United States Department of Agriculture
Natural Resources Conservation Service

Part 628 Dams
National Engineering Handbook

Chapter 50 Earth Spillway Design

Issued February 2014

Acknowledgments

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Chapter 50 Earth Spillway Design

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628.5000 Scope

Chapter 50 describes the design considerations and processes involved in earth spillway design. It does not contain the detailed hydrologic or hydraulic procedures used to synthesize the anticipated storm flow conditions. It also does not contain details required for geologic investigation or laboratory testing and analysis.

628.5001 Basic concepts of earth spillway design

Spillway stability is determined by comparing the spillway's allowable erosion resistance to the applied hydraulic stresses for a given design storm. If the applied stresses do not exceed the allowable values, the spillway is considered stable. Spillway integrity is the measure of a spillway's resistance to breaching failure. It is the most fundamental consideration in an earth (soil, rock, or both) spillway design. Although large discharges may cause significant erosion, the spillway must not breach during passage of the freeboard hydrograph.

(a) Hydraulic and structural concerns

Open-channel earth spillways must perform satisfactorily both hydraulically and structurally. From a hydraulic standpoint, the spillway must convey the required range of flows with a predictable stage versus discharge relationship. From a structural standpoint, the design of an earth spillway considers both the stability and integrity of the spillway. The structural analysis is based on the concepts that some erosion or scour is permissible if its occurrence is infrequent, maintenance is provided, and if the spillway will not breach during passage of the freeboard hydrograph.

(b) Stability analysis

The stability analysis is an evaluation of the erosion potential for a given design storm for the constructed spillway exit channel. The designer selects the spillway dimensions and layout required to maintain hydraulic stresses below the erosion threshold for the design hydrograph. The erosion threshold is the stress level associated with the initiation of erosion of the spillway surface. For flows larger than the design hydrograph, spillway erosion may occur. The eroded spillway will probably require maintenance.

(c) Integrity analysis

The integrity analysis is an evaluation of the breach potential of the spillway in passing the freeboard hydrograph. A spillway is considered breached if the spillway crest is degraded by erosion and floodwater is released through the spillway below the crest elevation. Breach potential is a function of the spillway system, the characteristics of the spillway outflow hydrograph, the erodibility of the earth materials, spillway layout and bottom width, and maintenance. Designers should conduct the integrity analysis all the way to the valley floor. The integrity analysis indicates whether the spillway design must be modified to ensure that the spillway will not breach. Once integrity is assured, anticipated maintenance costs associated with the passage of the freeboard hydrograph may control the spillway design.

628.5002 Basic concepts of spillway performance

An earth spillway is an open channel that generally consists of an inlet channel and an exit channel. The inlet channel includes the spillway crest, or level section, and the constructed spillway upstream from the crest. The exit channel is the constructed spillway downstream from the crest. A spillway may be designed with or without a control section. If a control section is used, the flow is subcritical in the inlet channel and supercritical in the exit channel. A spillway that conveys only subcritical flow is acceptable. Proper spillway function is considered in terms of hydraulic and structural performance.

(a) Hydraulic performance

For optimum hydraulic performance, the spillway layout should convey uniformly distributed flow across the entire spillway cross section. To accomplish this, layouts should not have flow-concentrating features, such as short radius curves and nonlevel sections perpendicular to the direction of flow.

The layout must ensure a predictable reservoir stage versus discharge relationship. This predictability may be accomplished by using a control section such that inlet channel flow will be subcritical and the exit channel flow will be supercritical for most of the expected range in discharges.

Computer technology and computational methods allow determination of stage versus discharge relationships even when the control section shifts with discharge. Thus, a forced control section is not essential for predicting the rating of the spillway. Therefore, topography, stability, and integrity may govern the design of the spillway surface profile.

Topographic features, such as depressions, drainage patterns, and steep slopes, can significantly affect hydraulic performance by concentrating flow and inducing erosion. Although this erosion may initiate in areas outside the spillway, it can migrate into the spillway and adversely affect spillway performance. Align spillways to avoid topographic features that concentrate flow. Divert natural drainageways around the spillway and release in a manner that avoids potential erosion of the spillway, gutters, retaining dikes, or the dam.

(b) Structural performance

The structural performance of an earth spillway is a function of its vegetal and geotechnical resistance to hydraulic erosion. Good spillway design depends upon proper geologic investigation and assessment of the erosion resistance of the vegetation and earth materials at the site.

The erodibility of an earth material is contingent upon both material properties and in-place mass properties. For soils, material properties include plasticity, grain size distribution (particularly percent clay), bulk density, consistency, and strength. Mass properties include the occurrence of discontinuities in soils, such as soil joints, desiccation cracks, and root or animal holes. Discontinuities significantly weaken the integrity of an earth material and increase its erodibility.

Material properties of rock or rock-like material include rock type, constituent grain size, hardness, and unconfined compressive strength. Mass properties of rock or rock-like material include stratigraphic and structural discontinuities. Important stratigraphic breaks include abrupt lateral or vertical changes in rock type; such breaks may place very dissimilar materials adjacently with widely contrasting erodibility characteristics. Structural discontinuities, especially persistent, intersecting joint sets that are systematically spaced and oriented, increase the erodibility of the mass. The engineering significance of various attributes of discontinuities is described in detail in NEH 628.52.

The ability of vegetation to protect erodible geologic material at the spillway surface is dependent on the length, density, and uniformity of the vegetal cover. For vegetal protection to be effective, adequate rooting depth must be available. Cover uniformity is especially important since locally weak areas may substantially reduce the protective value. An adequate depth of suitable topsoil is necessary to provide an erosion resistant sod. In cases where only a few inches of topsoil is placed over dense erosion resistant materials, flow tends to cause large sections of this sod to be rafted out of the spillway. Generally, a 1-foot thickness of topsoil is adequate to prevent this action. Vegetal erosion protection is most effective for flow depths less than 3 feet and for exit channel slopes less than 6 percent.

Where spillway integrity is questionable, consider incorporating a barrier into the spillway channel as an additional defense against headcut breach. The barrier must consist of erosion resistant material in a configuration that will remain stable when subjected to the hydraulic attack associated with the anticipated headcut erosion. Where earth spillway layouts cannot ensure stability or integrity, or both, a structural spillway is required.

628.5003 Spillway investigation guidance

(a) Topographic surveys

A satisfactory hydraulic design and layout strongly depend upon accurate and complete topographic surveys of all practical sites for the spillway in the vicinity. The surveys must cover an area large enough to enable proper layout studies for geologic investigation, preparation of final grading plans, and estimates of quantities of soil and rock excavation. Topographic maps on a scale of 1 inch equals 20, 40, 50, or 100 feet and a contour interval of 1, 2, or 5 feet are satisfactory for most spillway layouts. For areas under consideration for a spillway, a 1- or 2 -foot contour interval is recommended where abutment slopes are less than 30 percent, and a 5-foot interval where slopes exceed 30 percent.

(b) Geologic investigation

Requirements for geologic investigation and sampling must be consistent with policy. The requirements vary according to the size and purpose of the dam, economic and safety considerations, and geologic complexity of the site.

Before initiating a field investigation, the geologist should study all pertinent technical materials, such as regional geologic maps, published and unpublished reports, topographic maps, site surveys, aerial photographs, soil survey reports, geotechnical maps, and reports of the site or similar sites. Local outcrops and roadcuts should be inspected to ascertain major structural features and dominant earth materials. These preliminary studies aid in determining the appropriate level of intensity for the detailed field investigation.

The field investigation consists of whatever borings, test pits, or test trenches are necessary to identify, classify, log, and correlate earth materials using standard Natural Resources Conservation Service (NRCS) (formerly the Soil Conservation Service, SCS) procedures. The geologist may use geophysical methods to supplement the investigation process. Assessment of the erodibility of soil materials may include the use of a submerged jet erosion tool (see NEH 628.52). The geologist:

- develops an engineering geologic map at an appropriate scale showing the location, extent, and distribution of earth materials at the site
- makes the mapping area large enough to encompass all probable layouts as well as any areas directly downstream of the constructed exit channel that flow may impact
- develops representative profiles and cross sections of all mappable earth materials
- differentiates mapping units by the headcut erodibility index

See NEH 628.52 and other pertinent documents for guidance on assessing earth material for hydraulic erodibility.

The maps may indicate zones of highly erodible materials that should be avoided in the design layout. Conversely, zones identified as highly erosion-resistant may be exploited in the design and layout of the spillway, particularly in the outlet channel, crest, and other sensitive areas.

Determine the elevation and seasonal range of the water table or location of water-bearing strata to facilitate the design of any required abutment slope drainage, relief drainage within the spillway, or additional slope stability protection.

Collect representative samples as needed for laboratory analysis in accordance with requirements in Geology Note 5, Sample Size Requirements, to support engineering decisions regarding the:

- the suitability of earth materials in the spillway excavation for use in construction of the dam
- the suitability of earth materials at and directly below the spillway grade line for establishing and maintaining good vegetative cover
- the suitability of available topsoil for establishing and maintaining good vegetative cover
- the erodibility of all earth materials in the profile of the spillway and along the flow path to the valley floor

- the stability of the side slopes of the spillway
- the optimum methods for correcting or stabilizing slides or for precluding potential slides in the vicinity of the spillway cut

628.5004 Spillway design guidance

(a) Layout and alignment

Earth spillways may be located either in the abutment at one or both ends of an earth embankment or through a topographic saddle at some point along the periphery of the reservoir. The layout and alignment of a spillway should take into consideration the engineering geologic map of the site that delineates zones of earth materials with similar erodibility characteristics. To the extent practicable, the layout should avoid zones of highly erodible earth materials, particularly in the following areas: the crest, exit channel sections with changes in slope, locations where hydraulic jumps may form, any point on the constructed exit channel, and on the natural slope downstream of an exit channel. Conversely, the layout should, to the extent possible, take advantage of zones of earth material that are erosion resistant with respect to the anticipated hydraulic energy. Reinforce, protect, or replace earth material having unacceptable erodibility characteristics. The reinforcement or protection may consist of many options, such as engineered earth or barriers.

(b) Inlet

If a control section is used, the inlet channel is to be level for a minimum distance of 30 feet upstream from the control section. This level part of the inlet channel is to be the same width as the exit channel, and its centerline is to be straight and coincident with the centerline of the exit channel. A curved centerline is permissible in the inlet channel upstream from the level section, but it must be tangent to the centerline of the level section.

A large cross-sectional area of flow in the inlet channel, in comparison with the flow area at the spillway crest section, facilitates a uniform distribution of flow within the inlet channel and minimizes energy losses. The flow area in the inlet channel may be increased by widening, deepening, or both, the inlet channel. However, deepening the inlet channel reduces the quantity of earth material available to resist potential headcut movement; therefore, consider all aspects in designing the inlet. Minimize energy losses and flow concentrations in the inlet channel by prohibiting obstructions, such as trees, structures, and debris accumulations.

(c) Hydraulic control

If a control section is desired at the spillway crest, the slope of the exit channel immediately downstream of the control section must be steep enough to ensure that all significant flows will be supercritical. This requirement ensures that the position of the control section will remain fixed and that the stage versus discharge relationship will be unique.

The control section may be positioned anywhere along the spillway. However, the further downstream it is located, the higher will be the reservoir stage for any given discharge because of increased head loss resulting from an increase in length of the inlet channel. Any increase in head loss requires an increase in embankment height. Generally, the further downstream the control section is located, the more spillway bulk is provided to help resist spillway breaching.

(d) Outlet

When a control section is desired, the exit channel must have a slope that ensures supercritical flow for all significant flows. However, slopes greater than 4 percent generally meet this requirement. Significant flows are flows equal to or greater than 25 percent of the peak discharge associated with passage of the freeboard hydrograph. All flows that would require a slope greater than 4 percent to ensure supercritical flow may be considered insignificant.

Uniform flow distribution must be maintained for supercritical flows, particularly if overtopping of a retaining dike poses a risk of erosion to the embankment or gutter (fig. 50–1). Therefore, if supercritical flow may occur, the channel alignment should be straight to that point downstream where overtopping of the dike would not cause erosion of the dam embankment or gutters. Curvature in the exit channel alignment causes flow concentrations and enhances erosion in the exit channel.

Ensure that the exit channel, including cross section, slope, alignment, and enclosing cut slopes or dikes, is sufficient to contain the discharge for the freeboard hydrograph and to release the flow without eroding the embankment or gutters (fig. 50–2 and 50–3).

A uniform flow condition does not concentrate hydraulic attack within the channel. Figure 50–4 illustrates how concentrated flow initiates gullies that can migrate upstream through the exit channel and breach the crest and inlet channel. The more uniform the slope and cross section, the more uniform the flow, thereby reducing the maximum hydraulic attack.

Figure 50–1 Erosion of spillway and retaining dike resulting in failure of dike and erosion of toe of dam

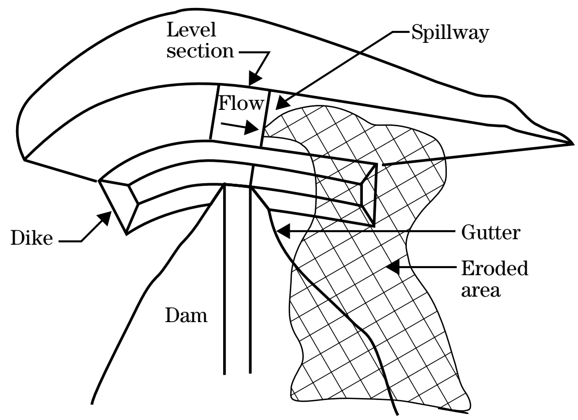
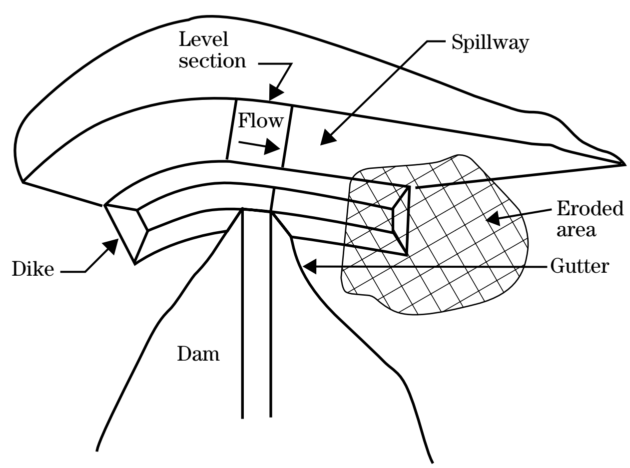


Figure 50–2 Early failure of retaining dike



To reduce tractive stress and erosion potential in the exit channel, the optimum layout for the exit channel is a uniform slope of 4 percent or less from the crest section to the floodplain. If this configuration is not feasible, design the slope to be as uniform as possible and avoid major changes in slope that would induce the formation of hydraulic jumps. Figure 50–5 shows grades increasing in the downstream direction. An alternate layout could be assessed that uses a uniform grade of about 7 percent from the crest to the floodplain. The alternate layout will increase excavation.

The advantage of the spillway exiting to a hillslope is a flatter exit channel slope that results in less excavation, a larger volume of material to resist headcut erosion, and smaller erosive forces in the spillway itself (fig. 50–5). When considering an exit to a hillslope, the investigators must carefully assess the erodibility of the earth materials in the exit channel and on the hillslope. If an evaluation of this configuration predicts the development of an overfall that could adversely affect the function and safety of the spillway, consider designing a steeper exit slope to either a more stable outlet or to the floodplain (fig. 50–6). Other alternatives may be to locate the spillway into more favorable earth materials or in a more favorable topographic setting for the exit area. For an earth spillway to function properly, the layout must meet the following requirements:

Design the layout to ensure that the energy loss is reasonably equal along all flow lines through the inlet (from the reservoir to the crest). Such a layout ensures that the discharge per unit width at the crest is constant across the full width of the spillway.

Design and construct (within construction tolerances) level spillway crest perpendicular to flow.

Design a straight exit channel that extends beyond the downstream toe of the dam. If curvature of the exit channel is required, it shall be beyond the downstream toe of the dam.

NRCS experience recommends dividing the spillway width into bays of 200 feet or less to prevent wide velocity variations within spillway cross sections. Divide the bays by dikes extending from at least the upstream end of the crest to the downstream end of the exit channel. It may be advantageous to extend the dikes further upstream in curved inlets to assist in creating more uniform flow conditions. The top of the dikes, at all points along their lengths, must be at or above the maximum water surface elevation attained during passage of the freeboard hydrograph. Design the dikes to have a minimum top width of 10 feet, minimum side slopes of 2 horizontal to 1 vertical (2:1), and a constant base width to maintain a constant bottom width for each bay of the spillway.

Figure 50–3 Erosion of spillway and retaining dike resulting in breach of spillway, dike, and dam

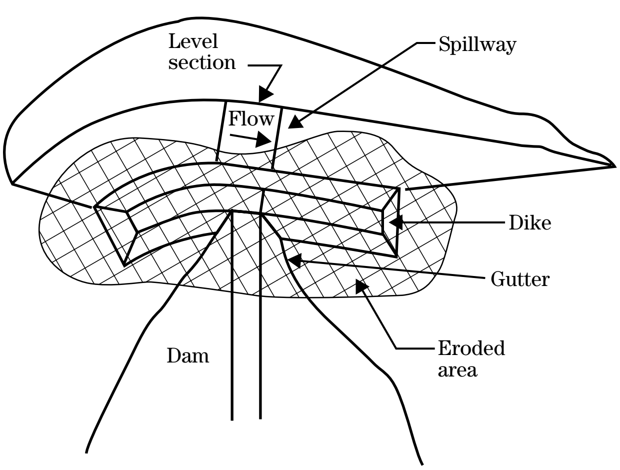


Figure 50–4 Spillway gully resulting in breach of spillway slope and cross section, the more uniform the flow, thereby reducing the maximum hydraulic attack

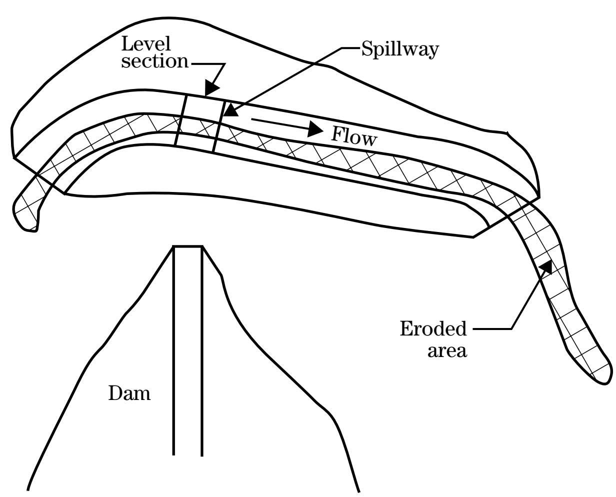
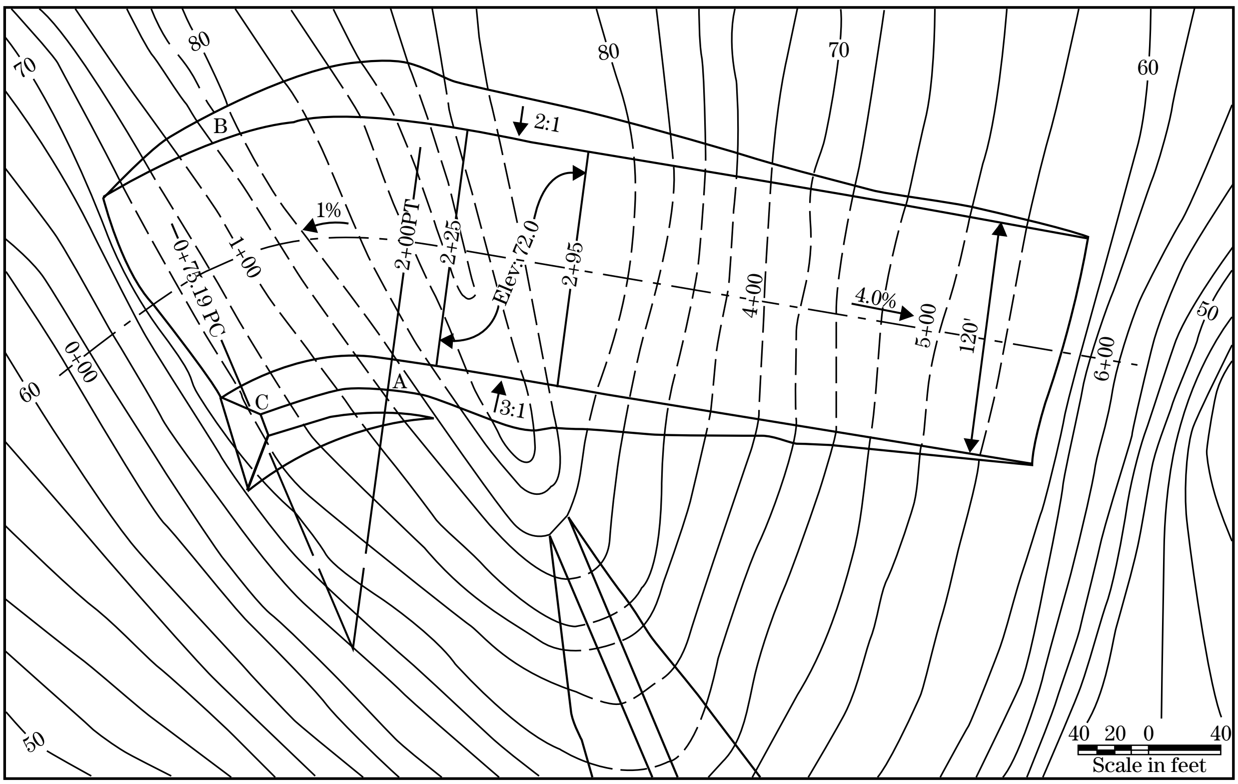


Figure 50–5 Outlet of spillway exit channel discharges to hill slope

Spillway plan



Centerline profile

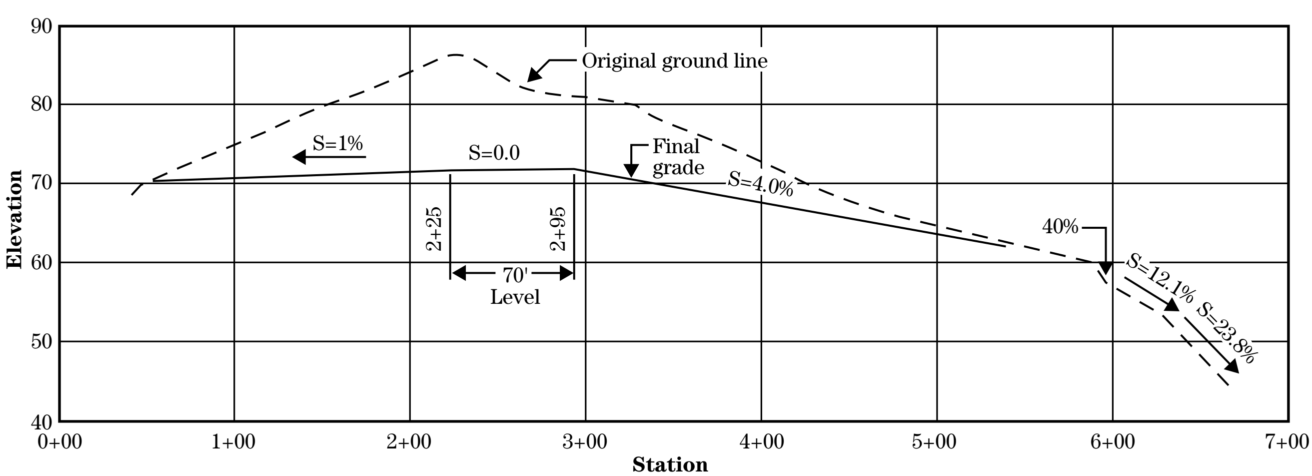
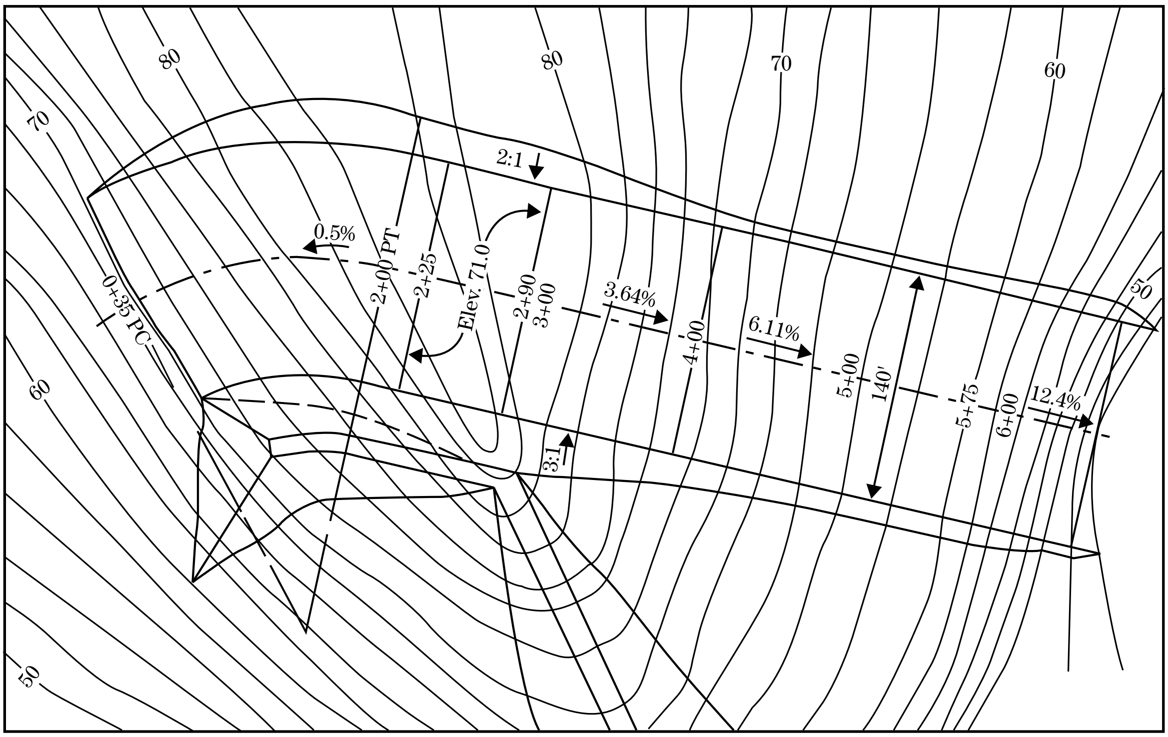
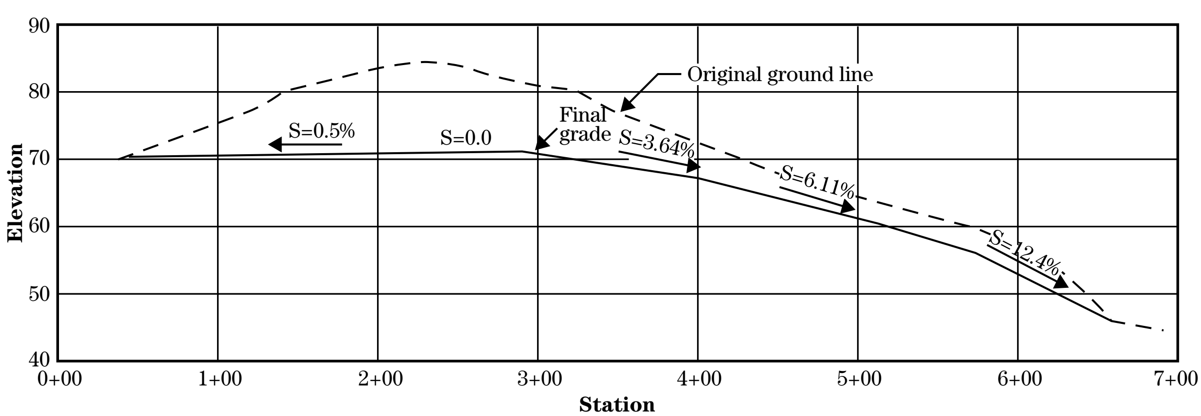


Figure 50–6 Outlet of spillway exit channel extended to floodplain

Spillway plan



Centerline profile



Design the exit channel slope immediately downstream of crest. If a hydraulically stable control section is desired at the spillway crest, design the exit channel slope immediately downstream of the crest so that supercritical flow occurs for all discharges equal to or greater than 25 percent of the peak discharge associated with passage of the freeboard hydrograph.

If reinforcement barriers are used to stop anticipated headcut movement, locate them near the upstream end of the crest. At this location the barrier will be subjected to the least attack (hydraulic loading) for the least amount of time because a longer time is required for the headcut to reach the upstream edge of the spillway crest.

Protect the dam and the gutter between the spillway and the dam by providing sufficient lateral bulk between the spillway and the gutter at all points along the spillway. Meet the following requirements for any cross section normal to the spillway centerline between the projected centerline of the dam and the downstream toe of the dam:

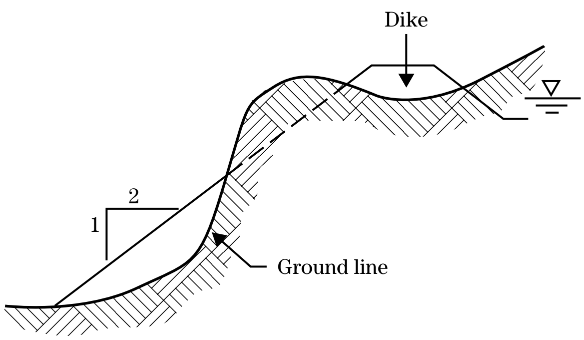
- On the side nearest the dam, make the spillway side slope 3 horizontal to 1 vertical (3:1) or flatter for spillways in soil.
- If a dike is required between the dam and the spillway, do the following:
  - — At each cross section, design the top of the dike to be at or above the calculated maximum water surface associated with passage of the freeboard hydrograph.
  - — Design the top width of the dike to be at least 12 feet.
  - — In the plane of the cross section, ensure that a 2:1 slope projected downward from the top edge of the dike nearest the dam does not fall above the ground at any point.
- At any cross section where a dike is not required, ensure that the ground line is on or above a hypothetical dike cross section as defined above.

Figure 50–7 illustrates these lateral bulk requirements.

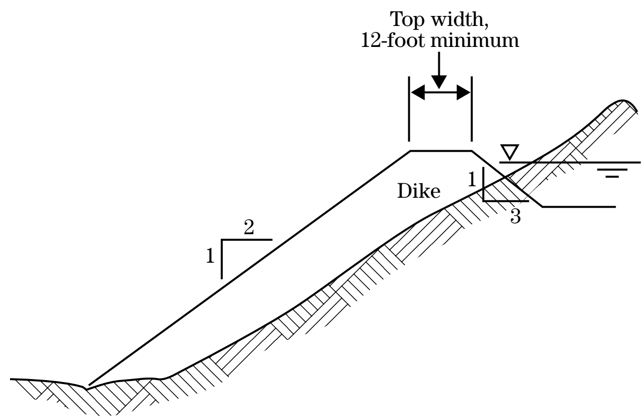
Figure 50–5 shows a spillway layout that outlets onto the hillslope. Some features of this layout are:

- A 70-foot-long level section (exceeds NEH 628.5004 guidance).
- A 95-foot-long straight section upstream of the control section. Within practicable limits, the longer this section, the better the opportunity to develop uniform flow conditions after flow leaves the curved section of the inlet channel.
- A gradual inlet curve having a long radius and limited deflection. This will not disrupt uniform flow conditions as would a curve with a short radius and substantially deflected alignment.
- An upstream, inside dike to guide flow into the spillway entrance. If no dike were used and the pool was at elevation 79, flow would enter the spillway laterally over the cut slopes to points A and B. Flow entering over the right side slope just upstream from point A would tend to inhibit the formation of uniform flow because of its angle of entry and its proximity to the crest. The addition of the dike forces the flow into the mouth of the spillway (water surface at point C). This causes the flowlines from B and C to the crest to be approximately equal thus enhancing uniform flow conditions.
- A straight exit channel that exits essentially perpendicular to a contour line. This eliminates the concern for curvature in supercritical flow. It also makes both sides of the exit channel essentially the same length thus eliminating the possibility of a flow concentration at the outlet of the shorter side.
- An exit channel dike is not provided. The maximum freeboard discharge would create flow over the top of bank starting at station 4+40. Because this overbank flow is shallow, it will not flow toward the dam, but will parallel the within-bank flow. A dike is not deemed necessary; however, in some circumstances, an outside dike may be needed to maintain the spillway flow within the land rights limits.
- Note the short reach of 40 percent slope at the outlet. This steep reach is undesirable because a headcut will most likely start in this location.

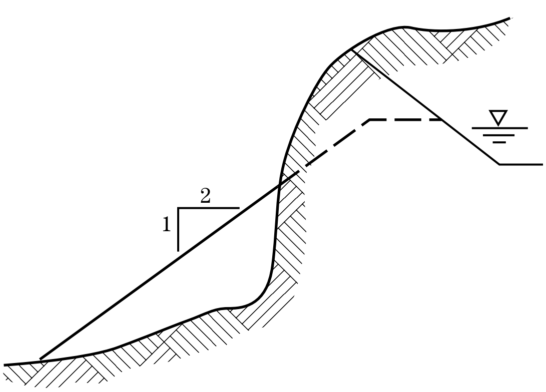
Figure 50–7 Lateral bulk requirements



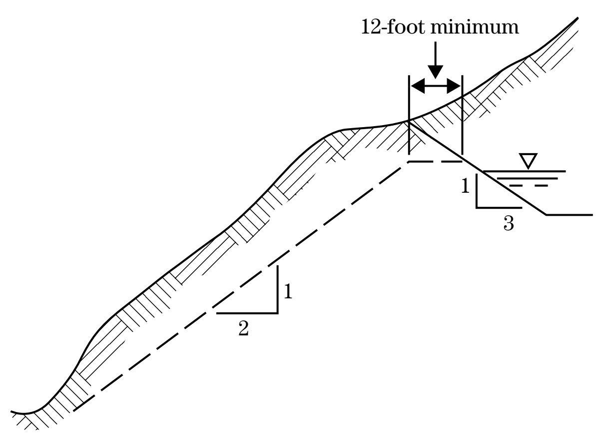
Not acceptable



Acceptable - not desirable



Not acceptable



Acceptable and desirable

This short, steep reach can be eliminated by shifting the spillway upstream until the exit slope daylights at the head of the 12.1 percent reach, or by increasing the outlet slope to 4.6 percent, thus eliminating the 40 percent slope. Spillway layouts that create overfalls shall be avoided.

Figure 50–6 shows a spillway that extends to the floodplain. It has features similar to the spillway shown in figure 50–5. They are:

- A gradual curve in the inlet channel.
- An extended level section.
- A straight outlet channel.
- An upstream dike.
- No downstream dike as the flow is contained within the cut section.
- Spillways with variable slopes are not desirable.

(e) Earth material erodibility

The spillway erosion model in the NRCS Water Resource Site Analysis program (SITES) divides the physical processes of spillway erosion into three phases. Because the processes acting in each phase are unique, each phase uses a different approach to determine the earth material erodibility. Phase 1 is the surface failure stage, which includes the combined effect of the vegetation and earth material and predicts the timing or rate of surface erosion. Phase 2 is a headcut formation stage during which a surface detachment phenomenon is assumed to occur until a headcut forms. Phase 3 predicts the rate and distance of headcut movement as well as downward erosion in the plunge pool area downstream of the headcut.

Analysis of the erodibility of a spillway requires a detailed geologic investigation of the spillway site. The investigation will gather information used as input to the SITES program.

In the Phase 1 analysis, the model uses plasticity index to represent the erodibility of the surface geologic material. The model represents vegetated cover by a retardance curve index and vegetal cover factor (see Agriculture Handbook 667, Stability Design of Grass-Lined Open Channels, and NEH 628.51). The user must also identify cover discontinuities. In the Phase 2 analysis, the model represents geologic material by particle size, bulk density, and percent clay (see NEH 628.51 and NEH 628.52).

The Phase 3 analysis requires an earth material erodibility index to predict spillway erosion. The investigation to determine an erodibility index involves the measurement, description, and documentation of specific geologic parameters (see NEH 628.51 and NEH 628.52). The index is a measure of the hydraulic erodibility of any natural or engineered earth material, including soil and rock. The geologic parameters that constitute the index include earth mass strength, particle or block size, discontinuity or interparticle bond strength, and orientation and shape of material units relative to the flow field. The index represents a rational correlation between stream power and an erodibility classification of all earth materials.

(f) Hydrologic and hydraulic routing results

Refer to the requirements in Section 2, Hydrology in TR–60 Earth Dams and Reservoirs, for the hydrologic criteria for determining spillway discharges and floodwater storage volumes. Use the SITES program to perform the routing of the design hydrographs used in determining the proportioning of the dam and spillways. The SITES analysis is a multiple pass solution using spillway system alternatives.

(g) Stability analysis

Stability analysis is an evaluation of the spillway dimensions, grades, and vegetation to maintain hydraulic stresses below the threshold level for a given design storm. The SITES program output provides information for the stability analysis of the spillway. This program follows the procedure in Agriculture Handbook No. 667 to determine the stability of the spillway for a given hydrograph.

(h) Integrity analysis

The integrity analysis is an evaluation of the breach potential of a spillway during passage of a specified hydrograph. The SITES program provides an erosion and sediment transport analysis to indicate the extent and depth of any headcuts and thus assesses the integrity of the spillway.

The Agricultural Research Service (ARS) developed the model within SITES that makes this analysis. It is based upon performance information for spillways that experienced flows and on research conducted at the Outdoor Hydraulics Laboratory in Stillwater, Oklahoma.

The evaluation of spillway breach potential requires separate evaluation of each reach of the spillway and natural hillslope from the crest to the elevation of tailwater during flow. The model uses the SITES generated outflow hydrograph in predicting each of the three phases of spillway erosion and headcut movement. In making these predictions, the model uses data on the in-place earth materials as well as the spillway layout, vegetation, and maintenance. The model is described in detail in NEH 628.51.

628.5005 Maintenance considerations

The quality of spillway maintenance can have a significant effect on the potential severity of spillway erosion. Experience indicates that for similar flow situations, a well maintained spillway requires less repair after a spillway flow than one that is poorly maintained.

(a) Vegetation

A good, uniform cover of vegetation in the spillway reduces the tractive stress applied to the soil. To maintain good cover condition, do not allow roads or trails of any kind in any part of the spillway. This restriction is particularly important for roads or trails in the exit channel that are parallel to flow. These features disturb the vegetative cover, reduce flow resistance, and cause significant flow concentrations.

Consult an agronomist for the vegetal species appropriate for the local conditions.

(b) Flow disturbance

A flow disturbance is any local phenomenon that causes the flow to deviate from uniform flow conditions. A minor flow disturbance will occur at the upstream end of the longitudinal splitter dikes. This is a subcritical flow area, and the effect is negligible.

Generally, exit channel flow is supercritical. Anything in the exit channel that disturbs flow and tends to concentrate flow increases the risk of erosion. Features that can create significant flow disturbances and concentrations include trees, signs, pipelines, fences, boulders, roads, trails, debris associated with side slope failure, and gullies. Regular maintenance is essential to restrict such encroachments in the spillway.

628.5006 References

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