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# HYDRAULIC PERFORMANCE CHARACTERISTICS OF A VORTICAL SPILLWAY WITH A TANGENTIAL VORTEX GENERATOR IN THE FLOW

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The possibility of using vortical spillways in medium- and high-head hydraulic facilities as structures ensuring effective energy suppression of the flow within the discharge path makes them extremely attractive in hydraulic construction. The chair of the GTS MGUP has conducted model investigations of a vortical tunnel spillway with tangential vortex generators (Fig. 1) For this purpose, we conducted experiments under conditions with and without air fed into the core through the end of the vortex generator, free discharge of the flow from the tunnel into the lower pool, and underflooding of its discharge section. A model of the vortical spillway was fabricated from acrylic plastic and consisted of the following parts: a water intake, a segment of a shaft with a slope of 60°, a chamberless tangential vortex generator with a plane conduit section ($\beta$ = 90°), a discharge tunnel, and a toe basin. The discharge tunnel had a longitudinal slope i = 0.0038. The geometric parameter of the vortex generator characterizes the swirl intensity of the flow [1]; it assumed different values during the experiments. This was done by varying the angle $\alpha$ of the internal section of the shaft of the swirling apparatus (Fig. 1). The model parameters of the hydraulic regimes of the experiments that we conducted are presented in Fig. 1.

We measured the carrying capacity of the spillway, the piezometric pressures on the walls of the water conduit, the vacuum in the core, and the coordinate of the center and the area of the cross section of the core at the end of the vortex generator. For all experiments, the water level was maintained constant in the upper pool, and H and $H_s$ corresponded to the maximum possible settings. The upper and lower pools were previously constructed for model hydraulic investigations of a high-head shaft vortical spillway at the Tel'mamsk hydraulic facility on the Mamakan River [2], and was left unchanged due to the cumbersomeness of the structure. This also explains the certain limitedness of the H and $H_s$ values. The investigations indicated that the core – the region of the break in flow continuity under centrifugal forces – is extended over the entire length of the water conduit in the form of an elongated spiral (Fig. 2). The helical shape of the core is explained by the fact that the flow is swirled by a tangential swirling apparatus that governs the asymmetry of the swirled flow delivered to the discharge conduit. Generally no core is formed in the toe basin for regimes 1, 2, and 4 (Table 1), while a break in flow continuity occurs and the core acquires an expressed shape for regimes 3, 5, and 6. Underflooding of the outlet section of the water conduit results in disappearance of the core or to a reduction in its cross-sectional area (regimes 4 and 6, respectively). For a vortex generator with a geometric parameter A = 1.245, the formation of a zone in which a marked variation occurs in the cross-sectional area and shape of the core, i.e., a hydraulic jump, is observed in the tunnel at a distance of 0.2-0.3 m from the axis of the shaft. In that case, the latter is observed both with and without underflooding of the outlet section of the water conduit.

The core is more open along the length of the length of the water conduit for all A values when air is fed into the end of the vortex generator. The cross-sectional areas of the core and opening through which the air is fed are the same. As is indicated above, a hydraulic jump is formed in the tunnel for regimes 8-12. Its propagation ranges from 0.25-2.5 m from the beginning of the tunnel. It must be pointed out that a trend toward leveling of the core axis is observed with increasing A of the vortex generator both with and without the air feed.

The relationship between the reduced flow rate and the geometric parameter of the core generator $Q_I' = f(A)$ is shown in Fig. 3. For similar A, the absolute values of the vanishing points for all regimes differed negligibly one from the other $\Delta$ = 0-1.86%. The exception comes from comparison of regimes 1 and 7, when $\Delta$ = 6.04%. As is apparent from the relationships, the carrying capacity of the spillway increases with increasing A; this can be explained by an increase in the

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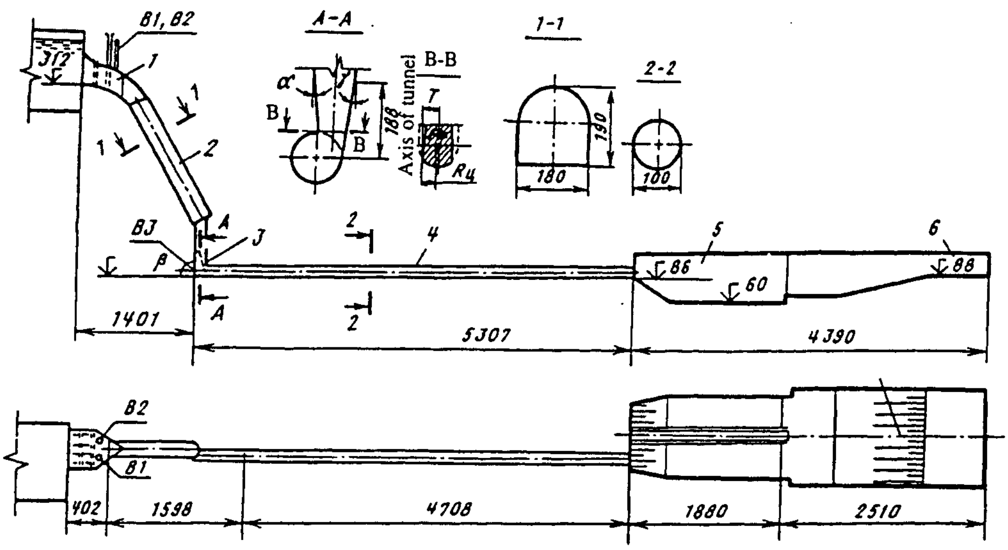

Fig. 1. Schematic diagram of hydraulic model of vortical spillway with tangential vortex generator (dimensions in mm): 1) water intake; 2) inclined section of shaft; 3) tangential vortex generator; 4) discharge tunnel; 5) toe basin; 6) outflow canal; 7) separating partition; B1, B2, and B3 – air conduits.

swirl angle of the flow and the break in flow continuity. Even this distribution of the flow curve of the spillway is explained by the fact that until the hydraulic jump reaches the swirling apparatus (as in our case), the flow rate attained will be determined only by the inlet head $H_{in}$ [3]. The scatter of the $Q_I' = f(A)$ curves in Fig. 3 results from the fact that the $H_{in}$ value used in the equation for determination of $Q_I'$ decreases with increasing hydrostatic head $H_s$.

Curves of the relative vacuum $\bar{H}_{co}$ in the core versus the parameter A are presented in Figs. 4 and 5. The vacuummetric pressure was measured by a U-tube from the end of the vortex generator. Significant vacuums are observed for regimes with no air in the core (Fig. 4). A drop in $H_{co}$, the rate of which is greater for regimes with $H_s = 0$, occurs with increasing A. Underflooding of the outlet section of the tunnel gives rise to an increase in the vacuum in the core, with the exception of the condition A = 0.6 (Table 1).

Air fed into the core sharply reduces its vacuum, and the value of the latter is close to zero (Fig. 5). As is indicated above a drop in vacuum is observed with increasing A. Only for the case in question is the vacuum in the core higher for $H_s = 0$ than with the hydrostatic head. The significance of $H_{in}$, which decreases with increasing $H_s$, manifests itself in the distribution of the relative $H_{co}$ values.

A plot of the relationship between the coordinate of the center of the core at the end of the vortex generator and the geometric parameter A of the vortex generator is presented in Fig. 6. It can be stated that for regimes with and without an air feed, the centers of the core essentially coincide at the end of the tunnel for a single A value. As is apparent from the plot, the center of the core shifts toward the axis of the water conduit with increasing parameter A, i.e., with increasing swirling. This is associated with the fact that the moment due to the average flow velocity at the inlet section of the water conduit increases; this brings about an increase in the swirl rate of the flow. In this connection, the carrying capacity of the vortex generator is reduced, and the sectional area of the core increased.

The relationship between the relative area $\bar{\omega}$ occupied by the swirling flow at the end of the vortex generator and the geometric parameter A is shown in Fig. 7. The sectional area of the core increases with increasing A; this was indicated above. For the no-air regimes, the core is not opened when A = 0.6; therefore, $\bar{\omega} = 1$. As is apparent from the relationships, air fed into the core has little effect on the area of its cross section at the end of the vortex generator as A increases. In our case, the two curves virtually coincide when A = 1.245$\bar{\omega}$. We observed a similar pattern during model hydraulic investigations of the vortical shaft spillway at the Tel'mamsk hydraulic facility [4].

The studies indicated that regimes with no air fed into the core are most favorable in terms of the pressure distribution against the wall of the conduit (Fig. 8). Despite the fact that the core has a helical shape and a significant internal vacuum (Fig. 4), an excess pressure distributed essentially uniformly over its section is observed over the length of the conduit. A vacuum, which is removed by minor underflooding in the direction of the lower pool is recorded on the crown of

TABLE 1

| Regime | A | $Q$, $m^3$/sec | $Q'_1$, $m^3$/sec | $H$, m | $H_{in}$, m | $H_s$, m | $H_{co}$, m | $H'_s$ | $\bar{H}_{co}$ | $\bar{H}$. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | No air fed into core | | | | | |
| 1 | 0.600 | 0.0286 | 1.819 | 2.833 | 2.471 | 0 | -2.700 | 1.092 | -1.092 | 0 |
| 2 | 0.600 | 0.0284 | 1.871 | 2.651 | 2.301 | 1.199 | -2.530 | 1.186 | -1.100 | 0.086 |
| 3 | 0.925 | 0.0247 | 1.585 | 2.839 | 2.438 | 0 | -1.800 | 0.738 | -0.738 | 0 |
| 4 | 0.925 | 0.0251 | 1.670 | 2.653 | 2.270 | 0.197 | -2.155 | 1.036 | -0.949 | 0.086 |
| 5 | 1.245 | 0.0215 | 1.301 | 2.833 | 2.731 | 0 | -1 | 0.366 Jump | -0.366 | 0 |
| 6 | 1.245 | 0.0217 | 1.340 | 2.653 | 2.624 | 0.197 | -1.750 | 0.742 Jump | -0.667 | 0.075 |
| | | | | | With air fed into core | | | | | |
| 7 | 0.600 | 0.0268 | 1.694 | 2.833 | 2.516 | 0 | -0.150 | 0.060 | -0.059 | 0 |
| 8 | 0.600 | 0.0268 | 1.750 | 2.650 | 2.356 | 0.200 | -0.075 | 0.116 Jump | -0.032 | 0.085 |
| 9 | 0.925 | 0.0247 | 1.572 | 2.839 | 2.476 | 0 | -0.125 | 0.050 Jump | -0.050 | 0 |
| 10 | 0.925 | 0.0245 | 1.618 | 2.652 | 2.303 | 0.198 | -0.100 | 0.130 Jump | -0.043 | 0.086 |
| 11 | 1.245 | 0.0219 | 1.337 | 2.843 | 2.681 | 0 | -0.035 | 0.013 Jump | -0.013 | 0 |
| 12 | 1.245 | 0.0219 | 1.382 | 2.653 | 2.511 | 0.197 | -0.010 | 0.082 Jump | -0.004 | 0.078 |

**Note.** Q and $H = P/\rho g + v^2/2g - H_s$ is the flow rate and head of the spillway structure; $Q_1' = Q/D^2\sqrt{H_{in}}$ is the flow rate reduced to 1 m of head and discharge-conduit diameter D equal to 1 m; $H_{in} = Z_{in} + P_{in}/\rho g + v_{in}^2/2g - H_s$ is the head at the inlet section of the tangential vortex generator (Fig. 1); $H_s$ is the underflooding from the side of the lower pool, i.e., the depth of immersion of the axis of the discharge conduit on the side of the lower pool; $H_{co}$ is the pressure (vacuum) in the core; $H_s' = (H_s - H_{co})/H_{in}$ is the underflooding index in the lower pool with allowance for the pressure in the core; $H_s' = H_s/H_{in}$ is the relative depth of underflooding in the lower pool, normalized by the inlet head; and, $\bar{H}_{co} = H_{co}/H_{in}$ is the relative pressure in the core.

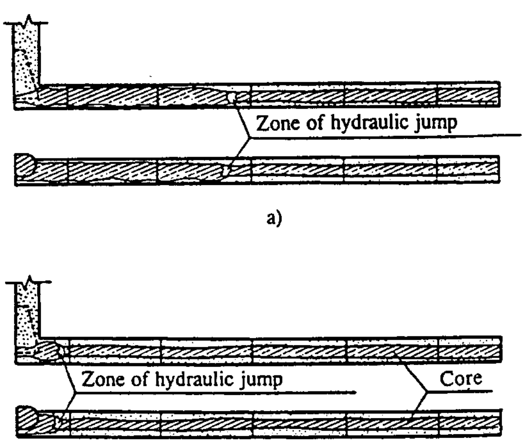


Fig. 2. Shape of core of swirled flow in discharge conduit for regimes 9 (a) and 10 (b).

the tunnel at the point where it meets the toe basin. A local air feed can also be an effective method of eliminating the vacuum [5, 6]. Underflooding from the direction of the lower pool will not result in a pressure increase on the walls along the conduit, if the vacuum in the core increases simultaneously. The tangential swirl assembly is one of the sources of cavitation in the type of vortical spillways under consideration. In our studies, a vacuum was recorded for regimes 1-4 at points where the edges of the delivery and discharge conduits meet (Fig. 8). Investigations [7, 8] have indicated that the mating edge is a vigorous cavitation inducer. A cavitation flare in the form of a second, finer, vortical core, which was

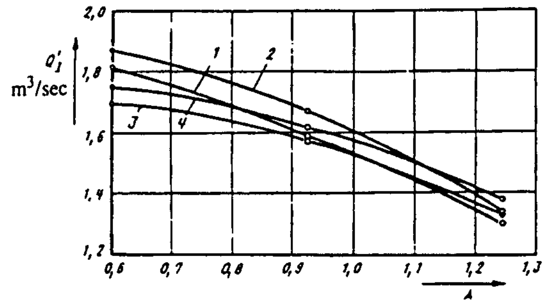


Fig. 3. Relationship between reduce flow rate and geometric parameter $Q_I' = f(A)$ of vortex generator: 1, 2) for regimes with no air fed into core and $H_s = 0$ and $H_s > 0$, respectively; 3, 4) for regimes with air fed into core and $H_s = 0$ and $H_s > 0$, respectively.

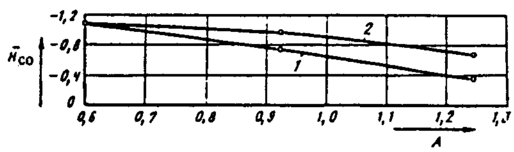


Fig. 4

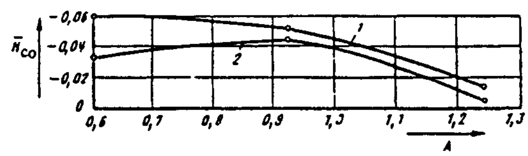


Fig. 5

Fig. 4. Relationship between relative vacuum $H_{co}$ in core and parameter A for air-free regimes: 1) for $H_s = 0$; 2) for $H_s > 0$.

Fig. 5. $H_{co}-f(A)$ relationship for regimes with air fed into core: 1) for $H_s = 0$; 2) for $H_s > 0$.

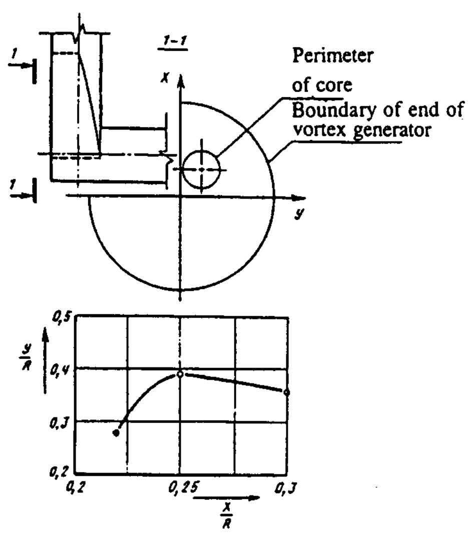


Fig. 6. Plot showing relationship between coordinate of center of core at end of vortex generator and geometric parameter A: ◐) A = 0.6; o) A = 0.925; ◑) A = 1.245; y, x) vertical and horizontal axes of discharge conduit; dimensions of core and tunnel are proportional (regime 11 shown).

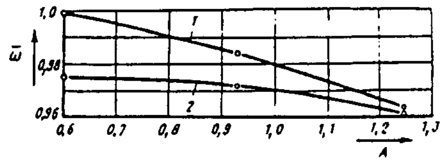


Fig. 7. Curves of relative area occupied by flow at end of tunnel $\bar{\omega}$ versus geometric parameter A of vortex generator: 1) no-air regimes; 2) for regimes with air fed into core.

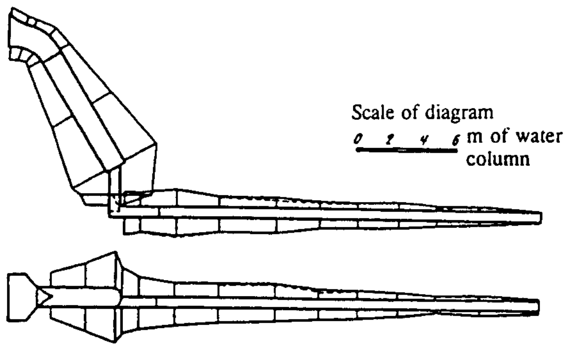


Fig. 8

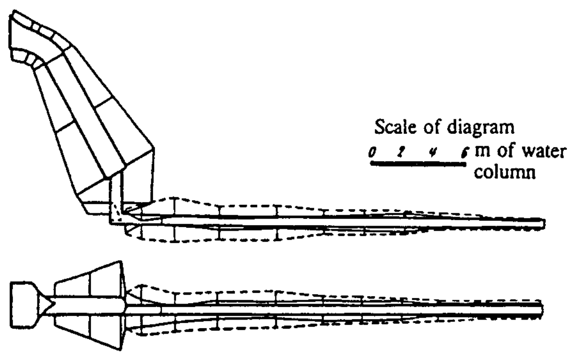


Fig. 9

Fig. 8. Plots of piezometric pressure on walls of conduit for regimes with no air fed to core and vortex-generator parameter A = 0.925: ——) for $H_s = 0$; – – –) for $H_s > 0$.

Fig. 9. Plots of piezometric pressure on walls of conduit for regimes with air fed into core and A = 0.925: ——) for $H_s = 0$; – – –) for $H_s > 0$.

joined to the central core of the eddy flow formed downstream, was clearly overlooked in experiments conducted by Rozanov and Fedorkov [7]. Since closure of the cavitation flare occurs within the flow, its existence may not result in surface failure. This suggests that ultrasonic sensors – hydrophones – installed on the model along the trajectory of the flare did not record cavitation signals.

For the regimes where air is fed into the core (with the exception of regime 10), the pressure distribution on the walls of the conduit is characterized by pronounced nonuniformity and lower values (Fig. 9). Vacuums are recorded both at the beginning, and also at the end of the tunnel, and the effect of underflooding in the lower pool is noted at a distance of 2/3 its length. In regime 10, when the zone of the hydraulic jump is displaced toward the beginning of the tunnel (Fig. 2b) with its sections underflooded in the lower pool, an entirely different pattern is observed for the plot of the piezometric pressure. An excess pressure (broken line in Fig. 9) is recorded over the entire length of the discharge conduit, and its distribution is rather uniform.

## CONCLUSIONS

Model investigations of the hydraulic operating conditions of a vortical tunnel spillway with a tangential vortex generator indicated that:

a trend toward leveling of the core axis is observed with increasing geometric parameter A of the vortex generator both with and without air fed into the conduit;

insignificant underflooding of the outlet section of the tunnel (their difference for all regimes does not exceed 1.7%) exerts a minor influence on the carrying capacity of the spillway; here, underflooding even increases the flow rate of the spillway in the absence of air when A = 0.925 and 1.245;

an air feed also has little effect on the carrying capacity of the structure, with the exception of the layout containing a vortex generator with A = 0.6 ($\Delta = 6.04\%$ when A = 0.6, $\Delta = 0\%$ when A = 0.925, and an air feed increases the flow rate of the spillway by $\Delta = 1.86\%$ when A = 1.245);

significant vacuums, the absolute values of which drop rapidly from $H_{co} = -2.7$ m to $H_{co} = -1$ m with increasing A, are observed for regimes with no air fed to the core;

air fed into the core sharply lowers the vacuum in the latter, and its value approaches zero;

the center of the core at the end of the vortex generator shifts toward the axis of the conduit with increasing parameter A; and,

regimes with no air fed to the core are most favorable in terms of pressure distribution on the wall of the conduit.

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