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Structural Analysis and Design of 1.2 MW Mini Hydel Power House

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Abstract – The structural design of hydropower plants depends on numerous factors. Due to the nature and size of these structures, not only these are responsible for a high economic impact, but also a high social and environmental impact. Therefore, it is essential to define an accurate structural design in reinforced concrete, in order to ensure the overall stability of the structure. This dissertation aims to analyse and verify the global and internal stability of structural elements of a hydroelectric power station. So, it was necessary to define the structural materials and determine the reinforcement of several structural elements, taking into account the actions on the structure. Throughout the paper, general rules for the design of reinforced concrete structures are used, as well as their applicability in larger-scale structures is discussed.

Index Terms – Hydropower plant, reinforced concrete, stability, hydrostatic pressure, collapse, cracking.

1. INTRODUCTION

This work aims to evaluate the structural stability of a hydroelectric power station. The geometric definition of the complete structure is present in general arrangement drawings. To do so, it is firstly executed the two-dimensional geometric model, so that the structural weight can be estimated. Secondly, the power house global stability is assessed by determining safety coefficients (sliding; uplift; toppling) and the stresses in the foundation. Then, it is evaluated the internal stability of the structure based on simple models and by designing some reinforced concrete elements. In this dissertation, the following elements are evaluated: (i) the slabs and beams of the floors; (ii) the upstream wall; (iii) the columns and support beams of the crane rail; (iv) the buttresses of the downstream wall; and (v) the draft tube. Based on these models, the reinforcement of the elements (i) to (v) is shown in reinforcement detail drawings.

According to the Indian Standard, there are two types of hydropower plants: (i) surface and (ii) underground power plants.

The powerhouse type selection depends on factors, such as:

1. Power station should be the lowest possible.
2. Geological constraints: plants must be always founded on rock to ensure the stability of the structure.
3. Topographic constraints: the form of the land has a great impact on the location of the plant (eg. steep banks can lead to expensive excavations and stability problems).
4. The tailwater level: a high level might rule out indoor surface type power plants.
5. Other constarints: related to environmental social and economic aspects.

2. MODELLING

Using STAAD software, the two dimensional model of the power house was built.

3. STRUCTURAL COMPONENTS

The durability of a reinforced concrete structure must be taken into account in its design, in order to ensure that it operates adequately, without unforeseen maintenance/ repair costs during its working life.

Since this is an important structure (working life of 100 years, structural steel of FE500 is used. The concrete in each zone of the structure was chosen bearing in mind different needs i.e resistance, low heat of hydration, low permeability, among others.

4. DESIGN METHODOLOGY AND LOAD COMBINATIONS

According to the IS regulations on water retaining structures, the design of a structure should take into account a (i) current scenario and a (ii) failure scenario.

The current scenario (CS) corresponds to combinations of actions with a high probability of occurrence during the working life of the structure under normal hydrological conditions. This situation is characterised by a downstream average water level (AWL). The occurrence of an average earthquake (AE), under normal hydrological conditions (AWL), is also defined as a current scenario.

The failure scenario (FS) corresponds to a combination of actions with a low probability of occurrence during the working life of the structure under exceptional hydrological conditions. This situation is characterized by a downstream maximum high water level (MHWL). The occurrence of a maximum earthquake (ME), under normal hydrological conditions (AWL), is also defined as a failure scenario.

All the scenarios are also defined by a flow rate and a water level at the upstream reservoir.

The most relevant limit states to check for global stability are

1. Loss of equilibrium of the structure due to uplift by water pressure (UPL)
2. Loss of equilibrium of the structure (as rigid body) due to toppling and/or sliding (EQU)
3. Failure or excessive deformation of the ground (GEO)

According to IS basis of structural design

When considering a limit state of static equilibrium of the structure (EQU), it shall be verified (1)

When considering a limit state of rupture or excessive deformation of a section or a member (STR and/or GEO), it shall be verified (2)

The verification of SLS is related not only with the proper functioning of the structure, but also with its appearance and comfort to its users. Therefore, it shall be verified (3)

The common serviceability limit states are:
(i) stress limitation
(ii) crack control
(iii) deflection limitation

According to IS 456 stresses should be limited both for steel and concrete. When it comes to crack control, the crack width must be limited as recommend by importance of structure. Deflections were mainly controlled by checking basic ratios span/effective depth.In this paper; it was only considered the characteristic combination for SLS verification.

4. LOADS

In this paper, the following actions were considered:
(i) dead loads
(ii) live loads
(iii) hydrostatic pressures
(iv) hydrodynamic pressure
(v) uplift pressure
(vi) seismic action

5. GLOBAL STABILITY

The overall stability is based on the hypothesis that the structure moves as a rigid body and it is generally ensured by the structure self-weight.

1. Sliding: Forces considered for verification against failure by sliding are hydrodynamic pressure, seismic action and uplift pressure
2. Uplift: Verification against uplift failure is provided by AWL and MHWL
3. Toppling: Verification against failure by toppling is provided by AWL and MHWL
4. Stresses in foundation: According to IS 456 it shouldn't be allowed tension on the foundation, since this could result in cracks, and consequently lead to the structure instability.Stresses must be calculated except when this causes tension. In that case, stresses should be recalculated.

6. INTERNAL STABILITY

Slabs and beams: The thickness of the floor slabs and its concrete cover is considered since it regards an exposure and The length of the spans in each direction is considered. The slab forces and the respective number of bending bars are necessary to ensure ULS safety were determined. The beams have a height and a width in the x direction and y direction. The slabs loads are supported by the beams. While beams (x) are considered fixed on both ends, beams (y) are supported by beams. It is essential to ensure minimal reinforcement bending and shear in order to control cracking, it should also be used a minimum amount of bonded reinforcement, Since beams can be considered as indirect supports, it is also important to add supporting reinforcement to shear reinforcement regarding SLS, crack width should not surpass The reinforcement considered should be verified and stress limitations should be verified.

Upstream wall: Due to exposure class, the upstream wall has a concrete cover using a cantilever model subjected to hydrostatic pressures, the main bending moments were determined. The most relevant section is the fixed one for the failure scenario(MHWL). It is required to use a shrinkage and temperature reinforcement to minimize cracking. In this case, it was used a mesh in the inner face of the wall. The wall is also subjected to axial loads. Since axial forces are beneficial, it is only considered the crane rail and the wall self-weight. The reinforcement needed in order to verify ULS for the verification of the shear resistance, it is only required the minimum shear reinforcement. Regarding SLS and according to crack width limitation is defined as a function of the ratio of the hydrostatic pressure to the wall thickness of the structure. The reinforcement considered for ULS did not verify this criterion, so it had to be increased.

Columns and corbel of crane rail: For exposure class, it is adopted a concrete cover for both beams and the columns. The beam is simply supported at both ends and is subjected to moving loads (equivalent to 4 wheels per beam). Using specific tables for moving loads, the correspondent forces were determined for maximum loads. For the y-z plane, it is required a bending reinforcement and a shear reinforcement. To minimize cracking, it is required a minimum reinforcement. Regarding the columns, it was considered a cantilever model subjected to biaxial bending. The loads considered were the ones that caused higher forces in the column. Likely to other elements, it must be ensured a minimum longitudinal reinforcement. In order to verify ULS it was adopted for y-direction and for x-direction (per face). To verify the shear resistance, it is only required the minimum shear reinforcement Note that, to design the column corbel it should be used a strut-and-tie model. Using this type of model, it is required for the corbel reinforcement. Regarding SLS, crack width should not surpass. The beams reinforcement had to be slightly changed in order to verify this criterion. According to the maximum horizontal displacement in support columns of crane rails cannot exceed the ratio H/300. The use of rock nails in the upstream wall is a possible solution. In this case, it would be necessary.

Butress of d/s wall: According the elements subjected to water percolation, must have a minimum concrete cover the cross section considered for calculation purposes considering a cantilever model subjected to hydrostatic pressures, the axial bending of the element is characterized by a bending moment and an axial force for a failure scenario.

Draft tube: According to elements subjected to fast-flowing water, must have a minimum concrete cover using specific tables for pipes the draft tube forces were calculated for two different
situations:
(i) when it's full (subjected to hydrostatic pressures);
(ii) when it's empty (subjected to maximum vertical loads and uplift pressure).
The forces in the draft tube vary along its center line, but it is generally required for its longitudinal reinforcement. Regarding SLS, crack control can be determinant when comparing to ULS. The high thickness of the concrete cover results in an increase of the amount of reinforcement needed. If the concrete cover was decreased by half it would only be required about 60% of the reinforcement.

7. REINFORCEMENT DETAIL

It is shown a summary of the amount of longitudinal reinforcement used in the analyzed elements, in order to verify ULS and ELS. Thus reinforcement corresponds to the last floor. The reinforcement of the remaining floors is shown in detail drawings. The beams reinforcement varies in each floor, so it won't be presented (it is shown in detail drawings). The draft tube reinforcement is also variable along its center line, but it is generally required.The reinforcement of all elements is represented in reinforcement detail drawings.

8. STAAD MODELLING

In order to assess the structure overall behavior, it was built a 2D model in STAAD. Thus, it was possible to compare the results obtained with simplified models previously described. In general, the adopted solution described previously was suitable for the forces obtained using STAAD. There were minor differences that most likely are due to the difference between the support conditions assumed in both methods. While STAAD is able to calculate the stiffness of each structural element, in simplified models approximations were considered. However, it is important to bear in mind that it is possible to consider limited redistribution and for that reason no change in reinforcements is needed.

9. CONCLUSION

The design of complex structures, such as hydropower plants must be carefully done, in order to enable structural safety and proper operation. Not only is conception important, but also the material selection, execution, quality control and inspections are important steps to take into account when designing and building a structure. Regarding the structure overall stability, we can conclude that uplift is the scenario that leads to the lowest safety coefficients. This is why an accurate calculation of concrete volumes is essential. Regarding the structure internal stability, we can conclude that, in many cases, the SLS verification (crack control) is determinant. A higher thickness of concrete cover results in higher amounts of reinforcement, which sometimes seems excessive, when comparing to other countries regulations. However, a higher thickness might prevent a more hazardous consequence (water erosion). All in all, the adoption of simplified models represent an acceptable method for designing concrete reinforcements, as the results obtained with the two dimensional model in STAAD were similar. Nevertheless, STAAD results viability depends on the finite element. The existing differences between the results are linked to the support conditions assumed in simplified models. To sum up, general rules and principles for common structures, studied throughout this master's degree, can be applied to more complex structures as a first approach unless proper adjustment and verification must be carried out.

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