## RIP-RAP

Equation Selection and Rock Sizing


## Common Rock Sizing Relations

- HEC-11
- USACE
- Isbash
- CALTRANS
- USBR
- ASCE
- USGS


## DEVELOPMENT OF RELATIONSHIPS

## Common Rock Sizing Relations

- HEC-11
- USACE
- Isbash
- CALTRANS
- USBR
- ASCE
- USGS


## HEC-11 Method

- Published by FHWA in 1989
- Combination of theory and field observations
- Use in rivers and streams with:
- Discharges greater than 50 cfs
- Uniform or gradually varied flow conditions
- Straight or mildly curving reaches
- Uniform cross section geometry


## HEC-11 Method

$$
\mathrm{D}_{50}=\mathrm{C}_{\mathrm{s}} \mathrm{C}_{\mathrm{sf}} \frac{0.001 \mathrm{~V}_{\mathrm{a}}^{3}}{\sqrt{\mathrm{~d} K_{1}^{1.5}}}
$$

## HEC-11 Method

$$
\mathrm{D}_{50}=\mathrm{C}_{\mathrm{s}} \mathrm{C}_{\mathrm{sf}} \frac{0.001 \mathrm{~V}_{\mathrm{a}}^{3}}{\sqrt{\mathrm{~d} \mathrm{~K}_{1}^{1.5}}}
$$

Where:
$D_{50}=$ stone size ( ft )
$C_{s}=\left(2.12 /\left(G_{s}-1\right)^{1.5}\right)$
$C_{s f}=(S F / 1.2)^{(1.5)}$
$V_{a}=$ average channel velocity ( $\mathrm{ft} / \mathrm{s}$ )
$\mathrm{d}=$ average flow depth (ft)
$K_{1}=\left[1-\left(\sin ^{2}(\theta) / \sin ^{2}(\Phi)\right)\right]^{(1 / 2)}$

## HEC-11 Method

$$
\mathrm{D}_{50}=\mathrm{C}_{\mathrm{s}} \mathrm{C}_{\mathrm{si}} \frac{0.001 \mathrm{~V}_{\mathrm{i}}^{3}}{\sqrt{\mathrm{~d} \mathrm{~K}_{1}^{1.5}}}
$$

- Used field observations to verify theoretical approach
- Water surface slope 0.00006-0.0162
- Maximum flow depths 4.8-48.5 ft
- Average velocities 2.4-12.5 fps
- Channel discharges 1,270-76,300 cfs
- $\mathrm{D}_{50}$ range 0.5 - 2.3 ft


## HEC-11 Method

$$
\mathrm{D}_{50}=\mathrm{C}_{\mathrm{s}} \mathrm{C}_{\mathrm{sf}} \frac{0.001 \mathrm{~V}_{\mathrm{a}}^{3}}{\sqrt{\mathrm{~d}} \mathrm{~K}_{1}^{1.5}}
$$



- Provides guidance for SF selection
- For varying (R/W) ratios
- SF = 1 - 1.2 for $R / W>30$
- $S F=1.3-1.6$ for $10<R / W<30$
- $S F=1.6-2$ for $R / W<10$


## HEC-11 Method

$$
\mathrm{D}_{50}=\mathrm{C}_{\mathrm{s}} \mathrm{C}_{\mathrm{sf}} \frac{0.001 \mathrm{~V}_{\mathrm{a}}^{3}}{\sqrt{\mathrm{~d}} \mathrm{~K}_{1}^{1.5}}
$$

$C_{f}=\left(\frac{\text { safety_factor }}{1.2}\right)^{1.5}$

- Provides guidance for SF selection
- For varying flow conditions
- SF = 1-1.2 for uniform flow, no impact from wave or floating debris and complete certainty in design parameters
- $\mathrm{SF}=1.3-1.6$ for gradually varying flow with moderate impact from debris or waves
- $\mathrm{SF}=1.6-2$ for rapidly varying or turbulent flow, significant impact from debris or ice and wave heights up to 2 feet.


## Common Rock Sizing Relations

- HEC-11
- USACE
- Isbash
- CALTRANS
- USBR
- ASCE
- USGS


## USACE Method

- Published in 1994 in EM-1601
- Use in man-made or natural channels with:
- Low turbulence
- Slopes less than 2\%
- Not immediately downstream of turbulent areas


## USACE Method

$\left.D_{30}=S_{f} C_{s} C_{v} C_{t} d\left(\frac{\gamma_{w}}{\gamma_{S}-\gamma_{w}}\right)^{0.5} \frac{V}{\sqrt{K_{1} \mathrm{gd}}}\right)^{2.5}$

## USACE Method

$$
\mathrm{D}_{30}=\mathrm{S}_{\mathrm{f}} \mathrm{C}_{\mathrm{s}} \mathrm{C}_{\mathrm{v}} \mathrm{C}_{\mathrm{t}} \mathrm{~d}\left(\left(\frac{\gamma_{\mathrm{w}}}{\gamma_{\mathrm{s}}-\gamma_{\mathrm{w}}}\right)^{0.5} \frac{\mathrm{~V}}{\sqrt{\mathrm{~K}_{1} \mathrm{gd}}}\right)^{2.5}
$$

Where:
$D_{30}=$ stone size ( $f t$ )
$S_{f}=$ safety factor (1.25)
$C_{s}=$ stability coefficient for incipient failure 0.3 for angular rock
$C_{v}=$ vertical velocity distribution coefficient
1.0 for straight channels, inside bends
$1.283-0.2 \log (R / W)$, outside bends
$C_{+}=$thickness coefficient
1.0 for $1^{*} D_{100}$ or $1.5^{*} D_{50}$

## USACE Method

$$
D_{30}=S_{f} C_{s} C_{v} C_{t} d\left(\left(\frac{\gamma_{w}}{\gamma_{s}-\gamma_{w}}\right)^{0.5} \frac{V}{\sqrt{K_{1} g d}}\right)^{2.5}
$$

Where:
d = local depth of flow (ft)
$\mathbb{m}_{s}=$ unit weight of stone (lbs/ft ${ }^{3}$ )
${ }^{5}$ w $=$ unit weight of water (lbs $/ f t^{3}$ )
$V=$ local depth averaged velocity ( $\mathrm{ft} / \mathrm{s}$ )
$g=$ gravitational constant (ft/s2)
$\mathrm{K}_{1}=$ side slope correction factor

$$
\begin{aligned}
& 1.0 \text { for bottom riprap } \\
& \left(1-\frac{\sin ^{2} \theta}{\sin ^{2} \phi}\right)^{0.5}
\end{aligned}
$$

## USACE Method

$$
D_{30}=S_{f} C_{s} C_{v} C_{t} d\left(\left(\frac{\gamma_{w}}{\gamma_{s}-\gamma_{w}}\right)^{0.5} \frac{V}{\sqrt{\left(K_{1} g d\right)}}\right)^{2.5}
$$

- Method based on lab data from late 80's
- $\mathrm{D}_{50}: 0.5-2.0$ inches
- Thickness: 0.75-2 inches
- Average velocity: $0.6-6.6 \mathrm{ft} / \mathrm{s}$
- Discharge: 15-100 cfs
- Bed slope: 0.00087-0.015
- Max side slope: 1.5:1
- Verified with some field data


## Common Rock Sizing Relations

- HEC-11
- USACE
- Isbash
- CALTRANS
- USBR
- ASCE
- USGS


## ISBASH Method

- Developed by Isbash in 1936
- Adopted by USACE in 1971
- Developed for construction of dams by placing rock in flowing water


## ISBASH Method



## ISBASH Method

$$
\mathrm{D}_{50}=\frac{\mathrm{V}_{\mathrm{a}}^{2}}{2 \mathrm{gC}^{2}\left(\mathrm{G}_{\mathrm{s}}-1\right)}
$$

Where:
$D_{50}=$ stone size ( $\mathrm{f} \dagger$ )
$V_{a}=$ average channel velocity ( $\mathrm{ft} / \mathrm{s}$ )
$G_{s}=$ specific gravity of stone
$G=$ gravitational constant ( $\mathrm{ft} / \mathrm{s}^{2}$ )
$C=0.86$ for high turbulence zones
1.20 for low turbulence zones

## ISBASH Method

$$
\mathrm{D}_{50}=\frac{\mathrm{V}_{\mathrm{a}}^{2}}{2 \mathrm{gC}^{2}\left(\mathrm{G}_{\mathrm{s}}-1\right)}
$$

- Empirical values for $C$ determined to be 0.86 for minimum velocity required to move stones
- Empirical values for $C$ determined to be 1.20 for maximum velocity required to move stones
- Rock size ranged from 4.7 to 9.8 inches


## Common Rock Sizing Relations

- HEC-11
- USACE
- Isbash
- CALTRANS
- USBR
- ASCE
- USGS


## CALTRANS Method

- Developed the California Bank and Shore Protection method to protect highway embankments
- Result of a study by the Joint Bank Protection Committee appointed in 1949
- Incorporated lab and field data
- Recommends individually designed layers of protection


## CALTRANS Method

$$
\mathrm{W}_{33}=\left(\frac{0.00002 \mathrm{~V}^{6} \mathrm{G}_{\mathrm{S}}}{\left(\mathrm{G}_{\mathrm{S}}-1\right)^{3} \sin ^{3}(\rho-\theta)}\right)
$$

## CALTRANS Method

$$
\mathrm{W}_{33}=\left(\frac{0.00002 \mathrm{~V}^{6} \mathrm{G}_{\mathrm{s}}}{\left(\mathrm{G}_{\mathrm{s}}-1\right)^{3} \sin ^{3}(\rho-\theta)}\right)
$$

Where:
$W_{33}=$ minimum weight of outside stone (lbs)
$V=$ stream velocity at bank ( $\mathrm{ft} / \mathrm{s}$ )

$$
4 / 3 \mathrm{~V} \text { a for impinging flow }
$$

$2 / 3 \mathrm{~V}_{\mathrm{a}}$ for tangential flow
$\mathrm{V}_{\mathrm{a}}=$ average channel velocity ( $\mathrm{ft} / \mathrm{s}$ )
$Q=70^{\circ}$ for randomly placed rubble
置= bank angle (degrees)
$G_{s}=$ specific gravity of stone

## CALTRANS Method

$$
\mathrm{W}_{33}=\left(\frac{0.00002 \mathrm{~V}^{6} \mathrm{G}_{\mathrm{S}}}{\left(\mathrm{G}_{\mathrm{S}}-1\right)^{3} \sin ^{3}(\rho-\theta)}\right)
$$

- Face of slope revetment no steeper than 1.5:1
- Stone weight values tested:
- 3-30.4 lbs for impinging flow
- 1-950 lbs for tangential flow
- Velocities examined
- Average velocity 4.5-24 fps
- Impinging velocity 6-32 fps
- Tangential velocity 3-16 fps


## Common Rock Sizing Relations

- HEC-11
- USACE
- Isbash
- CALTRANS
- USBR
- ASCE
- USGS


## USBR Method

- Developed by Peterka and published in EM-25 in 1958
- Developed for estimating rock size for use downstream of stilling basins
- Procedure based on prototype installations


## USBR Method

## $\mathrm{D}_{50}=0.0122 \mathrm{~V}^{2.06}$ 50

## USBR Method

## $\mathrm{D}_{50}=0.0122 \mathrm{~V}_{\mathrm{a}}^{2.06}$

Where:
$D_{50}=$ stone size $(\mathrm{ft})$
$\mathrm{V}_{\mathrm{a}}=$ average channel velocity $(\mathrm{ft} / \mathrm{s})$

## USBR Method

## $\mathrm{D}_{50}=0.0122 \mathrm{~V}_{\mathrm{a}}^{2.06}$

- Prototype velocities ranged from 1-8 ft/s
- Tests conducted on sands, gravels and stone up to 2.5 inches
- Field observations of riprap up to 18 inches
- Riprap layer must have no more than $40 \%$ smaller than stable stone size


## Common Rock Sizing Relations

- HEC-11
- USACE
- Isbash
- CALTRANS
- USBR
- ASCE
- USGS


## ASCE

- Published by Vanoni in 1977
- Based on Isbash (1936)
- Modified to account for channel slope
- Rocks size dependent on:
- Flow velocity
- Unit weight of stone
- Channel side slope


## ASCE Method

$$
\mathrm{D}_{50}=\left(\frac{6 \mathrm{~W}}{\pi \gamma_{\mathrm{S}}}\right)^{1 / 3}
$$

## ASCE Method

## $\mathrm{D}_{50}=\left(\frac{6 \mathrm{~W}}{\pi \gamma_{\mathrm{S}}}\right)^{1 / 3}$

Where:
$W=\frac{0.000041 \mathrm{G}_{\mathrm{S}} \mathrm{V}^{6}}{\left(\mathrm{G}_{\mathrm{S}}-1\right)^{3} \cos ^{3}(\theta)}$
$D_{50}=$ stone size ( $f t$ )
$W=$ weight of stone (lbs)
$\mathrm{V}=$ local depth averaged velocity ( $\mathrm{ft} / \mathrm{sec}$ )
$\mathrm{m}_{s}=$ unit weight of stone (ib/ft3)
? ${ }^{\text {w }}=$ unit weight of water ( $\mathrm{lb} / \mathrm{ft}^{3}$ )
$G_{s}=$ specific gravity of stone $\left(\mathrm{m}_{s} / \mathrm{m}_{w}\right)$

## ASCE Method

$$
\mathrm{D}_{50}=\left(\frac{6 \mathrm{~W}}{\pi \gamma_{\mathrm{S}}}\right)^{1 / 3}
$$

- Based on Isbash equation with a modification to account for channel bank slope
- Uses Isbash because it is "in line with experience" to rock size that will resist movement by flow
- Velocity taken 10 feet from bank
- Angle of attack less than 30 degrees


## Common Rock Sizing Relations

- HEC-11
- USACE
- Isbash
- CALTRANS
- USBR
- ASCE
- USGS


## USGS Method

- Result of analysis by Blodgett (1981) examining field data from Washington, Oregon, California, Nevada and Arizona
- Published equation stated to apply to all channels, curved or straight, with side slopes less than or equal to 1.5:1
- Incorporated HEC-11 relationship


## USGS Method

$$
D_{50}=0.01 V_{a}^{2.44}
$$

## USGS Method

## $D_{50}=0.01 V_{a}^{2.44}$

Where:

```
\(D_{50}=\) stone size ( \(f t\) )
\(V_{a}=\) average cross section velocity ( \(\mathrm{ft} / \mathrm{s}\) )
```


## USGS Method

## $D_{50}=0.01 V_{a}^{2.44}$

- Incorporated 26 sites and 39 flow events
- 14 failure points due to particle erosion
- Utilized HEC-11 velocity/D 50 values to add points to plot
- Approximate range of velocities utilized: $2.5<V_{\text {averag }} e<17 \mathrm{fps}$
- Approximate range of median rock sizes: $0.5<\mathrm{D}_{50}<3.0 \mathrm{ft}$


## Abt and Johnson

- Steep slope sizing equation
- Result of flume testing by Abt and Johnson (1991)
- Developed for the NRC to protect low level waste impoundments


## Abt and Johnson (1991)

$$
D_{50}=5.23 S^{0.43} q_{d}^{0.56}
$$

Rule of thumb:
Increase $q_{d}$ by $35 \%$ to use as an envelope relationship

## Abt and Johnson (1991)

$$
D_{50}=5.23 S^{0.43} q_{d}^{0.56}
$$

## Abt and Johnson Method

$$
D_{50}=5.23 S^{0.43} q_{d}^{0.56}
$$

- Tested on slopes of $1,2,8,10$ and $20 \%$
- Unit discharges up to $\sim 7 \mathrm{cfs} / \mathrm{ft}$
- Rock sizes of $1,2,4,5$ and 6 inches


## Abt and Johnson (1991)

## $D_{50}=5.23 S^{0.43} q_{d}^{0.56}$

Where:
$D_{50}=$ stone size (in)
$S=$ bed slope
$q_{d}=$ unit discharge ( $\mathrm{ft}^{2} / \mathrm{s}$ )

## Summary of Methods

$$
y=10 f t, z=2, S F=1.5
$$



## Riprap Design Criteria, Specifications and Quality Control

NCHRP Report 568

## NCHRP Project 24-23 Objectives

## Riprap applications:

- Channel banks
- Bridge piers
- Bridge abutments
- Guide banks and other countermeasures
- Overtopping flow


## NCHRP Report 568 Objectives

## Product:

- Design guidelines
- Material specifications \& test methods
- Construction \& Quality Control guidelines


## Riprap size, shape, and quality



- Characteristic diameter "d" corresponds to the intermediate (B) axis
- A/C ratio should not exceed 3.0 so that particles are not needle-like, nor are they platy
- Particles should be angular, not round


## Riprap gradation



## Revetment Riprap



## Revetment Riprap


(Long-term degradation) + (Toe scour) + (Contraction scour)

## Revetment Riprap



## Alternative toe detail

## Revetment Riprap

$d_{30}=y\left(S_{f} C_{s} C_{v} C_{t}\right)\left[\frac{V_{\text {des }}}{\sqrt{K_{1}\left(S_{g}-1\right) g y}}\right]^{2.5}$

Note: $d_{50} \sim 1.2\left(d_{30}\right)$

US Army Corps of Engineers EM-1601

## EM-1601



## HEC-11



## Pier Riprap



Schoharie Creek, NY

## Pier Riprap



Schoharie Creek bridge pier No. 2

## Pier Riprap



Minimum riprap thickness $\mathrm{t}=3 \mathrm{~d}_{50}$, depth of contraction scour, or depth of bedform trough, whichever is greatest

Filter placement $=4 / 3(\mathrm{a})$ from pier (all around)

## Pier Riprap



Pier width = "a" (normal to flow)
Riprap placement = minimum 2(a) from pier (all around)

## Pier Riprap

$$
d_{50}=0.692\left[\frac{V_{\text {des }}}{\sqrt{\left(S_{g}-1\right) 2 g}}\right]^{2}
$$

FHWA Hydraulic Engineering Circular 23

## Abutment Riprap



## Abutment Riprap



## Abutment Riprap



## Abutment Riprap



## Abutment Riprap

$$
\begin{aligned}
& D_{50}=y \frac{K}{\left(S_{g}-1\right)}\left(\frac{V^{2}}{g y}\right) \quad \text { for } F_{r} \leq 0.8 \\
& D_{50}=y \frac{K}{\left(S_{g}-1\right)}\left(\frac{V^{2}}{g y}\right)^{0.14} \quad \text { for } F_{r}>0.8
\end{aligned}
$$

## Abutment Riprap

Abutment riprap sizing based on "Setback Ratio" (SBR) method:
$S B R=\frac{\text { Distance from main channel }}{\text { Flow depth in main channel }}$

## Abutment Riprap, SBR > 5



## Abutment Riprap, SBR < 5



CROSS-SECTION AT BRIDGE

## Abutment Riprap, SBR > 5 <br> SBR < 5





Abutment vs. guide bank

## ISBASH Method

- Developed by Isbash in 1936
- Adopted by USACE in 1971
- Developed for construction of dams by placing rock in flowing water


## ISBASH Method



## ISBASH Method

$$
\mathrm{D}_{50}=\frac{\mathrm{V}_{\mathrm{a}}^{2}}{2 \mathrm{gC}^{2}\left(\mathrm{G}_{\mathrm{s}}-1\right)}
$$

Where:
$D_{50}=$ stone size ( $f t$ )
$V_{a}=$ average channel velocity ( $\mathrm{ft} / \mathrm{s}$ )
$G_{s}=$ specific gravity of stone
$G=$ gravitational constant ( $\mathrm{ft} / \mathrm{s}^{2}$ )
$C=0.86$ for high turbulence zones
1.20 for low turbulence zones

## Revetment Riprap

$d_{30}=y\left(S_{f} C_{s} C_{v} C_{t}\right)\left[\frac{V_{\text {des }}}{\sqrt{K_{1}\left(S_{g}-1\right) g y}}\right]^{2.5}$
$C v=1.25$
Note: $d_{50} \sim 1.2\left(d_{30}\right)$
US Army Corps of Engineers EM-1601

