Optimization of concrete gravity dams foundation drainage systems

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ABSTRACT: Numerical three-dimensional nonlinear flow analysis is a very efficient instrument for the optimization of the subsurface drainage systems of concrete gravity dams. Post-mortem optimization analyses of the intake and powerhouse structures of Isamu Ikeda dam indicated that the drains' lengths, spacings and diameters used in design were very close to optimum. The analyses have also indicated that the uplift force effectively acting at the structures' base is of the order of 25% of that obtained using the USBR design criterion. The introduction of an additional drainage gallery together with two lines of inclined drains, in all galleries, would have caused an additional reduction in the uplift force to a value near 10% of that indicated by the USBR criterion suggesting that if the present methodology had been available at the design stage of Isamu Ikeda dam it would have been possible to reduce the concrete structures' weight by nearly 40%.

1 INTRODUCTION

One of the most relevant activities of the geotechnical design of concrete gravity dams is the determination of its stability to sliding. Figure 1 shows the system of forces that acts on a typical dam.

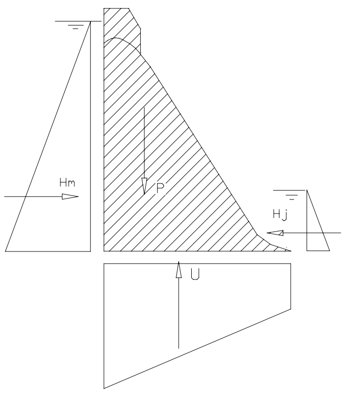

Figure 1 - Forces acting on a concrete gravity dam

The correlation between these forces, to maintain equilibrium, is given by the expression:

$$Fs = \frac{(P-U).tg\Phi + cA}{H_m - H_j} \quad (1)$$

where Fs is the shear safety factor, P is the total weight of the structure (kN), H_m is the thrust of the upstream reservoir (kN), H_j is the thrust of the downstream reservoir (kN), U is the uplift force caused by the water pressure acting at the dam's base, Φ is the friction coefficient (^{0}), c is the cohesion (kPa) and A the area of the base of the structure (m^2).

Expression (1) shows that the safety factor increases with increments in the weight of the structure or with reductions to the uplift force. As the structure's weight can be modified, through changes to its geometry, a reduction of the uplift force would allow for a reduction of the concrete volume and therefore of the structures' cost and construction time. Since the uplift force has such a strong influence both on stability and cost of the structure, its control is probably the most important aspect of the geotechnical design of concrete dams.

2 DETERMINATION OF THE UPLIFT FORCE

The uplift pressures caused by seepage through the foundations of concrete gravity dams has been generally estimated based on certain design criteria, the criterion proposed by the USBR (Davis, 1969) and indicated in Figure 2 being that most used.

The use of the USBR design criterion leads, in most cases, to the design of conservative structures in terms of safety factors to sliding but, sometimes, it can lead to the design of dams with inadequate safety factor values (Serafim & Del Campo, 1965).

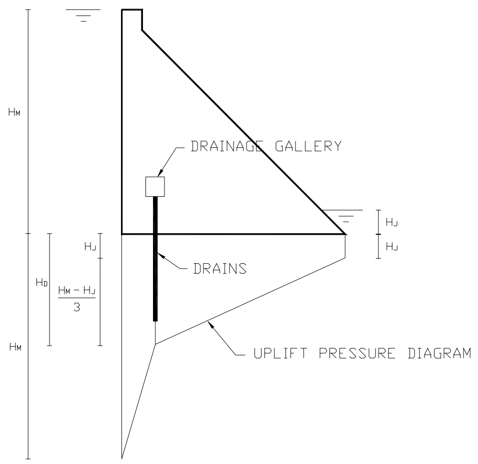

Figure 2 – USBR Design Criterion

In a previous paper (da Silva & da Gama, 2003), it was postulated that the most adequate form of estimating the uplift pressures in the foundation of concrete dams lying on continuous permeable rock would be through adequate seepage analyses capable of incorporating the three-dimensional and nonlinear characteristics imposed on the flow by the presence of the drains drilled from the drainage galleries. A numerical model which includes the above characteristics was developed by means of the finite element method and was denominated DW3D. The model accuracy was then verified comparing the results of the analyses with the instrumentation data of Isamu Ikeda dam, in operation in northern Brazil since 1982, and the agreement between observed and calculated pressure values was very good (da Silva & da Gama, 2003). The results have also shown that the uplift pressure diagram at the base of the structure as determined by the USBR criterion was much larger than that determined by means of the numerical model.

3 DRAINAGE SYSTEM GEOMETRY

In a subsequent paper (da Silva, 2005) the influence of the drainage system geometry on the uplift pressure under concrete gravity dams with drainage galleries and drains was discussed. The geometry of the drains (length, diameter, spacing, roughness and inclination) was investigated together with the number and position of the drainage galleries. It was concluded that the drainage system geometry has a large influence on the values of the uplift pressure.

4 FOUNDATION ANISOTROPY

In that same paper (da Silva, 2005) the influence of the foundation materials anisotropy on the uplift pressure was investigated and the conclusion was that its influence is also very large.

Therefore, the determination of the permeability tensors for the foundation materials, through special field tests (de Quadros, 1992), is a requirement for the realization of adequate flow analyses.

5 OPTIMIZATION OF DRAINAGE SYSTEMS

The optimization of foundation drainage systems of concrete gravity dams consists in determining the number and position of the drainage galleries and the positions, inclinations, lengths, diameters and spacings for the drains in order to reduce the uplift pressure to adequate values.

Reductions to the uplift force (U) will permit the structure’s weight (concrete volume) to be also reduced without changes to the safety factor value, as indicated in expression (1).

6 THE ISAMU IKEDA DAM

Figure 3 shows a cross-section through the structures of block number 2, one of the four blocks that comprises the intake and powerhouse complex of Isamu Ikeda dam. This block has been chosen because it contains the piezometers installed in the dam’s foundations. More details can be found in da Silva & da Gama (2003).

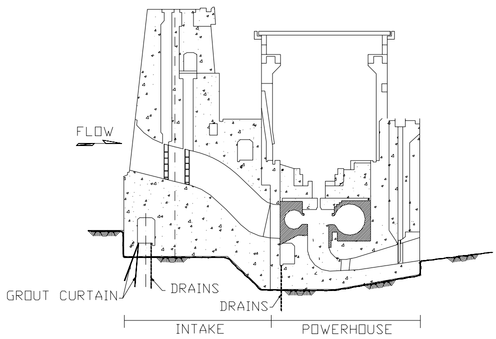

Figure 3 – Typical cross section of block 2 of the intake and powerhouse structures of Isamu Ikeda dam

7 OPTIMIZATION OF ISAMU IKEDA DAM

7.1 Original drainage system geometry

The drainage system built for the structures is indicated, schematically, in Figure 4. The system is comprised of two drainage galleries with one line of vertical drains each. The drains on both galleries have diameters of 76mm(3"). The spacing of the drains in the upstream gallery is 3m and in the downstream gallery is 4.5m. The drains’ lengths are 16m and 7.5m respectively.

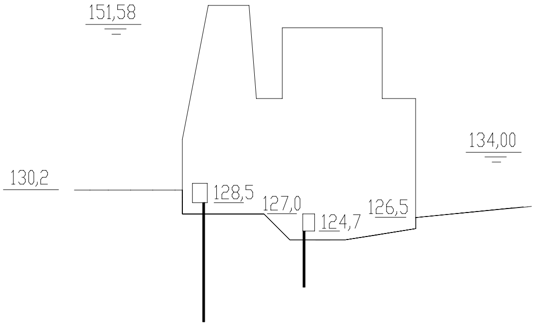

Figure 4 – Original drainage system

7.2 Uplift pressure at the base

A flow analysis, using model DW3D, was performed for the original drainage system and the resulting pressure diagram at the dam's base is shown in Figure 5 together with the USBR diagram. The uplift force (U) resulting from each diagram was 1075.5 kN/m (DW3D) and 4482.0 kN/m (USBR).

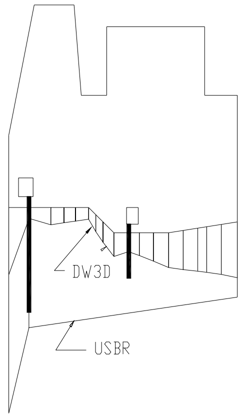

Figure 5 – Uplift Pressure Diagrams at the base of Isamu Ikeda dam (da Silva & da Gama, 2003)

7.3 Reduction of the uplift pressure

As discussed elsewhere (da Silva, 2005), the following actions generally provide reductions to the uplift pressures:

- longer drains

- smaller spacing between drains

- larger diameter drains

- relocation of galleries

- additional galleries

- lines of drains duplicated and inclined

A discussion on the influence of each of these measures to reduce the uplift pressure in the foundations of Isamu Ikeda dam follows.

a) Longer drains

The drains at the upstream gallery were increased in length from their original 16m to 21m and the drains at the downstream gallery from 7.5m to 10m. For this new situation the uplift force (U) at the base is equal to 1071.5 kN/m, indicating a very small reduction. This is in accordance with previous studies, since the drains' original lengths in Isamu Ikeda dam are close to the reservoirs' water heads and, therefore, are already optimized in this respect (da Silva, 2005).

b) Smaller spacing

The spacing between drains was then reduced by 50% from 3m to 1.5m for the upstream drains and from 4.5 to 2.25m for the downstream drains. The shortening of the distance between the upstream drains alone led to a reduction of (U) to a value of 1043.8kN/m. The same action applied to the downstream drains reduced (U) to a value of 1039.9kN/m. The shortening of the drains' spacings in both galleries caused a further reduction of (U) to a value of 1008.7kN/m. It can be seen that the reduction of (U), by shortening the drains' distances was small, of the order of 6%, and this is explained by the fact that the original spacings were already adequate (da Silva, 2005).

c) Larger diameter drains

The drains' diameters were increased from 76mm (3") to 100mm (4") resulting in no changes to the uplift pressures, as expected (da Silva, 2005).

d) Relocation of gallery

The downstream gallery was relocated to the position shown in Figure 6. This change reduced (U) to a value of 1015.3 kN/m.

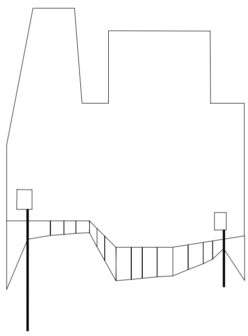

Figure 6 – Uplift pressure diagram with the gallery closer to the downstream face

e) Additional gallery

An additional gallery was introduced in the position shown in Figure 7. This measure caused a significant reduction in (U) to a value of 702.8kN/m.

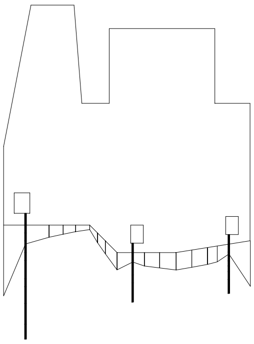

Figure 7 – Uplift pressure diagram for three galleries

f) Additional drain lines

The vertical line of drains in the upstream gallery was then replaced by two inclined lines of drains. Figure 8 shows the resultant pressure diagram. The (U) value was equal to 641.7kN/m.

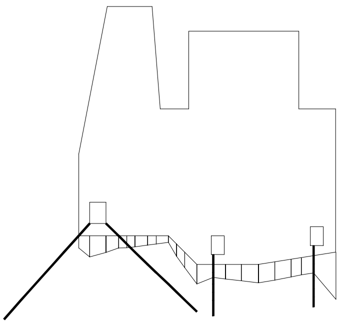

Figure 8 – Uplift pressure diagram for two inclined lines of drains in the upstream drainage gallery

The same action on the intermediate gallery led (U) to a value of 651.0kN/m. This situation is indicated in Figure 9.

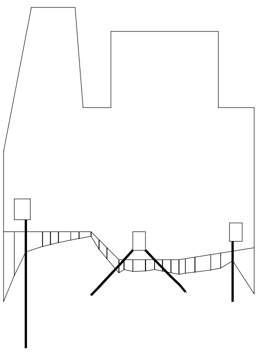

Figure 9 – Uplift pressure diagram for two inclined lines of drains in the intermediate drainage gallery

The introduction of two inclined lines of drains in the downstream gallery, as shown in Figure 10, led (U) to a value of 671.2kN/m.

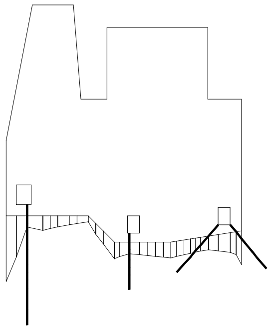

Figure 10 – Uplift pressure diagram with two inclined lines of drains in the downstream drainage gallery

Finally, the introduction of two inclined lines of drains in all galleries, simultaneously, as shown in Figure 11, led (U) to a value of 542.3kN/m.

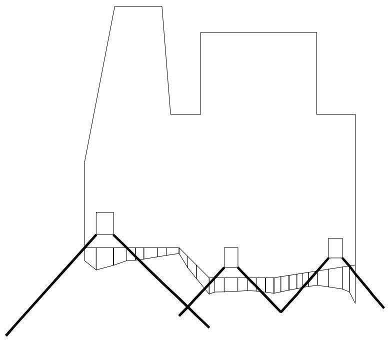

Figure 11 – Uplift pressure diagram for two inclined lines of drains in all galleries

7.4 Summary of the analyses results

Table 1 presents a summary of all cases analyzed and the corresponding values of the uplift force U.

From Table 1 it can be observed that the largest reduction in the value of the uplift force, resulting from use of the USBR criterion, occurred by actually taking into account the original geometry of the drainage system in the DW3D flow analysis. This fact alone led to a reduction of 76% in (U) values at the base of the structures, as shown in Figure 12.

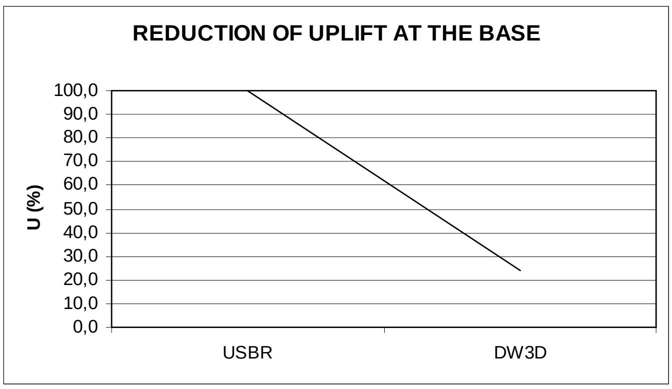

Figure 12 – Reduction of uplift pressure at the base of the structures - Original drainage system

Case	Description	(U) (kN/m)
Case 1	USBR design criterion	4482.0
Case 2	Basic case - Original drainage system	1075,5
Case 3	Longer drains	1071,5
Case 4	Smaller spacing - upstream drains	1043,8
Case 5	Smaller spacing - downstream drains	1039,9
Case 6	Smaller spacing - upstream and downstream drains simultaneously	1008,7
Case 7	Larger drain diameters	1075,5
Case 8	New position for the downstream gallery	1015,3
Case 9	Additional gallery	702,8
Case 10	Additional gallery - Two lines of inclined drains - upstream gallery	641,7
Case 11	Additional gallery - Two lines of inclined drains - central gallery	651,0
Case 12	Additional gallery - Two lines of inclined drains - downstream gallery	671,2
Case 13	Optimized case - Additional gallery - Two lines of inclined drains - all galleries	542,3

Table 1 - Cases analyzed and corresponding values of the uplift force at the base of the structures in relation to the USBR value

The use of longer drains, shorter distances between drains or larger diameter drains caused small reductions in U values. As explained, this is due to the fact that these parameters are already very close to their optimum values.

However, as indicated in Figure 13, the introduction of an additional gallery together with double lines of inclined drains in all galleries caused a further reduction in U of the order of 50% (from 25% to 12%). This means that after the optimization process the final value of U is nearly 12% of that indicated by the USBR criterion.

7.5 Stability analyses

Following the original design, stability analyses were carried out along the horizontal plane (A-A), shown in Figure 14.

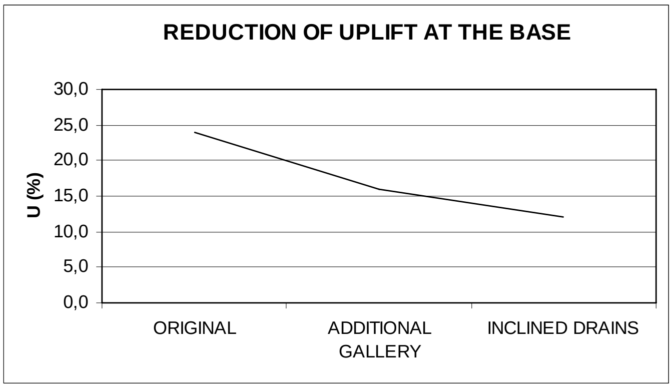

Figure 13 – Reduction of uplift pressure at the base of the structures as a result of the drainage system's optimization

The hatched areas represent blocks of rock and water wedges that have been incorporated into the stability analyses by the designer.

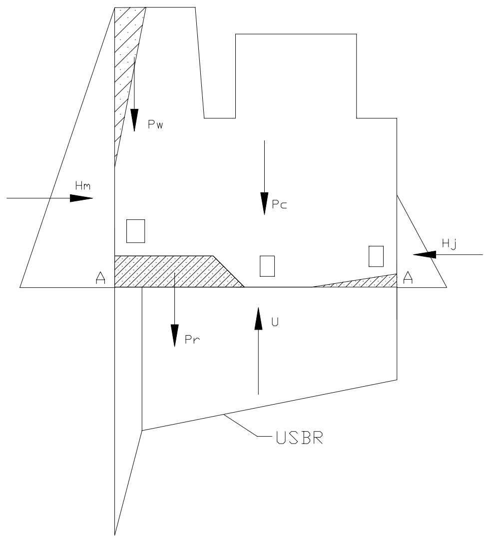

Figure 14 – Sliding stability analysis for the uplift pressure on Plane A-A – Basic Case

From Figure 14 we have:

$$P = Pc+Pr+Pw \qquad (2)$$

where P is the total weight of the structures (kN/m), Pc is the concrete weight (kN/m), Pr is the weight of the rock blocks (kN/m) and Pw is the weight of the water wedges (kN/m).

Taking expression (2) into expression (1) we have the following expression to determine the weight of concrete (Pc) for the structures:

$$Pc = \frac{Fs(Hm - Hj) - cA}{tg\phi} + U - Pw - \mathrm{Pr} \qquad (3)$$

- Design parameters

In all stability analyses the following parameters were assumed constant:

Pw = 322 kN/m

Pr = 1414 kN/m

H_m= 4061 kN/m

H_j= 551 kN/m

$\Phi = 30^O$

c = 0 kPa

FS = 1.5

Introducing the values of these parameters in (3), we have:

$$Pc = 7385.25 + U \qquad (4)$$

This expression gives the variation of the structures' concrete weight as a function of the uplift force (U), acting along plane (A-A), for a safety factor of 1.5.

Figure 15 depicts expression (4) in graphical form.

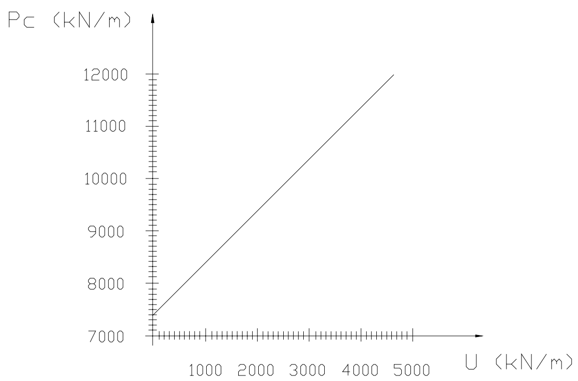

Figure 15 – Variation of the structures' concrete weight as a function of the uplift force on plane A-A

- *Cases analyzed*

Two cases were analyzed: the basic case and the optimized case, the difference between them being the drainage systems and therefore the values of U on plane (A-A).

- *Basic case:*

The drainage system, for the basic case, is shown in Figure 4 and corresponds to the original system designed and constructed for the structures of the intake and powerhouse.

In this case the uplift force (U) on plane A-A, indicated in Figure 14, was determined using the USBR criterion and its value was equal to 4397 kN/m.

For this value of (U) Figure 15 indicates that the concrete weight Pc would be equal to 11780 kN/m.

- *Optimized case:*

The drainage system for the optimized case is indicated in Figure 16.

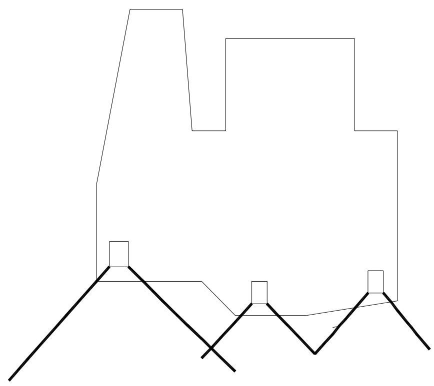

Figure 16 – Optimized drainage system

The diameter of all drains is equal to 76mm(3"). The spacing of the drains in the upstream gallery is 3m and in the intermediate and downstream galleries is 4.5m. The length of the upstream gallery drains is 16m and in the other galleries 7.5m.

In this case, the uplift force on plane A-A, indicated in Figure 17, has been determined by means of the DW3D model and resulted in 973 kN/m. For this value of (U) Figure 15 indicates Pc = 8356 kN/m.

The results show a difference of 41% in the structures' concrete weight between the basic case and the optimized case.

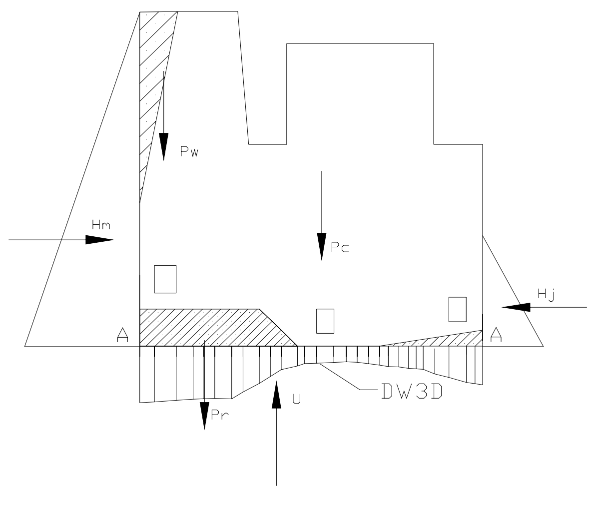

Figure 17 – Sliding stability analysis for the uplift pressure on Plane A-A – Optimized Case

8 CONCLUSIONS

The flow analyses, realized with the intention of optimizing the subsurface drainage system of the structure formed by block 2 of the intake and power-house of Isamu Ikeda dam, have shown that the lengths, spacings and diameters originally designed were already very close to their optimum values. The flow analyses performed for the original drainage system geometry have shown that the uplift force value at the dams' base is of the order of 25% of the value estimated through the USBR criterion. This represents a decrease of 75% in the value of (U) as compared to the value used in design. The optimized drainage system consisting of three drainage galleries together with double lines of inclined drains, replacing the single vertical line in each gallery, induced a further 50% reduction in the uplift pressure to a final value near 10% of that indicated by the USBR criterion. This is a reduction of nearly 90% in the value of (U) as compared to the value used in design. A comparison between the sliding stability analyses performed using the USBR uplift pressure diagram and the pressure diagram obtained through DW3D for the optimized drainage system, has shown that if the present approach had been available at the design stage of Isamu Ikeda dam there could have been a reduction of nearly 40% in the structures' concrete weight for a safety factor value of 1.5. It is concluded that flow analyses, along the proposed lines, are a very good instrument for the optimization of subsurface drainage systems of concrete gravity dams and can lead to appreciable reductions in their costs and construction time.

9 REFERENCES

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