Aspects of Levee Structure Design

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Aspects of Levee Structure Design

Key Focus

Engineering aspects of levee and flood wall structural design related to storm surge and wave loading

Excluded

Geotechnical foundation design aspects, scour, and estimation of storm surge and wave parameters

Aspects of Levee Structure Design

Contents

- Requirements for Levee Structure Design
- Available Tools for Levee Structure Design
- Predictive Capability
- Design Variables

AP Photo

Requirements for Levee Structure Design

Design Objectives

A successful structure must be…

- Properly designed by engineers
- Constructed by competent builders
- Continue to serve its primary functions at design conditions (even with some damage)
- Relatively easy to maintain and repair
- Tolerant of differential settlement
- Reasonably easy to upgrade
- Cost effective
- Safe for permitted traffic

Requirements for Levee Structure Design

Required Hydrodynamic Design Input

(in order of importance)

1. Estimated high-water storm surge level
2. Estimated wave height (H_{mo}) and peak wave period (T_p) parameters associated with storm surge level
3. Duration of peak surge and waves

Requirements for Levee Structure Design

Other Design Requirements or Restrictions?

(Random order)

- Is some degree of wave overtopping allowed? How much?
- Geotechnical restrictions
  - Maximum crest elevation
  - Maximum foundation load
  - Mild levee slope to prevent slip circle failure
- Crown wall?
- Crest width, access/inspection road?
- Slope armoring?
- Gates and access structures?
- Material availability and costs

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Available Tools for Levee Structure Design

Empirically Derived Design Guidance

- Based largely on small-scale laboratory physical model tests
- Normal wave incidence, flat approach bathymetry
- Includes the most common geometries and configurations
- Should not be applied outside the range of tested parameters
- Not appropriate for some cases, particularly innovative designs

Available Tools for Levee Structure Design

Empirical Design Formulas

- Irregular wave runup
- Irregular wave overtopping
  - Average rates
  - Maximum single wave overtopping
  - Overtopping thickness and flow velocity
- Steady flow overtopping
- Front-side armor stability
- Toe protection
- Forces on vertical walls (overtopped and submerged)

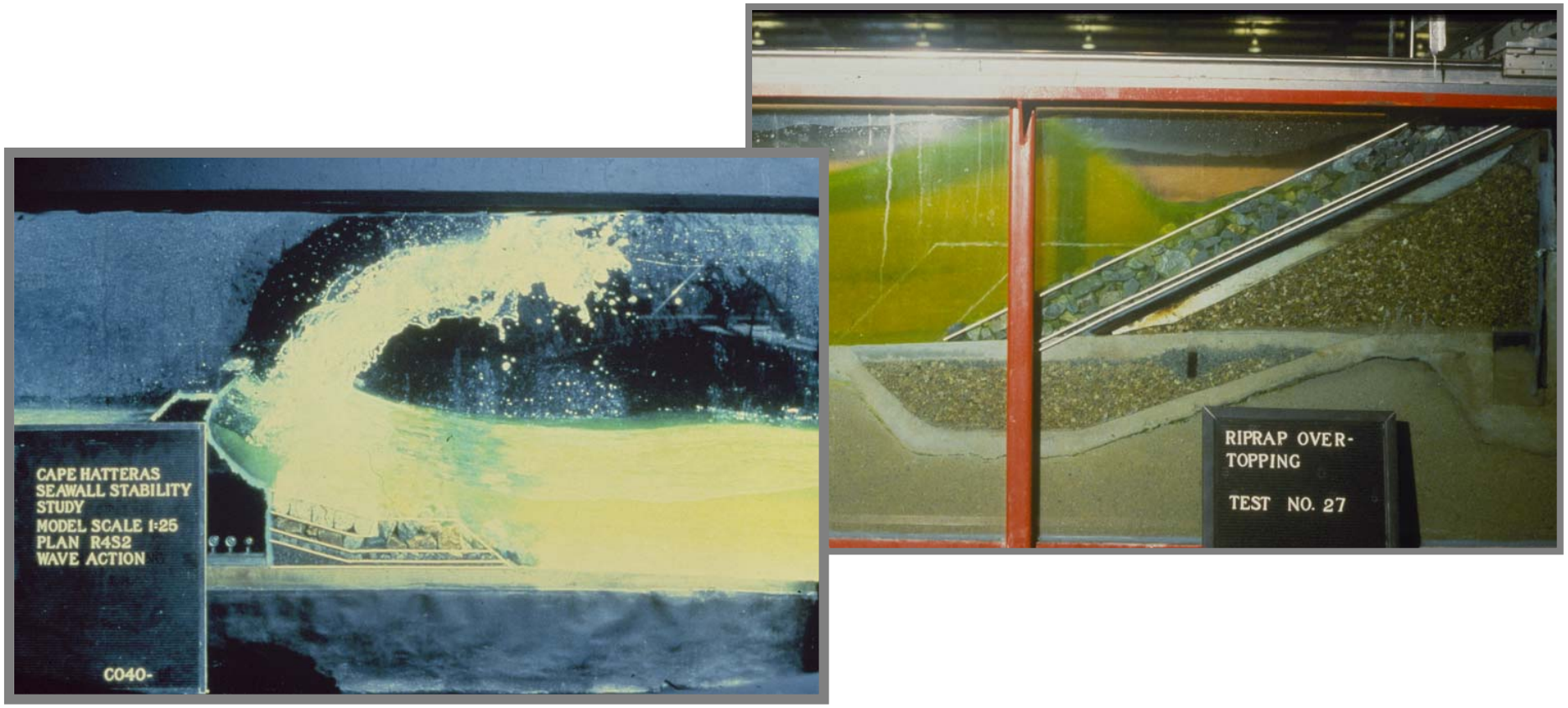
Available Tools for Levee Structure Design

Physical Model Testing

- Steps in physical model testing
  1. Construct small-scale model (2D and/or 3D)
  2. Test model over expected range of environmental conditions
  3. Measure relevant parameters (e.g., runup, overtopping, armor stability, wave forces)
  4. Optimize design for full functionality at minimum cost
- Necessary for structures outside range of empirical guidance and for innovative/new protection
- Appropriate for large, expensive structures to achieve substantial cost savings
- Useful to help minimize risk of catastrophic failure

Available Tools for Levee Structure Design

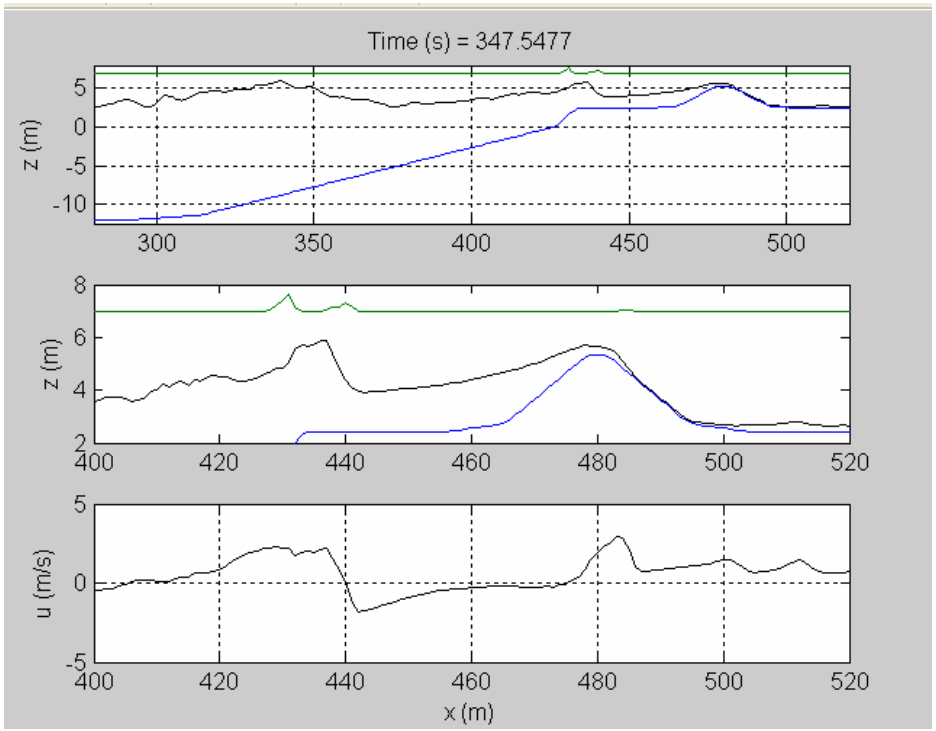
Physical Model Testing



Available Tools for Levee Structure Design

Boussinesq Numerical Model

- Time-dependent simulation of waves on structures
  - Runup
  - Overtopping
- Adjustable friction factor
- Flow velocities at any point on the levee
- Best to verify with physical model measurements



Available Tools for Levee Structure Design

What's Missing?

- **Knowledge of failure modes**
  - Progressive
  - Catastrophic
- **Details of failure progression**
  - Initiation of damage
  - Damage sequence
  - Time rates of damage
- **Probabilities related to damage and failure modes**

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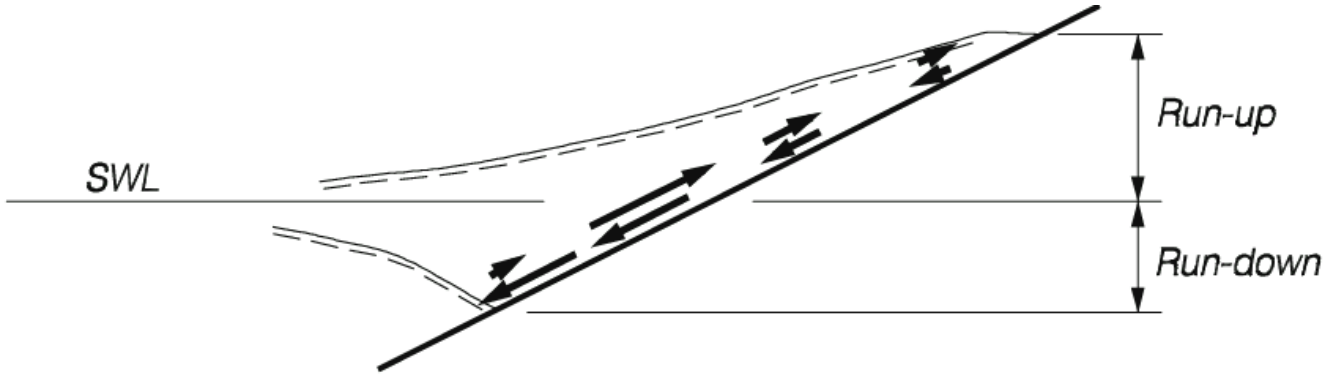
Predictive Capability

Wave Runup



- Vertical distance from SWL
- SWL = surge + wind setup
- Wave setup included in runup estimates
- Typically use $R_{2\%}$ for design

Predictive Capability

Wave Runup

$$R_{u2\%} \sim (H_{mo})^{1/2}, \quad T_p, \quad \tan\theta$$

Assumptions

- Smooth, impermeable, plane slope
- Head-on waves
- Reduction factors for…
  - Slope roughness
  - Fronting berm
  - Permeability
  - Oblique wave approach
  - Shallow water

Predictive Capability

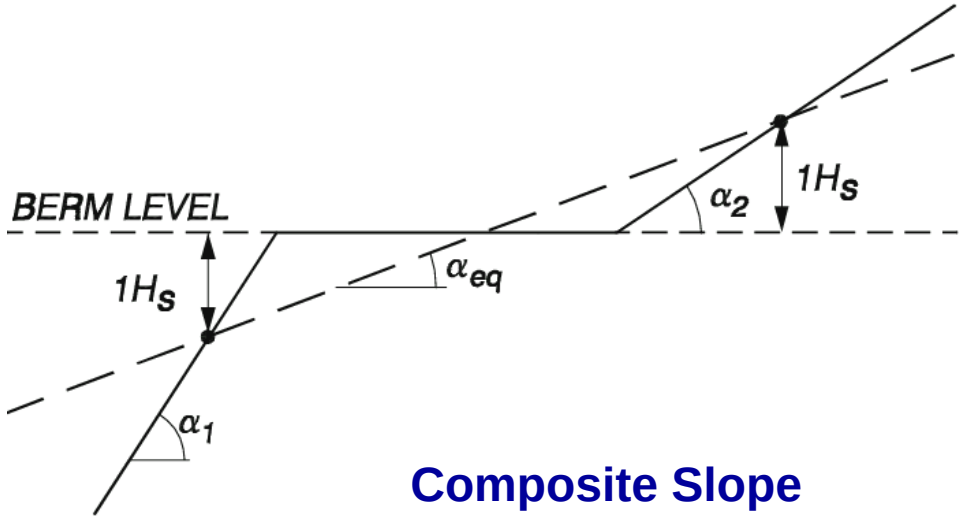
Wave Runup

Runup on Composite Slopes

- Determine equivalent slope
- Apply empirical equation

Stepped Slopes

- Limited guidance available
- Project specific
- Lab testing recommended



Composite Slope

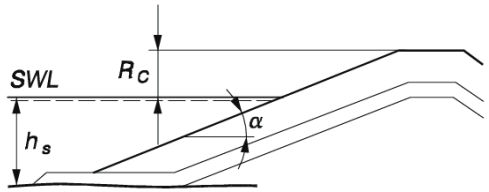
Predictive Capability

Wave Overtopping

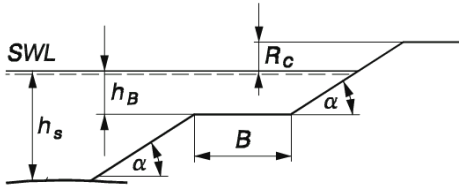
Consequences

- Flooding
- Leeside slope scour
- Leeside toe erosion
- Structure failure

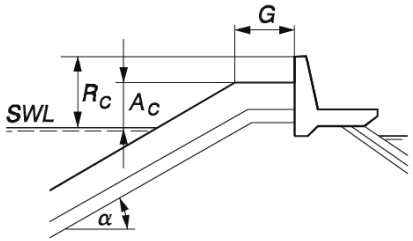
a) Straight slope



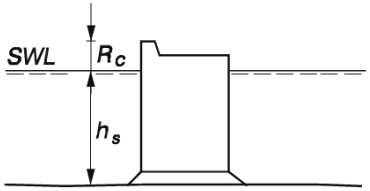
b) Bermed slope



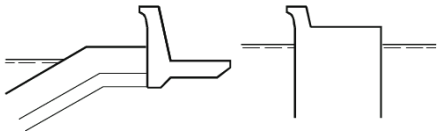
c) Slope with crown wall



d) Vertical wall



e) Recurved walls



Predictive Capability

Wave Overtopping

For plane, impermeable slopes…

$$q = f\left(H_{mo},\ \ T_p,\ \ R_c,\ \ \tan\theta\right)$$

where

q	=	Average overtopping discharge per unit length of structure
H_{mo}	=	Energy-based zeroth-moment wave height
T_p	=	Wave period associated with spectrum peak
R_c	=	Structure freeboard
$\tan\alpha$	=	Front-side slope

Reduction factors for roughness, berms, oblique waves, shallow water, short-crested waves

Predictive Capability

Wave Overtopping Flows

Issues

- Leeside scour
- Supercritical flow
- Hydraulic jump

Tools

- Analytical
  - Layer thickness
  - Flow velocities
  - Range of tests
- Boussinesq models
- Physical models

H. Schüttrumpf, H. Oumeraci / Coastal Engineering 52 (2005) 473–495

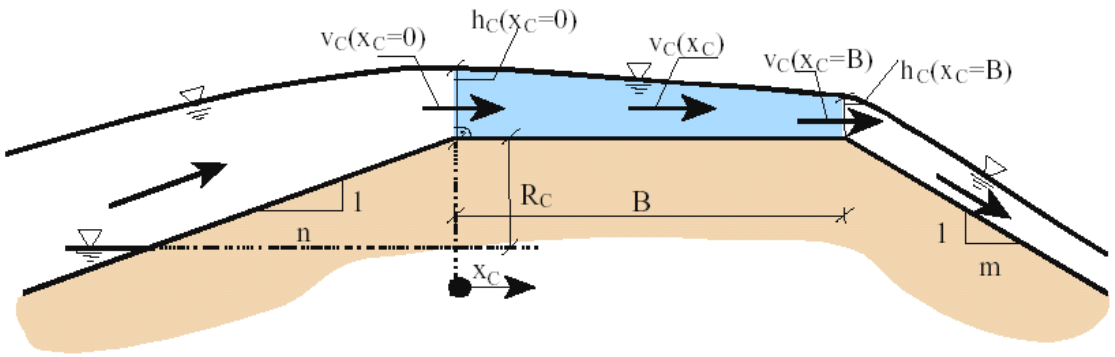


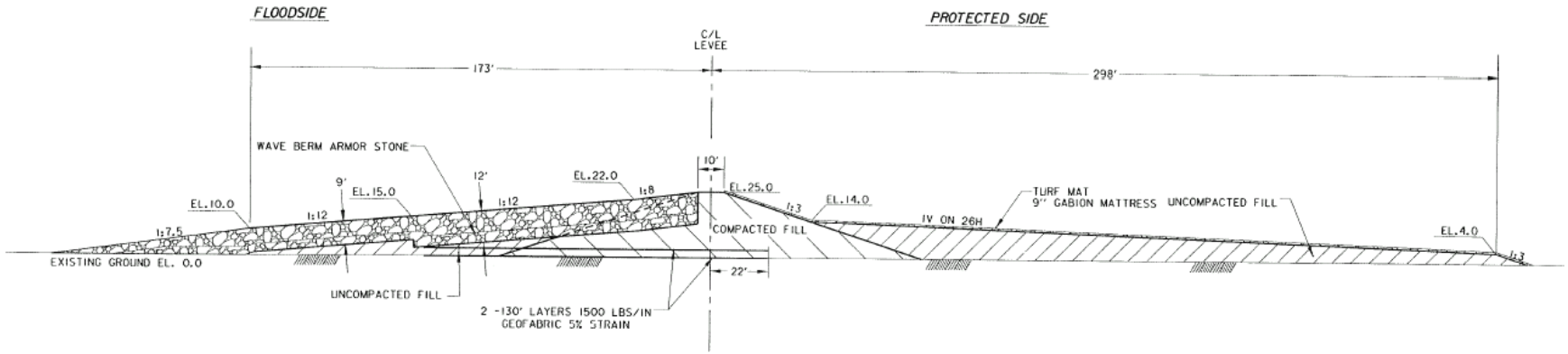
Fig. 10. Layer thickness h_C and velocity v_C on the dike crest (definition sketch).

Table 1
Investigated combinations of seaward and landward slopes

Seaward slope	Landward slope
1:6	1:3, 1:4, 1:5, 1:6
1:4	1:2, 1:3
1:3	1:2, 1:3

Predictive Capability

Levee Slope Protection



Purpose

- Retain underlying materials and soil
- Dissipate wave energy and reduce wave runup (i.e., lower crest)
- Protect against slope erosion by currents
- Prevent leeside slope erosion due to overtopping

Predictive Capability

Levee Slope Protection

For plane, impermeable rock-armored slopes…

$$W_{50} = \frac{w_a \ (H)^3}{K_D \left(\frac{\rho_a}{\rho_w} - 1\right) \cot\theta}$$

Front-side armor stability

- K_D varies for breaking, nonbreaking waves and placement style
- Wide range of cases tested
- Mildest slopes tested have been 1:6
- Armored front-side slopes reduce runup by about 1/2

Predictive Capability

Levee Slope Protection

Marine Mattresses

Leeside protection

- Articulated mats, riprap, geo-tubes, gabions, marine mattresses, etc
- Little-to-no design guidance available
- Necessary if overtopping anticipated
- Maintenance/repair considerations important

Predictive Capability

Levee Slope Protection

Marine Mattresses

Predictive Capability

Wave Forces on Vertical Walls

Full-Height Flood Walls and Gates

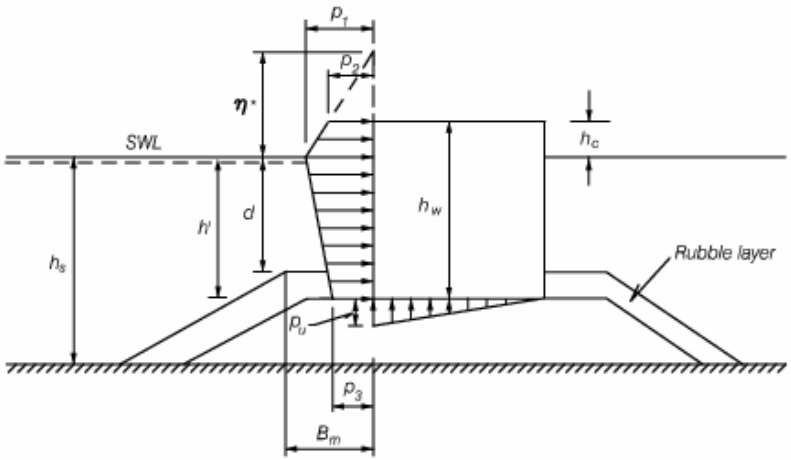
- Empirical guidance for irregular wave forces is reliable
- Wave impact (slamming loads) not well predicted
- New empirical guidance for heavily overtopped walls

Crown Walls and Parapet Wall

- Empirical guidance for common configurations

Predictive Capability

Wave Forces on Vertical Walls



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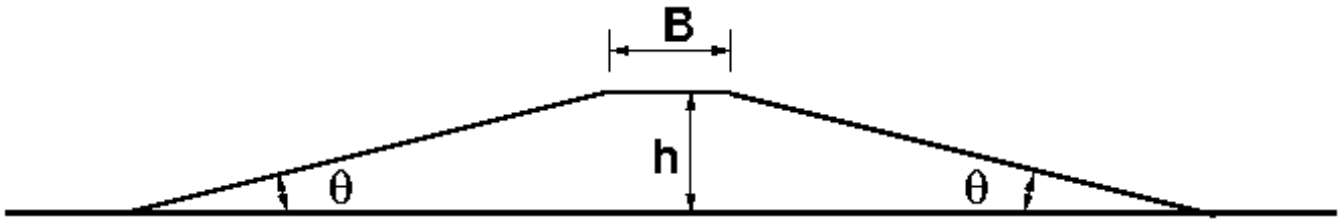
AP Photo

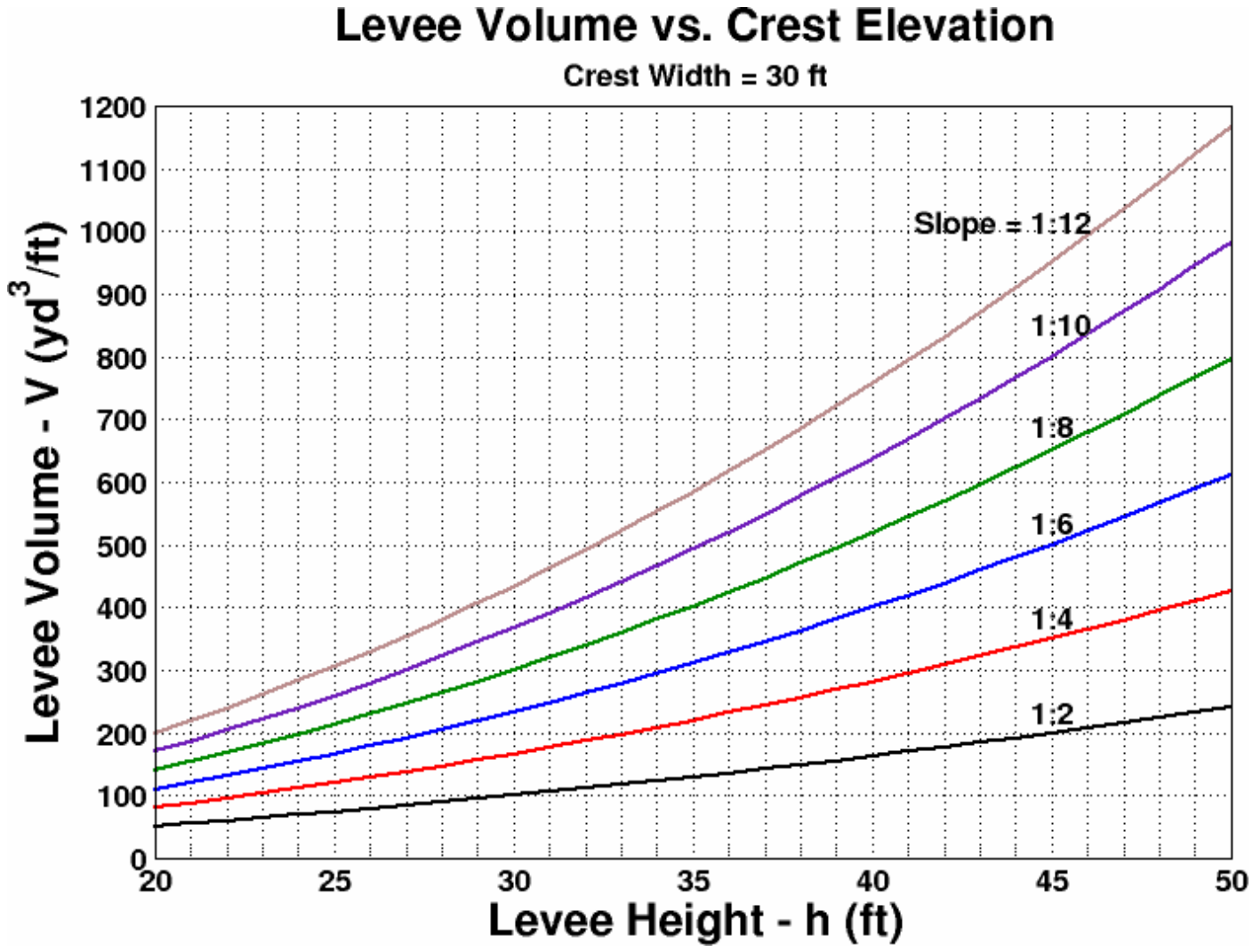
Design Variables

Assume a Simple Cross Section



$$\frac{\text{Volume}}{\text{Length}} = h[B + h\cot\theta]$$

Design Variables



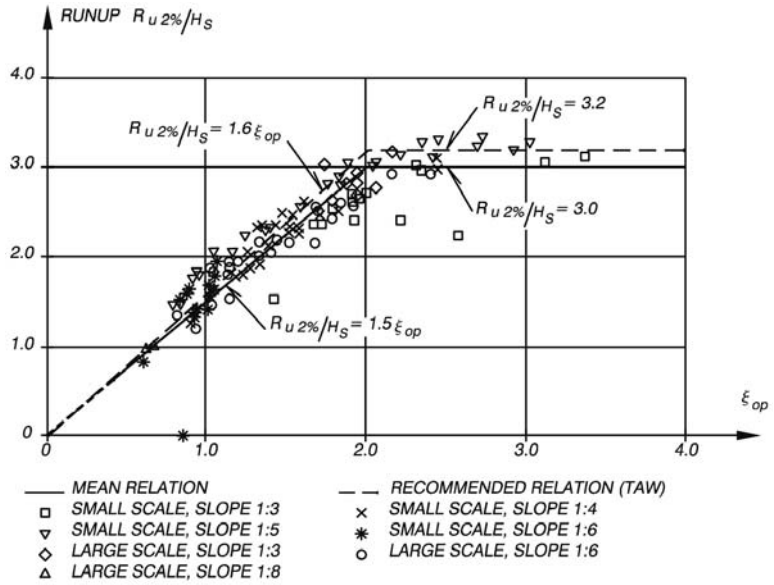
Design Variables

Empirical Runup Formula

$$\frac{R_{u2\%}}{H_{mo}} = \begin{cases} 1.5\,\xi_{op} & \text{for} \quad 0.5 < \xi_{op} < 2.0 \\ 3.0 & \text{for} \quad 2.0 < \xi_{op} < 4.0 \end{cases}$$

where

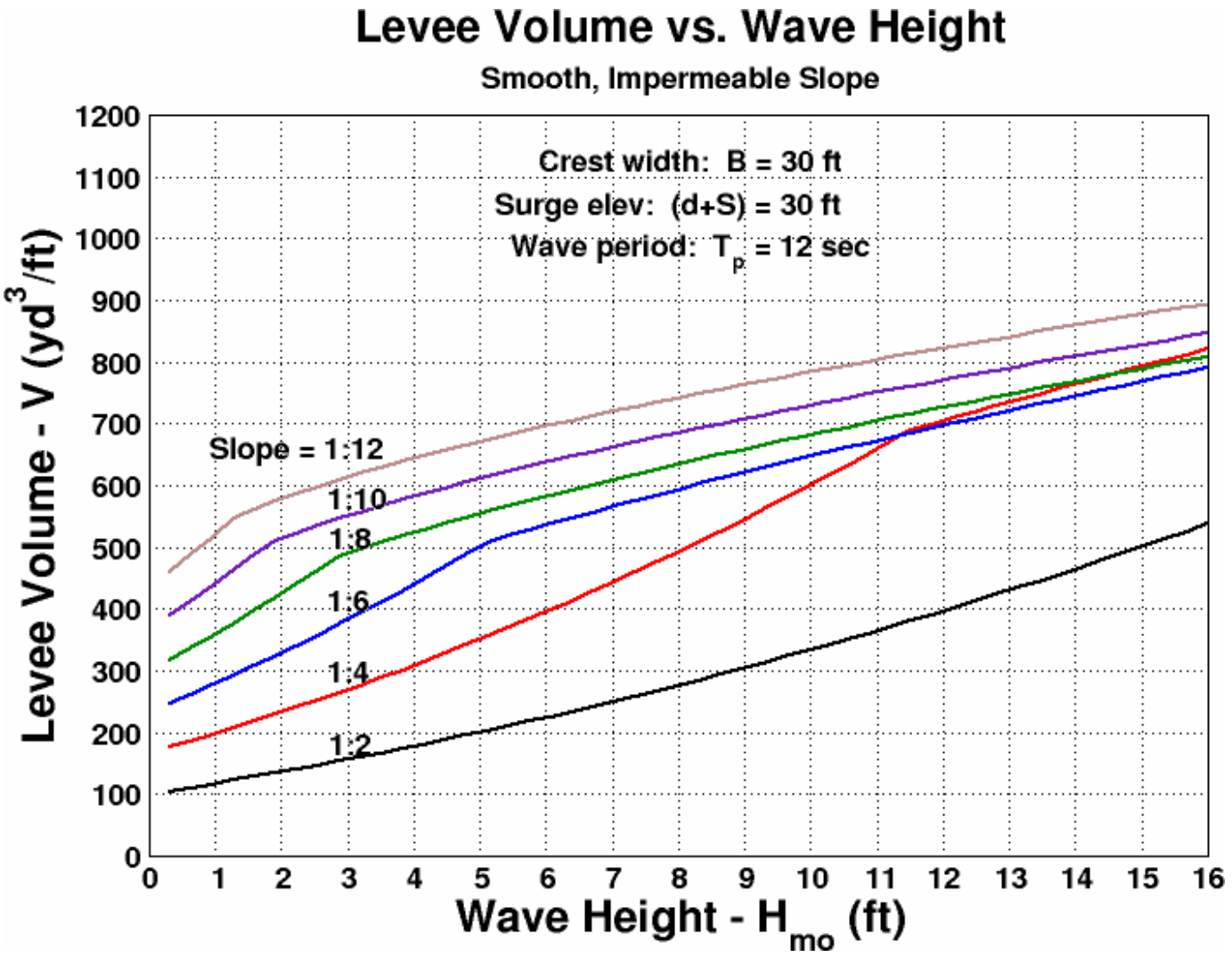
$$\xi_{op} = \frac{\tan\alpha}{\sqrt{H_{mo}/L_{op}}}$$



$R_{u2\%}$	–	vertical runup distance exceeded by 2% of runups
H_{mo}	–	zeroth-moment energy-based significant wave height
ξ_{op}	–	deepwater Iribarren number based on peak period T_p
L_{op}	–	deepwater wave length $[= (g/2\pi)\,T_p^2]$
g	–	gravitational acceleration
T_p	–	wave period associated with peak spectral frequency
$\tan\alpha$	–	structure slope

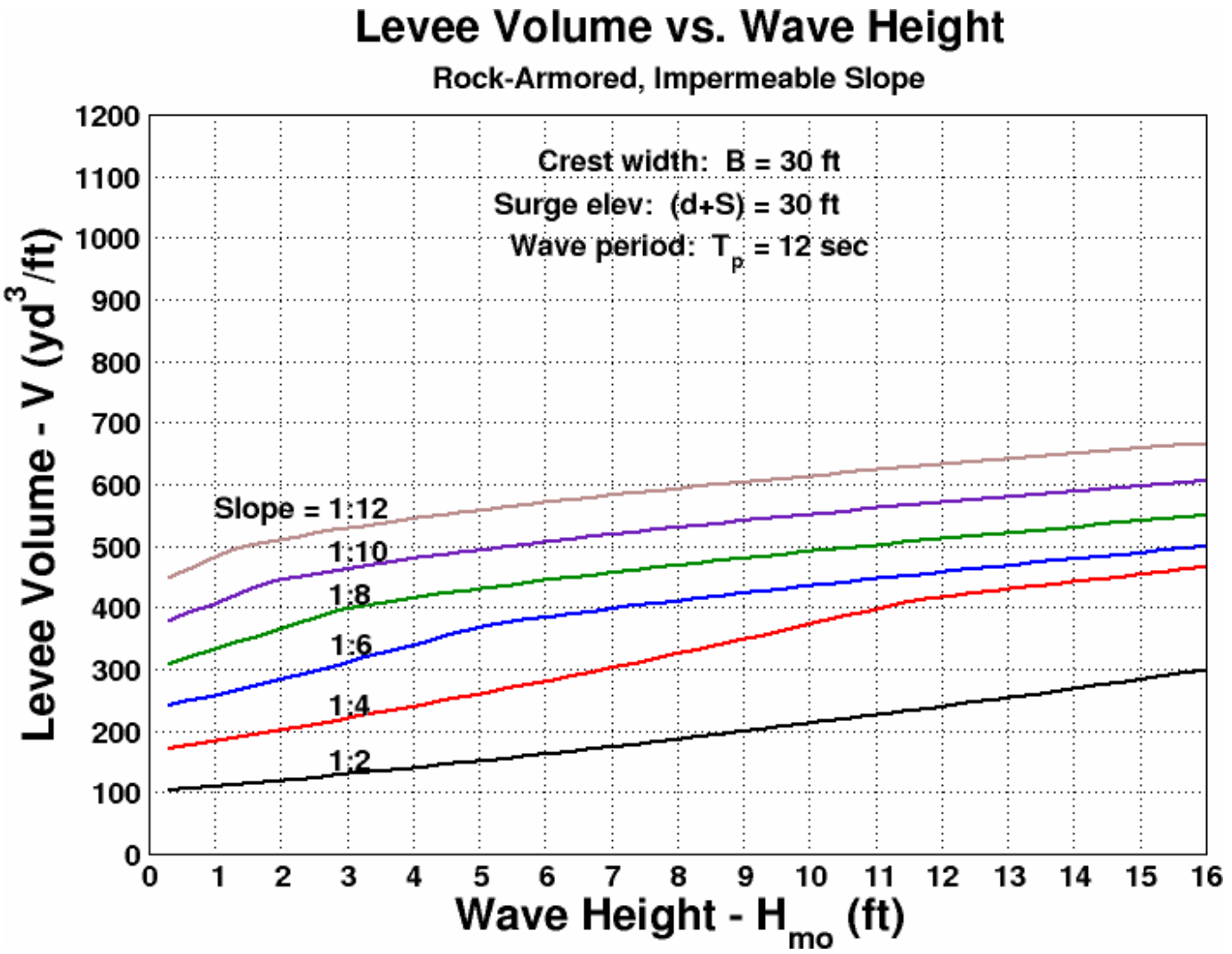
Design Variables

Smooth Slopes



Design Variables

Rock-Armored Slopes



Design Variables

Should Some Wave Overtopping Be Allowed in the Design?

Positives

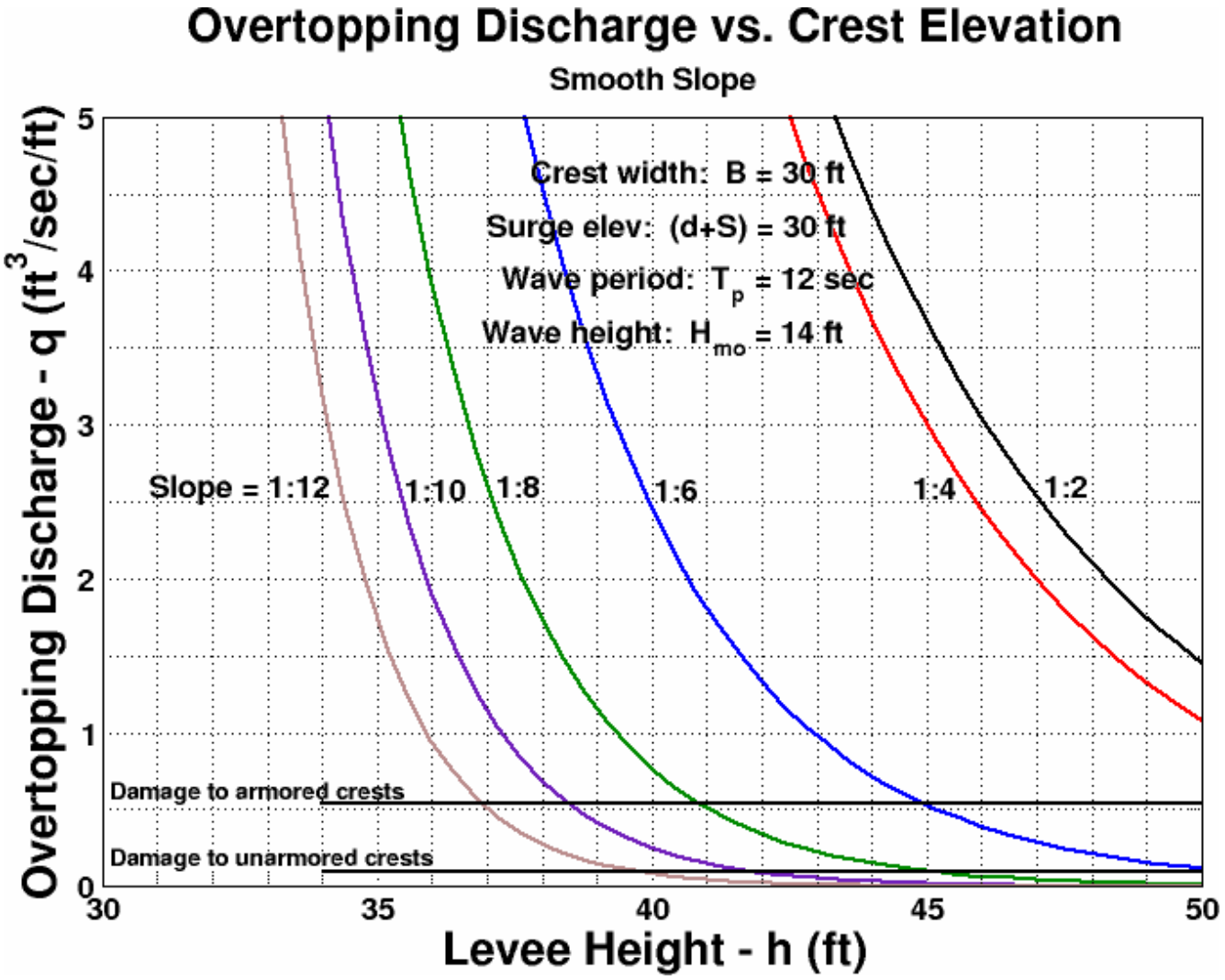
- Lower crest elevation (less fill material)
- Lower foundation load

Negatives

- Increased armoring cost (and weight)
- Dealing with overtopped water
- Greater potential for leeside scour

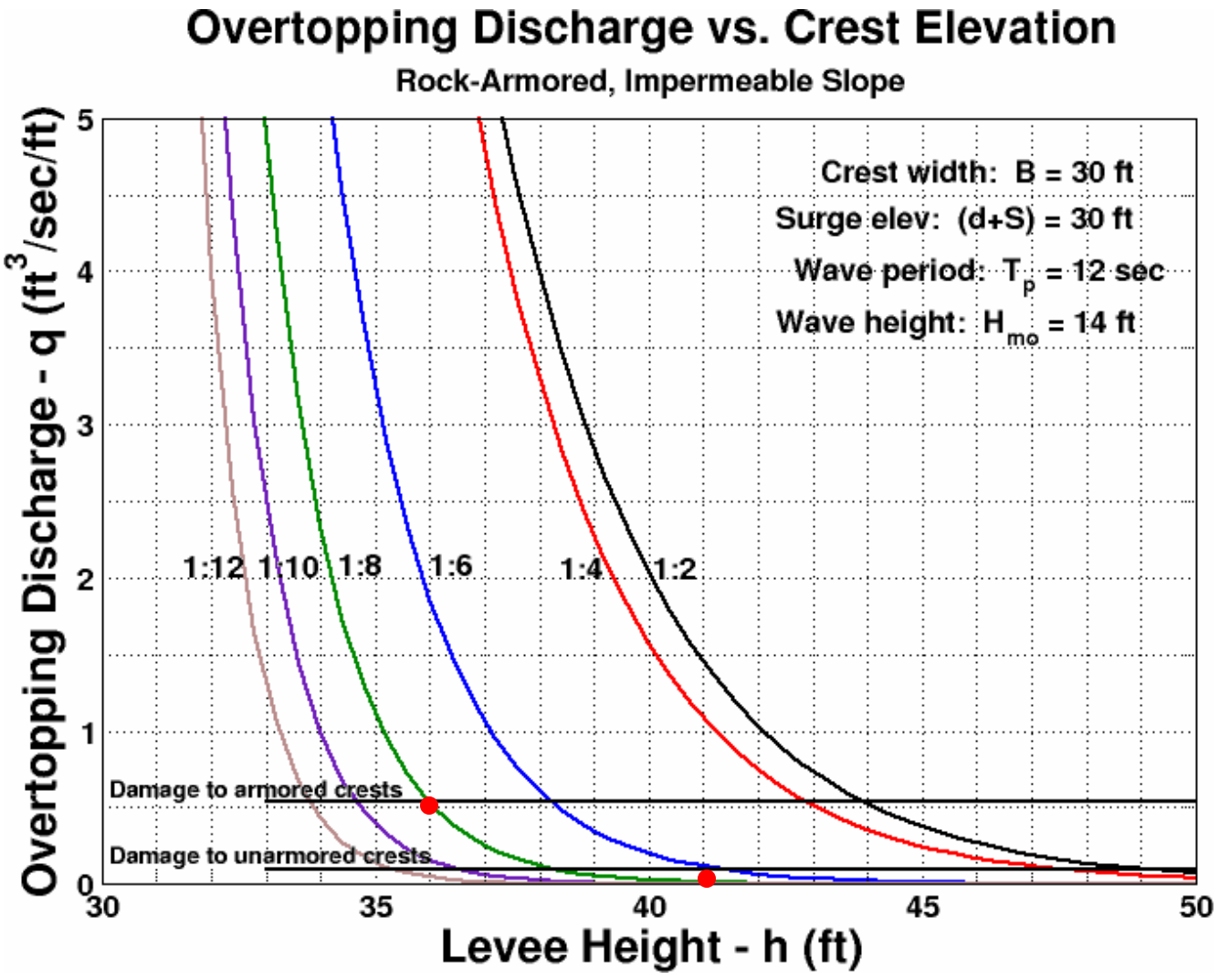
Design Variables

Smooth Slopes



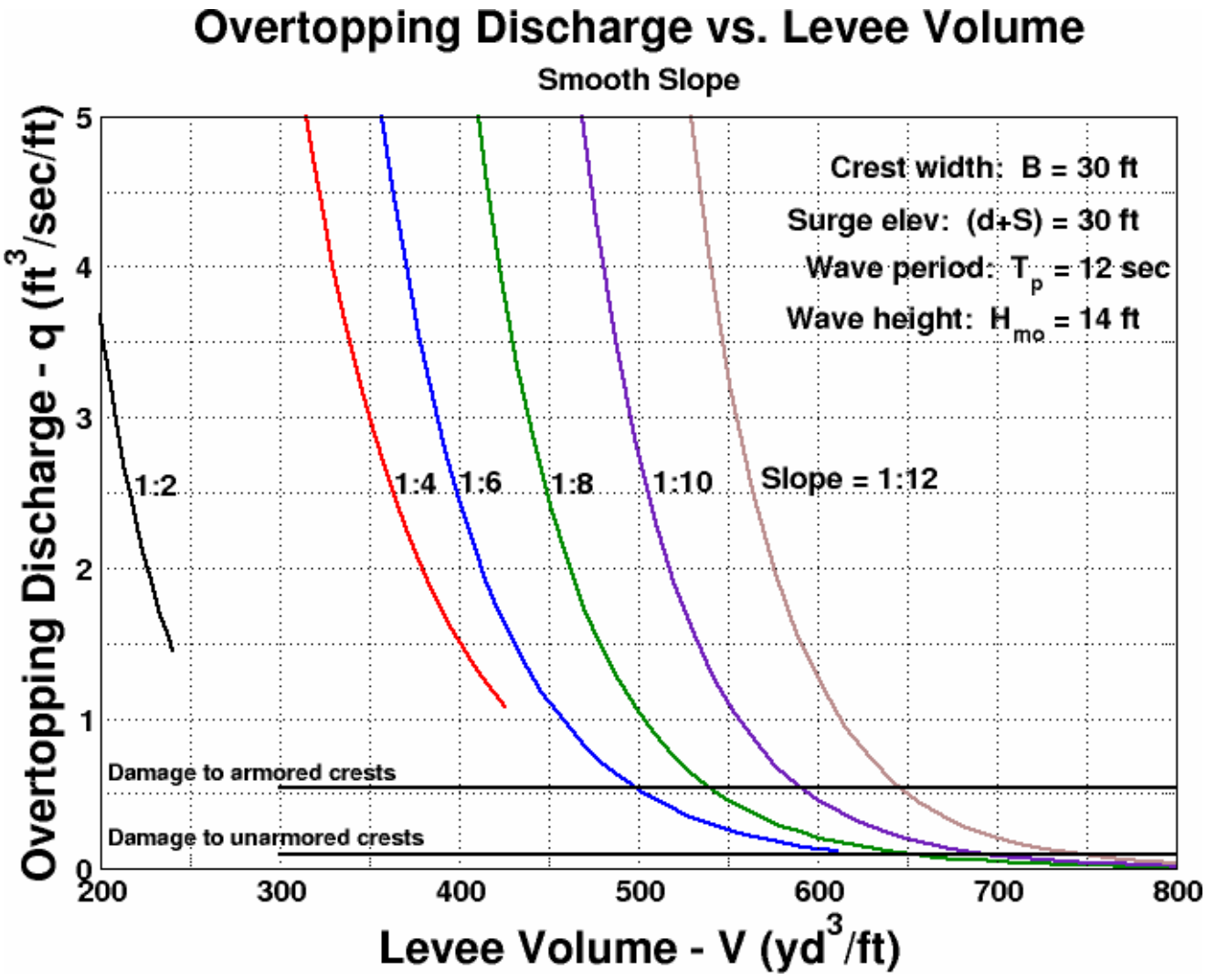
Design Variables

Rock-Armored Slopes



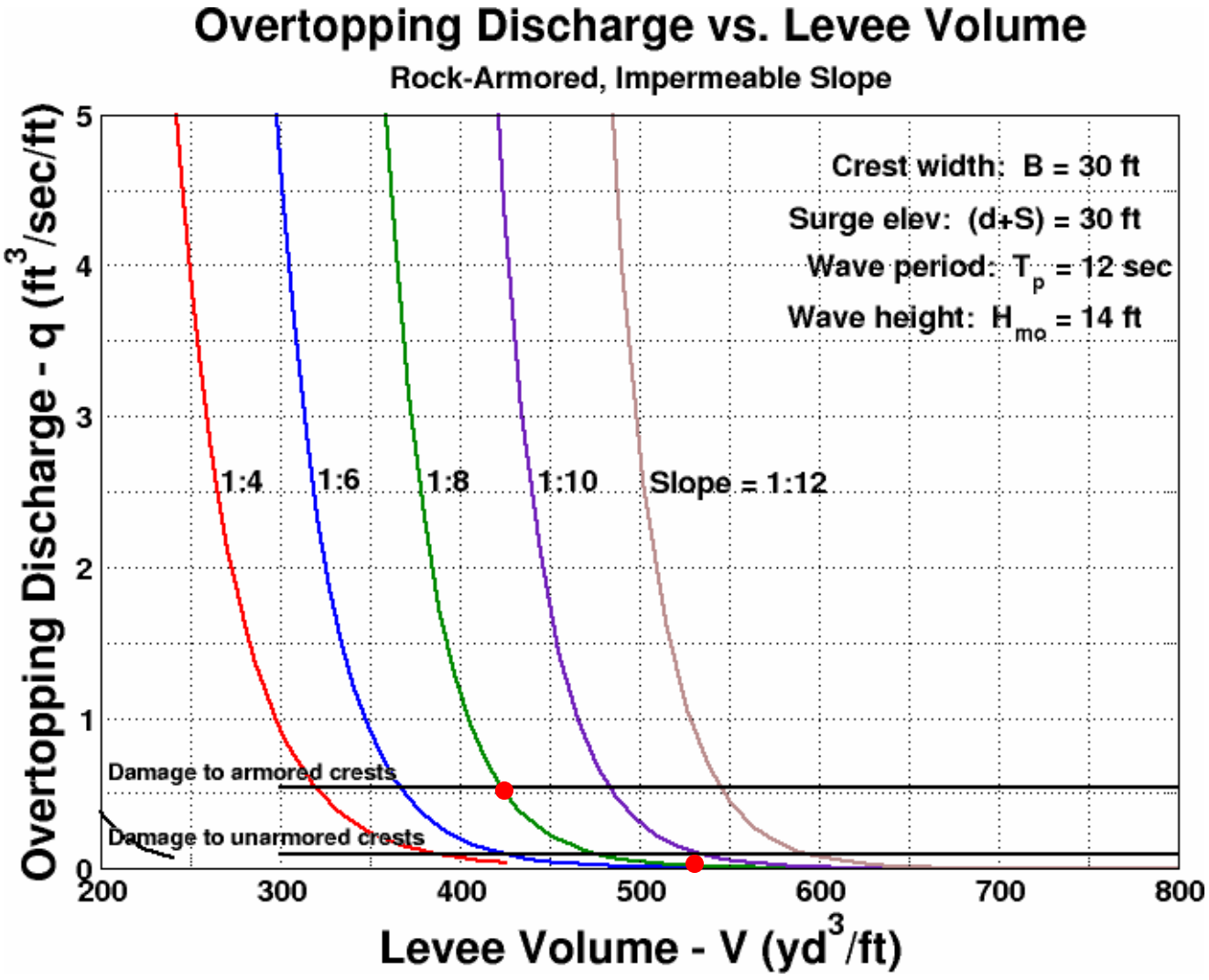
Design Variables

Smooth Slopes



Design Variables

Rock-Armored Slopes



Design Variables

Overtopping Quantities

Damage to Rock-Armored Crests

q = 0.5 ft^3/s per ft

or q = 218 acre-ft/hr per mile

Damage to Unarmored Crests

q = 0.1 ft^3/s per ft

or q = 44 acre-ft/hr per mile

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Questions?

Comments!