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ENERGY DISSIPATION STRUCTURE FOR FIXED-CONE VALVES

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ABSTRACT

Results of a model study to investigate the hydraulic performance of a proposed energy dissipation structure for fixed-cone valves are presented. Procedures for estimating pressures and airflow rates are discussed. Similar structures are currently in use or under construction at three Bureau of Reclamation dams.

INTRODUCTION

Fixed-cone valves are widely used for regulating releases through outlet works of large dams. A conical element of the valve is used to disperse pressure flow from a conduit or tunnel radially outward. As its name implies, the central cone is fixed and flow regulation is provided by axial movement of a cylindrical closure member surrounding the central cone and radial orifices. The flow energy is dissipated by the resulting free discharge to the atmosphere as a hollow, expanding jet. Where the wide dispersion of the flow and resulting spray must be confined, the valve may be provided with a fixed steel or concrete hood, or be located within a containment structure. Hooded valves are commercially available for heads up to 175 feet. For higher heads or special applications, a containment structure will provide the necessary energy dissipation while producing minimal spray. A reinforced concrete containment structure is currently in use at the Bureau of Reclamation's Stony Gorge Dam (California) to provide energy dissipation for two 42-inch, fixed-cone valves with a maximum head of 100 feet. Similar structures have been designed by the Bureau of Reclamation for two 78-inch valves with a 295-foot head at Jordanelle Dam (Utah) and for two 132-inch valves with a 190-foot head at New Waddell Dam (Arizona).

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RESULTS OF HYDRAULIC MODEL STUDY

Two 132-inch, fixed-cone valves were selected for regulating reservoir releases from New Waddell Dam to the Waddell Canal. Preliminary dimensions for a reinforced concrete energy dissipator were developed by scaling the smaller Stony Gorge structure using the 3.14 ratio of valve diameters. A 1:22 scale model using a single 6-inch valve was constructed to verify the adequacy of the structural dimensions for hydraulic performance, determine optimum dimensions for the air vent, obtain dynamic loads acting on the structure due to the annular jet, and estimate spray, noise, and vibration during operation. Froude-based scaling laws were applied since gravity and inertia forces are dominant. The prototype configuration and dimensions are shown in figure 1.

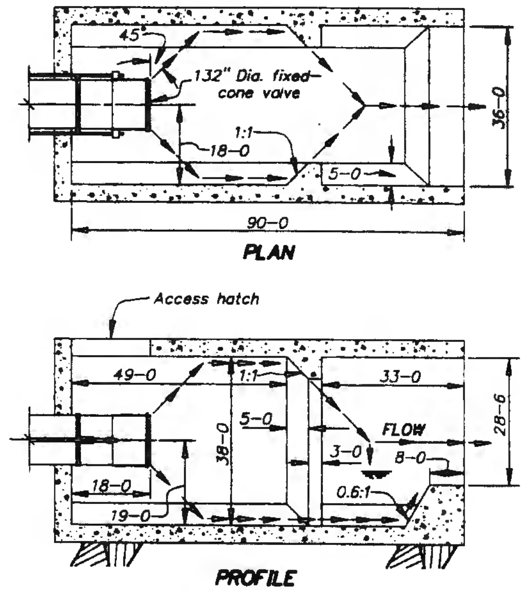

Figure 1. - Prototype dimensions.

The model was operated through a range of heads, with valve openings from 5 to 100 percent of the maximum sleeve travel. A maximum valve flow area of 89.6 ft^2 was established to maintain control at the downstream end of the valve, thereby limiting the maximum sleeve travel to 0.45 times the valve diameter. This restricts the valve flow area to an amount less than is available within the upstream flow passage, so that back pressure is maintained on the vanes and control does not shift to the leading edge of the vanes. A discharge coefficient (C_D) of 0.78 was recorded for the maximum sleeve travel using the standard orifice equation with the area of the upstream pipe.

Operation of the valve produces a conical jet which strikes the vertical and horizontal surfaces within the containment structure at 45° angles along a hyperbolic intersection. Upon impact, the majority of the flow continues downstream along the structure surfaces until being deflected away from the roof and sidewalls to a common point within the downstream chamber. Finally, the flow passes over the end sill to the outlet channel or canal. This type of structure is not suitable for submerged flow.

The energy dissipator easily contained the energy for the conditions observed. To facilitate construction, the side deflectors were moved upstream into the same vertical plane as the roof deflector for the final model configuration. This caused no discernible change in the flow leaving the dissipator. There were no problems with spray or the condition of the flow leaving the dissipator for either deflector design.

Air Vent Design

An air vent should be provided in the roof or walls upstream from the impact zone to prevent the formation of very low pressures within the flow which could lead to cavitation. Falvey [1980] states that the relative airflow rate (Q_{air}/Q_{water}) in fixed-cone valves is a function of valve opening and total upstream head. Thus,

$$\frac{Q_{air}}{Q_{water}} = f\left[G, \frac{\Delta p/\gamma}{H_t}\right] \qquad (1)$$

where
- G = valve opening
- H_t = total potential and kinetic energy upstream
- Δp = difference between atmospheric pressure and air pressure at the end of the vent
- γ = specific weight of water

Using the relationship shown in equation (1), empirical data plots of relative air pressure measured at the valve versus relative airflow rate were drawn for five valve openings and various heads. Shown in figure 2 are the six plots derived for a 67 percent valve opening. Percent of maximum valve flow area was used rather than percent sleeve travel because the model valve does not represent the prototype valve for discharge calibration purposes in terms of sleeve travel.

According to Falvey [1980], the relative airflow rate can be expressed as:

$$\frac{Q_{air}}{Q_{water}} = \frac{A_v}{A_p C_D}\left[\frac{\rho_{water}/\rho_{air}}{K_s + fL/4R}\right]^{1/2}\left[\frac{H_{air}}{H_{water}}\right]^{1/2} \qquad (2)$$

where
- A_v = cross-sectional area of the air vent (ft^2)
- A_p = area of pipe immediately upstream of valve (ft^2)
- C_D = discharge coefficient of the valve
- ρ = density ($slugs/ft^3$)
- K_s = total of singular (form) losses in air vent
- f = Darcy-Weisbach friction factor
- L = air vent length (ft)
- R = hydraulic radius of air vent (ft)
- H_{air} = difference between atmospheric and energy dissipator pressure head (ft)
- H_{water} = water pressure head on centerline of valve (ft)

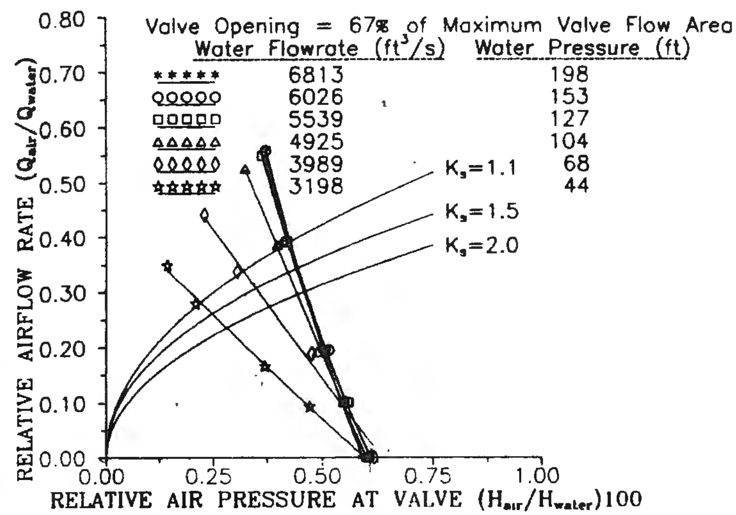

Figure 2. - Typical dimensionless relationship between pressure and flow rate.

To determine airflow rate and air pressure for a given air vent design at a valve opening of 67 percent, equation (2) should be plotted on figure 2. Equation (2) is solved by assuming values of H_{air}/H_{water} and calculating the corresponding value of Q_{air}/Q_{water}. The intersection of the empirical data plot and the computed curve gives the relative airflow rate and the relative air pressure for a given flow of water and vent design. The airflow rate and air pressure for other valve openings can be obtained in a similar manner with the use of the appropriate plots.

Example Vent Design Calculation

Three curves were drawn on figure 2 with the use of equation (2). Singular loss coefficients (K_s) of 1.1, 1.5, and 2.0 were assumed for air vents having streamlined bellmouth, square-edged, and pipe entrances, respectively, which include entrance, bend, and exit losses. The following values were used in equation (2) for all three air vent types.

$$A_v = 10.0 \text{ ft}^2$$
$$A_p = 95.0 \text{ ft}^2$$
$$C_D = 0.54$$
$$\rho_{water} = 1.94 \text{ slugs/ft}^3$$
$$\rho_{air} = 0.00187 \text{ slugs/ft}^3$$
$$fL/4R = \text{assumed negligible}$$

The computed airflow curve for $K_s = 1.1$ intersects the empirical data curve for a water flow rate of 4,925 ft^3/s and a water pressure head of 104 feet at a relative airflow rate of 0.38 and a relative air pressure of 0.0040. Therefore,

$$Q_{air} = (0.38)\ (4925) = 1870 \text{ ft}^3/\text{s, and}$$
$$H_{air} = (0.0040)\ (104) = 0.42 \text{ ft}$$

The air pressure inside the energy dissipator will always be less than atmospheric since the direction of airflow is into the structure. In this example, the pressure head inside the structure is 0.42 feet of water below atmospheric pressure. The allowable air velocity is often limited by factors such as noise or accessibility of the air vent openings to people. The limiting air velocity with respect to noise is 100 ft/s, above which an objectionable whistling sound occurs. Air velocities should be kept below 50 ft/s at vents accessible to people [Falvey, 1980]. In the above example, the air velocity (Q_{air}/A_v) would be 187 ft/s through the vent. If it is felt that the air velocity or the air pressure inside the dissipator is not acceptable, a new air vent design could be selected and the above process repeated until acceptable values are obtained.

Structural Design Considerations

The forces exerted on the structure by the impacting jet are proportional to the water density, flow rate, and component of the velocity normal to the surface (in accordance with momentum principles) and, therefore, are a function of velocity head and valve opening. Maximum pressures exerted on the roof and walls occur in a region near the center of the impact area of the annular jet (region of highest velocity). These maximum pressures are equal to the velocity head due to the normal velocity component. The region of highest velocity will shift due to turbulence in the flow. Roof pressures due to vertical components of velocity are reduced by the vertical distance from the valve, as a result of gravitational forces on the jet. The impact pressures decay exponentially away from the region of maximum pressure [George, 1980].

Nineteen piezometer taps and five pressure transducers were installed in the model to measure pressures at various locations on the roof and along the top, bottom, and end deflectors. Maximum recorded point pressures on the roof typically were lower than predicted average values because the piezometer taps were not located in the areas of

maximum impact pressures for all discharges. The band width of significant pressures on the roof varied with the valve opening, ranging from about 10 feet in the prototype for the valve fully open, to less than the piezometer tap spacing of 1.8 feet for the smallest opening. Pressures recorded near the floor downstream from the side deflectors approximated the hydrostatic head.

Finite element plate analysis should be performed for the structural design of the roof and sidewalls. If comprehensive model data are not available, a uniform pressure distribution (based on the normal velocity head) should be applied to the central portion of the hyperbolic impact zone (based on valve opening). Concrete dead loads and gravitational forces will reduce the effect of impact loading on the roof. The upstream end wall must be designed for the maximum thrust resulting from full reservoir head on the closed valve. The downstream chamber should be designed for maximum hydrostatic loads. For higher heads, as for the Jordanelle Dam structure, the impact areas may be steel lined.

CONCLUSIONS

The proposed energy dissipation structure performed well in the model studies throughout the range of operating conditions. Minimal vibration and spray was observed. A methodology for determining air demand and air pressure inside the energy dissipation structure is presented. Air demand may normally be met by venting through the access hatch above the valve. It is recommended that the relative dimensions of the structure not be reduced due to the short distance available for air entrainment of the jet leaving the valve and because a decrease in structure dimensions will reduce energy dissipation capability. Further studies of dynamic pressures are desirable; however, conservative loads may be assumed based on the velocity head and width of the jet. Similar structures are in use or under construction for valve diameters from 42 to 132 inches, and for heads from 100 to 295 feet.

APPENDIX 1 - REFERENCES

1. Falvey, H. T., "Air-Water Flow in Hydraulic Structures," Engineering Monograph No. 41, Bureau of Reclamation, December 1980.

2. George, R. L., "Impinging Jets," REC-ERC-80-8, Engineering and Research Center, Bureau of Reclamation, October 1980.

APPENDIX 2 - U.S. CUSTOMARY - SI CONVERSION FACTORS

1 inch = 25.4 millimeters
1 foot = 0.3048 meters
1 slug/ft^3 = 515.4 kg/m^3