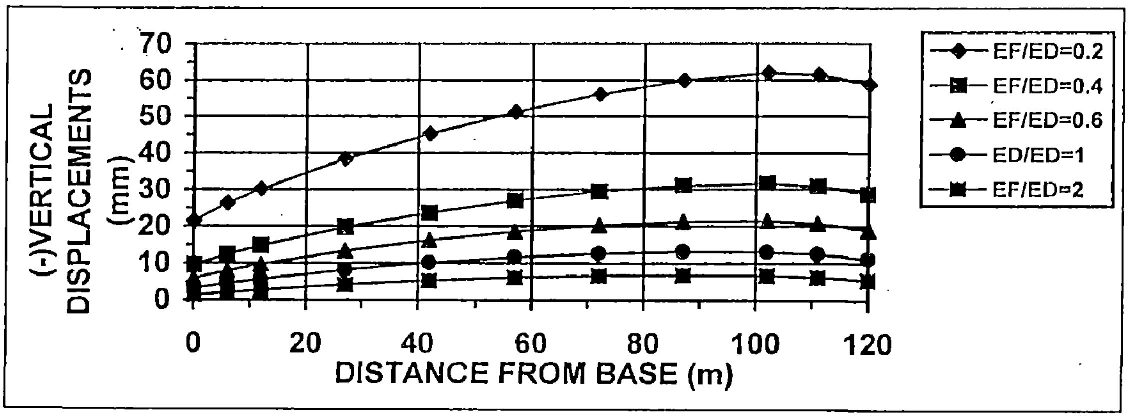


b. ALONG THE U/S FACE

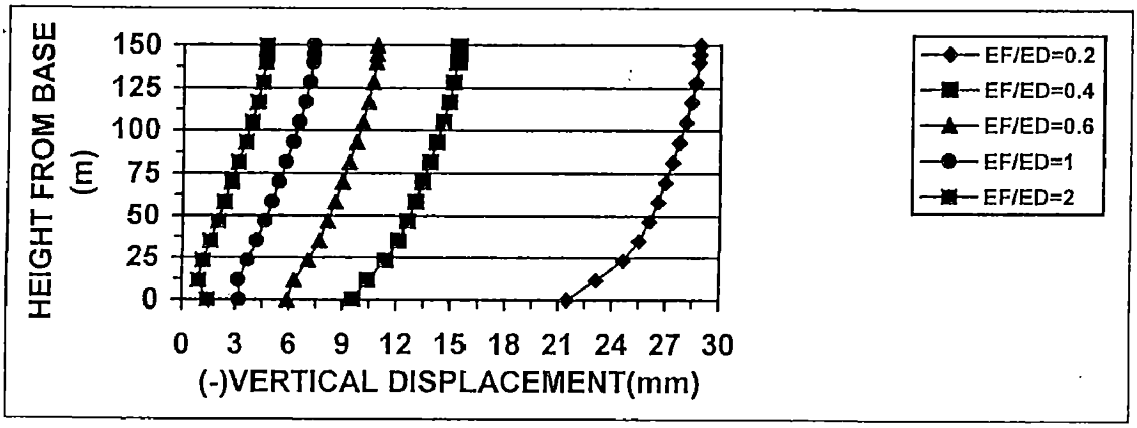


c. ALONG THE D/S FACE

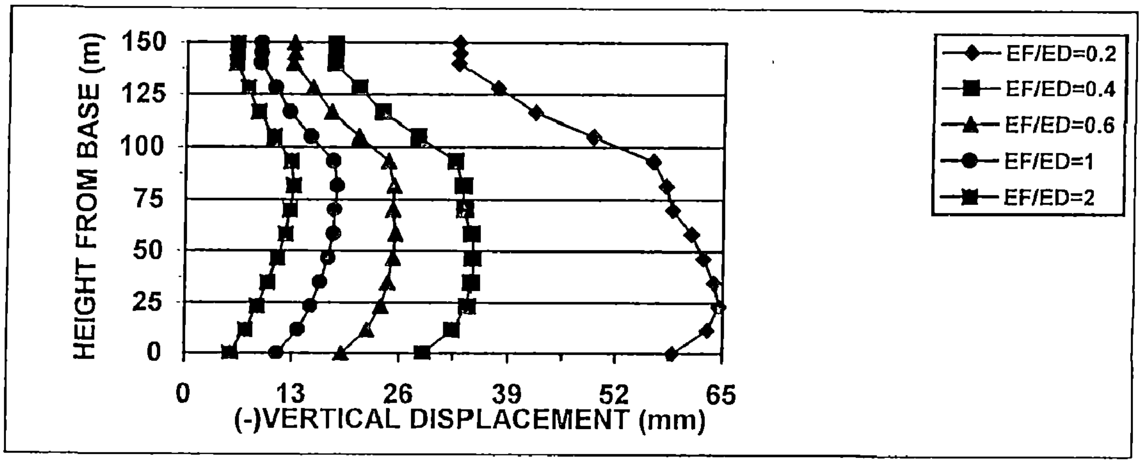
FIG 3.13 VERTICAL DISPLACEMENTS ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=125M).



a. ALONG THE DAM BASE

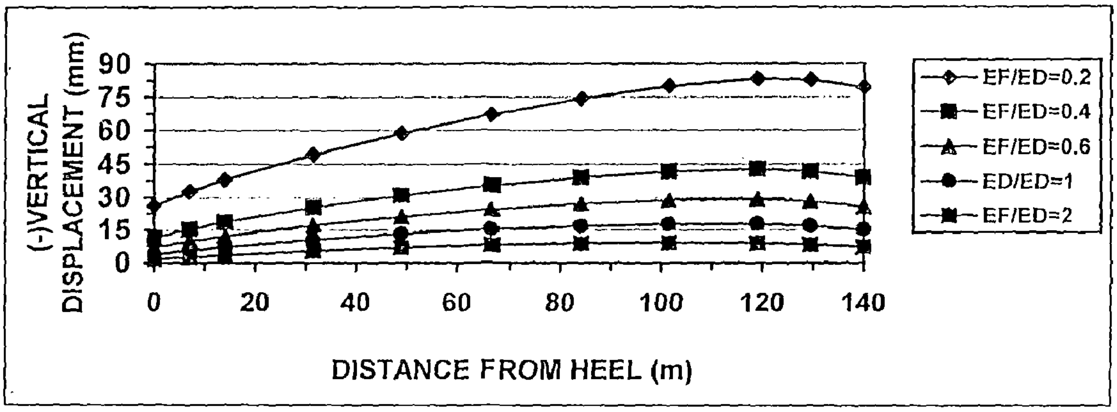


b. ALONG THE U/S FACE

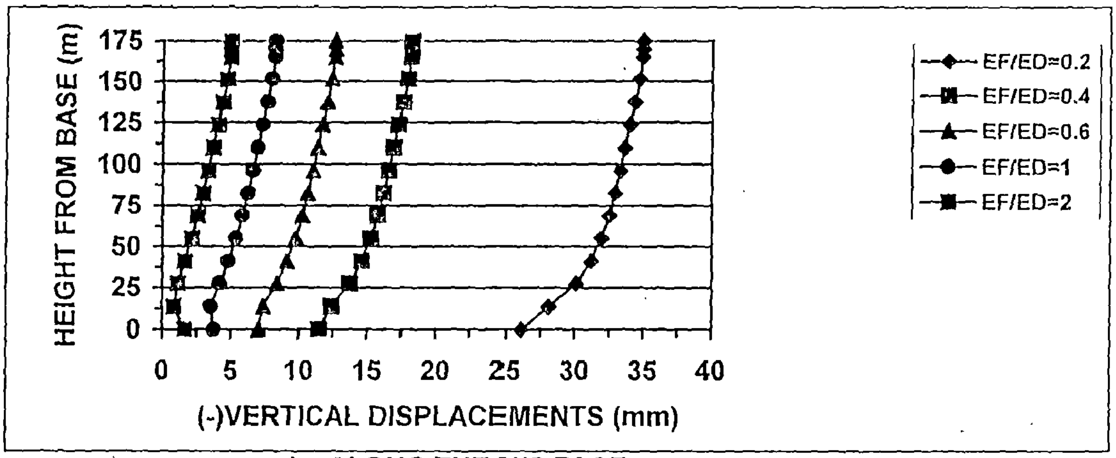


c. ALONG THE D/S FACE

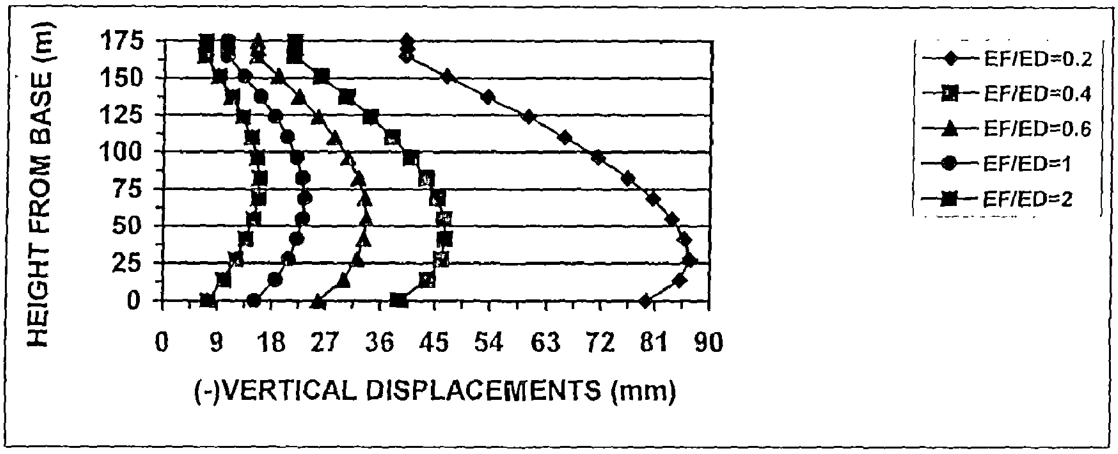
FIG 3.14 VERTICAL DISPLACEMENTS ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIOS (HEIGHT=150M).



a. ALONG THE DAM BASE

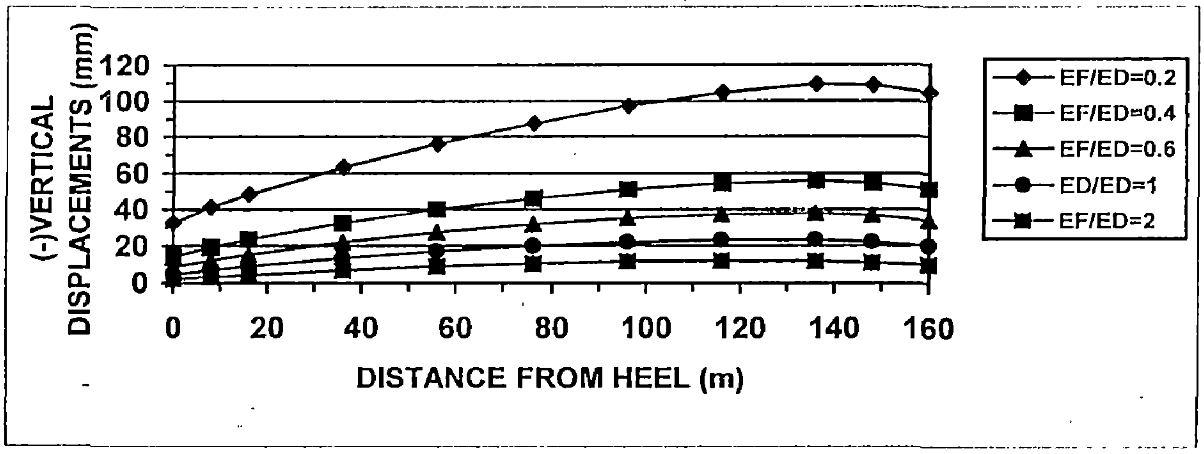


b. ALONG THE U/S FACE

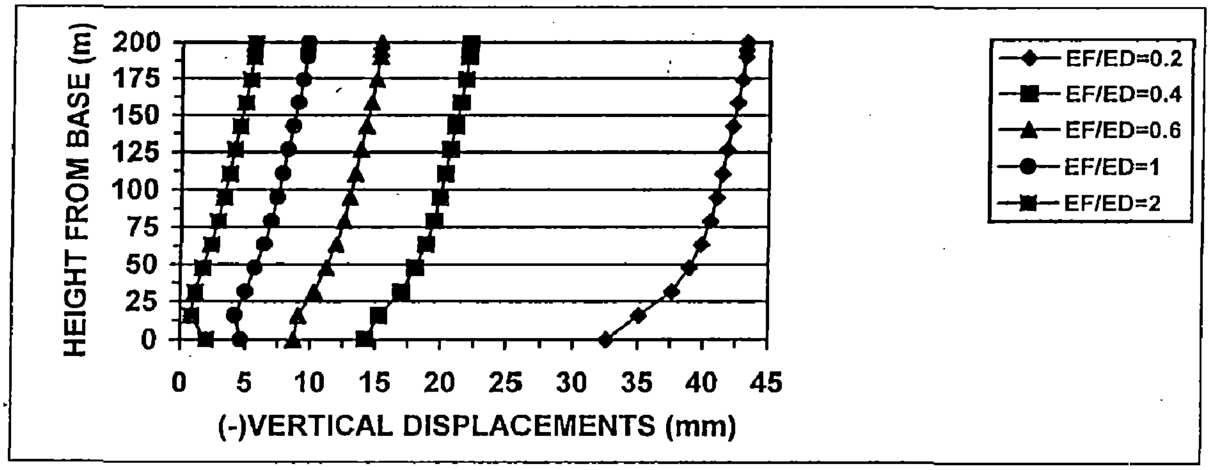


c. ALONG THE D/S FACE

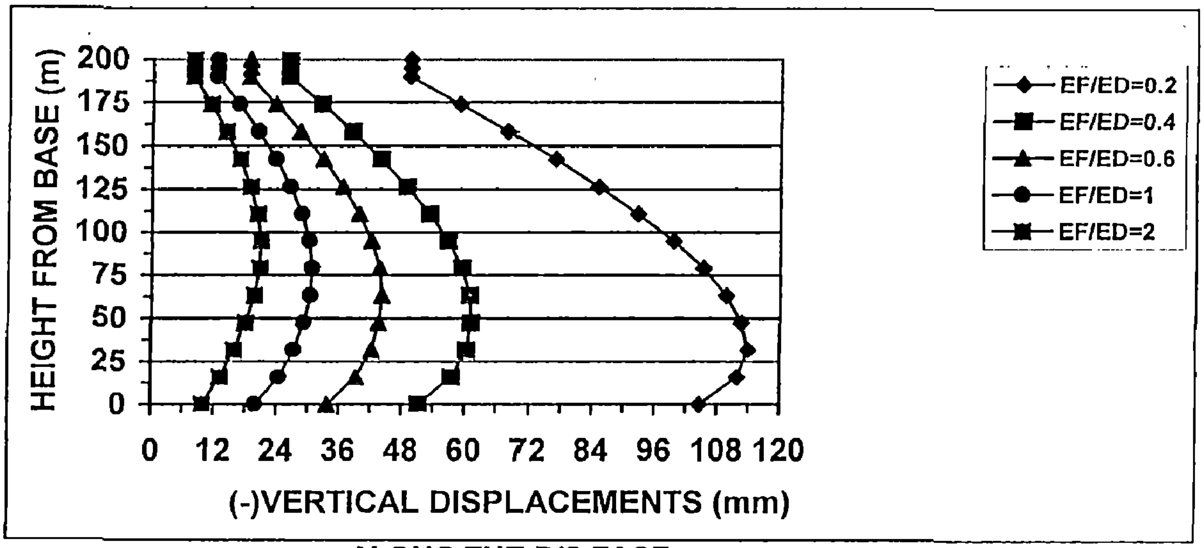
FIG 3.15 VERTICAL DISPLACEMENTS ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=175M).



a. ALONG THE DAM BASE

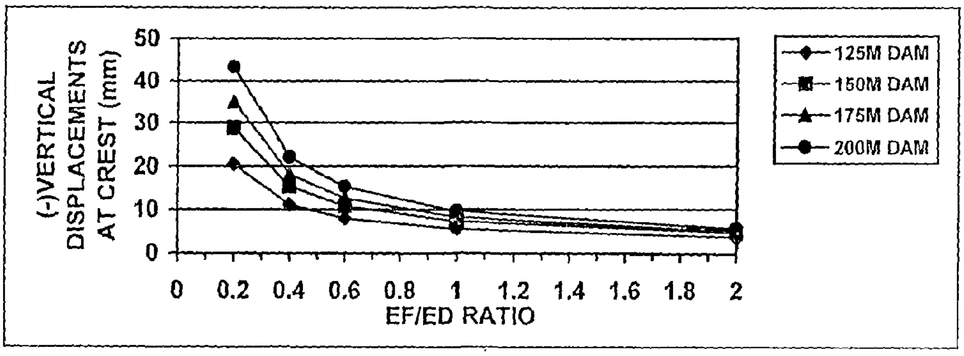


b. ALONG THE U/S FACE

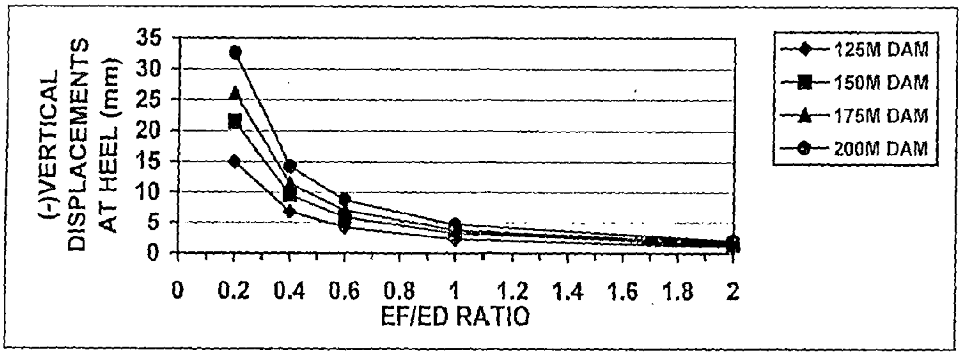


c.- ALONG THE D/S FACE

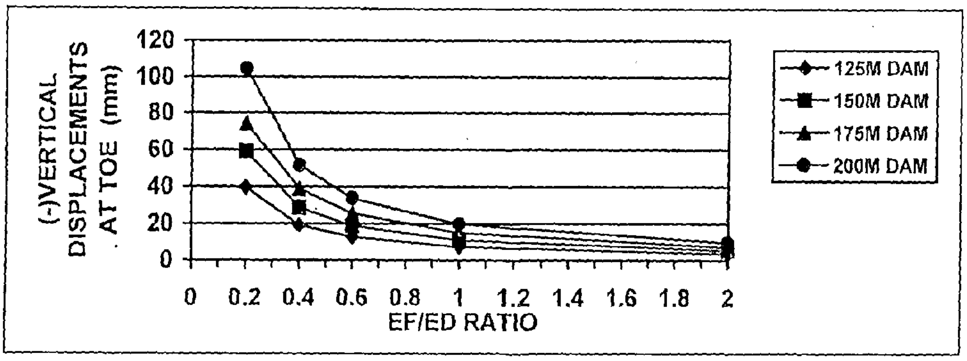
FIG 3.16 VERTICAL DISPLACEMENTS ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=200M).



a. AT CREST LEVEL

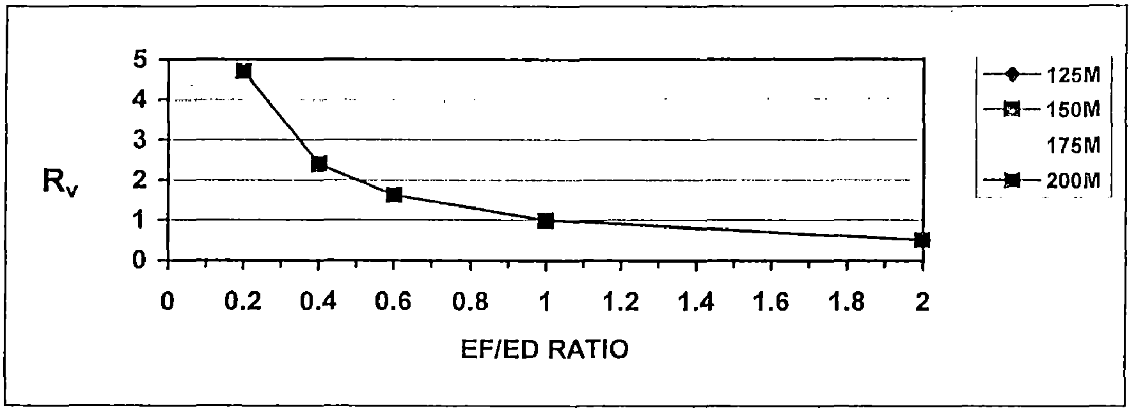


b. AT HEEL

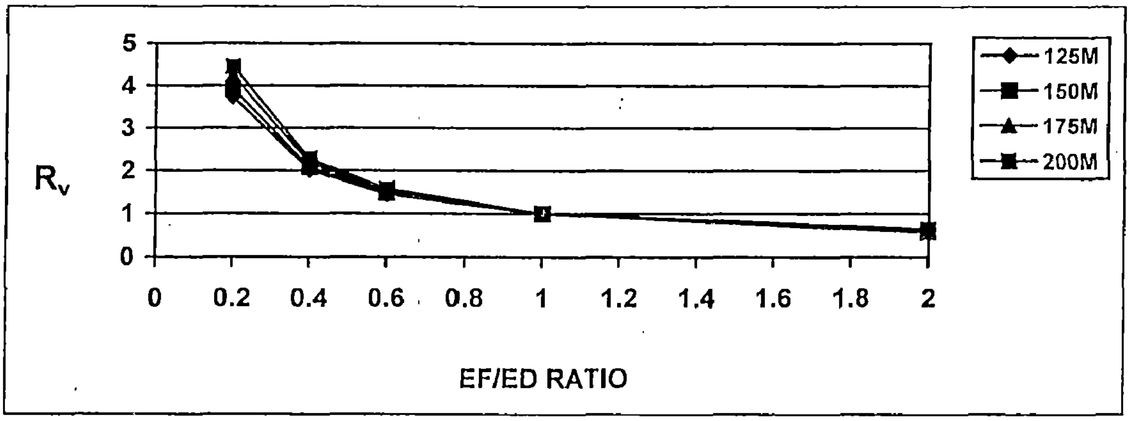


c. AT TOE

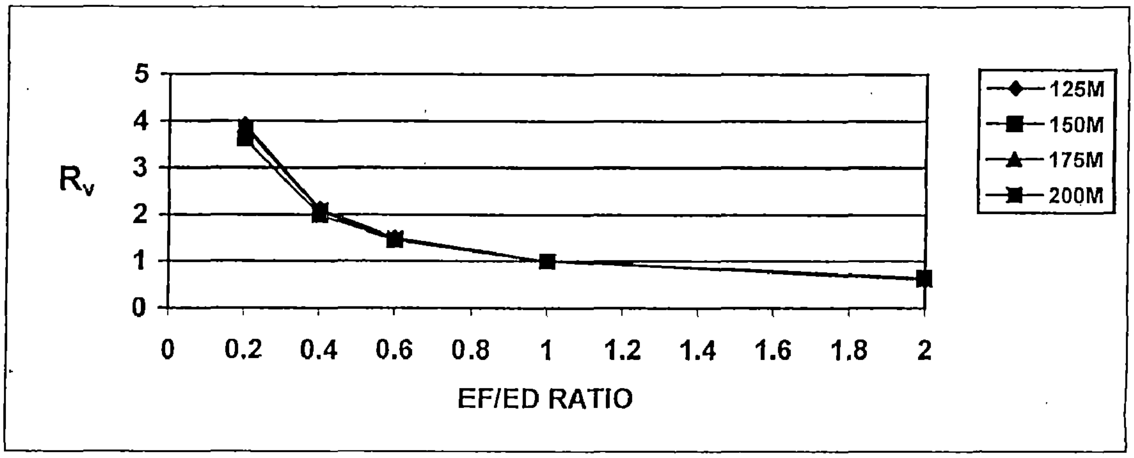
FIG 3.17 VARIATION OF VERTICAL DISPLACEMENT WITH EF/ED RATIOFOR DIFFER DAM HEIGHTS.



a. ALONG THE DAM BASE.

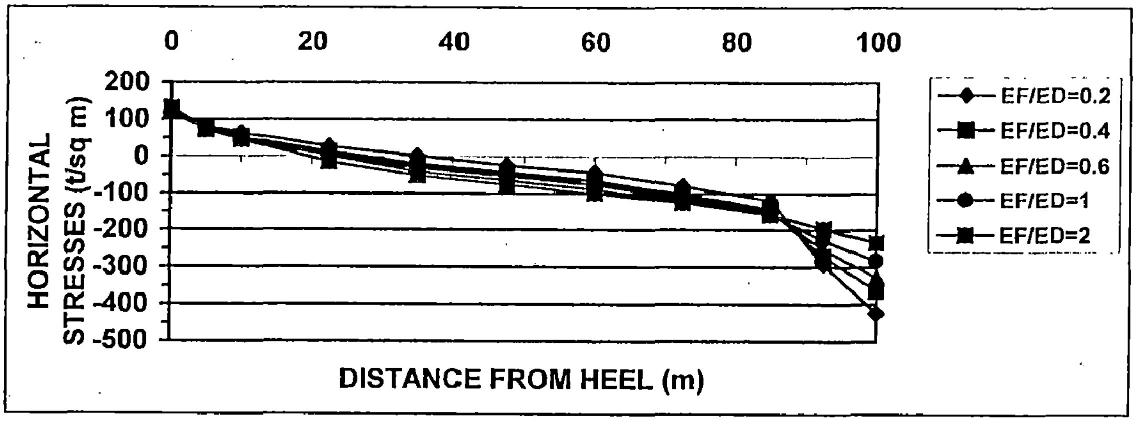


b. ALONG THE U/S FACE.

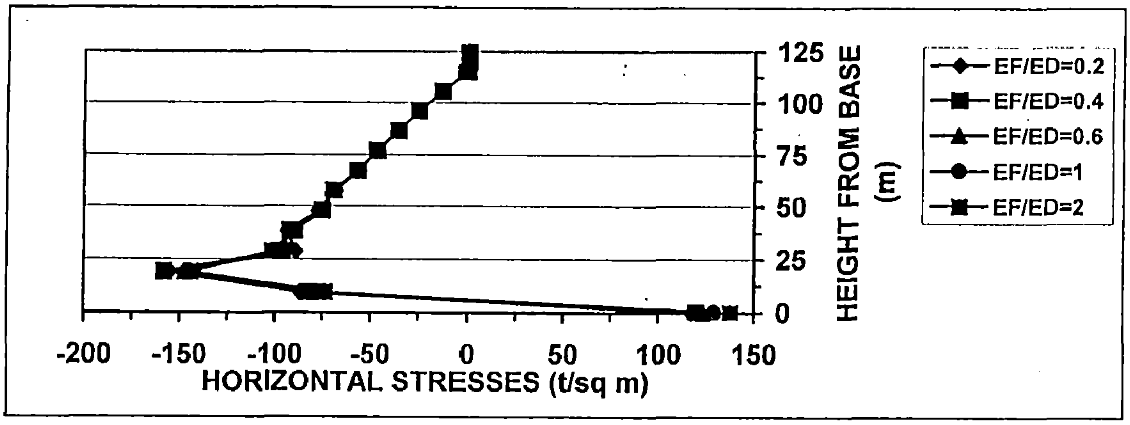


c. ALONG THE D/S FACE.

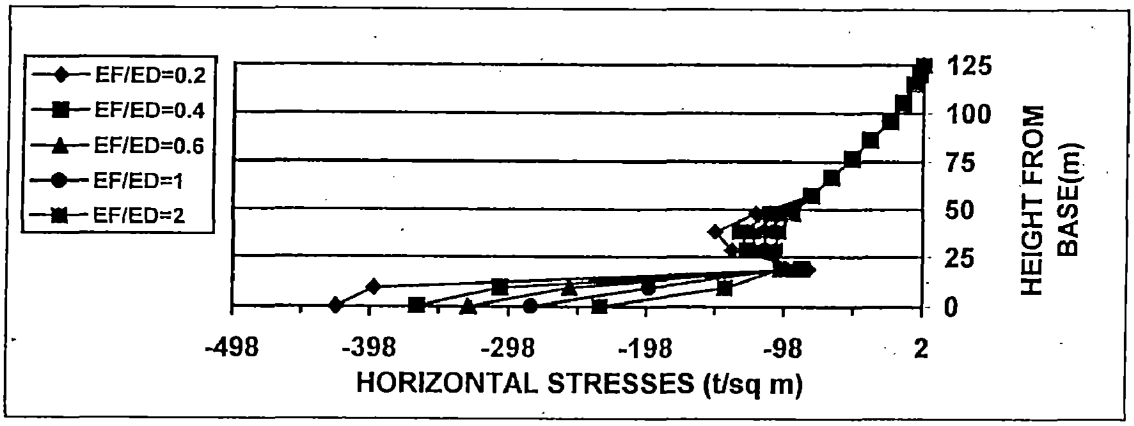
FIG 3.18 VARIATION OF R_v WITH EF/ED RATIO ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT DAM HEIGHTS.



a. ALONG THE DAM BASE

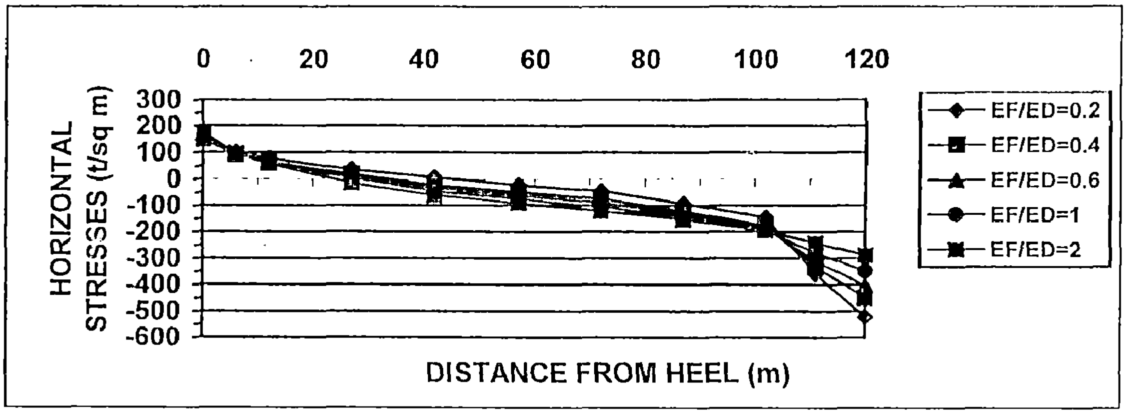


b. ALONG THE U/S FACE

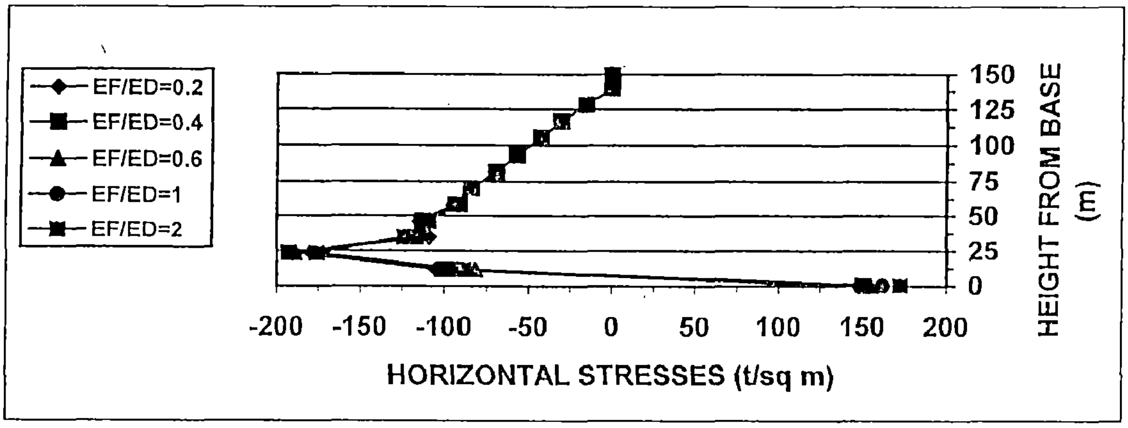


c. ALONG THE D/S FACE

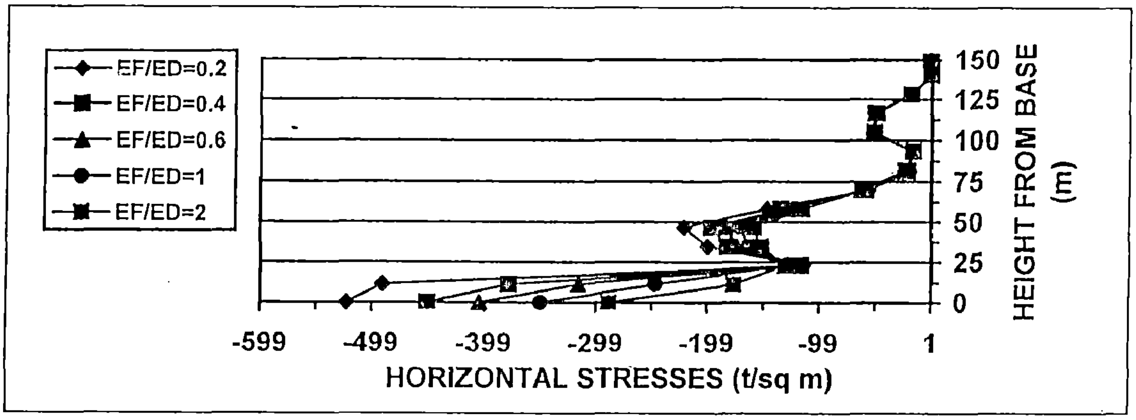
FIG 3.20 HORIZONTAL STRESSES ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=125M).



a. ALONG THE DAM BASE

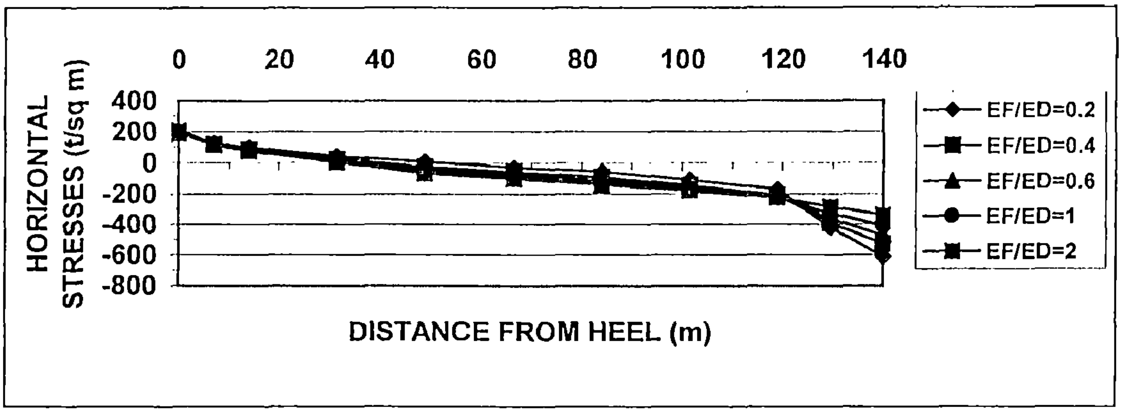


b. ALONG THE U/S FACE

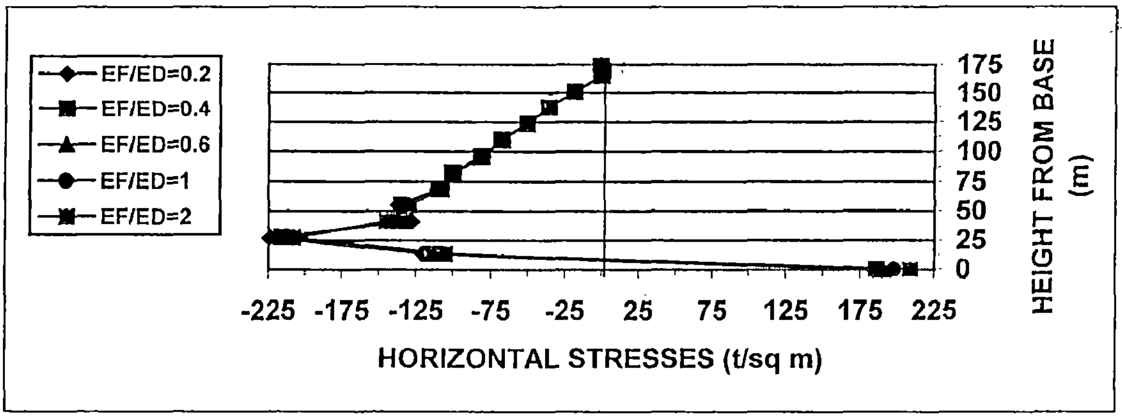


c. ALONG THE D/S FACE

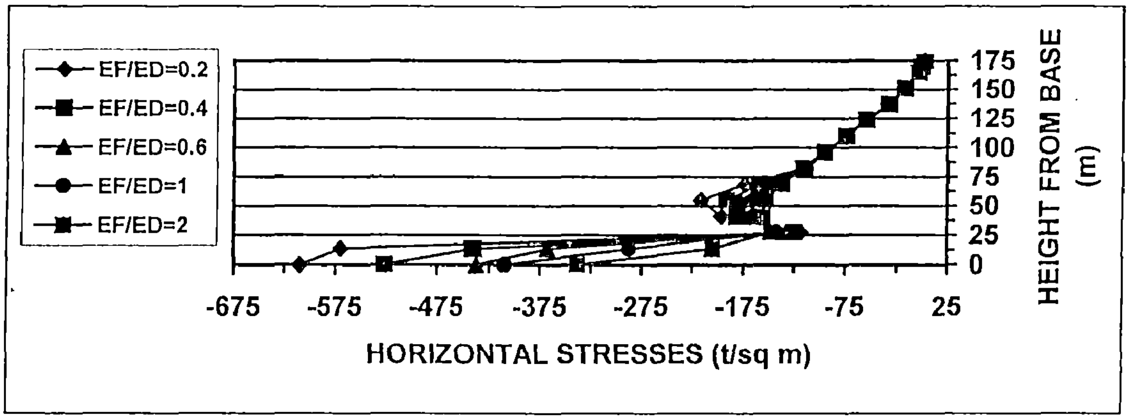
FIG 3.21 HORIZONTAL STRESSES ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=150M).



a. ALONG THE DAM BASE

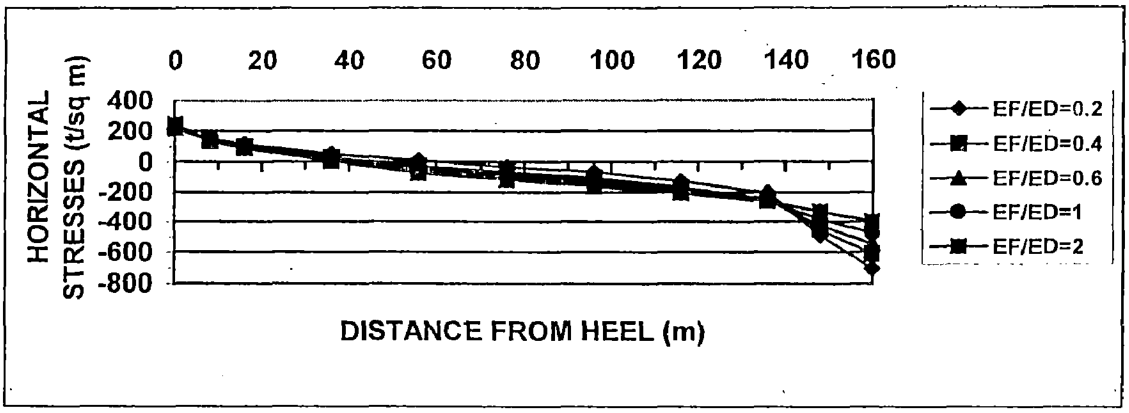


b. ALONG THE U/S FACE

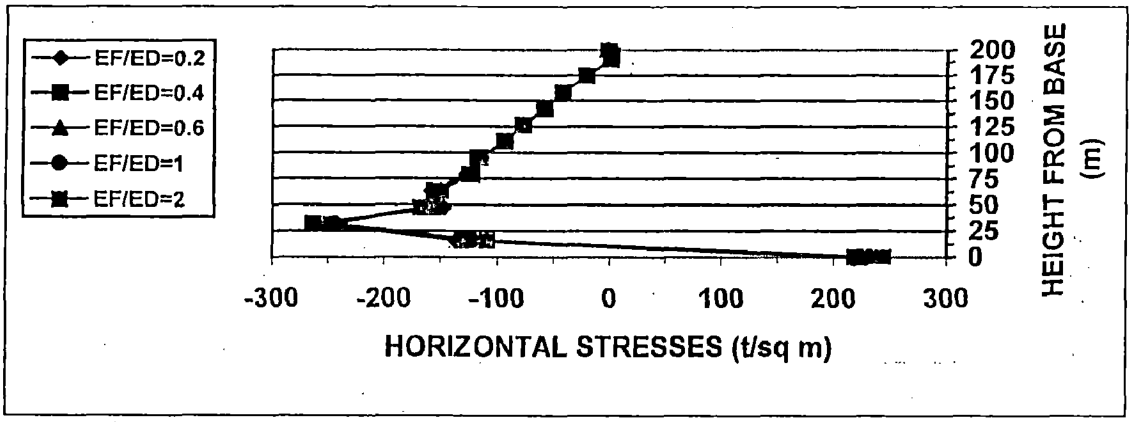


c. ALONG THE D/S FACE

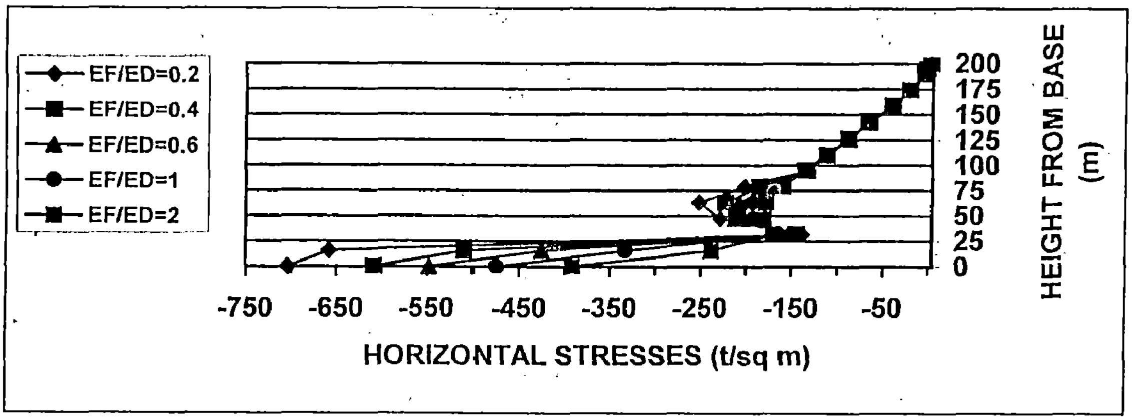
FIG 3.22 HORIZONTAL STRESSES ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=175M)



a. ALONG THE DAM BASE

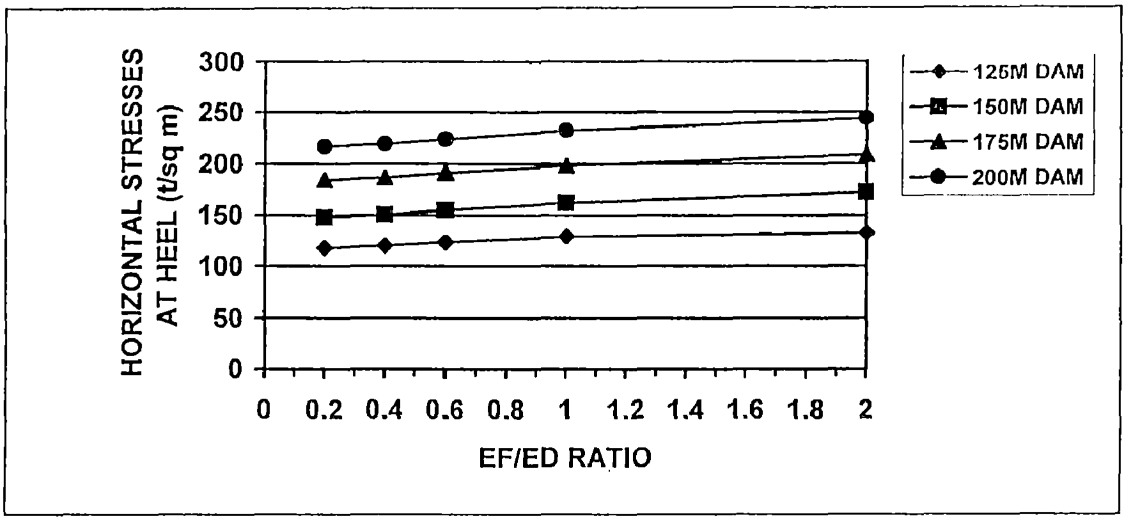


b. ALONG THE U/S FACE

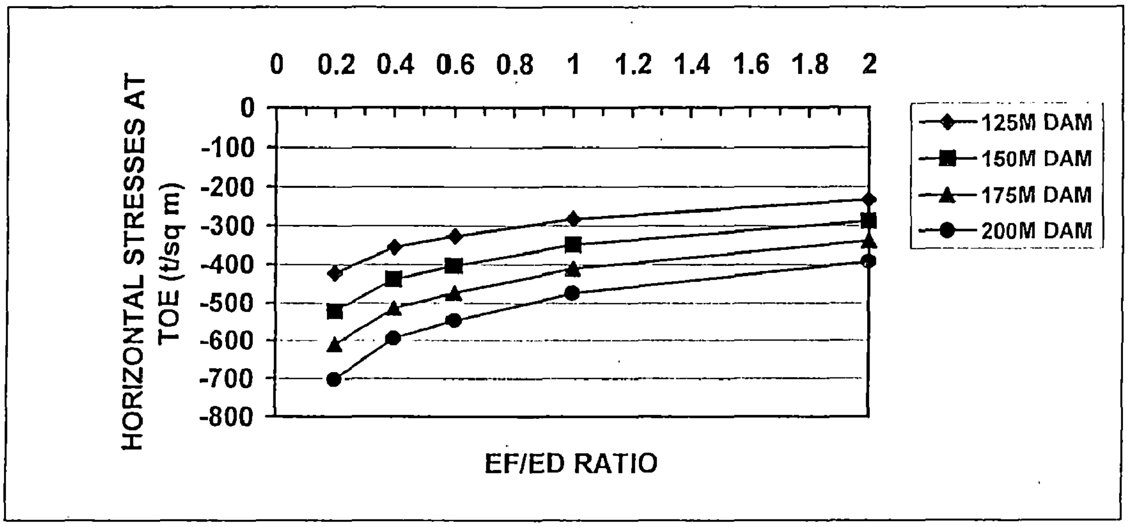


c. ALONG THE D/S FACE

FIG 3.23 HORIZONTAL STRESSES ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=200M).

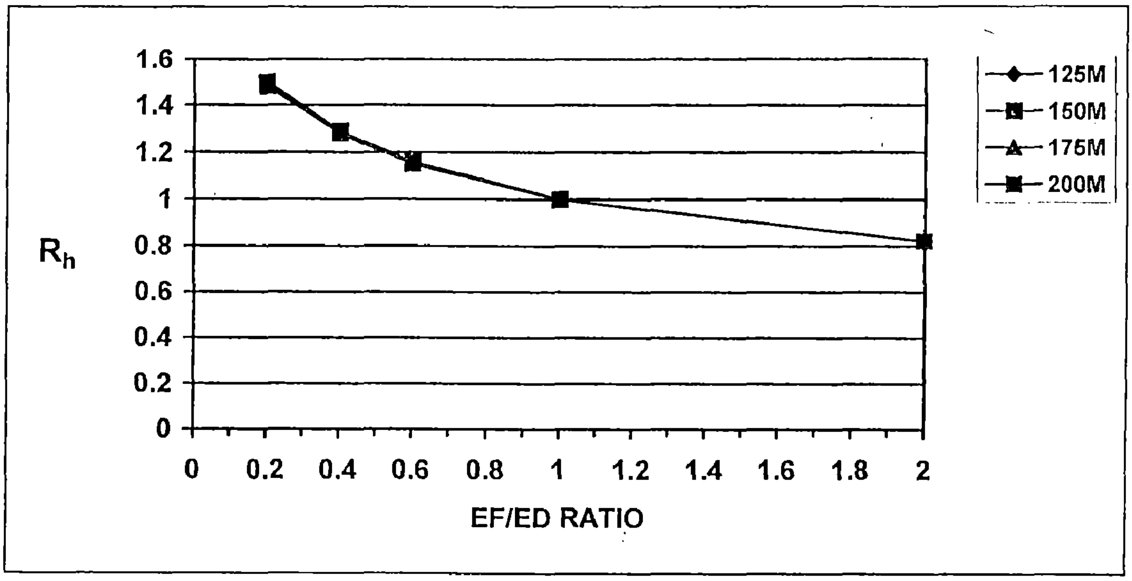


a. AT HEEL

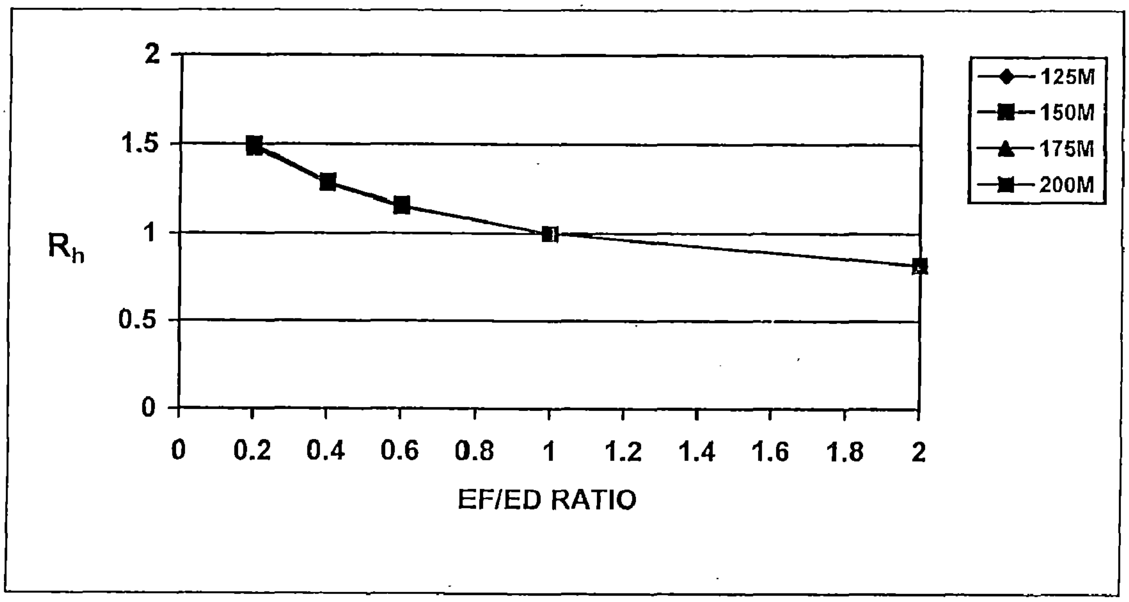


b. AT TOE

FIG 3.24 VARIATION OF HORIZONTAL STRESSES WITH EF/ED RATIO FOR DIFFERENT DAM HEIGHTS.



a. ALONG THE DAM BASE



b. ALONG THE D/S FACE

FIG 3.25 VARIATION OF R_h WITH EF/ED RATIO ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT DAM HEIGHTS.

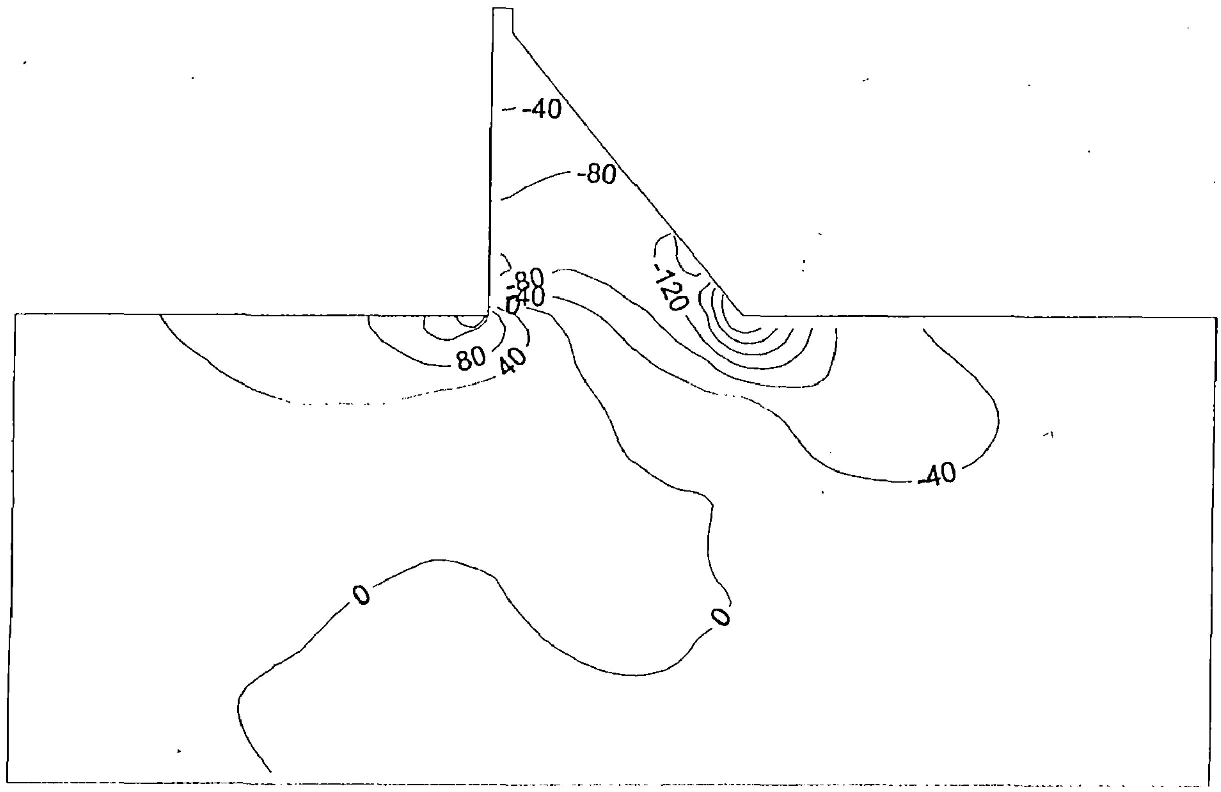
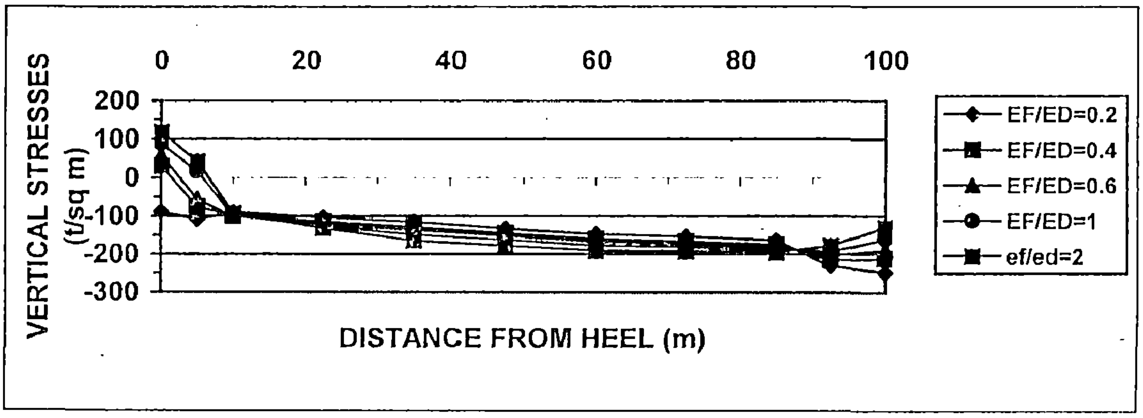
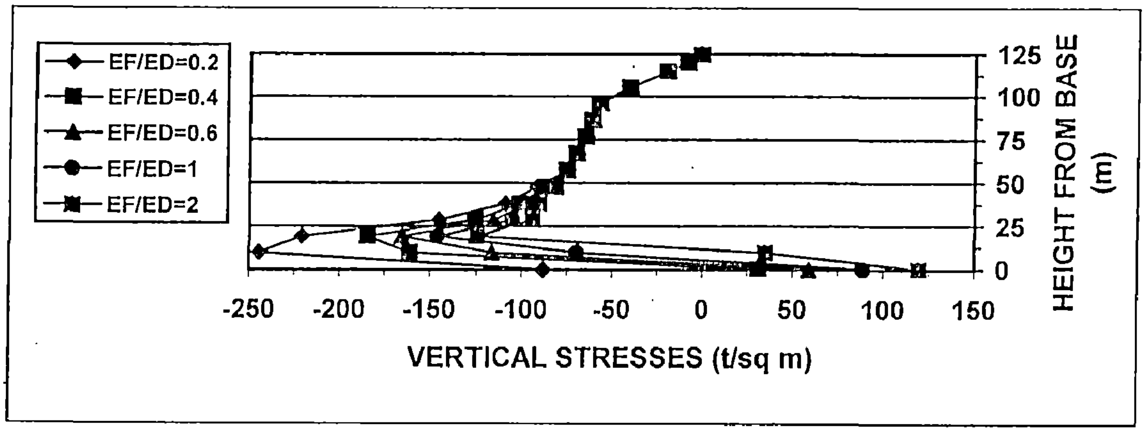


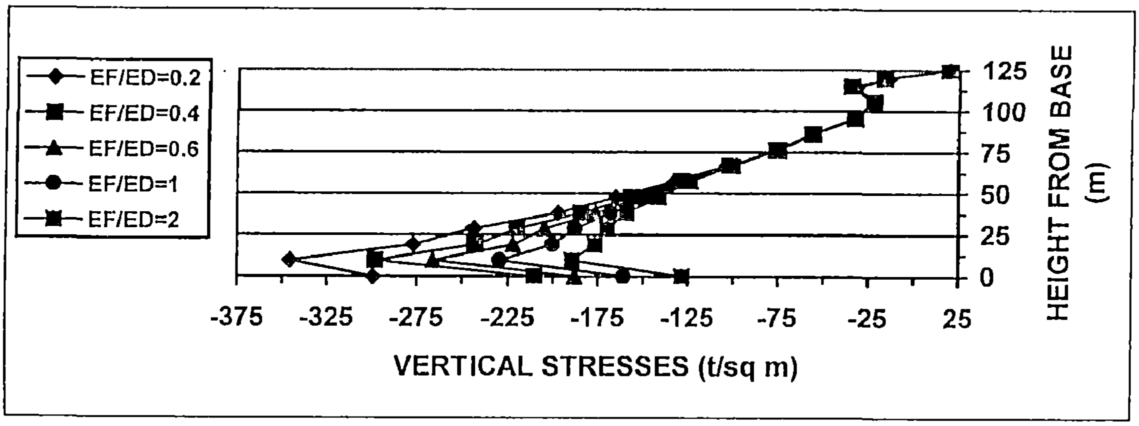
FIG 3.26 HORIZONTAL STRESS (t/sq m) CONTOURS OF HEIGHT 125M (CASE 1) FOR EF/ED=0.6



a. ALONG THE DAM BASE

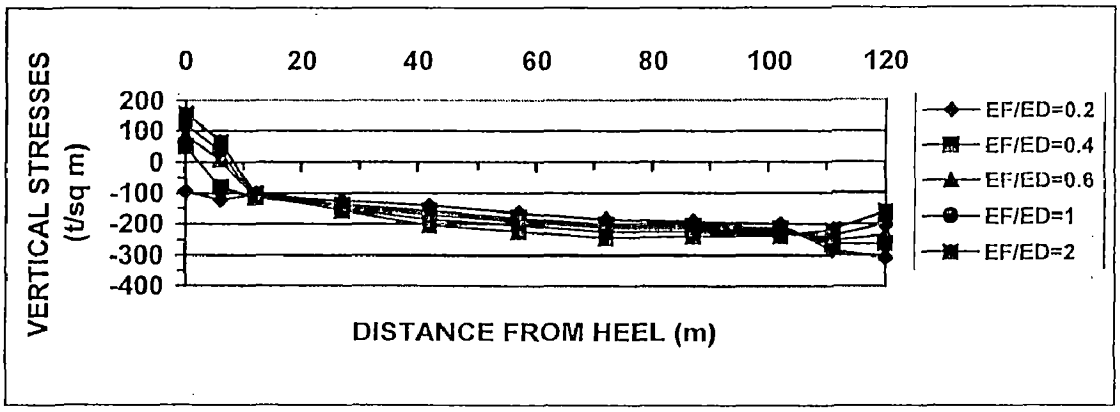


b. ALONG THE U/S FACE

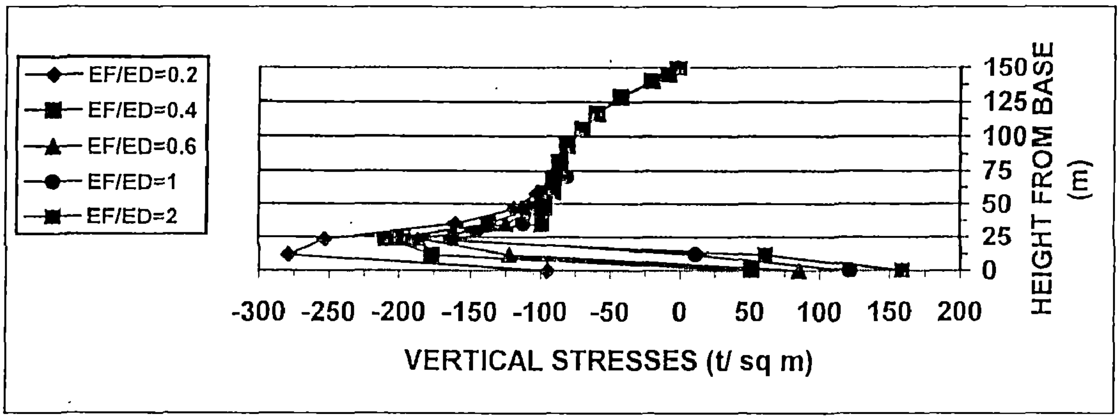


c. ALONG THE D/S FACE

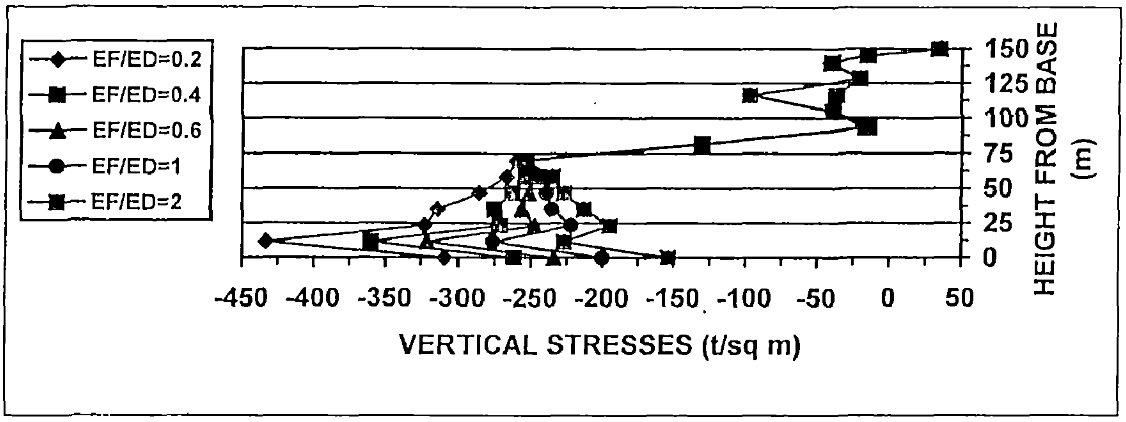
FIG 3.27 VERTICAL STRESSES ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=125M).



a. ALONG THE DAM BASE

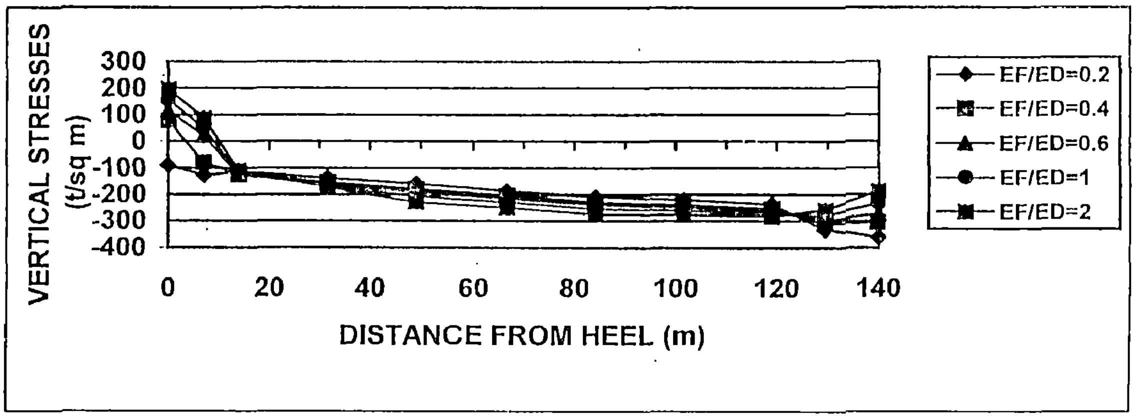


b. ALONG THE U/S FACE

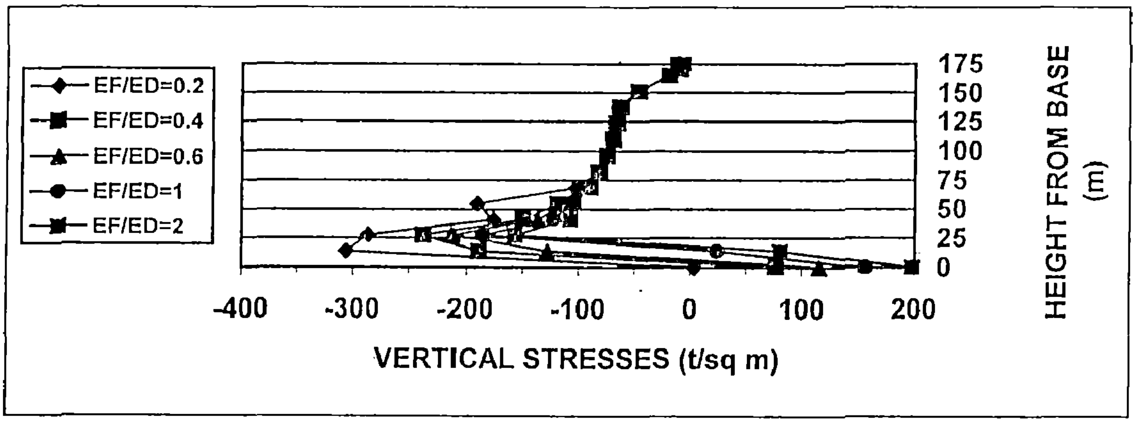


c. ALONG THE D/S FACE

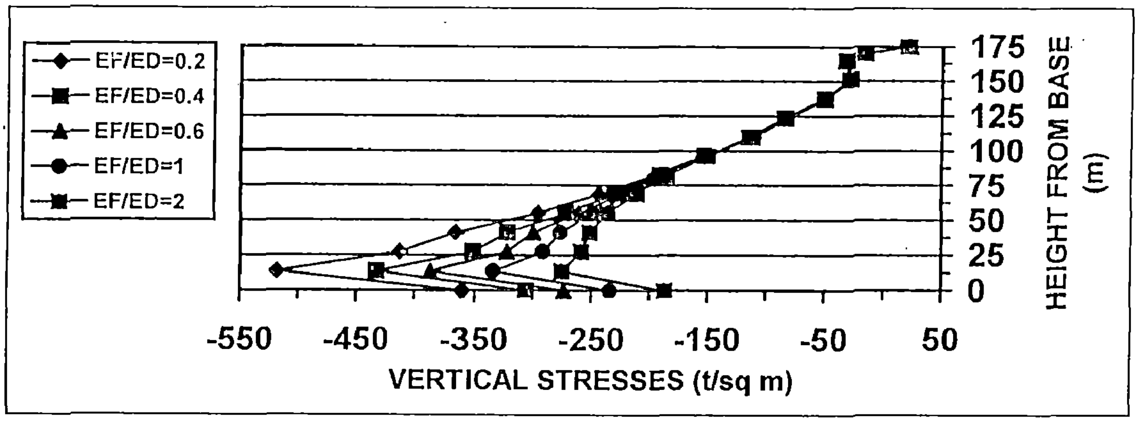
FIG 3.28 VERTICAL STRESSES ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=150M).



a. ALONG THE DAM BASE

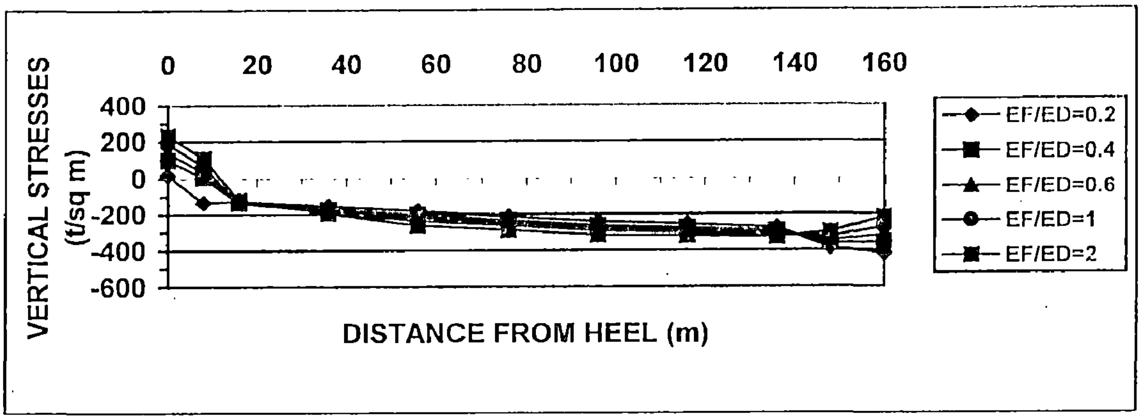


b. ALONG THE U/S FACE

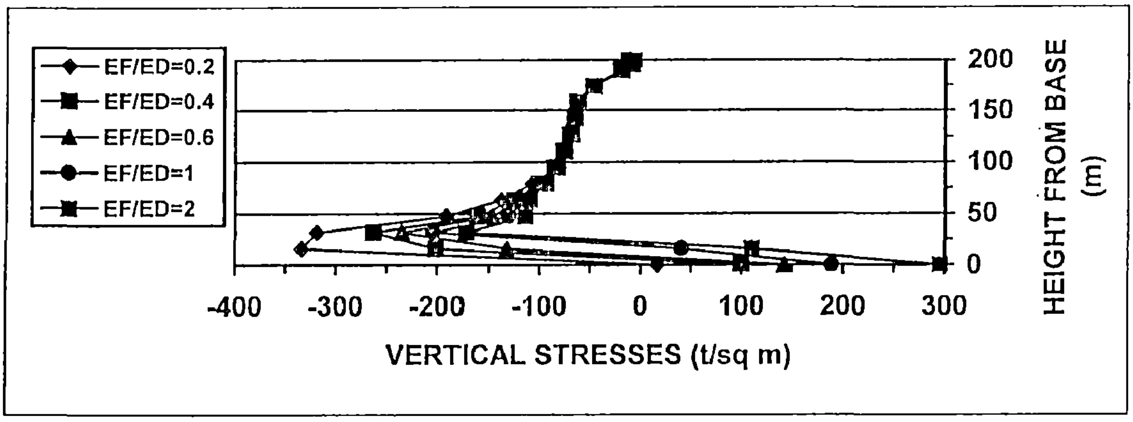


c. ALONG THE D/S FACE

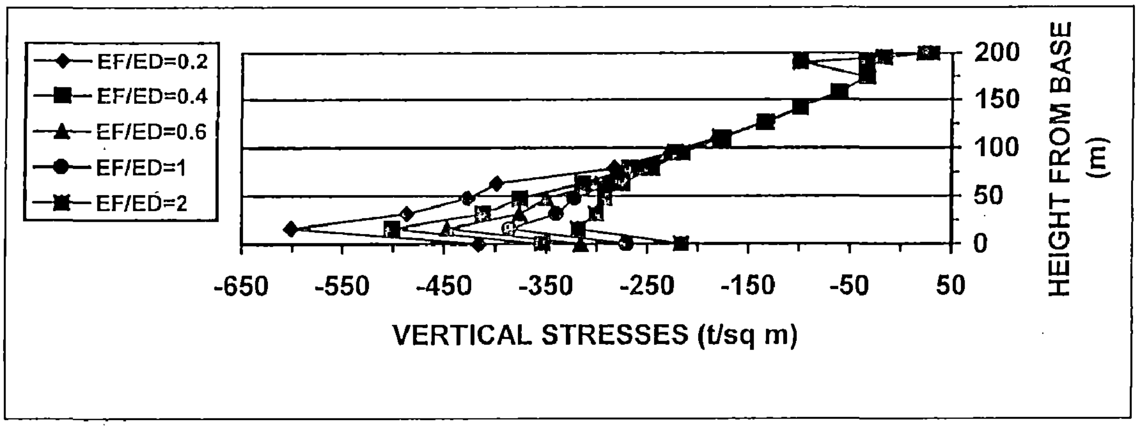
FIG 3.29 VERTICAL STRESSES ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=175M).



a. ALONG THE DAM BASE

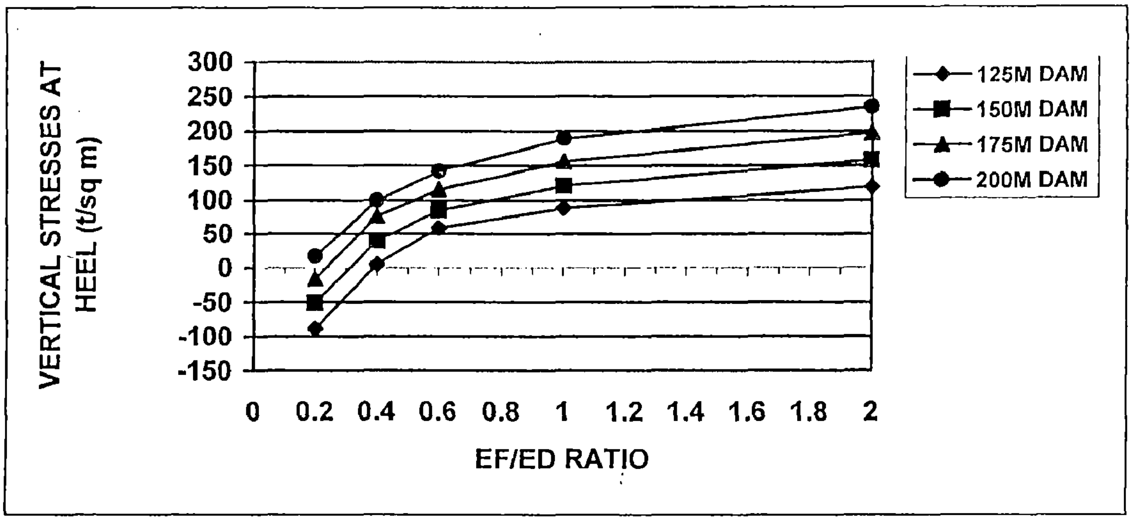


b. ALONG THE U/S FACE

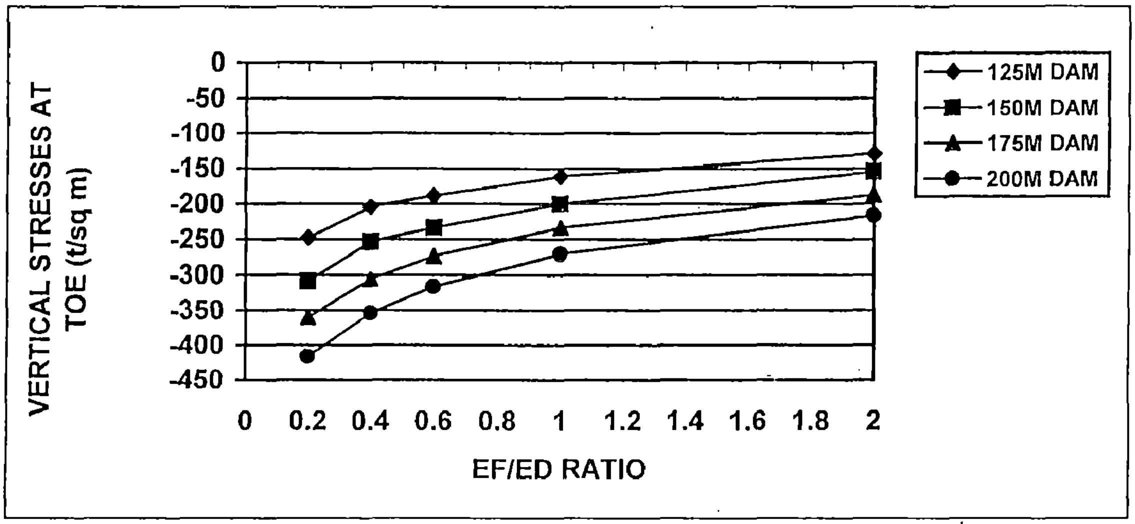


c. ALONG THE D/S FACE

FIG 3.30 VERTICAL STRESSES ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT EF/ED RATIO (HEIGHT=200M).

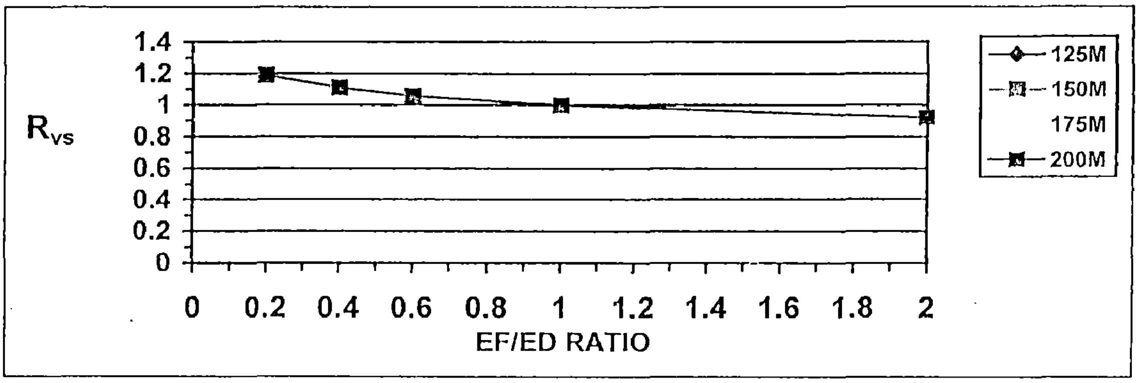


a. AT HEEL

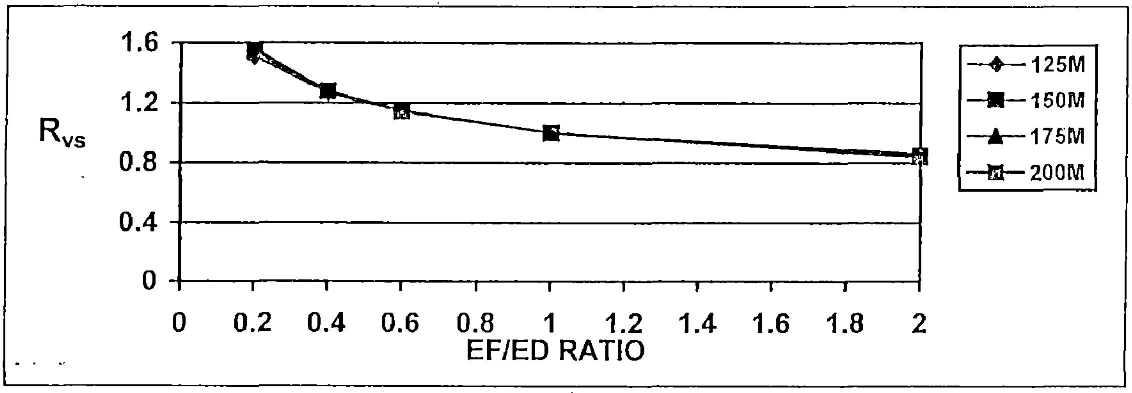


b. AT TOE

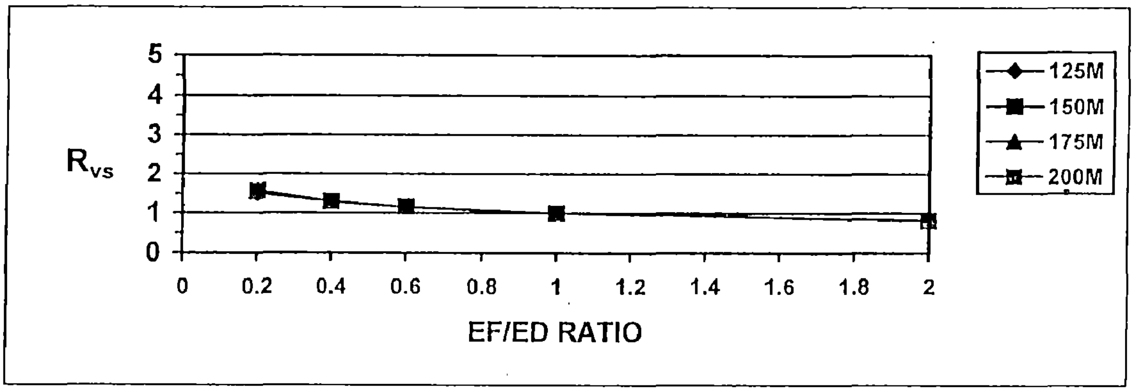
FIG 3.31 VARIATION OF VERTICAL STRESSES WITH EF/ED RATIO FOR DIFFERENT DAM HEIGHTS.



a. ALONG THE DAM BASE



b. ALONG THE U/S FACE



c. ALONG THE D/S FACE

FIG 3.32 VARIATION OF R_{vs} WITH EF/ED RATIO ALONG DIFFERENT LOCATIONS IN DAM FOR DIFFERENT DAM HEIGHTS.

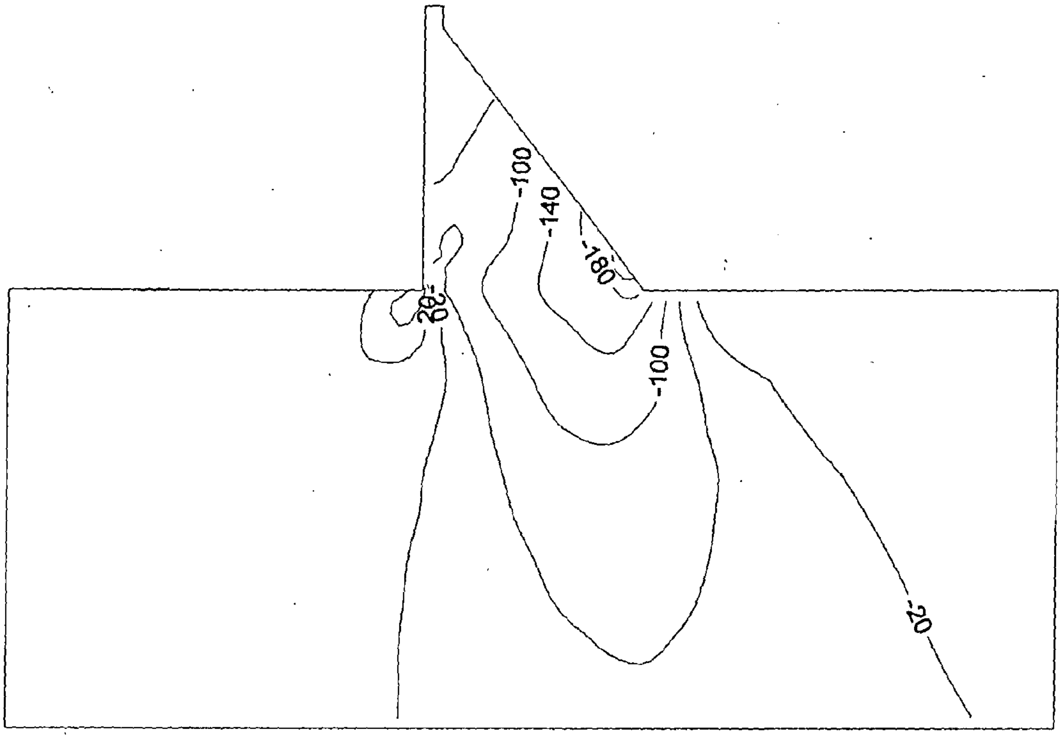


FIG 3.33 VERTICAL STRESS (t/sq m) CONTOURS OF HEIGHT 125M (CASE 1) FOR EF/ED=0.6

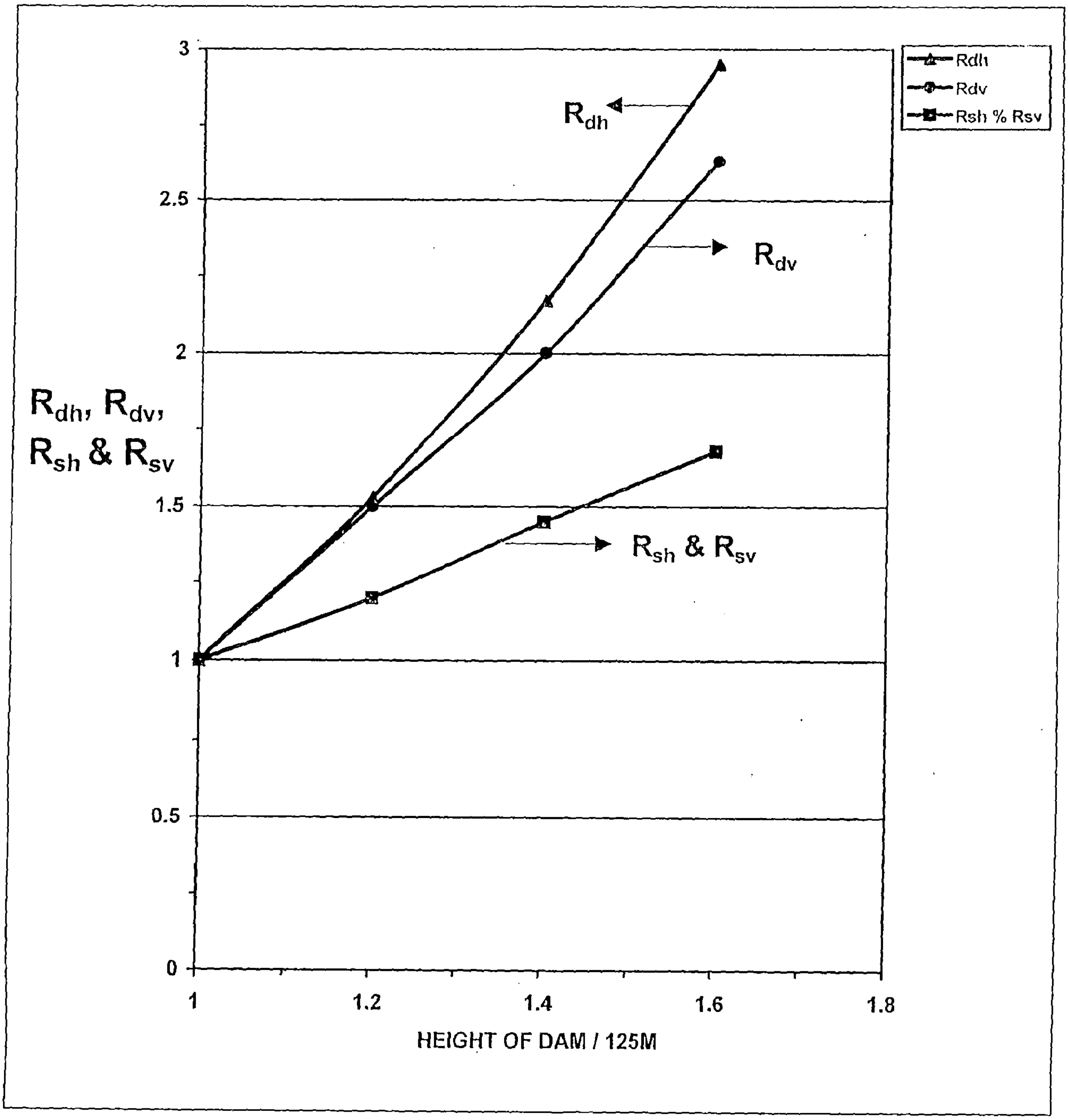


FIG 3.34 VARIATION OF R_{dh}, R_{dv}, R_{sh} AND R_{sv} WITH HEIGHT RATIO.

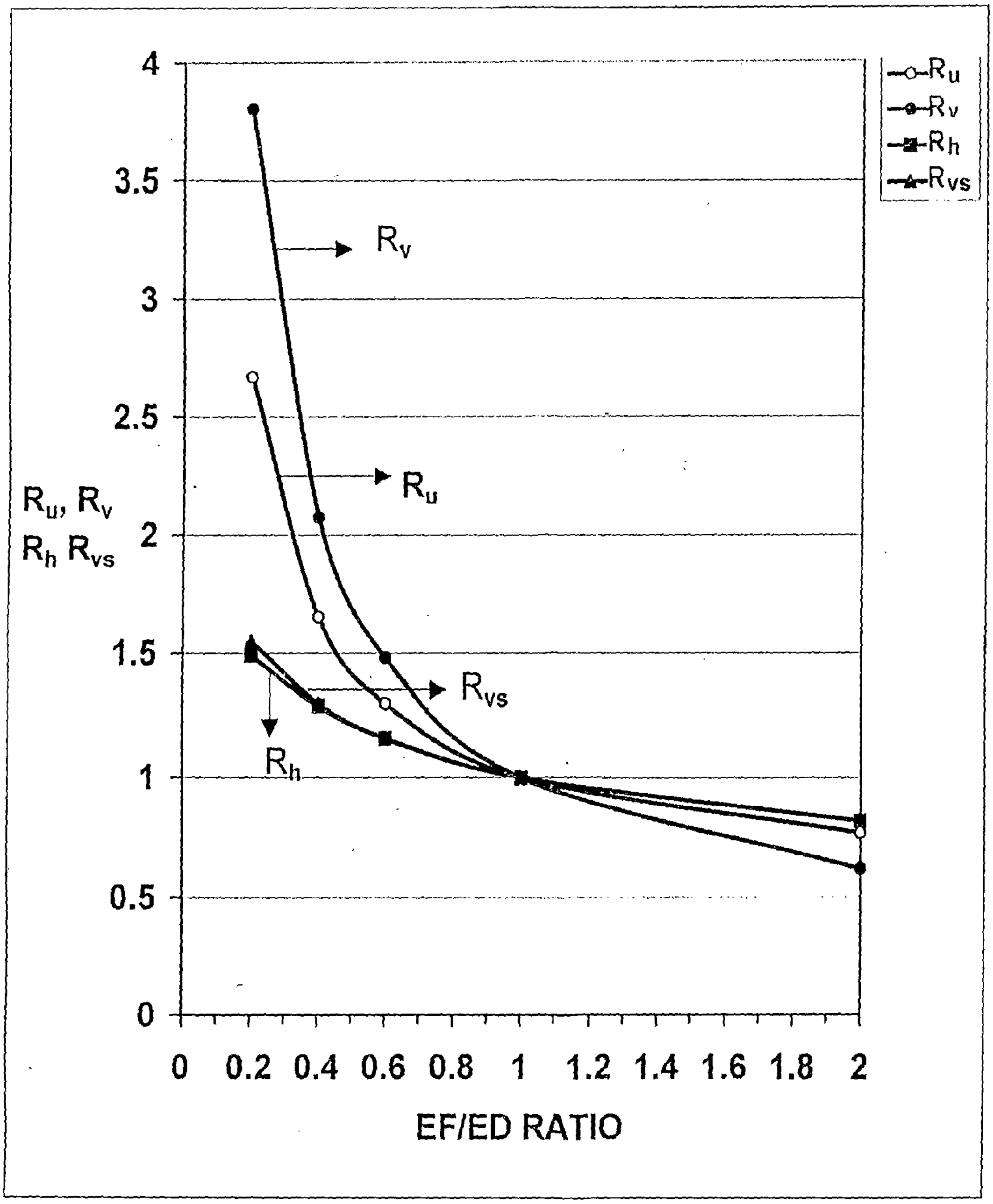


FIG NO 3.35 VARIATION OF R_u, R_v, R_h AND R_{vs} WITH DIFFERENT EF/ED RATIO.

CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS FOR FURTHER STUDIES

4.1 CONCLUSIONS

The following conclusions are derived from the 2D-FEM study of high concrete gravity dams of different heights founded on the rock of varying modulus of elasticity.

- The horizontal displacement is maximum at the top. It increases with the height of dam. It also increases with decrease in EF/ED value. There is sharp increase in this displacement for EF/ED values less than 0.6.

Height of dam (m)	EF/ED Ratio	Horizontal Displacement (mm)
125	0.2	92.04
	0.6	44.16
	2.0	25.89
200	0.2	262.49
	0.6	127.71
	2.0	76.95

- The vertical displacement (settlement) is maximum at the toe of the dam. It is found to increase with the increase in the height of dam. It also increases with the decrease in EF/ED values. There is sharp increase in this displacement for EF/ED values less than 0.6

Height of dam (m)	EF/ED Ratio	Vertical Displacement (mm)
125	0.2	39.64
	0.6	12.81
	2.0	3.71
200	0.2	104.66
	0.6	33.77
	2.0	9.78

- The study of normal horizontal, normal vertical and principal stresses in the dam has shown concentration of tensile stresses around the heel and compressive stresses around the toe. Maximum compressive stress is found on the downstream face a little above the base in all cases. These stresses for all values of EF/ED greater than 0.6 and all heights of dam are found with in the recommended limit of 70 kg/sq cm (700 t/sq m).
- The compressive stresses around the toe are found to increase with the increase in height of dam and decrease in the value of EF/ED (1166 t/sq m for 200m and EF/ED=0.2, and 318 t/sq m for 125m height and EF/ED=2.0).
- The tensile stresses around heel are found to increase with the increase in height of dam and in the value of EF/ED (154 t/sq m for 125m height and EF/ED=0.2 and 417.53 t/sq m for 200m height and EF/ED=2.0).
- The stresses are found to vary sharply for EF/ED values less than 0.6.

- The effect of dam height and foundation elasticity is found more pronounced on displacements than on stresses as is evident from Fig 3.34 and 3.35. These can be used to determine the stresses and displacements in dams of any height and EF/ED within the range of values for which this study is made. From the Figures 3.34 and 3.35 the values of stresses and displacements can be predicted with an accuracy of 98% to 99% in the dam.

4.2 RECOMMENDATIONS

1. Foundations having EF/ED equal to or more than 0.6 are suitable for high concrete dams.
2. In view of rock modulus values of some dam sites given in Table 4.1, it is recommended that Himalayan rocks are generally not suitable for high concrete gravity dams.

4.3 SUGGESTIONS FOR FURTHER STUDIES.

- Effectiveness of fillets in reducing the tensile stresses around may be studied.
- Effectiveness of grouting transverse joints in reducing displacements may be studied using 3D-FEM analysis.

Table 4.1: Elastic constants of foundation rock of some concrete, earth and Rock-fill dams in Himalayan Region.

SL No.	Name of Dam	Type of Rock	Elastic Constants	
			Elasticity in $t/m^2 \times 10^6$	Poisson's Ratio (v)
1.	Bhakra Dam(India) (concrete)	Sand stone with clay bands	0.28 to 2.4	0.1 to 0.3
2.	Ichari Dam (India) (concrete)	Granite, lime stone, schist	0.5	0.2
3.	Jamrani Dam (concrete) (India)	Silt stone, sand stone	0.025 to 0.05	0.21
4.	Proposed Lakhwar Dam (concrete) (India)	Phyllite, slates, quartzite lime stones	0.04 to 0.255	0.19-0.23
5.	Proposed Srinagar Hydel Scheme (concrete)(India)	Quartzite, metabasic	0.025 to 0.325	0.18-0.25
6.	Ramganga E&RF Dam (India)	Sandstone, clay shale	0.002 to 0.0875	0.18-0.23
7.	Proposed Kotlibehl E&RF Dam (India)	Fine grained coarse grained sand stone	0.0075 to 0.075	0.2-0.24
8.	Tehri E&RF Dam (India)	Phyllites, quartzite	0.01 to 0.1	0.2-0.23

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11. Varsney R. S. (1982) "Concrete Dams" Mohan Primlani for Oxford IBH 66, Janpath, New Delhi.

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