# Risk Analysis of Levee Failure: Optimization of Levee Height and Crown Width


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University of California Davis

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## 1. Introduction

- Levees provide partial protection against floods by earthen dam construction
- Historically, risk analyses of levee failure only consider overtopping failure, ignoring intermediate failure modes
- The minimum federal standards are defined in PL 84-99 for agricultural levees [Table 1]
- Design flood is increased to 1:200 years for urban levees
- Two decision variables:
  - **Levee height**, H, determines type of failure, overtopping or intermediate
  - **Levee crown width**, Bc, affects the likelihood of intermediate failure, specified by levee fragility curves
- Risk based optimization model for levee design or evaluation of existing levees is developed by minimizing the total costs

*Table 1.* Minimum levee standards to qualify for flood damage federal aid [1]

| Standards Source | Crown width (ft.) | Land-side slope | Water-side slope | Design Flood (yrs.) |
|---|---|---|---|---|
| PL 84-99 | 16 | 3:1 – 5:1 | 2:1 | 1:100 |

1. Delta Levees Maintenance Subventions Program (2011), Guidelines: Procedures and Criteria, California Department of Water Resources.

## 2. Methods

**Model description**

- Symmetrical river cross section
- Dimensions meet minimum levee standards to qualify for federal aid under PL 84-99

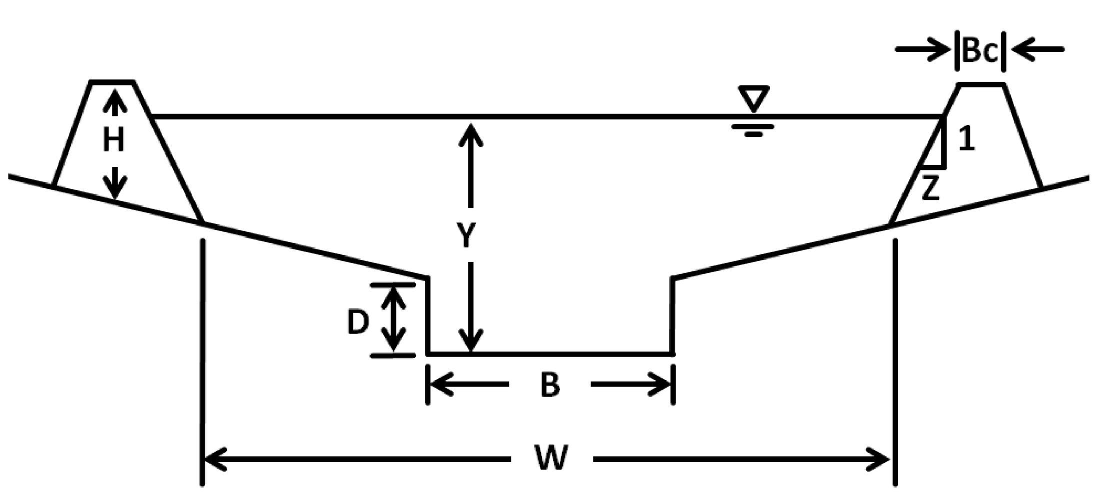


*Figure 1.* Idealized cross-section of a symmetrical two levee river channel system

**Levee Fragility Curves**

Levee fragility curves graphically illustrate the levee failure probability for intermediate modes based on conceptual curves

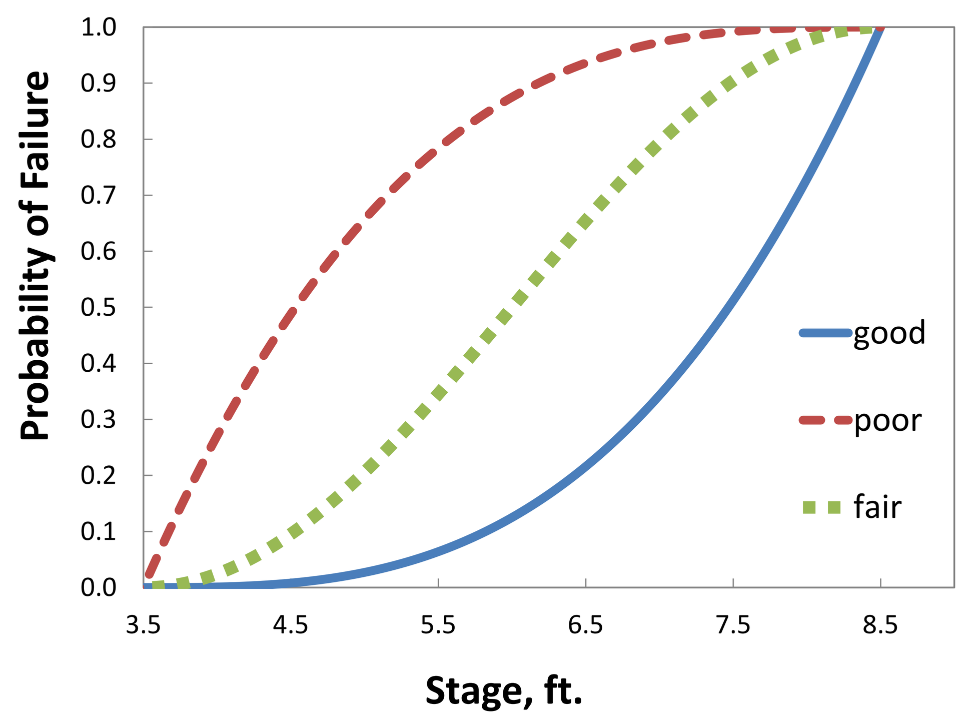


*Figure 2.* Levee fragility curves for levees in good, fair, and poor condition

## 3. Optimization

**Objective Function: minimize total cost**

$$\text{Min } TC = EAD + ACC$$

$TC$ = total expected annual cost
$EAD$ = expected annual damage cost
$ACC$ = annualized construction cost

$$EAD = D\int_0^{Q_c} f_q(Q) * f_L(Q)dQ + D * [1 - F_Q(Q_C)]$$

$D$ = damage per flood in \$
$Q_c$ = flow capacity of the levee system in ft$^3$/sec.
$f_q(Q)$ = probability distribution function of the flow
$f_L(Q)$ = probability of levee failure for the given flow
$F_Q(Q_C)$ = cumulative flow distribution function

$$ACC = (s * V * c) * \left[\frac{i*(1+i)^n}{(1+i)^n - 1}\right] + LC$$

$s$ = cost multiplier (1.3)
$V$ = volume of the levee along the reach in yd$^3$
$c$ = soil compaction cost per area (\$10/yd$^3$)
$i$ = interest rate (5%)
$n$ = number of years the levee will be repaid over (50 yrs.)
$LC$ = land cost of the levee in \$

$$LC = UC * A * i$$

$UC$ = unit cost of the land in \$/ft$^2$
$A$ = area of land the base of the levee occupies in ft$^2$
$i$ = discount rate (5%)

Physical constraints:

- Non-negative constraints for all variables
- Upper and lower limits for levee height
- Upper and lower limits for crown width

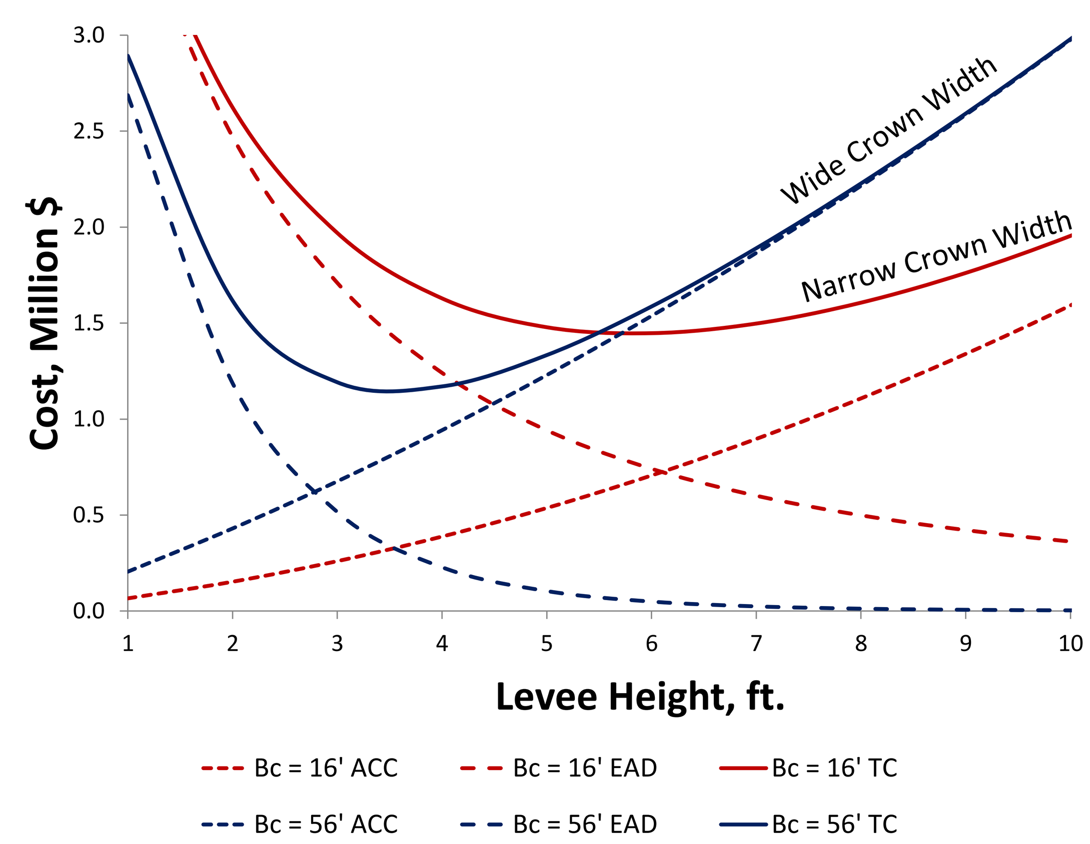


*Figure 3.* Annualized construction cost, expected annual damages, total costs for minimum and maximum crown widths

## 4. Results

**Small Levee System: Cosumnes River**

- Agricultural/rural levee
- Mean annual peak flow = 930 cfs

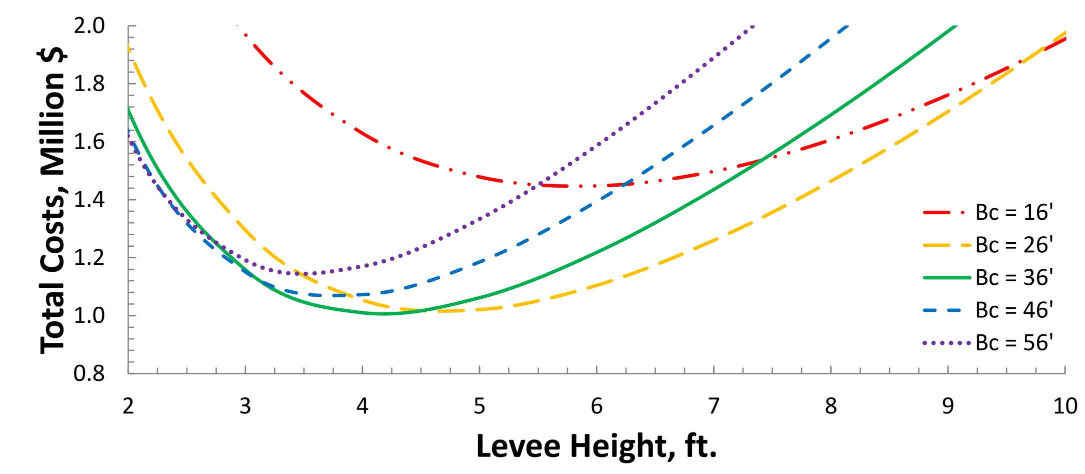


*Figure 4.* Results of total costs for various levee geometries for the Cosumnes River levees

Optimum Results

- H= 4.4 ft.
- Bc= 31 ft.
- Return Period = 144 yrs.
- Probability of overtopping failure = 0.7%
- Probability of intermediate failure = 2.5%
- Required freeboard = 1.5 ft.

**Large Levee System: Sacramento River**

- Urban levee
- Mean annual peak flow = 60,000 cfs

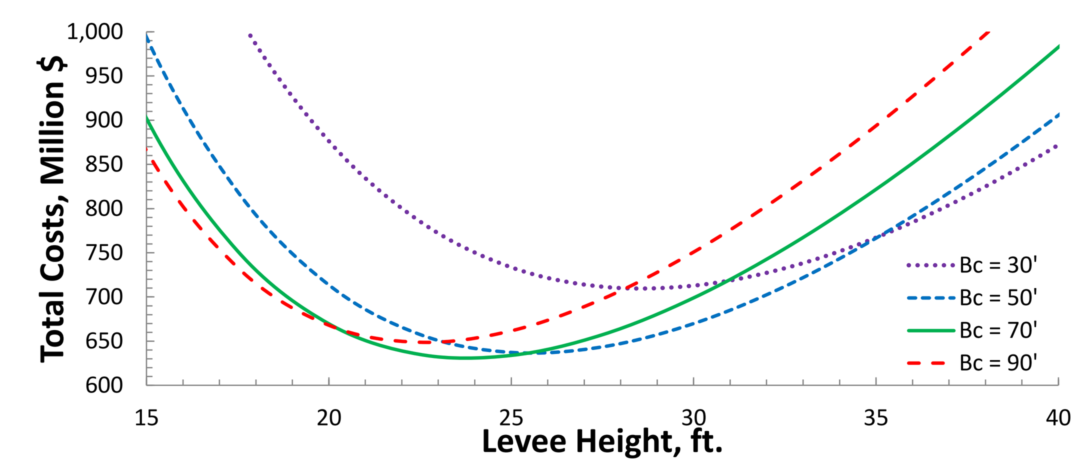


*Figure 5.* Results of total costs for various levee geometries for the Sacramento River levees

Optimum Results

- H= 24.3 ft.
- Bc= 61 ft.
- Return Period = 150 yrs.
- Probability of overtopping failure = 0.7%
- Probability of intermediate failure = 2.1%
- Required freeboard = 3 ft.

After the addition of a 3 ft. freeboard, the return period increases to above the 200 year minimum.

## 5. Conclusions

- For minimum total costs, increasing crown widths will decrease optimal levee height.
- Probability of intermediate failure can exceed overtopping, and so should not be ignored
- Increasing crown width mitigates seepage and decreases intermediate failure.
- For urban levees, space limitations may restrict levee crown width to less than optimum levels, in this case slurry walls may be considered to decrease seepage and intermediate failures.
- Future Work: nonsymmetrical levees to provide flood protection preference to urban land over rural land to reduce damage related costs and provide increased protection to the urban development.


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