Positive Influences of some Infirmities and Non-homogeneity of Foundation Rocks on Stability of Gravity Dams

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Abstract

An elastic and homogeneous foundation is usually assumed in calculating stresses in a gravity dam. The gravity analysis for a gravity dam assumes solid rock continuum, which is far from reality. Therefore existence of softer rocks, faults and joints in foundation rock mass below gravity dams are considered as a source of scare and worry for the safety of the structure. All efforts are made to treat, consolidate and grout such infirmities to obtain as sound and hard rock as is practicable, which naturally involves a time consuming and costly process.

Contrary to such apprehensions, research has shown that infirmities like anisotropy, joints, layers and faults can help towards safety of the dam. When such infirmities are in certain locations at the dam base and have certain orientations, they improve stress pattern in the rock foundations and stress distribution in the dam body.

Gravity dam design – non-linearity of stresses

Gravity dams are designed usually on the gravity analysis method, which is based on two main assumptions: (a) that the normal vertical stress on horizontal planes is linear and (b) that the foundation rock is isotropic, homogeneous and is practically same in elastic properties as the concrete of the dam i.e. E_c/E_r is nearly unity (E_c/E_r being deformation modulus of concrete and rock respectively. However neither the normal vertical stress is linear nor the foundation rock mass is homogeneous and isotropic. The foundation rocks are sometimes traversed by joints and faults and possess different elasticities.

Studies show that geological conditions of the rock mass, such as existence of joints, layers and faults affect the stresses in the dam body. The fabric-conditioned morphological anisotropy creates a mechanical anisotropy, which affects not only the strength and deformation behaviour of the rock mass, but also the stress distribution in it. The case is analogous to a statically undefined system. Just as in a structure, the strongest member draws the greatest part of the load on to itself, so also the anisotropy of the rock directs the stress in that direction in which the material is rigid. This behavior of rock usually dilutes the undesirable tension conditions at the heel of the gravity dam and at certain other locations. Such interesting cases of rock infirmities that help in improving stress pattern in the dam by reducing tensile stresses in the heel region of a gravity dam are examined below.

Gravity dam resting on soft foundations

While designing a gravity dam, the section is so chosen (widened) that there is less and/ or no tension at the heel region. The gravity analysis assumes rock as strong as concrete. But, when the same dam and with similar rock condition is checked by finite element method (F.E.M.), tension appears at the heel region. By making foundation rock stronger than concrete the tension zone

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increases in magnitude and extent as shown by f.e.m studies. Fig.1 shows the effect of foundation elasticity on vertical normal stress o_y and o_x for varying E_c/E_r ratios 0.1 to 5.

The variation of o_y indicates the following:

(i) that the normal vertical stress o_y is not linear in the lower 40 per cent of the dam height.

(ii) that the stress at the heel is practically zero for normally assumed rock conditions with no earthquake (E_c/E_r = 1). The stress becomes tensile with rigid foundations (E_c/E_r <1.0) and is compressive for soft foundation (E_c E_r >1.0). This shows that hard foundations induce tension at the heel portion, which can accentuate with earthquake conditions. On the other hand softer foundations induce compression.

(iii) The maximum compressive stress is not at the toe, but usually at one eighth of base width upstream. This means that richer concrete need not be placed at the outer edge but along one eighth of the base width upstream.

Gravity dam on stratified foundations

Stratified rock foundations are of common occurence in nature. The laminations may be horizontal or inclined. Generally the arrangement of layers is quite irregular and only becomes clear in a statistical representation.

Studies were conducted to determine stresses in foundations and gravity dam with 2 to 6 layers of rock, for example, a 4 layer system with 3 layers each of thickness one fourth of dam base, in between the dam and the infinite rock continuum at the bottom was considered. Each layer was assumed individually isotropic and homogeneous.

Fig.2 shows distribution of principal stresses (ref. 6) in laminated rock mass having 4 to 6 layers. Results of the study can be grouped in two ways; viz group 1 - no rock layer has elasticity less than that of concrete and group 2 – one layer has elasticity modulus lower than that of concrete. The tensile stress 0_1 zone for stratified rocks was larger compared to that of homogeneous foundations and the tensile stress magnitudes were larger in case

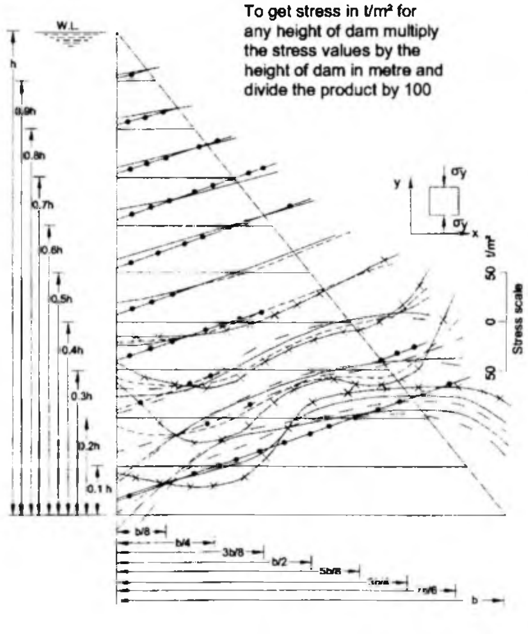

Fig. 1a. Effect of foundation elasticity on vertical normal stress ay gravity hydrostatic and uplift loads

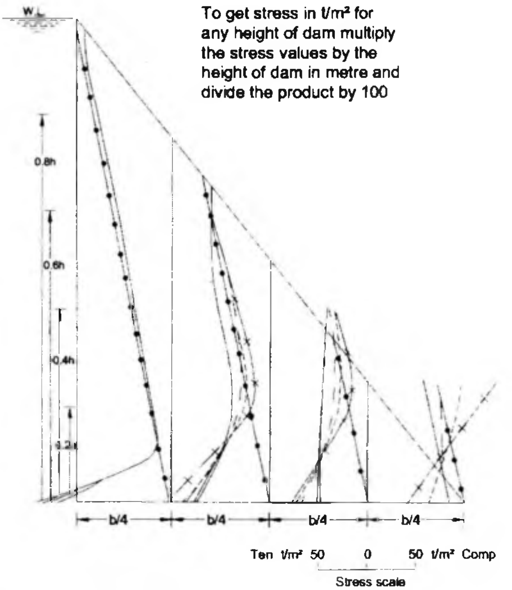

Fig. 1b. Effect of foundation elasticity on horizontal normal stress gravity hydrostatic and uplift loads

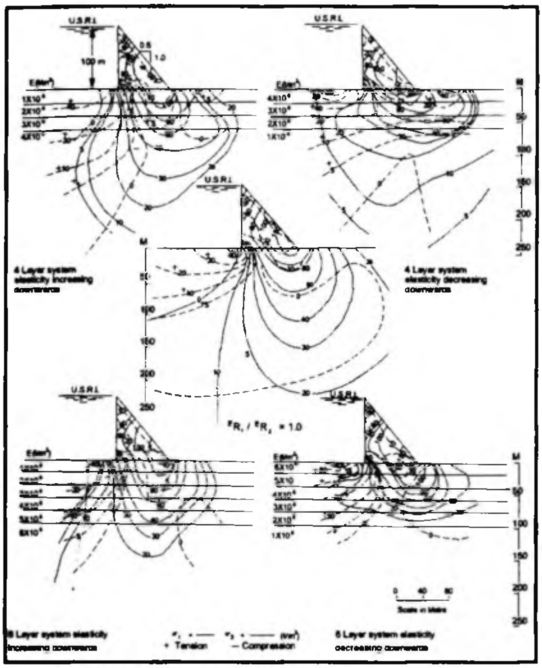

Fig. 2: Distribution of principal stresses in a laminated rock mass below a gravity dam.

b/h=4. Normal uplift

of foundations having elasticities decreasing from higher to lower strata. In case of group 2 results, the stress concentration occurs in layers having high elasticities. The soft layers have tendency to spread deformations and stress curves. Therefore among laminated foundations those with the upper layers comparatively softer than the lower layers offered better foundation conditions.

Gravity dam on foundation with joints

In these studies the existence of a joint was assumed at five locations viz. heel, quarter point, mid base, three quarter point and toe, with inclination of joint varying at 30^0, 60^0, 90^0, 120^0, and 150^0 from base measured from toe side clockwise; the ratio of elasticities on left and right sides of joint viz. E_{r1} / E_{r2} was taken as 0.1, 0.4, 1.0, 2.5 and 10.0. In all 150 different cases were thus analysed 7. The tensile zone at heel was found to vary as below:

a. The stresses become more tensile with increase in the value E_{r1} / E_{r2} and the value of σ_1 becomes more tensile as the joint orientation changes from 30^0 to 90^0, but with further increase of inclination the stress becomes less tensile.

b. in general with one particular orientation of joint, the tensile stress goes on reducing as the joint shifts from heel to toe.

c. For different locations of the joint, the inclination for maximum tension at heel varies in a fairly regular manner. Thus with joint at heel, quarter point, mid base, three quarter point and toe, the maximum tension at heel occurs at ø equal to 75^0, 90^0, 105^0, 120^0, and 135^0 respectively.

Thus in a foundation if joint is far away from heel nearest to toe and the angle ø is less, the tension at heel is controllable.

Dam resting on foundations having faults

In Himalayan region it is difficult to find a site without minor faults. The usual practice is to plug the fault to a certain depth as per empirical relations of USBR (ref.1&2). Studies done by the author show that faults are not always dangerous in every position. Five different cases of presence of a fault with a width $1/8^{th}$ of dam base and eleasticity of fault material as $1/10^{th}$ of the foundation rock were studied 7 & 8 viz:

(i) Fault at heel, vertical.

(ii) Fault at mid base, (a) inclined upstream at 45^0 (b) vertical and (c) inclined downstream at 45^0.

(iii) Fault at toe, vertical.

The effect of faults (with and without plug) on vertical normal stresses σ_y are illustrated in Fig.3.

Studies indicated the following :

(i) The effect of fault location and its orientation is felt more on a plane 10% of dam height above the dam base rather at the dam base.

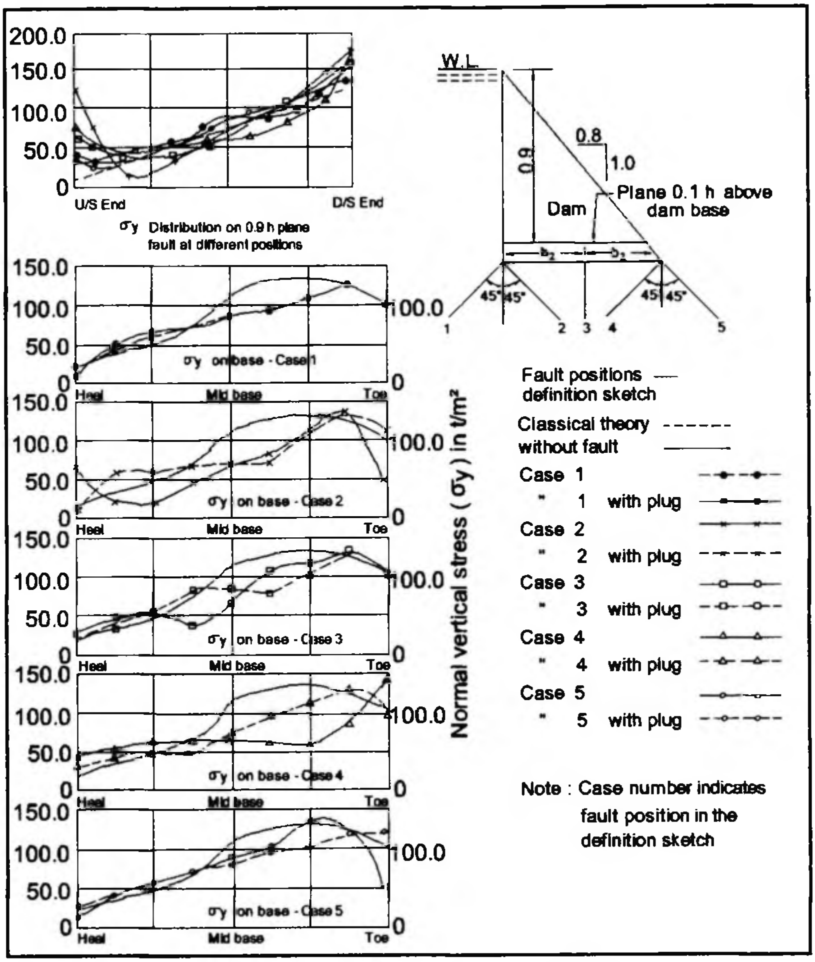

Fig. 3: Effect of faults (with and without plug) on vertical normal stress qy

(ii) The stresses increase rapidly and become unfavourable when the fault is near the downstream toe of the dam.

(iii) Faults located at the heel or at the centre of the dam base do not create a dangerous situation when they are vertical or sloping upstream. Dangers arise when the fault is located at the centre or downstream towards the toe and is oriented downstream. This means that a fault having its axis conceding with the major principal stress of the downstream side of the dam is definitely undesirable.

(iv) A plug depth of about 20-30% of the height of the dam is desirable.

(v) The safety of the foundation rock is not so low as might be expected when the fault is located on the downstream side of the extension of the downstream toe of the dam.

Thus a fault is not such a dreadful thing in all positions. In case it is at the heel or even at any point up to mid base and so long as its inclination is vertically down or inclined upstream, it rather improves conditions in the heel region.

Conclusions

The elastic analyses indicate that by suitably adjusting the location of weak zones, infirmities, joints and faults vis-a-vis the dam orientation the problematic zones can be turned into helpful areas by reducing tensile zone at heel and adding to the safety of the structure.

References

Varshney R.S. (1988). "Concrete Dams" 2nd ed. 2nd Printing. M/s Oxford & IBH Pub. Co. New Delhi.

Varshney R.S. (2001). "Hydropower Structures" 4th ed. M/s Nem Chand & Bros, Roorkee.

Varshney R.S. (1974) "Dams on Rocks of Varying Elasticity" Int. Jn. of Rock. Mechanics, Mining Sc. & Geomechanics Vol. 11 page 1-12 Pergaman Press, U.K.

Varshney R.S. (1978). "Tension in the Heel Region of Concrete Dams " Proc. 47th Research Session of CBI&P Vol. 1. Hubli Dharwar Karnataka November.

Tandon G.N. & Varshney, R.S. (1979). "Tensile Stresses around the Heel of Solid Gravity Dams and World's Highest Cored Gravity Lakhwar Dam 13th ICOLD New Delhi Oct. 29-Nov. 2, Q 48 R 53.

Varshney R.S. "Stresses in the Layered Half Plane below a Gravity Dam" Int. Jn. of Rock Mech. Min. Sc. and Geomech. Vol. 12 pp159-164 Pergamo Press U.K.

Bharat Singh, & Varshney, R.S. (1994). "Effect of Faults in the Foundations on Dam Behaviour" Jn. Irrig. & Power CBI&P, pp 451 – 467

Varshney R.S. (1972). "Rock Foundation Characteristics and Dam Design" Int. Jn. Rock Mech. Sc. & Geomech. Vol. 9 pp 645-059 Pergamo Press, U.K.