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Technical Note

# Determination of Strength Parameters of a Masonry Dam by Flat Jack Method

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**Key words**

Flat jack, deformation modulus, masonry dam, insitu stress, dynamic analysis

**Abstract:** The Kolkewadi dam situated at Alore village, Chiplun district of Maharashtra is one of the major stages of the Koyna Hydro Electric Project. The length and height of the dam are 497.0 m and 56.80 m with gross storage of 36.22 Mm³.The dam was constructed in 1975, when the seismic activity was at low level in Koyna region. The Government of Maharashtra constituted an Experts' Committee after the Killari earthquake of magnitude 6.4 on 30th September 1993. The Committee recommended dynamic analysis of Kolkewadi dam using measured strength parameters. The different portions of dam have been constructed with cement concrete and uncoursed rubble (UCR) masonry with different combinations of mortar ratios. Laboratory test results of masonry cores indicated large variation in properties due to the variation of percentage of mortar/orientation of stones. Hence insitu Flat jack testing of masonry portion of the dam was carried out for the determination of strength parameters. Flat jack tests were carried out on the vertical surface of the upstream side of the dam in masonry of 1:4 and 1:3 and in masonry of 1:5, which is existing on the downstream. Deformation modulus for the masonry of 1:3, 1:4 and 1:5 is found to be 32.1 GPa, 23.3 GPa and 13.7 GPa respectively. Poisson's ratio is found 0.236, 0.18 and 0.108 for the masonry of 1:3, 1:4 and 1:5 respectively. Induced stresses are found to be nearly equal to the overburden.

## Introduction

Non Destructive Techniques (NDT) such as ultrasonic pulse velocity or hardness testing may be able to locate flaws or provide a comparative survey of masonry quality, but they can not provide the quantitative data required for engineering evaluation and analysis. The flat jack method is unique in that as it provides a direct measure of masonry strength and modulus parameters. The equipments used for carrying out flat jack tests are very simple and cost effective. This paper presents an overview of measurement of strength parameters by in-situ stress test, in-situ deformability test and Poisson's ratio test carried out by flat jacks, at the Kolkewadi dam.

### Stress Measuring Methods

Of the several methods devised for measuring in-situ stresses, three methods i.e. over coring, hydraulic fracturing and flat jack methods have been widely used in rock masses. These are described in detail in, ISRM (1987). All these methods are based on the assumption that the rock mass is linearly elastic, homogeneous and isotropic in the zone influencing the measurement. From a practical point of view a simpler technique which would enable a number of measurements to be made easily and cheaply will be useful for determination of representative stress in a masonry dam. The flat jack method is one of such techniques.

Flat jack techniques are well established in the field of rock mechanics for determining stresses and material deformability in the rock structure of tunnels and mines (Binda Maier et al., 1983). The technology of the flat jack test has been modified and adapted to the purpose of evaluation of brick and stone masonry structures in Italy by Rossi (1982, 1985, 1987). 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. Wang and Wang (1988) developed a relatively thick flat jack with large displacement capabilities for use on very soft masonry materials typically found in China.

Analytical studies have been carried out in support of the experimental results. Sachhi-Landriani and Taliercio (1986) conducted extensive nonlinear finite element analyses of both the single and double flat jack tests in masonry. They found their numerical models to be generally in support of experimental evidence, and offered some insight concerning the effect of certain assumptions on the accuracy of the results. For example, the accuracy of the in-situ deformation test is compromised because of the restraining effects of the vertical boundaries of the "in-situ prism". Based on their analytical work, they recommended that if the two flat jacks test is carried out up to the failure strength, the failure stress should be reduced by 20% to yield the unrestrained compressive strength.

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## Single Flat-Jack Test

The test is based on the principle of partial stress release and involves the local elimination of stresses, followed by controlled stress compensation. The Indian Standard (IS 13946 Part IV, 1994) on flat jack describes the method and the test procedure. A thin flat jack (Figure 1) of size 30 × 30 cm used for the studies is introduced into the slot. With the aid of this device, pressure (compressive stress) is applied to the masonry (Figure 2). This causes a partial restoration of the initial displacement field, which at some point reach (approximately) the previously measured values. The necessary pressure is called cancellation pressure and can be related to the compressive stress in the direction normal to the slot. This is caused by the inherent stiffness of the flat jack, which resists expansions when the jack is pressurized. Another factor that contributes to this effect is the difference between the area of the jack and the area of the slot (the latter being greater than the former). Both these factors are taken to be in account when interpreting test results.

The test, as described above, is based on the following assumptions: the stress in place of the test is compressive; the masonry surrounding the slot is homogenous; the masonry deforms symmetrically around the slot; the state of stresses in the place of the measurement is uniform; the stress applied to masonry by the flat jack is uniform; the value of stresses (compared to compressive strength) allows the masonry to work in an elastic regime.

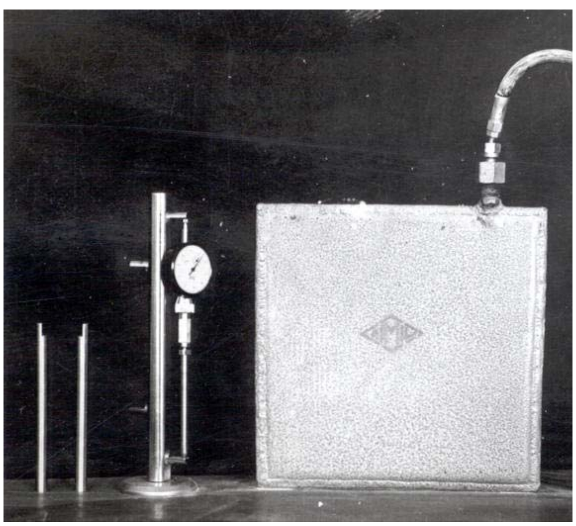

Fig. 1 A set of flat jack, dial gauge and pins

Fig. 2 Placing of dial gauge after fixing flat jack between the two pins

# Applications of Single Flat Jack

## Evaluation of Insitu Stresses

For evaluation of insitu stresses an opening is required to be made and flat jack tests are conducted in these openings. In actual tests, the length of the slot may be bigger than the jack and the slot may not be of uniform width. Further the stress acting in the plane parallel to the major axis of the slot also affects the contraction of the slot. $K_1$, $K_2$, $K_3$ are constants which are determined to account for the above affects. At each of the test locations several tests are to be carried out to obtain statistically viable results. The formulae as given below that account for the effect of all the above factors can be used for evaluating the stresses.

$$PK_1=P\theta K_2+PH\ K_3 \tag{1}$$

Where P is the flat jack cancellation pressure, A slot cut in the horizontal direction yields $P_\theta$ and one cut in the vertical direction yields $P_H$. $K_1$, $K_2$, $K_3$ are constants and can be expressed by the following equations:

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

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

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

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

$2C_o$ = Length of Flat Jack, $\nu$ = Poisson's ratio, 2C = Length of slot, 2Y = Distance between two reference pins, $2Y_o$ = Width of slot. $P_\theta$ and $P_H$ are the stresses induced on the boundary of the opening. Since these induced stresses are a function of the insitu stresses and the shape of the opening, it is possible to evaluate the insitu stresses. When two mutually perpendicular to each other openings are available close to each other for measuring the stresses, the measured stresses would be:

$$P_\theta = K_v \sigma_v + K_H\ \sigma_{H1} \qquad (5)$$

$$P_H = \sigma_{H2} + \nu(K_v - 1)\ \sigma_v + \nu\ (K_H - 1)\ \sigma_{H1} \qquad (6)$$

$$P_L = \sigma_{H1} + \nu\ (K_v - 1)\ \sigma_v + \nu\ (K_H - 1)\ \sigma_{H2} \qquad (7)$$

$P_\theta$ – Stress on the boundary of the opening and tangential to the boundary

$P_H$ – Stress on the boundary of the opening and parallel to the axis of the opening

$P_L$ – Stress on the boundary of the opening and perpendicular to the axis of the opening

$K_v$ – Concentration factor at location $P_\theta$ due to in-situ vertical stress

$K_H$ – Stress concentration factor at location $P_H$ due to in-situ horizontal stress

With the knowledge of measured $P_\theta$, $P_H$ and $P_L$ values and stress concentration factors $K_v$, $K_H$, it is possible to evaluate $\sigma_v$ and $\sigma_H$. For regular geometrical shape such as circle, D shape, rectangle and square shapes, stress concentration factors $K_v$, $K_H$ can be obtained from available monographs. For other shapes, the same could be obtained by photo elastic or mathematical models. For circular openings, it is possible to estimate the magnitude of the principal stresses $\sigma_v$ and $\sigma_H$ in a horizontal plane using the relation from various $P_\theta$ values.

$$P_\theta = (\sigma_v + \sigma_H) - 2(\sigma_v + \sigma_H) \cos 2\theta \qquad (8)$$

Where θ is the angle between the location of $P_\theta$ and direction of $\sigma_v$. $P_\theta$ is the measured induced stress around the opening at different points.

## Evaluation of Deformation Modulus, $E_m$

When slot is made in the masonry wall, stress originally existing across it relieves the masonry surface of the existing stresses. Because of the stress relief, the sides of the slot converge. The amount of convergence which depends upon the stresses in the masonry and its elastic properties are given by the equation (9).

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

$a_o$ is determined as $\sqrt{1+\frac{Y^2}{c_o^{\ 2}}}$

Where, w is the amount of convergence between two points spaced at equal distance Y from the plane of the slot along the centre line normal to its plane due to stress P, $E_m$ is the Modulus of deformation , $2C_o$ is the length of Flat Jack, and $\upsilon$ is Poisson's ratio.

The flat jack is then embedded tightly in the slot by filling the gap between the jack and the slot with cement mortar. Pressurizing flat jack with the help of a hydraulic pump applies the load to the walls 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 and decrease with reduction in pressure. By gradually increasing the pressure, the stress-strain relationship can be determined. Loading-unloading cycles are performed. Based on an experimental stress-strain curve, the value of deformation Modulus can be calculated. If extended damage in the specimen is acceptable, the compressive strength of masonry can be obtained.

## Evaluation of In-situ Poisson's Ratio, $\upsilon$

$E_m$ values are determined by adopting the assumed value of $\upsilon$, but when Poisson's ratio is to be determined then convergence of the slot is to be measured between four reference pins i.e. two pins are fixed at a known distance on either side of the slot instead of one, prior to cutting of the slot (Figure 3).The consecutive stress-displacement envelope is obtained for inside pins fixed at a distance of about 25.40 cm and also for the outside pins fixed at a distance of about 34.50 cm (Figure 3) simultaneously while hydraulic stressing/distressing of the flat jack. From the stress-displacement values of inside pins $E_m$ is determined in terms of $\upsilon$ by using equation 9. Similarly for the stress-displacement values of outside pins $E_m$ is determined in terms of $\upsilon$ by using the same equation. $E_m$ values are suppose to be same for the inside and out side pins being determined for the same area, so these two values in terms of $\upsilon$ are equated. From these two equations the unknown value of $\upsilon$ is calculated by elimination process.

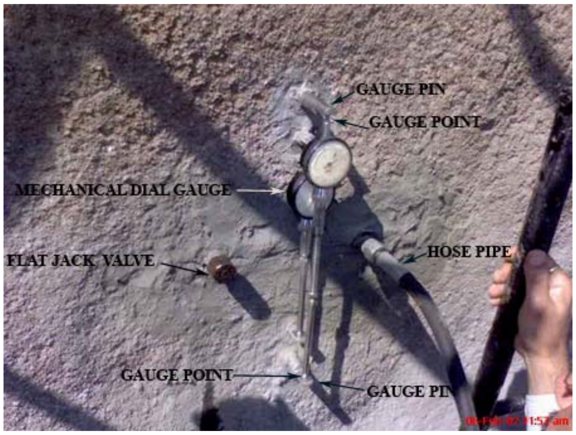


Fig. 3 View of embedded flat jack and four reference pins in the slot

## Two Flat-Jacks Test for Determination of Deformation Modulus, $E_m$

The principle of the test is similar to a standard compressive test. The difference is that it is performed in-situ and two flat-jacks are used to apply the load. Two pins are fixed in-between the two identified slots at a distance of about 25.40 cm and exact distance between two pins are measured by dial gauge. By cutting two parallel slots at a distance of about 40 cm on both sides of pins at equal distance, part of the wall is isolated from the surrounding masonry. Masonry between the flat-jacks is assumed to be unstressed. Flat-jacks are then introduced into both slots, and the initial distances between gauge points are measured. By pressurizing flat jacks, the load is applied by creating an approximately uniaxial state of compressive stress.

## Three Flat Jacks Test for Determination of Insitu Shear Parameters

A new technique has been developed for determination of insitu shear parameters with the help of flat jack method. The insitu shear test as defined in IS 7746-1975 is normally a push test, where normal and horizontal loads are applied and shear stress corresponding to incipient failure is determined for each normal stress.

In three flat jacks test, the normal stress is controlled by two flat jacks fixed at the above and below of the test point/joint at a distance of about 40 cm. Two pins are fixed in the centre of two flat jacks at a distance of about 25.4 cm and one more flat jack is fixed in between two pins perpendicular to the two flat jacks (Figure 4). The test is conducted at the same joint for several normal loads. For different normal loads strain values are determined by inflating perpendicular jack in-between two horizontal flat jacks. Then shear parameters are determined from normal stresses and their corresponding peak shear.

## Determination of Strength Parameters of Dam by Laboratory Tests

Laboratory tests have been conducted on 15 cm diameter and 30 cm length cores extracted from UCR masonry. These cores were extracted from different levels of dam strata for cement mortar (CM) ratio's of 1:3, 1:4 and 1:5.

Laboratory tests are carried out on UCR masonry and rock cores to determine Elastic modulus ($E_L$), Poisson's ratio ($\upsilon$), unconfined compressive strength ($\sigma_c$) and tensile strength ($\sigma_t$) and their values are given in Table 1 indicate large variation in the properties of UCR.

## Determination of Strength Parameters of Dam by Flat Jack

Flat jack tests were conducted on the vertical surface of the upstream side of dam in UCR masonry of 1:4 and 1:3 and in UCR masonry of 1:5 which is existing on downstream sloping side of the dam. The results of insitu flat jack tests are given in Table 2.

### In-situ Test Locations

The strength parameters induced stress, elastic modulus and Poisson's ratio are to be determined for different variation of masonry existing in the Kolkewadi dam. In the upstream side, flat jack tests are conducted in masonry with cement mortar ratio of 1:4 at KRL 134.80m at four locations at chainages of 162.50, 193.40, 231.0 and 266.50m.

Flat jack tests have been conducted at KRL 132.40m at five locations at chainages of 162.50, 193.90, 216.0, 231.0 and 266.0m in the upstream side masonry with cement mortar variation of 1:3 (Figure 5) and at four locations at chainages 150.0, 151.34, 216.0 and 281.50 in the down stream side masonry with cement moprtar ratio of 1:5.

## Modulus of Deformation, $E_m$ by Flat Jack

The static deformation modulus determined from second cycle of stress displacement curve (Figure 6) for1:3 masonry is varying from 32.80 to 45.60 GPa. Out of the five values three values, are nearly equal to 32.80 GPa and adopted for analysis for 1:3 masonry portion.

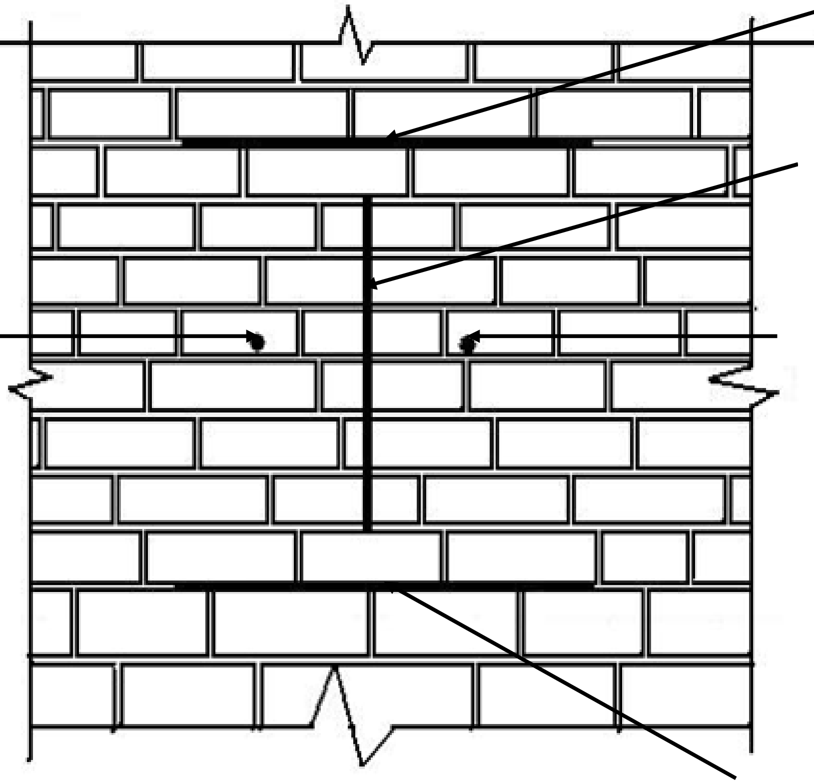


Fig. 4 Insitu shear test set-up by three flat jacks

Table 1 Properties of UCR masonry of Kolkewadi dam determined by laboratory testing

| Type of UCR masonry | No. of specimens | 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 |

The static modulus of deformation for the 1:5 masonry is varying from 11.30 to 24.30 GPa. Flat jack No. JH-1 and JH-2 were fixed in the vertical surface near to the penstock gallery and part of column structure. The flat jacks JV-1 and JV-2 were fixed in the body of the dam, an average value of 13.70 GPa. is adopted for the analysis.

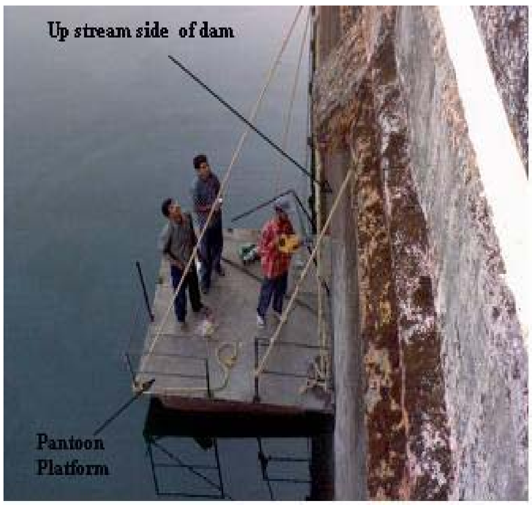


Fig. 5 Arrangement for a test setup for flat jack test on upstream side of dam

### In-situ Poisson's ratio, $\upsilon$ by Flatjack

Poisson's ratio is determined from the ratio of two set 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 Stress by Flat Jack

The induced stress in the vertical direction, for1:3 masonry is varying from 1.20 to 2.29 MPa and average value is 1.84 MPa. With top level of dam at 139.30m and flat jack level at 132.40m. The calculated and measured stress values are found to be matching. The induced stress in the horizontal direction is varying from 1.30 to 3.65 MPa and average value is 2.10 MPa. The induced stress in the vertical direction, for1:4 masonry is varying from 0.48 to 0.95 MPa and average value is 0.75 MPa. With top level of dam at 139.30m and flat jack level at 134.80m, the calculated value of stress is 1.15 MPa. The induced stress in the horizontal direction is varying from 1.49 to 1.52 MPa and average value is 1.51 MPa. The induced stress for1:5 masonry could not be measured due to non-availability of vertical surface as the downstream side of dam has slope surface

## Results and Discussion

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. Laboratory results were found to be not representing the real properties of masonry, which could be adopted for the analysis. Hence flat jack tests were carried out, which gave better representation of the properties of the masonry than those obtained by laboratory tests (Wittke and Polczyk, 2002).

Average $E_m$ by flat jack test for 1:3 masonry was equal to 32.8 GPa. The laboratory $E_L$ for 1:3 masonry from stress strain cycles worked out to be 26.0 to 48.0 GPa. Due to the large variations in laboratory $E_L$ values, $E_m$ value of 32.8 GPa determined by the flat jack method, is adopted for the 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 analysis as there was large variations in the values of laboratory $E_L$.

Average $\upsilon$ 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 $\upsilon$ determined by the static loading machine for the 1:3, 1:4 and 1:5 masonry worked out to be 0.17, 0.12 and 0.11. As per practice, $\upsilon$ determined in laboratory from the intact sample is more reliable due to intactness of the sample, so laboratory values could be adopted for the analysis.

The statically mean value of $\sigma_c$ determined by laboratory for UCR masonry 1:3, 1:4 and 1:5 were 22.62, 28.48 and 13.21 MPa respectively. These $\sigma_c$ values were adopted for the analysis.

## Conclusions

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 from the body of the structure due to inconsistency in the results of masonry which 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, field testing with no damage to the structure was the need of the time. 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 even laboratory testing. Flat jack once embedded in the structure is not extracted, so it becomes part of the structure. Flat jacks can be fixed in all directions of the structure so that the strength parameters can be determined for different directions of the structure.

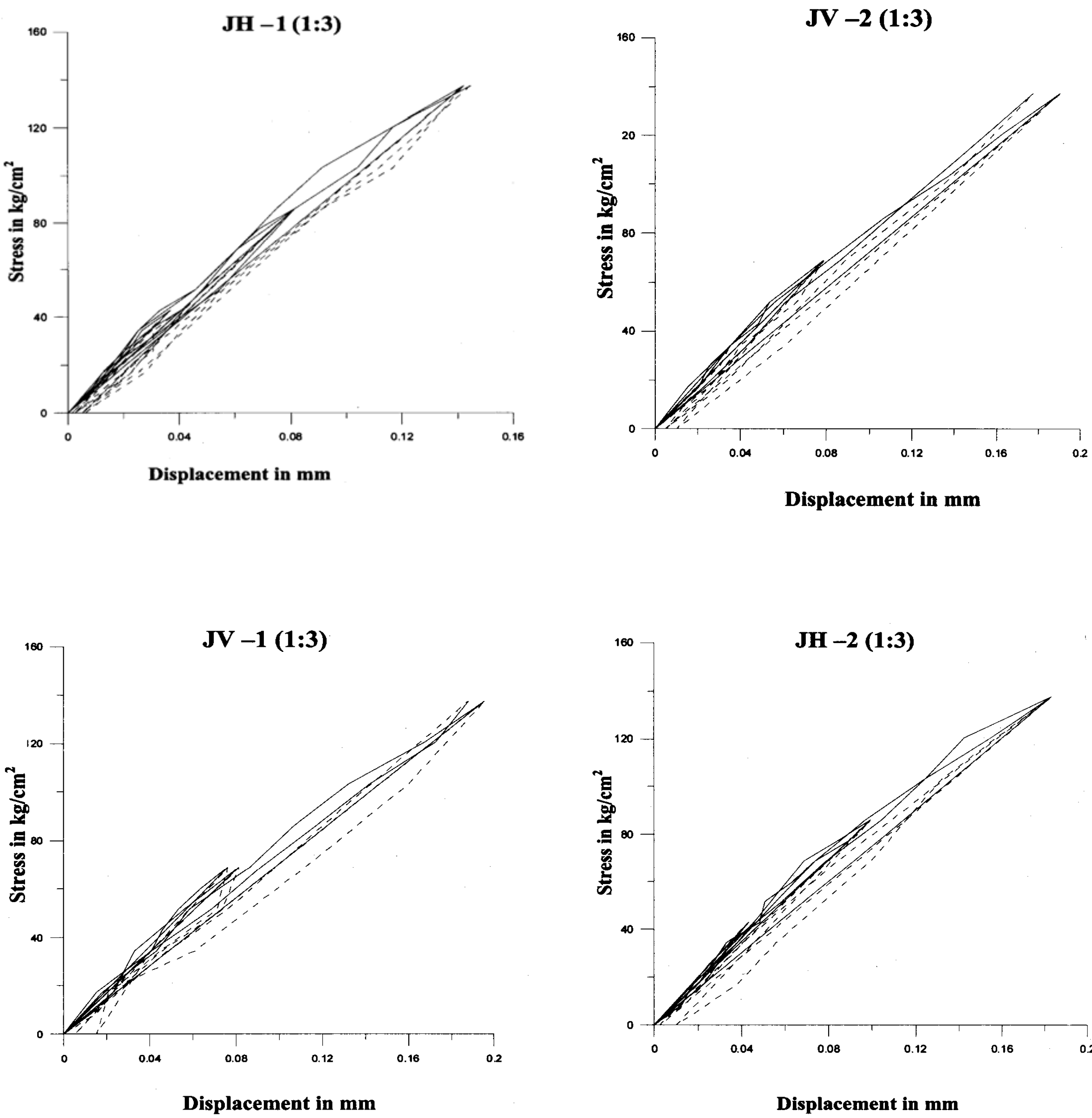


Fig. 6 Stress vs. displacement envelopes from Flat Jack test locations at Kolkewadi dam for UCR 1:3

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, $\upsilon$ | Induced Stresses(MPa) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | S | Q |
| 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 | - | - |

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