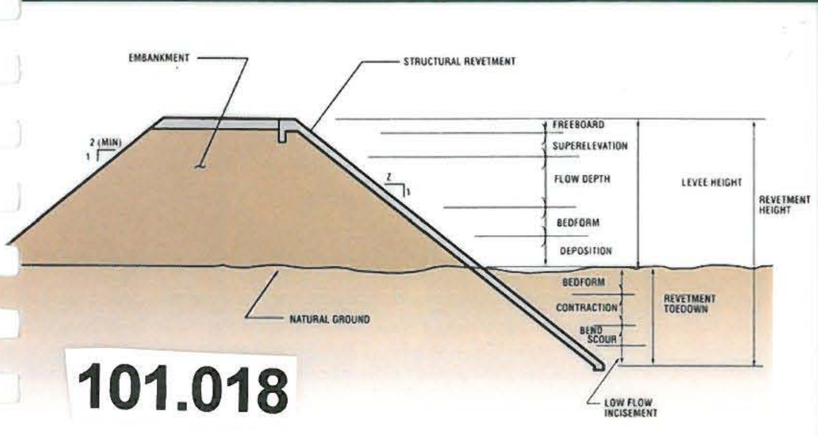


LEVEE DESIGN *for* FLOOD PROTECTION *on* ALLUVIAL FANS

Preparde by:

Flood Control District of Maricopa County

Preparde by:

PACE Advanced Water Engineering

PBS&J

LEVEE DESIGN FOR FLOOD PROTECTION ON ALLUVIAL FANS

FEMA Levee Analysis Requirements for Flood Mapping
For
Flood Control District of Maricopa County
April 10, 2008

Table of Contents

- **"FEMA Levee Analysis Requirements for Floodplain Mapping" – PowerPoint Presentation by David T. Williams, Ph.D., P.E., P.H., CPESC, CFM – National Technical Director, Water Resources, PBS&J, Denver, CO**

- **"Levee Design for Flood Protection on Alluvial Fan" – PowerPoint Presentation by Bruce M. Phillips, P.E., - Senior Vice President, Stormwater Division, PACE, Fountain Valley, CA**

- **"Levee Design for Flood Protection on Alluvial Fan" Abstract Paper written by Bruce M. Phillips, P.E., - Senior Vice President, Stormwater Division, PACE, Fountain Valley, CA**

- **" Design of Flood Protection for Transportation Alignments on Alluvial Fans" Abstract Paper written by Richard H. French, Member of ASCE**

- **"Estimating the Depth of Deposition (Erosion) at Slope Transitions on Alluvial Fans" Abstract Paper written by Richard H. French, Julianne J. Miller and Steve Curtis**

- **"Alluvial Fan Levee Design Example Calculations" Prepared by Bruce M. Phillips**

PBS&J

PACE
Advanced Water Engineering

FEMA Levee Analysis Requirements for Floodplain Mapping

Flood Control District of Maricopa Co.

April 10, 2008

David T. Williams, Ph.D., P.E., P.H., CPESC, CFM
National Technical Director, Water Resources
PBS&J, Denver, CO
dtwilliams@pbsj.com

Special thanks are extended for the contributions of Jennifer Marcy and Michael DePue, both of PBS&J.

PBSJ

PBSJ

Outline

- **Flood Insurance and Levees**
- Levee Policy Background
- How does a Levee get Certified?

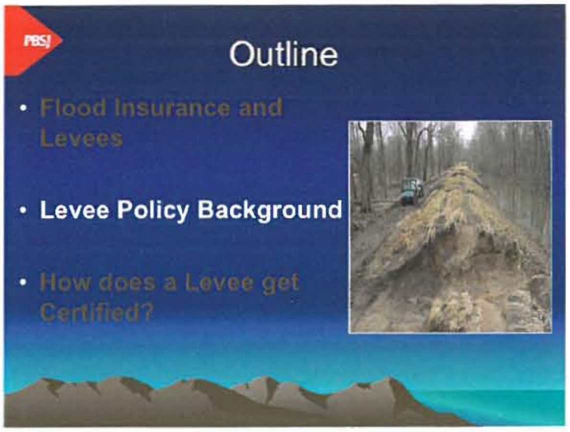
PBSJ

Flood Insurance and Levees

- FEMA does not certify levees
- FEMA can only Accredit a levee that has been Certified to provide base flood protection

Accredited Levee

Non-Accredited Levee



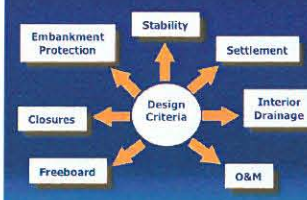
Phasing in over 10 year
Required on all Corps funded structures
Risk + uncertainty analysis in addition to 3' - brought about because of uncertainty such as:
- hydrology
- mapping
- mobile bed
- change in watershed
- N values
- subsidence
- model used
- clear water

Risk vs confidence rating could go down to 2 feet if documented

(95% confidence elev less than 2' then can use 2' feet)

Levee Policy Background

1986: 65.10 - *Mapping of Areas Protected by Levee Systems*

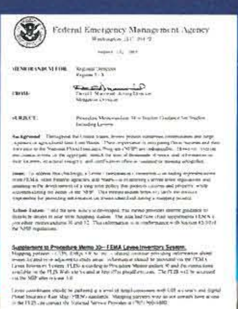


- Contains many elements of the 1981 interim policy
- Requires detailed evaluation of levees before mapping them as providing protection
- Allows for "de-certification" of levees that do not continue to meet criteria

RESPONSIBILITY – AGENCY/COMMUNITY

de-CERTIFICATION OF LEVEES THAT DO NOT CONTINUE TO MEET CRITERIA

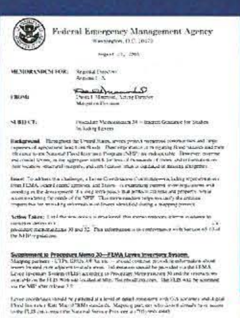
Levee Policy Background


Federal Emergency Management Agency
Washington, D.C. 20472

- August 22, 2005: Procedure Memo #34
  - Reaffirms FEMA's 1986 policy on levees
  - Reiterates that communities are to provide detailed documentation of levee certification
  - FEMA to review data provided and determine if that data supports continued accreditation of levee

up-ROAR over #34
budget
time

Levee Policy Background


Federal Emergency Management Agency
Washington, D.C. 20472

- September 25, 2006: Procedure Memo #43
  - Allows communities up to two years to provide certification data for levees that are reasonably expected to provide base flood protection
  - Provides for a 2-year, "Provisionally Accredited" status for these levees on new Flood Insurance Rate Maps

BASED UPON UP-ROAR WROTE #43

"Provisionally Accredited" – Already shown on Maps + substantially certified – ADDITIONAL data is needed

Levee Policy Background

- What does "Reasonably Expected to Provide Base Flood Protection" mean?
  - For Private Levees, it means that:
    - The levee is already accredited on the current FIRM, and
    - The community (or levee owner/sponsor) has submitted an adequate Operations ad Maintenance Plan and has signed a statement that, to the best of their knowledge, the levee does provide at least base flood protection

Levee Policy Background

- What does "Reasonably Expected to Provide Base Flood Protection" mean?
  - For Federal levees, it means:
    - The levee is already accredited on the current FIRM
    - The levee has not failed or experienced overtopping in a less-than-base flood event
    - The levee has not received a Fair, Poor, or Unacceptable rating from the USACE
    - If the levee is in the Rehabilitation and Inspection Program, its status has not been switched from "active" to "inactive"
    - The levee provides an adequate level of flood protection based on USACE levee inventory data
    - The community has not received a letter from the USACE identifying known maintenance deficiencies with the levee

Levee Policy Background

- February 2007: USACE issues a list of levees that have "Maintenance Concerns"
  - Levees on the list will be given a year to comply with maintenance standards before they will be considered to be non-compliant
  - If they are considered non-compliant after a year, they will no longer be eligible for FEMA's Provisionally Accredited status

PL –

Corps has judiciary function

Levee Policy Background

- In response, FEMA a revised version of PM 43 in March 2007, allowing levees with maintenance only concerns a one-year period of time before they will be no longer eligible for the PAL
- This applies to both Federal and Private levees

Levee Policy Background

- Private Levees are:
  - Levees not authorized by Congress or other Federal agency authority;
  - Levees built by other (non-USACE) Federal agencies and not incorporated into the USACE Federal System;
  - Locally built and maintained levees built by a local community; and
  - Privately built by a non-public organization or individuals and maintained by a local community.

← MAINTAINED BY local COMMUNITY

Levee Policy Background

- Federal Levees are:
  - Levees built by the USACE;
  - Levee projects constructed by non-Federal interests that were incorporated into the USACE Federal System by specific Congressional action;
  - Federal projects that are either operated and maintained by the USACE or turned over to a local sponsor for operation and maintenance; and
  - Non-Federal projects within the Rehabilitation Inspection Program.

Outline

- Flood Insurance and Levees
- Levee Policy Background
- **How does a Levee get Certified?**

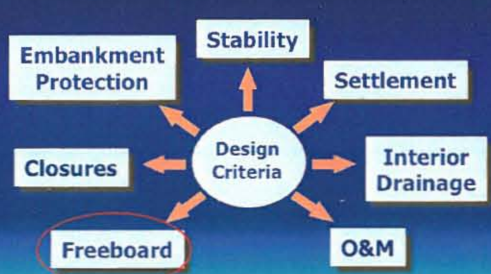
FEMA's Levee Review

FEMA's levee review include asking questions like:

- Is data current (within last five years)?
- Is data stamped by a professional engineer or provided under the cover of a federal or state agency?
- Does data show compliance with structural requirements in 44CFR 65.10 (b)(1) through (7)?

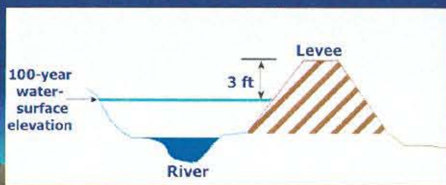
– community responsibility

Detailed Levee Certification Data

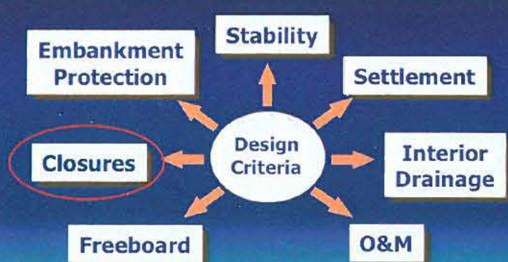


Freeboard

- 3' above BFE all along length
  - Additional 1' within 100' of structures
  - Additional ½' at the upstream end of levee
- Exceptions allowed with detailed statistical analysis, but never less than 2' of freeboard



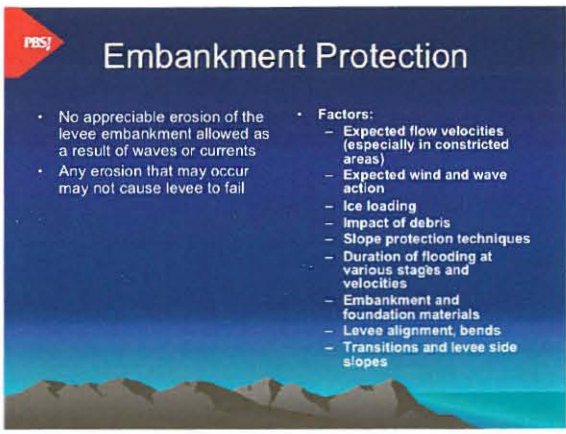
Detailed Levee Certification Data



CANALS + RAILROADS

Closures

- All openings must be protected with closures
- Closure of sufficient strength and height
- Clear closure plan in O&M manual



- LEVEE to fail vs overtopping

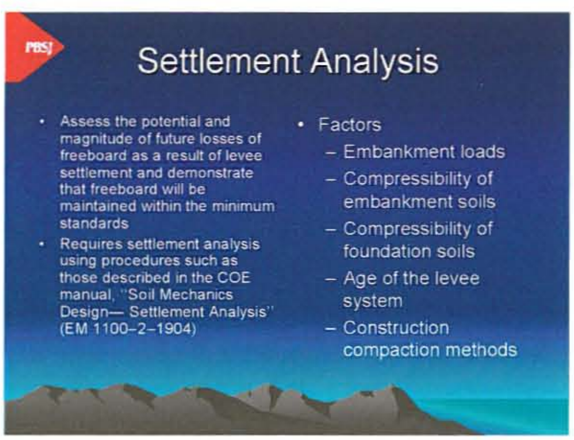
- if overtops then can not erode to toe

- DURATION of flooding = seepage

- DROWN OUT spillways

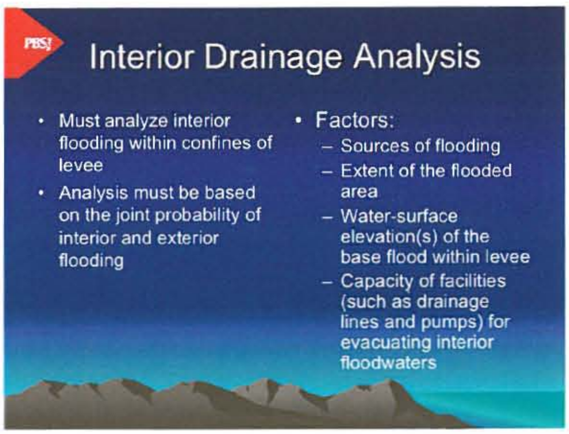
flood in backwater areas such as upstream of BRIDGES

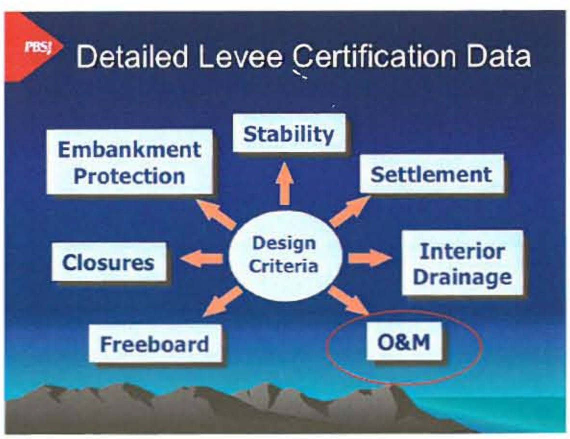
piping in old thalways - boils



SETTLEMENT = SUBSIDENCE


Detailed Levee Certification Data
Embankment Protection
Stability
Settlement
Closures
Design Criteria
Interior Drainage
Freeboard
O&M


Interior Drainage Analysis
• Must analyze interior flooding within confines of levee
• Analysis must be based on the joint probability of interior and exterior flooding
• Factors:
– Sources of flooding
– Extent of the flooded area
– Water-surface elevation(s) of the base flood within levee
– Capacity of facilities (such as drainage lines and pumps) for evacuating interior floodwaters


Detailed Levee Certification Data
Embankment Protection
Stability
Settlement
Closures
Design Criteria
Interior Drainage
Freeboard
O&M

Operation & Maintenance Plan

Must address the following:

- Closures:
  - Documentation of the flood warning system used to trigger emergency operation activities
  - Demonstration that sufficient flood warning time exists for the operation of all closure structures
  - Plan of operation including specific actions and assignments of responsibility by individual name or title
  - Provisions for periodic testing, at not less than one-year intervals, of the closure structures

Operation & Maintenance Plan

Must address the following:

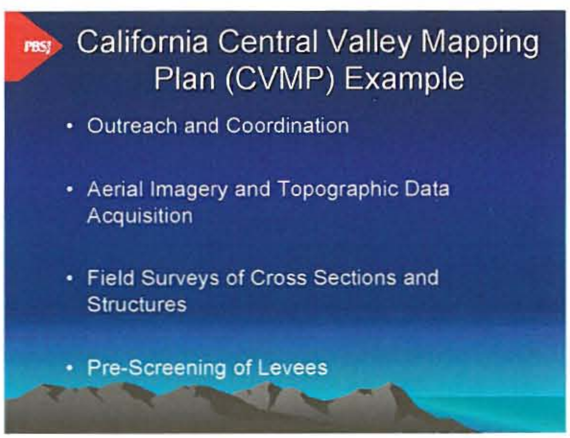
- Interior Drainage Systems:
  - Map of storage areas, gravity outlets, pumps, etc.
  - Documentation of the flood warning system used to trigger emergency operation
  - Demonstration that sufficient flood warning time exists for the operation of all systems

Operation & Maintenance Plan

- Interior Drainage Systems:
  - Plan of operation including specific actions and assignments of responsibility by individual name or title
  - Provisions for periodic testing, at not less than one-year intervals, of the system
  - Provision for manual backup of automatic systems
  - Provisions for periodic inspection of interior drainage systems


Operation & Maintenance Plan
Must address the following:
• Maintenance plans
– All activities must be under jurisdiction of:
• Federal or State agency, or,
• Agency created by Federal or State law, or
• Agency of a community participating in the NFIP

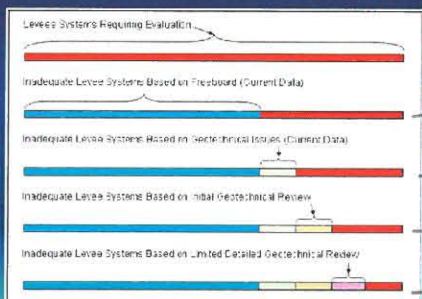

Operation & Maintenance Plan
• Maintenance plans
– Plan must document procedure for maintaining levee's
• Stability
• Height
• Overall integrity of levee and associated structures
– Plan must specify:
• Maintenance activities to be performed
• Frequency of performance
• Person responsible for performance


California Central Valley Mapping Plan (CVMP) Example
• Outreach and Coordination
• Aerial Imagery and Topographic Data Acquisition
• Field Surveys of Cross Sections and Structures
• Pre-Screening of Levees

California Central Valley Mapping Plan (CVMP) Example

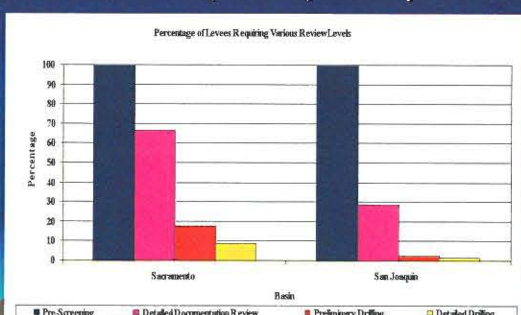
- Detailed Documentation Review for Levees
- Detailed Hydrology & Hydraulics
- Preliminary Drilling and Field Work for Levees
- Detailed Drilling and Field Work for Levees
- Detailed Floodplain Mapping

Staged Levee Review Process

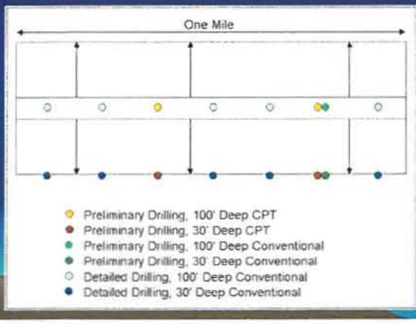


SUBSIDENCE
CURRENT DATA
DATA INDICATES PROBLEMS
ADDITIONAL DATA INDICATES PROBLEMS

California Central Valley Mapping Plan (CVMP) Example



Drilling Locations Per Levee Mile

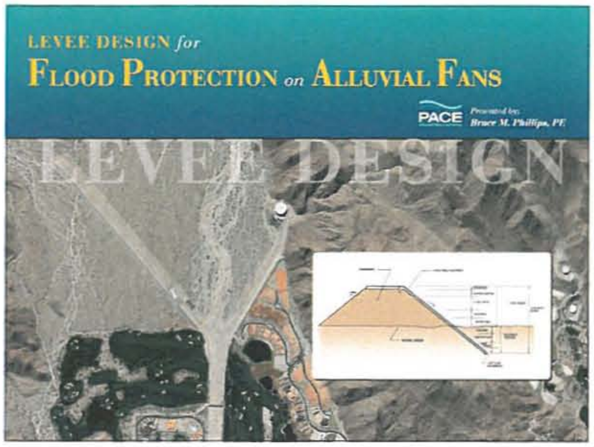


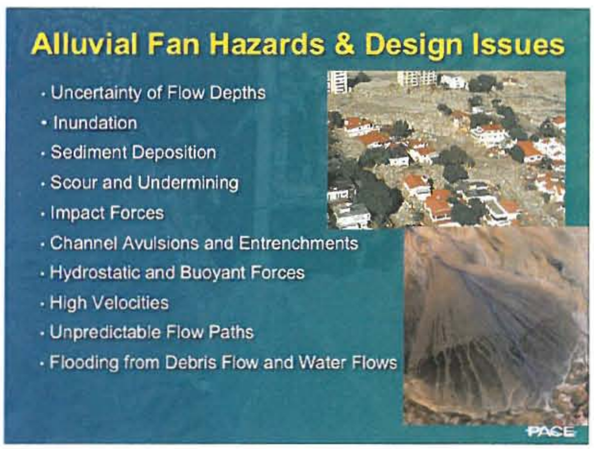
Drilling along toe - for toe scour

Additional Information Determined for CVMP

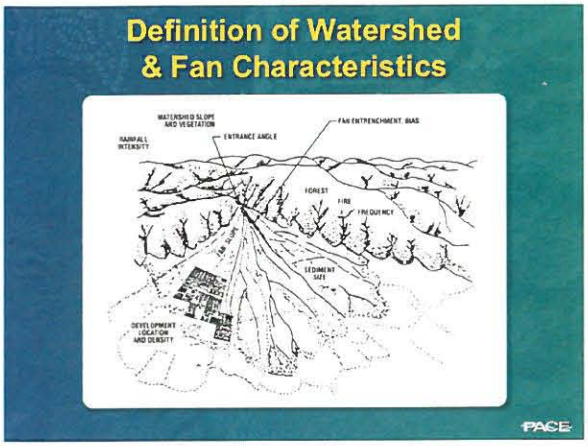
- Unit Costs
  - Labor
  - Drilling
  - Other Direct Costs
- Costs by Subbasin
- Mileage by Subbasin
- Costs by tasks

Questions?

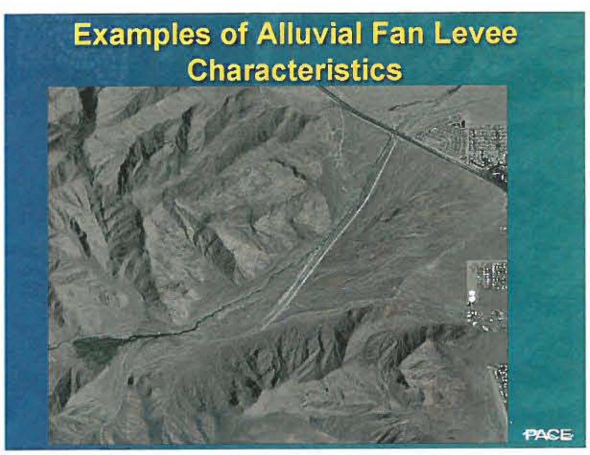




65.10 – DEFINES RIVERINE



ARC-length = flow discharge



ENTRENCHMENT RESULTING FROM TRAINING DIKE

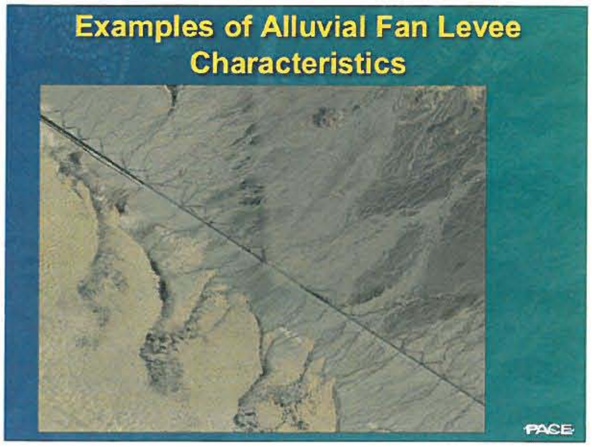
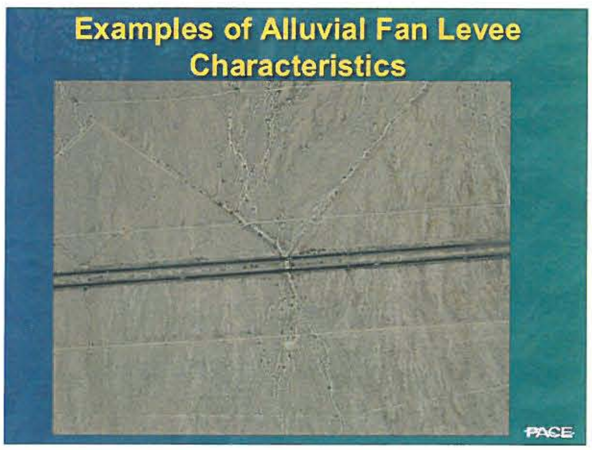
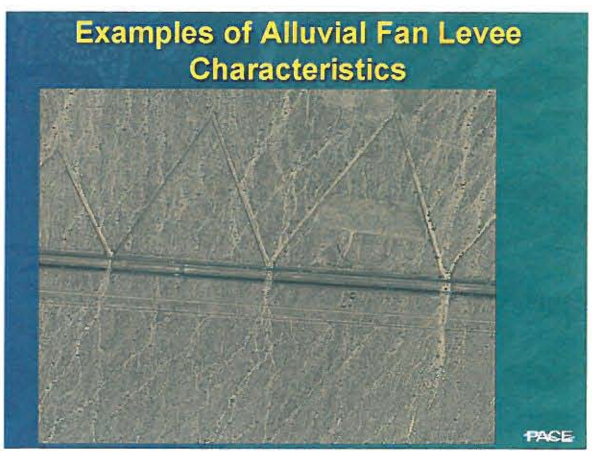


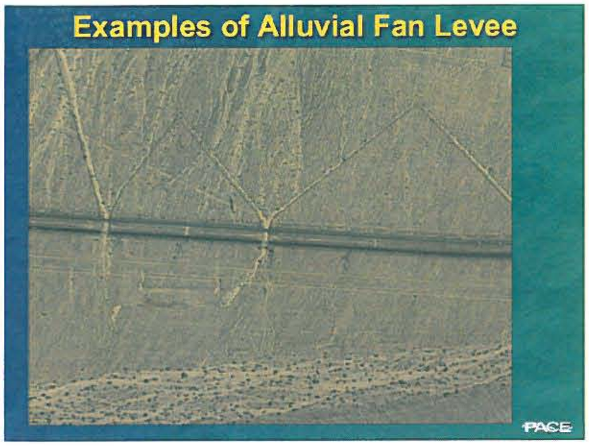
Photo of
INDIO + BLYTHE



· slope down fan is steeper than slope along levee

angle of convergence





wide variety of angle based upon watershed characteristics

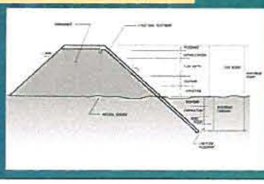
DAMS vs DIKES

DAMS vs DIKES

Critical Design Objectives for Levees on Alluvial Fan

1. Minimize Potential for Overtopping
2. Prevent failure of Embankment Slope Revetment
3. Eliminate failure from Erosion

Critical Design calculations:
- ***Levee Height***
- ***Revetment Toedown Depth***

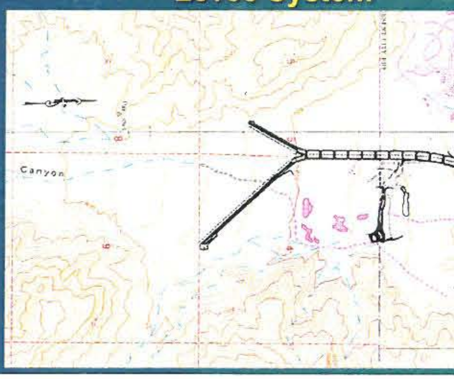


PACE

RESIST LOCALIZED SCOUR

key failure is undermining

Typical Alluvial Fan Protective Levee System



PACE

Minimum Applicable FEMA Requirements

- Applicable NFIP Regulations
  - Levees 44 CFR Ch. 1 § 65.1
  - Alluvial Fans 44 CFR Ch. 1 § 65.13
- Minimum Riverine Levee Freeboard 3.0 feet and 4.0 feet at Bridge Structures
- Supercritical hydraulics
- Inspection and Maintenance program
- Settlement
- Interior drainage
- Embankment geotechnical requirements
- Embankment protection
- Upstream Termination Freeboard 3.5 feet

National Flood Insurance Program NFIP Administered by FEMA

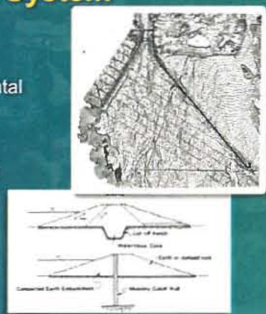
FEMA

PACE

use supercritical velocities for toe-protection

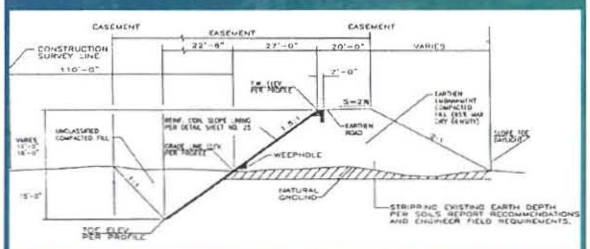
Critical Design Elements of Levee System

1. Alignment
- Orientation Angle / Horizontal Alignment
2. Termination Points
3. Embankment Cross Section Geometry
4. Levee Height
- Levee Vertical Profile
5. Revetment or Armoring
- Toe-down Requirements
6. Geotechnical Features



PACE

Typical Levee Section Design Elements



PACE

Special Design Considerations for Levees on Alluvial Fans

- Variable Flow Paths
- Direct Flow Impingement from Alternate Flow Paths
- Sediment Ramping
- Debris Deposition
- Local Scour
- Channel Entrenchments
- High Velocity and Erosive Flows
- Water Surface Runup / Superelevation on Upstream Side of Levee
- Impact Forces from High Velocity Flows

PACE

Local - general - long term

ENTRENCHMENT HYDRAULICS

1. Levee Alignment Selection

- Levee Orientation Relative to Fan Geometry
  - *Optimum or Maximum Acceptable Divergence Angle*
- Maximum Horizontal Limits of Levee
  - *Entire Fan*
  - *Tie to Limits of Alluvial Fan*
  - *Limited by Risk Assessment and Historical Flow Paths*

PACE

optimum angle – 45°-60°

flatter angles = higher levee section

Evaluating Effects of Alternate Flowpath Impingement

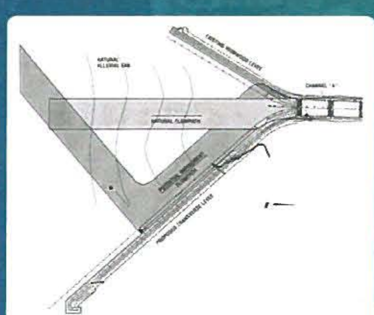
- Direct Impingement Would Result in Alternate flow Path Parallel to Levee
- Reduced Slope for Alternate Flow Path and Reduced Sediment Transport Capacity
- Aggradation Occurs Along Alternate Flow Path to Re-establish Sediment Equilibrium
- Area Between New Bed Profile and Existing Bed Profile Filled from the Differential Sediment Transport Rates

PACE

SEDIMENT RAMPING

flatter angle = MORE SEDIMENT DEPOSITION which NEEDS TO BE ADDED TO levee height

Levee Direct Impingement Flow Path



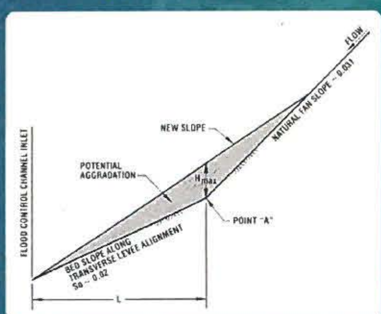
PACE

Evaluating Effects of Alternate Flowpath Impingement

- Calculate the Maximum Deposition Height at Levee:
  - *Calculate the deposition volume from the Sediment transport rates and hydrographs*
  - *Deposition width from the self-forming channel width*
  - *Applying geometrical relations maximum deposition depth computed at contact point*
  - *Trial and Error Procedure Applied to Vary Contact Length along Levee for Maximum Depth*

PACE

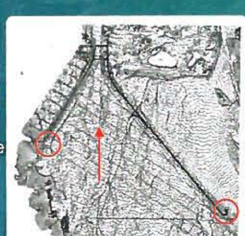
Levee Direct Impingement Deposition Model



PACE

Upstream Levee Termination Points

- Extend to maximum limits of fan flooding
- Increase freeboard per FEMA
- Extend to hard-point for tie-in
- Potential for "flanking" if Levee cannot be extended to maximum fan flooding limits
- May not be economically feasible or environmental / jurisdictional limitations / property ownership
  - Estimate the amount of flow that will flank upstream limits of levee
  - Apply French's procedure



PACE

Levee Flanking Analysis on Alluvial Fan

- Apply probabilistic approach by FEMA to establish N-year flooding

$$P(H = I) = \int_{y_1}^{\infty} P_{H,Q}(I,q) \frac{\exp[-0.5(y-\mu)^2/\sigma^2]}{\sigma\sqrt{2\pi}} dy$$

- Flood width for N-year discharge

$$\frac{I}{N} = \frac{9.408\, C\, A}{W} P'(Y_N)$$

PACE

Levee Flanking Analysis on Alluvial Fan

- Procedure by French (1988) for a reduced "contour" width across the active fan at a particular elevation

1. Contour width measured at head of levee and amount of contour not covered within levee
2. Compute flow statistics for discharge at apex of fan for mean, variance, and skew coefficient
3. Calculate transformed statistics for alluvial
4. Calculate probability for reduced fan width
5. Calculate discharge with that probability

$$\log_{10} = k\sigma + \mu$$

PACE

2. Alluvial of Alluvial Fan Hydraulics For Flood Protection

- Limited Procedures Available for Evaluation of Alluvial Fan Hydraulics
- Empirical Procedures to Evaluate Self-Forming Channel Hydraulics
  - *Dawdy (Critical depth stabilize where decrease in depth results in two-hundred fold increase in width)*

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

  - *Edwards - Thielman (Application of Mannings Equation and Dawdy procedure)*

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

- Fixed Bed Water Surface Profile Hydraulic Models (HEC_RAS)
  - *Cross Section Orientation*
- 2 - dimensional Hydraulic Models (ie. FLO-2D)

PACE

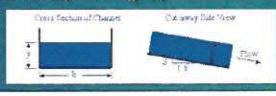
DAWDY = CRITICAL
self forming channel

EDWARD - Thielman
supercritical

Approximating Self-forming Channel Hydraulics of Alluvial Fan

- Dawdy Empirical Procedure Alluvial Fan Hydraulics
  - Channel Width $W = 9.5\ Q^{0.4}$
  - Procedure Assumes Critical Depth $N_F = 1.0$

- Can develop the following hydraulic relationships for "self forming" channel
  - Velocity = $1.5\ Q^{0.2}$
  - Depth = $0.07\ Q^{0.4}$
  - Unit Flowrate = $q = Q / W = 0.105\ Q^{0.6}$
  - Shear Velocity = $V_* = (gRS)^{1/2}$



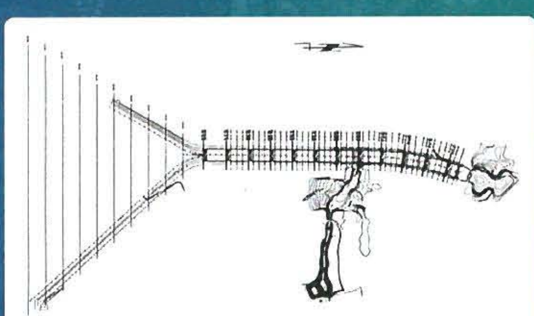
PACE

Alluvial Fan Water Surface Hydraulics for Flood Protection

- HEC-RAS Hydraulics Analysis with Levee System
  - Mannings roughness value selection
    - Strickler & Anderson Equations for mannings based on bed material size
    - $n = 0.04\ d_s^{1/6}$
    - Cowan's procedure
  - Orientation of HEC-RAS cross sections with Levee
    1. Parallel to fan contours
    2. Normal to Levee orientation
    - Intent is to maximize the depth to prevent overtopping for worst case
- Compare analysis with empirical fan hydraulics

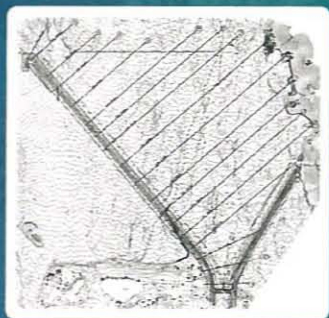
PACE

Normal HEC-RAS Cross Section



PACE

Transverse HEC-RAS Cross Sections



PACE

doesn't self form; channel vary as one goes down stream

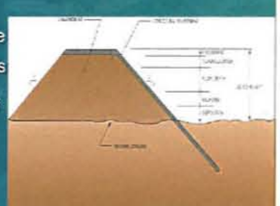
3. Levee Revetment / Armoring Requirements

- Historically Unarmored Levees are Ineffective
- Armoring Selection Based Upon Tractive Force or Velocity Requirements
- Alternative Revetments Available
- Concrete Slope Lining
  - *Grouted Stone*
  - *Soil Cement*
  - *Rock Rip-Rap*
- Evaluate Performance and Least Cost

PACE

4. Evaluation of Levee Height Requirements

- Levee Height Accounts for Moveable Bed and Rigid Boundary Conditions
- Calculate Height from Summation of Individual Components:
  - ***Bedform Height***
  - ***Superelevation***
  - ***Flow Depth Compared to Critical Depth***
  - ***Deposition from Alternate Flow Path***



$$Height_{Levee} = Depth_{flow} + Z_{deposition} + Y_{superelevation} + 1/2\ Antidune\ Height + F.B.$$

$$Height_{Levee} = Critical\ Depth + F.B.$$

- Compare Calculated Height to Total Specific Energy

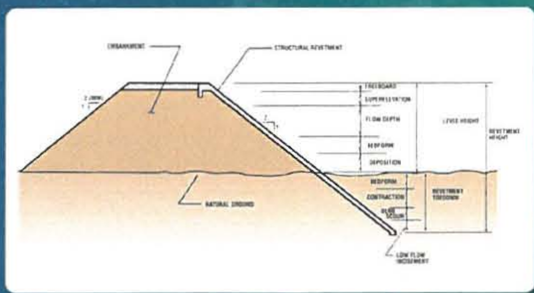
PACE

superelevation assessed for bed ramping

All flows are bulked

← use higher of two

Definition of Levee Design Variables



PACE

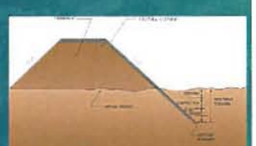
Levee Height Design Variables

- Antidune Height: $0.027\,V^2$ (Kennedy)
  - *If Calculated Antidune Height Exceeds Flow Depth, Use Flow Depth*
- Calculate Hydraulics for (1) Actual Flow Depths and (2) Self-forming Channel
- Superelvation: $1.3\,V^2\,(b+2zD)\,/\,(gR)$
  - *Minimum Radius Calculated From Topwidth Equal to Curve Tangent*
- Aggradation Potential (see *Impingement Analysis)*
- If Depth plus Superelevation Exceeds Specific Energy then Use Specific Energy

PACE

RADIUS is w.th of self forming channel

5. Levee Toedown Protection Requirements



- Primary Failure of Mechanism of Bank Protection is Scour Below Revetment Toe Depth
- Toe Depth Evaluated Through Empirical Design Charts / Tables
- Toe depth Calculated From Summation of Individual Components:
  - ***Bedform***
  - ***Bend Scour***
  - ***Low flow Incisement***
  - ***Contraction Scour (Applied only at Channel Entrance for Training Levees)***

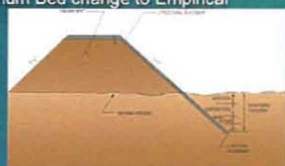
PACE

Levee Toedown Protection Requirements

- Hydraulics Evaluated for (1) Actual Flow Depths and (2) Self-forming Channel Hydraulics

$$z_{Toe\ Down} = z_{Bend} + z_{Contraction} + z_{Bedform} + z_{Low\ Flow\ Incisement}$$

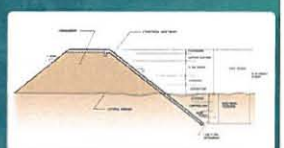
- Compare Calculated Maximum Bed change to Empirical Toedown Design Charts



PACE

6. Additional Levee Design Considerations

- Uncertainty of Levee Performance
- Levee Closures
- Long Term Maintenance
- Levee Crossings
- Vehicular Access for Flood-fighting
- Aesthetics
- Environmental Mitigation / Maintain Natural Flowpaths
- Freeboard
- Least cost-Evaluation of Alternative Systems



PACE

Summary of Design Procedures for Levees on Alluvial Fans

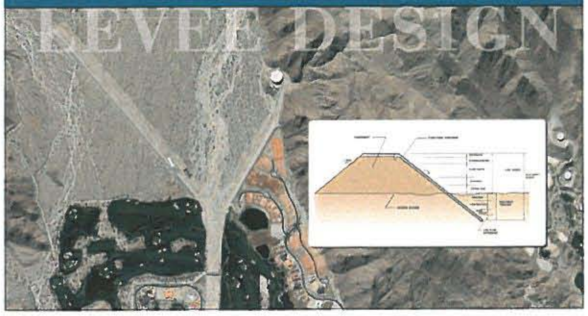
- Evaluate Rigid Boundary and Alluvial Channel Hydraulics
- Apply Simplified Alluvial Fan Hydraulics
- Development Horizontal Alignment to Minimize Impacts
- Levee Height Calculated to include Maximum Flow Depth and Aggradation
- Revetment Toedown Depth Calculated Below Maximum Potential Scour Depth
- Slope Revetment Designed to Resist Maximum Tractive Force

PACE

LEVEE DESIGN *for*

FLOOD PROTECTION *on* ALLUVIAL FANS

PACE Presented by: Bruce M. Phillips, PE



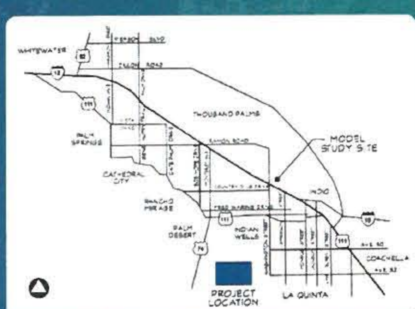
Implementing Floodplain Management

Measures for Alluvial Fans – Levee Design

-- CASE STUDY --

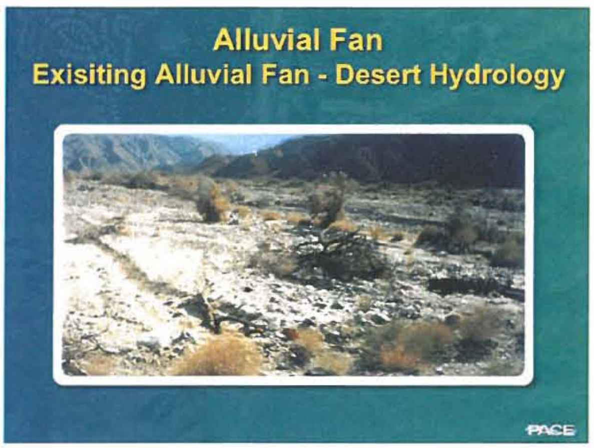
PACE

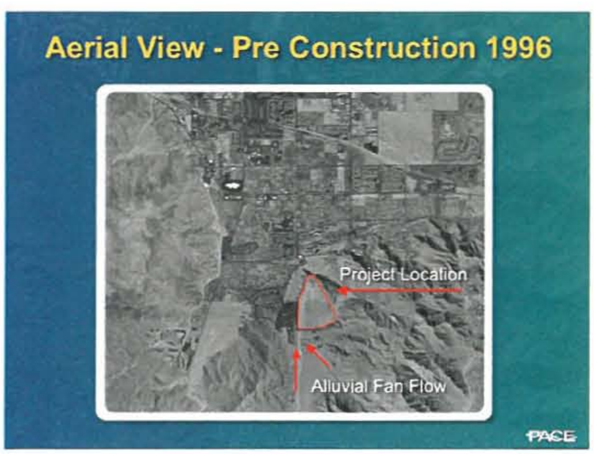
Project Vicinity Map



PACE


The Reserve Development Project
Location & Description
· Location in both cities of Palm Desert and Indian Wells, CA
· High-End luxury residential golf course development
· 500 acres of land adjacent to Ironwood Country Club
· Situated entirely on the active deep canyon alluvial fan
· Proposed 18-hole championship golf course
· 250 residential sites
· Encompass portion of living desert regional debris basin


Alluvial Fan
Exisiting Alluvial Fan - Desert Hydrology

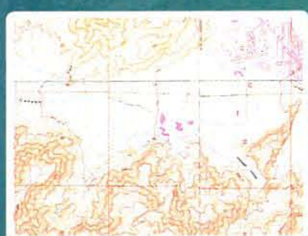

Aerial View - Pre Construction 1996
Project Location
Alluvial Fan Flow

Aerial View - Post Construction 2005

PACE

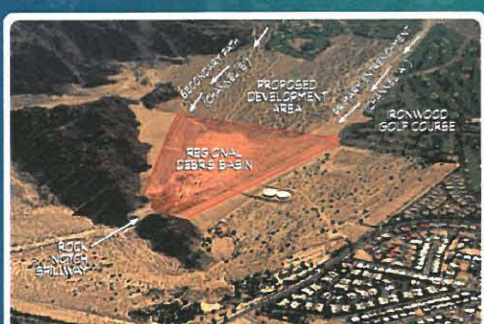
Flood Control Design Constraints

- Existing Flood Hazards
- Alluvial Fan hydraulics
- Debris Flow Quantities
- Environmental Regulatory Agencies
- Jurisdictional Agencies (CVWD and Cities)
- University of California Ecological Reserve
- CVWD Regional Debris Basin
- Existing Ironwood Golf Course
- FEMA



PACE

Aerial Schematic of Development Area



PACE

Watershed Description

- 46.4 square mile deep Canyon Watershed Tributary to living desert debris basin
- Deep canyon is tributary to Whitewater River
- Two independent drainage basins tributary to project boundary (A & B)
- Extremely rugged mountains and steep rocky canyons of Santa Rosa mountains
- Elevation variation extremes from 8,716 feet to 460 feet at project
- 17.7 miles watershed length
- Average slope 9%

PACE

Watershed Hydrology Investigation

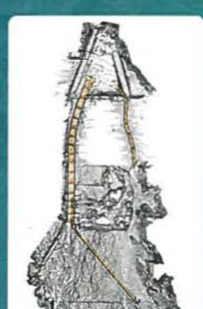
- Ungaged watershed
- Design storm – standard project flood (SPF)
- 6-hour 1939 Indio storm (6.45 inches)
- HEC – 1 synthetic hydrographs
- Bulking factor of 1.2 applied to clear water flows
- Bulking factors based on adjacent dead Indian wash debris basin ACOE study

FREQUENCY	CHANNEL "A" (42.7 sq. mi.)	CHANNEL "B" (3.7 sq. mi.)	COMBINED (46.4 sq. mi.)
SPF	35,570 cfs	5,360 cfs	36,950 cfs
100-year	14,700 cfs	2,930 cfs	16,400 cfs

PACE

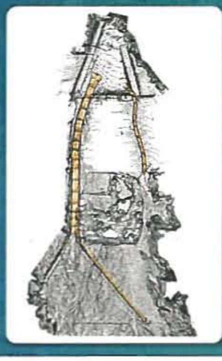
Description of Channelization Facilities

- Twelve concrete grade control structures (Net Drop 6.5 feet)
- Channel 5,000 feet long
- Plunge-pool channel outlet structure (Net Drop 18 feet)
- Small entrenched sediment basin
- 1,400 feet golf course channel
- Water feature grade control



PACE

Proposed Reserve Development With Flood Control Improvements



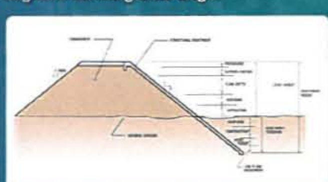
PACE

Plunge Pool Channel Outlet With Aesthetic Treatment

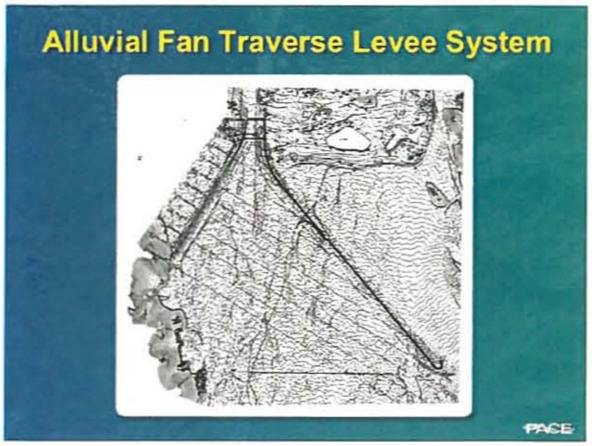
PACE

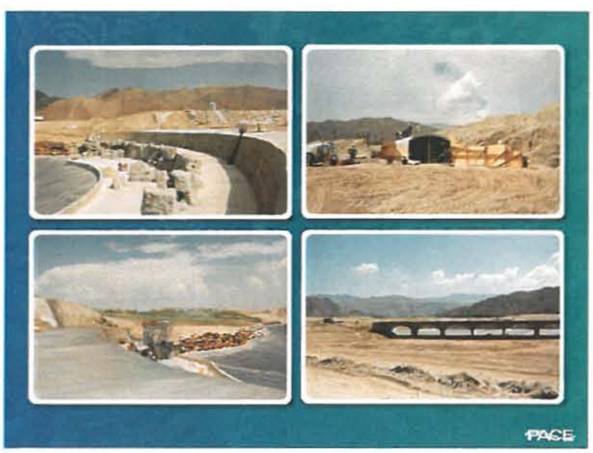
Alluvial Fan – Protective Levees

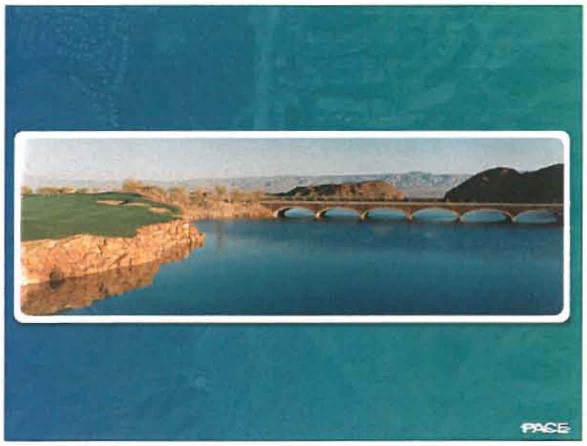
- Primary transverse levee 3,900 feet long
  - Convergence angle 40 degrees
  - Concrete slope lining
  - Height = 18 ft and Toedown = 15 ft (min)
- Funnel Levees 400 feet long
  - 45 degrees convergence angle

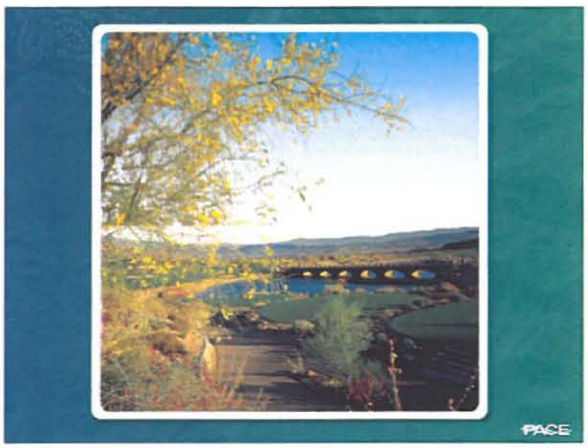


PACE


Alluvial Fan Traverse Levee System

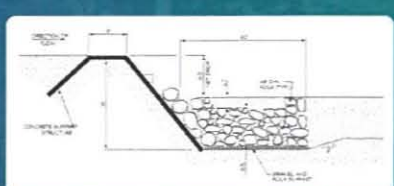






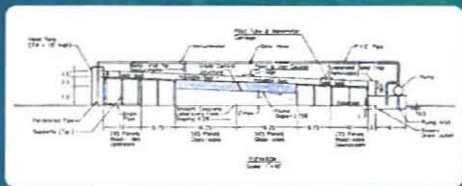
Physical Model Study Objective

- Evaluate the modification to the Erosion patterns with alternative design of grade control structures
- Investigate the hydraulics of different grade control geometric configurations
- Determine the effect to the local scour from an artificial horizontal armor blanket



Model Description

- Model construction and operated by PACE
- Experimental setup located outdoors under protected covered carport in Palm Desert
- 80-foot long and 24" wide flume



PACE

Model Scale to Prototype

- Scales selected to provide the minimum dimensions which erosion features could be adequately observed & measured
- Linear scale of Lr = 1:16
- Discharge sable Qr = 1:1,024
- Time scale Tr = 1:16
- Velocity scale Vr = 1:16
- Selection of model sand-bed material

PACE

PACE

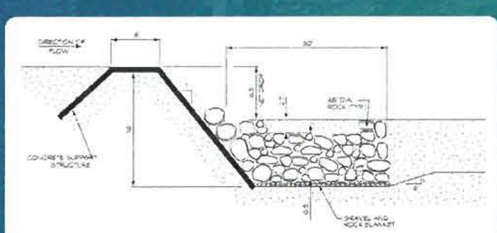
PACE

Prototype - Model Data

DESCRIPTION	PROTOTYPE	MODEL
Model Portion of Channel Width	32 feet	2.0 feet
SPF Discharge	5,380 cfs	5.25 cfs
Structure Net Invert Elevation Drop	6.5 feet	4.88 inches
Modeled portion of The Hydrograph	480 minutes	120 minutes

PACE

Model Study Configuration



PACE

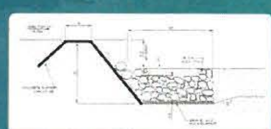
Testing Program Results

EXPERIMENT DATE	DISCHARGE (PROTOTYPE)[1]	MODEL BLANKET CONFIGURATION[2]	ACTUAL PROTOTYPE ROCK LENGTH	MODEL MAX. SCOUR DEPTH MEASURED
Nov. 21, 1996	100-year	37.5" length Rip-Rap	50 feet	9.0 inches [3]
Dec. 4, 1996	SPF	19.5" length Rip-Rap	26 feet	7.75 inches
Dec. 4, 1996	SPF	none	none	21 inches (flume bottom)
Dec. 11, 1996	SPF	13.5" length Rip-Rap	18 feet	Failed (flume bottom)
Jan. 3, 1997	SPF	23.5" length Rip-Rap	31.3 feet	5.75 inches
Jan. 8, 1997	SPF	19.5" length Rip-Rap	26 feet	Failed (flume bottom)

PACE

Recommendation and Conclusions From Model Study Investigation

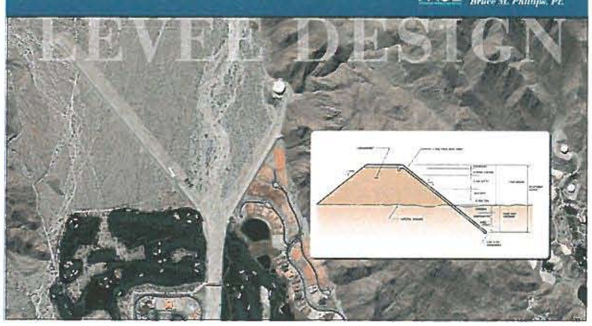
- Rip-rap armor blanket provided downstream from toe of grade control structure
- Length of armor blanket a minimum of 30-feet
- Blanket should be configured so it resembles shape of the scour hole
- Thickness of the armor blanket should be a minimum of 6.5-feet with 48" diameter rock
- Geometry of the rock blanket is important and should provide a 3-foot high thickened sill
- The minimum vertical height of the concrete lining for the chute is 16-feet compared to the original 24-feet from empirical equations



PACE

LEVEE DESIGN *for* FLOOD PROTECTION *on* ALLUVIAL FANS

PACE Presented by: Bruce M. Phillips, PE



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 Senior Vice President, PACE, 17520 Newhope Street, Fountain Valley, CA, 92708, Phone: (714)-481-7231 Fax: (714)-514-8804 E-mail: bphillips@pacewater.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.

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

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

PROBABILITY ANALYSIS OF LEVEE BYPASS

Although the physical information provided regarding the alluvial fan flooding indicates that the levee alignment selected would contain the anticipated flooding, we want to quantify the potential for flanking of the fan through the application of the FEMA methodology for probability of flooding at a specific location on the alluvial. However, as identified by many investigator this procedure assumes complete randomness of flooding and does not evaluate the potential that floods are more likely to follow previously defined flowpaths (ie. French, et. al, 1993). The procedure was adopted in order to satisfy the most conservative evaluation of the flooding condition to satisfy the identified concerns.

The objective of the technical analysis was to determine the amount of flow which could potentially bypass the head of the transverse levee. Although this would be physically difficult for this situation to occur based upon the items previously identified which included the fan configuration and geomorphology. Current studies regarding the techniques of alluvial fan flooding evaluation which were incorporated into this analysis included: (1) *Alluvial Fan Flooding Methodology - Final Report* (October 1996), prepared by Bechtel Corp. for the Army Corps of Engineers, Los Angeles District, (2) *FEMA Fan, An Alluvial Fan Analyzer User Manual* (February 1998), US Army Corps of Engineers, and (3) *Design of Flood Protection for Transportation Alignments on Alluvial Fans*, French. This studies refine the FEMA methodology on alluvial fans for specific applications which can be applied to our situation. An earlier study prepared for the Arizona Department of Transportation (FHWA-AZ88-802) *Analysis of Flows on Alluvial Fans* (1988) was also evaluated, but it did not apply the probability function to the analysis and only relied upon uniform distribution of the flows across the fan, so was not incorporated.

The procedures which were outlined in the preceding references were applied to determine the 100-year flowrate at a specific distance below the apex of the alluvial which is an amount lower than that at the apex. The alluvial fan flooding can be categorized into two particular regions, either the single channel zone or the multiple channel zone. The proposed location of the upstream levee head is located in an area which is defined as "single channel" based upon channel and fan slope (FEMA, 1985). The theoretical approach utilized by FEMA to

$$P(H=1)=\int_{Y_T}^{\infty} P_{H\_Q}(1,q)\,\frac{\exp[-0.5\,(y-\mu)^2/\sigma^2]}{\sigma\sqrt{2\pi}}\,dy$$

establish the N-year alluvial fan flooding results in the following basic form of the equation:

The flood width for N-year discharge can be reduced to the following form which is utilized

$$\frac{1}{N}=\frac{9.408\,C\,A}{W}\,P'(Y_N)$$

for the current analysis:

Where Y_n is the $\log_{10}Q$ and P' represents the probability density function that follows a log Person type III distribution. The constants C, A, and N are the transformation constant for the frequency distribution, avulsion parameter, and the return period, respectively. This is consistent with the procedures also reviewed by French (1988) for a reduced contour width over the entire fan width at a particular contour elevation. The application of this procedure utilizing the following procedure:

1. The contour width was measured at the head of the transverse levee to determine the value, W, in the equation indicated. The width was measured over the maximum limits of the fan which included the area that could be flank around the levee.

2. Perform the computation of the flow statistics for the calculated peak discharges at the apex of the fan. The flow statistics include the mean (μ), variance (σ), and skew coefficient (g). These values were calculated from the hypothetical discharges previously determined in the regional hydrology analysis for this project A least-squares best fit analysis can be performed on the $\log_{10}$ of the data and result in clear water discharges estimated from the HEC-1or other hydrology model for μ, σ, and g.

3. Calculate the transformed statistics for the alluvial fan for the log-person

$$C = [\frac{\lambda}{\lambda - 0.92}]^k \exp(0.92\, m)$$

distribution based upon FEMA methodology:

4. Calculate the probability associated with the flood width for the contour width at the levee head when the avulsion factor, A, is 1.0.

5. Calculate the associated discharge with this probability utilizing the frequency factor for a log person type III distribution.

$$\log_{10} = k\sigma + \mu$$

This will provide the flanking discharge applying FEMA methodology.

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

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

scour (primarily contraction or abutment scour), and (4)low-flow entrenchment.

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

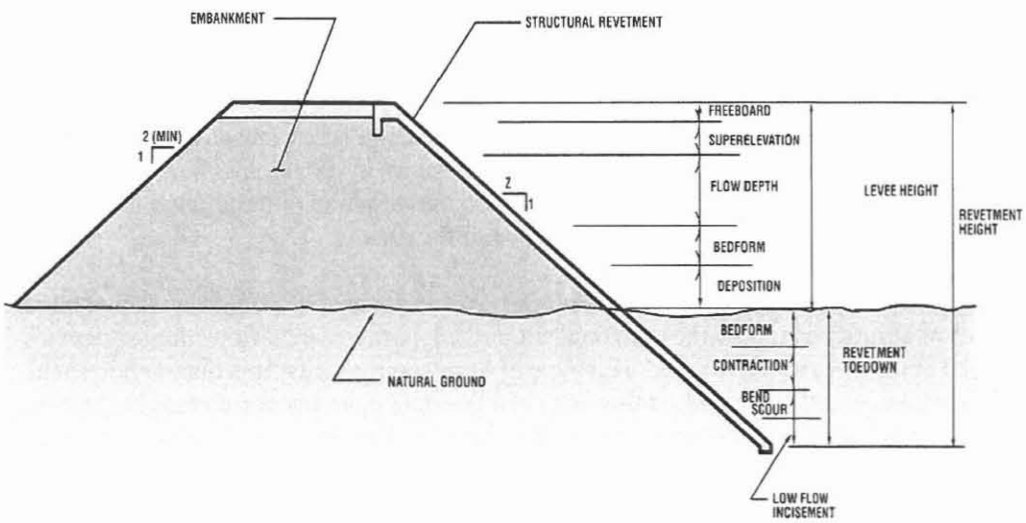
$$\frac{y_2}{y_1} = \left(\frac{Q_{mc2}}{Q_{mc1}}\right)^{6/7} \left(\frac{W_{c1}}{W_{c2}}\right)^{K_1} \left(\frac{n_2}{n_1}\right)^{K_2}$$

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.



Design of Flood Protection for Transportation Alignments on Alluvial Fans

By Richard H. French,[1] Member ASCE

Abstract: The method of floodplain delineation on alluvial fans developed for the National Flood Insurance Program (NFIP) may be modified to provide estimates of peak flood flows of specified return periods at transportation alignments, such as aqueducts or railroads, crossing alluvial fans. The modified methodology divides the total length of the alignment into segments, and the peak flow expected in each segment during a flood event is estimated as a function of the return period of the event, the segment length, and the location of the alignment on the alluvial fan. This estimate of the peak flow can be used to properly size the facilities such as dikes, berms, and culverts to protect the alignment from flood damage. The proposed methodology has potential applications in any environment where transportation alignments must cross alluvial fans on which the hydraulic processes are similar to those for which the NFIP methodology was developed. An example of the use of this methodology is provided.

Introduction

It is generally recognized that the design of flood-control facilities in the arid and semiarid western United States is often more difficult than in the more humid areas of the country for a number of reasons. First, the traditional methods of flood frequency analysis using historic stream flow records are generally not applicable because of a lack of data and the highly episodic nature of flood events in the desert environment. Second, precipitation records are generally short, the gaging stations poorly distributed, and the records available often erratic and unreliable. Therefore, the use of precipitation-driven watershed models in the arid environment yield estimates of flood hydrographs with a greater degree of variability than similar hydrographs in other regions. Furthermore, there are usually not sufficient data to either fully calibrate or validate the watershed models used. Third, sediment transport is a more serious consideration in the arid environment than in humid areas. Fourth, in the alluvial fan environment, which is a significant portion of the area in the southwestern United States, the channels are neither well defined nor stable.

A methodology was developed to identify flood hazard zones on alluvial fans, by Dawdy (1979), for the National Flood Insurance Program (NFIP). In its intended application, this methodology defines the boundaries of the flood hazard zones but provides minimal information to the hydraulic engineer for the design of drainage protection. An extensive review of the literature, French et al. (1991), also revealed that there is minimal guidance regarding the design of drainage protection for transportation systems crossing alluvial fans.

In this paper, the Federal Emergency Management Agency (FEMA) method of delineating floodplains on alluvial fans is modified and used to

---

[1]Res. Prof., Water Resour. Ctr., Desert Res. Inst., P.O. Box 19040, Las Vegas, NV 89132-0040.

Note. Discussion open until September 1, 1992. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on April 5, 1991. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 118, No. 2, March/April, 1992. ©ASCE, ISSN 0733-9437/92/0002-0320/$1.00 + $.15 per page. Paper No. 1659.

estimate peak flood flows at transportation alignments, such as aqueducts and railroads, crossing alluvial fans. The total length of the alignment is divided into segments, and the peak flow expected in each segment during a flood event is estimated as a function of the return period of the event, the segment length, and the location of the alignment on the alluvial fan. The proposed methodology has potential applications in any environment where transportation alignments must cross alluvial fans on which the hydraulic processes are similar to those for which the FEMA alluvial fan methodology was developed.

Background

From a geomorphologic viewpoint, an alluvial fan is a triangular or fan-shaped deposit of boulders, gravel, and finer sediment found at the base of desert mountain slopes deposited by intermittent streams as they debouch onto the valley floor (Stone 1967). There are many other definitions of alluvial fans; for example, FEMA (Federal Register 1989) stated the following definition:

> "Alluvial fans are geomorphic features characterized by cone- or fan-shaped deposits of boulders, gravel, sand, and fine sediments that have been eroded from mountain slopes, transported by floodwater draining upstream watersheds, and then deposited on the adjacent valley floor. . . . flooding that occurs on active alluvial fans is characterized by fast-moving debris and sediment laden shallow flows. The paths followed by these flows are prone to lateral migration and sudden relocation to other portions of the fan. In addition, these fast moving flows present hazards associated with erosion, debris flow, and sediment transport."

Bull (1968) noted that no single criterion should be used to define an alluvial fan. From the viewpoint of hydraulic engineering, the focus of the definition of alluvial fan should be the processes that formed and continue to modify the fan, or fan-like landform, rather than a description of the landform itself. If such a viewpoint is adopted, then an alluvial fan should exhibit the following characteristics. First, the surface must be a feature on which deposition and erosion are active processes on an engineering, as opposed to a geologic, time scale. Surface activity is a primary characteristic, since stable incision of a channel on an alluvial fan surface can result in portions of the surface being abandoned and thus becoming inactive. Channel incision may also result in the effective apex of the fan being moved down the fan. Over any reasonable time scale (engineering or geologic), an alluvial fan must, on the average, be an aggradational feature, in both time and space. However, at specific location during a specific period of time erosion may be taking place.

Second, there should be a defined apex that is the highest point on the active surface where the stream that forms the surface emerges from either the mountain front or from an area on the surface where the channel is stably incised.

Third, the primary slope of the surface is in the radial direction, Fig. 1, with small slopes in the transverse directions. In the case of fans in the United States, the radial slope should, in general, range between 0.0087 ft/ft and 0.14 ft/ft (Anstey 1965).

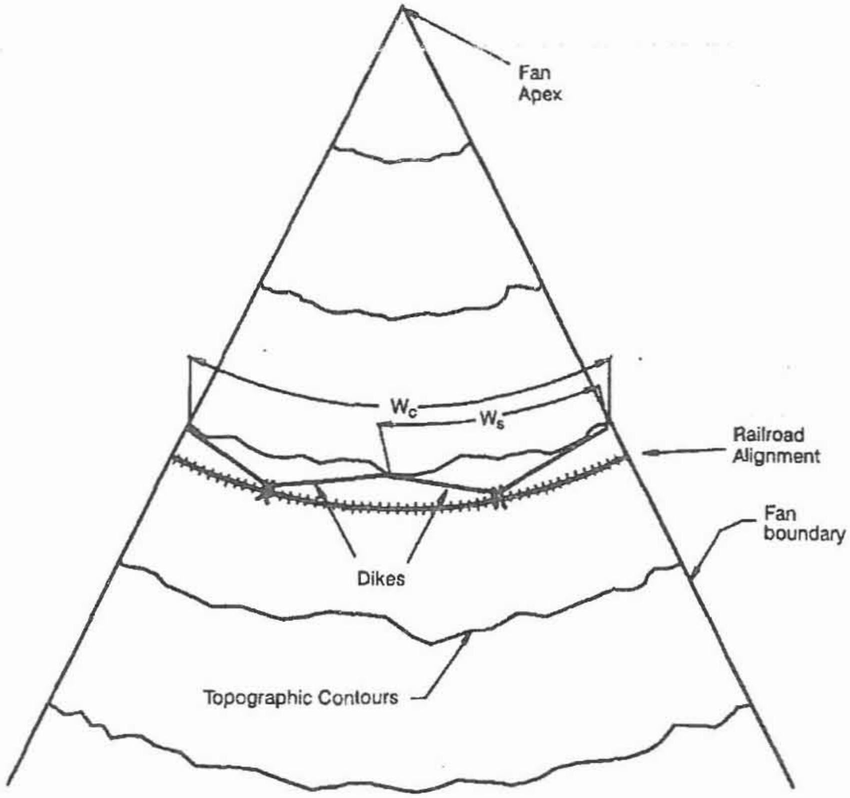


FIG. 1. Schematic Definition of Idealized Alluvial Fan and Proposed Railroad Alignment Crossing Fan. Topographic Contours Shown, Schematically, are Equally Spaced

Fourth, channels on the fan surface are poorly defined and are not stably entrenched. Flood flows on the fan surface will cut their own channels through the existing alluvial material by bottom scour and channel side-wall erosion; and these channels, during either a single event or over a series of flood events, will migrate across the surface (Dawdy 1979). Therefore, the location of the channel on an alluvial fan surface is random.

Development of Methodology

As described elsewhere, Dawdy (1979), Mifflin (1988), and French (1987), because the location of the channel on an alluvial fan is hypothesized to migrate during a single event or over a series of events, FEMA developed a stochastic methodology to assess flood hazard on alluvial fans. This stochastic methodology takes into account the hydraulic and geomorphologic processes that formed the surface and continue to modify it; that is, channel migration is essential if a symmetric landform is to be developed. In the following paragraphs, the equations composing the FEMA methodology are briefly developed; for a more detailed development, the reader is referred to Dawdy (1979) or FEMA (Fan 1990).

Let H be a random variable that has the following meaning for discrete points on an alluvial fan

$$H = \begin{cases} 1, \text{ if the point is flooded} \\ 0, \text{ if the point is not flooded} \end{cases}$$

Let Q be a second random variable that is the peak flood flow rate resulting from a precipitation event of a known return period occurring in the upstream watershed. If $f(q)$ is the probability density function (PDF) of Q, then the probability of a point being flooded during an event with a peak flow rate of at least q_o is

$$P(H = 1) = \int_{q_o}^{\infty} P_H|_Q(1,q)f(q)\,dq \quad \text{.......................} \quad (1)$$

where $P_H|_Q(1,q)$ = the probability of the point of interest being flooded given that the peak flood discharge is q_o. The PDF of Q is generally assumed to be log-Pearson type III (LP3) (Dawdy 1979), which is a log-normal distribution when the LP3 skew coefficient is zero. In this development, the skew coefficient will be assumed to be zero, for notational convenience and brevity, with the understanding that a similar development can be performed in the case where the LP3 skew coefficient is nonzero. When $f(q)$ is assumed to be described by an LP3 distribution and the skew coefficient is zero, Eq. (1) becomes

$$P(H = 1) = \frac{1}{T} = \int_{y_T}^{\infty} P_H|_q(1,q)\,\frac{\exp\left[\dfrac{-0.5(y - \mu)^2}{\sigma^2}\right]}{\sigma\sqrt{2\pi}}\,dy \quad \text{..........} \quad (2)$$

where $y_T = \log_{10}(q_T)$; q_T = peak flood flow with a return period of T years; μ = mean value; and σ = standard deviation of the PDF of Q.

Since FEMA must delineate areas of flood hazard on alluvial fans for the NFIP, the original FEMA methodology estimated the probability of hazard at points on the alluvial fan. As noted by French and Lombardo (1984) and Mifflin (1988), when the facility of interest has finite size, the floodplain delineation methodology must be modified. In the case of a transportation alignment crossing an alluvial fan, the facility has a finite length; and in many cases, the alignment would extend completely across the alluvial fan (Fig. 1). In such cases, one drainage design approach is to subdivide the total alignment length into segments and provide adequate facilities (dikes, berms, culverts) in each segment to pass the flow under the alignment in the case of railroads and highways and over or under the alignment in the case of canals. If the length of a drainage design segment is W_s and the width of the fan contour at the location of the alignment is W_c, then a simple equation quantifying $P_H|_q(1,q)$ is

$$P_H|_Q(1,q) = \frac{w + W_s}{W_c} \quad \text{.................................} \quad (3)$$

where w = width of the channel cut by the flood flow crossing the fan and subject to $(w + W_s) \leq W_c$. Eq. (3) tacitly assumes that there are not preferred directions of flow on an alluvial fan surface, and having taken the size of the facility into account, the probability of flooding along a topographic contour is uniform. Other equations quantifying $P_H|_Q(1,q)$ could be hypothesized; however, given the available data, more complex forms are not currently justified.

Based on limited field observations, Magura and Wood (1980) asserted that alluvial fan channels stabilize at a point where a decrease in the depth of flow results in a 200-fold increase in width. This assumption, combined with the assumption that during flood events flow in these channels occurs at critical depth (Dawdy 1979), yields an equation, in English units, for the width of the channel or

$$w = 9.41q^{0.4} \qquad (4)$$

Other assumptions can be made regarding the width of the channel cut through the alluvium; see for example, Edwards and Thielman (1984).

Additional field observations, DMA (*Alluvial Fan* 1985) or French (1987), resulted in the hypothesis that near the apex of the fan, flood flows are confined to a single channel, and at some point down the fan from the apex, the flood flow is conveyed in multiple channels. In Fig. 2, the radial distance from the apex of the alluvial fan to the point on the fan where the single channel branches into multiple channels is plotted as a function of the ratio of the slope of the canyon upstream of the apex to the slope of the fan. In the multiple channel region of the alluvial fan, limited field observations suggest that the aggregate width of the channels is 3.8 times the width estimated by (4), French (1987), or FEMA (*Fan* 1990). Therefore, in the multiple channel area

$$w = 35.8q^{0.4} \qquad (5)$$

Substitution of (3) in (2) yields

$$\frac{1}{T} = \int_{y_T}^{\infty} \left(\frac{w + W_s}{W_c}\right) \frac{\exp\left[\dfrac{-0.5(y - \mu)^2}{\sigma^2}\right]}{\sigma\sqrt{2\pi}}\, dy \qquad (6)$$

Substitution of either (4) or (5) in (6) yields after manipulation

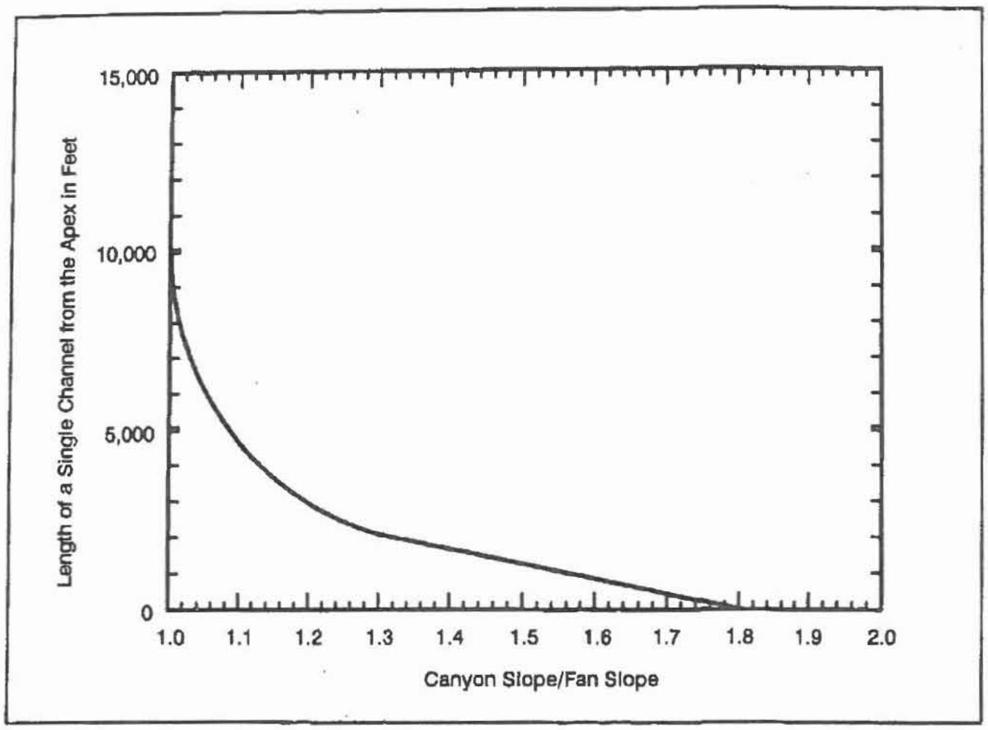


FIG. 2. Relationship between Length of Single Channel and Ratio of Canyon Slope to Fan Slope ("Flood Insurance" 1985)

$$\frac{1}{T} = \frac{AC\beta}{W_c}\int_{y_T}^{\infty}\frac{\exp\left[\frac{-0.5(y-\mu')^2}{\sigma^2}\right]}{\sigma\sqrt{2\pi}}dy$$

$$+\frac{W_s}{W_c}\int_{y_T}^{\infty}\frac{\exp\left[\frac{-0.5(y-\mu)^2}{\sigma^2}\right]}{\sigma\sqrt{2\pi}}dy \quad \ldots\ldots\ldots\ldots (7)$$

where

$$C = \exp(0.92\ \mu + 0.42\ \sigma^2)$$

$$\mu' = \mu + 0.92\ \sigma^2$$

and $\beta = 9.41$ in the single channel region and $\beta = 35.8$ in the multiple channel region. The coefficient A in (7) is the avulsion coefficient that takes into account that during a flood event the flow may abandon one channel and either follow or form a new channel. An avulsion can result from the sudden deposition of sediment and/or debris with the flow then overtopping the channel banks or by erosion of the banks. If the probability of an avulsion occurring in any one event is 0.5, A would have a value of 1.5.

On the right-hand side of (7), the first term is the probability of a point on the alluvial fan contour of length W_c, Fig. 1, being flooded, on the average every T years; and the second term is the probability of the flow rate q_T being equaled or exceeded at the apex of the fan. The integral in the first term is a transformed log-normal PDF, and the integral in the second term is an untransformed log-normal PDF. Values of the log-normal and LP3 deviates are tabled in WRC (*Guidelines for* 1981) as a function of the skew coefficient and exceedance probability. The form of (7) masks the fact that it is only valid when $(w + W_s) \leq W_c$ in (3).

Application

In Fig. 1, a hypothetical railroad alignment is shown crossing an idealized alluvial fan. This alignment nearly parallels an alluvial fan contour, which, given the grade limitations on railroads, is realistic. Similar grade limitations also apply to irrigation and water-supply aqueducts crossing alluvial fans; and therefore, this example is equally applicable to the design of drainage protection for aqueducts crossing alluvial fans. The length of the alluvial fan contour (W_c) at the elevation of the proposed crossing is approximately 3,000 ft (910 m).

In the first section of this paper, a number of difficulties associated with estimating flood flows in the arid southwestern environment were enumerated. A typical approach to this problem is to use a watershed rainfall-runoff model, such as HEC-1, in the watershed above the fan apex to predict peak flows at the apex of the alluvial fan; see for example, Burkham (1988). The input to the watershed model would be regional analyses of precipitation such as Miller et al. (1973) or the results of local studies such as Clark County Regional Flood Control District (CCRFCD) (*Hydrologic Criteria* 1990). The estimated peak flood flow rates are then used with the equations provided by WRC ("Guidelines for" 1981) or Dawdy (1979) to estimate the LP3 mean, standard deviation, and skew coefficient required for the analysis described previously. In general, the skew coefficient for watersheds in the arid southwest should have a value near zero; see for example, the generalized skew coefficient data provided by WRC ("Guidelines for" 1981).

For the purposes of the example problem, it is assumed that commonly accepted rainfall-runoff modeling of the watershed above the fan has resulted in the following estimates of the LP3 parameters: $\mu = 2.06$, $\sigma = 0.496$, and $G = 0$ where G is the skew coefficient. The values of the parameters for the transformed log-normal PDF, the first term in (7), are $\mu' = 2.29$ and $C = 7.38$. If the avulsion coefficient is assumed to have a value of 1.5 ("Flood Insurance" 1985), which is a standard assumption lacking data to the contrary, then substitution of values in (7) yields

$$\frac{1}{T} = 0.035 \int_{y_T}^{\infty} \frac{\exp\left[\dfrac{-0.5(y - 2.29)^2}{0.496^2}\right]}{1.24}\, dy + \frac{W_s}{3{,}000} \int_{y_T}^{\infty} \frac{\exp\left[\dfrac{-0.5(y - 2.06)^2}{0.496^2}\right]}{1.24}\, dy \quad \text{(8)}$$

in the single channel region of the fan. In the multiple channel region of the fan, the coefficient preceding the integral in the first term would have a value of 0.13.

If the event return period, T, for which alignment protection is to be provided, is selected, then (8) can be solved for various values of W_s to estimate the peak flow rate q_T that can be expected to occur in a drainage segment every T years. For example, given the data provided and with T

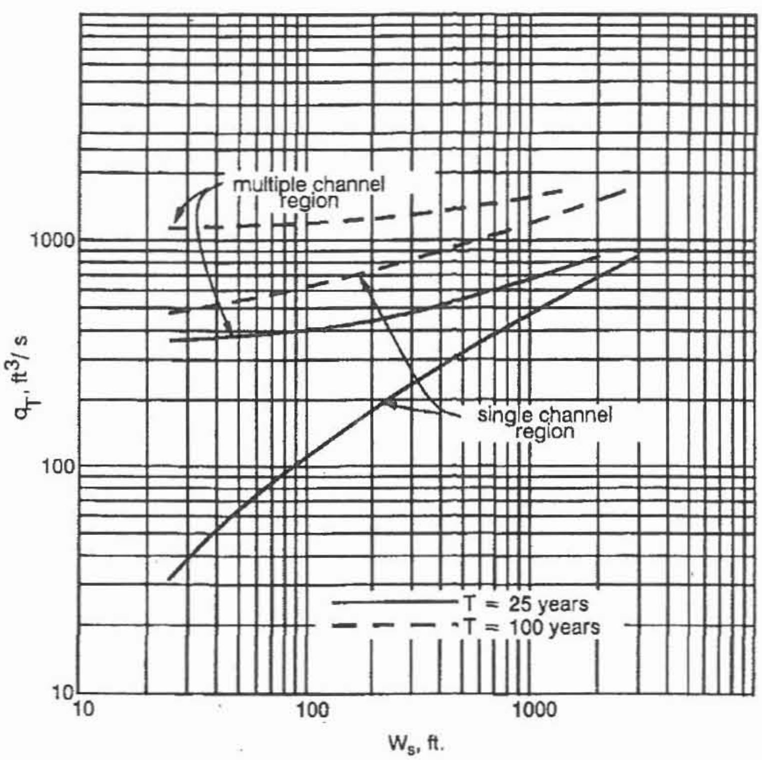


FIG. 3. Expected Flow at Alignment with Return Period of *T*-years, as Function of Length of Drainage Segment (0.305 m = 1 ft and 0.028 m³/s = 1 cu ft/sec)

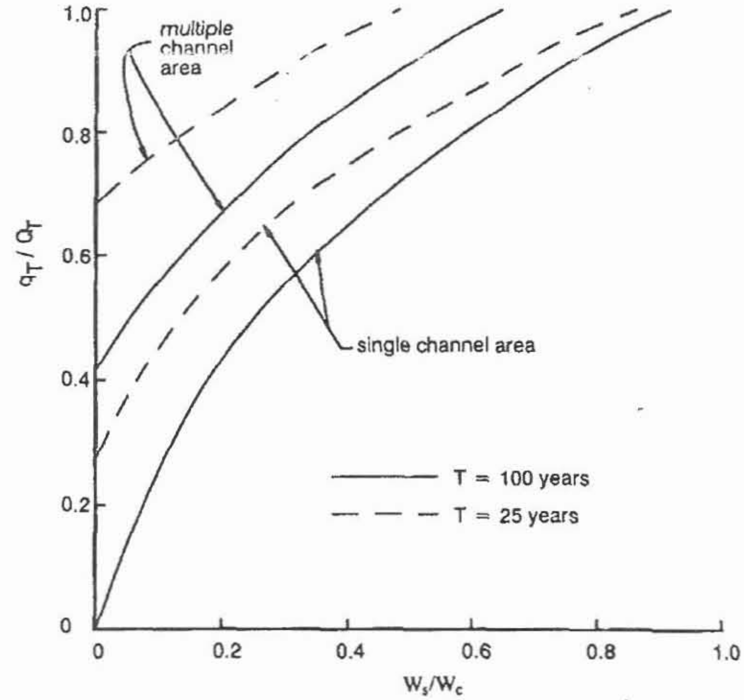


FIG. 4. Ratio of q_T/Q_T as Function of Ratio W_s/W_c

= 25 years and W_s = 1,000 ft (305 m), in the single channel region of the fan the first term = 0.007 and the second term = 0.033 when q_T = 510 cu ft/sec (14 m^3/s). For these data, the left-hand side of (8) has a value of 0.04 and the right-hand side (the first and second terms) also has a value of approximately 0.04. Therefore, the estimated peak flood flow rate at the alignment with a return period of 25 years is 510 cu ft/sec (14 m^3/s) when the drainage segment length is 1,000 ft (305 m).

In solving (8), care is required for two reasons. First, as noted previously, $(w + W_s) \leq W_c$. In (8), W_s is an explicit variable; however, the value of w is not obvious. Second, the flow rate q_T at the alignment cannot exceed the flow rate of the same return period at the apex of the fan, Q_T. Given the form of (8), these are not completely independent requirements.

In Fig. 3, q_T is plotted as a function of W_s for the hydrologic data provided; return period of 25 and 100 years; and an avulsion coefficient value of 1.5. For the hydrologic data provided, the LP3 estimated flow rates with return periods of 25 and 100 years are Q_{25} = 850 cu ft/sec (24 m^3/s) and Q_{100} = 1,640 cu ft/sec (46 m^3/s), respectively. In Fig. 3, the curves are terminated where $q_T = Q_T$; and at these points of curve termination the condition $(w + W_s) \leq W_c$ is also satisfied. In Fig. 4, the data presented in Fig. 3, in the range of valid solutions, are plotted in dimensionless form. In Fig. 5, q_T is plotted as a function of W_s for avulsion coefficient values of 1.0, 1.5, and 2.0. In Fig. 5, the return period is 25 years; and only the results for the single channel region of the fan are presented.

With regard to Figs. 3–5, the following observations are pertinent. First, q_T is the peak flood flow rate that will occur in a drainage segment of specified length on the average once every T-years. As W_s approaches W_c, q_T approaches Q_T, (Figs. 3 and 4). This is a reasonable result; that is, as the drainage segment length becomes large relative to the fan contour width, there is an increasing probability that the T-year event at the apex will strike it. Second, whether the alignment is in the single or multiple channel region of the alluvial fan, it has a significant effect on the value of q_T (Figs. 3 and

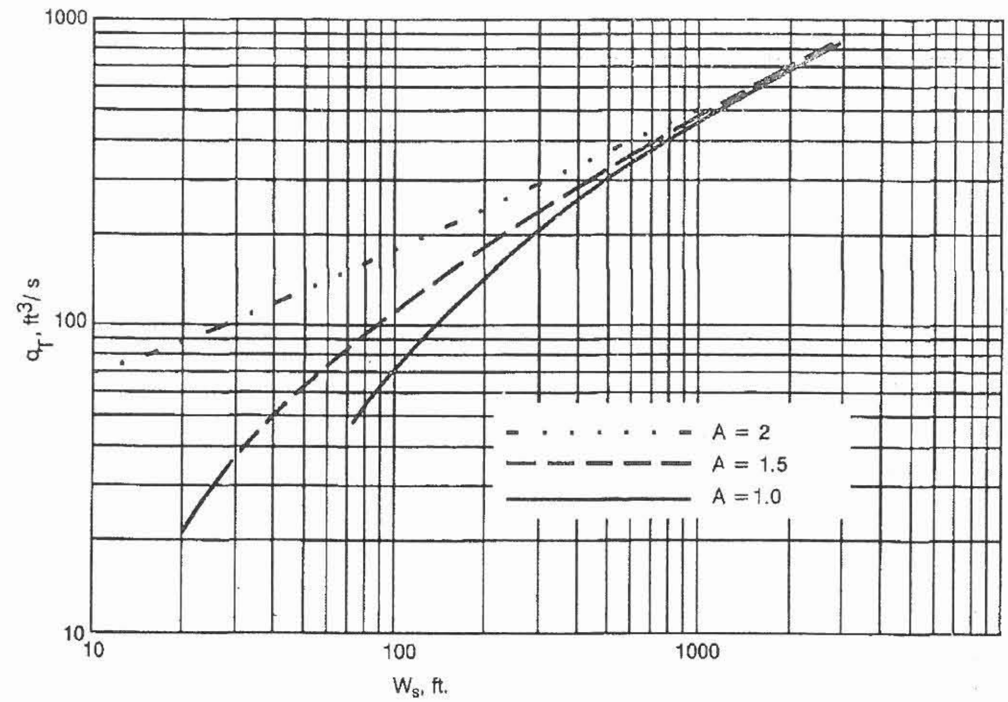


FIG. 5. q_T **as Function of** W_s **for Various Values of** A**, Avulsion Coefficient. In this Figure,** T **= 25 years and Only Results for Single Channel Region of Fan are Presented (0.305 m = 1 ft and 0.028 m³/s = 1 cu ft/sec)**

4). Third, the results for the multiple channel region of the fan are conservative since it is not certain that all of the multiple channels conveying the flood would impact the same drainage segment length. Fourth, the effect of the value of the avulsion coefficient on q_T is the most pronounced when W_s is small relative to W_c (Fig. 5). In (8), as W_s approaches W_c, the value of the second term becomes large relative to the first term; and therefore, the effect of the avulsion coefficient on the result becomes less.

CONCLUSION

The methodology developed and discussed in the previous sections of this paper is intended to provide discharge estimates as a function of return period that will allow drainage protection for transportation alignments crossing alluvial fans to be designed on a rational basis. The proposed methodology takes into account the hydraulic and geologic processes that formed and continue to modify alluvial fan surfaces and is a modification of the methodology used by FEMA to define floodplains on alluvial fans. Given that the proposed methodology is based on the FEMA methodology, it is subject to the same limitations. It must be admitted that the FEMA methodology is based on an incomplete and empirical understanding of the hydraulic processes on an alluvial fan and contains a number of assumptions that have not been validated. However, even given the limitations of the base methodology, the approach presented here provides a rational basis for sizing transportation drainage structures given the location of the alignment on the fan, the return period of the design event, and the drainage segment length.

Acknowledgment

The work on which this paper is based was supported by the U.S. Department of Energy under Contract No. DE-AC08-90NV10845. However, the opinions and interpretations discussed in this paper are not necessarily those of the Department of Energy. The comments of the reviewers were appreciated as were the comments of Syndi Flippin, Research Engineer, Water Resources Center, Desert Research Institute, Las Vegas, Nevada.

Appendix I. References

Alluvial fan flooding methodology: An analysis. (1985). DMA Consulting Engineers, Marina del Rey, Calif.

Anstey, R. L. (1965). "Physical characteristics of alluvial fans." *Technical Report ES-20*, U.S. Army Natick Lab., Natick, Ma.

Bull, W. B. (1968). *Alluvial fans.* Nat. Sci. Foundation, Washington, D.C.

Burkham, D. E. (1988). "Flood-prone areas in the Great Basin of Nevada and adjacent states." *Water Supply Paper 2316*, U.S. Geological Survey, Washington, D.C.

Dawdy, D. R. (1979). "Flood frequency estimates on alluvial fans." *J. Hydr. Div.*, ASCE, 105(11), 1407–1412.

Edwards, K. L., and Thielman, J. (1984). "Alluvial fans: novel flood challenge." *ASCE, Civ. Engrg.*, ASCE, 54(11), 66–68.

Fan: An alluvial fan flooding computer program. (1990). Fed. Emergency Mgmt. Agency, Washington, D.C.

Federal register. (1989). 54(156), 33547.

"Flood insurance study: Guidelines and specifications for study contractors." (1985). *FEMA-37*, Fed. Emergency Mgmt. Agency, Washington, D.C.

French, R. H. (1987). *Hydraulic processes on alluvial fans.* Elsevier Science Publishers, Amsterdam, The Netherlands.

French, R. H., and Lombardo, W. S. (1984). "Assessment of flood hazard at the radioactive waste management site in Area 5 of the Nevada Test Site." *DOE-NV-10162-15.* Water Resour. Ctr. Desert Res. Inst., Las Vegas, Nev.

French, R. H., Preator, L., and Nicholson, R. (1991). *Development of methodologies for the identification of flood hazard zones along potential rail access corridors to the Yucca Mountain Site. Water Resour. Ctr., Desert Res. Inst., Las Vegas, Nev.*

"*Guidelines for determining flood flow frequency.*" (1981). *Bulletin 17B*, U.S. Water Resour. Council, Washington, D.C.

Hydrologic criteria and drainage design manual. (1990). WRC Engineering, Inc., Denver, Colo.

Magura, L. M., and Wood, D. E. (1980). "Flood hazard identification and flood plain management on alluvial fans." *Water Resources Bulletin*, 16(1), 56–62.

Mifflin, E. R. (1988). "Design depths and velocities on alluvial fans." *Proc. of the 1988 Nat. Conference on Hydr. Engrg.*, ASCE, 155–160.

Miller, J. F., Frederick, R. H., and Tracey, R. J. (1973). *Precipitation-frequency atlas of the western United States.* Volume VII, U.S. Dept. of Commerce, NOAA, Nat. Weather Service, Silver Spring, Md.

Stone, R. O. (1967). "A desert glossary." *Earth science reviews*, 3. Elsevier Publishing Co., Amsterdam, The Netherlands, 211–268.

Appendix II. Notation

The following symbols are used in this paper:

A = avulsion coefficient;
C = computed coefficient;
$f(q)$ = probability density function of Q;

H = random variable;
Q = peak flood flow rate resulting from precipitation event of known return period;
Q_T = peak flood flow rate with return period of T-years at apex of alluvial fan;
q = flow rate in alluvial channel of width w;
q_T = peak flood flow rate with return period of T-years at a point in the drainage segment;
T = event return period in years;
W_c = alluvial fan contour width;
W_s = drainage segment length;
w = width of channel cut by flood flow across alluvial fan;
y_T = dummy variable of integration;
β = coefficient which has value of 9.41 in single channel area of alluvial fan and 35.8 in multiple channel area;
μ = mean value of log-normal PDF;
μ' = mean value of transformed log-normal PDF; and
σ = standard deviation of log-normal PDF.

Estimating the Depth of Deposition (Erosion) at Slope Transitions on Alluvial Fans

By Richard H. French,[1] Julianne J. Miller,[2] and Steve Curtis[3]

Abstract: A typical flood mitigation structure on an alluvial fan consists of a dike/channel system that deflects the flow away from the area requiring protection. Such a structure results in a change in channel slope from steep to mild when the flow first encounters the structure and from mild to steep when the flow is released at the downstream end of the structure. These slope changes result in sediment deposition at the point where the flow encounters the structure and erosion at the point of release. In designing the structure, the length and maximum depth of deposition (erosion) are critical variables that must be estimated. A simple model to estimate these variables is proposed and developed. The hypothesized model has been used to estimate the length and depth of deposition (erosion) on several projects in southern Nevada.

INTRODUCTION

Sediment transport problems related to the identification and mitigation of flood hazard on alluvial fans in arid and semiarid environments is a current and critical concern of the engineering profession. In particular, estimating the length and maximum depth of deposition or erosion that occurs during a flow event when there is a change in the longitudinal slope of the channel is an important problem. Deposition occurs when the slope changes from steep to mild and erosion occurs when the slope changes from mild to steep. Although the focus of this paper is on deposition, the method is equally applicable to erosion, under certain conditions.

Flood control structures on alluvial fans protecting downstream facilities often consist of deflecting dikes and channel systems crossing the fan transversely (Fig. 1). At the point where the flow is intercepted by the dike/channel system, the ngitudinal slope of the conveyance channel changes from steep to mild and deposition results. When the flow is released at the end of the dike, the change is from mild to steep and erosion results. The length over which deposition occurs during a flow event is a critical issue since it determines the maximum depth of deposition, which can have a significant effect on the height of the dike. Existing 1D and 2D models provide little assistance in addressing this problem, because in these models, deposition must occur over the channel reach lengths defined by the user. Therefore, the length and maximum depth of deposition are somewhat arbitrary and have no theoretical basis.

The purpose of this paper is to describe an approach that has been used in Clark County, Nevada, and on the Department of Energy's Nevada Test Site to estimate the length and maximum depth of deposition when dike/channel systems transversely cross alluvial fans. Although neither field data nor observations are available to validate the approach described, it is hoped that the publication of this paper may stimulate discussion and identify data either justifying the approach or suggesting modification. It is appropriate to note that throughout history civil engineers have had to design structures to improve the quality of life and allow the validity of the approach to be proven in the future.

ASSUMPTIONS

In developing this approach, two assumptions were made. First, without geologic controls (such as an erosion resistant caliche, fault, or soil layer or bedrock) longitudinal slope transitions do not abruptly occur in alluvial fan channels. Therefore, when the longitudinal slope of a channel changes from steep to milder, deposition occurs; and it is hypothesized that the deposition will form a smooth transition between the slopes over some unknown distance.

Second, the slopes and geometries of the conveyance channels, hydrograph, sediment size characteristics, and other variables and parameters controlling sediment transport are known. Modeling unsteady sediment transport across alluvial fans is often based on sediment routing procedures. That is, the event hydrograph is partitioned into increments during which the flow can be assumed pseudo-steady. Then, using these quasi-steady flows, a sediment transport algorithm is used to estimate the equilibrium sediment transport rate for the specified flow rate, channel geometry, sediment size characteristics, and channel longitudinal slope. Therefore, when the longitudinal slope of the channel changes from steep to milder, the volume of sediment that must be deposited is estimated by subtracting the downstream equilibrium transport rate from the upstream transport rate and integrating over time.

Therefore, it is hypothesized that the sediment deposition will form a smooth transition between the steep and milder slopes; and further, this transition can be approximated by a vertical parabolic curve that smoothly joins the slopes (Fig. 2). The hypothesized transition curve is similar to the approach

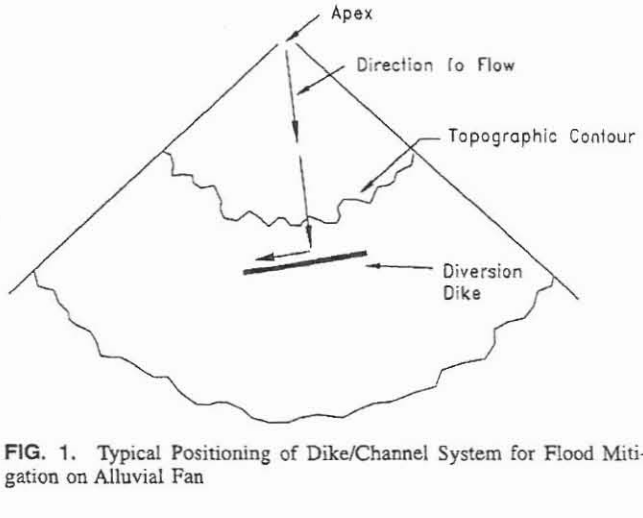


FIG. 1. Typical Positioning of Dike/Channel System for Flood Mitigation on Alluvial Fan

[1]Res. Prof., Div. of Hydrologic Sci., Desert Research Inst., 7010 Dandini Blvd., Reno, NV 89512.

[2]Asst. Res. Hydro., Div. of Hydrologic Sci., Desert Research Inst., 7010 Dandini Blvd., Reno, NV 89512.

[3]Asst. Res. Hydro., Div. of Hydrologic Sci., Desert Research Inst., 7010 Dandini Blvd., Reno, NV 89512.

Note. Discussion open until February 1, 2002. To extend the closing 'ate one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this technical note was submitted for review and possible publication on March 6, 2000; revised April 19, 2001. This technical note is part of the *Journal of Hydraulic Engineering*, Vol. 127, No. 9, September, 2001. ©ASCE, ISSN 0733-9429/01/0009-0780–0782/$8.00 + $.50 per page. Technical Note No. 22283.

JOURNAL OF HYDRAULIC ENGINEERING
TECHNICAL NOTES

Technical notes provide a way of publishing: (1) Original, practical information; (2) preliminary or partial results of research; (3) concisely presented research results; and (4) innovative techniques to accomplish design objectives. Technical notes should not exceed 3,500 words or word-equivalents in length. An abstract of 150–175 words, which will be published if length permits, should be submitted with the technical note. Abstracts for technical notes are included in *Transactions, ASCE Publications Information*, and Civil Engineering Database. Discussions may be written on Notes.

Five copies of the original note (and all figures and tables) should be submitted to the Journals Department, ASCE, 1801 Alexander Bell Dr., Reston, VA 20191–4400. Authors must state which journal their paper is being submitted to. (Some journals further require that authors state which technical or task committee is appropriate to review the paper.) The review and publication procedures will be faster if the basic requirements, listed here, are followed.

1. The manuscript including abstract and references must be typed double-spaced (10 mm baseline to baseline) on one side of 215 mm × 280 mm (8.5 × 11 in.) paper.
2. The length of titles must not exceed 70 characters and spaces.
3. Authors can approximate manuscript length by counting the number of words on a typical manuscript page and multiplying that by the number of total pages (except for tables and figures). Authors should add word-equivalents for figures and tables by estimating the portion of the journal page each will occupy when reduced, usually 50% to 75%, to fit within the 185 mm × 250 mm live area of the journal page. (A journal page contains approximately 1,260 words; e.g., a figure reduced to one-quarter of a page would be 315 word-equivalents.) When reduced, the figure must be legible and its type no smaller than 6 point (2.12 mm). Overlength manuscripts that receive a positive review must go through a special approval process before publication; however, this procedure is not intended to discourage valuable overlength contributions.
4. Authors need not be Society members. Each author's full name and Society membership grade (if applicable) should appear immediately beneath the title. Each author's present title and affiliation, and complete mailing address must appear as a footnote at the bottom of the first page of the note.
5. All mathematics must be typewritten, and special symbols must be identified. Letter symbols should be defined in the text when they first appear and arranged alphabetically in a section entitled "Notation" at the end of the paper.
6. Standard definitions and symbols should be used. Authors should refer to the lists published by the American National Standards Institute and the *ASCE Authors' Guide to Journals, Books, and Reference Publications.*
7. Figures: Line art should be submitted in black ink or laser printed; halftones and color should be original, glossy art. Figures should be submitted at final width: 88 mm (3.5 in.) for one column and 185 mm (7.25 in.) for two columns. Lettering and symbols should be legible at final size. For maximum readability, letters should be in upper and lower case in a sans serif typeface. Background screening and grids should be eliminated.
8. Each table must be typed on one side of a single 215 mm × 280 mm sheet of paper.
9. References cited in the text should be listed in alphabetical order in "References," double-spaced, and placed at the end of the paper (but preceding any "Notation" section).
10. An abstract of 150–175 words should be provided.
11. Each author must use SI (International System) units and units acceptable in SI. Other units may be given in parentheses following the appearance of SI units or in an appendix.
12. If experimental data and/or relations fitted to measurements are presented, the uncertainty of the results must be stated. The uncertainty must include both systematic (bias) errors and imprecisions.

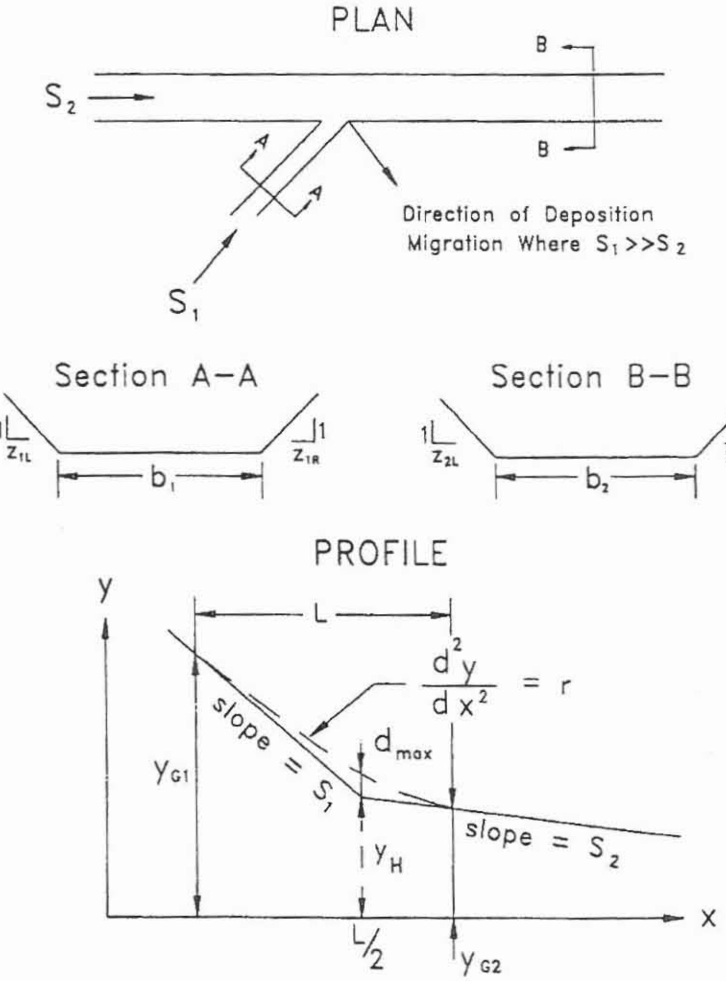


FIG. 2. Schematic Definition of Variables

described by the U.S. Bureau of Reclamation (USBR 1987) to estimate erosion in a channel below a detention basin releasing desilted water.

THEORETICAL DEVELOPMENT

In Fig. 2, a hypothetical situation is shown in plan and profile. In this figure, the following variables are defined: x = horizontal coordinate, y = vertical coordinate defining the elevation of the channel bed above an arbitrary datum, L = total horizontal length of deposition, and y_H = hinge point elevation of the channel above the datum. Of the common channel shapes, a trapezoid with unequal side slopes is the most complex, but also the most general. For example, if the bottom width is zero, then the shape is triangular; and if the side slopes are zero, the channel shape is rectangular. For the channels shown in Fig. 2, the following variables are defined:

For $0 \le x \le 0.5L$ (Reach 1)
- Right side slope: z_{1R}
- Left side slope: z_{1L}
- Bottom width: b_1
- Longitudinal slope: S_1

For $0.5L \le x \le L$ (Reach 2)
- Right side slope: z_{2R}
- Left side slope: z_{2L}
- Bottom width: b_2
- Longitudinal slope: S_2

The differential equation defining the vertical curve smoothly joining the two channels in Fig. 2 is

$$\frac{d^2y}{d^2x} = r = \text{constant} \tag{1}$$

and the boundary conditions are

$$\text{at } x = 0;\quad \frac{dy}{dx} = S_1 \tag{2}$$

$$\text{at } x = L;\quad \frac{dy}{dx} = S_2 \tag{3}$$

$$\text{at } x = 0;\quad y = y_H - \frac{S_1 L}{2} \tag{4}$$

Integrating (1) twice and applying the boundary conditions yields

$$y_T = \frac{(S_2 - S_1)x^2}{2L} + S_1 x + y_H - \frac{S_1 L}{2} \tag{5}$$

where y_T = vertical elevation of the curve connecting the two channel reaches.

It can be shown that the depth of deposition in Reach 1 (y_1) is

$$y_1 = y_T - y_{G1} = \frac{(S_2 - S_1)x^2}{2L} \tag{6}$$

and integration of (6) provides an estimate of the volume of deposition or

$$V_1 = \frac{b_1(S_2 - S_1)}{48} L^2 + \frac{\theta_1(S_2 - S_1)^2}{640} L^3 \tag{7}$$

where

$$\theta_1 = \frac{z_{1R} + z_{1L}}{2} \tag{8}$$

Analogously, in Reach 2, the depth of deposition is

$$y_2 = y_T - y_{G2} = \frac{(S_2 - S_1)x^2}{2L} - (S_2 - S_1)x + \frac{(S_2 - S_1)L}{2} \tag{9}$$

and the volume of deposition is

$$V_2 = \frac{b_2(S_2 - S_1)}{48} L^2 + \frac{\theta_2(S_2 - S_1)^2}{640} L^3 \tag{10}$$

where

$$\theta_2 = \frac{z_{2R} + z_{2L}}{2} \tag{11}$$

The total volume of deposition in the two reaches is

$$V_D = V_1 + V_2 = \frac{(\theta_1 + \theta_2)(S_1 - S_2)^2}{640} L^3 + \frac{(b_1 + b_2)(S_2 - S_1)}{48} L^2 \tag{12}$$

If V_D is the volume of material to be deposited during an event, then the governing equation is

$$0 = \frac{(\theta_1 + \theta_2)(S_1 - S_2)^2}{640} L^3 + \frac{(b_1 + b_2)(S_2 - S_1)}{48} L^2 - V_D \tag{13}$$

which is a cubic equation that can be easily solved. In the case of a rectangular channel ($z_{1R} = z_{1L} = z_{2R} = z_{2L}$), (13) reduces to a quadratic equation. The maximum depth of deposition, which occurs at the hinge point, is given by

$$d_{max} = \frac{(S_2 - S_1)L}{8} \tag{14}$$

CONCLUSION

The foregoing methodology is an approach for estimating the length and maximum depth of deposition that takes place on an alluvial fan when the longitudinal slope changes from steep to milder. The method is equally applicable to estimating the length and maximum depth of erosion that takes place when the longitudinal slope changes from mild to steeper, if the channel bed does become armored and nonerodible subsurface layers are not encountered. It is a relevant question whether this approach provides reasonable estimates of the maximum depth of deposition. For the situation shown in Fig. 1, the approach is believed to be reasonable because the point where the channels join would migrate from the initial point of intersection in the direction shown in Fig. 1.

Finally, although this methodology has been used in the design of several large dike/channel systems on alluvial fans (Boyle Engineering Corp. 1992; Poggemeyer Design Group 1994; Bechtel Nevada 1999), there are neither laboratory nor field data supporting the validity of the hypothesized approach. Rather, it is a rational approach to an important engineering problem that currently lacks a proven solution. Studies are currently being proposed, which if funded, may demons the validity of the approach suggested or an alternative proach.

ACKNOWLEDGMENTS

The writers gratefully acknowledge the financial support of the U.S. Department of Energy under contract number DE-AC08-95NV11508. The writers also acknowledge Mark Glidden, HDR, Inc., Denver, Colorado, who in 1990–1991 worked with the first writer to develop the original concept.

REFERENCES

Bechtel Nevada. (1999). "As-built design analysis for the 25-year, flood protection system, Area 5, Radioactive Waste Management Site, Nevada Test Site, Nevada." Las Vegas.

Boyle Engineering Corp. (1992). "Supporting documentation for review of hydrologic changes resulting from the construction of the Range Wash Diversion Dike for the City of North Las Vegas." Las Vegas.

Poggemeyer Design Group. (1994). "Design memorandum for the Equestrian Detention Basin." Las Vegas.

USBR. (1987). "Sedimentation." *Design of small dams*, U.S. Department of Interior, Denver.

NOTATION

The following symbols are used in this paper:

- b_1 = channel bottom width in Reach 1;
- b_2 = channel bottom width in Reach 2;
- d_{max} = maximum depth of deposition (erosion);
- L = length over which deposition (erosion) occurs;
- S_1 = longitudinal slope of Reach 1;
- S_2 = longitudinal slope of Reach 2;
- V_D = total volume of deposition (erosion) over length L;
- V_1 = volume of deposition (erosion) in Reach 1;
- V_2 = volume of deposition (erosion) in Reach 2;
- x = longitudinal coordinate;
- y = vertical coordinate;
- y_H = pre-event hinge point elevation;
- y_{G1} = elevation of channel bottom where deposition (erosion) begins (Reach 1);
- y_{G2} = elevation of channel bottom where deposition (erosion) ends (Reach 2);
- y_T = elevation of post-event channel bottom;
- z_{1L} = channel left bank side slope in Reach 1;
- z_{1R} = channel right bank side slope in Reach 1;
- z_{2L} = channel left bank side slope in Reach 2;
- z_{2R} = channel right bank side slope in Reach 2;
- θ_1 = defined parameter; and
- θ_2 = defined parameter.

ALLUVIAL FAN LEVEE DESIGN

Example Calculations

1. Alluvial Fan – Self Forming Channel Hydraulics

The most widely known procedure for conducting hydraulic analysis of alluvial fans is the methodology adopted by FEMA. The procedure was originally developed by Dawdy (1979) and resulted in the development of the following equation for an self-forming entrenched channel on the alluvial fan. The procedure relies heavily on empirical equations relating depth and width of flow to discharge. The geometry of the alluvial fan channel is based upon field evidence that the channel will stabilize into the self-forming channel section (ie. erosion of the banks will cease) at a point where a decrease in depth causes a two-hundred fold increase in width.

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

where: W = channel width (ft)
Q = discharge (cfs)

Assuming that the hydraulic regime of the flow in this self-forming channel approaches critical (for best efficiency), the Froude number, F=1.0.

$$F = 1.0 = \frac{V}{\sqrt{g\,D_h}}$$

where: D_h = hydraulic depth (ft)
V = velocity (fps)

For a wide channel the hydraulic depth is considered equal to the flow depth, D:

$$D = \frac{Q}{WV} = \frac{\left[\frac{Q}{(9.5\,Q^{0.4})}\right]}{\sqrt{gD}} = \frac{Q^{0.6}}{9.5\sqrt{g\,D}}$$

This results in the following equations developed by Dawdy (1979) including the relationship between velocity and discharge:

$$V = 1.5\,Q^{0.2}$$

$$D = 0.07\,Q^{0.4}$$

$$q = \frac{Q}{W} = 0.105\,Q^{0.6}$$

Edwards and Thielman developed a modified procedure for the evaluation of the alluvial fan hydraulics based upon the application of Manning's equation for a wide rectangular channel, assuming a supercritical flow regime, and the use of Dawdy's original criteria that the self-forming channel will stabilize at a point where a decrease in depth causes about a two-hundred fold increase in width. Edwards and Thielman procedure resulted in the following equations:

$$D = \left(\frac{Qn}{178.8\sqrt{S}}\right)^{3/8}$$

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

Example:

Description	Example Fan Characteristics
100-year Discharge	14,720 cfs
Fan Slope (S_o)	0.030
Dawdy Procedure	
Width	441 ft
Velocity	10.22 fps
Flow Depth	3.25 ft
Edwards-Thielman Procedure	
Width	394 ft
Velocity	11.47 fps
Depth	3.28 ft

2. Levee Revetment Toedown Calculation

Slope Revetment Toe Protection Requirements

The primary failure mechanism of rigid bank protection revetments for alluvial channel systems is generally due to under scouring at the toe of the revetment. The design of the channel bank revetment must provide adequate toe-down protection below the earthen channel invert to account for dynamic changes in the streambed elevations during the passage of a storm hydrograph. The toe-down depth must consider the potential of general bed degradation, bend scour (for curved portion of the channel horizontal alignment), bedform height, abutment or contraction scour, and scour associated with hydraulic structures. Local scour needs to be

$$Z_{Total} = Z_{General} + Z_{Bend} + Z_{Bedform} + Z_{Structure} + Z_{Low\ Flow\ Incisement} + Z_{Contraction}$$

considered in addition to development of the potential long- term equilibrium channel slope or invert elevation that may develop from general degradation and sediment deposition.

Antidune Height

Bedforms usually develop in sand bed channels and create a succession of crest and troughs in a sinusoidal pattern along the channel bed depending upon the flow conditions. The potential exists for the creation of antidunes within an alluvial channel when the Froude number of the design flow is near or greater than 1.0. The distance between the mean bed elevation and the trough of the antidune is approximately equal to the distance from the mean bed elevation to the antidune crest, and the sum of these distances is termed the antidune amplitude. The amplitude

$$Z_A = 0.027\,V^2$$

of the antidune wave height, Z_A, is estimated by the following equation proposed by Kennedy (1963):

In this equation ***V*** is the flow velocity. If the antidune wave height computed from the above equation exceeds the flow depth, then the flow depth should be used rather than the computed value. Half the antidune wave height is the amount of scour that may have the potential to occur adjacent to a levee for the toe-down consideration. **However, if the calculated dune height exceeds the depth of flow, then the depth of flow is used for the dune height value** for toedown and channel height analysis.

Bend Scour

Bend scour occurs due to the transverse or secondary currents which develop as the flow is forced to change direction through impingment on the channel bank. Scour takes place along the outside of a bend and deposits along the inside of the bend. It is important to note that this scouring mechanism is caused by the spiral pattern of secondary currents, and is not due to a shift of the maximum longitudinal velocity against the outer bank. An estimate of the bend scour magnitude can be evaluated utilizing the relationship developed by Zeller (1981), which is based

$$Z_{Bend} = 0.0685\,D\,V^{0.8}\,(1.59\,(\frac{W}{R})^{0.2} - 1.0)/(D_h^{0.4}\,S_e^{0.3})$$

upon the assumption of constant stream power through the channel bend and can be used to determine the maximum bend scour component in sand-bed channels.

where: V = velocity of upstream flow
- D = upstream flow depth
- D_h = upstream hydraulic depth
- S_e = upstream energy slope
- W = channel width
- R = radius of curvature of the bend

Contraction or Abutment Scour

The proposed configuration for the upstream channelization inlet and flow training devices will develop the potential for abutment scour. The scour results from obstructions created to the natural floodplain width and the decreased flow area of the contraction channel section due to the channelization. With a decrease in flow area, there is an increase in average velocity and bed shear stress through the contraction. The abutment scour will occur in the stream bed upstream of the channel inlets. The increase in transport of bed material from the channel reach will lower the streambed elevation. Lauren (1960) derived the following live-bed contraction scour equation based upon a simplified sediment transport function:

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

where: Q_{mc}= flow in the main channel

W_{mc}= bottom width of the main channel

n = Manning friction factor

K_i = coefficient which is a function of bed material transport or shear

$$Z_{contraction\ scour\ depth} = y_2 - y_1$$

velocity/fall velocity, generally equals 0.69

The subscripts 1 and 2 refer to the upstream and contracted portions of the channel respectively. Where the main channel narrows naturally and there is no overbank flow, then the equation can be reduced to the ratio of the widths with an exponential term.

$$Z_{contraction} = 1.1\,(a/D)^{0.4}\ F^{0.33} \qquad (0 < a/D < 25)$$

An alternative procedure to evaluate the magnitude of the abutment scour utilizes the following

$$Z_{contraction} = 4.0\ F^{0.33} \qquad (a/D > 25)$$

relationships from Simons and Senturk (1974):

where: D = upstream flow depth (ft)

a = length which extends into the flow path (ft)

F = upstream Froude number

Determination of the local scour associated with the contraction of the channel section utilized one of these empirical methods, which ever provided the **largest scour depth**. The results will not be summed with the other scour components since these also involve the mechanics of flow impingement.

Low Flow Channel Entrenchment

The mechanics of alluvial streams generates a small, incised channel during period of low-flow rates or during the recession of the storm hydrograph. The incisement,when located adjacent to flood control channel revetments, can subject the structures to failure during subsequent major flood events. The magnitude of potential low-flow incisement that may occur in the vicinity of the proposed channel and transverse levees was estimated upon field reconnaissance. Field observation indicated that depths of incisement up to **two feet** can be anticipated and this value is recommended for use in the levee and channel toe-down design. The channelized portion will also be able to limit the maximum value of the low-flow incisement depth with the grade control structure spacing and the low-flow notch in the structure.

Channel Toedown Example Calculation

Toe Protection Depth = Bend Scour + Contraction Scour + ½ Antidune + Low Flow Incisement

$$\textbf{Toe-down}_{\text{Line A Levee}} \mathbf{= 5.9 + 17.0 + 4.8 + 4.0 = 26.0 \text{ ft (max)} \qquad 15.0 \text{ ft (min)}}$$

The levees function to train flows on a wide flood into a confined channelized section. As indicated previously, contraction scour will occur due to the associated change in cross section area. The toe-down near the channel entrance must account for this potential scour in addition to the other degradation components. The maximum toe-down requirement for the levees was estimated to include the sum of the streambed adjustments from (1) bend scour, (2) contraction or abutment scour, (3) one-half of antidune wave amplitude, and (4) low-flow incisement along the levee. The contraction scour is only applied within the influence zone near the levee entrance to the channelized section.

3. Levee Height

Training Levees and Transverse Levees (Use larger of heights)

· Total Height = $(\text{Critical Depth})_{100}$ + Deposition + Superelevation + 0.5 Antidune

· Total Height = $(\text{Total Energy})_{100}$

The 100-year flow depths were calculated with the HEC-RAS values

$$\textbf{Height}_{\text{Levee Sample}} \mathbf{= 8.7 + 1.8 + 2.3 + 5.2 = 18.0 \text{ ft}}$$

This maximum height of levee can be compared to the **specific energy for the 100-year event** as a worst case scenario for the design criteria and ensures that the flows can be intercepted by the channel system even if the incoming flow looses all velocity. The specific energy associated with the self-forming alluvial fan channel is **17.3 feet.**

4. Flow Impingement Deposition on Levee

The disruption in hydraulic and sediment transport characteristics that would be incurred as a result of the flow following this path could cause channel deposition and buildup upstream of the transverse. Flow which follows a path which impinges on the sample levee would encounter a reduction in slope. The slope along the upstream sample alluvial fan is approximately **0.031**, and the slope along the proposed transverse levee is **0.020**. The milder slope which occurs along a path adjacent to the transverse levee would generate lower average velocities and would develop the potential for deposition to occur within this zone. 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 the existing bed profile would be filled with sediment deposited due to the differential sediment transport rates of the upstream fan slope and the reach along the levee.

The sediment deposition volume over the 100-year flood hydrograph was determined by comparing the sediment transport capacity upstream of the fan (inflow sediment load) and that of the reach with a path parallel to the transverse levee (outflowing sediment). The sediment transport rates computed over a range of flood discharges were integrated over the entire 100-year flood hydrograph in order to estimate the total volumes. The inflowing sediment volume delivered from the upstream alluvial fan for a 100-year flood was estimated to be **107,880 cubic yards**. The computed outflowing sediment volume was **99,720 cubic yards**. The volume of sediment which would potentially be deposited is **8,160 cubic yards**.

The depositional area for the sediment volume would occur along a length upstream of the contact point with the transverse levee and extend to the channel inlet. The maximum deposition depth at the impingment point along the transverse levee can be computed based upon simple geometric relationships for the assumed deposition pattern and knowing the initial slope of the existing upstream alluvial fan, the reach along the transverse levee, computed deposition volume, and the deposition width. The deposition would develop a new slope along the reach described. The width of the deposition area was estimated as the flow width computed for the 100-year flood based upon the alluvial fan hydraulic relationships. Using geometric relationships of the assumed triangular deposition pattern, the maximum deposition depth that may occur would depend upon the location of the contact point measured along the transverse levee, upstream of the inlet from the engineered channel. Using a trial and error procedure, the value of this distance was varied to obtain the maximum deposition depth which was determined to be **2.0 feet** under the 100-year flood condition. Design of the transverse levee height incorporates the potential sediment aggradation because of the flow path uncertainty on the active alluvial fan area.