Geometric Design of Underground Openings for High Horizontal Stress Fields

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SUMMARY Tunnels and hydro-power stations are frequently excavated in layered rock within 500 metres of the surface where the horizontal virgin stress can be expected to be greater than the vertical. The selection of the most suitable shape for such excavations is an important part of the design process and is usually based on stress analyses using elastic theory. This paper uses cross-anisotropic elastic theory to investigate the problem of the stress in the crown areas of common tunnel shapes in layered rocks with high horizontal stress fields. The paper also shows how consideration of the three dimensional aspect of hydro-power stations leads to an unusual chamber shape when high horizontal virgin stresses exist.

1. INTRODUCTION

A major aspect to the design of an underground structure is the selection of the shape of the opening. Within the constraints of the function of the opening the shape must be optimised in terms of the rock mass properties and the virgin stress field. The many measurements of these stresses made throughout the world have shown, (Herget 1974, Orr 1974, Blackwood 1978, Brown and Hoek 1978) that for depths of less than 1000m the major and intermediate principal stresses are likely to act horizontally or sub-horizontally. Such relatively high horizontal stresses have an important bearing on opening shape selection. In particular when combined with sub-horizontally bedded material, these virgin stresses can lead to unexpectedly high compressive stress concentrations. For homogenous, isotropic rock, optimum tunnel shapes are known for certain virgin stress fields provided body forces are excluded. These are :

(i) circular tunnel for a hydrostatic stress field,

(ii) elliptical tunnel with axis ratio equal to K (σ_h/σ_v) for a biaxial stress field,

(iii) deloid (Richards and Bjorkman, 1978) for a biaxial stress field with the horizontal component increasing linearly with depth.

For anisotropic rock, optimum tunnel shapes are not known even for a hydrostatic stress field. However, this paper does not attempt to solve this general problem but is rather directed to the practical problem of the stresses in the crown areas of common tunnel shapes in layered rock with K>1.0. The paper also presents an important practical consequence of considering the three dimensional aspect of excavations for hydro-power stations.

2 PATTERN OF HORIZONTAL STRESS

The measurement of virgin rock stress is difficult and thus while very many measurements have been conducted throughout the world, the accuracy of many results is suspect. However, it is quite clear that the general relationship between average horizontal stress and overburden pressure is as shown in Figure 1. It appears that this pattern of stress reflects primarily the effect of surface denudation (unloading) of virtually all continental crust. The process whereby such load removal (overconsolidation) generates values of K ($\sigma_{h\ ave}/\sigma_v$) greater than 1.0 is well established in soil mechanics theory. The linking of this theory to virgin rock stress in sedimentary rocks is given by Voight (1967). In the case of igneous and probably certain metamorphic rocks Goodman (1970) has shown how denudation will lead to very high horizontal stresses.

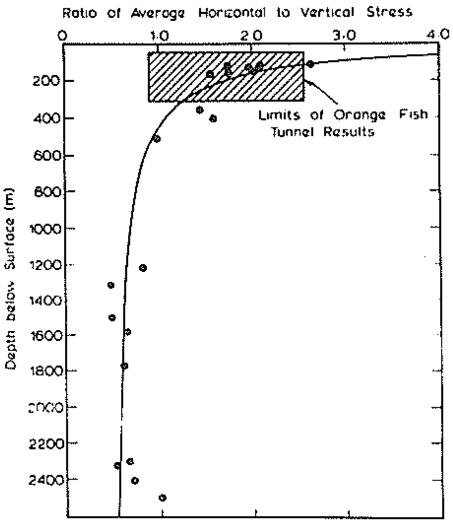


Figure 1 Variation of horizontal to vertical stress ratio with depth in Southern Africa (Van Heerden, 1976)

Imprinted over this high horizontal near surface stress pattern are the stresses associated with tectonic forces and also topographical variations. In certain areas e.g. Broken Hill, Australia the pattern of major and secondary horizontal stress can be closely linked with the tectonic features. However, there also appear to exist overall continental patterns; although to what extent these very near surface stresses can be linked to continental movements is at present uncertain. While it would be valuable in a predictive sense to understand what has led to the observed patterns of horizontal stress, it is more important to realise that most civil engineering underground openings must be designed for K values greater than 1.0.

3 CONSEQUENCES OF HIGH HORIZONTAL STRESSES ON TUNNEL DESIGN

In essence high horizontal virgin stresses lead to high compressive stresses in the roof (crown) of an underground excavation and usually tensile stresses in the sidewalls. Sometimes the compressive stress levels are not high enough to cause compressional failure in the form of slabbing or shear. In such cases the opening shape is selected on the basis of rock mass discontinuities so that critical wedges can be properly supported (Cording and Mahar, 1978). However, particularly in horizontally bedded sedimentary strata, compressional failure may well be a potential problem in the roof and also large zones of tension in the sidewalls may cause difficulties. The question is whether the selection of a suitable shape for the tunnel or power station chamber may minimise these problems. Certainly significant failures have occurred in conventionally shaped tunnels due to high horizontal stresses. For example certain sections of the 80 km long Orange-Fish tunnel (constructed in mudstone) showed major longitudinal compressional cracks in the roof shotcrete associated with shearing along bedding planes. This shearing reached such a magnitude that rock bolt holes closed up sufficiently rapidly to make redrilling necessary. A programme of rock stress measurement was instigated as a result of these problems and showed values of K ranging from 1.0 to 2.6 (Van Heerden, 1972). Similar problems were encountered in two tunnels in shale in Toronto where again high horizontal stresses were measured (Lo and Morton, 1976).

At least one case is recorded in the literature where an underground opening in sedimentary rock was designed specifically to reduce the effects of high horizontal virgin stresses on roof instability. This was the Poatina power station in Tasmania (Endersbee and Hofto 1963) which was successfully constructed with the shape shown in Figure 2. Some of the ideas adopted at Poatina were successfully incorporated in the shape design for the Drakensberg pumped-storage station (Bieniawski, Orr and Pells, 1974). The remainder of this paper shows how these ideas are of general validity and suggest tunnel and power station shapes somewhat different from the basic circle or horseshoe shape usually adopted.

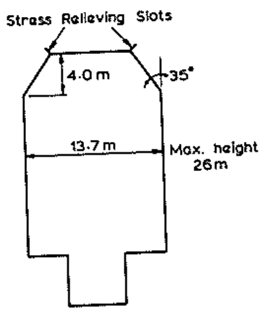


Figure 2 Poatina power station final design cross section

4 TUNNEL SHAPES IN HORIZONTALLY BEDDED OR LAMINATED ROCK

Because of their length, tunnels can be analysed in two dimensions and usually tunnel shapes are evaluated on the basis of solutions for isotropic elasticity. While the finite element method has been developed to the stage that virtually any discontinuous, non-linear rock mass can be modelled (Pells, 1974) it remains true that most opening shape selection is based on isotropic elasticity. This is usually satisfactory as comparisons of elastic solutions for different shapes enable one to select the optimum shape on the basis of :

(i) the minimum volume of rock subject to high compressive stresses,

(ii) the magnitude of the maximum compressive stress on the opening surface,

(iii) the location and magnitude of tensile stress zones,

(iv) the length of planar surfaces parallel to the direction of maximum compressive stress (Cording and Mahar, 1978).

In the case of openings in horizontally bedded rock subject to high horizontal stress fields, isotropic elasticity is unsatisfactory in indicating the magnitude and size of zones of compressive stress in the crown area. Where the rock layers are massive but separated by clearly defined bedding discontinuities, it is possible to use joint elements in numerical analysis of particular openings. However, for shales and closely bedded siltstones, mudstones and sandstones this approach is not feasible. It is suggested that these latter materials can be modelled using cross-anisotropic elasticity (Salomon, 1968). This involves five independent elastic parameters, namely :

E_v = Young's modulus in the vertical direction

E_h = Young's modulus in the horizontal direction (parallel to bedding)

ν_{vh} = Poisson's ratio for effect of vertical stress on horizontal strain

ν_{hh} = Poisson's ratio for effect of horizontal stress on horizontal strain

G = Independent shear modulus in a vertical plane.

It is postulated that the behaviour of closely layered rock around a tunnel can be modelled by assuming $E_h=E_v$, $\nu_{hh}=\nu_{vh}$ but with G being low so that $E_h/G >> 2(1+\nu)$. This model is analogous to a stack of playing cards with the cards being held together with extremely thin layers with very low shear stiffness. In reality, for bedded sedimentary rocks E_h is usually 1.5 to 3 times E_v (Gerrard, Davis and Wardle, 1972) but if all other parameters remain the same then such small differences between E_h and E_v have little effect on the overall stress pattern around a tunnel, although the maximum stress concentration at the periphery is increased.

Lo and Morton (1976) have analysed the stress concentrations around the periphery of a circular tunnel in cross-antisotropic rock and show (see Figure 3) how the stress concentration in the crown increases rapidly with increasing values of E_h/G. A similar increase in stress concentration was obtained by Goodman (unpublished) by considering a single horizontal bedding discontinuity at different distances above the crown of a circular tunnel. Both

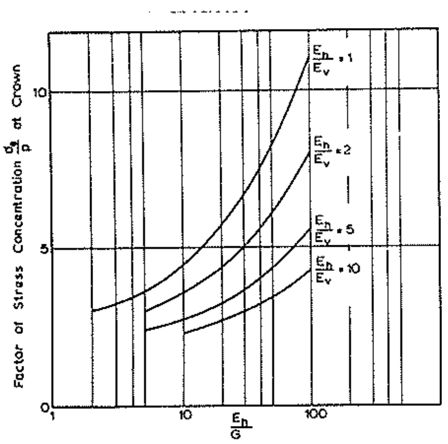


Figure 3 The effect of the ratio E_h/G on the stress concentration factor

these approaches show quite clearly that compressional failure may occur in the crown area of openings with circular roofs in bedded rock when conventional isotropic stress concentration factors would indicate stability.

In the light of the experience at Poatina it was decided to investigate the stresses around flat topped tunnels with bevelled corners using the anisotropic rock mass model described above. The analyses were conducted using 8 node isoparametric finite elements and it was assumed that the tunnels were sufficiently deep that the unit weight of the rock could be ignored. Two, square, flat-topped tunnels were considered with bevelled corners of 0.1 and 0.2 times the tunnel height respectively. For comparison purposes the circular tunnel was also analysed.

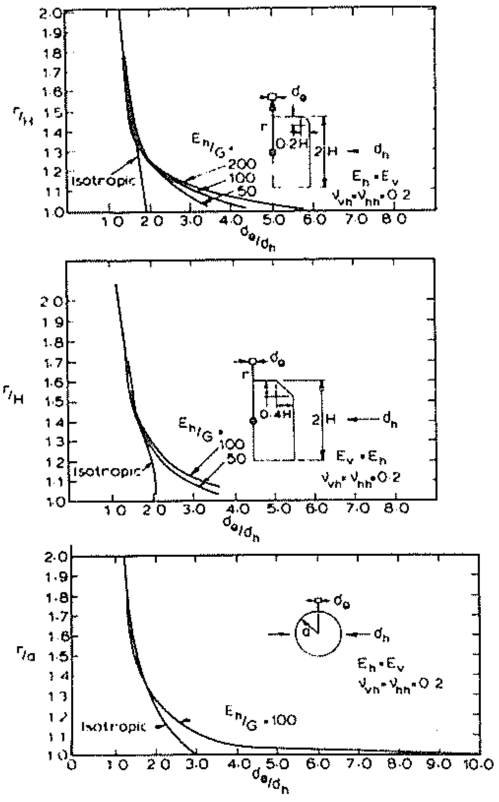


Figure 4 Stress concentration in tunnel crowns

Figure 4 shows the horizontal stress concentration for a purely horizontal virgin stress along the vertical axis at the centre of the roof, for each of the three tunnel shapes, for different values of E_h/G. Also shown are the values for isotropic rock. For this purely horizontal stress field and for E_h/G = 100 the contours of horizontal stress for the three shapes are given in Figure 5. Finally for a purely vertical virgin stress field the horizontal stresses above the crown centreline are shown in Figure 6.

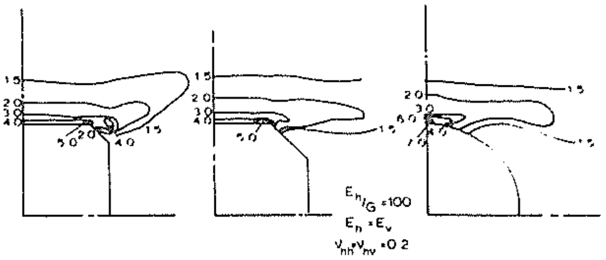


Figure 5 Contours of horizontal stress as a function of the virgin horizontal stress field

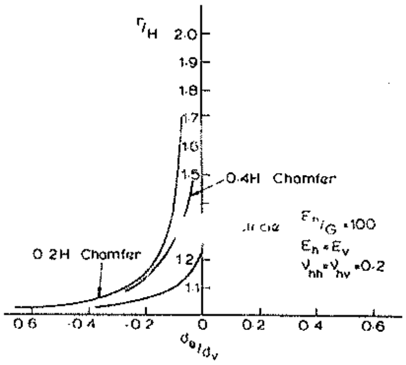


Figure 6 Horizontal stress concentration in crown for vertical virgin stress field

Examination of the results presented in Figure 4 to 6 reveals the following points :

(i) The greatest value of the horizontal stress concentration is in the crown of the circular tunnel. This value is greater than the stress concentration above the haunches in the square tunnels. This is similar to the situation for square tunnels with rounded corners in isotropic rock (Obert and Duval 1967).

(ii) The horizontal stresses above the flat roof are similar for both square tunnels with the stress being equal to about 4 times the virgin horizontal stress for a distance of 0.04H into the rock. The maximum stress is thus directed parallel to the bedding which is a situation that Cording and [illegible] (1978) suggest should be avoided. However, the present author considers this preferable to the situation in the circular tunnel where, in the centre of the roof, for a distance of 0.04D into the rock, the horizontal stresses exceed 6x the horizontal virgin stress field. Furthermore Figure 6 shows that the vertical stress field will reduce the crown stresses to a greater extent in the flat topped tunnels than in the circular tunnel.

(iii) The horizontal stress concentration above the flat topped tunnels decays more slowly with depth than above the circular tunnel. Thus the shear stresses on the bedding planes are greater above the circular tunnel.

(iv) The stresses above both square tunnels are very similar and thus the use of a large haunch is indicated as this reduces the flat roof span.

It would thus appear that the roof shape adopted at Poatina is valid for reducing compressive roof stresses in all situations where high horizontal virgin stresses occur, particularly where these are associated with horizontally bedded strata. However, it should be noted that where compressive failure will not occur but where the rock mass is blocky, this flat topped shape is probably undesirable.

5 UNDERGROUND POWER STATION SHAPES FOR HIGH HORIZONTAL STRESS FIELDS

5.1 The Drakensberg Pumped Storage Power Station

The author's comments on the subject of shape selection for underground power stations dates from his involvement in the design of the 1000 MW Drakensberg pumped storage scheme (Bieniawski, Orr and Pells, 1974). This power station has recently been completed and is excavated in horizontally bedded Triassic mudstones and sandstones. At the early design stage it was suspected that the horizontal virgin stress would be greater than the vertical but because stress measurements had not yet been performed, all analyses were carried out for K = 0.4, 1.0 and 2.0. The initial shape selection was based on the results for K = 2.0. Subsequent measurements indicated that the horizontal stress varied from 1.2 to 2.6 times the vertical stress with an average value of 2.1.

In the initial design three shapes were considered. The first, shown in Figure 7a, is the classic shape for an underground power station. The second, shown in Figure 7b, is based on the Waldeck II power station in West Germany. The third shape was based on the Foyers pump storage scheme in Scotland. This involved placing the machines in shafts and not in a massive machine hall. At Foyer's the shafts were excavated from the surface and the control building is a surface structure. At Drakensberg, proposal 3 was for two 36m diameter shafts for the 4 x 250 MW machines but excavated underground with the control system being housed in an underground chamber passing over the two shafts. Figure 7c shows a cross-section of this proposal.

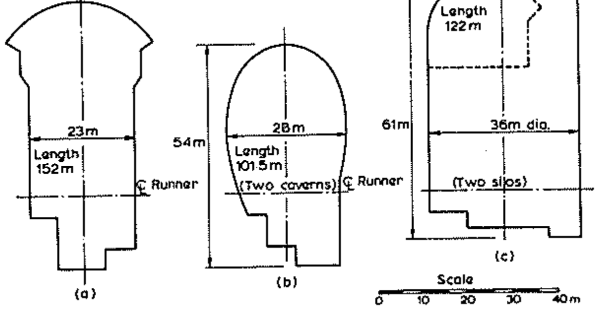


Figure 7 Three alternative shapes for the power station

5.2 Stress Analyses

Isotropic elastic analyses were used in all cases. Shape proposals 1 and 2 could be analysed in two dimensions but proposal 3 involved a 3D finite element analysis. Figure 8 shows the outline of the block that was divided (by hand) into 1522 eight node brick elements.

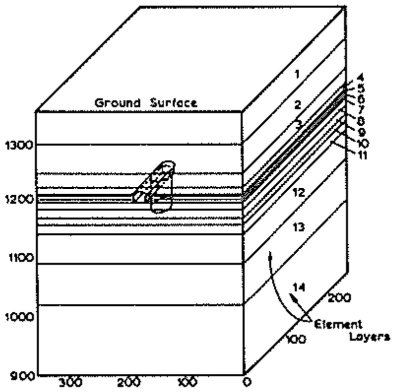
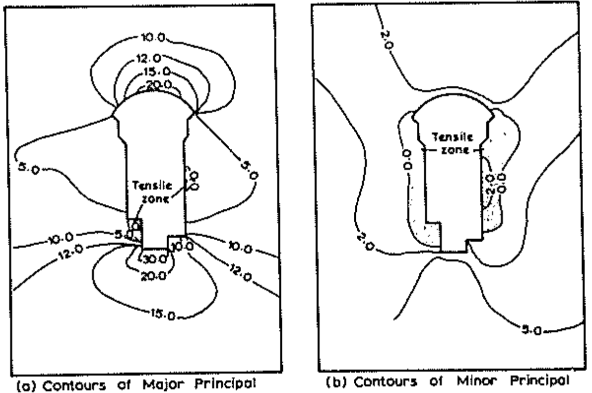


Figure 8 Three dimensional finite element model of shape proposal 3

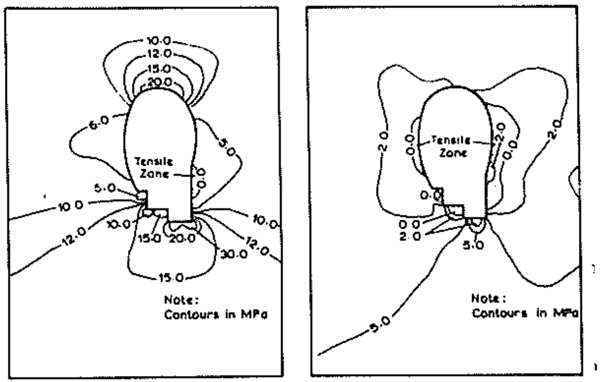
Figures 9 and 10 show the contours of major and minor principal stress for a virgin stress field ratio K = 2.0, for shapes 1 and 2. In both cases there are large zones of tensile minor principal stress in the sidewall with small regions of tensile major principal stress. Also in both cases the crown compressive stresses exceed 20 MPa which was greater than the unconfined strength of certain of the mudstones.



(a) Contours of Major Principal Stress

(b) Contours of Minor Principal Stress

Figure 9 Shape proposal 1: horizontal stress = 2 x overburden pressure



(a) Contours of Major Principal Stress

(b) Contours of Minor Principal Stress

Figure 10 Shape proposal 2: horizontal stress = 2 x overburden pressure

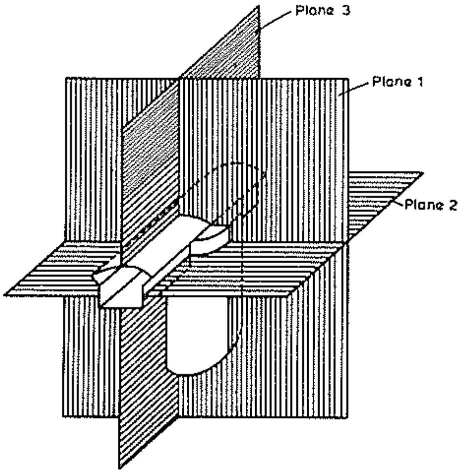
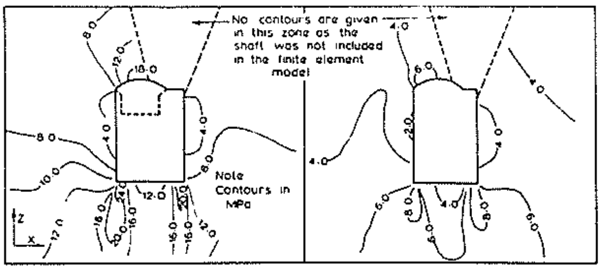


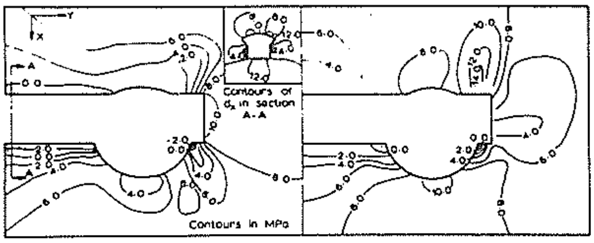
Figure 11 Shape proposal 3 planes on which stress contours are given in Figures 12,13 & 14

Figure 11 shows the three planes in which stress contours were produced from the 3D analysis of proposal 3. The contours are given in Figures 12, 13 and 14. In considering those contours, two particular points arise. The first is that, as opposed to shapes 1 and 2, very limited zones of tensile stress occur in the sidewalls of the machine chamber. This is because this shape offers a circular "ring" to the high horizontal stresses and not a long and high, flat or slightly curved wall. The second point is that the stresses induced in the roof are less than those in shapes 1 and 2.



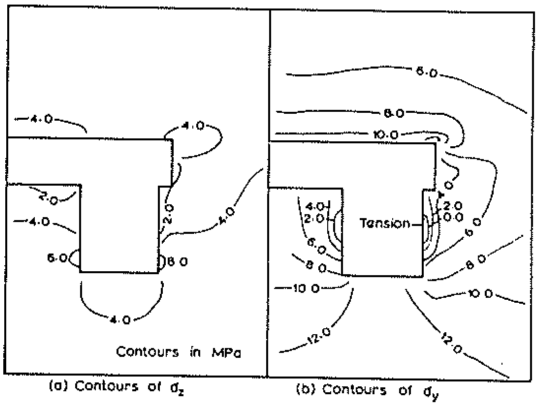
(a) Contours of σ_x (b) Contours of σ_y

Figure 12 Shape proposal 3
Contours of stress in plane 1



(a) Contours of σ_x (b) Contours of σ_y

Figure 13 Shape proposal 3
Stresses in plane 2



(a) Contours of σ_z (b) Contours of σ_y

Figure 14 Shape proposal 3
Stresses in plane 3

As a result of these analyses and certain other practical considerations it was proposed that the final power station shape be based on a combination of the shaft feature of proposal 3 with the roof shape used at Poatina. This is shown in Figure 15. As described by Bowcock, Boyd, Hoek and Sharp (1977) the final power station shape did incorporate the features suggested in Figure 1 and has been successfully completed. It is suggested that these features could be incorporated in any underground power station constructed in similar rock and virgin stress conditions.

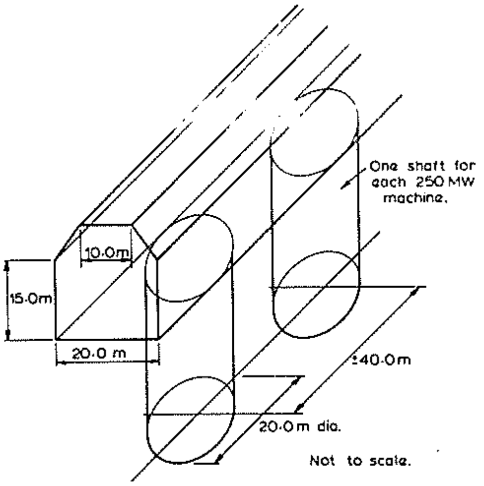


Figure 15 Suggested optimum shape for power house

CONCLUSIONS

1. The use of cross-anisotropic elasticity with high values for the ratio E_H/G appears to provide a good model for the evaluation of tunnel shapes in layered rock.

2. Openings constructed in layered rock and subject to relatively high horizontal stress fields may be subject to very high crown compressive stresses.

3. In horizontally bedded strata with high horizontal stresses, it appears that flat topped openings with large corner haunches are more suitable from the point of view of compressive roof stresses that openings with circular roofs.

4. The most suitable shape for large underground hydro power stations in layered rock subject to high horizontal stresses involves the machines being housed in individual shafts with a relatively low height control chamber passing over the shafts. The roof of this control chamber should be flat topped with large corner haunches.

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