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Research Article

Analysis and Design of Composite Power House Sub-Structure

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Abstract

The project deals with the analysis and design of substructure of a Hydro Power House located in Indonesia named as 'Karai 7'. Though each and every hydro power plant have mostly similar components and machines but the analysis and design of civil structures in a plant are always done with different ideas and optimized techniques. Hence this case study is based on some new and different considerations in analysis and design aspects and optimization. The objective of this project also lies in knowing the difference between analysis and design of conventional structures and important structures or special structures. The components such as floating raft, flood protection wall, column footing with gantry loaded on it, draft tube box, penstock encasing block, anchor block, machine foundations and tail race channel in the power house to be studied, analyzed and designed. The necessity to study these components is because of new components and concepts used to analyze and design them. The design of gantry columns depends upon the moment and axial loads transferred by steel super-structure. In case of hydro-power generation plants usually situated at river side the uplift pressure is of major concern to deal with due to high water table condition. The massive hydrostatic pressure coming on the flood protection walls of power house leads to main consideration in designing of power house components. There are huge different machines in power house which are subjected to axial thrust as well as vibrations. The design of their foundations is different than conventional designs. The super structure results found by means of staad.pro. Analysis based on static and dynamic load cases will be used to design substructure. Optimum analysis results in optimum design.

Keywords: *Hydrostatic, uplift pressure, sub-structure, butter-fly valve, floating raft, penstock, flood protection wall.*

1. Introduction

Water from canal, dam and river or from any other source situated at high level than the further adjacent ground profile is brought into the turbine through penstock in order to generate power of particular amount depending on head and discharge available at the location. A diversion structure in a river is to be constructed to store the water on the upstream side. The diversion structure may be made of reinforced concrete, earth work or by providing gates. The water stored in the reservoir is then diverted towards power house through intake structure. The intake structure is further connected to fore-bay tank through canal system. Fore-bay is a temporary storage tank having its outlet as penstock pipe through which water is carried up to power house and connected to turbine which rotates due to the pressure of water and power is generated through generator. The water, after generation of power, is allowed to flow through tail race channel and further connected to the main source at downstream of river.

According to researches made till now on hydro power project specially or particularly we can see that there is no analysis and design related history though hydro power plants deal with mostly the same factors in analysis and design under better consideration of site condition. There are so many components in hydro power plant to deal with, dealing with all those parts at once would not be a better option so it is been structurally divided in two parts i.e. substructure and super-structure. The main components coming under substructure part of power plants are as follows:

- Floating raft
- Flood protection wall
- Penstock encasing block
- Thrust block
- Moment resisting column and footing
- Draft tube box
- Stages of concreting
- Machine foundations
- Tail race pool
- Penstock encasing block

The major factor to be taken in consideration of designing and analyzing the components is water level. Power houses are mainly situated around rivers so the water pressure effecting the strength and stability of

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structure is very devastating. Along with water pressure the power house has also to prove its stability against earthquake and wind forces.

2. Site details

The said power house is located in hilly area having heavy rainfall for about 10 months annually and very close to the Karai river. The Indonesian rivers are perennial and prone to flooding. Also, the substrata rocks at the site is heavily disintegrated sandstone with very less bearing capacity i.e. not more than 30 ton/m2. Therefore, uplift due to flooding has to be considered while dealing with substructure and special treatment is required in designing the power house foundation. Here it shows that the conventional characteristics of dry soil are not applicable as water pressure acting beneath the disintegrated sandstone decreases the bearing capacity. The power house is near the river side. Wind is dominant and severe. Vibrations due to earthquake with minimum rishters scale are dominant. Rivers flow with design discharge for about 10 months a year. The output obtained or the million unit capacity obtained from such a design discharge is worth complimenting. There are two machines of 3.25 MW in the power house. There are two penstocks, two generators, draft -tubes, two penstock encasing blocks, two turbines, two butterfly valves, two anchor blocks and two tail race pools. The contour of the site as shown in map above is very steep. The estimated cost of the project comes out to be 30 cr.

3. Considerations, analysis and design approach

3.1 Floating raft

A raft is usually designed when isolated column footings come nearby or if the bearing capacity of strata is less. A raft so designed conventionally is usually for axial load and moment on it.

Generally power house is built far away from or at some distance from dam or river. But the site here is near the river and Indonesian rivers are perennial. The raft so constructed here has uplift pressure acting. During flooding of a river or dam the uplift pressure acting on raft will be so heavy that it may have tendency to float. Thus to restrict it from floating it is necessary to balance or counteract the uplift pressure on the raft to keep it un-float. The raft is usually constructed in reinforced concrete. The difference between the level in high flood and the lowest RL of the bed is 11.850 m i.e. the pressure head. Thus, assuming density of water as 9.81 KN/m3. The uplift pressure comes out to be 11.850 x 9.81 = 116.2485 m2. Also assuming that the pressure acting on an area of power house about 803 m2 will not be same everywhere. Optimizing the pressure acting as 70 % of uplift it comes out to be as =0.7 x 116.2485= 81.375 m2. Now constructing a raft in concrete for such a uplift pressure will be = 81.375/25=3.255 m. which is very costly. Also in power house structure it is seen that some pockets or sumps have to be left open throughout their lifetime and some during constructing stage, so there are also chances for raft to float during constructing stage if high flood level is obtained during that course. So it was decided to counter balance the uplift pressure using UCR masonry where there are no pockets and with a RCC raft where there are pockets. Now counter balancing the uplift partly with UCR masonry and partly with RCC found out to be optimized one. As the raft is designed for uplift, the tension comes out to be on upper face and compression on other face. Now designing the raft below open spaces or pockets which were going to be in open condition through out there lifetime was not conventionally possible because to design it as slab there were no supports on either side of open pockets to define the length and breadth. Thus an innovative idea was implemented that those areas which were having heavy machines or equipments on them were considered as supports for the slab or raft below the open pockets and were designed for bending.

3.2 Flood protection wall

The retaining wall is called as flood protection wall here because in Power House Structure, the wall, not only retains soil but also retains water pressure and is built up to the level to protect it during flood. Water levels are classified as minimum water level and maximum water level. Minimum water level is the level which is always maintained in power house. Maximum water level is the level which is obtained during flooding of dam or reservoir. Numerous conditions of soil are analyzed to build a flood protection wall they are as follows:

Conditions

- Water is up-to minimum tail water level and soil is saturated.
- Water is up-to max tail water level and soil is submerged.
- No water pressure on stem of wall but uplift acting at the base of flood wall.
- Soil is partly saturated and partly submerged.

Designing the retaining wall on the basis of conventional steps will never lead to a smart and optimized design when such high economy projects are to be done.

In Conventional design base width of RCC retaining wall is usually taken as to be 0.6 of height of wall which would come to be about 0.6 x 8.95= 5.37 m in this particular case. The base of a wall of height 8.95 m retaining soil and water pressure if comes to be 5.37 m it will be very costly comparing structure alone comparing the cost of whole power house.

There are different water levels around power house for which the retaining wall around the power house is affected. Different Water levels are maximum water level also called flood level, tail water level, it is the water table which is maintained after the generation in powerhouse also called as normal water level, and minimum water level, it is the water level which is always maintained at power house plant.

Conditions

- Water is at high flood level, soil is submerged and uplift pressure is acting
- Water is at normal level, soil is partly saturated and partly dry
- Water is at base level of wall only water uplift is acting, retaining soil is totally dry.

According to IS-3370 a design code for water retaining structure while designing a wall according to first condition at high flood level the permissible stresses is to be increased up-to 33 percent. Flooding condition in power house being a rare condition the structure so analyzed and designed for such a rare condition will not be optimum design. The wall is also analyzed when water is at normal level. Flood wall passes through columns on which gantry runs. Thus the reinforcement of flood wall also passes from columns of the structure. As reinforcement of the flood wall has to be passed from columns the cantilever action of the flood wall is disturbed there. The main steel of cantilever RCC wall now becomes the distribution steel because the columns have axial load on them and are mostly acting and considered as fixed support for the stem of the walls. Thus the cantilever stem of the wall now becomes the slab resting on three sides. The slab so taking the support of columns and the footing of flood wall is also a continuous one and the main steel of cantilever wall acts as during a negative moment at fixed supports. This is very different condition than a conventional design of retaining wall. The wall and column footing here are to be casted monolithically and the reinforcement has to be passed through them because it is necessary to make it a water tight structure. If the reinforcements are not passes through them it will cause water to pass from them and thus affect the design conditions and damage the structure.

Flood wall were distributed in two types as flood wall type A and flood wall type B. The level of base of flood wall type A was 297.05 while at location of penstock it was not possible to construct the wall of type A because a penstock of diameter 2.42 m was passing centrally at the level of base of flood wall type A. Now thinking it in a easier way we could construct the same analyzed and designed wall of type A above the penstock encasing block (it is a structure built around the penstock to carry vibrations and thrust in penstock, explained in detail in further chapters). But if we think construction wise it would be very difficult to lay shuttering for casting. Thus considering ease in construction it was decided to reduce height of stem and let the base of wall to be above penstock encasing block (as shown in figures below)

The design of retaining wall here is not a conventional nor educational one because of the stresses differentiated according to different conditions, also the consideration of bond between the raft of uniformly course rubble masonry with layer of PCC on it and RCC base slab of the retaining walls which resists the overturning moment due to soil and water at large extent also sliding is resisted to great extent.

Thus the geometry of structure works out to be an optimized one.

When high flood level of water was considered the permissible stresses in concrete and steel were allowed to increase to 33 percent. Stem of the wall acting as a slab resting on three sides is also checked.

3.3 Draft tube

Draft tube is that part in power house through which the water after generation is allowed to flow from close conduit into the following further stream. It is the structure which is situated at the lowest level in power hose. As said earlier the power house being situated near the dam there are more chances of flooding. Thus the closed conduit to be analyzed for water pressure from inside and soil or concrete or any other material from outside with water pressure is really a complex situation and not a conventional condition. There are many different conditions for which the draft tube is to be checked depending upon the power house in working condition or not, water at high flood level (HFL), Tail Water Level (TWL) or normal water level (NWL). The draft tube section was checked for about 15 conditions and from that the optimum designed was obtained.

3.4 Machine foundations

Machine foundations require a special consideration because they transmit dynamic loads to soil in addition to static loads due to weight of foundation, machine and accessories. The dynamic load due to operation of the machine is generally small compared to the static weight of machine and the supporting foundation. In a machine foundation the dynamic load is applied repetitively over a very long period of time but its magnitude is small and therefore the soil behavior is essentially elastic, or else deformation will increase with each cycle of loading and may become unacceptable. The amplitude of vibration of a machine at its operating frequency is the most important parameter to be determined in designing a machine foundation, in addition to the natural frequency of a machine foundation soil system. There are many types of machines that generate different periodic forces.

3.5 Selection of foundation

A suitable foundation is selected, depending upon the type of machine. For compressors and reciprocating machines, a block foundation is generally provided (Fig.1a). Such a foundation consists of a pedestal resting on a footing. If two or more machines of similar type are to be installed in a shop, these can profitably be mounted on one continuous mat. A block foundation has a large mass and, therefore, a smaller natural frequency. However, if a relatively lighter foundation is desired, a box or a caisson type foundation may be provided. (Fig.1b) The mass of the foundation is reduced and its natural frequency increases. Hammers may also be mounted on block foundations, but their details would be quite different than those for reciprocating machines. Steam turbines have complex foundations that may consist of a system of walls columns, beams and slabs. (Fig.1c) Each element of such a foundation is relatively flexible as compared to a rigid block and box or a caisson-type foundation. The analysis of a block foundation is relatively simple as compared to a complex foundation. There are several methods of analysis for both the block and the complex foundations. The criteria for designing machine foundations shall be discussed first followed by the methods of analysis. The machines which are placed in a hydro power house are

- Generator
- Scroll case
- Butterfly valve

3.6 Generator foundation

Generator is one of the most weighted machines in power house. Vibrations caused during starting and stopping of the generators are devastating. Concrete being brittle material it cannot bear any vibration. It starts cracking as soon as it is allowed to vibrate. Thus in analysis of generator foundation the resonance of concrete geometry around its foundation and resonance of generator are checked and a range is specified in IS code of generator foundation design which is satisfied for a safe design of foundation. Vibrations in foundations are so vital and there is no any perfect and optimized method for such unidentified vibrations in foundations. The generator so situated in the case was surrounded by concrete all over its base foundation bolts and so the resonance checks and the vibratory behavior of the generation was nullified to a greater extent. Now while starting the generator having 10 number of bolts each bolt would have different eccentricity and different pulling out property for which it had to be designed, so that the bolts would not be pulled out. Thus the generator was just checked for pulling out test. Its calculations are as follows

3.7 Butterfly valve foundation

A butterfly valve is a valve which can be used for isolating or regulating flow. The closing mechanism takes the form of a disk. Operation is similar to that of a ball valve, which allows for quick shut off. Butterfly valves are generally favored because they are lower in cost to other valve designs as well as being lighter in weight, meaning less support is required. The disc is positioned in the center of the pipe, passing through the disc is a rod connected to an actuator on the outside of the valve. Rotating the actuator turns the disc either parallel or perpendicular to the flow. Unlike a ball valve, the disc is always present within the flow, therefore a pressure drop is always induced in the flow, regardless of valve position.

A butterfly valve is from a family of valves called quarter-turn valves. The butterfly is a metal disc mounted on a rod. When the valve is closed, the disc is turned so that it completely blocks off the passageway. When the valve is fully open, the disc is rotated a quarter turn so that it allows an almost unrestricted passage of the fluid. The valve may also be opened incrementally to throttle flow.

There are different kinds of butterfly valves, each adapted for different pressures and different usage. The resilient butterfly valve, which uses the flexibility of rubber, has the lowest pressure rating. The high performance butterfly valve, used in slightly higher-pressure systems, features a slight offset in the way the disc is positioned, which increases the valve's sealing ability and decreases its tendency to wear. The valve best suited for high-pressure systems is the triple offset butterfly valve, which makes use of a metal seat, and is therefore able to withstand a greater amount of pressure.

3.8 Scroll case foundation

Spiral cases should be designed to withstand the bursting pressure of maximum headwater plus water hammer.

The type of spiral case depends on the power plant being considered.

(1) For low-head plants they may be of unlined concrete with engineered reinforcement to withstand applied dead, hydraulic and equipment loads.
(2) For medium and high head plants, they should be made of steel plate with shop welded longitudinal joints. Circumferential joints may be either field welded or high strength bolted, depending on the turbine manufacturers design. Welded joints should be double-vee butt joints made under strict quality control and in accordance with the provisions of ASME. It is preferred that the c sections of spiral cases requiring field welding be butt-welded to skirt plates which should be shop-welded to the stay rings. All longitudinal welds should be radio-graphed. Ordinarily, stress relieving will not be required. When considering spiral cases under high head, and when shipping, handling, and erection cost would control, consideration should be given to the use of high strength steels. Completed spiral cases should be proof tested hydrostatically with a test pressure equal to 1-1/2 times the maximum design pressure.

3.9 Generator pedestals

The generator, except in some low-head plants, is usually supported on a heavy concrete pedestal. The details of this pedestal will depend on the make and type of generator to be installed. It should be of massive construction and should be designed to resist vibration forces from the moving mechanical parts, the heavy loads from the thrust bearing, and the short circuit torque of the genera-tor. It is usually designed to support the generator room floor also. Openings in the pedestal should be provided on all four sides when practicable for access to and ventilation of the turbine pit. Adequate head room should be provided between the underside of the generator and the generator platform, if one is used, and between this plat-form and the turbine walkway.

3.10 Column footing

In said power house owing to severe earthquake and wind there it was decided to construct retaining wall to retain the earth pressure in substructure and column footing were designed only for gantry load during wind and earthquake forces. The frame model of superstructure was analyzed in STAAD Pro. Different combinations were made to find the maximum axial load on column footing. In power house the gantry is allowed to travel once in its life time. Now assuming that during travelling of gantry once in its lifetime an earthquake would occur and designing column footing for such a rare condition would not be applicable for a structural designer to do it practically. Thus it was considered that gantry is standing in its rest position in one bay and earthquake of zone 3 and wind is acting on structure. The forces and moments due to soil pressure than were tabulated for which the column footing were designed. Owing to gantry standing on one bay the lumped masses during the earthquake were very heavy. Also the continuous water uplift acting below the base made the eccentricity of the footing to go beyond the limit. Analyzing the structure to its exact behavior is never possible for a structural engineer but here each and every possible condition was checked for analysis right from construction stage to its actual behavior. The substructure components being below the ground it was very much necessary to make all components water tight. Different combinations of dead load, live load, wind load ad earthquake load as in I.S. code were used to analyze the axial loads and moments acting on column. On safer side and owing to devastating water pressure on site it was nece1qssary to consider more factor of safety of against workmanship for each and every stage during concreting of different components. Different from the combinations as given in I.S. 456:2000 the structure was made to act for.

Staad Results for maximum load condition (DL +LL+GANTRY LOAD) including soil and water load.

COLUMN NAME	PU(KN)	MZ(along depth)	MY(along width)
GC-1	420.4049	0	0
GC-2	435.63	372.86	0
GC-3	448.85	369.33	0
GC-4	454.48	421.33	0
GC-5	458.19	326.79	0
GC-6	442.0191	0	0
GC-7	266.61	8.41	0.49
GC-8	512.73	0	373.85
GC-9	663.21	52.14	8.24
GC-10	707.31	65.36	6.28
GC-11	748.21	68.05	0.268
GC-12	741.59	69.51	6.22
GC-13	730.52	0	353.18
GC-14	358.7	35.042	2.6981
C-1	127.1057	398.23	0
C-2	41.45	6.43	0.05
C-3	184.3706	0	0
C-4	268.4891	196.22	0
C-5	289.2859	206.59	0
C-6	320.3806	181.45	0
C-7	303.9723	193.19	0
C-8	396.2514	0	0
C-9	126.58	32.22	12.57

Here GC stands for gantry columns i.e. the columns on which gantry is going to travel while column named as C are the columns on which there is no gantry loads.

Group 1- In column Footings GC-1, GC-6, C-3 and C-8 which are at corners of the structure the soil pressure and water pressure is acting from adjacent sides also at the offsets of the slant portion of the stem. But owing to its stiffness from both sides as it has a retaining wall to resist it from deflection the columns of this group are only designed for axial loads acting on them. The footing available as of flood protection wall is checked for bending and shear.

Group 2- The column footings GC-9, GC-10, GC-11 and GC-12 are not subjected to earth pressure thus from analysis results as given in above table the maximum values are taken and the bearing, shearing and bending of the footing is checked.

Group 3- The remaining column footing are subjected to moment due to earth pressure, earthquake force and wind forces with their axial loads due to gantry on it. The moment so acting on the footing when gantry is at far distance from any of the column comes out to be very heavy for which the column footing had to be designed. The stiffness of the wall to be considered for columns on either side is unpredictable. The stressing of column due to gantry load shared by them was very important factor to make it realize that deflection of column will be different from that of retaining wall at its sides. But it was also necessary to make columns acting as stressed one before setting of gantry on it. Designing columns as retaining wall and a axial member was practically possible but laying the designed steel and casting of concrete in column was a difficult task because main steel of two types one as cantilever stem and the other straight bars for axial load both had to be casted at a time. Considering some practical possibilities it was decided only to pass only horizontal distribution steel throughout to increase the stiffness and to make it a water tight structure. The above factors make this structure a lot different from conventional structure also to add impact on the moral here the footings width is restricted as width of column. There is possibility in geometry to increase its width for resistance against moment. The final design sheet prepared after numerous revisions and was approved for construction.

Conclusion

1) Structural design of power house components itself in it is a innovative project. Literature available on analyzing and designing the whole is very scarce.
2) The bond strength considered against overturning and sliding of flood wall reduces the base width and increases anchoring strength of footing.
3) Floating raft is totally a new concept.
4) Monolithic casting of flood wall and column footing though necessary for water tightening, but it increases the complexity of design as cantilever retaining stem of the wall becomes a slab resting on three sides and also a continuous one, so analyzing and designing such a complex structure is totally different from conventional structures.
5) Increase in permissible stresses for rarely occurring conditions is as in I.S.3370 is better way of optimization.
6) Though there is complexity in analyzing and designing of structure, instead of making it over safe optimized designs are incorporated
7) Severe uplift pressure is counter balanced by an economized raft provision
8) Measures are taken to avoid floating of whole structure
9) Column footings are designed for 0.5 L.L. + D.L + Gantry load with EQ and WL L.L. + D.L. + Gantry load with EQ and WL. Reducing live load increases the moment on structure which is very important for column footings as no risks can be allowed for main foundation of whole structure.
10) RCC Draft tube is analyzed and designed for about 15 different conditions.
11) No either conventional structure is such a complicated one.
12) Check for sliding and overturning are reduced from 1.5 to 1.2 times the stabilizing moment when designed for high flood level condition (rare one).
13) Practical construction is also given a greater preference.
14) Resonance of vibration of generator is reduced to larger extent by mass concreting around it.
15) Scroll case, butterfly valve and their foundation analysis is totally new concept.

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