River Diversion Structures

Conception, Design and Adaptation to Definitive Structures

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1. Introduction

The diversion structures are the group of works necessary to guarantee that the river can bypass the dam site during the main structure construction. The primary function of the diversion structure is to protect and ensure the site safety during construction.

The river diversion may take various configurations exposing the ones that are considered most important in the present study. It should be noted that the design of the river diversion begins with the preliminary study of the hydrological characteristics of the watercourse, as well as the morphological characteristics of the site.

The river diversion through tunnel has great applicability in embankment dams. This type of river diversion comprises three sub-structures: upstream structure, tunnel and downstream structure. The study of flow through the tunnel is hampered by the tunnel geometry. The tunnel cross section assumes generally circular or horseshoe geometry. Thus, it is important to trace the backwater curves for diversion tunnel with the goal of establishment the various flow depths along the structure allowing the flow classification.

The occurrence of hydraulic jumps inside the river diversion tunnel can cause structural problems. By establishing the different depths inside the tunnel is possible to determine the amount of total movement inside it and the hydraulic jump position.

In case of using a river diversion tunnel is possible to convert it in the bottom discharge of the final structure. This approach has advantages, especially in project costs.

2. River diversion structures

2.1. Introduction

A river diversion can be of various types. The implemented structure design is based on a compromise between the cost of the diversion facilities and the amount of risk involved. The following factors should be analyzed **(BUREC, 1987):**

- Streamflow characteristics;
- Physical characteristics of the site;
- Type the dam that requires river diversion;
- Definitive structures on the dam;
- Sequence of construction operations.

Generally, the river diversion is designed aiming at the goal of its use, even partial, for the construction of permanent works. The use of part of the river diversion works will make the structure composed with temporary and permanent structures, more economical and integrated.

3. Types of river diversion

3.1. River diversion tunnel

The river diversion tunnel has the highest costs, and usually only applies when other solutions are unfeasible. The geotechnical conditions of the implantation site are very important in the execution tunnel feasibility study. This type of river diversion is common in valleys, regardless of the dam type and, as statement previously, the application of this solution is considered when other solutions are difficult to implement and may incur increased costs.

In this diversion type the structure lining takes an important role. The lining is in most cases in concrete. Its main functions are **(Rocha and Tamanda, 2006):**

- Ensure good conditions for sustainability of the tunnel;
- Decreasing the roughness of the tunnel increasing the diversion capacity.

The scheme of this type of diversion is characterized by the completion of the diversion tunnel and two cofferdams (upstream and downstream) that will dry the area in which they intend to carry out the dam. The river diversion tunnel has the function to drain the bypass flow, and may have several sections. However, the sections most frequently used are circular and horseshoe. The choice and design of the type of section employed is related to the final design of the diversion tunnel in relation to its integration or not in the definitive structure **(Vischer and Hager, 1998).**

The diversion of the river through tunnels can be held in free surface or pressure flow. In most cases, it takes place in free surface flow and should not exceed 70% of the tunnel capacity. When deploying a river diversion with pressure flow, it must be ensured that the structure's altimetric track allow the respective domes to always be situated below the isometric line to avoid depressions that may cause structural and hydraulic inconvenient. **(Pinheiro, 2002)**.

3.2. River diversion in conduits

The river diversion in conduits constitutes an alternative to the tunnel diversion when the surrounding rock has no sufficient quality to perform a tunnel. Such diversion requires foundation conditions acceptable for implantation of the conduit, to ensure that the conduit does not suffer excessive settlement during the construction of the embankment dam, which could damage the structure. Economically this solution is very similar to the previous and associated costs are high **(Villegas and Mejía, 1988).**

When resorting to a temporary bypass pipeline there are two hypotheses in terms of construction, to its implementation. The structure can be implanted in the riverbank or riverbed. The latter involves moving the conduit under the dam body. Regardless of the conduit site, the diversion scheme is similar to that performed for the diversion tunnel, with the construction of two cofferdams ensuring that deployment takes place dry **(Vischer and Hager, 1998).**

The flow in this diversion structure can be in pressure or free surface, preceding the sizing of the conduit according to the flow characteristics. May be more economically advantageous implant various conduits in parallel with smaller size than a single conduit which ensures the diversion of the entire flow **(Vischer and Hager, 1998).**

3.3. River diversion in channel

The river diversion in channel is used for situations where it becomes economically unfeasible to carry out a tunnel or implant a conduit with sufficient size to ensure the flow of the design flow. The application of this solution is typical in sites where the topography is characterized by flattened valleys **(BUREC, 1987)**.

The river diversion in channel requires large earthworks for its structure construction. These moves allow the geotechnical characterization of the site where the diversion structure is required. The diversion channels lining takes a very important role in case of the very erodible soil or when safety conditions of the slopes are not guaranteed, with the possibility of collapse or slip. In the channel lining the most common materials are: concrete; stakes plank, rockfill and masonry **(ICOLD, 1986)**.

The type of scheme used in the construction of diversion channels depends on the type of dam that the scheme operates. This solution can be used in concrete and embankment dams.

3.4. Openings left in the dam body

This method has wide application in concrete dams, more especially arch dam, and consists in taking advantage of the openings left in the dam body to divert part of the flow, reducing the necessary diversion structures. In many cases the implemented diversion tunnels only ensure the passage of the normal flow of the river and the flood passage is ensured by the temporary openings left in the body of the dam.

The implementation of this solution is common in sites where medium to high flows are expected and it is concluded that it wouldn't be economically and technically feasible to perform a diversion structure which ensures the diversion of the entire flow.

3.5. Temporary diversion with laterally constriction of the river

This method consists in lateral contraction of the river section by constructing a cofferdam. Thus, obtaining a dry zone where it is possible to continue building the structures needed to the river diversion. During the construction of the flow diversion structures, flow proceeds through the zone contracted. In a second stage, the part which is already built can begin the draining of the river the completion of the work in the adjacent area can be continued. This type of river diversion is reserved to concrete dams, with wide applicability in the construction of mobile dams **(Pinheiro, 2002).**

According to **Vischer and Hager (1998),** this type of river diversion has flows with very specific characteristics. In the case of high rate of contraction, conditions are created for the occurrence of transient flows. In these cases, the structure becomes hydraulically similar to a Venturi tube, ie no change in the amount of the flow to significantly shrink the section the flow is subcritical and in the case of an incompressible fluid, the flow velocity increases. The flow velocity across the contraction increases and could result in erosion of the river bottom, caused by the waves.

4. Temporary tunnel diversion

4.1. Introduction

The temporary diversion tunnel is in most cases design in free surface. To establish backwater curves within the main structure of diversion tunnel, the study of the various strutures that make up this type of river diversion was carried out and simultaneously/complementarily the total momentum was analyzed in order to identify the location of the hydraulic jump.

The river diversion tunnel structure is divided into three major structures: inlet structure, tunnel or gallery, and downstream structure. The following paragraphs proceed the study of these structures in relation to their design criteria and the type of flow that develops inside, upstream and downstream the referred structures **(Pinheiro, 2002).**

4.2. Inlet Structure

The inlet structure promotes the flow acceleration, ensuring the transition from subcritical flow which is established upstream in the reservoir created by the construction of the cofferdam or, in some cases, the channel connecting the bed to the frame, to supercritical flow that occurs in the diversion tunnel. The implementation of this structure also aims to promote sufficient air to the flow, so that it develops a pressure equal to atmospheric pressure along the tunnel. This avoids the possibility of reaching pressures near the water vapor pressure, reducing the risk of cavitation phenomena in the diversion tunnel and hence its erosion **(Vischer and Hager, 1998).**

Regarding installation of the inlet structure it may be implemented directly on the ground or resort to auxiliary concrete or wood structures that supports it above the ground level. In the construction of the upstream structure it is usual to use various materials, especially concrete, wood and sheet piles **(Smith, 1967).**

In the inlet structure design it is important to proceed to the analysis of flow velocities that are practiced within and upstream the structure. To this end, the ratio of the velocity flow in the control structure and velocity flow upstream the structure must be in a range of 2 to 5 **(Smith, 1967).**

The inlet structure geometry must be hydrodynamic, both in plan and in longitudinal profile to avoid flow separation. The flow separation may occur in the transition river section with irregular section for the tunnel section, usually circular or horseshoe sections **(Pinheiro, 2002).**

4.3. Diversion tunnel

4.3.1. Introduction

The flow in a river diversion tunnel should occur in supercritical scheme to provide quick acceleration required by deploying of upstream structure. In the river diversion tunnel design it should be noted that in the river diversion through this structure, the flow depth should progress to uniform depth. Thus, it is necessary to define under which conditions the flow is processed along the diversion tunnel. Therefore, it is possible to conclude the existence of hydraulic jumps inside the tunnel and determine its location. Studying the flow conditions inside the tunnel consists of analyzing the flow depths along the tunnel by defining the backwater curves. In the present study only the most often used cross sections were considered – circular and horseshoe.

4.3.2. Flow conditions

Knowing the flow depths is very important in the study of the river diversion tunnel, so it is imperative to establish backwater curves inside the tunnel, for the most widely used cross-sections, circular and horseshoe. This study is based on the equation (1) resulting from the resolution of Bernoulli's theorem by the method of finite differences

$$(h_2 - h_1) + (y_2 - y_1) + \left(\alpha \frac{U_2^2}{2g} - \alpha \frac{U_1^2}{2g}\right) = -\frac{I_1 + I_2}{2} \Delta s \qquad \textbf{(1)}$$

With this equation it is possible to establish the depths along the flow diversion structure in order to verify whether the uniform flow is achieved inside the diversion tunnel.

4.3.3. Total momentum

When dimensioning the river diversion tunnel it is important to study the influence of the downstream level into the flow conditions inside the tunnel, once it may not be guaranteed that the establishment of the uniform system within the diversion tunnel ensures that free surface flow occurs along its entire length **(Pinheiro, 2002)**.

In order to proceed with the study of the downstream level influence, it is necessary to analyze the altimetric placement of diversion tunnel. A first stage begins by analyzing the total momentum inside the tunnel, comparing it with the natural bed total momentum. In the case of the natural bed total momentum overcome the values obtained in the tunnel, the hydraulic jump occurs inside the tunnel. Thus it is possible to determine the existence of hydraulic jump, and if there is, proceeding to its location **(Pinheiro, 2002).**

The occurrence of a hydraulic jump inside the diversion tunnel involves a correction of the upstream altimetric position. The determination of the total momentum is performed using equation (2) **(Manzanares, 1980)**.

$$|\mathrm{M} = \gamma A h_g + \frac{\alpha' \gamma}{g}\frac{Q^2}{A} \quad (2)$$

The calculation of the flow depths by defining curves backwater enables the calculation of the total momentum into the river diversion enabling comparison with the total momentum in the natural bed and the location of the hydraulic jump.

4.4. Outlet Structure

The return diverted flow, through the river diversion, can be made through direct connection to the river or by deploying outlet structure. The deployment of the restitution structure may have two objectives, the dissipation of excess energy or the recovery of part of the kinetic energy **(Pinheiro, 2002).**

The need to implant a restitution structure is associated with the fact that the flow in the tunnel that is supercritical or if the downstream section of the tunnel is elevated compared to the river bottom, hindering establishment subcritical conditions in the restitution area. The outlet structure can match the deployment of a transition structure or deployment of stilling basin.

4.5. Closing of river diversion

For diversion tunnels, it is necessary to lock up the tunnel to start filling the dam or divert the tributary flow through definitive structures that are completed. The temporary diversion closure can be permanent or temporary **(Pinheiro, 2002).** In temporary closure, it is common to use a gate. For permanent closing it is implanted a concrete plug inside the diversion structure.

The planned of temporary diversion closure must be programmed according to a study of local flow conditions, and the closing of the river coincide with the dry season. The type of diversion structure influences naturally provisional closing. In the case of the structure consist of two diversion tunnels it is possible to make the closing of one of the tunnels continuing the flow to be diverted by other tunnel **(ICOLD, 1986).**

5. Temporary diversion structure used for bottom outlet

5.1. Introduction

The river diversion structures are usually design to be used as final structures. The bottom outlet is an organ of dam safety mandatory implantation, according to the dam safety regulation, may stand out as major achievements **(Quintela, 1990):**

- Allow the partial or total emptying of the reservoir in situations where the danger is imminent failure or when there the need to carry out repairs on the dam;
- Permit monitoring of rising water level in the reservoir on a first filler.

The structure of bottom discharge implemented relates to the type of reservoir in which it is inserted. For embankment dams with bottom discharge process, it can be carried by galleries across the slopes, around the dam, or tunnels built by open pit and buried the embankment dam.

5.2. Bottom outlet constituents

The elements that constitute the bottom outlet include the tunnel through the dam, which should be provided, according to the safety regulations for dams and two safety devices. One of these devises will primarily aim at regulating the drained flow, it is common to use conical valves or gates for this purpose. There is also the need to implement a second security organ, usually a gate, which will have an emergency character **(Quintela, 1990).**

The operation of this second organ is associated with situations in which the flow regulation organ is locked in the open position, or when it is necessary to proceed to the emptying conduit, aiming operations of system maintenance or repairs on the organ flow control in case of failure **(Quintela, 1990).**

The flow control organ may lie upstream, in an intermediate chamber or downstream. Should, in all cases, provide the system with a emergency gate. The installation of the emergency gate involves making a tower to ensure access to the entire gallery.

In the tower will be placed maneuver equipment of the security gate and protection grid, if they proceed with their deployment. The devices are usually electrical switchgear and are termed servo-motors. As a safety procedure is in many cases the towers are flooded, to balance external forces to which they are subjected.

In Portugal there are several dams that used the river diversion structure to the bottom outlet as the Alvito dam, Minutos dam and Apartadura dam. In the following image there is a scheme of the bottom outlet structure of Alvito dam.

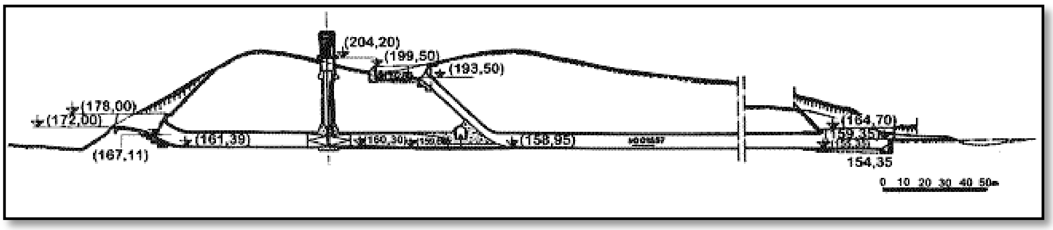

Figure 1- Hydraulic scheme of Alvito Dam

Conclusion

The river diversion can be of various types as evidenced throughout this paper. It was studied the several major diversion structures. The river diversion tunnel is the structure that has the highest costs associated with starting, resorting to this solution when the others are not viable. As regards the topography, such diversion is implanted in valleys, having in mind that in these conditions the other solutions are difficult to implement and may prove expensive.

In the river diversion tunnel study was concluded on the importance of this type of lining the structure. The tunnel lining diversion procedure enables the cross section reduction and increases the return period, which implies a reduced of overtopping risk.

The river diversion for conduct constitutes an alternative to river diversion tunnel, when the surrounding rock does not have enough quality to carry out a tunnel. In the study of this type of diversion, it was found that there are advantages in relation to temporary diversion in the tunnel. If the structure were implanted in the river bed it is possible to study the geological conditions of the site during the work. When analyses a river diversion in conduct, foundations are relevant, as it may ensure that the conduct does not suffer settlements after construction of the dam embankment. This type of diversion is common in embankment dams.

Another river diversion type is the channel. This type of river diversion has application in situations where it is not economically feasible to make a tunnel or implant a conduit. The construction of diversion channels is possible in embankment and concrete dams, having site topography characterized by flattened valleys. It was possible to conclude that the higher costs, which can be associated to this solution bypass refer to earthmoving, needed to perform the channel.

The following method, the most common application in concrete dams, consists in leaving openings in the dam body. By resorting to this method it is possible to have a reduced diversion tunnels performed. Among the various types of concrete dams could be concluded that the arch dams in the application of this type of river diversion is more common. The flow regime where is implement this solution is characterized by moderate to high flow rates.

In the second part of this paper we proceeded to further study of the river diversion tunnel. The study aimed to carry out a program that would allow tracing curves backwater to the main structure of diversion tunnel. The river diversion tunnels have cross-sections in many cases circular or horseshoe. It is important to define the different depths which occur inside the structure and thus the type of regime. With the data obtained we proceeded to evaluate the total momentum, aiming to verify that the hydraulic jump occurred inside the tunnel or in the downstream channel.

In a final phase, it was proceeded to study Portuguese in several dams that used the temporary diversion structure for bottom discharge. It was possible to study the changes performed to design a integrated project.

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