LEVEE DESIGN FOR FLOOD PROTECTION ON ALLUVIAL FANS

BRUCE M. PHILLIPS [1]

ABSTRACT

The dynamic nature of alluvial fans in arid environments offers numerous floodplain management challenges primarily due to unpredictability of flowpaths and delivery of significant sediment. Application of constructed **levees** on alluvial fans is one of the primary structural control measures utilized in historically successful “whole fan” floodplain management that address flood protection requirements. Levee design and hydraulic evaluation for alluvial fans are much different than similar applications for standard riverine locations, and the corresponding requirements by FEMA including flood hazard definition for alluvial fans. The primary design elements associated with levees which are unique for alluvial fans include (1) geometry and alignment, (2) embankment cross section and (3) armoring requirements. Geomorphic and flooding characteristics on an alluvial fan involves various sources of uncertainties that requires the application of statistical procedures to evaluate flooding at a given point on the alluvial fan. Armoring of the levee face is an essential requirement to ensure the successful operation and specific analysis must be applied to evaluate the vertical limits of the armoring, specifically toe-down depths, since scouring of the slope protection is one of the most common failure modes. The hydraulic evaluation must have the ability to analyze the potential for alternative flowpaths, flow-impingement on the levee, degradation, deposition, sediment ramping, and maximum flooding depths from a variable and random flowpaths. A detailed design procedure is reviewed which provides a systematic approach for evaluating the design hydraulic and sediment transport requirements of protective levees associated with alluvial fans.

ALLUVIAL FAN GEOMORPHOLOGY AND FLOODING CHARACTERISTICS

Alluvial fans are a dominant feature in the arid southwest where it is estimated that 15 to 25 percent of the area is covered by fans. Fans are depositional landforms which have developed over a geologic time scale and located at the base of mountain ranges where ephemeral mountain streams emerge onto the valley floors. The morphology of an alluvial fan is dependent upon a complex interaction of several variables which include: (1) area, mean slope, and vegetative cover of the source area, (2) slope of the stream channel, (3) discharge and climatic environment, and (4) geometry of the mountain front, adjacent fans and valley floor. The location of the stream channel on a fan is often erratic due to the rapid expansion of the width and highly variable sediment load. During a flood event, the flow may abandon the path it has been taking and follow a new one. This occurrence is termed an avulsion which can result from floodwater overtopping the original channel bank and creating a new channel. Through multiple avulsions over geologic time, the fan aggrades uniformly so that it tends to exhibit concentric, semi-circular contour lines. Changes in the flow or sediment supply can affect the morphology of the apex and fan surface. Understanding of the fan geomorphology is a critical step in the initial planning efforts for protective levees.

---

[1] Vice President, Stormwater Management, Pacific Advanced Civil Engineering, Inc., 17520 Newhope Street, Suite 200, Fountain Valley, California 92708 Phone: (714) 481-7300 Fax: (714)-481-7299 E-mail: bphillips@p-a-c-e.com

The flood dynamics of an idealized alluvial fan can be characterized by several zones which are defined beginning from the apex as: (1) channelized zone, (2) braided zone, and (3) sheet flow zone. The channelized zone is an entrenchment on the uppermost portion of the fan which can result in high velocity flow with significant debris/sediment load and unpredictable location. As the single channel encounters flatter slopes on the mid-fan area then a transition area develops where the channel becomes unstable and multiple sinuous flow path form in the braided zone. Flow velocities are further reduced near the base of the fan where the flow spreads out laterally and is very shallow.

ALLUVIAL FAN FLOODING DESIGN ISSUES AND MANAGEMENT MEASURES

Alluvial fan formations have topographic, morphologic, and hydrologic features which differ substantially from the characteristic riverine floodplains that influence the associated design requirements of flood protection measures. Alluvial fan floods do not exhibit the more predictable behavior and well-defined boundaries normally encountered in riverine floodplains which common hydraulic models are available. Application of standard riverine design criteria for protective levees on alluvial fans will not correctly address the complex hydraulics and ensure flood protection reliability. FEMA(1989) has identified the following flood hazards which are common characteristics of flooding on alluvial fans and include: (1) high velocity flow (15 to 30 fps) that can produce significant hydrodynamic forces on structures, (2) significant erosion/scour depths, (3) deposition of sediment and debris to depths of 15-20 feet during a single event, (4) debris flow and their associated impact forces and large sediment loads, (5) flash-flooding (little warning time) (6) unpredictable flow paths, (7) hydrostatic and buoyant forces, and (8) inundation. An issue associated with the application of a levee for flood protection on an alluvial fan is the consequences for events exceeding the design height capacity could be more catastrophic than the event would have been under non-leveed conditions due to the potential failure which might result in a catastrophic flood.

Floodplain Management tools available for alluvial fans which address the identified hazards can be generally categorized as either “whole fan” protection which focuses on regional solutions or “localized” protection which benefits individual developments. Typical management tools include (1) levees and floodwalls, (2) channelization, (3) debris and detention basins, (4) drop structures, (5) debris fences, (6) local dikes, (7) street orientation, (8) elevating structures, and (9) floodplain zoning. Levees are considered whole fan solutions and one of the few measures which is effective in the channelized flow zone of the alluvial fan. Levees provide regional flood protection of the down-fan area, but must be continuous from the apex or lateral boundary, to the toe of the fan.

ALLUVIAL FAN HYDRAULICS AND UNCERTAINTY

The methodology adapted by FEMA for conducting the evaluation of flood hazard zones on alluvial fans was based upon the procedures developed Dawdy (1979). The primary assumptions were (1) a critical flow condition, and (2) geometry of the channel entrenchment is based upon field evidence that the channel will stabilize into a self-forming channel section

$$W = 9.5\,Q^{0.4}$$

at a point where a decrease in depth causes a two-hundred fold increase in width.

Edwards-Thielman adjusted the Dawdy equation based upon studies for the alluvial fan in Cabazon, California, through the assumption of normal depth as a more realistic scenario than

$$W = \frac{17.16\,(Qn\,)^{3/8}}{S^{3/16}}$$

critical depth which resulted in the following:
The current FEMA methodology for computation of the fan width that defines the floodplain boundary for specific flood hazard zones (ie. depth/velocity zones) for any return period (n-year). The analysis for the single channel region involves the application of the probability density function of the apex discharge based upon a Pearson Type III distribution and a similar

$$W = \frac{N\_9.408\_A\_C\_[P'(y > \log_{10} Q_i) - P'(y > \log_{10} Q_w)]}{1 - N\_P(Q > Q_w)}$$

relationship has been developed for the multiple channel zone.
These empirical relationships provide the basic tools to assist in the evaluation of the alluvial fan hydraulics for maximum flow conditions or “worst case” scenario. Fixed bed water surface profile models should be developed to provide a sensitivity analysis of hydraulic characteristics of the floodplain adjacent to the levee for a range of potential flowpath orientations. Hydraulic characteristics from both the alluvial fan hydraulic relationships and water surface profile models should be applied for evaluation of the both height and toe-down requirements. Independent hydraulic analysis is required to determine the maximum requirements for both of these conditions which generally involves a sensitivity analysis of (1) the cross section orientation relative to the levee alignment and (2) variation of the mannings coefficient based upon relative changes in the streambed characteristics.

DESIGN OBJECTIVES AND SPECIAL CONSIDERATIONS

The primary design objective of the levee is to ensure that the potential for overtopping failure has been minimized and adequately addressing the uncertainties associated with the hydraulics and sediment / debris. Previous studies by the ACOE (1993) have assessed structural flood control measures on alluvial fans. The historical difficulties which were identified with levee failures on alluvial fans included (1) restricting sediment transport and causing deposition, (2) failure of rock rip-rap bank protection, (3) erosion failure of unarmored earthen embankments, and (4) toe failure of slope revetments. Standard FEMA requirements for levee design that should be addressed as part of the design include: (1) embankment geotechnical stability, (2) settlement, (3) slope revetment, (4) closures, (5) freeboard, (6) liquefaction, and (7) maintenance/inspection. Requirements for seepage and interior drainage are less of a concern on an alluvial fan because of fan orientation, duration of storm, and embankment slope revetment. Special design considerations associated with a protective levee on a alluvial fan includes (1) vertical and horizontal alignment, (2) orientation relative to the fan direction, (3) embankment cross section, (4) slope revetment or armoring, (5) embankment height, and (6) toe-down protection.

HORIZONTAL ALIGNMENT SELECTION

The lateral extent of the levee traversing the alluvial fan and the horizontal alignment relative to the orientation of the fan are primary design issues effecting hydraulic performance which requires evaluation of multiple alterative alignments. It is desirable to maintain the angle of orientation between the normal flow direction on the alluvial fan and the levee alignment as small as possible, generally not greater than 45°. Larger convergence angles result in significant reduction of hydraulic and sediment conveyance potential for flow following a path adjacent to the levee. However, the smaller convergence angle for the levee alignment generally results in a longer levee system to traverse across to the terminus point on the fan, smaller levee height, but ultimately requiring higher construction costs. A feasibility analysis should investigate several alignments to investigate the most cost effective facility.

The levee should follow an alignment which traverses across the entire extent of the alluvial fan and anchor beyond the lateral limits of the fan, preferably canyon walls. However, for many alluvial fans it is difficult to determine precisely the active lateral boundary of the fan, especially if several fans coalesce together. Significant importance is associated with the boundary delineation and a significant portion of the fan may be considered geologically inactive which could reduce the facility requirements. If the proposed levee terminates without extending to the upstream lateral boundary of the alluvial fan, then the potential for flow flanking the levee should be incorporated in the analysis and providing a secondary flow path to accommodate the by-pass as part of the flood protection. The potential for flanking of the fan can be quantified through the application of the FEMA methodology for probability of flooding at a specific location on the alluvial and using the fan contour width associated with the bypass area. This procedure will result in a discharge for that portion of the fan contour width below the apex and follows the analysis outlined by French (1991).

LEVEE EMBANKMENT HEIGHT REQUIREMENTS

The total height of the levee must be able to accommodate variable flowpaths and hydraulic characteristics, including potential sediment deposition associated with debris laden flows and alluvial stream mechanics. The criteria applied to evaluate the levee height above the natural streambed includes sufficient freeboard above the maximum design water surface elevation to consider variations of the fluvial system to assure overtopping does not occur. Alluvial fan design discharges from the watershed hydrology utilized for the hydraulic analysis should include an appropriate "bulking factor" to increase clear water discharges to account for sediment in the total flow volume. Additional items which should be accounted for in the total levee height above the water surface elevation include: (1)sediment deposition, (2) superelevation / surface wave formation, (3) bedform (anitdune height), and (4) residual freeboard. The maximum water surface elevation adjacent to the levee should be evaluated at critical depth which is consistent with FEMA requirements for floodplain analysis of supercritical alluvial channels. The supercritical hydraulic parameters generally associated with the fixed bed water surface profile analysis should be utilized to calculate the additional cumulative components. The minimum residual freeboard outlined by FEMA in Part 65.10 (b) (1) (ii) of the NFIP for levees is three feet with a 100-year design frequency. The required total levee embankment height calculated with this procedure should be compared to the specific energy for the supercritical conditions and the maximum height utilized.

$$\text{Levee Height} = H_t = Y_{\text{critical depth}} + \text{Deposition} + \text{Superelevation} + 0.5\ \text{Antidune} + \text{F.B.}$$

$$\text{or} \qquad \text{Levee Height} = \text{Specific Energy}_{\text{supercritical}}$$

FLOW IMPINGEMENT EVALUATION

Levee alignments which follow a transverse alignment across the alluvial fan have the potential for flowpaths to impinge directly on the levee and then convey collected flow along a path parallel to the levee. The impingement can result in (1) sediment ramping, (2) sediment agradation, and (3) water surface runup along the levee face. The disruption in the hydraulic and sediment transport characteristics that would be incurred as a result of the flow following this path could cause potential sediment buildup upstream along the levee face. Flowpaths which impinge on the levee would encounter a reduction in channel slope compared to the normal fan slope. The milder slope which occurs along a path adjacent to the levee would generate lower average flow velocities and a corresponding reduced sediment transport capacity. The mechanics of the flow conditions along this secondary path would attempt to re-establish a equilibrium sediment transport condition through gradual building of the slope to reflect the upstream fan slope. The area between the new bed profile and existing bed profile would be filled with sediment deposited due to the differential sediment transport rates associated with the two different flow paths. Effects of the water surface runup can be estimated from the amount of superelevation associated with a channel characterized by the "self-forming" channel geometry and minimum radius equivalent to this channel width.

An idealized representation of the impingement sedimentation process can be developed to estimate the potential maximum deposition depth at a point along the levee based upon simple geometric relationships. The maximum differential in sediment volume is calculated from the sediment hydrograph associated with the two different sediment transport capacities, either parallel to the fan or parallel to the levee. The maximum deposition depth that may occur would depend upon the location of the contract point if a triangular sediment deposition pattern is assumed. The width of the deposition pattern can be estimated as the self-forming channel width on an alluvial fan from the basic empirical relationships. Applying a trail and error procedure, the location of the impingement point is varied to obtain the maximum deposition depth for the differential sediment volume which occurs at the triangle apex and the new slope of the deposited material intersects upslope on the natural fan surface.

SLOPE REVETMENT AND TOE-DOWN DEPTHS

Structural slope revetment is critical design requirement for the levee construction since historically unarmored levees are extremely vulnerable to erosion and even rock rip-rap has exhibited historic erosion problems. The most common failure mechanism of rigid bank protection revetments for alluvial stream is generally due to under scouring at the toe of the revetment. The design of the slope revetment must ensure adequate toe-down protection below anticipated scour depths to account for dynamic changes in the streambed. Toe-down depth of the protective slope revetment must consider these potential adjustments which includes potential of (1)general alluvial streambed degradation, (2)bedform height, (3)local scour (primarily contraction or abutment scour), and (4)low-flow entrenchment.

$$Z_{Total} = Z_{General} + Z_{Bedform} + Z_{Low\ Flow\ Incisement} + Z_{Local\ Scour}$$

Bedform / Antidune Height - Supercirtical flow in alluvial streams will result in the potential formation of antidunes within the streambed. The antidune height can be estimated by the equation developed by Kennedy (1961) and if the calculated dune height exceeds the flow depth, then the flow depth should be used rather than the computed value. Half the antidune height is the allowance associated with bedform development for streambed adjustment.

$$Z_A = 0.027\ V^2$$

Low Flow Entrenchment - The mechanics of alluvial stream generate small incised channels during periods of low-flow rates or the recession of the storm hydrograph. The magnitude of the potential low-flow entrenchment that may occur on this portion of the alluvial fan should be estimated through detailed field reconnaissance of the area.

Local Scour - The potential for local scour can result in localized changes of the average hydraulics or abrupt changes in the horizontal alignment, particularly if flow training devises are utilized at the upstream terminus. This type of local scour results from obstruction to the natural floodplain width or decreased flow area of a floodplain contraction created by training levees constructed across a transverse alignment on the fan. The amount of local scour utilized the maximum depth indicated by the various empirical relationships for the different forms of local scour which may occur. Laursen(1960) derived the following contraction scour equation

$$\frac{y_2}{y_1} = \left(\frac{Q_{mc2}}{Q_{mc1}}\right)^{6/7} \left(\frac{W_{c1}}{W_{c2}}\right)^{K_1} \left(\frac{n_2}{n_1}\right)^{K_2}$$

based upon a simplified sediment transport function:

General Degradation - General scour can be evaluated through the application of one of the many available moveable bed sediment routing models. The sediment routing analysis can evaluate the design storm hydrograph and variable sediment inflow from the alluvial fan in order to quantify potential streambed adjustments.

DESIGN SUMMARY

The following guidelines provide a generalized procedure to assist the design development of levee facilities on alluvial fans, but each specific application must incorporate the unique local conditions and features to the design formulation. It should be recognized that continual maintenance and inspection is essential in order to ensure optimal performance and long term flood protection.