OPTIMIZATION OF AUTOMATIC GATES DESIGN USING FLOW HYDRODYNAMICS

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ABSTRACT. This article presents the proposal of automatic water-functioning gates for the dams in operation and under construction, analysis of conditions for opening and closing in a given head range, recommendations for use.

KEY WORDS: spillway, automatic water-functioning gate

In recent years the tendency to automatization of equipment and completely independence it from the power supply, personnel professional skill, in any condition natural phenomena, such as extreme floods, hurricanes, bank failure, upstream dam break, etc, has been observed. This tendency concerns not only of the construction of new dams, but also the modernization of already built. It is also important to enhance level of automatization of operation under extreme conditions, as well as under usual flood conditions. The known in hydraulics automatic gates, opening at appropriate upstream elevation, meet these requirements. The design and operation experience of such gates is known in the world. This idea was developed on the basis of expendable French gates “hydroplus”, used at peak flood as fuse plug dykes. These gates are widely used in the world practice in recent years.

At the beginning of this century the interest to construction of small hydro power plants operated off-line renews. As a rule, these projects are situated in remote or hardly accessible areas, not connected to other power supply sources. Under these conditions the role of automatization of spillway equipment and its independence from power supply grows. For that reason, in recent years the automatic water-functioning gates for operational service have been developed in the Laboratory of the Centre of hydraulic research in JSC “Scientific research institute of energy structures”. A number of variants of multiple times operated gates based on “Hydroplus” have been developed and tested in the Laboratory of the Centre of hydraulic research. However, the main defect of these gates is inevitability of lowering of upstream level up to sill elevation and use of mechanism for raising to
closed position. Thus, further developments led to design of fully automatic gates, opening and closing by hydrodynamic forces of the flow. In the first variant the filling of working chamber has been performed through the water intake situated at the crest of the gate (Fig.1, 2).

Fig.1. Scheme of automatic water-functioning gate:
   a - closed position; b - open position

Fig.2. Model of automatical water-functioning gate with top water intake

This design has such positive feature that the gates can be installed without intermediate piers close one to other. Such solution is economic, but it can not be applied in case of ice discharge, floating garbage, wood, etc. at the time of overflow. Ice or floating trees bulk on water intake results in off-design opening of the gate. Therefore, the second variant, where filling of working chamber is carried out from the water conduits in the pier through orifices in the side face of the gate (Fig.3), has
been developed. The rotation axis position is well calculated for opening by sum moment of gate with ballast and by hydrostatic pressure at design upstream elevation taking into account the dropping curve above the upper edge of the gate in closed position.

When the working chamber is empty the gate is stability closed and allows to pass a discharge overflowing the crest. The water intake of water supply system of working chamber is at design upstream elevation. When the working chamber is filled up and upstream level rises to design elevation, the sum moment from hydrostatics becomes negative and the gate is opened. The open gate position is retained by water moment in working chamber and sum moment of hydrodynamic forces of flow over open gate. To refill working chamber in open position, the second water conduit is in the pier. The sill of intake has the elevation at which the gate must be automatically closed. At that, inflow of working chamber ceases, the chamber empties through the drainage holes and the gate returns to closed position. The ballast in lower part of the gate contributes this, it equilibrates the moment by weight of gate. When the gate moves for opening, the sum moment of all forces changes (Fig.4). This process must be without change of sign. The volume of gate chamber must to exclude gate stop in intermediate position after chamber filling. After opening of the first gate the reservoir level may continue rise that provokes opening of other gates. The elevation of gate return in closed position has more complicated dependence on conditions in the span. When upstream level falls down to normal water level at the time of flood drawdown, the gates must be closed. The hydrodynamic forces are of great importance in this case. The dropping curve above the gate changes, consequently the pressure profile above the gate changes. When level falls down to elevation of gate rotation axis, the gate is closed under the action
of the ballast. However, this leads to heavy water loss in reservoir, as the gate axis is buried under upstream level at two thirds of gate height. Therefore, the solution was required to be found for gate return in closed position at upstream elevations just below than normal water level, that is to minimize water losses in reservoir. Here, the some factors need to be coordinated to achieve opening of gate at necessary elevation.

![Diagram showing changing of force moments at the opening of the gate](image)

**Fig.4. Changing the amount of force moments at the opening of the gate**

The main factors are:
- sill length and gate position on it;
- form of upper part of head covering;
- form of lower part of gate;
- final position of open gate;
- effect submersion of gate from downstream side.

Model experiments showed that these factors are interrelated and must be considered in complex.

These factors form hydrodynamic forces acting to the gate in open condition. The form of dropping curve depends on head, degree of contraction of flow in span, length of entrant section, length and height of sill, and gate.

The wide sill, on which experiments have been conducted, is 4.6 m long of flow (recalculated for nature) with ledges under the gate. The maximum head is 2.35 m, the head of gate return is 1.35 m, ratio \( L/H_{max} = 3.4 \). The gate was placed at the end of sill. Experiments showed that critical depth is located before the gate at all heads. This means that the gate has no influence on discharge capacity of spillway span. The specific discharge is calculated as for free spillway with wide sill by:
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\[ q = \frac{m_0}{(1 + \sigma^2 m_0^2)^{3/2}} \sqrt{2gH_0^{3/2}} \], where \( m_0 \) takes into account the speed of flow approach, side and vertical contraction at inlet of sill. If the sill is short \((L/H_0<3)\) and the gate is located in area of subcritical depths, it reduce discharge capacity of the sill that is undesirable. The rough flow, leaking to the verge of the gate, forms rise of free surface above head covering and separation zone from covering surface. In this zone the pressure decreases, the one of gate verge increases.

The pressure drop is calculated using the Bernoulli equation by:

\[ \Delta p = \frac{V_1^2}{2g} \left( \frac{1}{\varepsilon^2} + \zeta - 1 \right) \], where \( \varepsilon \) – degree of flow contraction by the gate, \( \zeta \) – coefficient of gate face resistance. Moment of forces closing the gate decreases. At relatively heavy head this results in change of flow regime above the gate. When head decreases, the hydraulic losses of inlet part of the gate and formation of roller in flow separation zone become sufficient to form hydraulic jump above the gate and to change the flow to quiet regime. At this the depth above inlet part of gate increases, that results in increase of moment of forces for gate closing. These losses are calculated by:

\[ \Delta h = \frac{(v_1 - v_2)^2}{2g} \], where \( v_1 \) – velocity of flow income, \( v_2 \) – velocity in contracted section after junction of the flow with the gate. This analysis allowed to obtain a method of moments regulation to calculate the level of gate return in the closed position. If the rib is placed on head covering across the flow, the pressure before the rib increases and behind the rib in separation zone decreases. Changing position of the rib relative to the gate rotation axis, an instrument for control of sum of forces moments and conditions of gate closing at given upstream elevation can be obtained. The rib increases losses of head in the flow above the gate that contributes to formation of hydraulic jump on the gate, but doesn’t influence on the flow under the gate. The upper part of head covering has surface fracture. In closed position this covering part takes up pressure of the upstream. Turning the gate in open position the covering pressure decreases. This decreases the negative moment and contributes to gate closing at more high upstream elevations. The gate return level can be raised by tilting of gate \((3\ldots7^\circ)\) in final open position (Fig.5). The increase of tilting leads to increase of return elevation.

The location of gate on wide and low sill can lead to jet underflooding that causes flow pressure of downstream covering, resulting in change of sum moment. This case is not examined.
Conclusions

The suggested gates are completely automated, operated only under the action of forces of flow pressure at design upstream levels. The gate can be installed at the dam crests in two positions:

− rotation axis is at elevation close to normal water level;
− upper edge of gate in closed position is at elevation close to normal water level.

The gates are calculated for operation without underflooding from downstream side.

In the first case the gate can be open by rising of upstream level up to gate crest or a little higher, admitting overflow. Thus, flood passing is always performed at level higher than normal water level that increases power output. Moreover, in this case, the inlet and sill shapes and gate sill position are of no importance. The gate is automatically closed when the overflow ceases above the open gate. The gate is calculated only by hydrostatic forces and moment of gate weight. In the second case the gate opening is calculated by hydrostatic forces at overflow at elevations between normal water level and maximum water level, and the gate closing is calculated at elevations below normal water level, but above gate rotation axis. Gate closing calculation at given upstream elevation is carried out taking into account hydrodynamic forces, conditions of flow sill inlet, length and height of sill, gate form.

Gate parameters can be calculated approximately. Elevation deviations of gate closing level can make up to 20% of level change value from maximum to minimum. The most precise solution may be taken for tests of design gate on full model of gate and fragment of dam with sill and piers.