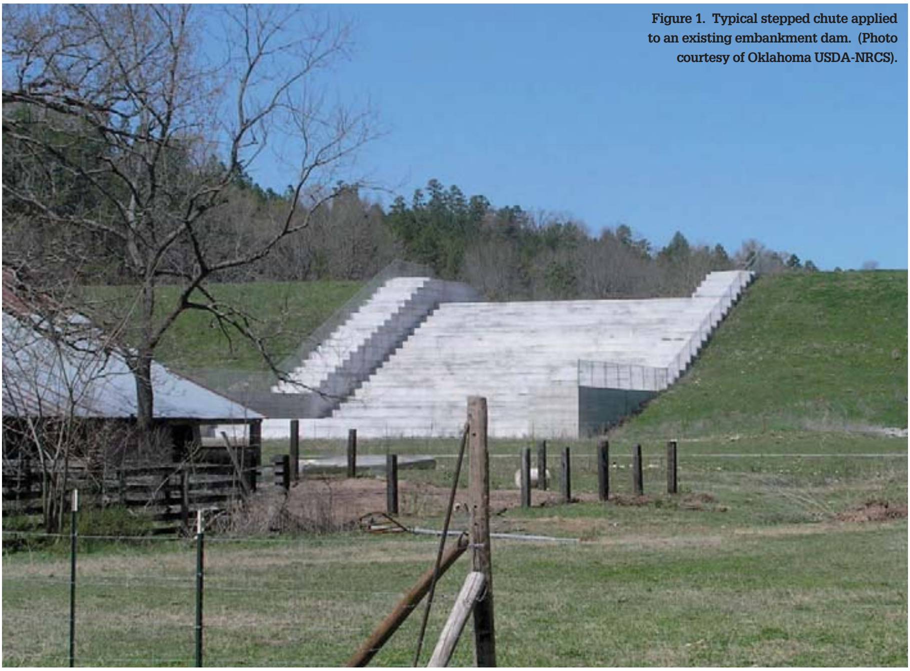

Figure 1. Typical stepped chute applied to an existing embankment dam. (Photo courtesy of Oklahoma USDA-NRCS).

Stepping up research efforts

A research programme is providing practical, straight-forward design solutions for broad-crested stepped chutes applied to slopes ranging from 10 to 30°. Sherry L Hunt and Kem C Kadavy from the United States Department of Agriculture's Agricultural Research Service give more details.

The United States Department of Agriculture (USDA) – Agricultural Research Service (ARS) is the principal in-house research agency within the USDA and provides research for finding solutions to agricultural problems. The Hydraulic Engineering Research Unit (HERU) within the USDA-ARS provides research in support of the USDA Small Watershed Programme. This programme, administered by the USDA-Natural Resources Conservation Service (NRCS), has provided financial and technical assistance for the construction of more than 11,000 flood control dams.

Historically, the HERU research programme has developed design criteria for hydraulic features including stepped baffled trash racks, plunge basins, riprap protection downstream of Saint Anthony Falls (SAF) stilling basins, and vegetated spillways in support of the construction of these flood control dams. Currently, the HERU research programme has two components:

1) Developing design guidelines for the use of hydraulic structures for flood control and embankment overtopping protection.
2) Developing computational software for predicting embankment breach by overtopping and/or internal erosion.

Many of the embankment dams constructed by NRCS were originally designed as low hazard dams for the flood protection of agricultural land. Through the years hazard creep, a change in hazard classification from low to significant or high, has occurred due to changing demographics in the vicinity of the dams. A higher hazard classification leads to more stringent dam safety standards for these dams; and thus spillway capacity is often identified as a deficiency. Options available for increasing spillway capacity for rehabilitation of these dams are somewhat limited due to the residential development, utilities and roadways near the dams. Stepped chutes are commonly chosen for use in rehabilitation because they:

- Provide increased spillway capacity.
- Offer ease of construction.
- May be applied to existing dams.
- Provide increased energy dissipation within the chute.

Figure 1 illustrates a typical stepped chute applied to an embankment dam.

The goal of the HERU research programme as it relates to stepped spillways is to develop generalised design guidelines for broad-crested stepped chutes more indicative of those applied to embankment dams, with slopes ranging between 10 and 30°. These guidelines include developing relationships for predicting:

- Surface inception point (L_i) (i.e. the visually observed location where the turbulent boundary layer has reached the free surface).
- Flow depth (y).
- Clear-water flow depth (y_{cw}).
- Average air concentration (C_{avg}).
- Energy coefficient (α).
- Converging stepped chute training wall height.

Engineers will be able to use these relationships for designing training walls and stilling basins for stepped spillways within the bounds indicated for embankment dams. Figure 2 illustrates the large-scale near prototype stepped chute testing facility used to minimise scale effects. Through the facility's windows, the flow could be monitored as it descended the chute steps as shown in Figure 2b. Testing was conducted over a range of unit discharges (q), step heights (h), and slopes (θ), so the impact of these parameters could be determined.

L/L_i is the ratio of length from the downstream edge of the broad-crested weir to the point of interest (L) to the length from the downstream edge of the broad-crested weir to the surface inception point (L_i). This term is vital for design purposes as it is key in determination of other design parameters including y, y_{cw}, C_{avg}, and α. Because of the broad database provided by this research programme, relationships for L_i in terms of step roughness (k_s) and Froude surface roughness (F_*) have been optimised.

Additionally, data indicates that chute slope (θ), normalised step height (h/d_c), and the normalised length from the crest (L/L_i) are key parameters for determining flow depth. The flow depth (y) decreases rapidly from the crest section to the surface inception point (L_i). Downstream of L_i, the clear-water flow depth (y_{cw}) becomes relatively constant for a given θ and h. A relationship for the normalised clear-water flow depth (y_{cw}/d_c) when $L/L_i > 1.0$ as a function of chute slope (θ) and the ratio of step height to critical depth (h/d_c) was developed. For $0.1 < L/L_i \leq 1.0$, the normalised flow depth (y/d_c) proved to be a function of θ, h/d_c, and (L/L_i). Training wall height for $0.1 < L/L_i \leq 1.0$ may be determined directly from the y and the angle of wall convergence. Training wall height for $L/L_i > 1.0$ is dependent on the bulked flow depth (y_{90}) (i.e. increased flow depth due to entrained air). y_{90} is a function of y_{cw}, and C_{avg}. If training walls converge, the angle of convergence must

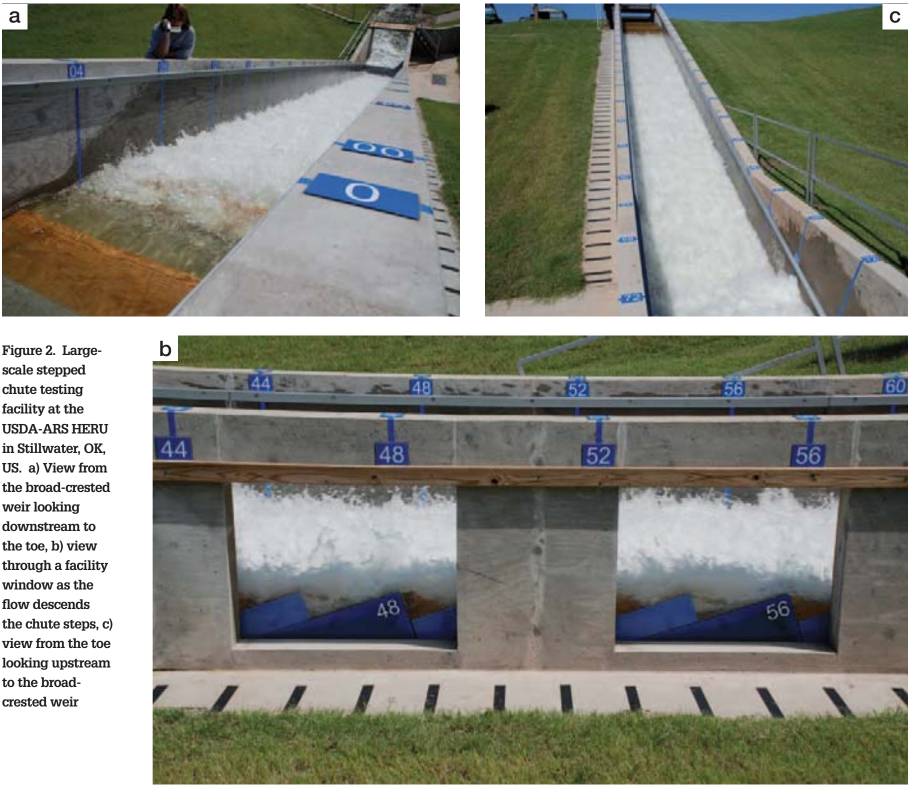

Figure 2. Large-scale stepped chute testing facility at the USDA-ARS HERU in Stillwater, OK, US. a) View from the broad-crested weir looking downstream to the toe, b) view through a facility window as the flow descends the chute steps, c) view from the toe looking upstream to the broad-crested weir

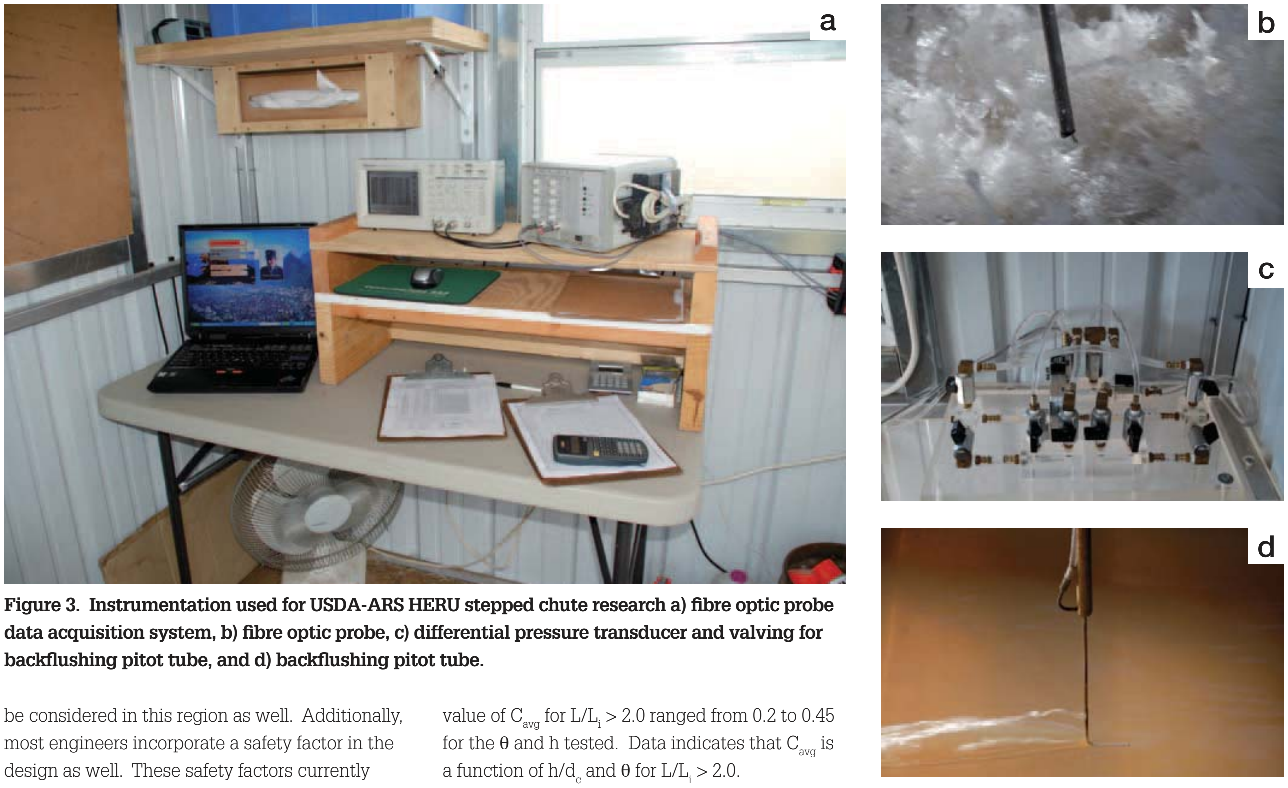

Figure 3. Instrumentation used for USDA-ARS HERU stepped chute research a) fibre optic probe data acquisition system, b) fibre optic probe, c) differential pressure transducer and valving for backflushing pitot tube, and d) backflushing pitot tube.

be considered in this region as well. Additionally, most engineers incorporate a safety factor in the design as well. These safety factors currently range from 1.5 to 2 depending whether non-aerated or aerated flow has developed. This research indicates further investigation may be warranted as the splash height may be significantly higher than what would be retained by the training walls if a factor of safety of 1.5 to 2.0 is considered.

Air concentration (C) profiles collected during testing were used to calculate C_{avg}. Velocities and flow depths were recorded using two methods: 1) a fibre optic probe coupled with a data acquisition system as shown in Figures 3a and 3b and 2) a backflushing pitot tube coupled with a differential pressure transducer as illustrated in Figures 3c and 3d. The fibre optic probe also allowed for the measurement of air concentration profiles throughout the testing. Upstream of L_i, the flow appears smooth and glassy before developing a minor undulating flow pattern near $L = 0.6$ to $0.7\ L_i$. This undulating flow pattern is attributed to turbulence observed at the water surface as well as entrapped air in the flow near $L/L_i = 1.0$. Very little entrained air in the flow profile was observed at the $L/L_i = 1.0$ with C_{avg} ranging from 0.1 to 0.2 depending on the θ and h. Between $1.0 \le L/L_i \le 2.0$, the flow behavior becomes more erratic, and entrained air develops in the flow profile resulting in a rapid increase in C_{avg}. In the region of $1.0 \le L/L_i \le 2.0$, C_{avg} is a function of h/d_c, θ, and L/L_i. When $L/L_i > 2.0$, the flow becomes fully developed air entrained flow, and C_{avg} trends to a constant value for a given θ and h. The air observed in the flow downstream of $L/L_i = 1.0$ is attributed to entrained air in the flow profile, entrapped air in the upper flow profile, and surface fluctuations due to turbulence. The value of C_{avg} for $L/L_i > 2.0$ ranged from 0.2 to 0.45 for the θ and h tested. Data indicates that C_{avg} is a function of h/d_c and θ for $L/L_i > 2.0$.

Depending on the chute slope, energy loss in the study ranged from 20% near $L/L_i = 1.0$ to as much as 85% near $L/L_i = 6.0$. α can range between 1.0 and 1.20 for a given θ and h/d_c, and peaks at $L/L_i \approx 1.0$. Downstream of $L/L_i = 1.0$, α decreases rapidly and then trends towards a constant value for a given h/d_c. From the data, the energy coefficient proved to be a function of h/d_c, θ, and L/L_i. α coupled with the value of y or y_{cw} can be used to determine the energy loss and Froude number at the toe of the chute and entrance to the stilling basin.

Preliminary results show that the Froude number ranges between 3.3 and 5.4 for typical design conditions indicating applicability of a Type III or Type IV stilling basin design developed by the United States Bureau of Reclamation (USBR). A Type IV stilling basin can be significantly longer than a Type III stilling basin because a weaker and more erratic hydraulic jump is produced when the Froude number falls within a range of 2.5 to 4.5.

Further investigation is recommended to examine the range of applicability of a Type III stilling basin for stepped chute applications given the comparatively higher cost of a Type IV stilling basin. If research proves a Type III stilling basin does not provide adequate performance for smaller Froude numbers, then a new economically feasible stilling basin design alternative may be developed.

In conclusion, a goal of the HERU research programme is to provide practical, straight-forward design solutions for broad-crested stepped chutes applied to slopes ranging from 10 to 30°. Much of the research is complete with relationships offered for the inception point, flow depth, clear-water flow depth, average air concentration, and energy coefficient. Examination of the splash height and safety factor for training wall height is recommended in future research. Additionally, further investigation is warranted to determine whether traditional stilling basin design procedures developed by the USBR are applicable to flow conditions at the exit of stepped chutes. Another area of interest for stepped chutes is those that converge and the impact this convergence has on training wall design. Relationships for training wall height for converging stepped chutes have been developed by scientists at the HERU, but it has only been validated for a small sub-set of data. Additional research is necessary to determine the range of applicable convergences. This research is expected to provide helpful tools in the design of stepped chutes applied to slopes ranging from 10 to 30°. ■

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