Flat Jack Method for Measuring Design Parameters for Hydraulic Structures of the Koyna Hydro Electric Project in India

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ABSTRACT: *The paper presents two different projects: The first involves a case with limited rock cover on a side of an excavated surge shaft located near a steep slope. The second involves the assessment of design parameters of an existing masonry dam for use as input in dynamic analysis. The induced stresses in the surge shaft of Koyna Hydro Electric Project (K.H.E.P.) stage-IV were measured with flat jack. These tests were first performed in a 4 m diameter pilot shaft and after the shaft was excavated to its full diameter of 22.70 m. The stresses increased from 3.96 MPa to 5.09 MPa, when the 4m-diameter surge shaft was expanded to its full diameter of 22.70 m, in the case where significant rock mass cover existed at EL 651.00 m. However stress reduction or no variation in the induced stress was measured in the portion of insufficient rock cover. In the second case, to determine the design parameters of Kolkewadi masonry dam of K.H.E.P stage-III, flat jack tests were conducted at the upstream side of Kolkewadi masonry dam in masonry of 1:4 and 1:3 and at downstream sloping side in masonry of 1:5. It is impractical and difficult to obtain mechanical properties of masonry in laboratory from the extracted core samples, due to intrinsic nonhomogeneity of the material. The brick/stone and mortar layers caused anisotropic behavior of masonry. Average deformation modulus for 1:3 masonry was 32.8 GPa. Similarly, the average deformation modulus for the 1:4 and 1:5 masonry was 19.0 and 13.7 GPa respectively and were adopted for the dynamic analysis. Induced stresses in the masonry dam were found to be nearly equal to the overburden.*

KEYWORDS: flat jack, masonry dam, surge shaft, deformation modulus, induced stresses

SITE LOCATION: IJGCH-database.kmz

INTRODUCTION

The surge shaft is an important component of the Koyna Hydro Electric Project (K. H. E. P), Stage-IV. Fig.1 shows the location of different stages of the K. H. E. P. The surge shaft is located in a narrow hill with low rock cover i.e. less than 4 times the surge shaft diameter. The lower rock cover is present around North-East-South (N-E-S) side of the surge shaft due to very complex topography. Fig.2 shows the location of the surge shaft in the hill slope. The effect of lower rock cover was required to be investigated (Dhawan and Singh, 2002). The rock cover effect was investigated around the 121 m deep; 22.70 m diameter surge shaft of K. H. E. P, Stage-IV, by flat jack tests around the surge shaft (Fig.3).

The local geology indicates presence of alternate layers of volcanic breccia and amygdaloidal basalt. Volcanic breccia is located between EL 682 to 692 m, 647 to 655 m and 610 to 619 m and the rest comprises of amygdaloidal basalt. As the upsurge in the surge shaft may reach up to EL 651.00 m, in-situ studies to determine the stresses near that level were required to be carried out. To determine the induced stresses and effect of lower rock cover, flat jack tests were conducted at two elevations: at EL 637.60 m in basalt and 651.0 m in volcanic breccia in the 4 m diameter pilot shaft (Fig.3) and at EL 651.0 m in the fully expanded surge shaft of 22.70 m diameter.

Another application of flat jack test is presented for the Kolkewadi uncoursed rubble (UCR) masonry dam located at Alore village, District Chiplun, Maharashtra and part of K.H.E.P. Fig.1 shows the location of Kolkewadi dam which is Stage-III of K.H.E.P. The length and height of Kolkewadi dam is 497.0m and 56.80m with gross storage of 36.22 Mm^3.The dam was constructed in 1975, when the seismic activity was considered low in Koyna region. The Government of Maharashtra formed an Experts' Committee after the Killari earthquake (magnitude 6.4 Richter scale) on 30th September 1993 near the

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dam. The Committee recommended carrying out dynamic analysis of Kolkewadi dam by adopting realistic design parameters for the different parts of the dam. These parameters needed to be determined. Major portions of the dam have been constructed with UCR masonry with different proportions of cement sand to mortar ratios of 1:3, 1:4, and 1:5. Cores of different sizes (100 and 150 mm diameter) were extracted from masonry parts of the dam body and were tested in the laboratory to assess the design parameters. Laboratory test results of masonry cores indicated large variation of properties due to variations in percentage of mortar, as well as orientation and size of stones in the extracted cores. Thus, in-situ testing of the masonry portion of the dam was required to be conducted using the flat jack method in an effort to assess the deformation modulus, Poisson's ratio and induced stresses.

The technology of the flat jack test has been modified and adopted for the purpose of evaluation of brick and stone masonry structures in Italy by Rossi (1982, 1985). Rossi developed initial specifications for the optimum size and placement of flat jacks, techniques for measuring deformations, the proper calibration of flat jacks, and post-test analysis of data. Analytical studies have been performed in support of the experimental results. Sachhi et al. (1986) conducted extensive nonlinear finite element analyses of both the single and double flat jack tests in masonry materials. They found their numerical models to be generally in support of experimental evidence, and offered some insight regarding the effect of certain assumptions on the accuracy of the results. Based on their analytical work, the authors recommend that if the flat jack test is carried out to failure on masonry, the failure stress should be reduced by 20% to estimate the unrestrained compressive strength. Similarly, the in-situ stress test may overestimate the actual state of stress by as much as 10% according to their models. It is explained that the Flat jack test provides a direct measure of the vertical stress at a point in the structure. Thus, the test provides an indication of the factor of safety in terms of compression failure in masonry. The test also yields deformation modulus and Poison's ratio of the tested material.

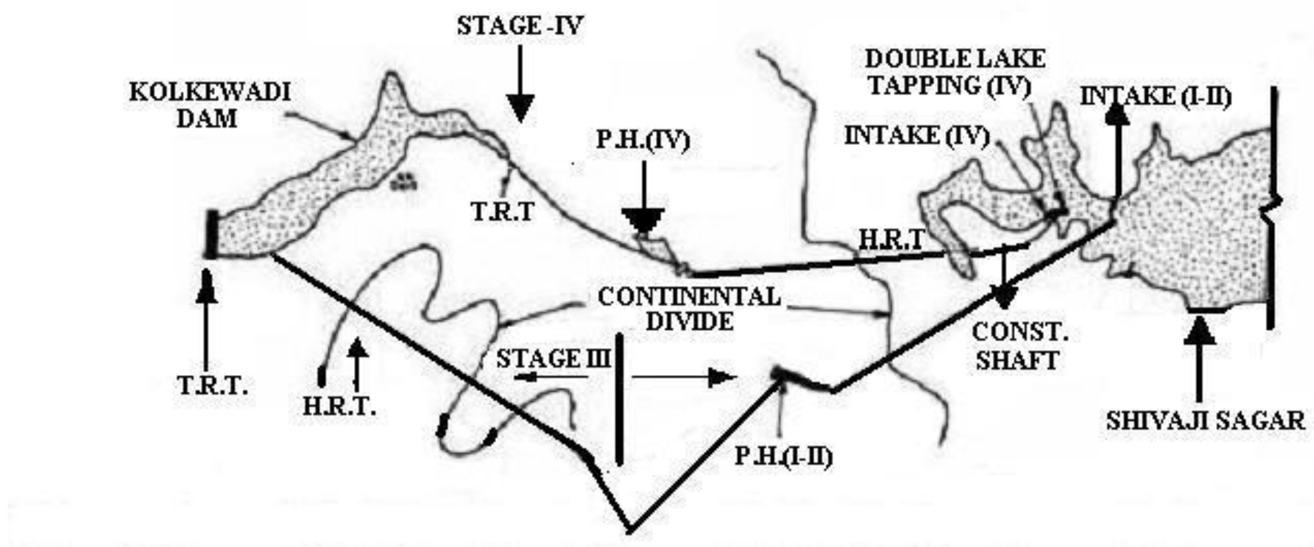

Figure 1. Koyna H.E. Project (Stage I-II-III-IV) schematic layout.

CASE STUDY I: IN-SITU STRESSES IN ROCK MASS AT SURGE SHAFT OF KOYNA H.E. PROJECT

In order to account for the lower rock cover available around the surge shaft, flat jack studies were performed to measure the induced stresses and deformability of the rock mass in the surge shaft at two stages of excavation (Dhawan and Singh, 2004). At the first stage the measurements were carried out in the 4 m diameter pilot shaft at two levels: at EL 637.60 m in amygdaloidal basalt and at EL. 651.0 m in breccia (Fig. 4), to allow for a comparison of the state of stress and deformability at these levels. In the second stage, measurements of induced stresses and deformability of the rock mass were made for the fully excavated surge shaft of 22.70 m diameter at EL. 651.0 m only (Fig.4), as adequate rock cover was available at EL. 637.00 m. The flat jack test locations are shown in Fig.4.

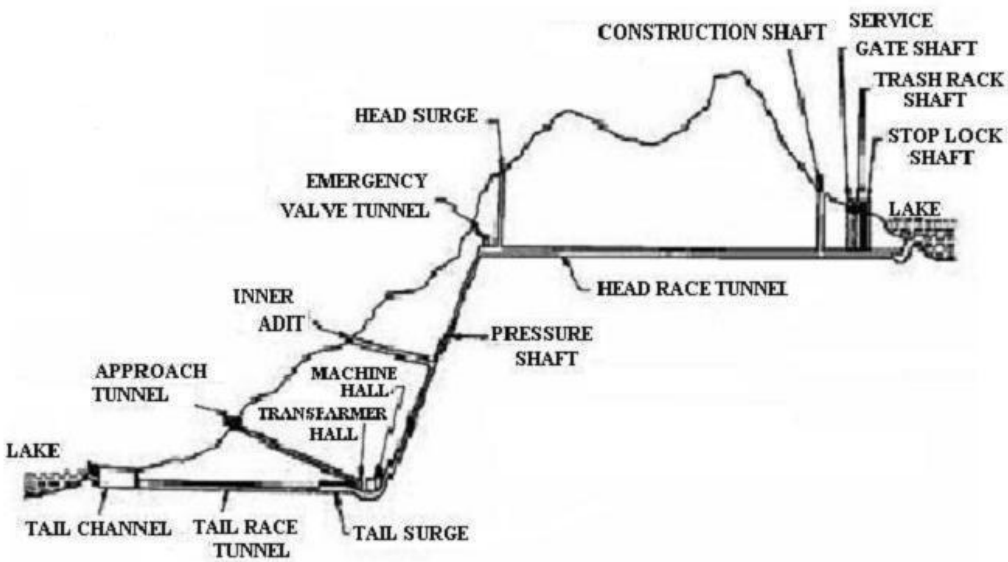

Figure 2. Schematic layout of Koyna H.E.Project stage-IV.

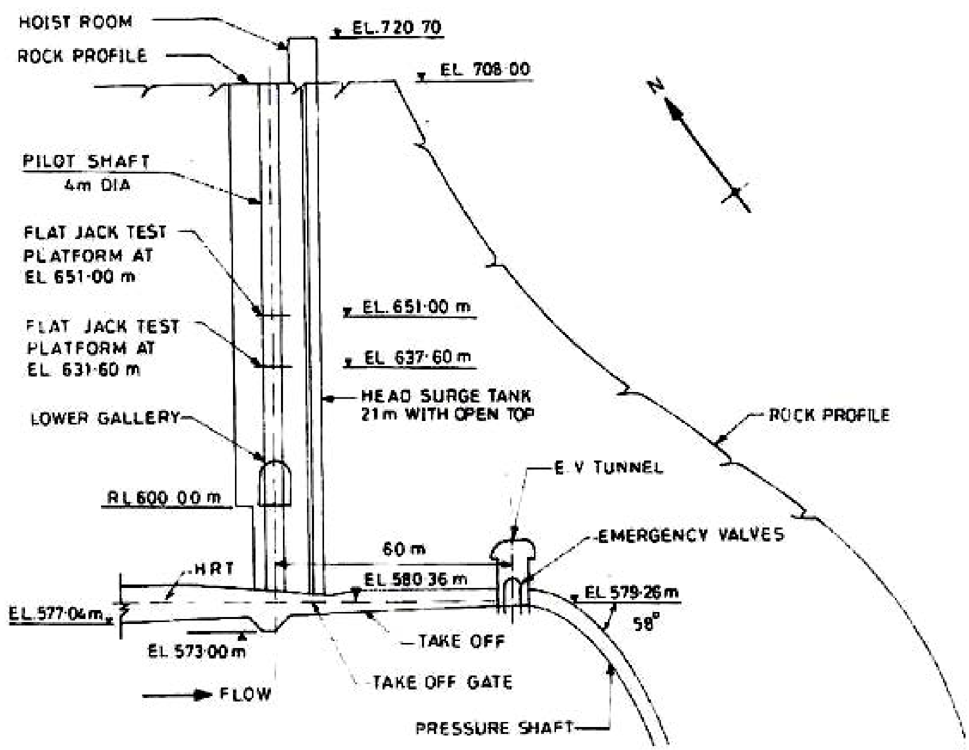

Figure 3. Location of flat jack test platforms in pilot shaft and other major constituents of the surge shaft.

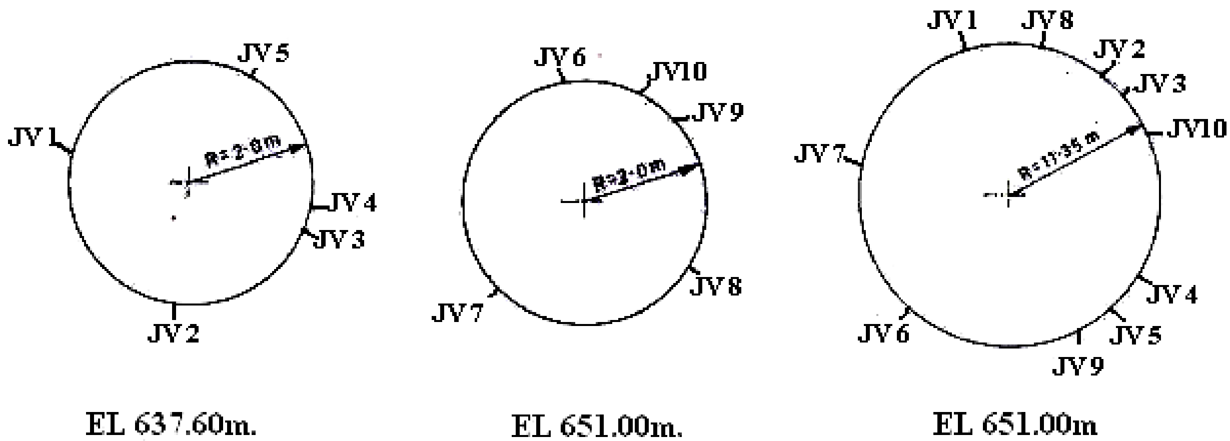

Figure 4. Location of flat Jack tests at EL 637.60 m. and 651.0 m. in pilot shaft and at EL 651.0 m. in fully excavated shaft (radii not in scale)

Evaluation of In-situ Stresses

When stresses are to be determined near the surface, as in this case, the flat jack method represents probably the most suitable method. The flat jack tests were carried out in the surge shaft, as per I.S.13946, Part IV, (1994). Equation 1 is used to evaluate the stresses:

$$PK_1=P_\theta K_2+P_h K_3 \quad (1)$$

Where P is the cancellation pressure, P_θ and P_h are the yielding stress in the horizontal and vertical slot directions respectively (Owen and Hinton, 1980). Constants K_1, K_2, K_3 are determined to account for the size of slot effects, expressed by equations 2, 3 and 4:

$$K_1 = C_o \left[(1-\upsilon)\left\{ a_o - \frac{Y}{C_o} \right\} + \frac{1+\upsilon}{a_o} \right] \quad (2)$$

$$K_2 = \left(\frac{1+\upsilon}{a} \right)(C+Y_o) + \left(a - \frac{Y}{C} \right)\left[C(1-\upsilon) - 2\upsilon Y_o \right] \quad (3)$$

$$K_3 = Y_o \left[2\upsilon \left(a - \frac{Y}{C} \right) - \right] \frac{1+\upsilon}{a} \quad (4)$$

where:

$$a_o = \sqrt{1+\frac{Y^2}{C_o^{\,2}}} \; and \; a = \sqrt{1+\frac{Y^2}{C^2}}$$

The length of flat jack is $2C_o$, Poisson's ratio, ν, length of slot is 2C, distance between two reference pins is 2Y and width of slot is $2Y_o$. The slot axis is passing through the center of slot section and parallel to the plane of slot width (Fig.5).

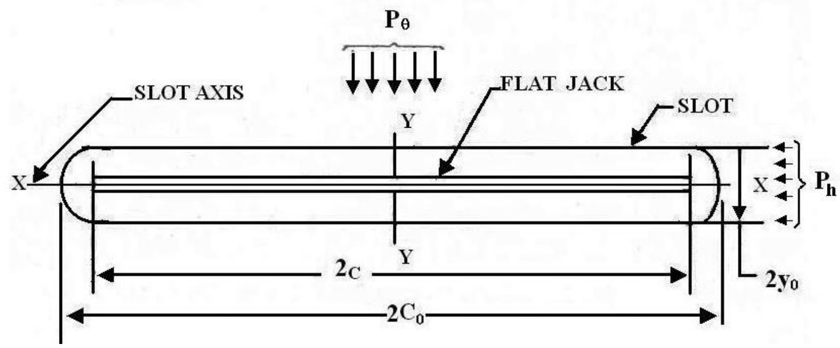

Figure 5. Stress field around the slot.

Stresses induced on the boundary of the opening are P_θ and P_h. Since these induced stresses are a function of the in-situ stresses and the shape of the opening, it is possible to evaluate the in-situ stresses from equations 5, 6 and 7:

$$P_\theta = K_v \sigma_v + K_h \sigma_{h1} \tag{5}$$

$$P_h = \sigma_{h2} + \nu(K_v - 1)\,\sigma_v + \nu\,(K_h - 1)\,\sigma_{h1} \tag{6}$$

$$P_L = \sigma_{h1} + \nu\,(K_v - 1)\,\sigma_v + \nu\,(K_h - 1)\,\sigma_{h2} \tag{7}$$

The stress on the boundary of the opening and tangential to the boundary is P_θ. The stress on the boundary of the opening and parallel to the axis of the opening is P_h. The stress on the boundary and perpendicular to the axis of the opening is P_L, The stress concentration factor due to in-situ vertical stress is K_v, and the stress concentration factor due to in-situ horizontal stress is K_h.

Once P_θ, P_h and P_L values are measured and the stress concentration factors are calculated, it is possible to evaluate σ_v and σ_h. For regular geometrical shape such as circle, D-shape, rectangle and square shapes, stress concentration factors can be obtained from available monographs. For other shapes, photo elastic or mathematical models could be used to calculate them. In cases where it is not possible to measure both P_h and P_L, the horizontal stresses σ_{h1} and σ_{h2} are assumed to be nearly equal and σ_v and σ_h are evaluated using equations 5 and 6.

For circular openings, it is possible to estimate the magnitude of the principal stresses σ_v and σ_h in an horizontal plane using equation 8 (Goodman, 1988).

$$\begin{Bmatrix} P_\theta \\ P_h \end{Bmatrix} = \begin{bmatrix} -1 & 3 \\ 3 & -1 \end{bmatrix} \begin{Bmatrix} \sigma_h \\ \sigma_v \end{Bmatrix} \tag{8}$$

The flat jack test was carried out by cutting a thin slot into the rock surface by overlapping drill holes with the help of a compressor rod. The sides of slot converge due to stress relief in the direction perpendicular to the longer axis of the slot. The 30x30 cm flat jack is embedded in the slot and the empty space in the slot is grouted with cement grout. After setting of the cement, the flat jack is pressurized to neutralize the convergence that occurred during slot construction. This pressure is called cancellation pressure, and is corrected for the influence of slot, flat jack geometry and the stress acting in the direction of the major axis of the slot. Assuming that the induced stress (P_h) parallel to the axis of the opening is the same in all directions, the induced stress (P_θ) tangential to the boundary of the opening is determined using correction factors for slot length, flat jack length, slot width, pin distance and Poisson's ratio (ISRM, 1987). The results of in-situ stresses by flat jacks are given in Table 1. The induced tangential stresses on the boundary of 4 m diameter pilot shaft are found to vary from 2.85 MPa to 6.58 MPa at EL 637.60 m in basalt. From the determined induced stresses at five points (Fig. 6), the principal stress value and orientation can be interpreted and is found to be oriented at N 80° W. The induced stress determined at five points varies from 1.32 MPa to 3.96 MPa at EL 651.0 m in volcanic breccia and is also shown in Fig. 6. The stresses are found to be higher in the portion of the shaft that is overlain by significant rock cover compared to the case where there is limited rock cover at N-E-S side at the same EL. 651.0 m in volcanic breccia. At both elevations, the induced stresses are compressive and could be considered adequate to balance the possible tensile stresses that are likely to be induced due to internal water pressure (Brown and Hoek, 1978).

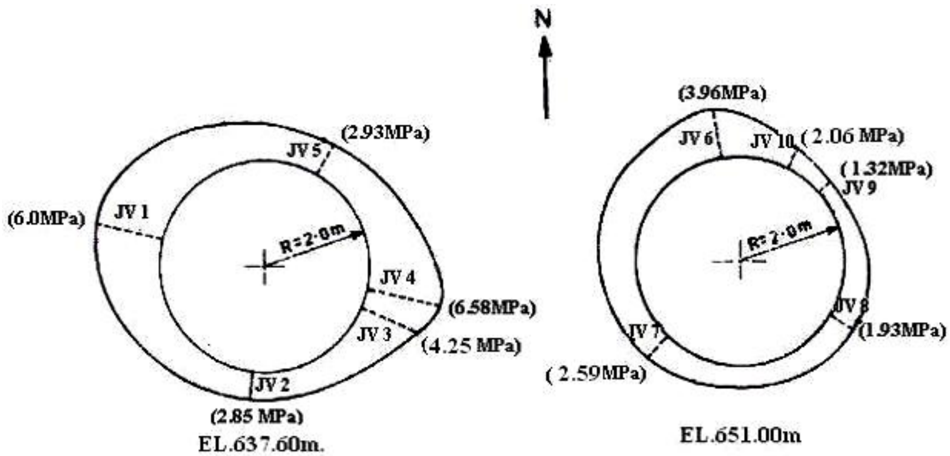

Figure 6. Measured induced stresses in the 4m diameter pilot shaft.

In the 22.70 m diameter fully excavated shaft, the induced tangential stresses determined at ten points at EL 651.0 m in volcanic breccia, is found to vary from 0.79 MPa to 5.09 MPa as shown in Fig. 7. When compared with the stresses measured at the 4 m pilot shaft, the induced stress are found to increase in the portion where significant rock cover is present (N-W-S side), but reduce in the portion where insufficient rock cover is existing (N-E-S side).

Evaluation of Deformation Modulus, E_m

When the slot is made at the surface of the surge shaft, stress originally acting across the surface is relieved. Because of the stress relief, the sides of the slot converge. The amount of convergence, which depends upon the stresses in the structure and the material's elastic properties, are given by equation 9. When deformations are measured with respect to load by in-situ testing, the calculated modulus with respect to load is called deformation modulus, as opposed to the elastic modulus that is measured in laboratory testing of rock samples with respect to load (ISRM, 1981).

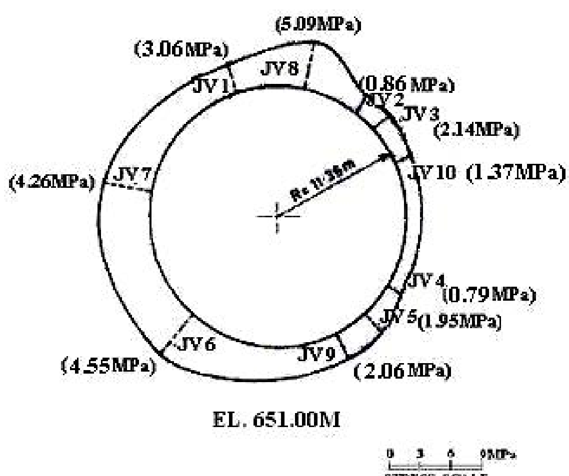

Figure 7. Measured induced stresses in fully excavated surge shaft in volcanic breccia at EL 651.00 m.

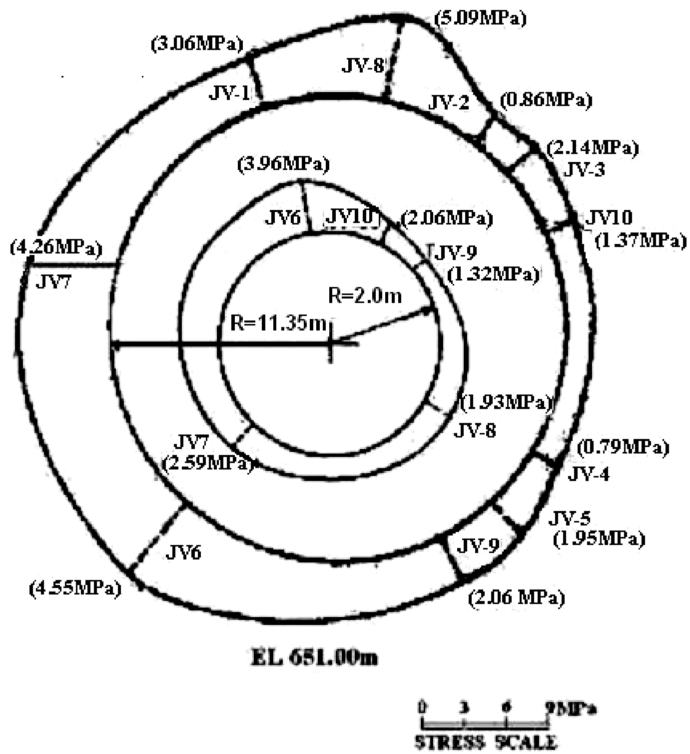

Figure 8. Comparison of measured stresses in pilot shaft and fully excavated surge shaft in volcanic breccia rock at EL 651.00 m.

$$E_m = \frac{2PC_o}{w}[(1-\upsilon)(a_o + \frac{Y}{C_o}) + \frac{1+\upsilon}{a_o}] \tag{9}$$

where $a_o = \sqrt{1 + \frac{Y^2}{c_o^{\,2}}}$

w is the amount of convergence between two points spaced at equal distance Y, $2C_o$ is the length of flat jack, and υ is Poisson's ratio.

After installing the 30 x 30 cm flat jack in the slots with cement grout, oil is pumped in the flat jack using a hydraulic pump. The hydraulic pressure is applied to the internal surfaces of the flat jack with its axis coinciding with that of slot and creating an approximately uniaxial state of compressive stress. With a pressure increase in the flat jacks, the distances between gauge point pairs increase. The distances then decrease with reduction in pressure (Fig.9). The stress-deformation relationship can be determined from loading-unloading cycles (Fig.10).

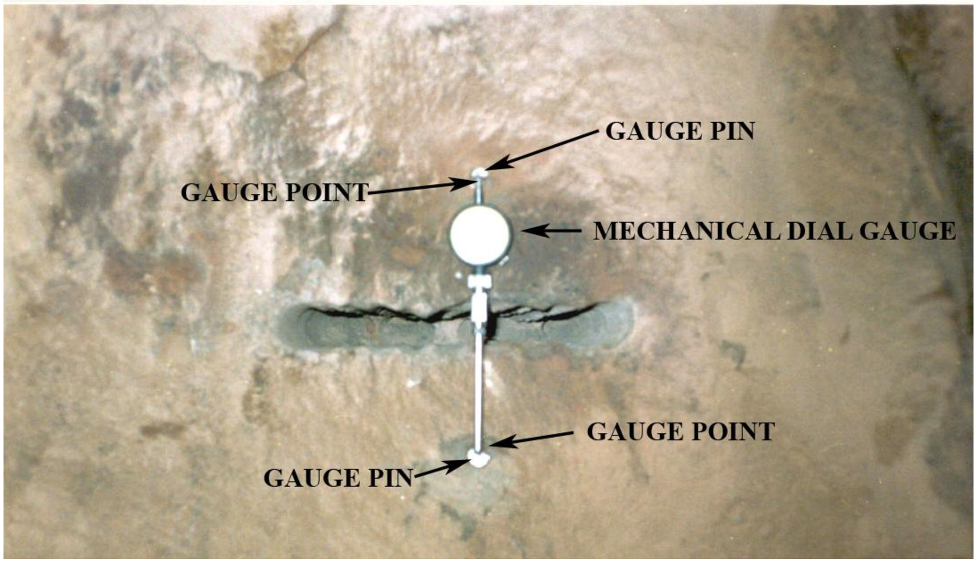

Figure 9. Deformations by dial gauge between two gauge pins after making a slot.

Several cycles of loading and unloading were performed at each test location. The stress-deformation envelope of flat jack test, JV-10 in volcanic breccia at 652.50 m is shown in Fig.10. Stress deformation values are used to evaluate the E values.
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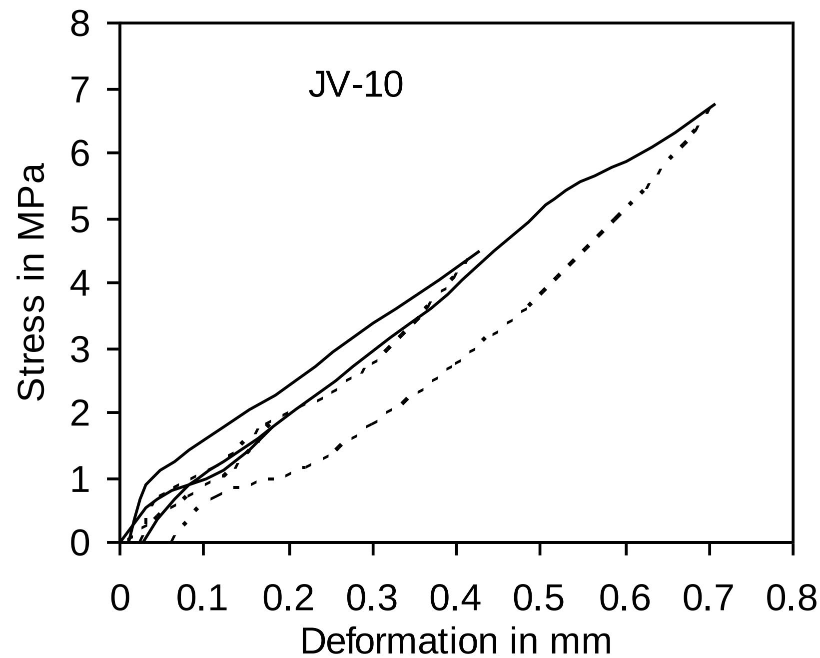

Figure 10. Stress-deformation envelope of flat jack test location JV-10 in breccia in pilot shaft.

Table 1: Results of in-situ stress and deformation modulus at different levels at surge shaft of Koyna H. E. Project stage-IV, Maharashtra.

Sl. No.	E.L.in m	Flat jack No.	Deformation modulus, E_m (GPa)	Cancellation pressure (MPa)	Induced stress (MPa)	In-situ stress (MPa)	
					P_θ	σ_1	σ_3
Pilot shaft of 4 m diameter in basalt at EL 637.60 m							
1.	638.30	JV 1	53.33	8.46	6.0	2.30	1.55
2.	639.16	JV 2	18.13	4.01	2.85		
3.	639.06	JV 3	---	5.76	4.25		
4.	638.12	JV 4	37.94	8.64	6.58		
5.	637.97	JV 5	59.81	4.41	2.93		
6.	639.02	JH 1	51.08	1.96	---		
Pilot shaft of 4 m diameter in volcanic breccia at 651.0 m							
7.	652.10	JV 6	7.35	5.17	3.96	1.30	0.89
8.	651.75	JV 7	6.37	3.34	2.59		
9.	651.93	JV 8	10.79	2.45	1.93		
10.	652.53	JV 9	4.31	1.63	1.32		
11.	652.08	JV 10	5.49	2.53	2.06		
12.	651.67	JH 2	5.78	1.43	---		
Fully excavated shaft of 22.70 m diameter in breccia at 651.0 m							
13	652.50	JV 1	6.08	3.82	3.06		
14	651.00	JV 2	4.51	0.93	0.86		
15	651.15	JV 3	6.18	2.44	2.14		
16	652.25	JV 4	2.74	0.91	0.79		
17	652.50	JV 5	4.31	2.37	1.95		
18	652.60	JV 6	9.31	5.41	4.55		
19	653.50	JV 7	6.27	5.43	4.26		
20	651.45	JV 8	9.02	6.52	5.09		
21	653.00	JV 9	6.67	2.70	2.06		
22	651.50	JV 10	5.10	1.75	1.37		
23	651.70	JH 1	7.25	3.17	---		
24	652.85	JH 3	5.88	3.29	---		

Note: JV-Jack vertically oriented for measuring P_θ; JH-Jack horizontally oriented for measuring P_h; P_θ- Induced stress tangential to the boundary of the opening; P_h- Induced stress parallel to the axis of the vertical shaft. σ_1 and σ_3 are principal stresses.

Discussion and conclusions for case study I

The maximum induced stress was 3.96 MPa in the pilot shaft of 4 m diameter in volcanic breccia, which increased to 5.09 MPa, when the surge shaft was excavated to its full diameter of 22.70 m on the side where significant rock mass cover existed at EL 651.00 m. No variation or reduction in the induced stresses was observed in the portion of the surge shaft in volcanic breccia rock mass that included lower rock cover, indicating that the rock mass is distressed due to lower rock cover. Stress direction could not be evaluated in breccia rock portion due to lower rock cover.

Cancellation pressure measured by horizontal jacks (JH1 and JH2) in 4m diameter pilot shaft at EL. 637.60 and EL 651.0 m is 1.96 and 1.43 MPa respectively, compared well with the overburden. After expanding the excavation of surge shaft to

22.70 m diameter, the measured cancellation pressure by horizontal jacks JH1 and JH3, was 3.17 and 3.29 MPa respectively. This is a very high value when compared to the rock mass overburden. The lower rock mass cover has caused distress in the rock mass, due to which stress adjustment and redistribution has taken place and caused development of high stresses and higher cancellation pressures.

The average deformation modulus from four values of amygdaloidal basalt is 50.54 GPa determined by eliminating the outlier value of 18.13 GPa. For breccia, the average deformation modulus from 15 values is 6.0 GPa, after eliminating three outlier values of 10.79, 2.74 and 9.31 GPa. The in-situ stress ratio, σ_3/σ_1 is 0.67 and 0.68 at EL 637.60 and 651.0 m in 4 m diameter pilot shaft. The in-situ stresses could not be determined in 22.70 diameter fully excavated shaft due to the limited rock cover.

CASE STUDY II: DETERMINATION OF DESIGN PARAMETERS OF MASONRY OF KOLKEWADI DAM BY FLAT JACK

Flat Jack Test Locations

Induced stress, deformation modulus and Poisson's ratio were determined for the masonry of the Kolkewadi dam. In the upstream side, flat jack tests were conducted in masonry with cement mortar ratio of 1:4 at KRL (Kolkewadi Reduced Level) 134.80 m at four locations (chainages 162.50, 193.40, 231.0 and 266.50 m as shown in Fig.11). Flat jack tests were also conducted at KRL 132.40 m at five locations (chainages of 162.50, 193.90, 216.0, 231.0 and 266.0 m) in the upstream side masonry with cement mortar variation of 1:3 (Fig.11) and at four locations (chainages 150.0, 151.34, 216.0 and 281.50 m) in the downstream side masonry with cement mortar ratio of 1:5. A pontoon platform constructed for the execution of the tests on the upstream side of dam is shown in Fig.12.

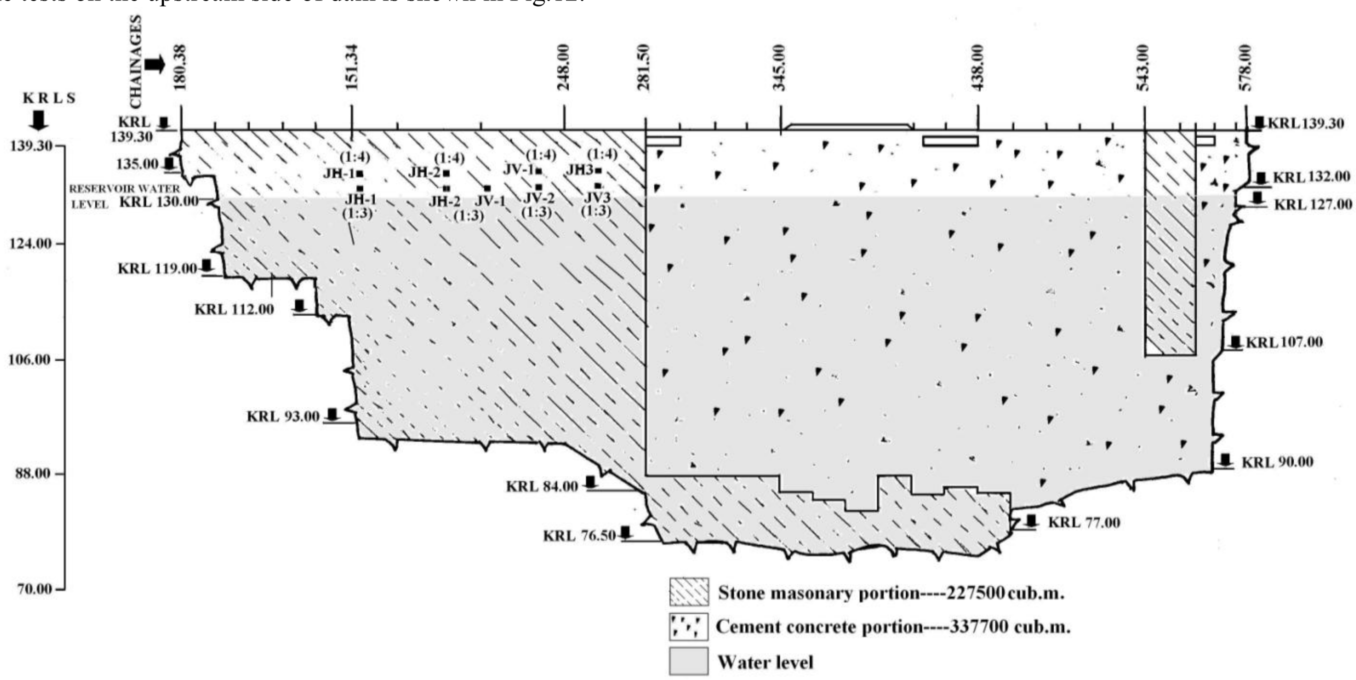

Figure 11. Flat jack test locations on upstream side of Kolkewadi dam.

Deformation Modulus E_m

The static deformation modulus derived from the stress vs. deformation relationship for 1:3 masonry varied from 32.80 to 45.60 GPa. Out of the five values three values were nearly equal to 32.80 GPa and this value was selected as representative of the 1:3 masonry. The static modulus of deformation for the 1:4 masonry varied from 17.40 to 23.30 GPa. A typical plot is shown in Fig.13. The average of the three values (i.e., 17.40, 19.80 and 19.80 GPa) is 19.0 GPa and this value was selected by ignoring the outlier value of 23.30 GPa. The static modulus of deformation for the 1:5 masonry varied from

11.30 to 24.30 GPa determined from four flat jacks fixed on the downstream side. Two Flat jacks JH-1 and JH-2 were fixed in the penstock gallery and two in the body of the dam.The selected average value was 13.70 GPa.

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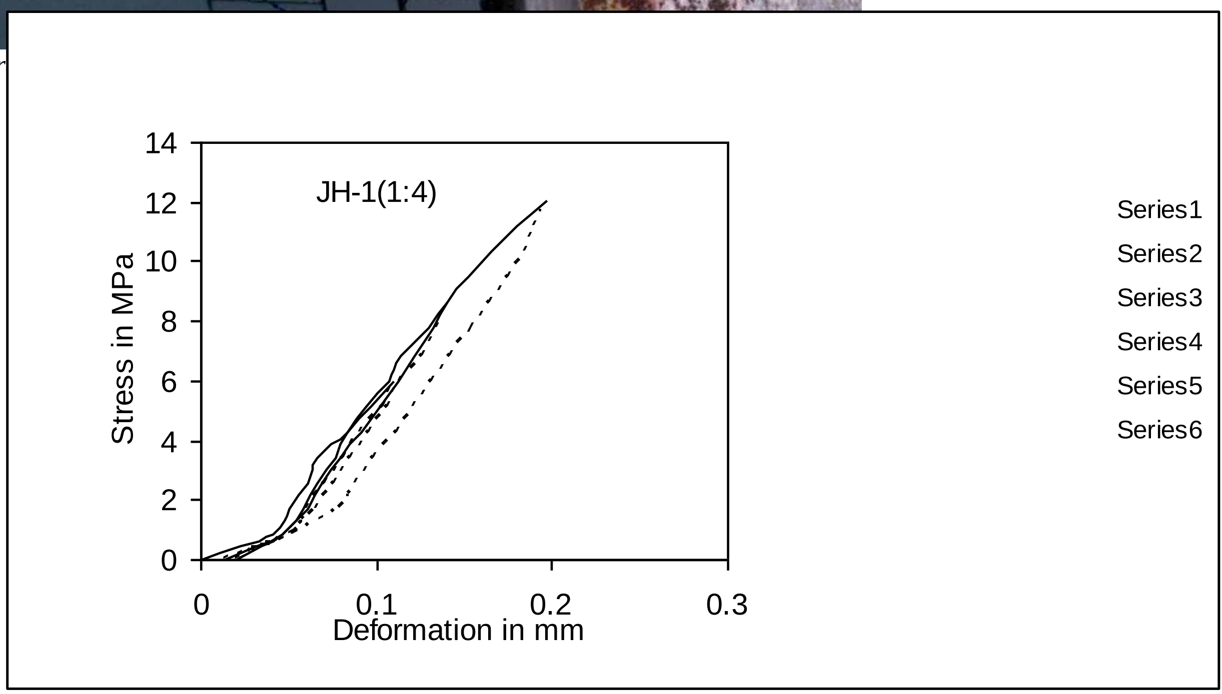

In-situ Poisson's ratio, υ

E_m values were evaluated by assuming a value of υ. In cases where Poisson's ratio was to be measured, the convergence of the slot was measured between four reference pins i.e. two pins fixed at a known distance on either side of the slot instead of one, prior to cutting of the slot (Fig.14).

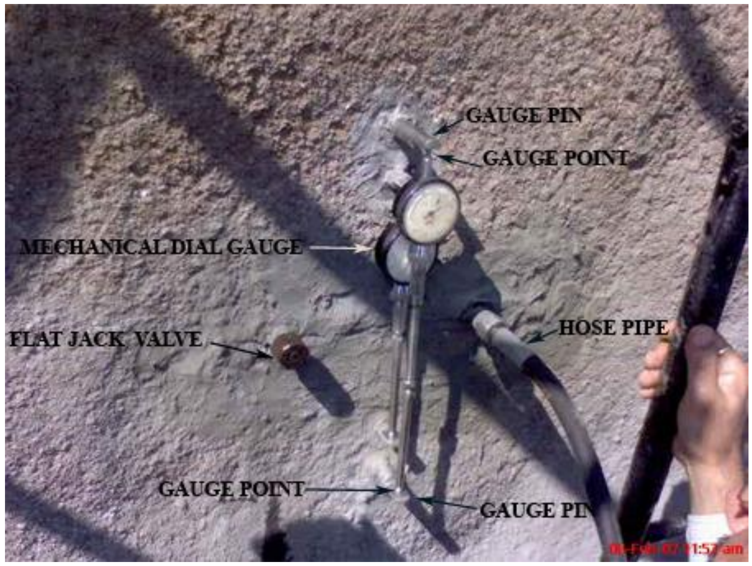

Figure 14. View of embedded flat jack and four reference pins in the slot.

The stress-displacement envelope is obtained for the inside pins that are fixed at a distance of about 25.40 cm and also for the outside pins that are fixed at a distance of about 34.50 cm (Fig.14) on both sides of the slot. From the stress-displacement measurements using the inside pins, E_m is determined in terms of υ using eq. 9. Similarly for the stress-displacement values using the outside pins, E_m is determined in terms of υ using the same equation. Ideally, E_m values are equal for the inside and outside pins in the same location, so these two values are equated to derive υ. From these two equations, the unknown value of υ is calculated by elimination process. Poisson's ratio is determined from the ratio of two sets of E_m values determined from the deformation values measured between inside and outside pins, while carrying out the cyclic test. The average Poisson's ratio of 1:3, 1:4 and 1:5 masonry is 0.236, 0.18 and 0.108 respectively.

Induced Stresses by Flat Jack

The most widely accepted assumption in dams is that the vertical stress at any point of the dam is equal to the weight of the overlying material ($W = \gamma z$). The stress in the horizontal direction is equal to $\gamma * z \times (\upsilon/1- \upsilon)$, where γ is unit weight of masonry, z is the depth of masonry above the point of consideration and υ is Poisson's ratio. In general, the measured vertical stress nearly agrees with overburden stress for the case of masonry dam. Horizontal stresses, however may not. It has been reasoned that besides the weight of the masonry itself, stresses of thermal origin, chemical reaction due to constituents of masonry, creep effects and water pressure contribute to the actual state of stress in dam.

The induced stress in the vertical direction, for 1:3 masonry varied from 1.20 to 2.29 MPa with an average value of 1.84 MPa. The top level of the dam is at 139.30m and flat jack level at 132.40m. The calculated and measured stress values are almost matching by adopting density value of 2568 Kg/m^3. The induced stress in the horizontal direction varies from 1.30 to 3.65 MPa with an average value of 2.10MPa. The induced stress in the vertical direction, for 1:4 masonry varied from 0.48 to 0.95 MPa with an average value of 0.75 MPa. The top level of dam is at 139.30m and the flat jack level at 134.80m, thus, the calculated value of stress is 1.15 MPa. The induced stress in the horizontal direction varied from 1.49 to 1.52 MPa with an average value of 1.51 MPa. The induced stress for 1:5 masonry could not be measured because the elevation of the sloping surface of the downstream side of the dam was unknown.

Laboratory tests were conducted on 15 cm diameter and 30 cm length cores extracted from uncoursed rubble (UCR) masonry. These cores were extracted from different levels of dam strata for cement mortar (CM) ratios of 1:3, 1:4 and 1:5. Laboratory tests were performed to determine Elastic modulus (E_L), Poisson's ratio (υ), unconfined compressive strength (σ_c) and tensile strength (σ_t). These values are presented in Table 3. The test results indicate large variation in the properties of UCR. The standard cement sand mortar properties from the Quality Control Manual (2003) are given in Table 4.

Table 2: Flat Jack test result at different locations of Kolkewadi dam.

Sl. No	Flat jack No.	Chainage in m	KRL In m	Masonry proportion	Deformation modulus, E_m (MPa)	Poisson's Ratio, υ	Induced Stresses (MPa)	
							P_θ	P_h
01	JV- 1	216.0	132.40	1:3	32.80	0.25	-	-
02	JV- 2	231.0	132.40	1:3	32.80	0.25	-	-
03	JH- 1	162.50	132.50	1:3	45.60	0.21	2.29	1.34
04	JH- 2	193.90	132.40	1:3	34.90	0.24	2.03	1.30
05	JH- 3	266.0	132.40	1:3	40.10	0.23	1.20	3.65
06	JV- 1	231.0	134.70	1:4	23.30	0.19	-	-
07	JH-1	162.50	134.80	1:4	19.80	0.19	0.95	1.51
08	JH-2	193.40	134.80	1:4	19.80	0.17	0.80	1.52
09	JH-3	266.50	134.80	1:4	17.40	-	0.48	1.49
10	JH- 1	150.0	121.90	1:5	24.30	0.10	2.39	1.64
11	JH- 2	151.34	121.75	1:5	22.40	0.11	-	-
12	JV- 1	216.0	119.85	1:5	16.10	0.11	-	-
13	JV- 2	281.50	119.75	1:5	11.30	0.11	-	-

P_θ-Stress in the vertical direction, P_h-Stress in the horizontal direction

Table 3: Properties of UCR masonry of Kolkewadi dam determined by laboratory testing.

Type of UCR masonry	No.of speci-mens	Density (kg/m^3)	Compressive strength (MPa)	Split tensile strength (MPa)	Modulus of elasticity (GPa)	Poisson's ratio
1:3	9	2550 to 2675	11.2 to 46.97	1.91 to 4.86	26 to 48	0.12 to 0.21
1:4	9	2359 to 2748	9.05 to 37.92	2.76 to 7.5	5.2 to 45	0.09 to 0.13
1:5	18	2377 to 2904	8.21 to 40.75	1.69 to 4.56	8 to 59.5	0.10 to 0.15

Table 4: Properties of cement sand mortar from Quality Control Manual.

Proportion of cement sand mortar	Curing Period (days)	Compressive strength (MPa)	Split tensile strength (MPa)	Modulus of elasticity (GPa)
1:3	60	30.7	4.50	33.5
1:4	60	17.8	3.0	24.0
1:5	60	13.9	2.60	17.0

Results and Conclusions for case study II

The inconsistency in the laboratory test results of masonry was attributed to the varying proportions of stones and mortar in the specimens of masonry of same grade and orientation of the stones in the sample. So laboratory results were found not to be representative of the real properties of masonry that are required for the dynamic analysis of the masonry dam:

- Average E_m by flat jack test for 1:3 masonry was equal to 32.8 GPa and comparable to the standard values. The laboratory E_L for 1:3 masonry from stress strain cycles was estimated to be 26.0 to 48.0 GPa. Due to large variations in laboratory E_L values, E_m value of 32.8 GPa determined by the flat jack method, was adopted for the dynamic analysis. Similarly, the average E_m value by the flat jack for the 1:4 and 1:5 masonry is 19.0 GPa and 13.7 GPa respectively and were adopted for the dynamic analysis. Large variations were observed in the values of laboratory E_L. These values were lower than the standard values due to lower bonding strength with stones for 1:4 and 1:5 masonry.
- Average υ determined by the flat jack test for the 1:3, 1:4 and 1:5 masonry was 0.236, 0.18 and 0.108 respectively. Statistical mean of υ determined by the static loading machine for the 1:3, 1:4 and 1:5 masonry yielded values of

0.17, 0.12 and 0.11. As per practice, υ determined in laboratory for the intact sample was more reliable, so laboratory values could be adopted for the dynamic analysis.

- The statically mean value of σc determined in the laboratory for UCR masonry 1:3, 1:4 and 1:5 were 22.62, 28.48 and 13.21 MPa respectively. These σc values were adopted for the analysis. Variation with the standard values is observed due to variability in the percentage of stones present in the masonry.

- The statically mean value of density determined in the laboratory for UCR masonry 1:3, 1:4 and 1:5 were 2568.33, 2489.21 and 2549.26kg/m3 respectively.

CONCLUSIONS

For the design of lining/supports in tunnels, shafts and under ground openings induced stresses in the walls of the openings are critical. When sufficient rock cover is not available, determination of in-situ stressses becomes very difficult and flat jack method is found to be most suitable method to estimate the existing stresses in the vicinity of the openings.

As per the standard practice, strength parameters for the old masonry dams/buildings are determined by testing the different sizes of cores extracted from different places of the structure's body. Due to inconsistency in the results of masonry that is attributed to the varying proportions of stone and mortar in the specimens of masonry of same grade and variable orientation of stones in the sample, non-destructuve field testing was necessary. Flat jack testing is found to be very useful and easy to use with no damage to the structure. Flat Jack tests are quicker and cheaper than laboratory testing because drilling different sizes of cores is time consuming and costly. Once embedded in the structure, the flat jack is not extracted, and becomes part of the structure.Flat jacks can be positioned in all directions of the structure allowing measurements of the strength parameters for different directions of the structure.

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