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DESIGN OF UNDERGROUND ARTIFICIAL DAMS FOR MINE WATER STORAGE

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SUMMARY

The paper describes the approaches used for design of underground dams in different countries. The merits and demerits of design methods are critically discussed. An approach based on thick plate theory developed by the authors is presented. The factors which govern the thickness of a dam are outlined. The influence of blasting on dam design and a method to estimate the dynamic stresses due to blasting is suggested. In the authors' view only arch shaped dams of cement concrete should be constructed. If the thickness of a dam exceeds 3 or 4 m a multistage dam is suggested. A case study and design details are included in the paper for guidance.

INTRODUCTION

In mines, underground dams are constructed mainly to prevent innundation of dip side workings by isolating the adjacent flooded areas. They are also used to flood a portion of a mine in case of a fire and to limit the amount of pumping and to keep water under control so that it may be drawn off as and when required. In some instances a dam is also fitted with a bulk head door whilst approaching old workings.

The factors which govern the design of a dam are the size of roadway, the nature of adjacent strata, the estimated water pressure and the form of dam. Care should be taken while estimating the maximum water pressure on a dam. Dynamic stresses are produced in the rock mass and in the accumulated water whenever blasting is carried out in the neighbourhood of a dam. The dynamic stresses increase the total head of water on a dam and therefore, should be estimated separately.

It is essential that a dam should be constructed in the strongest available strata, free from fissures and not likely to be disturbed by subsequent workings. The dam material and the ground must be strong, impervious to water and must resist deformation. A weak or fissured strata must be strengthened after completion of the dam by injection of cement under pressure and rock bolts. The width of the pillar in which the dam is to be constructed must be sufficient to withstand crushing from the strata forces.

DESIGN CONSIDERATIONS

The most important parameter in the design of an underground dam is the estimation of its safe thickness under a given set of conditions. The factors which are normally considered are:

1. the maximum water head to be resisted,
2. the nature and the geotechnical properties of the surrounding strata,
3. the crushing strengths of the materials to be used,
4. the cross-sectional area of the gallery,
5. the form of the dam - flat or straight, cylindrical or arched, and
6. the type of the dam - temporary or permanent.

Various approaches have been adopted to estimate the safe thickness of a dam. References relating to the design of safe thickness of a dam include Kalmykov (1), the Directorate General of Mines Safety in India (2), Aldis (3) and Peele (4).

ESTIMATION OF THE THICKNESS OF A DAM BASED ON THE CRUSHING STRENGTH OF THE MATERIAL

Equations, which estimate the thickness of a dam based on its crushing strength, assume a certain factor of safety. This is done to calculate the safe permissible crushing strength. Different authors have suggested different factors of safety for the purpose. Kalmykow (1) suggests a factor of safety of 3.5 to 4 on the ultimate crushing strength. Aldis (3) suggests a factor of safety of 10. In USA a factor of safety of 8 is most common (4). In India, DGMS suggests a factor of safety of 15. For designing cement concrete structures a factor of safety between 3 and 5 is normally taken by Civil Engineers. In authors view a factor of safety of 8 to 10 on the ultimate strength of dam material is more than adequate for design purposes keeping in view long term stability. A factor of safety of 8 is suggested for dams having life of 5 years and less.

It is appropriate to mention here that the ultimate crushing strength of a dam material should be determined whilst the dam is under construction. In one instance the authors observed that the ultimate crushing strength of cement-concrete samples, collected from the dam site, was only 40 percent of the design value.

Kalmykov (1) suggests the following equation to estimate the safe thickness of a cement concrete wedge shaped straight dam:

$$t = \frac{B + h}{4 \tan \alpha} \left(\sqrt{\frac{4 \lambda \, pBh}{4 \sigma_{c/f} (B + h)^2} + 1} - 1 \right) \quad (1)$$

where, t = thickness of the dam

B = width of the gallery

h = height of the gallery

α = angle of inclination of dam wedge at the side with the horizontal

σ_c = ultimate crushing strength of the cement concrete mixture

p = total water pressure on the dam

f = factor of safety to be provided for the dam material

λ = coefficient of overloading = 1.25

k = coefficient for strength variation = 0.6

The Director-General of Mines Safety in India (2) recommends the following empirical equation for estimating the thickness of cement-concrete dams:

$$t = \frac{0.3pB^{1.5}}{\sigma_c'} \tag{2}$$

where, t = thickness of dam in ft

p = total water head in ft

B = width of the gallery in ft

σ_c' = safe permissible crushing strength of the cement concrete mixture

$= \dfrac{\text{Ultimate strength}}{15}$

= 250 psi (1.724 Mpa) for a 1:1.5:3 cement-sand-concrete ratio (ultimate strength = 3750 psi (25.86 Mpa)

For the design purpose DGMS suggests an arbitrary addition of 25 percent to the calculated thickness for water heads between 60 m and 150 m. This is done to compensate for the variation in the strength of dam materials.

The majority of dams in Indian mines are made of bricks. The estimation of strength of a brick dam is not only difficult but there can be significant difference between the estimated and the actual strength. This is because of the large variations in the strength of bricks which are used for the construction purposes. Crushing strength of burnt bricks varies between 4.3 and 20.7 Mpa (625 and 3000 psi). The strength decreases when soaked in water by 25 percent approximately. Strength of unburnt (sun dried) bricks varies between 1.62 and 3.76 Mpa (235 and 545 psi). A brick of about 17.24 Mpa (2500 psi) in crushing strength has 6.62 Mpa (960 psi) in transverse strength, 4.69 (680 psi) in tensile strength and 1.73 Mpa (250 psi) in shearing strength (8).

Crushing strength of brick masonary is only 1/3 to 1/5 of the crushing strength of a single brick and depends upon the mortar used and the bond. The specific gravity of the brick should not be less than 1.8. Mortar can be 1:3 ratio. Addition of lime up to 1/4th of the volume of cement is beneficial as it improves the workability without impairing strength. The strength of such brick work would be up to 83 percent of the strength of the brick.

In one case authors' investigations revealed that the tensile strength of the bonding material (1:3:6 mortar) used for the brick work was less than 0.1 Mpa (14.5 psi). The crushing strength of the brick work (fully saturated) was 5 Mpa (725 psi) and the bending strength of 1.5 Mpa (217.5 psi). Thus, the strength values obtained were extremely low when compared to values commonly used for design purposes. The authors, therefore, do not suggest brick dams for underground.

Professor Aldis in the UK (3) suggests the following equation to estimate the thickness of a cylindrical dam:

$$t = r_i\left(1 - \sqrt{1 - \frac{20p}{\sigma_c}}\right) \qquad (3)$$

where, r_i = the shorter or the external radius of dam

p = total water pressure on the dam

σ_c = ultimate crushing strength of the dam material

It is to be noted that in equation 3 the value of the factor $20p/\sigma_c$ should always remain less than 1. This limits the application of the equation.

The shorter or external radius of a dam, r_i, can be estimated from the following expression:

$$r_i = \frac{B}{2 \operatorname{Sin} \alpha} \qquad (4)$$

where, α = half the central angle of curvature of the arch ≃ 20° to 30° in strong ground and 12° to 20° in moderately strong ground.

ESTIMATION OF THE THICKNESS OF A DAM BASED ON THE SHEAR STRENGTH

In underground situations, the normal ground stress acts on pillars which house the dam. Thus, only a portion of the ground stresses act over a dam. A dam is therefore, unlikely to fail under the normal ground stresses until such a time when the pillars supporting it fail. Estimation of the thickness of a dam based on the compressive strength of the dam material if therefore, unlikely to yield a realistic value.

An underground dam should be designed to withstand the maximum hydrostatic pressure of water. The governing factor, therefore, is the length of the shear plane of rock in which the dam is constructed or the safe permissible shear strength of the dam material. The greater of the two thickness is taken for the design purposes. The thickness of a rectangular dam to resist shear is:

$$t = \frac{Bhp}{2\,(B+h)\,\sigma_{s/f}} \qquad (5)$$

where, σ_s = ultimate shearing strength of the dam material or the rock whichever is less

f = factor of safety to be provided

The ultimate shear strength of the rock should be determined insitu as far as possible. A factor of safety of 2.5 on the in situ value should be sufficient for the design purposes.

In the laboratory the ultimate shear strength of the rock or the dam material can be determined by the use of double shear apparatus. Alternatively, it can be estimated, if the crushing strength and the tensile strength are known, by the use of the following relationship:

$$\sigma_s = \tfrac{1}{2} \sqrt{\sigma_c \sigma_t} \tag{6}$$

The tensile strength and the modulus of elasticity of a cement-concrete mixture can be estimated by the use of the following empirical relationship (5):

$$\sigma_t = 1/3 \sqrt{\rho \sigma_c} = 3.33 \text{ to } 4.02 \sqrt{\sigma_c} \tag{7}$$

where, σ_t = tensile strength of concrete (psi)

ρ = density of concrete in pcf (100 to 145 pcf)

σ_c = compressive strength (psi)

The modulus of elasticity (E_c in psi) can be estimated from the following relationship:

$$Ec = 33 \sqrt{\rho^3 \sigma_c} \tag{8}$$

The safe permissible shear strength of cement-concrete mixture can be estimated by taking a factor of safety of 10 on the ultimate strength. For coal pillars, the safe permissible shear strength can be estimated by taking a factor of safety of 15 on the ultimate strength determined in the laboratory. It can be argued that according to the weakest link theory, the strength of a coal pillar is about 7.5 times less than the laboratory strength. There is a further reduction in strength due to time which could be up to 50 percent. The safe permissible shear strength of coal can thus be estimated by the following relation:

$$\sigma_s' = \frac{\sigma_s}{15} = \frac{1}{30} \sqrt{\sigma_c \sigma_t} \tag{9}$$

where, σ_s' = safe permissible shear strength of coal

ESTIMATION OF THE DAM THICKNESS BASED ON THE TENSILE STRENGTH OF ITS MATERIAL

Peele (4) suggests that the thickness of a dam can be estimated by the use of the thick beam formula:

$$t = \sqrt{\frac{pB^2}{2\sigma_t'}} \qquad (10)$$

where, σ_t' = the safe permissible tensile strength of the dam material.

In the opinion of the authors, the thick beam formula assumes that two sides of a dam are supported at the side abutments. In fact this is not the case because a dam is supported on its four sides. Thus, the thickness of a dam can be estimated by assuming it is a plate supported on it's sides with a uniform distributed load over it. The final simplified solution takes the following form:

$$t = \left[\frac{3}{4} \; \frac{h^2 K \, p}{\sigma_{t/f}} \; \frac{(m + 1)}{m} \right]^{\frac{1}{2}} \qquad (11)$$

where, p = total water pressure on the dam

m = poissons number of the dam material

k = a coefficient which depends on the ratio of the two sides of the dam

$= \frac{(B/h)^2}{1 + (B/h)^2}$ where $B > h$

f = factor of safety to be provided

σ_t = ultimate tensile strength of the dam material

Thus, we see that equation 11 uses the tensile strength of the dam material. This equation is based on the maximum bending moment produced on the short span of the plate. The theory assumes that the dam will fail if the tensile stresses in the outer fibres of the dam exceeds the tensile strength of the dam material.

ESTIMATION OF THE DAM THICKNESS FROM THE WATER IMPERMEABILITY VIEW POINT

The thickness of a dam from the water impermeability view point can be estimated by the use of the following equation suggested by Kalmykov (1)

$$t = 48\, K_1 PA \qquad (12)$$

where, K_1 = coefficient of water impermeability of the dam material

$\simeq 1$ to 3.5×10^{-5} for cement-concrete of 1:2:4 ratio

P = water head

A = cross-sectional area of the roadway

ESTIMATION OF THE DEPTH OF CUT

The depth of cut to be provided on the four sides can be estimated from the following expression:

$$e = t \tan \alpha \tag{13}$$

where, e = depth of cut

t = thickness of the dam

α = angle the dam abutment sides make with the horizontal $\simeq 12°$ to $20°$

It should be noted that the depth of cut in the sides, roof and floor must cross all the major breaks and the loose materials.

It is a common experience that the sides of a coal pillar are generally weathered and fractured up to a depth of approximately 1 m. It is, therefore, suggested that in case of coal pillars the thickness of the weathered and fractures zone should be added to the value of e, estimated from equation 13.

ESTIMATION OF THE STABILITY OF A DAM AND OF A COAL PILLAR

Kalmykov (1) suggests the following equation to estimate the normal stresses on a dam:

$$\sigma = \frac{\lambda\ pBh}{2KNt\ (B + h + 2Nt \tan \alpha) \tan \alpha} \tag{14}$$

where, σ = normal stress on a dam

K = coefficient of working condition $\simeq 0.6$

N = Number of stages or segments in a dam.

For stability of a dam, the safe permissible compressive strength of a dam material must be more than the normal stresses. Thus, for stability, the factor of safety of a dam:

$$F = \frac{\sigma_c / f}{\sigma} > 1 \tag{15}$$

where, F = factor of safety of a dam

σ_c = compressive strength of the dam material

f = factor of safety $\simeq 10$ for cement concrete

σ = normal stresses on a dam

It is essential that a dam should be constructed in a coal pillar having adequate strength. The strength of a coalpillar can be estimated by the use of Salamon's formula (7):

$$S = K \frac{W^{0.46}}{h^{0.66}} = K \frac{(\sqrt{A})^{0.46}}{h^{0.66}} \quad (16)$$

where, S = strength of a pillar - psi

K = in situ strength of a unit cube of coal (of 0.3 m sides) - psi

W = corner to corner width of a coal pillar - ft

h = height of extraction - ft

A = area of cross-section of pillar - ft

The normal stresses on a coal pillar can be estimated by tributory area method:

$$\sigma = \frac{1.1\ (H_s + H_d)}{1 - e} (\cos^2 \phi + m_1 \sin^2 \phi) \quad (17)$$

where, σ = normal stresses on a pillar - psi

Hs = depth from the surface - ft

Hd = head created due to dynamic stresses in the rock mass, for ex.due to blasting in the neighbourhood of a pillar

ϕ = angle of inclination of the seam

m_1 = side thrust factor = 0.5 for hard rock and 1.0 for soft and loose rock mass

100.e = percentage of extraction

For stability, the factor of safety of a coal pillar can be expressed as

$$F = \frac{S}{\sigma} \geqslant 1.6 \quad (18)$$

ESTIMATION OF DYNAMIC STRESSES WHICH ARE PRODUCED DUE TO BLASTING

The dynamic stresses produced in a rockmass can be expressed by the following relationship:

$$\sigma d = \rho C V \quad (19)$$

where, d = dynamic stress in the rock mass

ρ = density of the rock

C = wave velocity in the rock

$= \sqrt{\frac{E}{\rho}}$

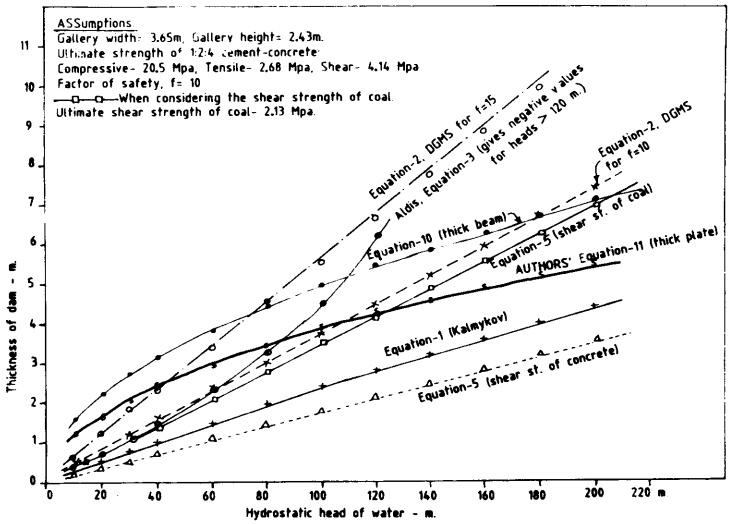

FIG:1. THICKNESS OF DAM AGAINST HYDROSTATIC HEAD- COMPARISION OF VARIOUS APPROACHES.

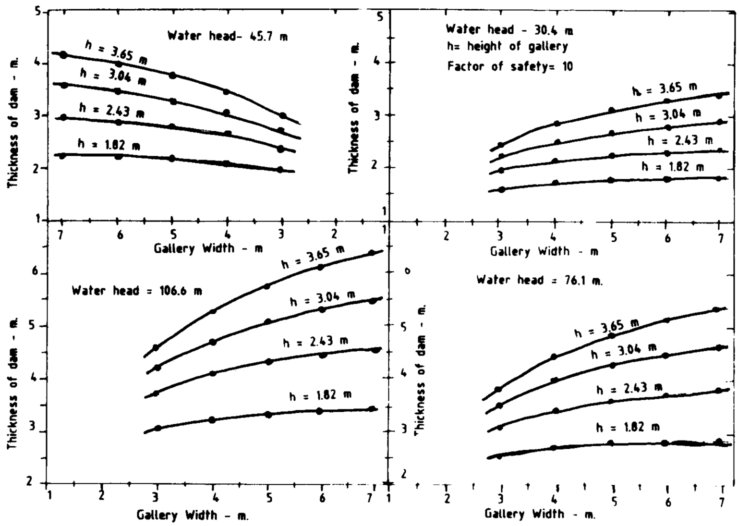

FIG. 2. DAM THICKNESS FOR VARIOUS HYDROSTATIC HEADS, GALLERY WIDTH AND HEIGHTS AS PER THICK PLATE EQUATION-11

E = tangent modulus of the rock mass

V = particle velocity in the rock

= $2 \pi na$

n = frequency of vibration

a = amplitude of vibration (peak to peak)

The safe permissible particle velocity for a cement-concrete structure should be less than 25 mm/s. Therefore the quantity of explosive and the distance of the blast hole should be controlled such that the particle velocity at the dam site remains within the permissible limits.

To compare the different approaches of dam design which are detailed earlier, the thickness of a dam is calculated by assuming the following parameters:

gallery width (B) = 3.65 m

gallery height (h) = 2.43 m

hydrostatic pressure (P) = 1.5 to 11 kg/cm^2 (0.15 to 1.08 Mpa)

properties of M-200 dense concrete with natural sand and water gravel as aggregates:

ultimate crushing strength = 263 kg/cm^2 (25.9 Mpa)

ultimate tensile strength = 27.2 kg/cm^2 (2.68 Mpa)

ultimate shear strength = 42 kg/cm^2 (4.14 Mpa)

The results obtained by the use of equations 1, 2, 3, 5, 10 and 11 are compared in Figure 1. It can be seen from Figure 1 that the thickness of a dam increases linearly with the increase in hydrostatic pressure, except when the thickness of a dam is estimated from equation 3, 10 and 11. With equation 3, the rate of dam thickness increases with increase in hydrostatic pressure. In fact the rate of increase in dam thickness should reduce with increase in hydrostatic pressure. Equation 10 and 11 give this trend as can be seen from Figure 1. As the dam can be considered as a thick plate therefore, the thickness of a dam can be estimated by the use of equation 11. Figure 2 shows the thickness of a dam for various hydrostatic pressures, gallery widths and heights, when calculated from equation 11.

Experience suggests that when the thickness of a dam exceeds 3 m a multi-stage dam should be designed as shown in Figure 4. The thickness should be estimated based on the crushing strength of the dam material (equation 1), shear strength of the pillar material as well as dam material, whichever is less (equation 5), tensile strength of the dam material (equation 11) and water impermeability view point (equation 12). In practice, the maximum of the four values should be taken for the design purposes. If the dam thickness to resist shear exceeds that obtained to resist tension, it is suggested to design the dam as shown in Figure 3. This approach, while giving a higher contract area against shear, gives savings in the dam material and therefore, is more economical, particularly in cases where the pillar material is weak.

EXAMPLE

Hydrostatic head of water = 32.8 m

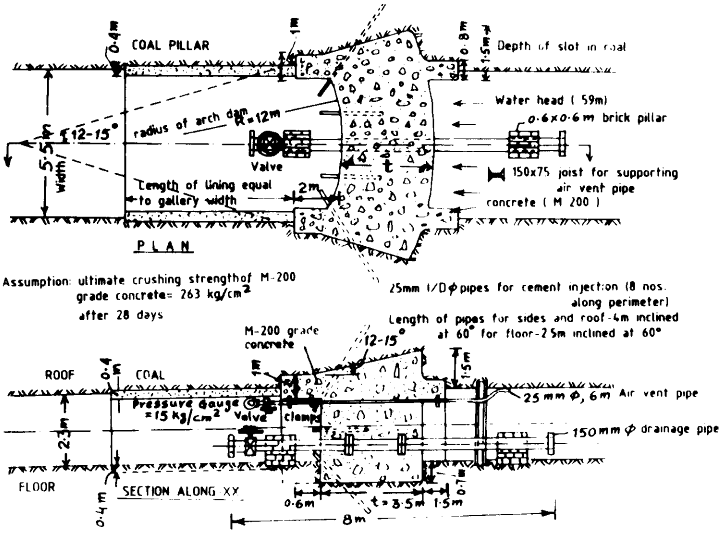

FIG.3. CONSTRUCTIONAL DETAILS OF AN UNDERGROUND WATER DAM

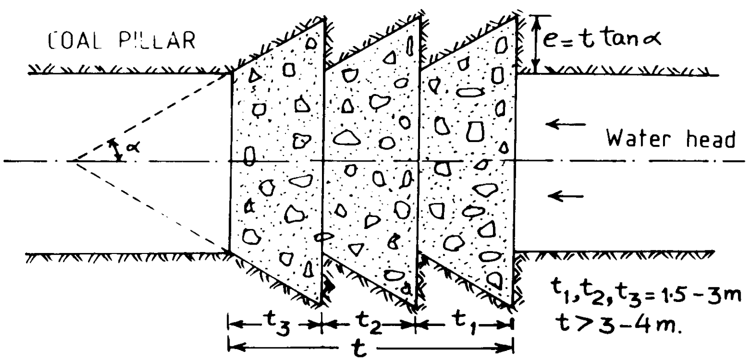

FIG.4. A MULTY-STAGE WATER DAM.

Gallery width	=	5.5 m
Gallery height	=	2.3 m

In-situ crushing strength of coal samples (cubical specimen of 0.3 m size) = 59 kg/cm² (5.82 Mpa).

Strength in Laboratory on Small Samples:

	Coal	Shale roof	Sandstone floor
Compressive strength	25.61 Mpa	63.03 Mpa	88.83 Mpa
Shear strength	2.31 Mpa	9.61 Mpa	11.95 Mpa
Tensile strength	0.67 Mpa	6.40 Mpa	5.99 Mpa
Modulus of Elasticity	2265 Mpa	-	10045 Mpa

Poissons ratio of M-200 cement concrete mixture = 0.3

An opencast working quarry existed on the rise side of the dam.

It was expected that due to heavy blasting in the opencast workings dynamic stresses would be produced in the rock mass. Assuming a maximum particle velocity of 50 mm/s and modulus of elasticity of the roof rock as 10,045 Mpa, the dynamic stress from equation 19 would be equal to 0.26 Mpa or 26.13 m head of water.

Thus, the anticipated water head on the dam = 59 m

The other dimensions of the dam are given in Table 1

TABLE 1

Thickness of dam (m) based on Compressive Strength			Shear Strength		Tensile Strength	Depth of the groove to be provided (m) eq.13			Factor of safety of	
Kalmykov eq.1	DGMS eq.2	Aldis eq.3	Cement concrete eq.5	Coal eq .5	Plate theory eq.11	Sides	Roof	Floor	Dam eq. 15	Coal pillar eq.18
1.63	4.5	3.4	1.14	3.5	2.9	1.33	1.33	0.72	2.3	3.3

A factor of safety of 10 has been assumed for calculating the thickness of a dam.

CONSTRUCTION DETAILS

Figure 3 shows the details of construction of the dam which has been built in a mine. During construction, cement-concrete cubical samples of 150 mm sides were tested in the laboratory after 28 days of curing in the mine atmosphere near the dam site. Four lots of samples were collected at different periods. Tests results showed wide variations in the strength values. The ultimate crushing strength was found to vary from 50 percent to 70 percent of the design value of 25.9 Mpa. It was, therefore, suggested that necessary correction in the thickness of a dam should be provided after determining the strength of the in-situ cement concrete mixture.

A cast iron or mild steel pipe of 150 mm internal diameter was provided at the centre of the dam at 1 m from the floor as shown in Figure 3. The sides, roof and floor of the roadway were cut to form suitable abutments for the arch shape dam. Another pipe of 25 mm internal diameter and about 6 m in length was provided in the centre of the gallery near the roof to vent air from the back of the dam as the water fills the roadway. A control valve and a pressure gauge of 1.5 Mpa capacity was fitted with the 25 mm diameter pipe, as shown in Figure 3, to measure the water pressure from time to time. To make the dam water-tight at the abutments, eight pipes of 25 mm diameter were provided around the periphery at the construction stage. Thin cement mixture was injected through these pipes at a pressure of 1 to 1.5 Mpa. The grouted type of roof bolts were provided at places where the coal sides were found fractured and loose. To prevent the side spalling and roof fall near the dam site, the periphery of the gallery was lined with 400 mm thick cement concrete for a length equal to the width of the gallery.

CONCLUSION

(1) The factors which influence the design of a dam are the size of roadway, nature of adjacent strata, static and dynamic water pressures and the shape of the dam.

(2) Dynamic stresses produced on the dam through the accumulated water due to blasting should be estimated and added to the static water head for the purpose of design calculations.

(3) The rock mass or the pillar which house the dam should be strong, free from fissures and not likely to be disturbed by subsequent workings. The factor of safety of coal pillars in and around the dam should be greater than 1.6.

(4) A factor of safety of 8 to 10 on the ultimate strength of dam material is suggested by the authors.

(5) Dams should be of arch shape and should be made of only cement concrete. Brick dams are not suggested due to large variation in their ultimate strength which is difficult to estimate.

(6) The strength of pillars should be estimated from the insitu crushing strength of coal. Similarly the ultimate compressive strength of cement-concrete should be determined from the insitu samples of 15 cm cubical size collected during construction of the dam.

(7) The thickness of dam should be estimated based on the crushing strength of the dam material (equation 1), shear strength of pillar as well as dam material (whichever is less) using equation 5, tensile strength of the dam material (equation 11) and water impermeability view point (equation 12). The maximum of the four values should be taken for the design purpose.

(8) If the thickness of a dam exceeds 3 to 4 m a multistage dam should be designed as shown in Figure 4.

(9) If the dam thickness to resist shear exceeds that obtained to resist tension, it is suggested to design the dam as shown in Figure 3 which gives higher contact area against shear while saving in the dam material and therefore more economical. Such situations arise where the pillar materials are weak.

(10) The dams must be fitted with a drain pipe of 150 to 200 mm diameter, an air vent pipe, pressure gauge and control valves as shwon in Figure 3. Weak pillar sides, roof and floor should be strengthened by cement injection and fully grouted bolts.

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The views expressed are those of authors and not necessarily of the Institution to which they belong.

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