Numerical Modelling of Underground Power Houses in India

B. Dasgupta
Advanced Technology and Engineering Services,
New Delhi- 110044, India
Tel. No. 0091-11-6949329
Fax No. 0091-11-6945456
L..J.Lorig
Itasca Consulting Group Inc., Minneapolis,
MN - 55415, USA

ABSTRACT

Numerical modelling is being increasingly used to study rock mechanics problems associated with large excavations in complex geologic formations. This paper concerns the stress analysis of three major hydro-electric projects in India. In one of the projects numerical modelling was used to understand the reasons for the observed behaviour of the rock mass and development of several cracks on the cavern walls. In the other two projects, numerical modelling is used to provide base for support design.

1. INTRODUCTION

There has been recent rapid growth in underground hydro power projects in India. The underground power house complex usually consists of large excavations such as power house cavern, transformer cavern, surge chamber etc. These caverns are joined by pressure tunnels, bus galleries, draft tubes tunnels and access adits. The rock medium in which these excavations are constructed is heterogeneous and anisotropic. Major geological structural features such as joints, major shear zones or faults intersecting the excavation area cause discontinuous behaviour of rock mass which may lead to complex rock mechanics problems. The construction of large and small excavations in such a complicated rock medium needs a thorough understanding of the response of the rock mass to the process of excavations. Numerical modelling is commonly used to study this response. This paper describes the role of numerical modelling in understanding the rock mechanics problems through back analysis and in predication of the rock mass response before construction.

2. NUMERICAL MODELLING

Numerical modelling has emerged as a powerful tool for stress analysis in the design of underground excavations. Several numerical techniques are available to model the rock mass as "equivalent" continuum or as discontinuum with explicit representation of the structural features. The outcome of such an analysis depends on the accuracy of the input data namely rock mass properties, in-situ stresses and information on discontinuities. However, it is rarely possible to generate these data with a high level of accuracy, as a result, rock mechanics problems are often "data limited" (Starfield and Cundall, 1988). In using numerical models for design, it is often helpful to establish the rock mass properties through back analysis based on instrumentation data.

The instrumentation data yield information on deformation and induced stress that can be used in back analysis. However, instrumentation for numerical modelling requires careful planning in terms of instrument location and timing of installation. When such planned instrumentation is absent, field observations of rock mass can yield useful information in validating the numerical models as was experienced in one of the cases discussed in this paper. Field observations of the rock mass failure can be used in correlating the stress concentration and relaxation zones indicated by the numerical models. It is possible with this approach to confirm on the in-situ stress and to establish the strength parameters of the rock mass to some extent.

3. POWER HOUSE PROJECTS AND ROCK MECHANICS STUDIES

The major on going projects in India are the Sardar Sarovar Project in the state of Gujarat, the Srisailam Left Bank Hydro-Power Project in Andhra Pradesh and Nathpa Jhakri Power Project in Himachal Pradesh. These projects are in various stages of construction. Rock mechanics problems in each of these projects are unique because of the geometry, rock formation, structural features and the state of stress. In the Sardar Sarover Project, the effect of the shear zones on the stability of the upstream and downstream walls studied by three dimensional discontinuum modelling. In Srisailam and Nathpa Jhakri projects, which are in early stages of construction, continuum analysis were used to study the stress distribution to aid in support design.

3.1 *Sardar Sarovar Project, Gujarat*

The underground power house of the Sardar Sarovar Project, planned to generate 1200 MW of power, is under construction on the right bank of the river Narmada in Gujarat in West India. The riverbed power house cavern located at a distance of 150 m downstream of the Sardar Sarovar Dam, is being excavated at a depth of 45 to 60 m below the surface. The power house is 210 m long, 23 m wide and 57.6 m high. Six pressure shafts of 9 m diameter are used for the intake of water, and six D shaped daft tube tunnels are used for drawing the water out to a collection pool. There are three D shaped bus galleries of 15 m width and 9 m height and 6 m diameter bus shafts to carry bus cables to surface transformer yard. In addition, there is an access adit, a control room and lift well.

The power house is being constructed in ballastic rock formation which is intruded by dolerite dyke and sill. Three major shear zones, viz. A, B and X, intersect each other to form a massive wedge on the upstream wall and cross the power house on the downstream wall between the bus galleries. Construction of the power house was performed by conventional drilling and blasting starting from a central drift widened to full width of the rock and benched down below the roof. The power house is supported by pattern rock bolts 6 m and 7.5 m long and by two layers of 38 mm thick shotcrete with wire mesh.

When the excavation of the power house was nearly complete, cracks were noticed in the walls and junctions of different excavations. However, at this stage, excavation of turbine pits, portion of draft tube tunnels near the cavern and a construction ramp of 8 m width attached to the downstream wall was not complete. The ramp slopes from the floor of the service bay at one end to the floor of the cavern at the other end. As a result the height between the ramp and floor of the bus galleries on the downstream side varies and the ramp height is the least below Bus Gallery 3, which is away from the service bay.

On the downstream side several cracks, vertical and parallel to the cavern axis, were noticed in Bus Gallery 3. The cracks developed up to 20 m inside the bus gallery, and appeared on the concrete lining, as indicated by dashed lines in Figure 1. Similar cracks were noticed in Pressure Tunnels 2 and 3 on the upstream side, as shown in Figure 2. The study performed to understand the reasons for the development of the cracks in the bus galleries and pressure tunnels is discussed in this paper. Cracks also developed on the upstream wall of the power house cavern is discussed in detail by Dasgupta et al (1995).

The cracks which developed in the galleries on the downstream side and pressure tunnels on the upstream side were analysed using 3DEC (Itasca 1993). The 3DEC model of reservoir dam block and various excavations is shown is shown in Figure 3. Shear zones X, A and B dipping at 20^{o}, 70^{o} and 80^{o}, respectively, were also incorporated in the model. By incorporating this shear zones the rock mass has been modeled as a discontinuum rather than as a continuum. The shear zones are narrow and consist of weak material. The Young's modulus of the weak material was 1 GPa and the cohesion and friction were 0 MPa and 36.5^{o}, respectively. The elastic modulus for the rock mass was estimated as 7 GPa. The rock mass behaviour was assumed to be linear-elastic, while a Coulomb slip criterion was used for the shear zones. The in-situ stresses were measured using the hydro-face tests. The horizontal major principal stress, along the longitudinal axis of the cavern is 3 times the vertical stress and the intermediate principal stress across the cavern is 1.4 times the vertical stress. To account for non-linear behaviour of shear zones in the model, excavation was performed in steps up to the stage described above. The excavation sequence in the model was planned coinciding more or less with the actual sequence followed at site.

The problem was analysed using the rock mass displacements and tensile stresses. The horizontal displacement contours on plan section through the power house are shown in Figure 4. The continuity of the displacement contour lines is disturbed on the upstream side in the area where Shear zones A and B intersect and on the downstream side in Shear Zone A near Bus Gallery 3. The discontinuity of the contour lines signifies the movement of the shear zones with respect to the surrounding rock mass.

The minimum principal stresses on the down stream side at EL 18 and on the up stream side at EL 6.5 are shown in Figures 5 and 6. In these figures only tensile stresses are shown. The zones of tension are observed at junctions of the cavern and bus galleries and the cavern and pressure tunnels. The zones of tension in Bus Gallery 3 are indicated by contours A to E. Contour F indicates compression. Contour A represents tension higher than 2.5 MPa and extends up to 2.1 m from the cavern wall. Cracks of 50 mm width, parallel to the cavern axis, were observed in this area as shown in Fig 1. Contours B(2-2.5 MPa), C(1-2MPa), D(0.5-1MPa) and E(0-0.5MPa) extend upto a distance of 7 m, 12 m and 18 m, respectively, from the cavern wall. Cracks of 5-8 mm width were observed between 2-8 m along the bus gallery wall and cracks of and 1-4 mm width were observed between 16-17 m from the cavern wall. However no cracks were observed beyond 18 m where the tensile stresses range between 0-0.5 MPa (Contour E). Tensile stresses are also seen in the wall of Bus Gallery 2, as indicated by contour C. Minor cracks (1-3 mm wide) were observed upto a distance of 15m. On the upstream side , cracks were observed in Pressure Tunnels 2 and 3 up to a distance of 10 m and 6 m respectively, from the cavern wall as shown in Fig 2. Minor cracks were also observed in pressure tunnel 5. The minor principal stresses (Fig 6) in this area show higher values of tensile stresses indicated by contour C, which extends upto 15 m and 5.2 m in Pressure Tunnels 2 and 3, respectively. It can be noted that the zones of tensile stresses correlate with the areas where cracks developed.

The three dimensional discontinuum analysis was found to be effective in understanding the observed behaviour of the rock mass on the upstream and downstream sides of the power house. Although tensile stresses develop at the intersection of the excavations because of high horizontal stress along the axis of the cavern, the weak shear zones in the present case played a role in the rock mechanics problem. Cracks, primarily formed because the tension, were observed mainly at those junctions where the shear zones existed, and the model results were consistent with the field observations of the cracks. From this analysis it is felt that reliable observations of the rock mass disturbances can be effectively used in analysing the rock mechanics problems using numerical methods.

This analysis was undertaken when most of the deformation had taken place and no instrumentation in the wall was available. An instrumentation program has been designed based on the modelling to correlate the numerical model results between the present and the final construction stages. Multi-point borehole extensometers were installed on the downstream side to obtain maximum information when the remaining excavations are made.

3.2 *Srisailam Hydro-Power Project, Andhra Pradesh*

The underground hydro-power project, with a capacity of 1200 MW, is under construction at Srisailam on the left bank of river Krishna. The power house complex is located on the downstream of the Srisailam dam in Andhra Pradesh in South India. The complex consists of three large caverns viz., power house cavern, transformer hall and surge chamber located about 200 m below the surface. In addition, there are six pressure tunnels, six draft tube tunnels, four bus galleries and an access adit in the complex. The power house cavern is 25.7 m wide and 52.4 m high. The transformer hall is 16.2 m wide and 26.5 m high while the surge chamber is 74.5 m high and 20 m wide(average). The three caverns are parallel to each other separated by 30 m rock pillars. The rock formation is horizontally stratified and consists of quartzite and siltstone. Within the power house area, three major closely spaced joint sets are present. One of the joint sets is almost horizontal and continuous, while the other two are near vertical and continuous.

Three dimensional stress analyses of the power house complex were performed to study the stability aspects of the rock pillars between the caverns and the interaction of various small and large excavations using 3DEC. However, only the study made to examine the stability aspects of the pillars is discussed. The excavation geometry in 3DEC model is shown in Figure 7. The in-situ stresses are estimated from the results of hydro-frac tests. The vertical stress was assumed to be equivalent to the overburden stresses. The horizontal stress along and across the cavern was estimated to be 1.4 and 0.8 times the vertical stress, respectively. The laboratory uniaxial compressive strength is 200 MPa and the elastic modulus of the rock mass was estimated from classification data as 20 GPa.

The stability of the pillars was studied using the factor of safety. It was found that the 3DEC model with Hoek and Brown failure indicated that the over stressed zone could extend to a distance of 4 to 7 m in pillars. However, the distribution of principal stresses were also examined for tensile zones for possible effect on joints. The minor principal stress contours in cross section and plan view are shown in Figures 8 and 9. The minor principal stresses in the pillars range from tensile to low compression as indicated by Contour A. The zone of tensile stress in the pillar between the power house and the transformer hall, which has a width to height ratio of 0.57, is restricted to the wall of the excavation. However, in the pillar between transformer hall and surge chamber, which has a width to height ratio of 0.4, tensile stresses have developed in the entire width of the pillar, as seen in Figure 9. The tensile stresses are also seen in the downstream wall of the surge chamber. The development of tensile stresses in the pillars and walls of the caverns may cause opening of the near vertical joints running parallel to the cavern axis.

The stress analysis using 3DEC has helped in understanding the stability aspects of the pillars between the caverns. The three dimensional stress analysis is currently being used to study the stress conditions at the intersections of the caverns and the tunnels.

3.3 *Nathpa Jhakri Hydro-Power Project, Himachal Pradesh*

The Nathpa Jhakri Hydro-Power Project in the state of Himachal Pradesh in North India is under construction. The underground power house was planned for six units of 250 MW each with a total capacity of 1500 MW. The water from the reservoir to be created by construction of a concrete gravity dam across river Sutlej at Nathpa, will be diverted through underground desilting chambers to the power house at Jhakri by 27 km long race tunnel. Hydro power will be generated utilising a head of 488 m available between Nathpa and Jhakri. Located at about 300 m below the surface in an area characterised by rugged topography and lofty hills of the lower Himalayas, the underground complex consists of a power house, a transformer hall and other associated tunnels. The main rock type in the power house area is quartz mica schist. Several shear planes cross the power house. At present, excavation of central portion of the crown is completed.

The project is in preliminary stage. Stress analysis is being used in this project to predict the rock mass behaviour and to supplement the design of the support system for the cavern roof and walls. An instrumentation program for back analysis was also initiated based on the stress analysis.

Three dimensional analysis is in progress using 3DEC to study the interaction of multiple intersecting excavations, treating the rockmass as continuum and discontinuum. The 3D model of the excavations in Figure 10 as viewed from the downstream side shows the power house, transformer cavern, six draft tube tunnels, six bus galleries, two cooling water rooms and six gate shafts. In addition, there are six pressure shafts and an access adit on the upstream side. Preliminary rock mass parameters were estimated from the laboratory testing of rock mass classification system from the exploratory drift and central portion of the crown. The in-situ stresses were measured by the hydro-frac tests and the horizontal stresses along and across the caverns are 1.4 and 0.67 times the vertical stress, respectively.

Initially stress analysis was performed with the available rock mass properties and geologic features from the pilot tunnel driven along the power house crown. As the excavation progressed with the opening of the central portion of the crown, more data for the input parameters were generated from the rock tests and geologic logging.

4. CONCLUDING REMARKS

The numerical modelling used for the stress and design of large underground excavations in three major hydro-power projects in India has been highlighted in this paper. The response of rock mass to the creation of large multiple caverns joined by several tunnels has been studied to aid in support design.

The studies have shown that the design analysis of power house complexes can benefit from the ability to represent the details of three dimensional geometry as well as to simulate the discontinuous rock mass behaviour by incorporating explicitly the major shear zones of discontinuities in the numerical models. It is demonstrated that the field observations of rock mass behaviour can be helpful in calibrating numerical models in the absence of reliable instrumentation data.

Experience showed that non-hydrostatic insitu stressess play a dominant role in development of tensile stresses and cracks in caverns and junctions of the underground openings.

ACKNOWLEDGEMENTS

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Starfield, A.M. and P. A.Cundall 1988. Towards a methodology for rock mechanics modelling. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., 25(3), 99-106.*

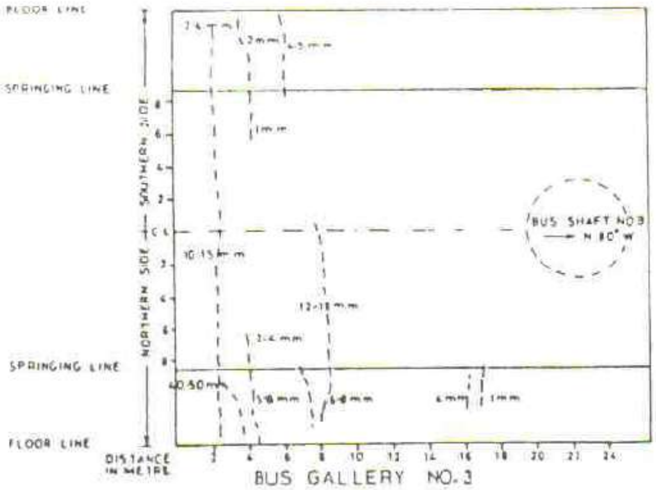
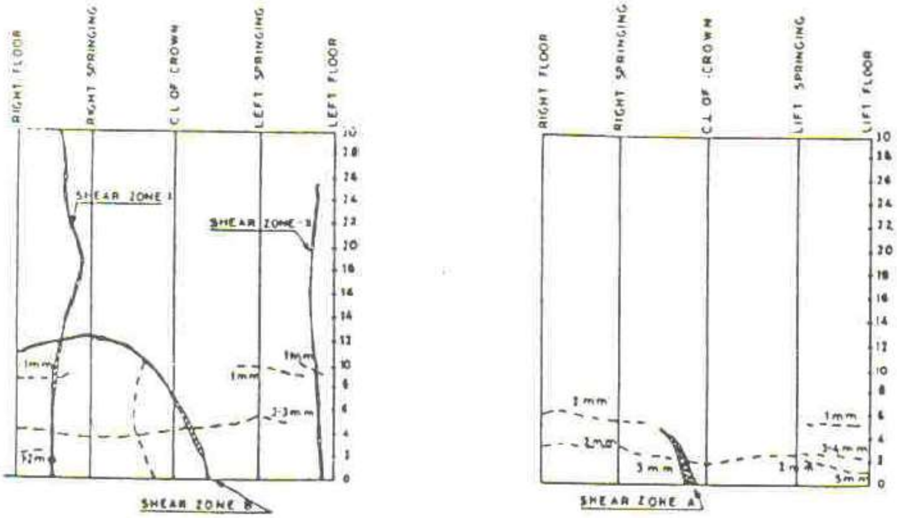


Fig. 1 Location and width of cracks (dashed lines) in Bus Gallery 3



PRESSURE SHAFT NO.2

PRESSURE SHAFT NO. 3

Fig. 2 Location and width of cracks (dashed lines) in Pressure Shafts 2 and 3

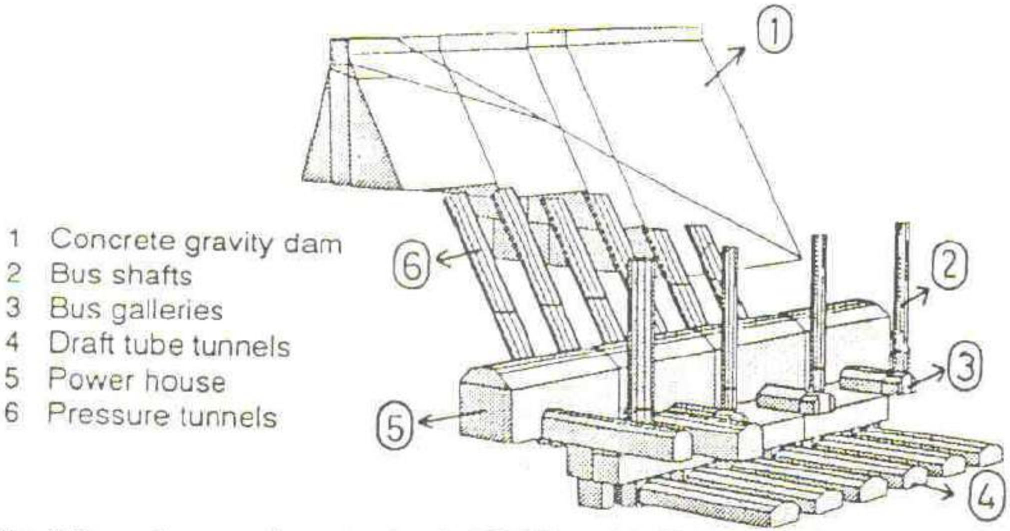


Fig. 3 Power house and gravity dam in 3DEC model of the Sardar Sarovar Project (see Fig. 11 also)

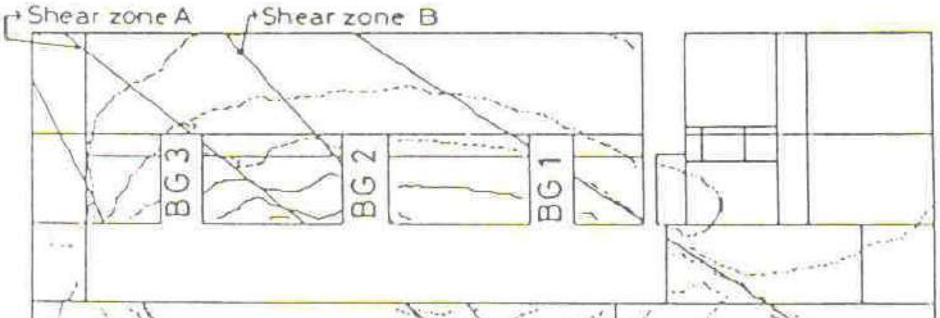


Fig. 4 Horizontal displacement contours in plan section at EL 18

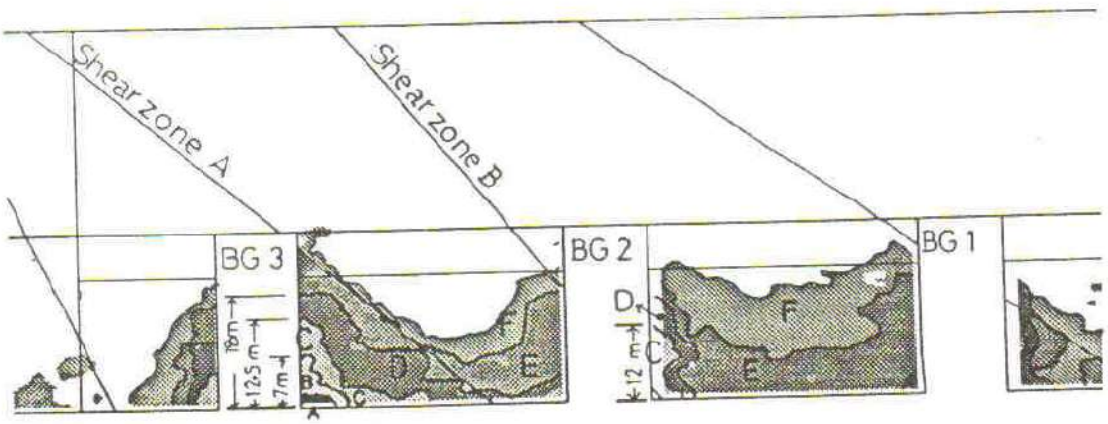


Fig. 5 Tensile zones on downstream side in plan section at EL 18

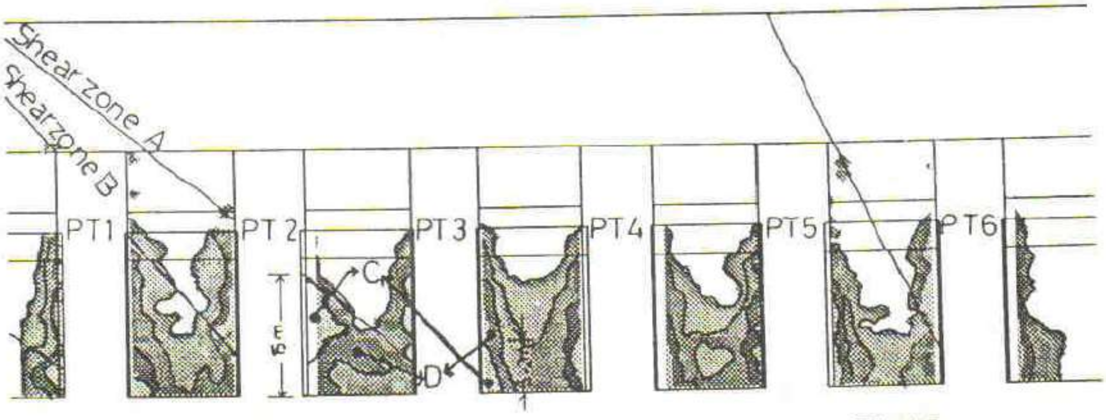


Fig. 6 Tensile zones on upstream in plan section side at EL 6.5

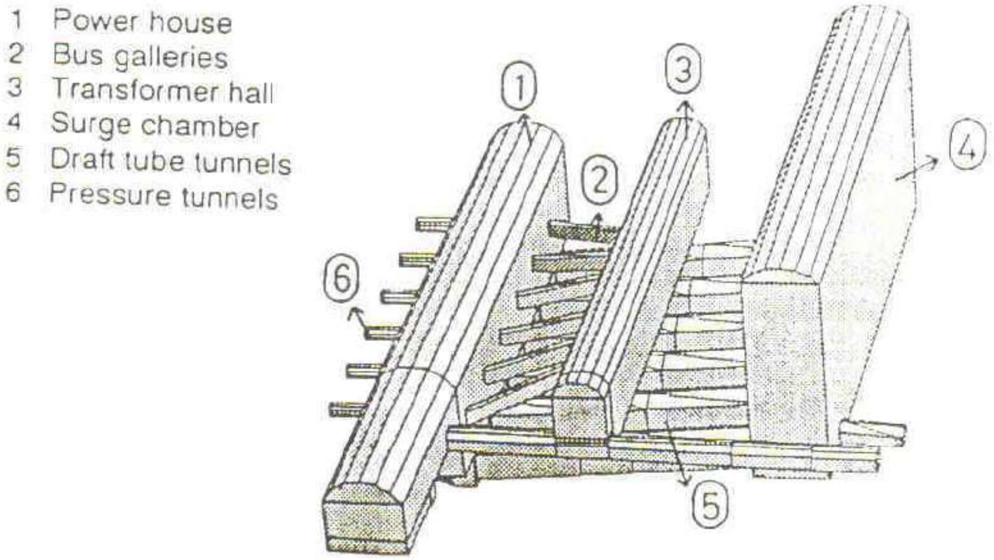


Fig. 7 3D model of excavations of the Srisailam power house complex (see fig. 12)

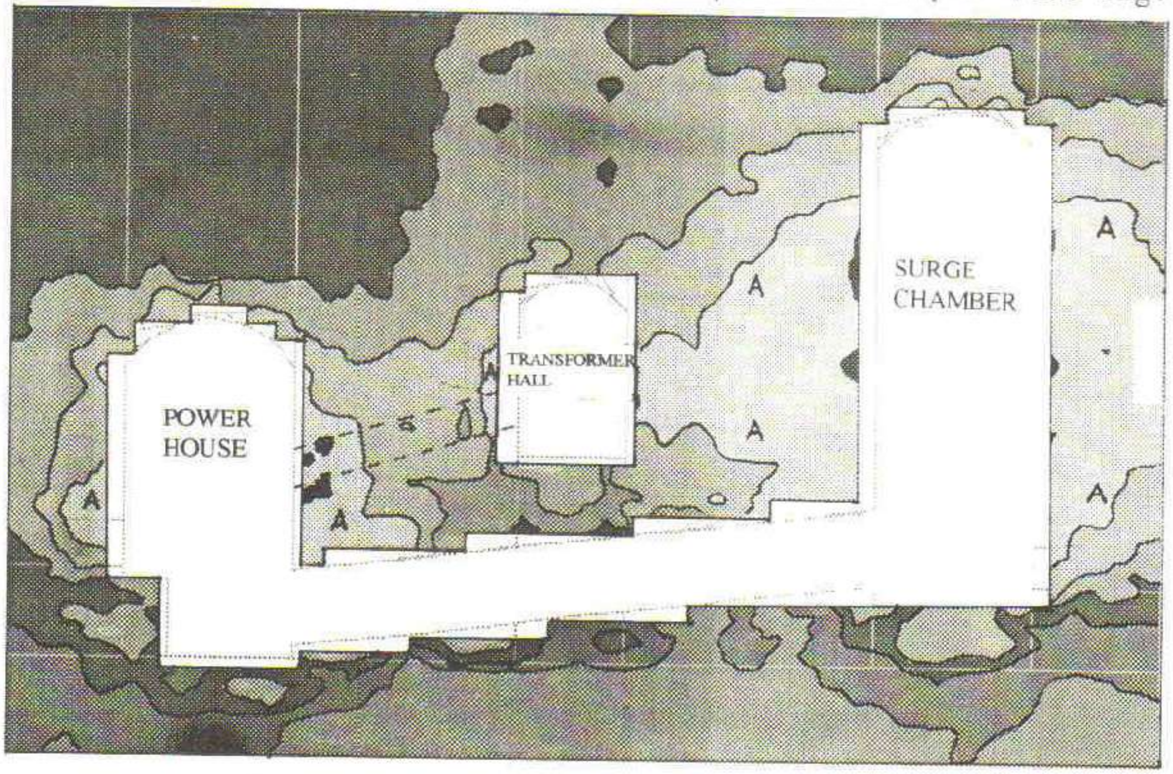


Fig. 8 Minor principal stress contours in a cross section

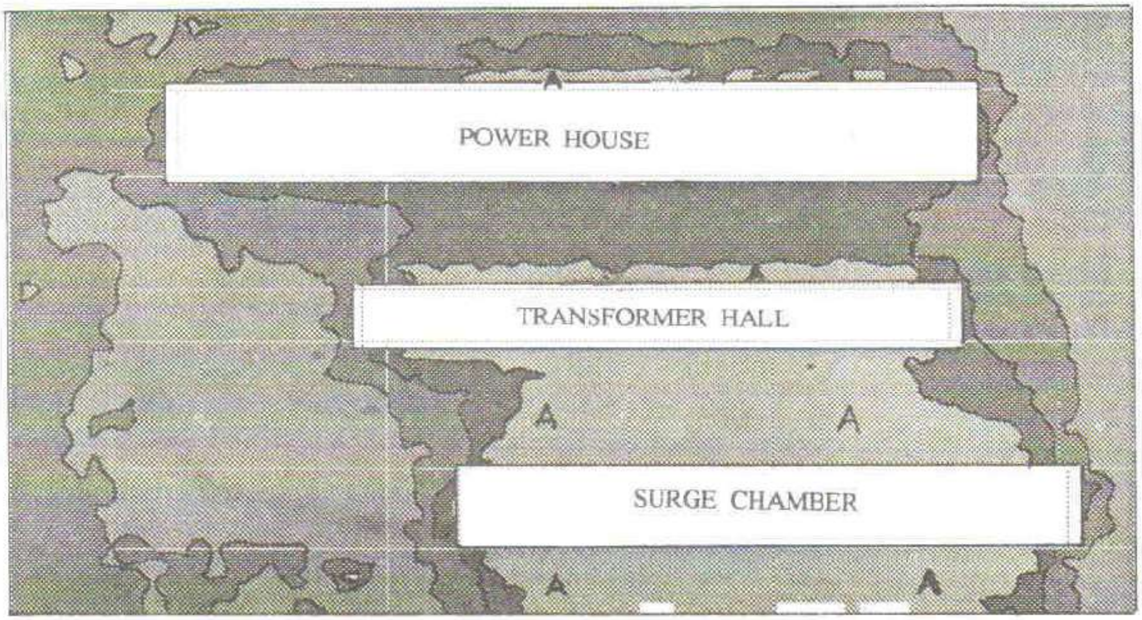


Fig. 9 Minor principal stress contours in a plan view

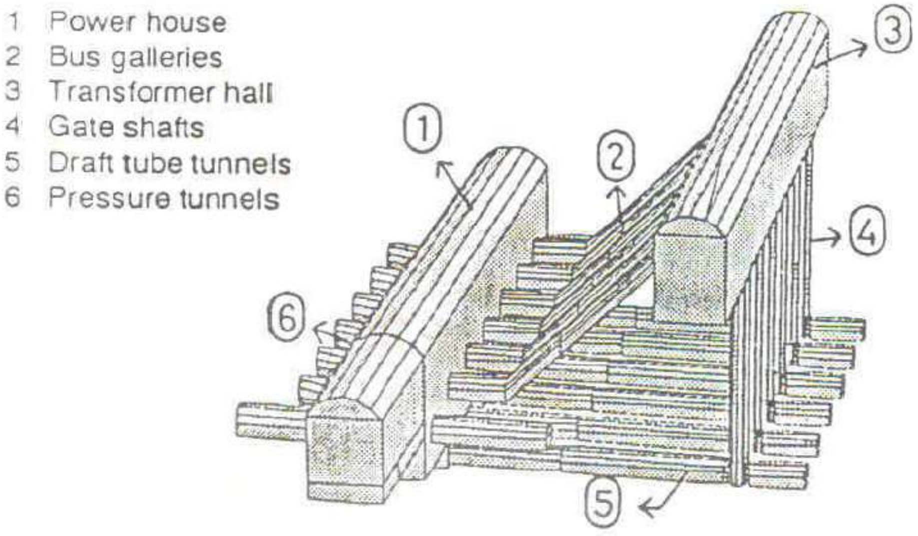


Fig. 10 3D model of excavations of the Nathpa Jhakri power house
(see Fig. 13 also)

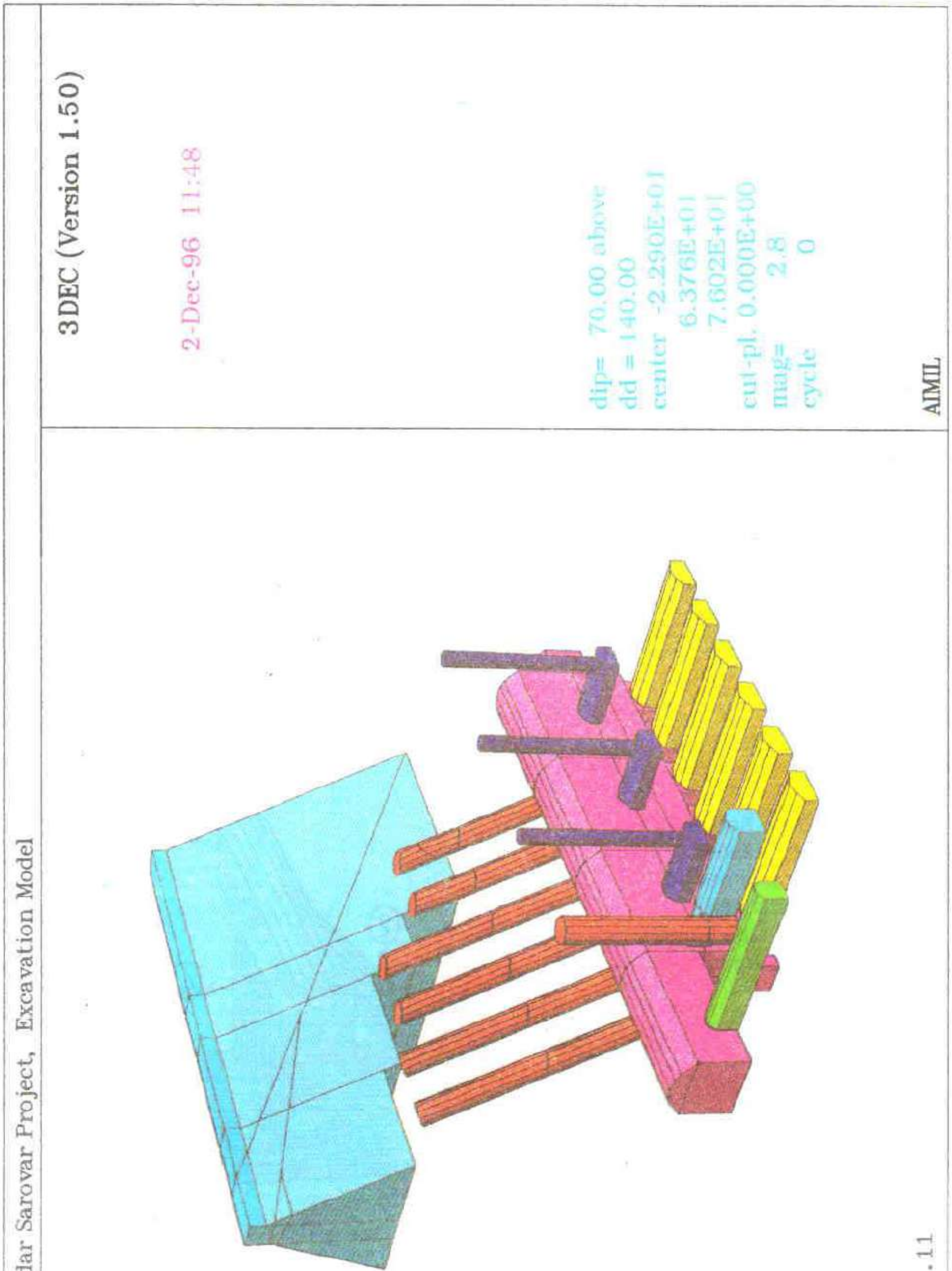

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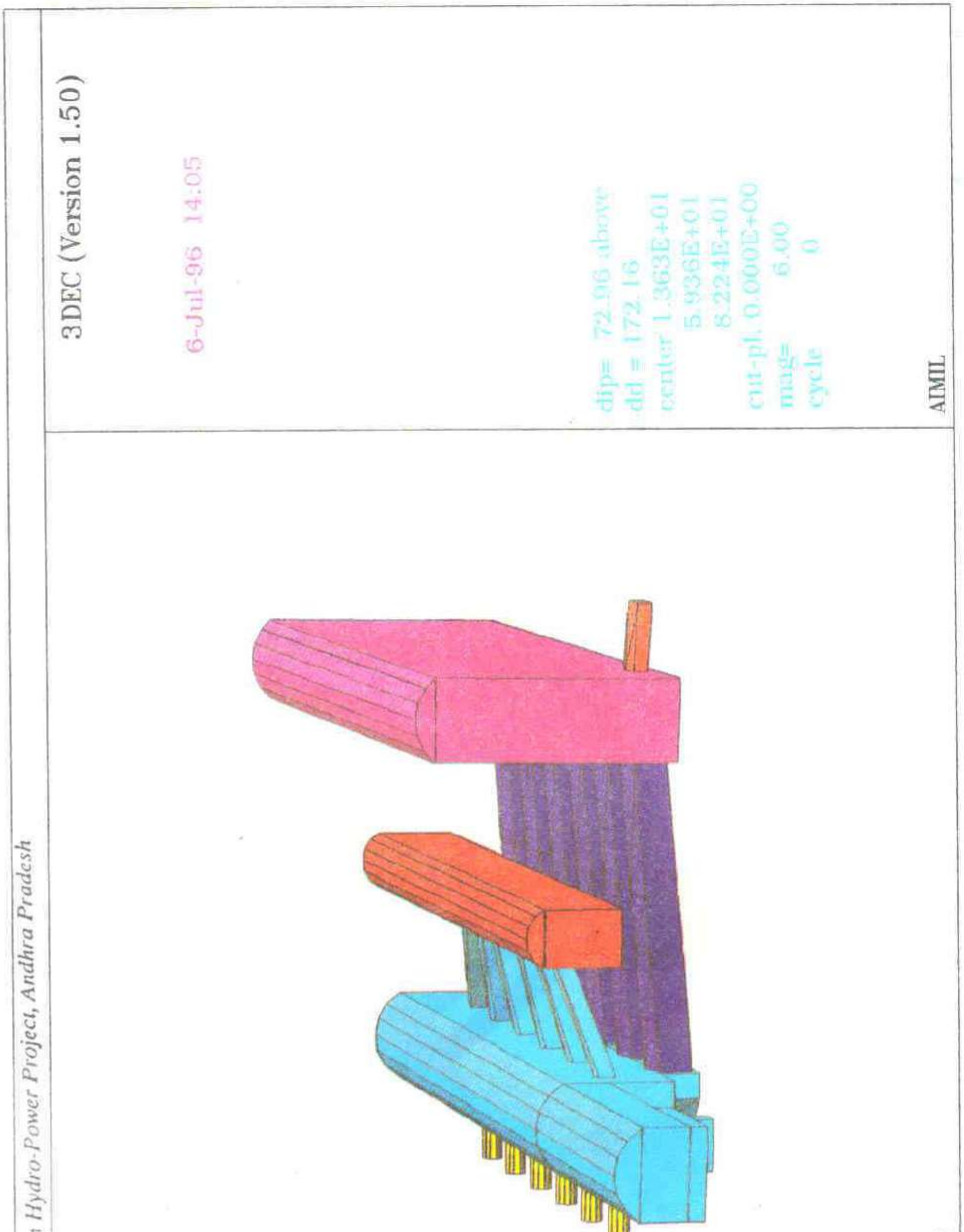
Fig.11



Srisailam Hydro-Power Project, Andhra Pradesh

Fig.12

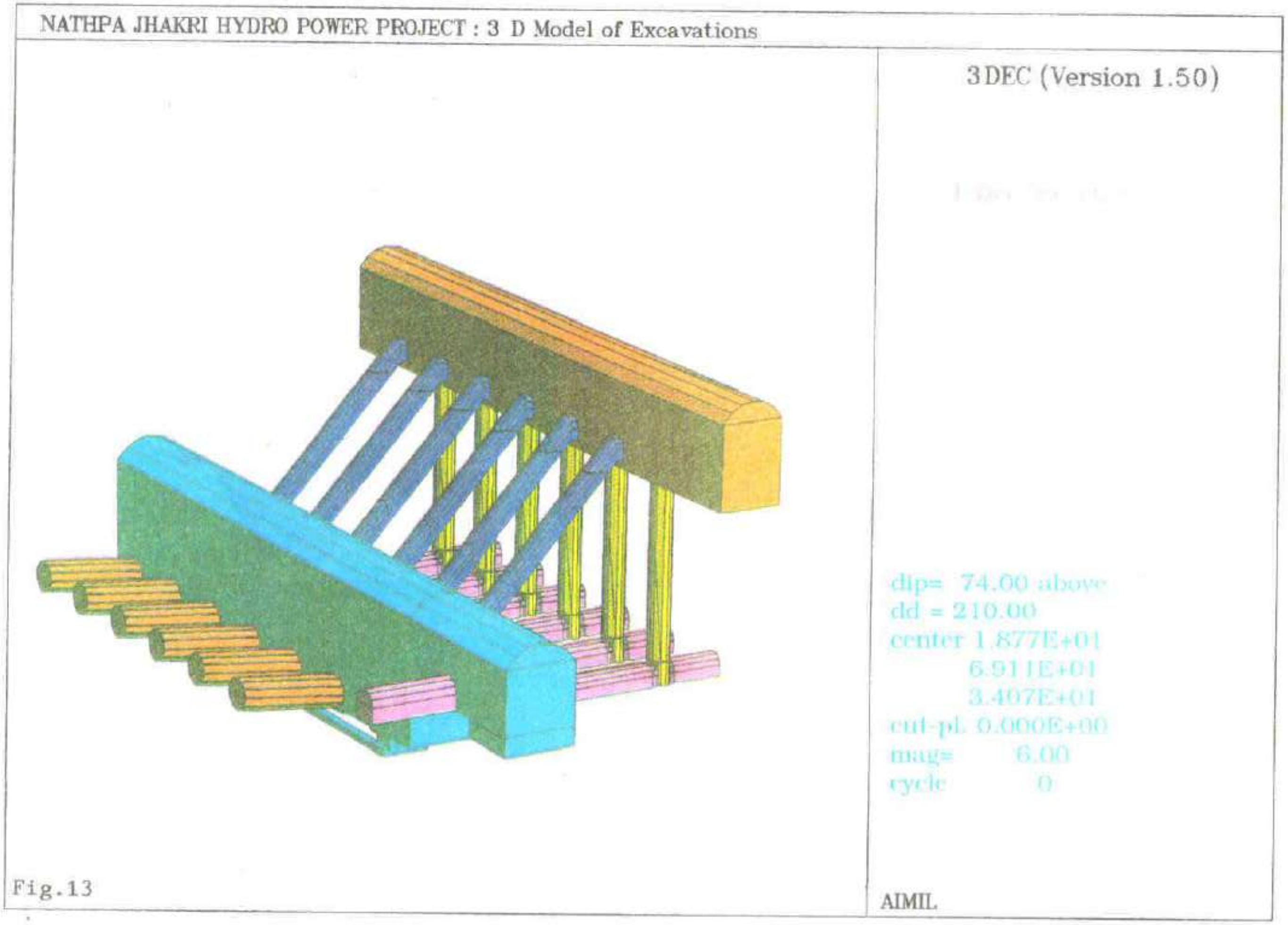

NATHPA JHAKRI HYDRO POWER PROJECT : 3 D Model of Excavations

Fig.13