Stepped Overlays Proven for Use in Protecting Overtopped Embankment Dams

by
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Introduction

The U.S. Bureau of Reclamation (Reclamation), in conjunction with EPRI (Electric Power Research Institute), and CSU (Colorado State University), has completed a four year research study on concrete step overlay protection for embankment dams. The program included laboratory flume studies of various step shapes covering 2:1 to 4:1 slopes and verification of the designs in a large scale facility with an individual block shape, representing the stepped overlay. These combined test programs showed that a properly designed stepped overlay is inherently stable due to the combined effect of the impact of the flow on the step surfaces and the ability of the stepped overlay to relieve the uplift pressure.

A brief summary of the large-scale facility used for testing the tapered block shape on a 2:1 slope will be presented. Test results from the large-scale facility show that the block system developed from the laboratory data (Frizell, 1992) is stable, allowing the results to be applied to an actual embankment dam with confidence. Although laboratory testing has been completed on 4:1 slopes, some analysis still remains before reporting results and extending results to other typical embankment slopes. Basic design guidelines, developed from the laboratory and large-scale testing, will be presented. The design guidelines will be demonstrated in the design of an overlapping, tapered block system for a small embankment dam.

Large-scale test facility and block description

The outdoor overtopping facility, located at CSU in Fort Collins, Colorado, was sized to be similar in height to a typical embankment dam in need of rehabilitation. The facility, fig. 1, consists of a concrete headbox, chute, tailbox, and sump with a pump. The concrete chute is on a 2:1 (H:V) slope and has a height of 50 ft. The maximum width of 10 ft was reduced to a width of 5 ft to increase the unit discharge capacity to 32 $ft^3/s/ft$ for the tapered block testing. Water is supplied through a 3-ft pipe from Horsetooth Reservoir. A portion of the flow can be recirculated by pumping back from the tailbox to increase the total discharge through the facility.

Based on prior laboratory studies, the overlapping, tapered, concrete blocks, shown in figure 2, were designed and constructed for the large-scale tests. The blocks are 1.23-ft-long and 0.21-ft-high with a maximum thickness of 0.375 ft. Drains, which aspirate water from the filter layer, are formed in the overlapped portion of the block. The blocks were placed over 0.5 ft of free-draining, angular, gravel filter material. The filter material and thickness were designed according to Reclamation design guidelines. The gravel filter was placed on the concrete floor with 4-in angle iron (with a gap above the floor to allow free discharge underneath) placed every 6-ft up the slope to prevent sliding of the gravel. A wooden strip was installed along each wall to easily screen the gravel filter and to prevent failure along the wall contact during operation. A combination of 2-ft and 1-ft-wide blocks were placed on the "embankment" shingle-fashion from the slope toe leaving no continuous seams in the flow direction.

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At the crest of the structure, a small concrete cap was placed to transition from the flat approach to the first row of blocks. At the toe of the concrete slope is a fixed concrete end block to support the blocks up the slope. About every twenty fifth row of blocks was anchored to the floor to prevent gradual migration of filter material which could result in bowing or settling of the block overlay. Where the blocks will be under the tailwater at the toe of the slope, the blocks are pinned together longitudinally through the overlapping area parallel to the slope.

Flow description - During initial startup of the flume, under a very low discharge, the fines and dirt were flushed from the filter material. Flushing lasted a very short time and was observed by the coloring of the water. After shutting off the water, slight settling of the blocks was apparent; however, there was no sliding or noticeable trend to the settling. Throughout the testing no further noticeable settling of the blocks occurred. The maximum settlement was about 1 in. The blocks were exposed to two winters of freezing conditions with no measurable movement or damage.

The many discharges tested in the flume produced varied flow conditions over the blocks. Very small flows were almost entirely broken up by the block shape leaving no noticeable thickness of solid water and a tumbling, highly-aerated, flow condition. As the discharge increased, skimming flow occurs. For the largest flow rate, the flow does not become fully aerated until traveling about half the distance down the slope. Uniform flow was attained for all flow rates tested.

Design criteria

Tests of the block system were completed in the large-scale, outdoor facility in the fall of 1993. The block system remained stable and performed excellently, even after some blocks were intentionally cracked and partially removed.

Model/prototype comparisons, between the laboratory and the outdoor facility, are complete. These results were used to develop general design guidelines that provide the necessary information to design a stepped overlay for embankment dams with downstream slopes of approximately 2:1 slope.

The design guidelines include:

- The discharge coefficient for a typical embankment dam crest shape to be used for flood routings.

- The block shape and vent port area required for use in determining block dimensions for various embankment slopes of about 2:1.

- The total force per foot of width of stepped overlay or the expected stability based upon the hydraulic forces. This will allow the designer to vary the block weight to provide a stable overlay for a given dam height, unit discharge, and predicted seepage.

- The velocity at the dam toe for any step height and total dam height to be used in designing toe protection or energy dissipators.

- The friction factor due to step roughness down the slope to be used with the bulked flow depth for designing wall heights.

Data for all step shapes (15°, 10°, and horizontal) and embankment slopes (2:1 and 4:1) tested, are currently being reanalyzed to include the results from the large-scale facility. These results will allow development of entirely generalized design criteria for embankment slopes from 2:1 to 4:1 and extrapolation up to larger unit discharges.

Discharge coefficient- The discharge coefficient for an overtopping embankment dam is a function of the upstream slope of the dam, the top width, and the abutment geometry (for short crest lengths), and varies with the overtopping head. An average coefficient of about 2.9 may be used for most flood routing applications to determine the depth of overtopping that will pass the desired Probable Maximum Flood (PMF).

Block shape - The most stable block shape on a 2:1 slope is the 15° tapered or sloping block (Frizell, 1992). Included in this recommendation is that the percent of the vertical block face area occupied by the vents be 2.8% (Baker, 1991). This block shape was tested in the large-scale facility for unit discharges up to 32 $ft^3/s/ft$. (Greater top slopes may produce instabilities by providing too large a low pressure zone or too small of a solid vertical block surface.) Any block design is based upon keeping the difference between the top slope and the embankment slope constant for a given embankment dam slope. Therefore, when designing a block with a top slope that provides effective aspiration, the difference between slopes is 11.56° (embankment slope = 26.56° (2:1) minus top slope = 15°). Obviously, this criteria is only applicable to embankment slopes greater than this difference.

In addition, the ratio of the step height to the step tread length exposed to the flow should remain between four and six. If the step height is chosen to match that of our testing, 2.5 in, then the tread length should optimally be chosen to match as well. This would produce slightly different horizontal tread lengths for dams of different slopes based upon the chosen top slope of the block. This horizontal tread length is then used to determine the length of the block surface along the embankment slope.

The block thickness is determined from the stability analysis. A minimal thickness of 2 in. at the upstream end of the block is required to maintain the integrity of the concrete and allow proper forming of the block.

Stability - The question of stability of the protective system is the most critical for an embankment dam. Any failure or instability in the system could cause a catastrophic failure of the entire dam during an overtopping event. Laboratory data shows that the ability of the blocks to relieve the uplift pressure, combined with the impact of the water on the block surface, make the blocks inherently stable. The 15° sloping block was used for the large-scale tests (fig. 2). The 1-ft-wide block used in the large-scale flume had a dry weight of 38.4 lbs.

Pressure data were gathered to compute the magnitude of the forces acting on the block surfaces and in the underlying filter. For discharges producing skimming flow, impact pressures increase to a maximum about 44 steps down the slope, then decrease due to aeration effects. The filter pressures were assumed to vary linearly between the measurement locations. The filter pressures show a gradual increase over about the top 40 steps, indicating a buildup of flow in the filter near the top of the slope. At about 45 steps down the slope, the filter pressures quickly decrease as aspiration increases to an average of about 0.1 ft at the toe of the slope for all flow rates.

The stability of the block system has been analyzed as a function of the total forces acting on individual blocks down the slope. Block weight and pressure yield a net downward or positive force normal to the slope. The uplift pressure in the filter material underneath the block and the low pressure zone created by the block offset act in an upward (negative) direction tending to lift the blocks from the embankment surface (fig. 3). Aspiration ports in the vertical face of the block limit the uplift forces by venting the filter layer to the low pressure separation zone. The gradation of the filter must be designed to prevent the filter material from being transported through the aspiration ports. In the analysis, a net positive force indicates a stable block.

The block geometry optimizes the hydraulic forces to produce downward impact pressure and aspiration of subgrade pressures. The stability of the block system is quantified in the graph showing the net force/foot of block width versus the vertical distance below the crest (fig. 4). This graph shows that the sum of the forces normal to the slope including integration of the pressure profile on the step tread and the measured filter layer pressure (uplift). The sum of the forces are positive for this block shape and filter indicating a stable overlay for a 2:1 slope for the range of critical depth (D_c) to step height (H_s) ratios tested. The submerged block weight of about 13 lbs. has been added to the forces in the curve formed by the dashed line for $D_c/H_s = 10.36$ to show the additional stability added by a block of minimal thickness. Not included in the analysis is the additional stability provided by the block overlap which creates an interlocking affect. These results indicate no decrease in block system stability with unit discharge.

The Construction Industry Research and Information Association (CIRIA) has developed a criteria for determining the optimum percent of port area to vertical surface area of the step face. Ports for providing aspiration of filter pressures should be 2.8% of the surface area of the step. Proper sizing of the port area will limit the uplift pressure developed in the filter layer. The length of blocks used across the width of the dam will also influence the amount of flow entering the filter. Using longer blocks across the dam width will reduce the jointing, thus the infiltration of flow to the filter layer. If excessive seepage is expected, then the block weight could easily be increased accordingly.

Energy dissipation or toe velocity - Of secondary benefit is the amount of energy dissipated by flow over the steps formed by the block surface. In general, a stepped surface reduces the energy of the flow at the dam toe compared to a smooth surface. Figure 5 allows the designer to vary the step height (within reason), for a dam of a given height and known unit discharge, to directly determine the desired velocity at the toe of the dam as a function of the energy remaining. The graph has been developed for unit discharges ranging from 3.3 to 32 $ft^3/s/ft$ using both laboratory and large-scale results. The laboratory data were adjusted for the effects of aeration by using the average air concentrations measured in the large-scale facility. The air content reduces the friction and; therefore, increases the velocity over that predicted by the laboratory data alone.

From the graph, the larger the step height, for a given dam height, the less the energy remaining in the flow at the toe of the dam. Conversely, as the ratio of the step height to dam height decreases the energy in the flow increases. The energy remaining in the flow is also a function of the critical flow depth to step height ratio. This graph includes a range of critical depths to step height ratios of 3.36 to 15.21. A designer should attempt to remain within this range if possible. At some point for all flow rates, uniform flow is attained and the energy per foot of width remains constant. This is shown by the indication of the leveling off of the curves as the step height to dam height ratio decreases. When uniform flow is reached then the velocity and depth will remain constant regardless of the dam height. (We are currently working to provide extrapolation of these curves to higher flow rates and to dams of other slopes.)

If the tailwater elevation and velocities indicate that a hydraulic jump will occur over the blocks, then the blocks should be pinned to restrict rotation caused by the dynamic pressure fluctuations of the jump (fig. 8). Loosely pinned blocks were successfully tested under a hydraulic jump at the CSU facility.

Roughness and bulked depth - Darcy-Weisbach friction factors are computed based upon velocity profiles, corrected for air concentration. The friction factor, f, varied down the slope, as the flow developed, eventually becoming constant at 0.11 (Manning's $n=0.03$) for uniform flow. Using this value in a standard step method calculation will determine the flow depths down the chute. An average air concentration of 34% is reached for the fully developed flow condition; therefore, the wall heights should be raised by 34% above the calculated flow depths to contain the flow. An additional safety factor may be added if deemed necessary.

Design example

This design example will demonstrate the use of the design information by presenting a feasibility level design of a block system on a small embankment dam. The design example will include the crest treatment, block dimensions and stability on the slope, and required toe treatment based upon energy remaining at the toe of the dam.

A small embankment dam owned by the Department of Interior is scheduled for rehabilitation due to its inability to pass the PMF. The embankment dam is about 27-ft-high with a 2.5:1 downstream slope. An outlet works tunnel is located through the dam on the right side and an emergency, grass-lined spillway on the left abutment. The lake formed by the dam is a highly used recreational site with hiking trails crossing the dam and following the left abutment. The top of the existing dam is at El. 2498. The 40-ft-wide grass-lined spillway with crest elevation 2495.6, is currently designed to pass less than 500 ft^3/s before the dam is overtopped. Overtopping is predicted to breach the dam, resulting in a discharge of 23,000 ft^3/s for 20 minutes, which is unacceptable. To prevent overtopping of the dam another spillway constructed with the tapered, overlapping blocks has been designed. The design must still allow pedestrian passage across the top of the dam and have minimal impact to the existing aesthetics. As a result, the block system will be covered with topsoil.

The reservoir water surface elevation is restricted to 2502 ft by reservoir rim development. The top of the dam will be raised by 5 ft with a rock and masonry wall tied to the existing impervious core wall to prevent overtopping of the existing dam during the PMF. Pedestrian access will be upstream of the dam raise, over the top of the covered blocks. After using several spillway crest elevations and widths to route the PMF with maximum water surface of El. 2502, the configuration shown on figure 6 was determined. (The design includes use of the existing grass-lined spillway. This may not be the case in the final design.)

☐ Flood routing, and crest detail - The block spillway will have a maximum spillway discharge of 4,183 ft^3/s (32.2 $ft^3/s/ft$). Using a crest coefficient of 2.9 in the flood routing, determined that a 130-ft-long block spillway crest at El. 2497, one foot below the top of the existing dam, is needed. The grass-lined spillway will pass a maximum of 2,230 ft^3/s and will begin discharging when the reservoir is 1.5 ft below the block spillway crest. The top of the dam upstream of the block spillway crest will also be covered with blocks to prevent undermining the slope protection by flows over the top of the dam. To prevent seepage through the dam, a cutoff trench will be placed along the axis of the dam that extends from the top of the existing core wall to the surface where the spillway blocks will be placed.

☐ Block design - The tapered blocks will be designed for effective aspiration or stability on the 2.5:1 (21.8°) downstream slope of the dam.

Top slope of block: $21.8^\circ - 11.56^\circ = 10.24^\circ$

This top slope on the block produces the following geometry for the remainder of the block surfaces on the 2.5:1 slope.
Tread length exposed to the flow: 11.71 in. (same as 15° step on 2:1 slope)
Horizontal length: 12.52 in.
Block length along the embankment slope: $11.52/\cos(21.8^\circ) = 12.41$ in.

Choose the step height to be between the ratio of tread length to step height of 4 to 6.
Step height, H_s: 2.5 in.

☐ Stability - The block thickness is then determined by finding the block weight required for stability based upon the predicted uplift or seepage pressure. Inspection of the dam indicates that excessive seepage will not be a concern. As a result, a free-draining gravel filter underneath the block system will be adequate and stability may be predicted from figure 4. A dam height, H_{dam}, of 27 ft and $D_c/H_s = 15.21$ gives a total positive force of about 60 lb/ft acting to hold the block on the surface. Therefore, a minimal block thickness at the upstream end of the block of 2 in. and appropriate aspiration port area will produce a stable block (fig. 7).

Figure 8 shows the toe block required for stability at the toe of the slope. The toe block is used as a base for the first row of overlapping blocks and continues completely across the spillway width at the toe of the dam. Blocks located beneath the tailwater should be cast with two holes per block to receive loose-fitting pins. This detail (fig. 8) will produce stability of the rows of block exposed to the fluctuating pressures of the jump.

☐ Toe velocity - The velocity at the toe of the dam may now be determined for the 2.5-in.-high block step height.

$H_s/H_{dam} = 2.5/12/27 = 0.0077$
$D_c = (32.2^2/32.2)^{1/3} = 3.18$ ft
$D_c/H_s = 3.18/0.2083 = 15.26$

Using figure 5, $q^*V^2/2g = 580$. Solving for the velocity gives 34 ft/s at the toe of the dam (assuming a 2:1 slope). Laboratory data has shown slightly less velocity for flatter downstream slopes; therefore, the toe velocity will be increased by 5% to 35.7 ft/s.

☐ Energy dissipator - Using a velocity of 35.7 ft/s and Reclamation's Monograph 25, the stilling basin length is determined. Using the continuity equation, the depth of flow at the toe of the dam is determined.

Depth at toe, d: $32.2/35.7 = 0.9$ ft
Froude number, $V/(gd)^{1/2}$: 6.63

Using these values in Reclamation's Monograph 25, figure 8, produces a required stilling basin length of 50 ft (Peterka, 1978). This is shown on figure 6, and will most likely be formed with grouted riprap.

☐ Spillway wall height - The wall height at the crest must be equal to the overtopping depth, or in this case, simply the reservoir elevation, giving a wall height of 5 ft. The flow depth down the chute is determined by using the friction factor and velocities down the slope in a standard step calculation. This calculation produces a required wall height that varies down the slope to a minimum of 1 ft at the toe. (As expected, this value compares well with the depth computed using continuity.) Adding the bulking due to 34% air concentration gives the necessary freeboard to contain the highly aerated flow over the spillway blocks and a wall height of 1.34 ft at the dam toe, measured from the tip of the steps. This wall could easily be obtained by anchoring highway jersey barriers in the embankment and butting the blocks up to them.

Cost

The dam owners have labor available to work on the rehabilitation of the dam. This makes the block design an attractive alternative. A general cost estimate obtained for manufacturing and installation of the block system on a typical embankment dam including crest and toe treatments, preparation of the embankment slope and filter placement with precast spillway walls, varied between \$110 to \$195/yd^2. The predicted cost for initial production of the forms for the blocks varied greatly and was probably greatly overestimated. Reclamation and CSU have both formed blocks with great success and minimal cost. For construction of the block overlay only (not the dam raise, etc), and assuming a coverage of 1050 yd^2, would produce a total cost of \$115,500 to \$204,750.

Conclusion

The tapered block system has been tested well beyond the limits of other concrete revetment systems. The design criteria presented defines their application for a wide range of overtopping. The block system is particularly applicable for dams in remote or environmentally sensitive locations where use of a batch plant or large machinery is limited. The cost of the system is not well known at this time, but will be competitive once the forms have been constructed and the ease of placement discovered.

References

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2. Baker, R., "Performance of Wedge-shaped Blocks in High Velocity Flow," CIRIA Research Project 407, Stage 2, University of Salford, England, August 1991.

3. Peterka, A.J., 1978, "Hydraulic Design of Stilling Basins and Energy Dissipators," Engineering Monograph No. 25, U.S. Bureau of Reclamation, Denver, Colorado, 1978.

Figure 1. - Large-scale, 50-ft-high, dam overtopping test facility, $q = 32\ ft^3/s/ft$.

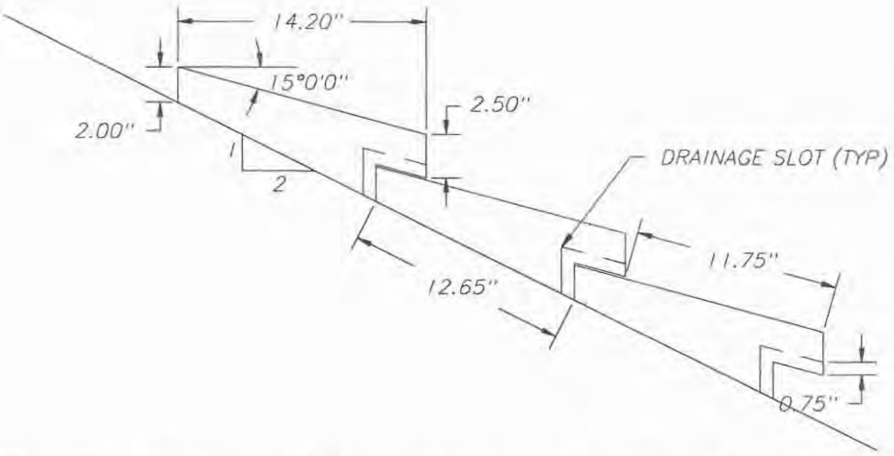

Figure 2. - Dimensions of the tapered blocks used in the large-scale facility.

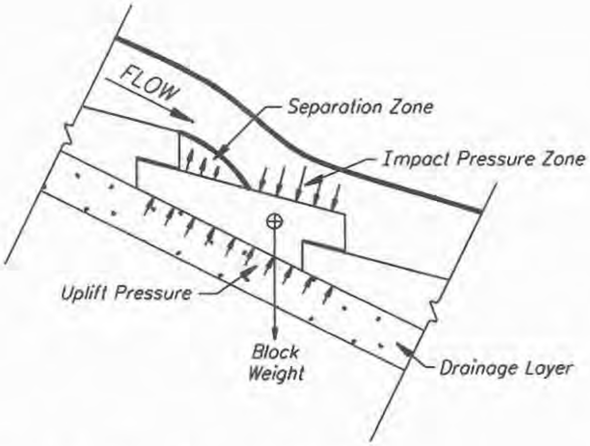

Figure 3. Forces acting on the tapered concrete block.

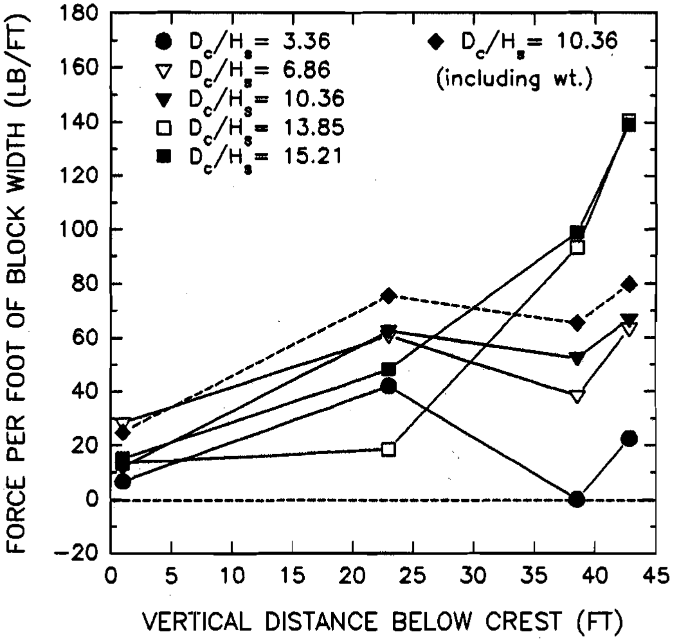

Figure 4. - Net force acting on the block versus distance below the crest.

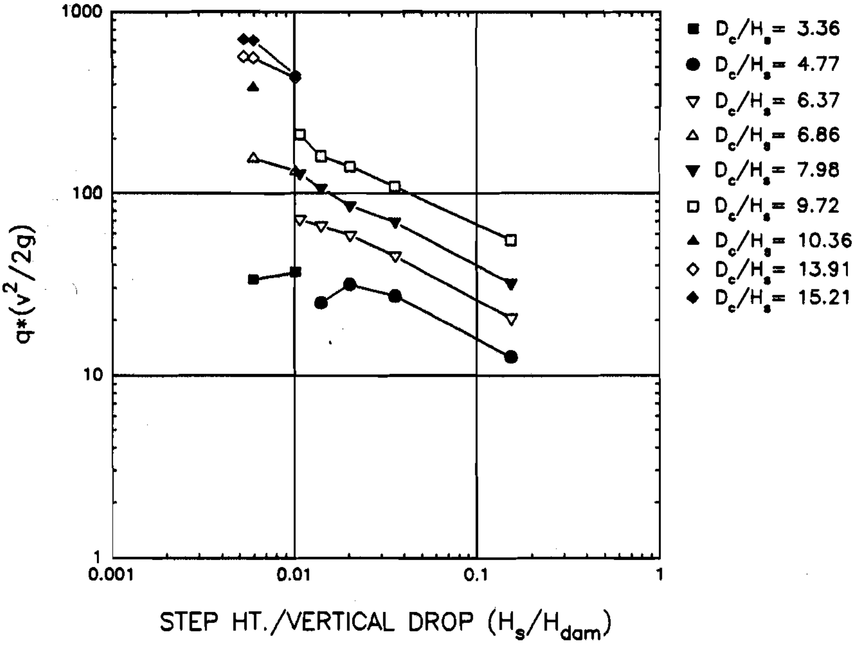

Figure 5. - Graph used to determine the velocity remaining in the flow after traveling down a stepped spillway with 15° tapered overlapping blocks on a 2:1 slope.

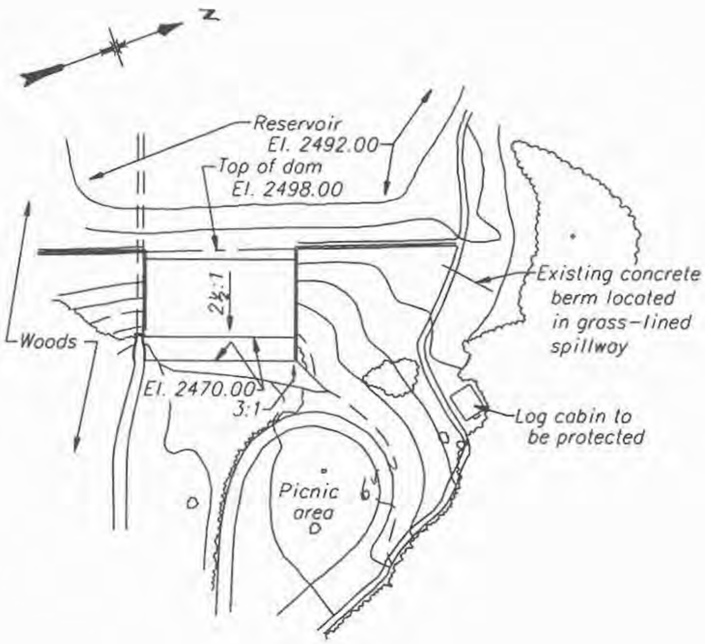

Figure 6. - General plan of the block spillway layout on the 27-ft-high embankment dam with 2.5:1 downstream slope.

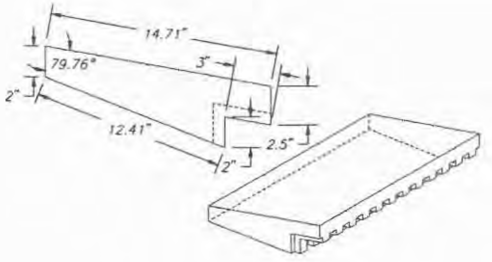

Figure 7. - Dimensions of the blocks designed for overtopping protection on a 2.5:1 slope.

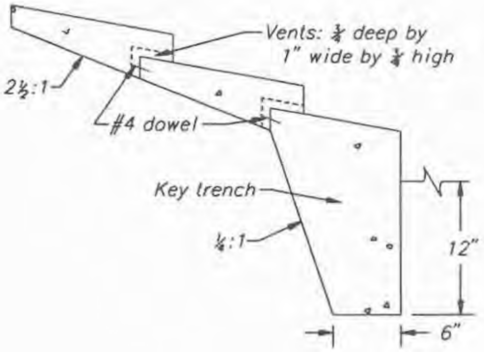

Figure 8. - Toe block and example of block pattern on 2.5:1 slope.