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STEPPED SPILLWAY DESIGN FOR FLOW OVER EMBANKMENTS

BY

KATHLEEN H. FRIZELL

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Kathleen Houston Frizell[1]

Abstract

Many embankment dams have been identified as unable to pass their design flows without failure due to overtopping. The U.S. Bureau of Reclamation (Reclamation) is currently at the forefront of pursuing the technology of providing overtopping protection for embankment dams. The major emphasis of Reclamation's research program is to determine the capability of a stepped concrete overlay to protect the embankment from erosion during passage of large design flows. This paper will discuss the test program, laboratory and near-prototype facilities, and the current test results for horizontal steps on a 2:1 slope.

Purpose

The purpose of the overtopping protection program is to provide a stable, nonerosive protective scheme for an embankment. A stepped protection should both enhance the stability of the protective layer by providing aspiration of subgrade seepage while providing the additional benefit of dissipating energy. The research program on stepped spillway protection will optimize the step geometry for typical embankment dam slopes. The results of pressure measurements will indicate low pressure regions for aspiration of seepage buildup to prevent uplift of the overlay and higher jet impact areas used in the stability analysis. Velocity profile measurements will be used to quantify the energy dissipation of each step shape. The optimum step geometry will then be chosen based upon both factors.

[1]Hydraulic Engineer, U.S. Bureau of Reclamation, PO Box 25007, Denver CO 80225

Test Program

The stepped concrete overlay test program is being conducted in two phases - the laboratory and large-scale or near-prototype tests. Step geometry is being developed using a laboratory flume. These laboratory results will then be tested in the near-prototype scale outdoor flume facility.

The laboratory flume facility has been operational since January 1990. This facility is being used to optimize the step geometry for 2:1, 3:1, and 4:1 slopes. Data collection for horizontal 0.167-ft (0.05-m) steps on a 2:1 slope has been completed. A new step shape with the tread offset away from horizontal by 15° is currently being tested. All testing for optimizing the step geometry on a 2:1 slope should be completed by mid 1991. The laboratory work to optimize step geometry for all slopes is due to be completed in 1992.

Construction of the near-prototype facility will start late spring of 1991 with completion slated for fall of 1991. This large outdoor facility will be constructed down a 2:1 embankment that provides about a 50-ft (15.24-m) drop, and be capable of passing a unit discharge of 50 $ft^3/s/ft$ (4.65 $m^3/s/m$) (depending upon the final width of the facility). This facility will allow investigation of aeration and dynamic pressure fluctuations on the stability and energy dissipation of the final step geometry determined from the laboratory studies. Future tests include other types of embankment protection schemes, such as blocks, riprap, and reinforced rockfill blankets.

Laboratory Flume Facility

The laboratory flume facility consists of a large reservoir head tank providing 15.5 ft (4.72 m) of vertical drop along a variable sloping flume (2:1 to 4:1) to a return channel with tailwater control. Elliptical shapes on both sides of a broad flat crest form the entrance into the 1.5-ft- (0.46-m-) wide Plexiglas-walled flume. The flume is presently set on a 2:1 slope (26.57°) where step optimization is being finished before changing the slope. Discharges up to 14 $ft^3/s/ft$ (1.3 $m^3/s/m$), measured with Venturi meters, and reservoir heads up to 2.8 ft (0.85 m) are used for testing.

A carriage traverses the entire length of the flume. This carriage is equipped with a point gage, water surface probability probe, and a laser-doppler anemometer mounted on the side. There are three measurement stations, at approximate third points down the flume, for measuring pressures on the step faces. Depth measurements are taken down the entire length of the flume, velocity profiles are measured every ten steps starting at step 3 down from the crest. All velocity and pressure data are taken with an IBM-compatible computer.

Data Analysis

The ability of the step shape to produce aspiration of the subgrade flows is determined by measuring the pressures on both the vertical and tread surfaces of the steps at the three measurement stations down the flume. The velocity profiles are analyzed and used to determine the energy dissipation down the slope produced by each step shape.

Pressures on step faces. - At each of the stations, 2 steps are instrumented, each with 11 piezometer taps, for a total of 22 taps per station and 66 overall. The upper station is located 2.5 ft (0.76 m) (steps 15 and 16) below the crest, the middle station 7.83 ft (2.39 m) (steps 47 and 48) down, and the lower station, near the toe, at 13.17 ft (4.01 m) (steps 79 and 80) down. The mean pressure from each piezometer tap is recorded and the profiles plotted over the steps at each station.

Figure 1, the pressure profiles for 1.67 ft (0.51 m) of overtopping head and the measured flow depth, clearly shows the characteristics of the flow. Comparison of the flow

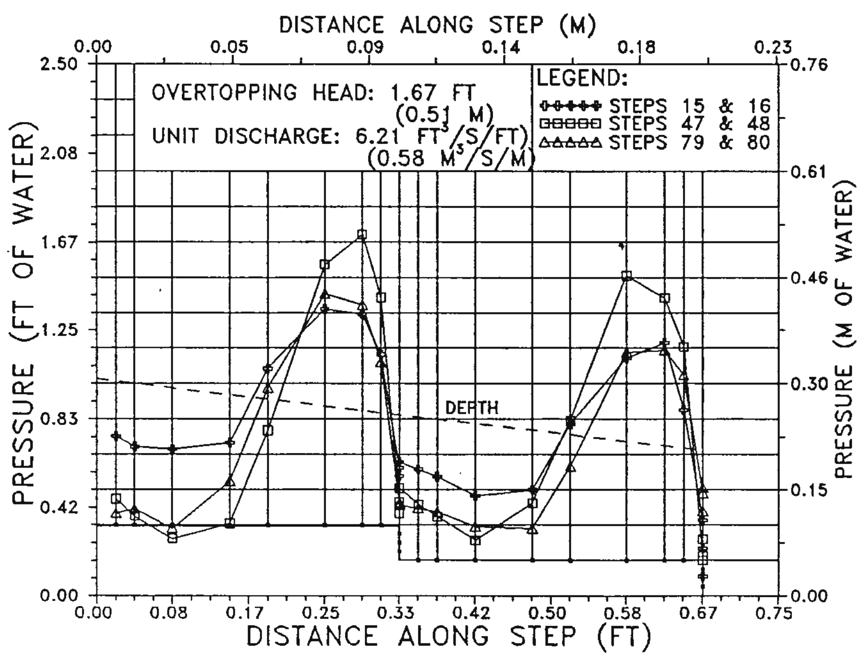

Figure 1.- Pressure profiles over horizontal steps for an overtopping head of 1.67 ft (0.51 m).

depth (dashed line) with the pressure profiles shows two distinct pressure zones. One where the jet impact on the downstream end of the step tread produces additional loading on the overlay; and the other where separation of the jet off the step produces reduced pressure in the offset area below the pitch line of the steps. When considering stability of the entire stepped overlay, the impact provides additional downward force when added to the flow depth; however, the pressure in the offset area is not low enough to provide continuous aspiration of the underlying filter zone. This area shows promise of allowing aspiration, provided the strength of the return flow is reduced. The step geometry will be optimized to provide an area of low pressure by using guidelines from the Russian wedge-shaped block (Pravdivets, 1989). Steps with tread offsets below horizontal of 10 and 15° have been designed to redistribute the flow below the step pitch line, thus allowing aspiration. Completion of these tests will determine the optimum step geometry from a stability and drainage aspect.

The pressure profiles also show an increase in impact head between the first and second stations, then a decrease at the last station. This interesting feature will hopefully be related to a reduction of energy as well.

Velocities down the slope. - Velocity profiles are being measured with a laser-doppler anemometer down the flume slope as far as possible. The flow is seeded with tiny air bubbles from a carbon aquarium air stone placed in the upstream head tank. Measurements are taken beginning at step 3, about every 10 steps down the slope, until surface aeration prohibits further measurement. Velocities are measured in both the horizontal and vertical planes from the tip of the step to near the water surface. Flow velocity profiles normal to the slope are shown on figure 2 for an overtopping head of 1.67 ft (0.51 m). The progressive flattening of the profiles at each station down the slope is indicative of the large step roughness. The profiles approach uniformity down the slope, indicating that the flow reaches a terminal velocity on the slope.

Curves are fit to the measured velocity profiles using a commercially available software program. The area under each curve is integrated and, if necessary, adjusted by a percent to match continuity.

Energy Dissipation

A ratio of flow kinetic energy at each velocity measurement station over the total head versus the number of steps down the slope is shown in figure 3. The kinetic energy per unit volume, or $\frac{1}{2}\alpha\rho V^2$, is calculated by integrating the area under the velocity profile, to determine α, the coefficient of kinetic energy. The total head, $\omega(H+H_s)$, is calculated by adding the overtopping head, H, to the vertical drop from the crest to the step location where the velocity measurement is taken, H_s, and multiplying by the specific weight of water, ω.

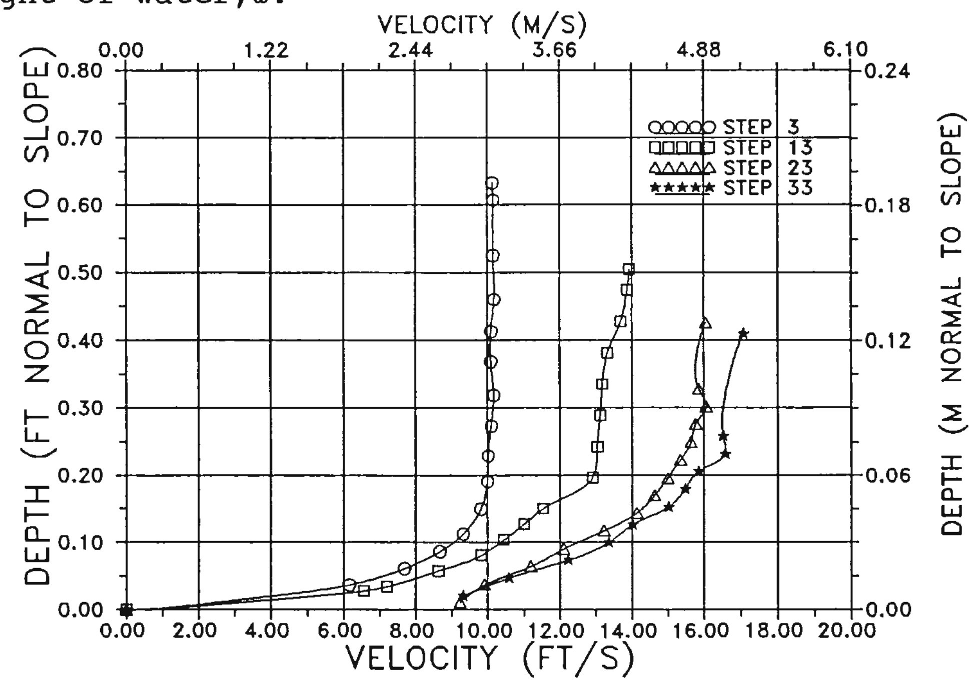

Figure 2.- Velocity profiles down 2:1 slope for horizontal steps under an overtopping head of 1.67 ft (0.51 m).

As would be expected, the energy ratio shows more dissipation with smaller flow depths once the flow is fully developed. This energy ratio does show some inconsistences at the measurement station at steps 3 and 13. Presently, this is attributed to the effects on the pressure and flow profile produced by curvilinear flow over the crest brink.

This nondimensional ratio allows the designer to determine the velocity at points along the slope or the toe of the slope for a given dam height with 2:1 downstream slope and horizontal steps. Determining the velocity at the toe of the dam will allow the designer to better assess the erosion potential of the foundation material and to determine required protection and/or length of the stilling basin.

Analysis is still ongoing, particularly in relation to shear velocity, roughness height to flow depth comparisons, and computations for form and frictional resistance.

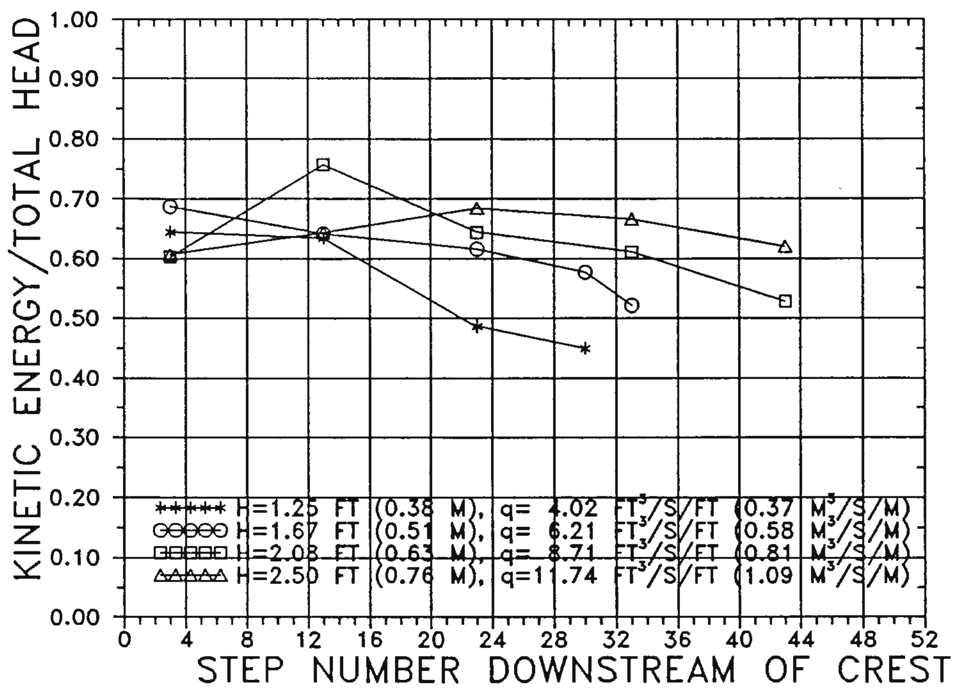

Figure 3.- Ratio of kinetic energy to total available head versus number of steps down the 2:1 slope for horizontal steps.

Near-prototype scale tests

The near-prototype scale tests are scheduled to begin in the fall of 1991. The test facility will model the entire height of many small dams, but will be only about 5-ft (1.52-m) wide. Tests will begin with determining the effects of aeration and dynamic pressures on the stability and energy dissipation characteristics of the concrete step geometry chosen from the laboratory tests. The facility is planned to be in use until 1994 for testing of many different types of embankment protective systems.

Appendix

Pravdivets, Y. P., and M. E. Bramley, "Stepped Protection Blocks For Dam Spillways," Water Power and Dam Construction, July 1989, pp. 49-55.