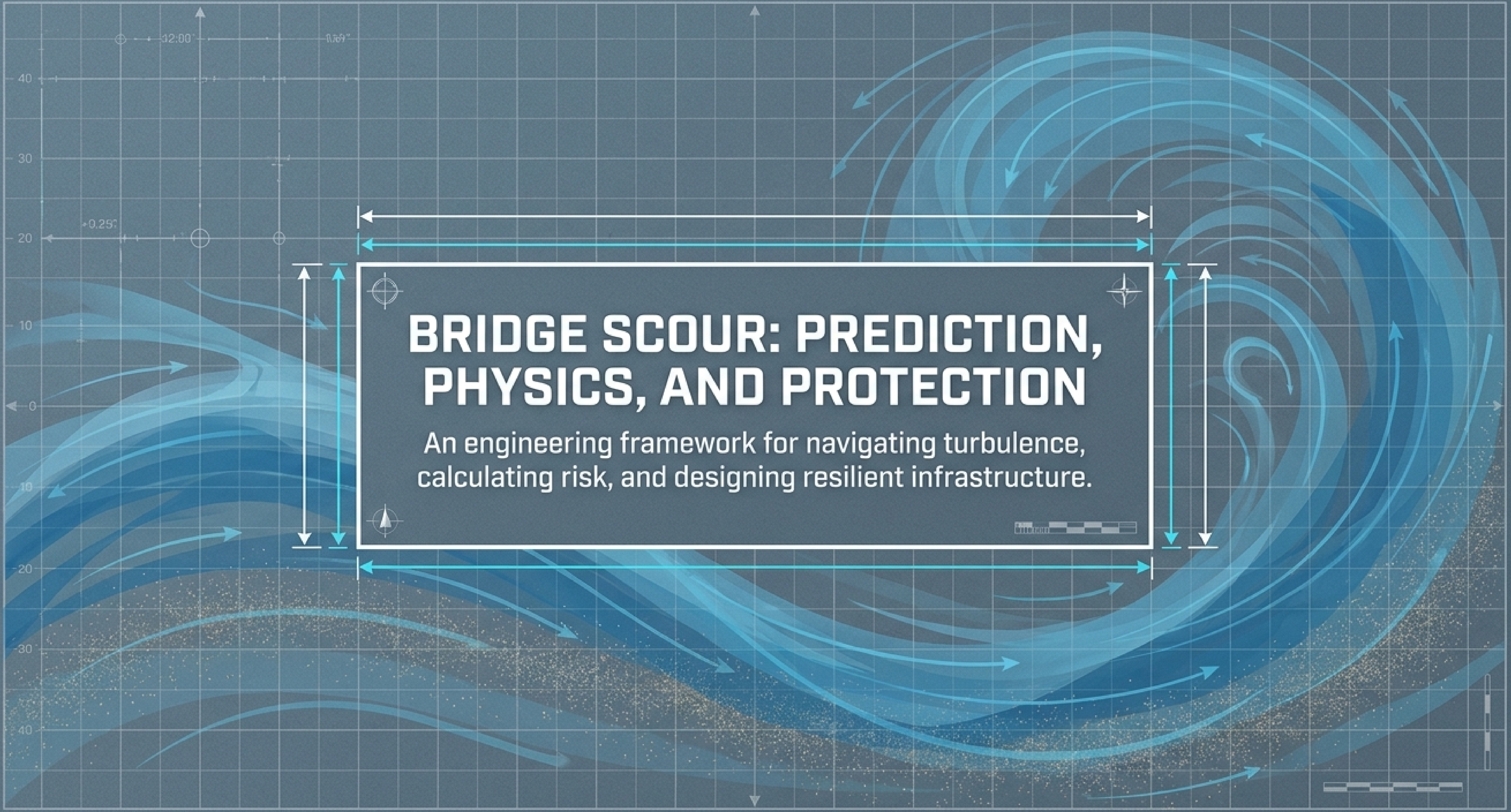


BRIDGE SCOUR: PREDICTION, PHYSICS, AND PROTECTION

An engineering framework for navigating turbulence, calculating risk, and designing resilient infrastructure.

The Hidden Threat Beneath the Surface

Bridge scour is the leading cause of bridge failure in the U.S.

1. Driven by Turbulence

It is the interaction of turbulent vortices and sediment, not just mean stream flow.

2. Hidden Nature

The most severe damage occurs out of sight during peak flood events.

3. The Engineering Triad

Mitigation requires integrating Hydraulics, Sediment Transport, and Engineering Judgment.

The Total Scour Equation

Total Scour = [Long-Term] + [Contraction] + [Local]

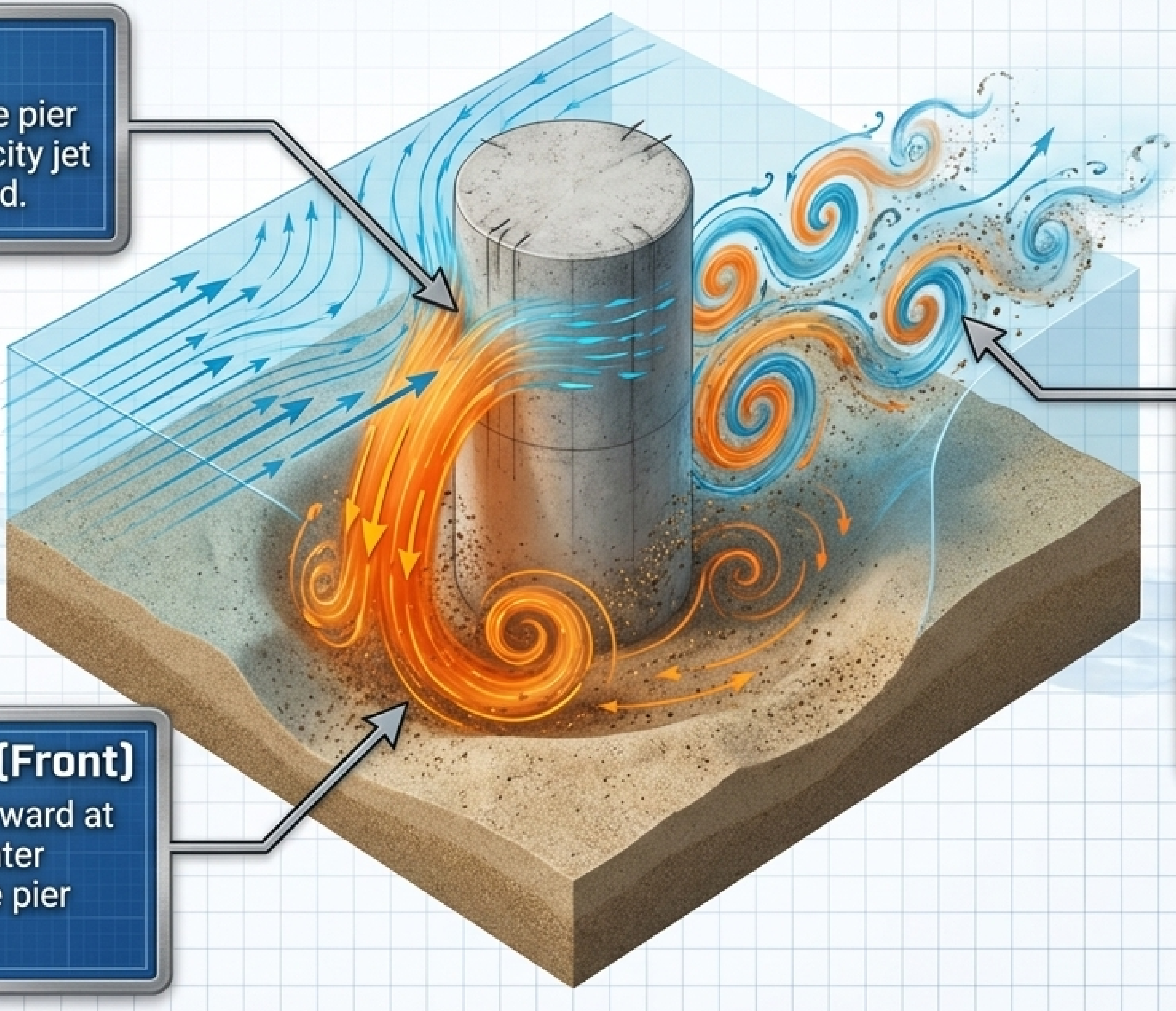
[Long-Term]: Basin-scale aggradation/degradation over decadal time scales (linked to the Exner equation for morphodynamics).

[Contraction]: Channel bottlenecks where reduced flow area increases velocity and shear stress.

[Local]: Intense vortex systems isolated around physical obstructions (piers and abutments).

Conservative Simplification: These components are added linearly in design, even though they may not always occur simultaneously at peak magnitude.

The Physics of Local Scour



1. Downflow Jet

Approaching flow hits the pier face, forcing a high-velocity jet straight down into the bed.

2. Horseshoe Vortex (Front)

The downflow curves forward at the bed, excavating a crater and wrapping around the pier base like a horseshoe.

3. Wake Vortex Shedding (Rear)

Shear layer separation creates a swirling “wake” behind the pier, transporting the lifted sediment away.

The Language of Scour (Dimensional Analysis)

Hydraulic Variables
(The Force)

Flow Depth
(y)

Velocity
(V)

Froude Number
$\left(Fr = \frac{V}{\sqrt{gy}}\right)$

Sediment Variables
(The Resistance)

Grain Size
(D_{50})

Relative Density
(s)

Sediment Mobility/ Shields Parameter
$\left(\theta = \frac{\tau'}{(\rho s - \rho)gD}\right)$

Structural Variables
(The Obstruction)

Pier Width
(a)

Relative Depth
(y/a)

Shape Factor

Regime Analysis: Clear-Water vs. Live-Bed Scour

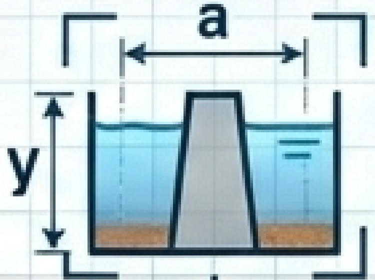
Diagnostic Comparison Matrix

Clear-Water		Live-Bed
No upstream sediment supply; bed is initially stable.	**Condition**	Incoming sediment transport is actively present.
Reaches equilibrium slower.	**Time to Equilibrium**	Reaches equilibrium faster. ↑
↓ Deeper potential scour.	**Maximum Scour Depth**	Generally shallower at the same velocity beyond critical.
True static equilibrium—no sediment refills the hole.	**Nature of Equilibrium**	Dynamic, fluctuating equilibrium—passing bedforms continually refill and re-excavate the hole.

Anatomy of the HEC-18 CSU Pier Equation

The **normalized target output** (Scour depth relative to water depth).

The **empirical base multiplier.**



Structural obstruction ratio (Pier width vs. water depth).

$$\frac{y_s}{y} = 2.0\, K_1 K_2 K_3 K_4 \left(\frac{a}{y}\right)^{0.65} Fr^{0.43}$$

The normalized target output (Scour depth relative to water depth).

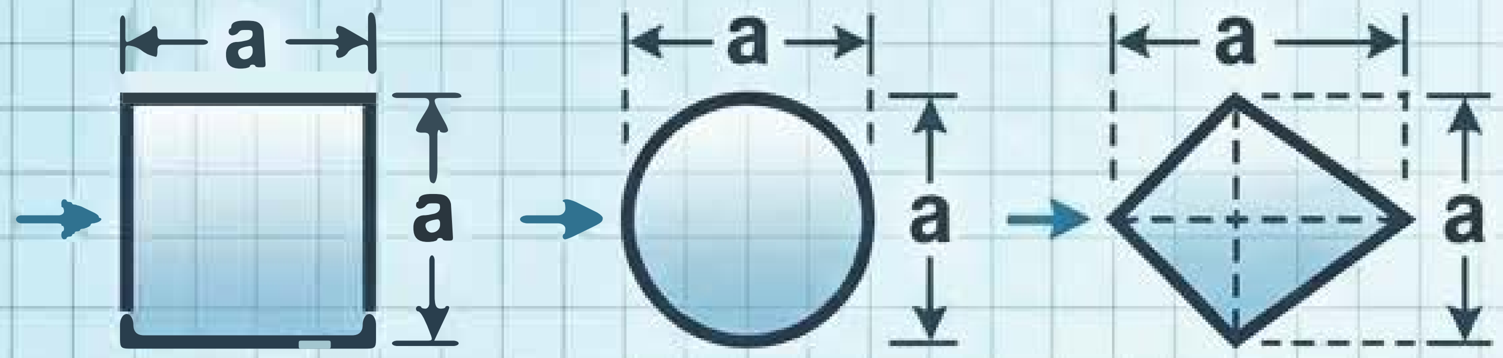
The specialized correction factors.

$Fr = V/\sqrt{gy}$

The hydraulic driver (Froude number).

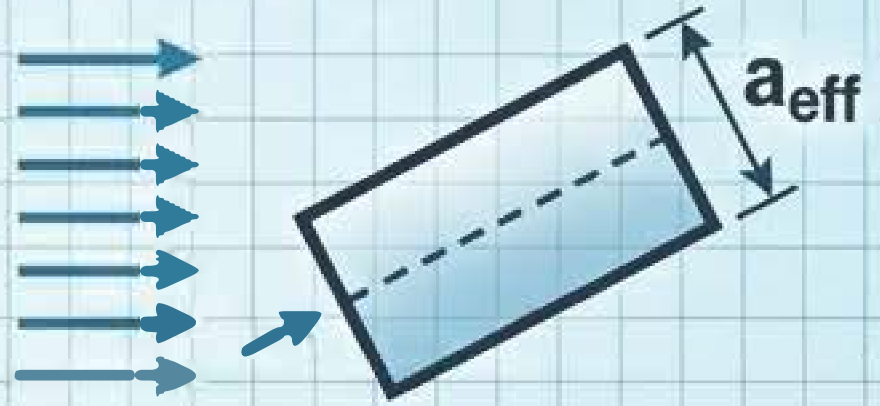
The Multipliers (K-Factors)

K1: Pier Shape



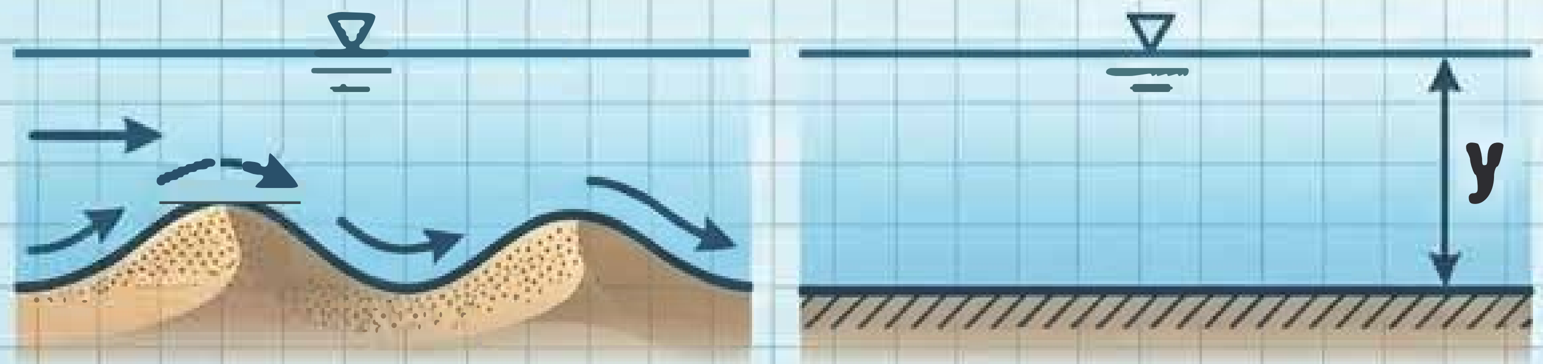
Circular = 1.0. Square = 1.1. Sharp nose < 1.0 (reduces scour penalty).

K2: Angle of Attack



Flow alignment drastically alters effective obstruction width.

K3: Bed Condition



Accounts for the presence of natural bedforms.

K4: Armoring

Accounts for the protective shielding of larger sediment sizes.

Applied Engineering: Predicting Scour

Input Data

Sand-bed river.

$y = 4.0\text{m}$
$V = 2.5\text{m/s}$
$a = 1.5\text{m}$

Factors: $K1=1.0$, $K2=1.1$, $K3=1.1$, $K4=1.0$

Step 1: Compute Froude

$$Fr = \frac{V}{\sqrt{gy}}$$

$$\frac{2.5}{6.26} = 0.40$$

Step 2: Apply HEC-18

Substitute variables into the CSU equation framework.

Step 3: Evaluate Terms

$$\left(\frac{1.5}{4.0}\right)^{0.65} \approx 0.529$$

$$(0.40)^{0.43} \approx 0.674$$

$$K_{total} = 2.42$$

Step 4: Result & Interpretation

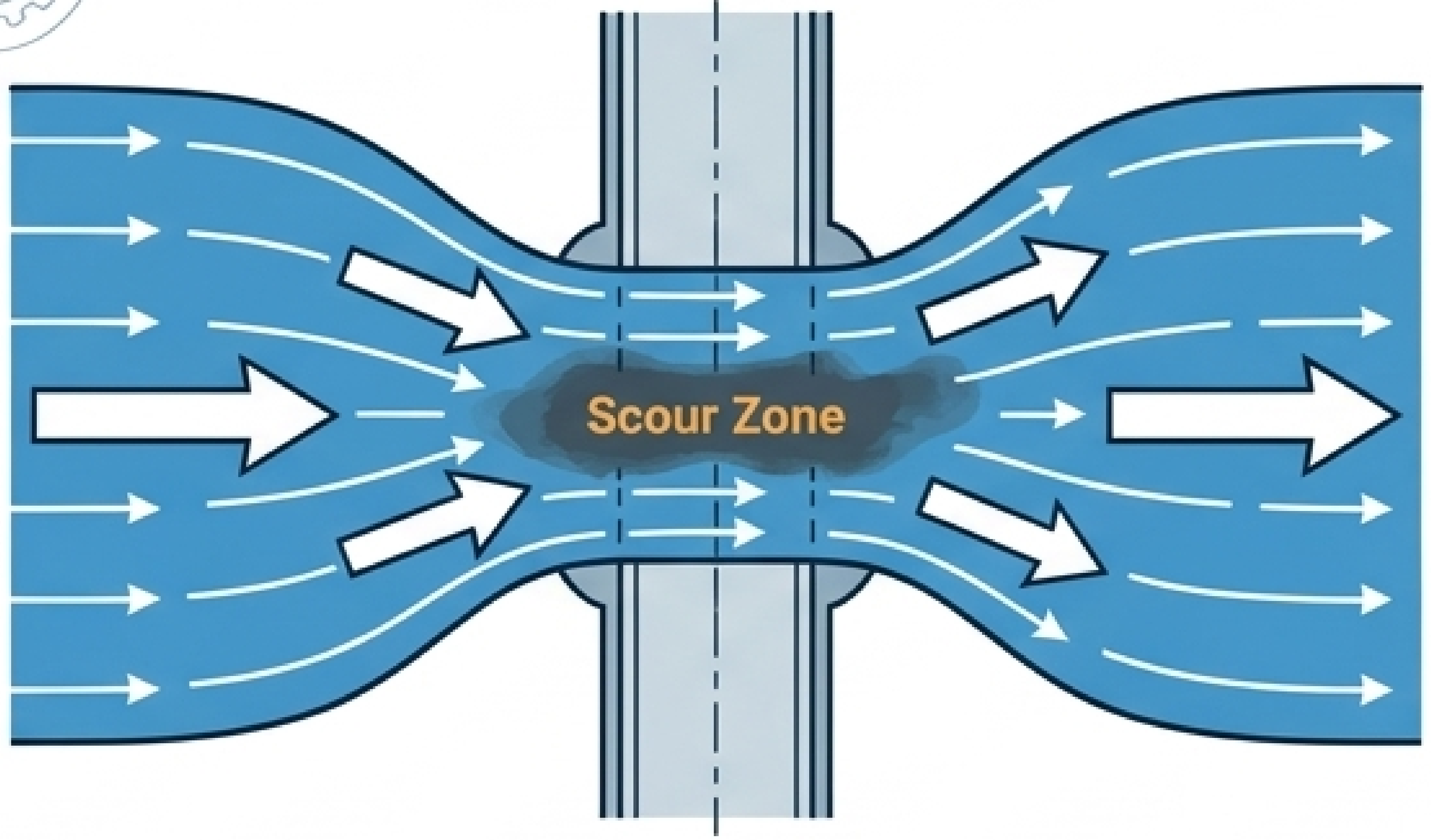
$$\frac{y_s}{4.0} \approx 0.863$$

$$y_s \approx 3.45\text{m}$$

Takeaway: Local pier scour alone can nearly equal the flow depth itself.

Beyond the Pier: Contraction & Abutment Scour

Contraction Scour

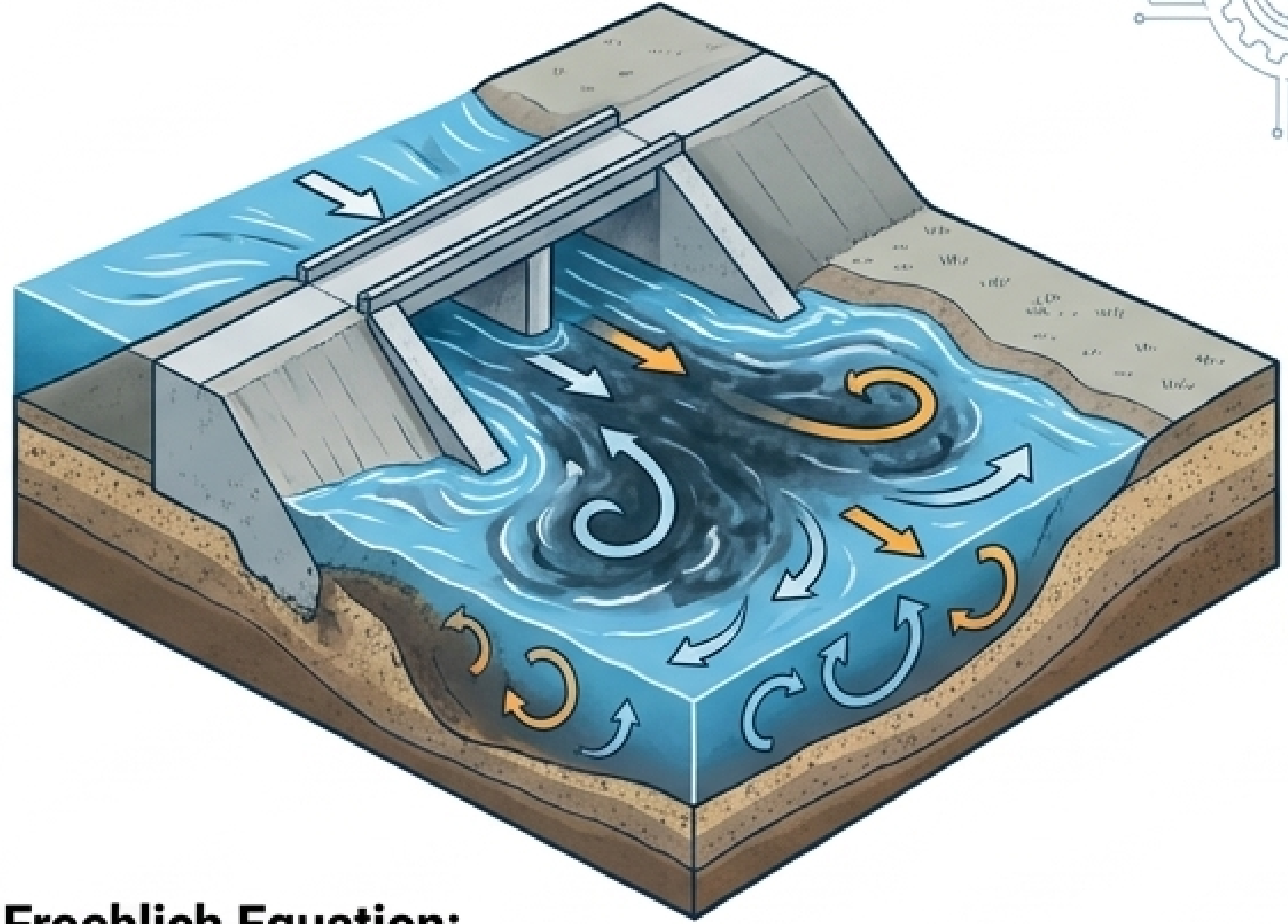


Mechanism: Driven by the continuity equation (Q=VA).

Chain Reaction: Flow Area (A) drops → Velocity (V) rises → Bed Shear Stress (τ_b) rises → Scour increases.

Note: Produces conservative estimates.

Abutment Scour

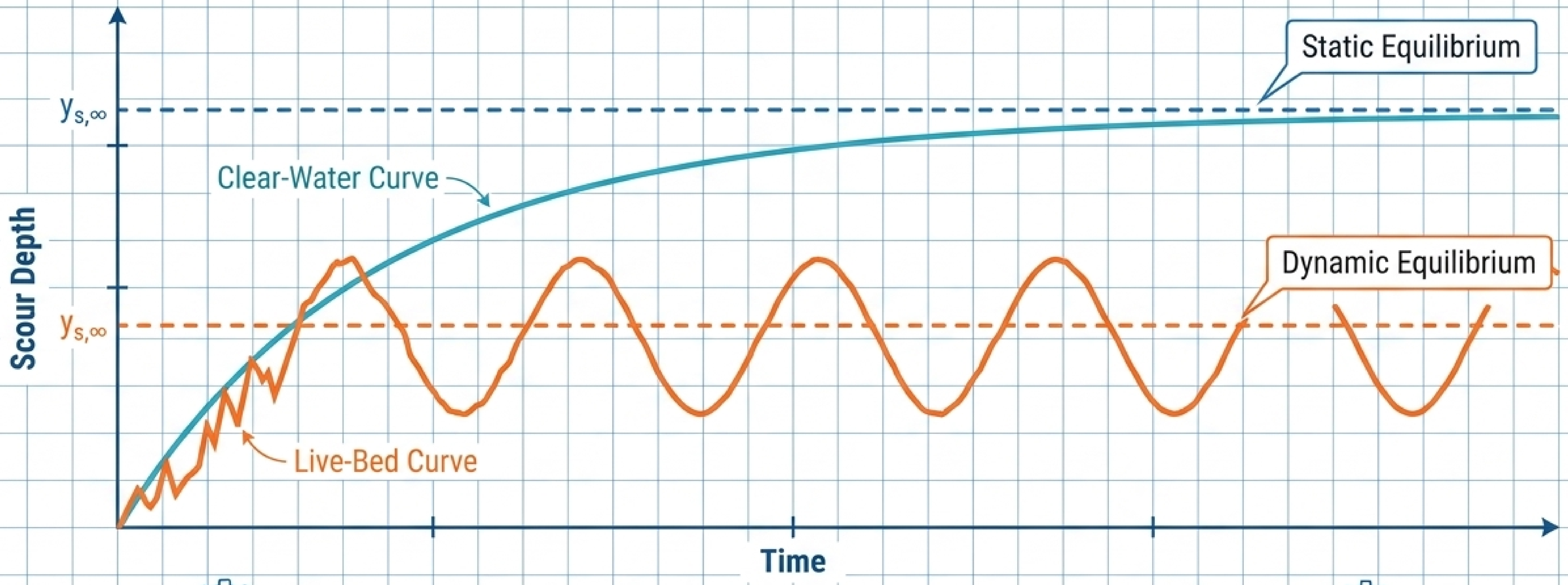


Froehlich Equation:

$$y_s/y_a = 2.27\, K_1\, K_2\, (L'/y_a)^{0.43}\, Fr^{0.61} + 1$$

Key Variables: L' (obstructed flow length), y_a (average floodplain depth), Fr (upstream Froude).

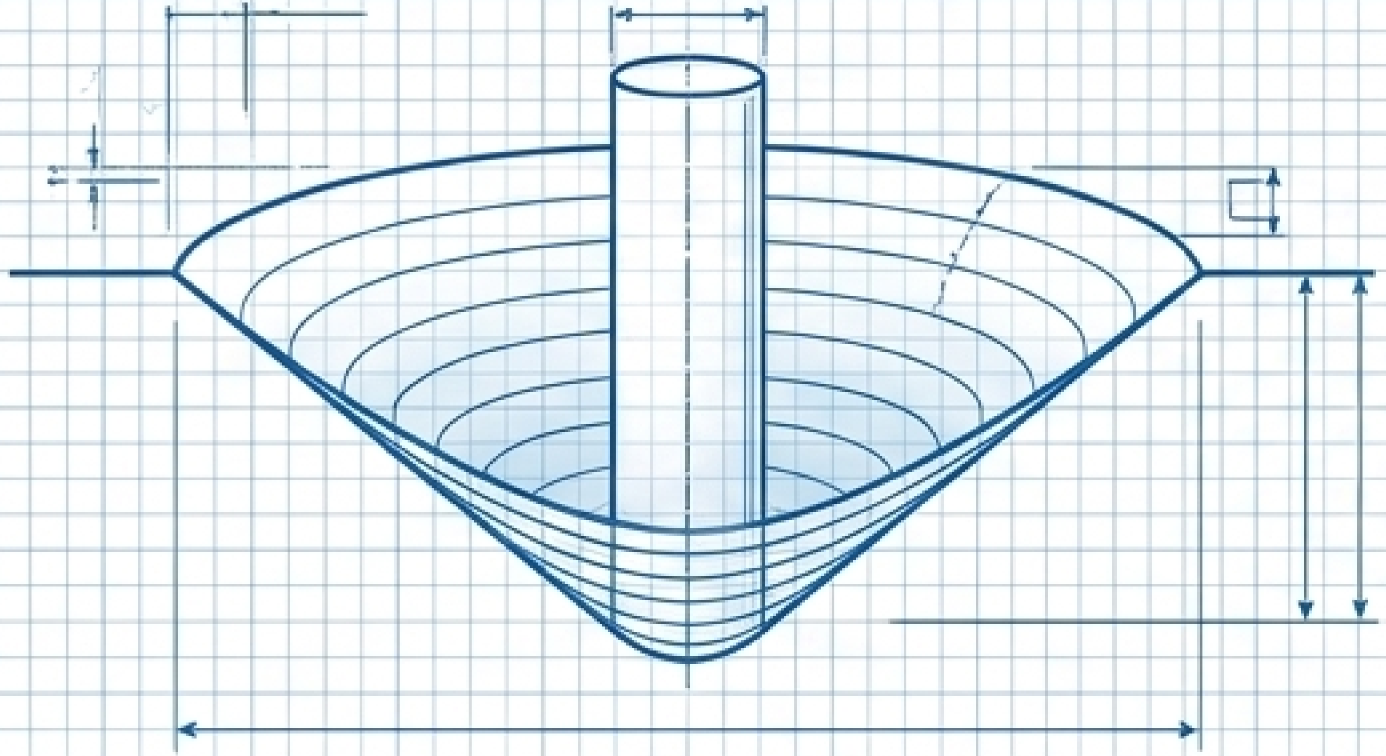
The Time Evolution of Scour



- **The Standard Formula:** $y_s(t) = y_{s,\infty}(1 - e^{-t/T})$
- **The Caveat:** This single-parameter exponential fit only applies well to clear-water. Live-bed scour fluctuates, rendering this equation a poor fit for active transport rivers.

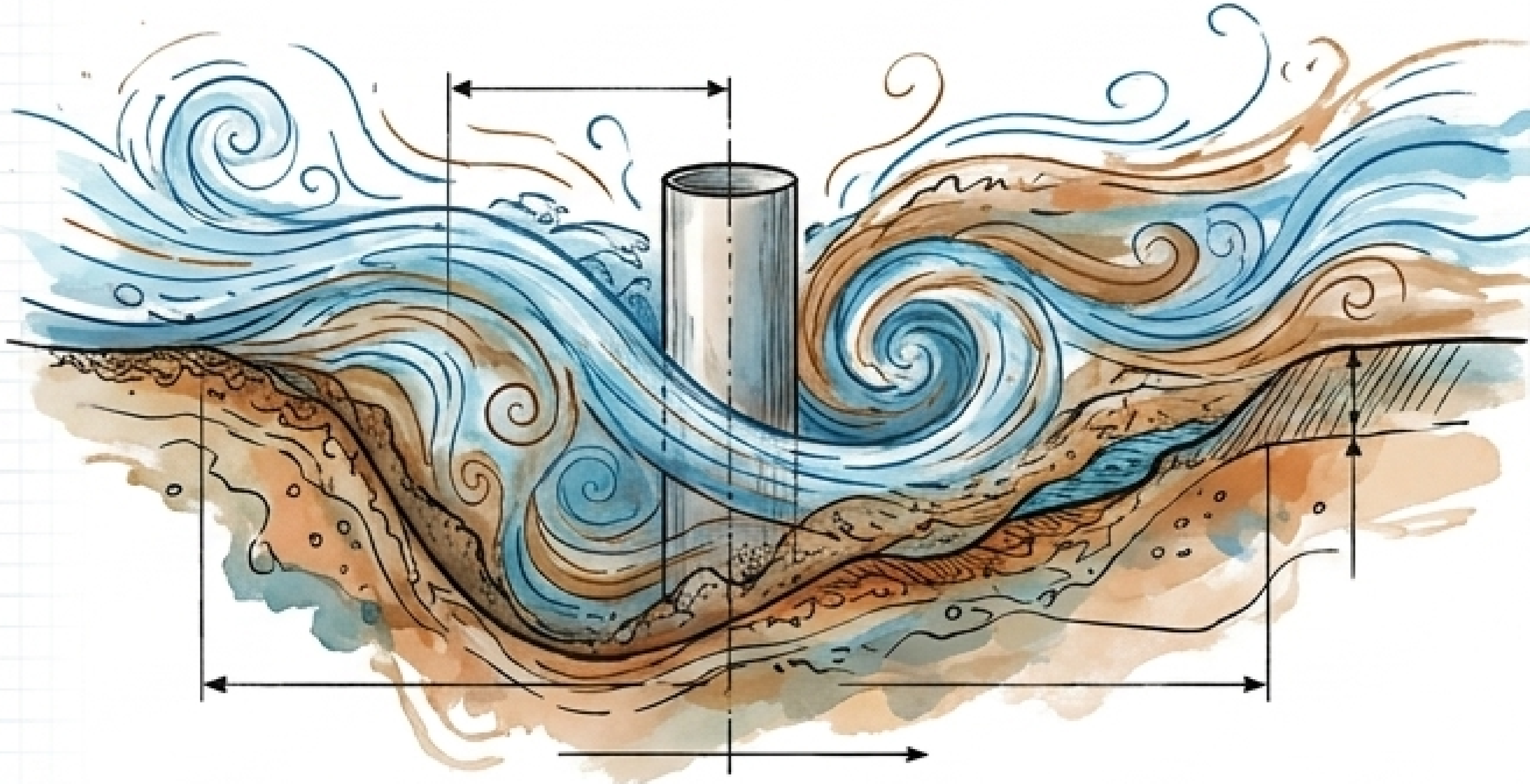
The Uncertainty Gap: Expectation vs. Reality

The Prediction Limitation (Capacity-Based)



- **HEC-18** equations assume instantaneous equilibrium.
- **Result:** Formulas routinely over-predict field scour by 50–100%.

The Field Reality



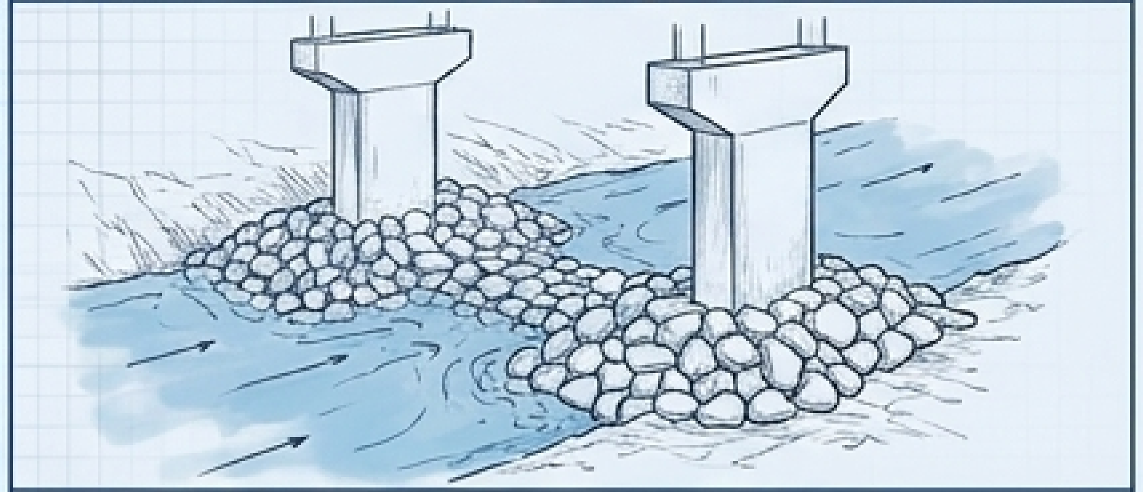
- **Lagged Response & Hysteresis:** The riverbed doesn't react instantly to flow changes; prior flood history matters.
- **Asymmetric Geometry:** Scour holes are rarely perfect cones. They have maximum depth at the pier front, radial decay outward, and skew heavily under angled flow.

Engineering ≠ Exact Science. These limitations enforce the need for **safety factors**

The Scour Protection Arsenal

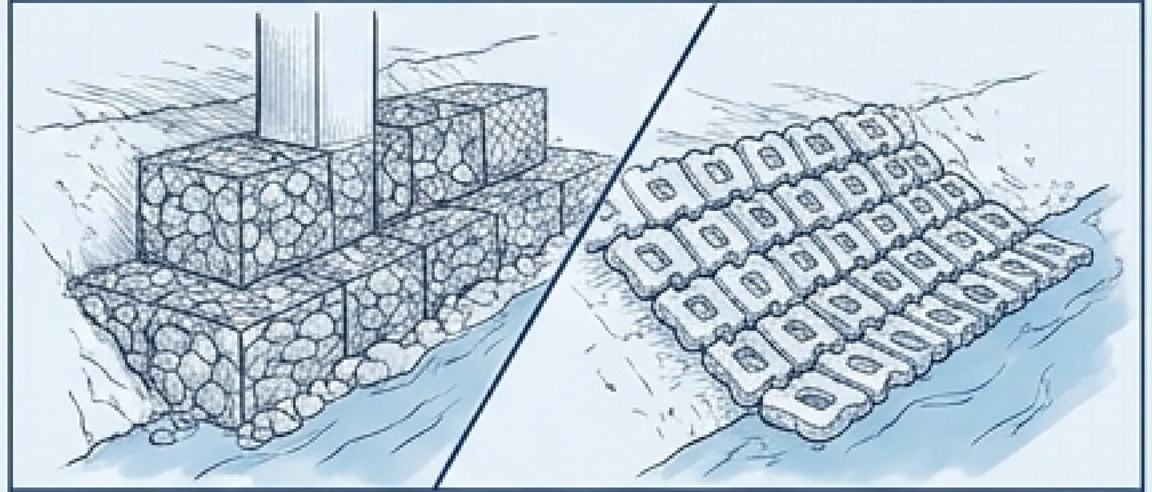
Common FHWA Methods (Industry Standards)

Riprap



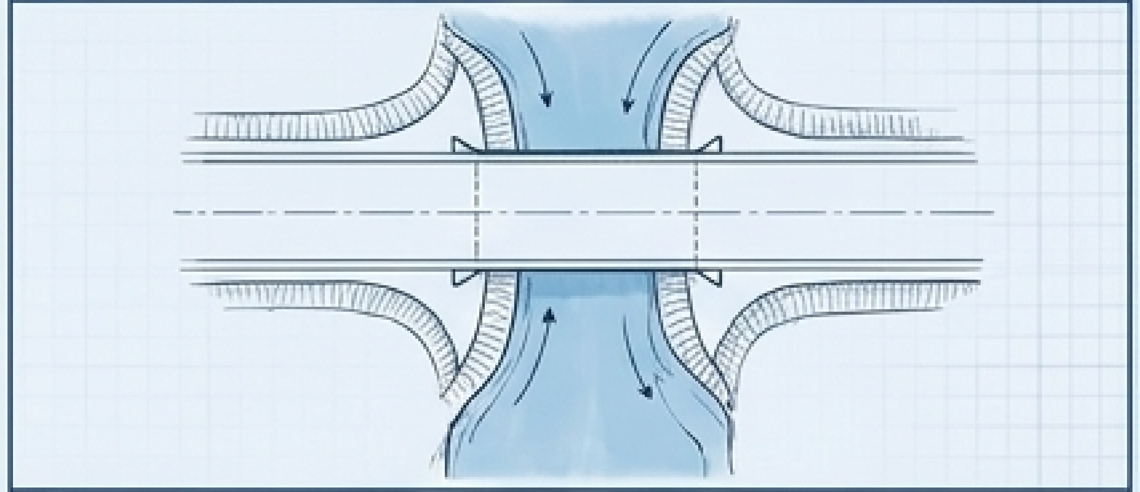
Mounded interlocking stone to armor the bed.

Gabions & ACB



Wire baskets filled with rocks or articulated flexible concrete mats.

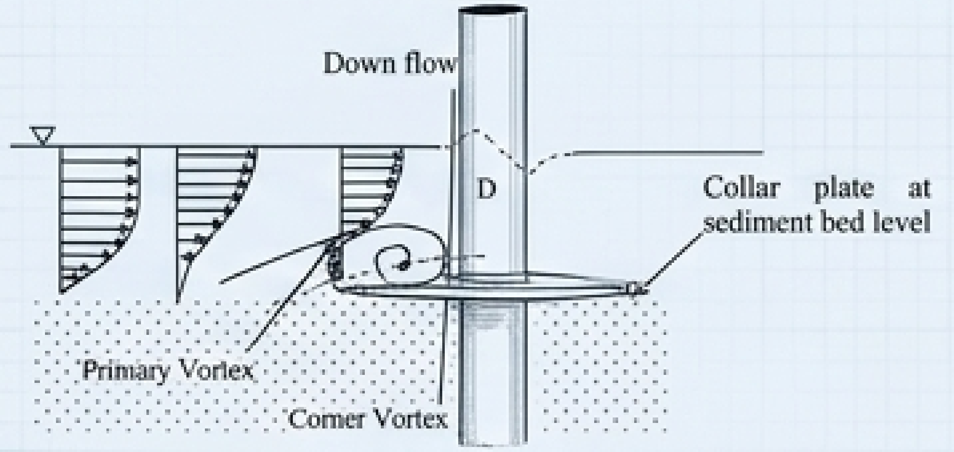
Guide Banks



Flow-aligning earthworks.

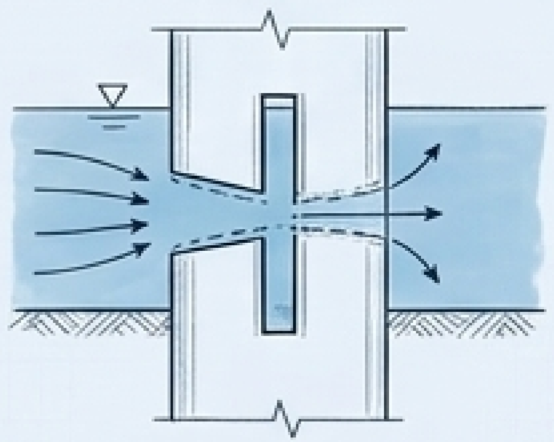
Emerging & Specialized Methods (Flow Alteration)

Collars



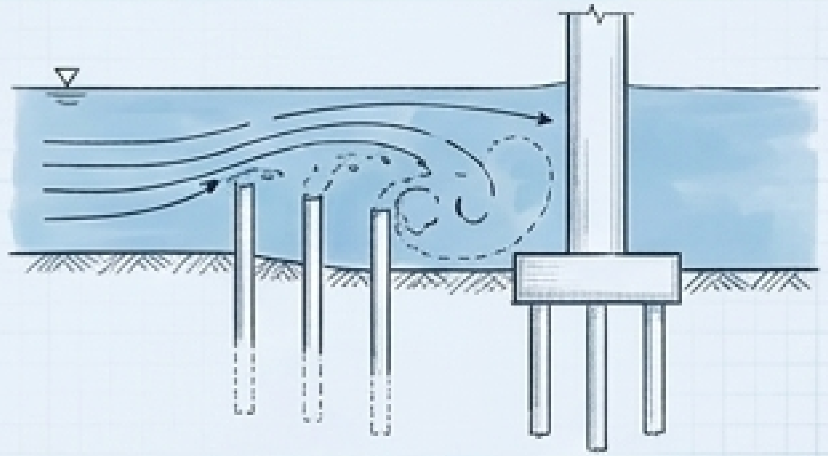
Plates installed at bed level to block the downflow jet.

Slots



Pass-through gaps in the pier to relieve pressure.

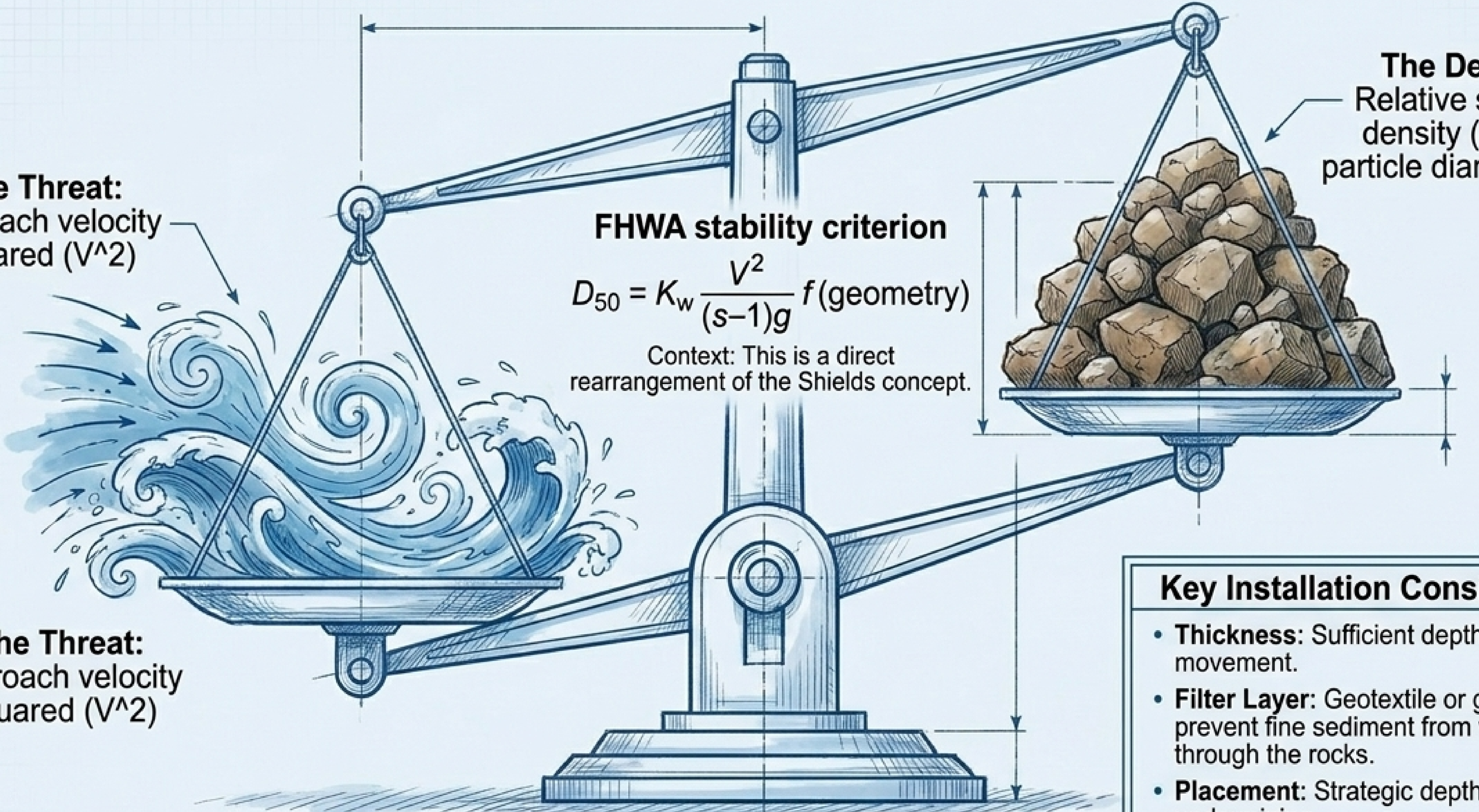
Sacrificial Piles



Upstream deflectors to take the brunt of the vortex shedding.

Engineering ≠ Exact Science. These limitations enforce the need for safety factors.

Riprap Stability Design



The Threat:
Approach velocity squared (V^2)

FHWA stability criterion

$$D_{50} = K_w \frac{V^2}{(s-1)g} f(\text{geometry})$$

Context: This is a direct rearrangement of the Shields concept.

The Defense:
Relative sediment density (s-1) and particle diameter (D_{50})

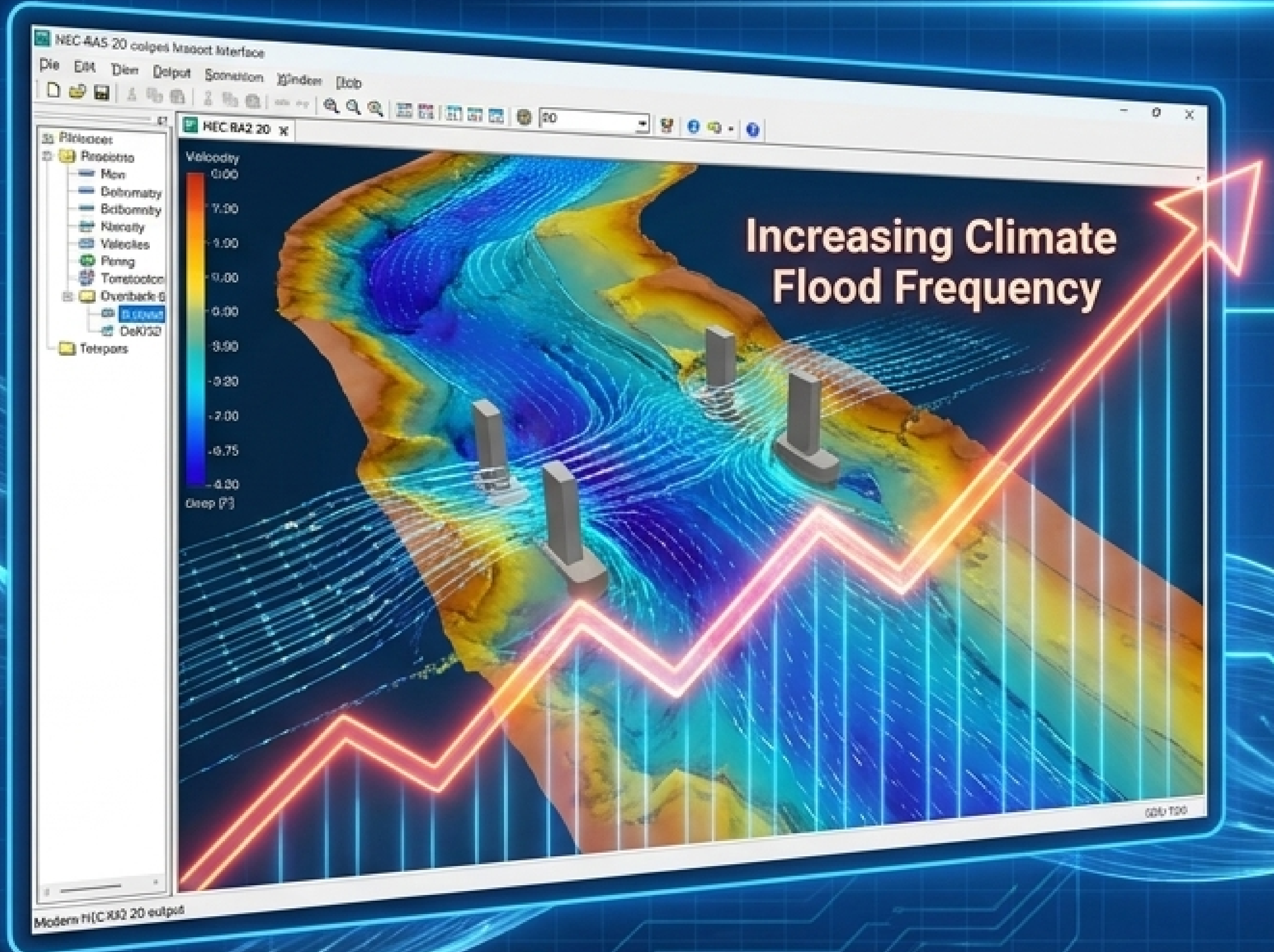
The Threat:
Approach velocity squared (V^2)

Key Installation Considerations

- **Thickness:** Sufficient depth to withstand movement.
- **Filter Layer:** Geotextile or gravel to prevent fine sediment from washing out through the rocks.
- **Placement:** Strategic depth to prevent undermining.

Engineering ≠ Exact Science. These limitations enforce the need for safety factors.

The Future of Scour Design



Increasing Climate Flood Frequency

Modern Tools (Numerical Modeling)

- Transitioning from 1D to 2D morphodynamics (HEC-RAS, SRH-2D, Delft3D).
- Capabilities include pinpointing exact flow fields and shear stress distributions.

The Climate Variable

- Increased flood magnitudes and altered frequencies mean 100-year and 500-year design floods must be revisited.
- Implication: Many existing bridges may currently be under-designed.

The Conservative Design Philosophy

1. Combine all scour components.
2. Calculate using worst-case flows.
3. Protect with compound safety factors.