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2-D STRESS ANALYSIS OF KOYNA DAM BY FINETE ELEMENT METHOD

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ABSTRACT

Numerical methods allied to powerful digital computers give to-day the possibility of solving almost all well defined physical problems with desirable accuracy. The finite element process of discretizing and approximating continuous problems has proved itself to be one of the most general and useful procedures. In the design of gravity dam's gravity method of analysis is widely used all over the world the gravity method of analysis of dams is based on many simplifying assumptions and cannot take into actual site conditions. Finite element method used in analysis of gravity dam because it gives more accurate results than conventional methods. In my thesis two dimensional finite element analyses is carried out because 1) in three dimensional analysis some loads are distributed to dam abutments so stresses are less compared to two dimensional analysis. 2) three- dimensional analysis is costlier, tedious than two dimensional analyses.

FEM requires the domain of interest be subdivided into a mesh of discrete elements or sub-domains. The accuracy and the expense of the calculations are strongly affected by the "goodness" of the underlying mesh.

Ideal mesh is characterized by finer elements at curved boundaries and also where stress concentration is high. To develop finer elements and data preparation for smaller elements by manually is very tedious, time consuming and error prone. Automatic mesh generation is used for creation of a well- conditioned mesh in two dimensions with a minimum of user interaction using isoperimetric quadrilateral elements.

Present work deals with the finite element method and it has been studied for both plain stress and plain strain condition. The convergence of the problem is checked with three different mesh types of 36 elements, 73 elements and 160 elements for all the cases stresses are worked out. The graph has been plotted for the normal and shear stresses. According to IS: 6512-1984 the analysis is carried for load combinations A and B. for all load combinations according to saint venant's principle foundation interaction of dam is included in stress analysis. Analysis is done for including and excluding the foundation interaction. It is observed that the stresses including foundation interaction are more compared with the stresses when foundation interaction not considered.

A programme in 'C' for analysis and BASIC programme for the mesh generation is used in the present thesis.

KEYWORDS: stresses, abutments, discrete elements, isoperimetric.

1. INTRODUCTION

It has been found that the results of the finite element method do not tally with the results of the conventional method of analysis and finite element results are closer to measured stresses in prototypes. It is further noted that the gravity analysis underestimates the tensile stresses on the upstream face and over estimates the compressive stresses on the downstream face in comparison to those obtained by finite element analysis.

The versatility of the finite element method permits easy introductions of the following in the dam models.

1. Non homogenous such as weak zones, faults, fissures and joints.
2. Irregular shapes and geometric
3. Galleries and openings of various shapes
4. Mixed loading conditions involving given loads at some locations and displacements at others.
5. Seepage and gravitational forces
6. Thermal stress
7. Hydrodynamic effects
8. Dynamic response during earth quake
9. Non linear problems.

FEM requires the domain of interest be subdivided into a mesh of discrete elements of sub-domains. The accuracy and the expense of the calculations are strongly affected by the "goodness" of the underlying mesh.

Ideal mesh is characterized by finer elements at curved boundaries. To develop finer elements and data preparation for smaller elements by manually is very tedious, time consuming and error prone. Today automatic mesh generation is understood to mean the creation of a well-conditioned mesh in two dimensions with a minimum of user interaction.

The continuous mathematical model consists of many d.o.f. so increasing d.o.f. in FEM gets good results; d.o.f. can be increased by increasing elements to the body and increasing nodes of the body. So increasing d.o.f. in FEM will give acceptable results.

The finite element analysis is used as a case study in this investigation to evaluate and compare the stresses in the koyna concrete gravity dam for different sizes of meshes, loading, and foundation rock conditions. In all cases isoperimetric quadrilateral element is used for descritization.

The objective of the present thesis is to get an insight in to the two-dimensional finite element analysis of plate element for plane stress and plane strain conditions using automatic mesh generation by isoperimetric quadrilateral element.

2. REVIEW OF LITERATURE

Gravity dams were very common in the early periods of dam construction. The most ancient gravity dam in records was built in Egypt before more than 400 years BC with un cemented masonry. The masonry dams built in Spain in the sixteenth and seventeenth centuries being about 20m in the height have a vertical upstream face and are approximately rectangular in section. The design of these old dams was based on thumb-rule methods and their profile departs considerably from the theoretical triangular section which entails maximum economy in material.

In some cases disasters have overtaken In such dams which were designed and built by those who were in their day acknowledged masters of their profession. Failures occurred because knowledge available at the was incomplete. A further advance in the technique of dam design could be achieved by systematic analysis of the circumstances and conditions and by discussions, not of one isolated case of failure but of several.

Although a few masonry gravity dams were built in Spain about the 16^{th} century AD. The French engineers developed the first rational theory of design and applying it to some of the height dams of that period. Sazilly, Rankine and Wegmann (1881) did pioneering work in this respect.

In the year 1909, William Cain presented a numerical solution for the principal stresses in a gravity dam at any point on a horizontal section. His method was laborious and involved, solving of no of equations.

Formulae for calculating the stresses in the interior of a gravity dam based on the straight line distribution of vertical stress and parabolic distribution of shear stresses were later developed by the United States Bureau of Reclamation (USBR) during design of Boulder dam.

It had been realized by early 1900's that the assumption of linear distribution of normal stresses on horizontal plane of the dam was incompatible with the theory of elasticity for regions near the base of the dam, Richardson (1909), Jacobsen (1932), Henry (1934), Levy (1935), Brahty (1938) and Zienkiewicz (1947) did extensive studies on this.

For a long time gravity dams being designed on the assumption that the entire water load would be carried to the foundation by cantilever gravity action. The perfection of the trail load method of analysis by the united states Beraue of Reclamation (USBR) made possible the analysis of load distribution, deflections and stresses consistent with the configuration of the foundations and layout of the dam.

A further note worthy improvement in design methods from the view point of view stress conditions has been the development of methods of analyzing the effects of foundation and abutment deformations, first begun by Vogt In 1925. The method was further refined by the USBR.

The finite difference process is oldest one for the application to problems of dam analysis first recorded in the analysis of the Aswan dam by l.f Richardson in 1908 with similar technique used later by Sienkiewicz 1945 employing south wells relaxation methods.

Since advent of computers many finite difference solutions have been utilized and their generality is advantageous. There are, however, two drawbacks arrived (I) the local differential equations govern the problem and present a difficulty of introducing boundary conditions. (II) The mesh generally should follow a regular pattern.

The theory of lattice analogy presented by Machinery (1948) permitted considerations of the effect of any difference between the elastic characteristics of the dam concrete and foundation rock. An extension of this method to handle three-dimensional cases was later developed by Wilson (1948).

The growth and development of electronic computers during the past two decades has resulted in new analytical methods of design. With the aid of the finite element method solutions to previously intractable problems have becomes now possible. Because of its simple logic and tremendous utility, the finite element method is increasingly favored.

The finite element concept in its modern form was established through the derivation of the stiffness matrix for the triangular element, based on assumed displacements. This work by M.J.Turnber, R.W.Clocgh, H.C.Martin and L.J.Topp (1957) was one of the key contributions in the discovery of finite element method.

The initial finite element method paper on large deflection, stability, problem and the extension of the finite element method to the geometrically non linear problems was first carried out by M.J.Turnber, E.H.Dill, H.C.Martin and R.J.Melosh (1960).

One of the first problems to receive attention was that of plate bending. R.J.Melosh (1961) and A.Adini, R.W.Clogh (1961) examined both the rectangle and triangle as possible elements for bending analysis. Inter element compatibility was not fully achieved in this early work. Interest in 2D and 3D elasticity problems motivated further development of suitable elements.

Irons, Zienkiewicz (1965) have investigated the isoparametric parabolic elements. The elements make it possible to generate that are non-rectangular and curved sides.

Numerically it had been observed for years that the finite element method often led to convergent results as the number of elements was increased. The earliest convergence studies of the fem were by Melosh and Lay (1967).

A comprehensive advanced study of the fundamentals of the finite element theory for 2 D problems and the computational aspects of F.E. theory was done by CA Felippa and R.W.Glough. (1968). By the end of 1970 the investigation on viscous flow problems had demonstrated the feasibility of the finite element method for under taking such problems.

S.S.Saini and S.K.Garg (1996) have done research on analysis of a gravity dam using sub structure technique and concluded that the substructure approach of analysis is quite effective in the analysis of dam-foundation system without any loss of accuracy in results. In general, substructure analysis is more efficient as compared to the one stage analysis. A saving of 74% and 40% in execution time and 42% and 20% in hard disc storage space has been achieved while using the reduced stiffness matrix method and interactive method system analyzed, as compared to one storage analysis.

D.K.Sehgal, U.K.Chopra (1996) have done research on analysis of a concrete gravity dam using optimum mesh and concluded that the results based on the optimum mesh are excellent. The error is quite less even by using coarse mesh. Hence large civil engineering structures can be easily solved on personal computers even with low in core memory. The technique is found to be very promising because it not only gives the density of the mesh but also it gives the idea about the shape of the element.

3. STATUS OF THE FINITE ELEMENT PROCESS IN DAM ANALYSIS

3.1 VARIOUS METHODS OF ANALYSIS:

The scope of analysis is the improvement of safety and working performance of the dam and the determination of the most economical design with constraints imposed.

The following methods are generally adopted for evaluation of stresses in a dam,

1. Gravity dam
2. Trail load twist method
3. Slab analogy method
4. Lattice analogy method
5. Experimental methods
    a. Direct method or three-dimensional method
    b. Indirect method or photo elastic method
6. Finite element method

3.2 FORCES CONSIDERED IN THE ANALYSIS OF GRAVITY DAM:

The following forces may be considered as affecting the design:

- Dead load
- Reservoir and tail water loads,
- Up lift pressure
- Earthquake forces
- Earth and silt pressures
- Ice pressure
- Wind pressure
- Wave pressure
- Thermal loads
- Seepage and pore pressures
- Surface temperature effects

3.3 LOAD COMBINATIONS:

Gravity dam design as per the IS 6512-1984 should be based on the most adverse load combination A, B, C, D, E, F, or G given below using the safety factors prescribed. Depending on the scope and details of the various project components, site conditions and construction programmers, one or more of the following loading combinations may not be applicable ipsofacto, and may need suitable modifications:

(a) Load combination A (construction condition) - dam completed but no water in reservoir and no tail water.
(b) Load combination B (normal operating condition)- full reservoir elevation normal dry weather tail water, normal uplift, ice and silt (if applicable)
(c) Load combination C (flood discharge condition)- reservoir at maximum flood pool elevation all gates open, tail water at flood elevation, normal uplift and silt(if applicable).
(d) Load combination D – combination A with earthquake.
(e) Load combination E – combination B, with earthquake but no ice load.
(f) Load combination F – combination C, but with extreme uplift (drains inoperative).
(g) Load combination G – combination E, but with extreme uplift drains inoperative.

4. AUTO DESCRITIZATION FOR FINITE ELEMENT FORMULATION

4.1 AUTOMETIC MESH GENERATION:

The finite element method (FEM) is one of the most powerful modeling tools available to the engineers. FEM require that the domain of interest be sub divided in to a mesh of discrete elements, the accuracy and the expense of the calculations are strongly affected by the "goodness" of the underlying mesh. An ideal mesh is characterized by small elements exceptionally adopted larger elements where stress gradients are small and elements are regular or undistorted in shape.

4.1.1MAPPING METHODS

Mesh generation by mapping is a technique where the element connectivity is simplified to a square or triangular grid system, which is then mapped in to the actual shape of the domain of interest. The two most common mapping methods are isoperimetric mapping and the I, J mapping.

In the mapping program each nodal points is identified by a pair of positive integers, denoted by (I, J). The scheme for mesh generation may be throughout of as representing a mapping of points from the (I, J) – plane in to the (x, y) –plane. Each quadrilateral in the (x, y)-plane is a square in the (I, J) –plane and may be identified by the (I, J) coordinates of its bottom left-hand corner in the (I, J) plane. The mesh generation is accomplished in the following manner.

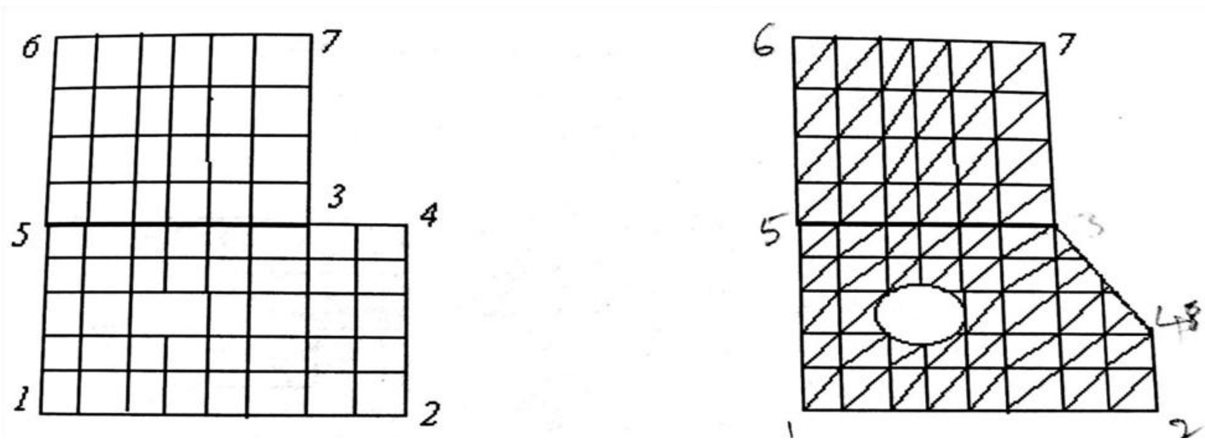

Fig.1 Mapping from (I, J) to (x, y) space

4.1.2 TREE STRUCTURE METHODS

Certain tree structure methods are used in solid modeling to represent design parts. The most common methods are the Bintree, quadtree and octree (for one, two, three- dimensional, respectively), modified octree & modified quadtree.

4.2 The analysis consists of the following steps

1. Discretization of the continuum
2. Selection of the displacement models
3. Derivation of the element stiffness matrix
4. Assemblage of algebraic equations for the overall discretized continuum
5. Application of boundary conditions
6. Solution for the unknown displacements
7. Evaluation of element strains and stresses

4.3 Discretization of continuum

Continuum is generally considered to be a single mass of material as found in concrete dam, deep beam, shear wall, plate and so on. Discretization is the process in which the given body is subdivided into an equivalent system of finite elements. The finite elements may be triangular, rectangular or quadrilateral for a two dimensional continuum as shown in fig.

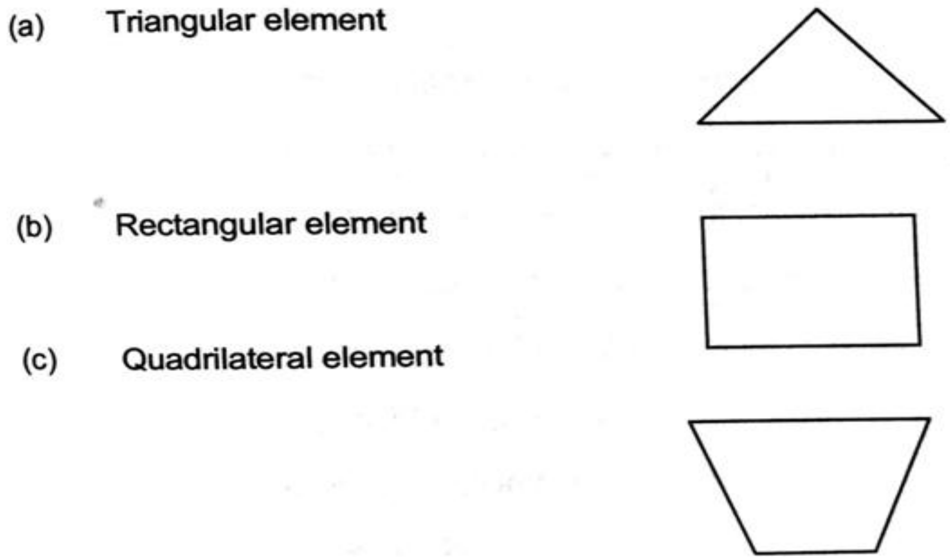

Fig.2 Discretization of continuum

5. PROBLEM MODELLING

5.1 Koyna hydro electric project:

Koyna hydro electric project is one among a number of very attractive and economical hydroelectric developments in the country exploiting the sharp drop of a few hundred meters available on western side of the Western Ghats escarpment.

The project is situated in Maharashtra state on Koyna river near Helwalk about 241.35km, south-east of Bombay (latitude 73^{o}-45^{1} E and longitude 17^{o}-25^{1}).

5.2 Salient Features – Koyna Hydro Electric Project:

Location	: Deshmubhwadi, koyna, satara district, Maharashtra
Purpose	: Hydro electric power and irrigation
Type of dam	: Gravity rubble concrete
Bed rock	: Basalt
Maximum height above the foundation	: 103.02m
Length at the top of the dam	: 808m
Total volume content	: 1.55 $x10^{6}$ m3
Type of spillway	: Ogee
Reservoir & gross storage capacity	: 2796.5 $x10^{6}$ m^{3}
Effective storage capacity	: 2662 $x10^{6}$ m^{3}

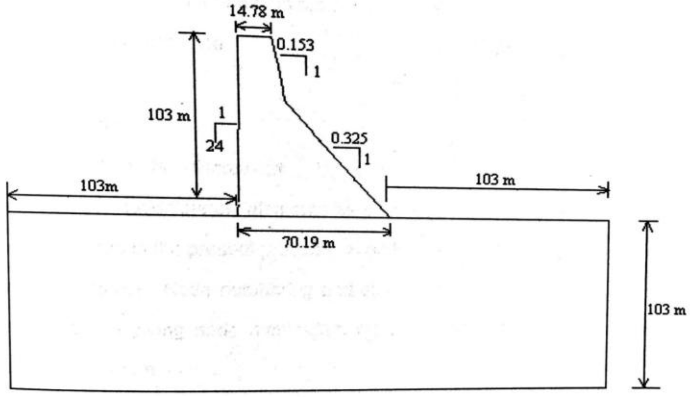

Fig. 3 Cross section of the dam along with the foundation rock

5.3 Dam material properties:

Cross section of the dam of unit thickness is taken up for the analysis i.e. for non-over flow section. The dam is made up of rubble concrete material. The dam engineering properties were given below

Elasticity of concrete (Ec)	= 31220 MPa
Elasticity of foundation rock (Er)	= 65000 MPa
Specific weight of water	= 10.0 kN/m^3
Specific weight of foundation rock	= 28 kN/m^3
Specific weight of concrete	= 26.5 kN/m^3
Poisons ratio of concrete	= 0.2
Poisons ratio of rock	= 0.2
Compressive strength of concrete	= 30 MPa
Compressive strength of foundation rock	= 25 MPa
Tensile strength of concrete	= 3 MPa

5.4 Evaluation of loads:

Loads considered in the analysis consist of self weight of the dam, hydrostatic water pressure and uplift forces. Other normal loads such as silt pressure, wave pressure, vertical water loading and thermal loads are not considered as their effect will be small on the dam behavior. Seismic loads can be rationally estimated by a dynamic analysis only and therefore not included in the present study.

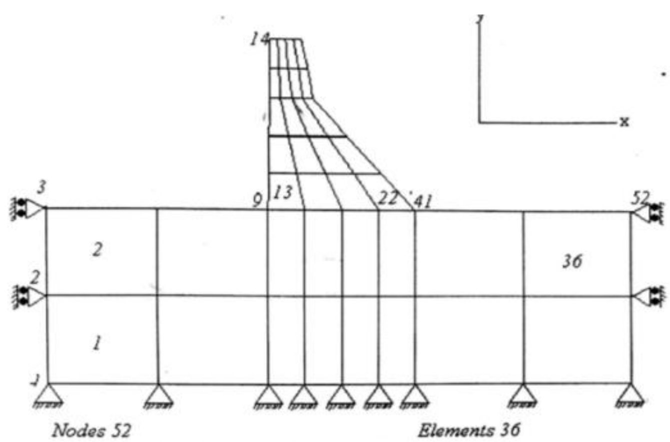

Fig.4 Finite element division of Koyna dam

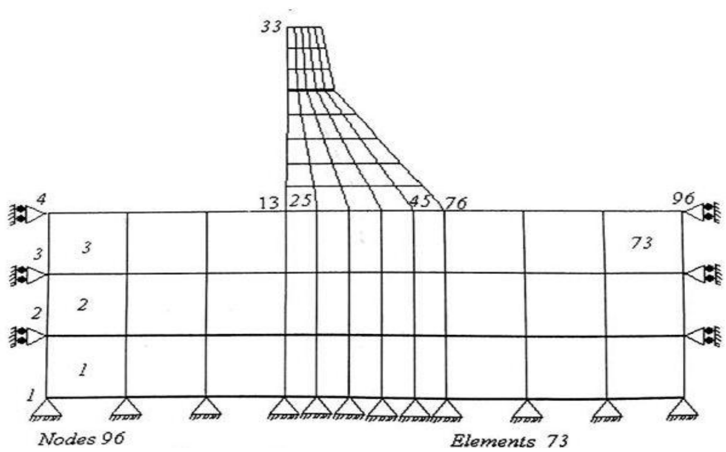

Fig.5 Finite element division of Koyna dam

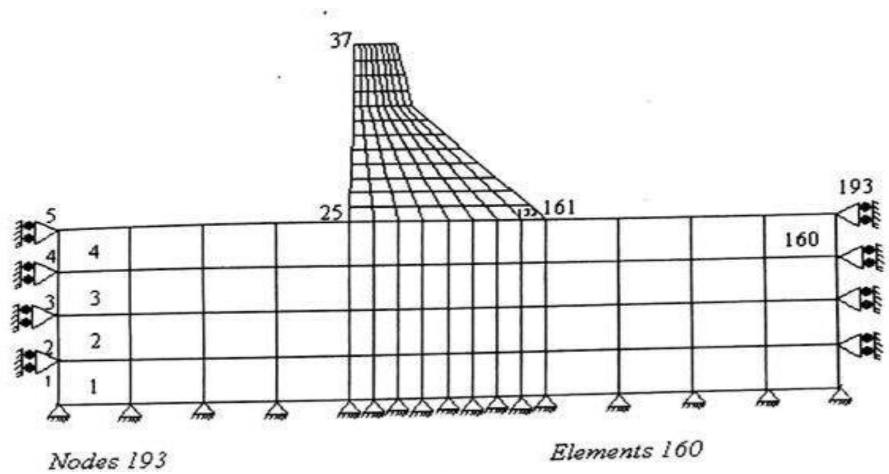

Fig.6 Finite element division of Koyna dam

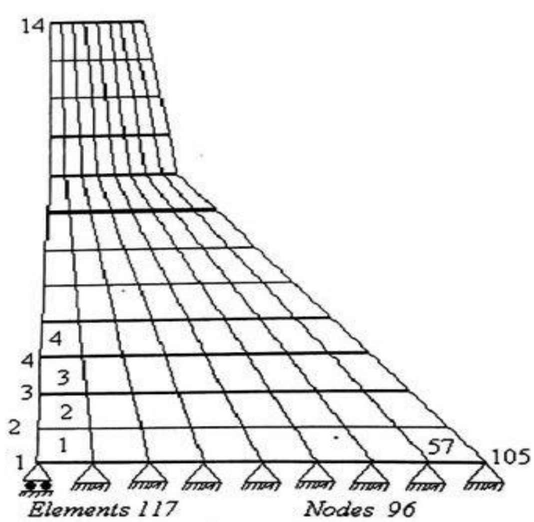

Fig.7 Finite element division of Koyna dam

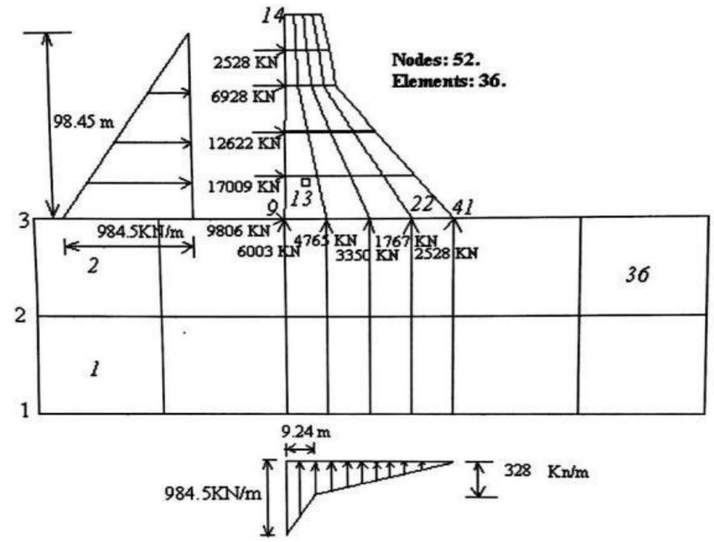

Fig.8 Distribution of water pressure on u/s side and uplift pressure at the foundation interface of a dam.

6. RESULTS

6.1 STRESS CONTOURS

Stress contours for the various combinations of loads and descretization are shown in fig no's: 9 to 14.

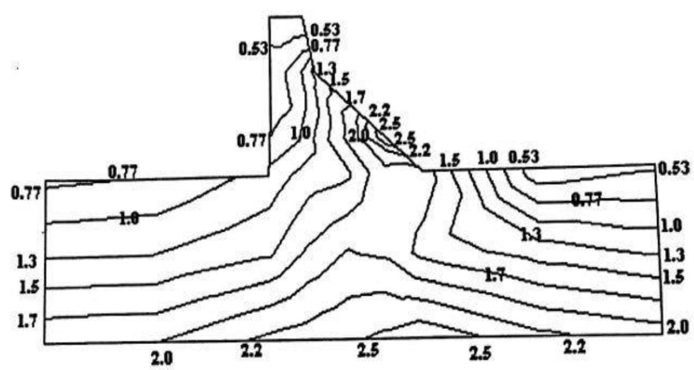

Fig.9 Vertical normal stress contours for case 1 in N/sq mm

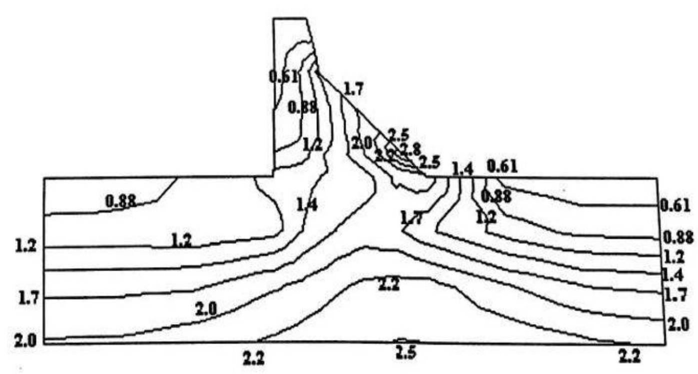

Fig.10 Vertical normal stress contours for case 2 in N/sq mm

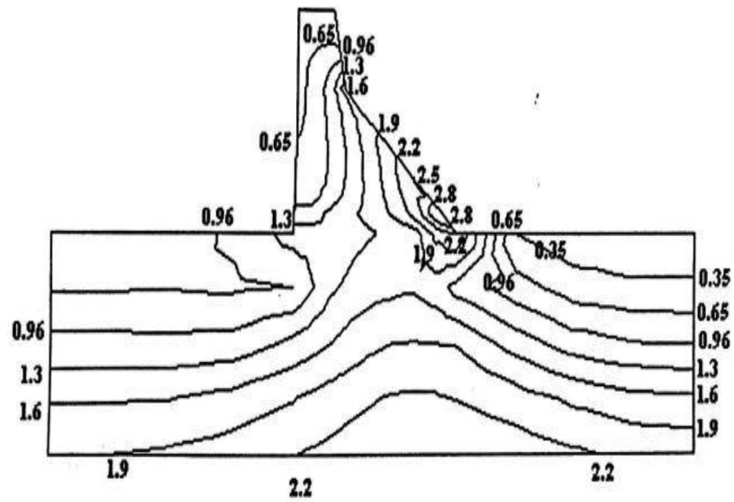

Fig.11 Vertical normal stress contours for case 3 in N/sq mm

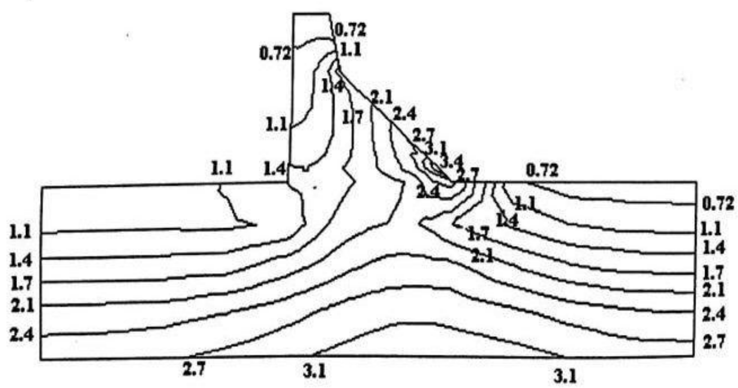

Fig.12 Vertical normal stress contours for case 4 in N/sq mm

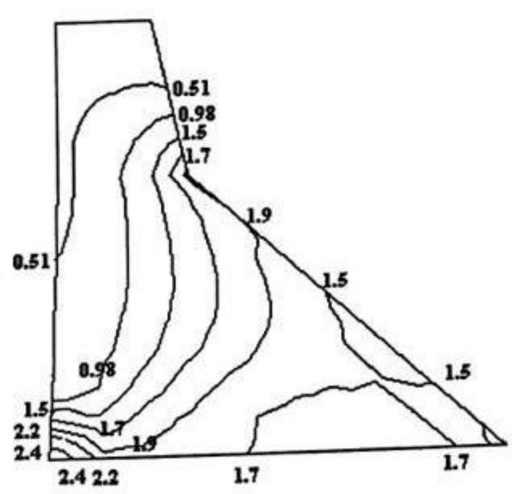

Fig.13 Vertical normal stress contours for case 5 in N/sq mm

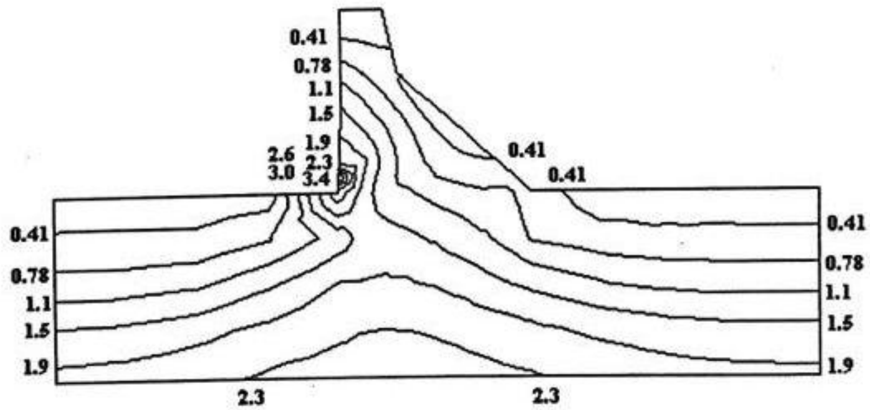

Fig.14 Vertical normal stress contours for case 6 in N/sq mm

Table 1: Stresses at the heel of the dam for different cases

SI No	Case	Node no	Normal Stress at heel Mpa	Shear Stresses at heel Mpa
1	1	9	-0.858	0.532
2	2	16	-0.967	0.600
3	3	25	-1.086	0.671
4	4	25	-1.065	0.697
5	5	1	-2.391	1.390
6	6	25	2.505	1.278

- **Tensile stress, + compressive stress**

Table 2: Stresses at the toe of the dam for different cases

SI No	Case	Node no	Normal Stresses at toe Mpa	Shear stresses at toe Mpa
1	1	41	1.640	0.838
2	2	76	1.882	0.961
3	3	161	2.197	1.134
4	4	161	2.540	0.726
5	5	105	1.319	0.730
6	6	161	0.621	0.342

7. DISCUSSIONS AND CONCLUSIOS

DISCUSSIONS:

Present work deals with the finite element method and it has been studied for both plane stress and plain strain conditions using isoperimetric quadrilateral elements through automatic descretization. The problem has been analyzed for various load combinations as per IS: 6512-1984.

Though Koyna dam stress analysis was carried out by finite element method for plane stress, the same is done by automatic mesh generation for plane stress and plain strain conditions, using automatically generated mesh.

In this method, first of all the convergence of the results has been checked by three different meshes as shown in figures 4 to 6. in these three meshes. As the number of elements increase there is a steep difference between the stresses at common nodes. Convergence requirements have been fulfilled at the node no 33, 127 for case 1, 3 respectively. The base width 52.64m from the tables no 1 and 2 for case: 3 and 4 deal with plane stress and plain strain for dam when foundation interaction considered and vertical normal stresses and shear stresses at heel and toe of the dam section are compared using higher order mesh (for 160 elements).

The gates closed condition with full reservoir level; the vertical normal stresses are tensile on upstream face and compressive on downstream face at the base of the dam (case 3).

It has been noticed that10.9% of change in the results of plane stress and plain strain. Variation of normal stress at the base of the dam for both plane stress and plane strain.

Conclusions:

1. As the stresses are changing with the increase in the number of elements of the mesh, convergence requirements are satisfied. Finer the mesh, results will be more accurate.
2. Finite element analysis of koyna Dam confirms that the vertical normal stress distribution is non-linear as it is assumed perfectly linear in gravity method of analysis. The results and graphs obtained by finite element analysis confirm the stress variation is not linear but parabolic.
3. The finite element analysis confirms the tensile stresses at the heel of the dam but the gravity method under estimate the same by 80 to 100%.
4. There is a difference of stress values from 10 to 15% for plane stress and plane strain cases and stress values in plane stress case are higher than in the plane strain case. Hence, selecting of exact two-dimensional case is plane stress or plane strain plays vital role in arriving the accuracy of the solution.
5. From the results and observation it is found that the stresses are varying considerably for the cases of with and without foundation interaction.
6. Stress analysis of koyna dam for various load cases shows that the results obtained by finite element analysis differ to a great extent from the results of the conventional method of analysis.
7. The statement of Buell and Bush that one of the incentives for automating mesh generation is to reduce the time and money spent creating a mesh, which could take half of the total time required to perfume the FEM analysis is supported by the present study.
8. The stress contours confirms the stress concentration near the base of the dam, specially at the heel and toe of the dam.

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