Title of the Thesis: ANALYSIS OF GRAVITY DAM-FOUNDATION SYSTEM FOR JOINTED ROCK FOUNDATIONS WITHOUT AND WITH SHEAR SEAMS

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Abstract:

At present, India’s installed capacity in the hydropower sector is approximately 44.47 GW out of total power capacity of 326.84 GW (CEA, 2018). Therefore, a substantial development of the hydropower is required which significantly depends on construction of dams. Concrete gravity dams (referred as dams) transmit large loads to the foundation, which requires detailed analysis of dam-foundation system. Rock mass comprises of joints and shear seams and hence distinct element models, DEM, that incorporates deformable blocks are required (Cundal, 1992).

The detailed project reports of 40 hydroelectric projects in the Himalayan region are reviewed and the apparent dips of the set of joints of these projects evaluated to access the combination of joint orientations used for analysis in this study.

The dam and foundation are modelled as two discrete blocks, which are interacting through an interface between them. Analysis is carried out for two loading conditions, viz., (i) Loading condition ‘A’ (construction condition), $LCA$, i.e., construction of dam completed but no water in reservoir and no tail water, and (ii) Modified loading condition ‘B’, $LCB$, i.e., full reservoir level, with extreme uplift, assuming the drainage holes to be inoperative. For $LCB$ both coupled hydro-mechanical analysis, $LCB_c$, and uncoupled hydro-mechanical analysis, $LCB_u$, (or mechanical analysis) are carried out.

To study the effect of joints and shear seams, dam-foundation analysis is carried out idealizing the foundation rock as (a) a discontinuum jointed rock mass foundation with one or two sets of joints, (b) a continuum rock foundation with shear seam, and (c) a discontinuum rock foundation with shear seam. For the present study elasto-plastic analyses has been carried out for 29,612 cases using the software Universal Distinct Element Code, UDEC (Itasca, 2011).

Analysis of the dam-foundation system with single set of joints are carried out to study the effect of (a) single set of joints: by varying the joint spacing, $s$, joint orientation, $\theta_j$ of the foundation joints; (b) foundation joint stiffness: by varying joint normal stiffnesses, $k_n$, and joint shear
stiffnesses, $k_s$ and (c) dam-foundation interface joint stiffness by varying the dam-foundation interface normal stiffness, $k_{ni}$, and dam-foundation interface shear stiffness, $k_{si}$.

As expected, it is observed that the major principal stresses are maximum at the heel for $LCA$ and at the toe for $LCB$ (both $LCB_c$ and $LCB_u$). For $LCB_c$, the uplift pressure distribution is non-linear and varies with the variation of joint orientation. For most cases for $LCB_c$, the factor of safety is higher than that from the conventional analysis. It is also observed that for both $LCA$ and $LCB_c$, major principal stress and crest displacement increase as joint spacing reduces, for all $\theta_j$. For values of $\theta_j$ from 0° to 30° and 105° to 180°, $LCA$ is the critical condition for stresses while for values of $\theta_j$ from 30° to 105°, $LCB_c$ is critical. For $LCA$, the displacements are minimum for sub-horizontal joints and maximum for sub-vertical joints. For $LCB_c$, the $x$-displacements of the crest are minimum for a sub-horizontal joint sets and maximum for a sub-vertical joint sets while the $y$-displacements of the crest are maximum for a sub-horizontal joint sets and minimum for a sub-vertical joint sets. It is observed that stresses and displacements under both loading conditions are dependent on the product of $k_n$ and $s$, and, for any value of $k_n.s$ greater than Young’s modulus of intact rock, $E_r$, i.e., $k_n.s > E_r$. It is generally observed that as the ratio $k_n/k_s$ increases, the stress and displacement increases.

The behaviour of rock foundation with two sets of joints is evaluated by varying the joint spacing, $s$, joint set orientation, $\theta_j$, and included joint angle, $\theta_i$. The joint set spacing for both joint sets are assumed equal. Critical joint set combinations for major principal stress are observed as 0°-120° and 120°-150° for $LCA$, and 0°-90° and 0°-150 for $LCB_c$. Crest displacements are observed to be critical for 60°-90° and 30°-60° for $LCA$. For $LCB_c$, critical joint combinations for $x$-displacements are 0°-120°, 30°-90° and for and $y$-displacements are 60°-90°, 30°-60°.

To study the effect of seam in the dam-foundation system, analysis has been carried out by idealising the foundation as equivalent continuum by varying the seam width, seam orientation, $\theta_s$, with respect to the upstream horizontal and seam strength properties namely, seam cohesion, $c_s$, and angle of friction, $\phi_s$. The locations of the seam are considered at Heel ($Hl$), Heel-Center ($HC$), Center ($C$), Center-Toe ($CT$) and Toe ($T$).

It is observed that due to the presence of a seam, the stresses and displacements are affected in the vicinity of the seam, in the dam and foundation. The deformation at the mid-point of the seam, $\delta_{ys}$, at the dam base is compared with the deformation at the same location without the seam, $\delta_y$. A seam influence factor ($I_f$) defined as the ratio of $\delta_{ys}$ to $\delta_y$ is calculated for each case, to study the impact of the seam.
Seam orientation of 90° and 120° is observed to be most critical for $LCA$ and $LCB_c$ respectively. A seam at the heel ($HL$) of the dam is most critical for both loading conditions. In all cases, the seam influence factor increases with increase in the seam width. For both loading conditions it is observed that as value of $c_s$ or $\phi_s$ decreases, values of $\delta_s$ and $I_f$ increase. The effect of change in $c_s$ or $\phi_s$ is greater for smaller values of $c_s$ or $\phi_s$.

In order to study the effect of shear seam on a jointed rock foundation, and, to calculate the optimum depth of plug for dental treatment, analyses are carried out for a gravity dam on a jointed rock foundation with a single set of joints along with shear seam and plugs for dams of different heights. Twelve different joint set orientations $(\theta_j)$, and a spacing of 2 m are considered for foundation joints. Seam of four different widths are considered at different locations below dam base. Analysis is carried out for both $LCA$ and $LCB_c$.

Additional analysis are carried out with concrete plugs of 4 different depths for each seam considered and plug efficiency curves are developed. The optimum plug depth is defined as the plug depth where the rate of change of plug efficiency reduces to 1%. A study of the optimum plugs for all cases considered showed that the impact of $\theta_s, \theta_j$ and seam location is negligible on the value of optimum plug depth for seam of various widths.

In order to develop an empirical equation for the optimum plug depth required for dental treatment of shear seam, the optimum plug depth is calculated for different dam heights and seam widths.

Based on the assessment of the impact of various parameters on the optimum plug depth, the relevant variables affecting plug depth, namely, dam height and seam width, have been identified, and an empirical relationship is proposed through regression analysis. The plug depth calculated from the derived empirical relationship has also been compared against other similar equations available for plug depth.

Numerical validation of empirical equation for optimum plug depth is carried out for variation in joint spacing; variation of ratio of Young’s modulus of intact rock blocks to that of dam concrete, $E_r/E_c$ ; and varying the ratio of Young’s modulus of rock blocks to that of shear seam blocks, $E_r/E_s$. Impact of variation in each of the parameters on the optimum plug depth is studied.

It is concluded from the above study that the empirical relationship developed in the present study is suitable for calculating the optimum depth of plug which should be provided for any given seam width and dam height.