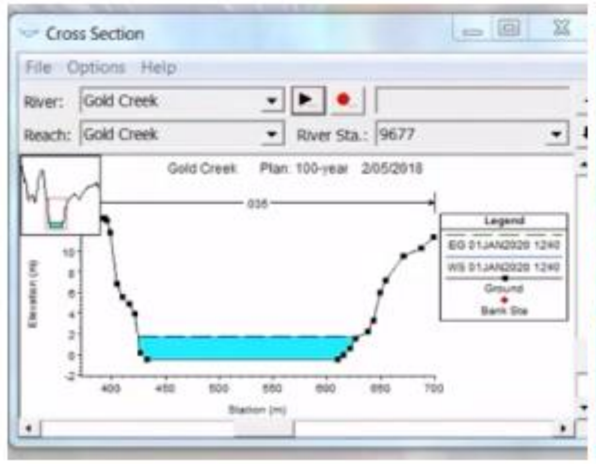
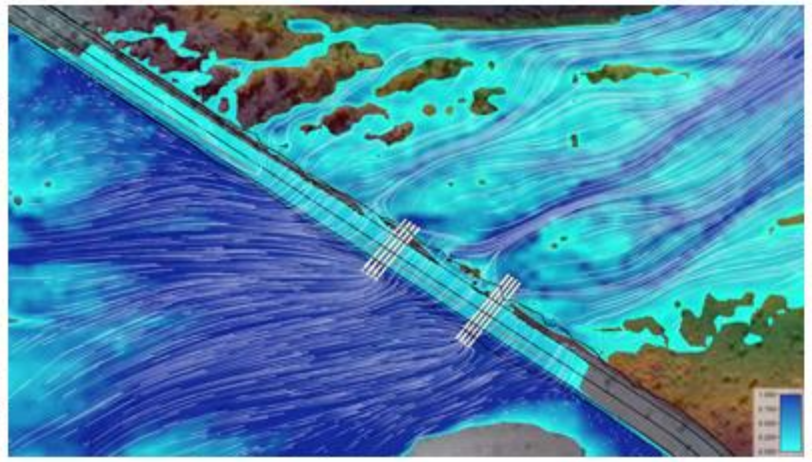
Estimating scour risks from 1D, 2D, and 3D flood model results

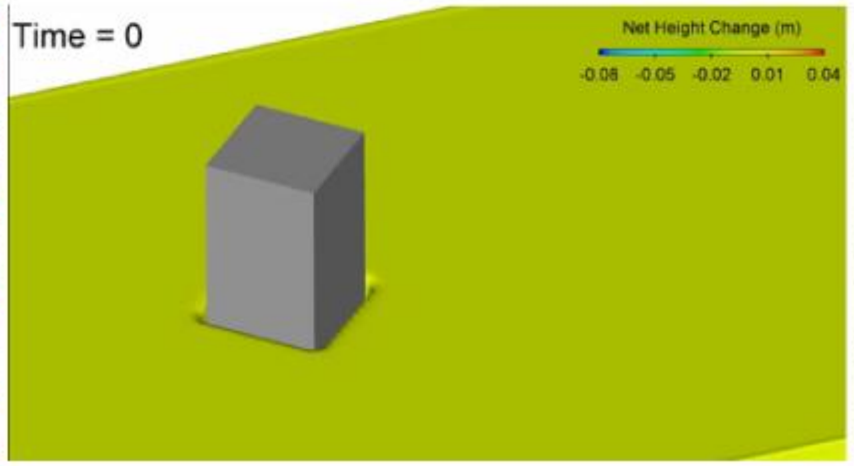
Krey Price
Surface Water Solutions

FMA National Conference
Toowoomba QLD
20 May 2022

Krey Price



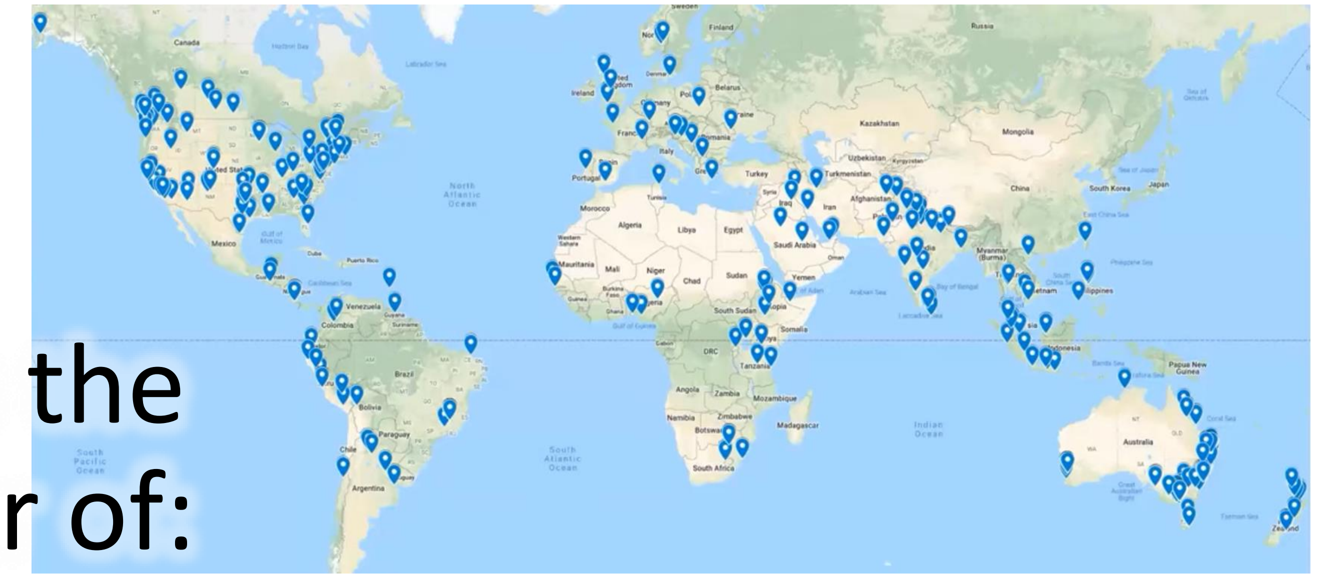


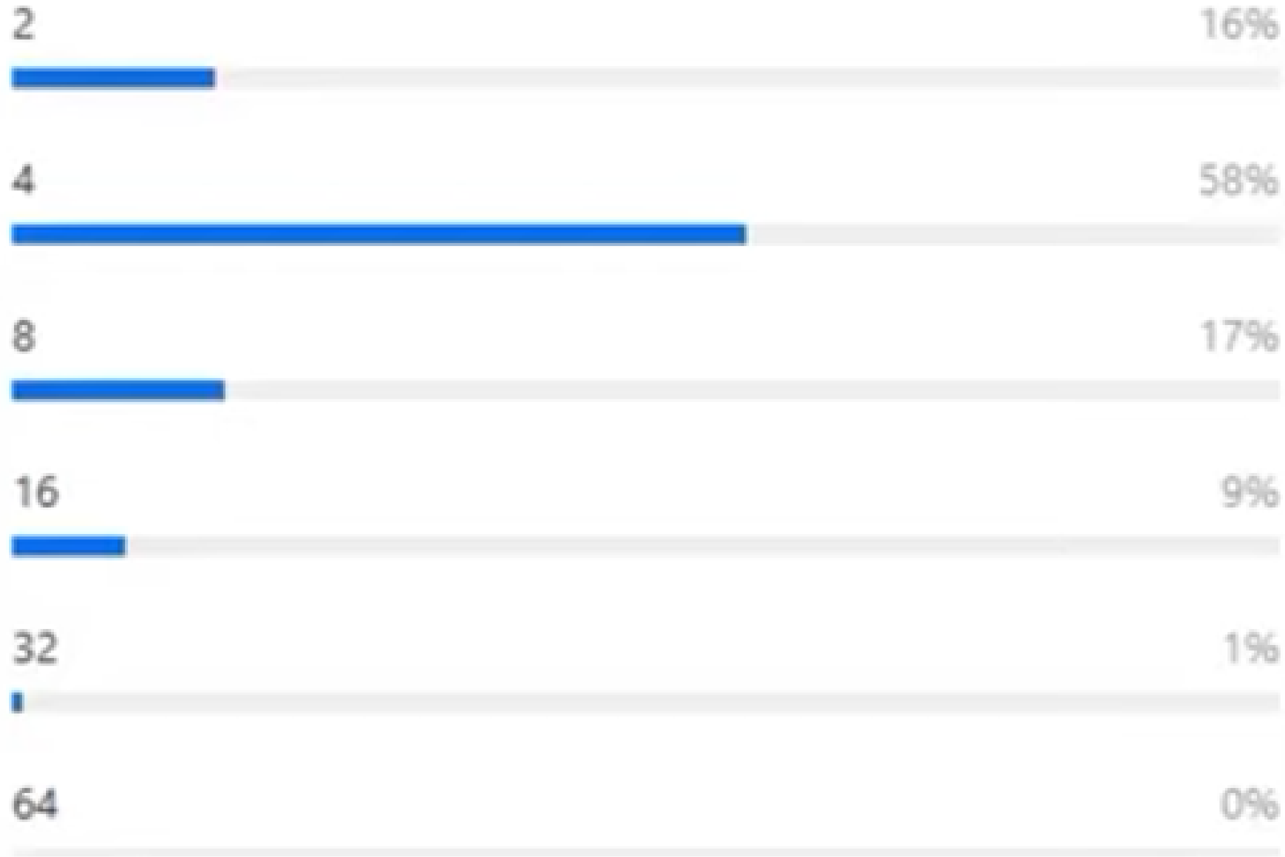


Poll Question

Doubling the velocity increases the required rock weight by a factor of:

- 2
- 4
- 8
- 16
- 32
- 64





Krey Price

Western Australia 2017

Krey Price


WA 2022
Source: Rob Minson via ABC News


NSW 2021
Source: ABC News

Krey Price


QLD 2022
Source: ABC News


SA 2022
Source: Spud's Roadhouse

Source: Childers-Biggenden

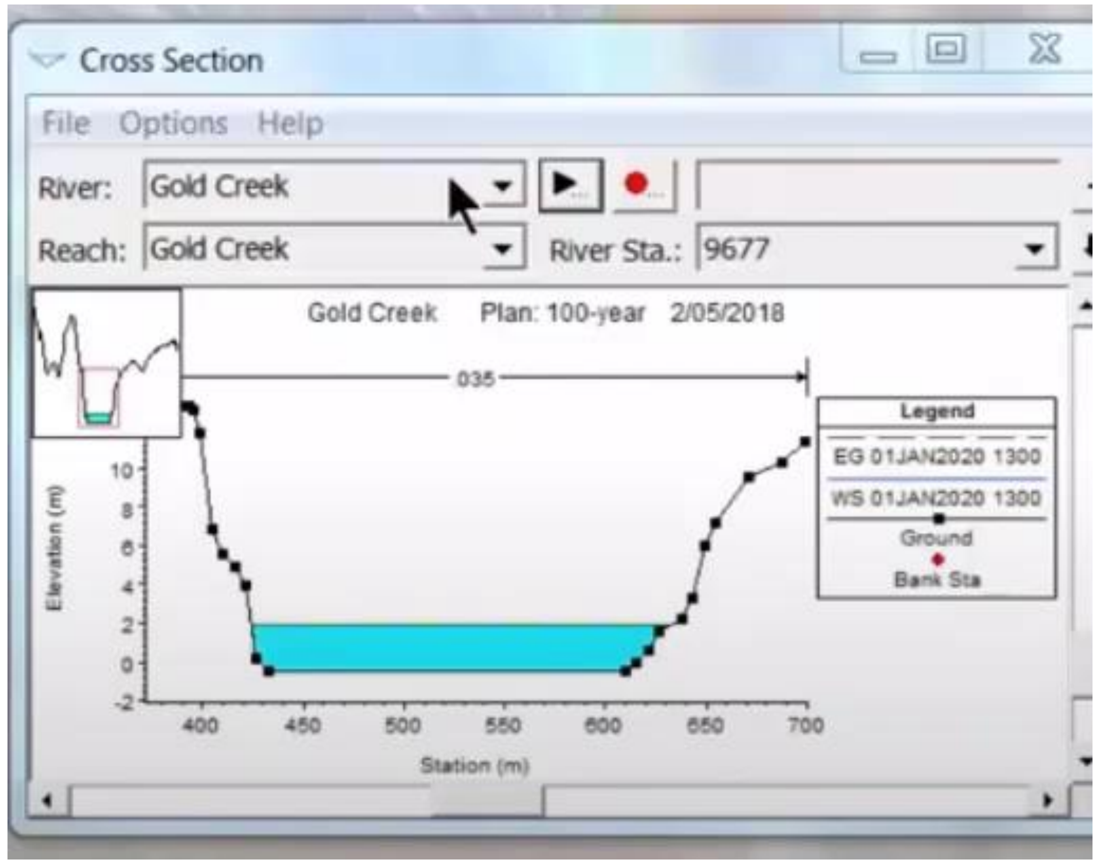
Source: Tweed Shire Council

Krey Price

Krey Price

1D Assumptions:

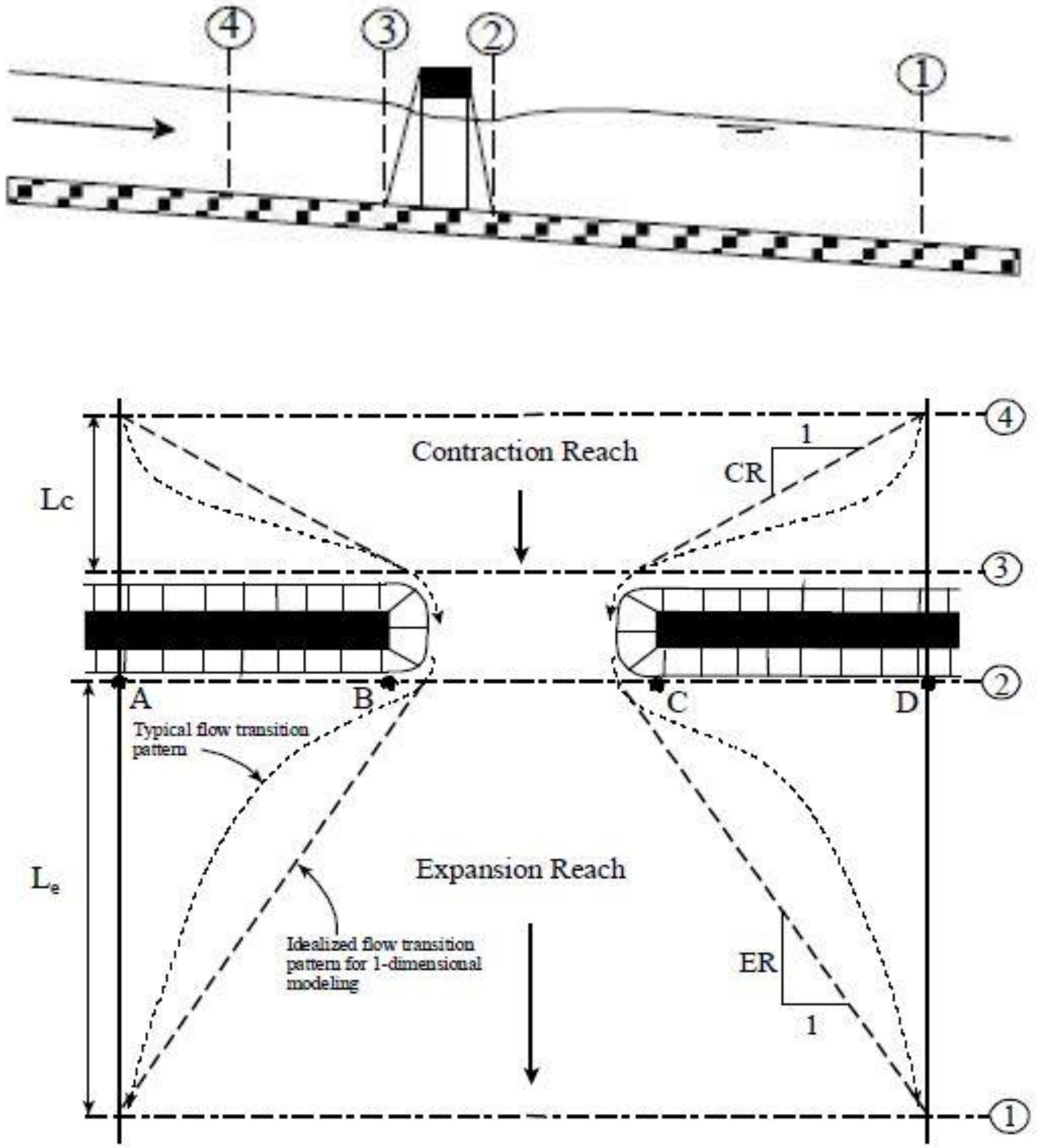
- Water surface elevations are flat across a cross section
- Velocities are flat across a cross section
- Energy gradient gradient levels are flat across a cross section
- Velocities are depth-averaged
- Normal (perpendicular) depth = vertical depth
- Horizontal length = slope length



Krey Price

1D Assumptions:

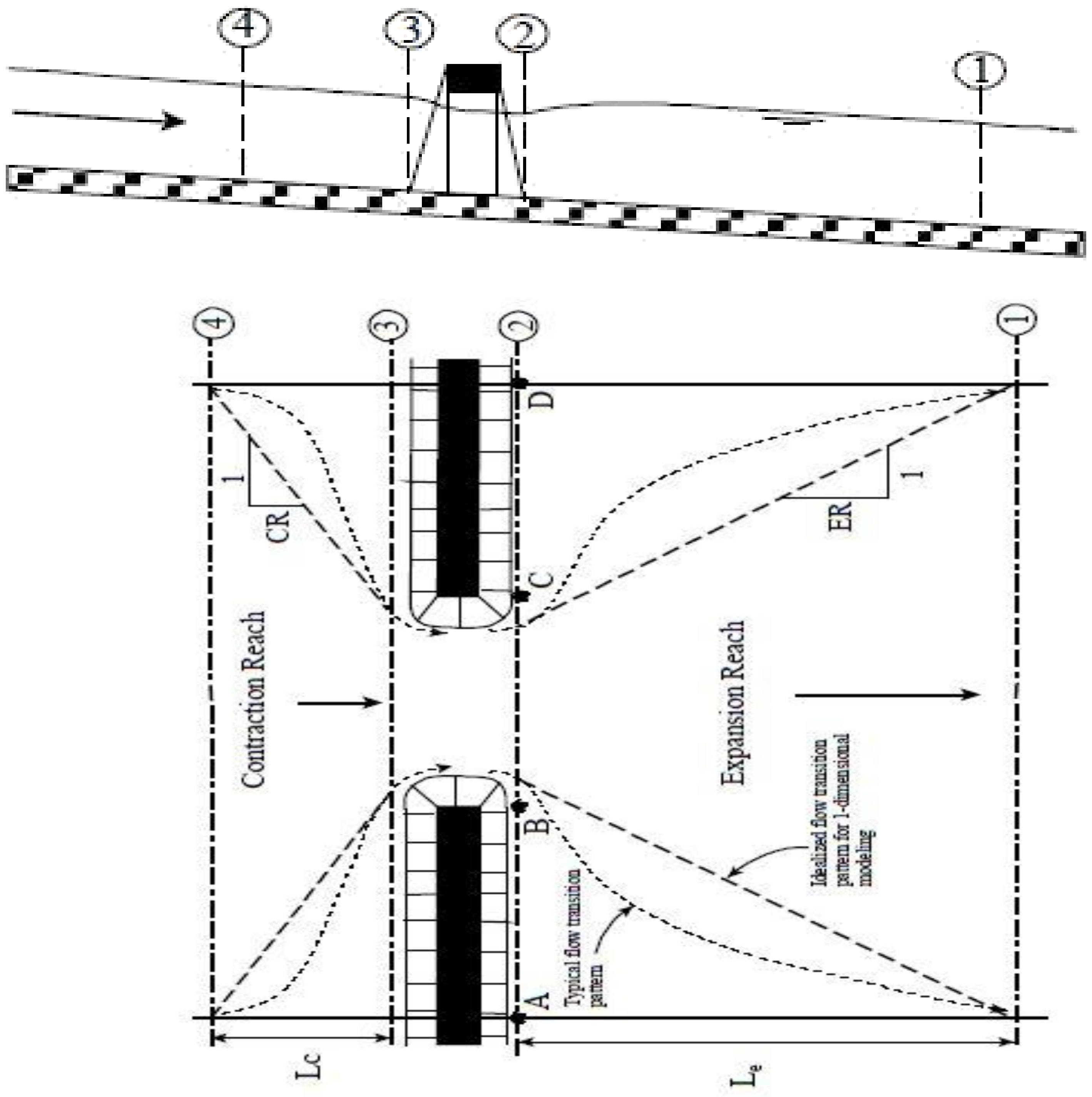
- Water surface elevations are flat across a cross section
- Velocities are flat across a cross section
- Energy gradient gradient levels are flat across a cross section
- Velocities are depth-averaged
- Normal (perpendicular) depth = vertical depth
- Horizontal length = slope length



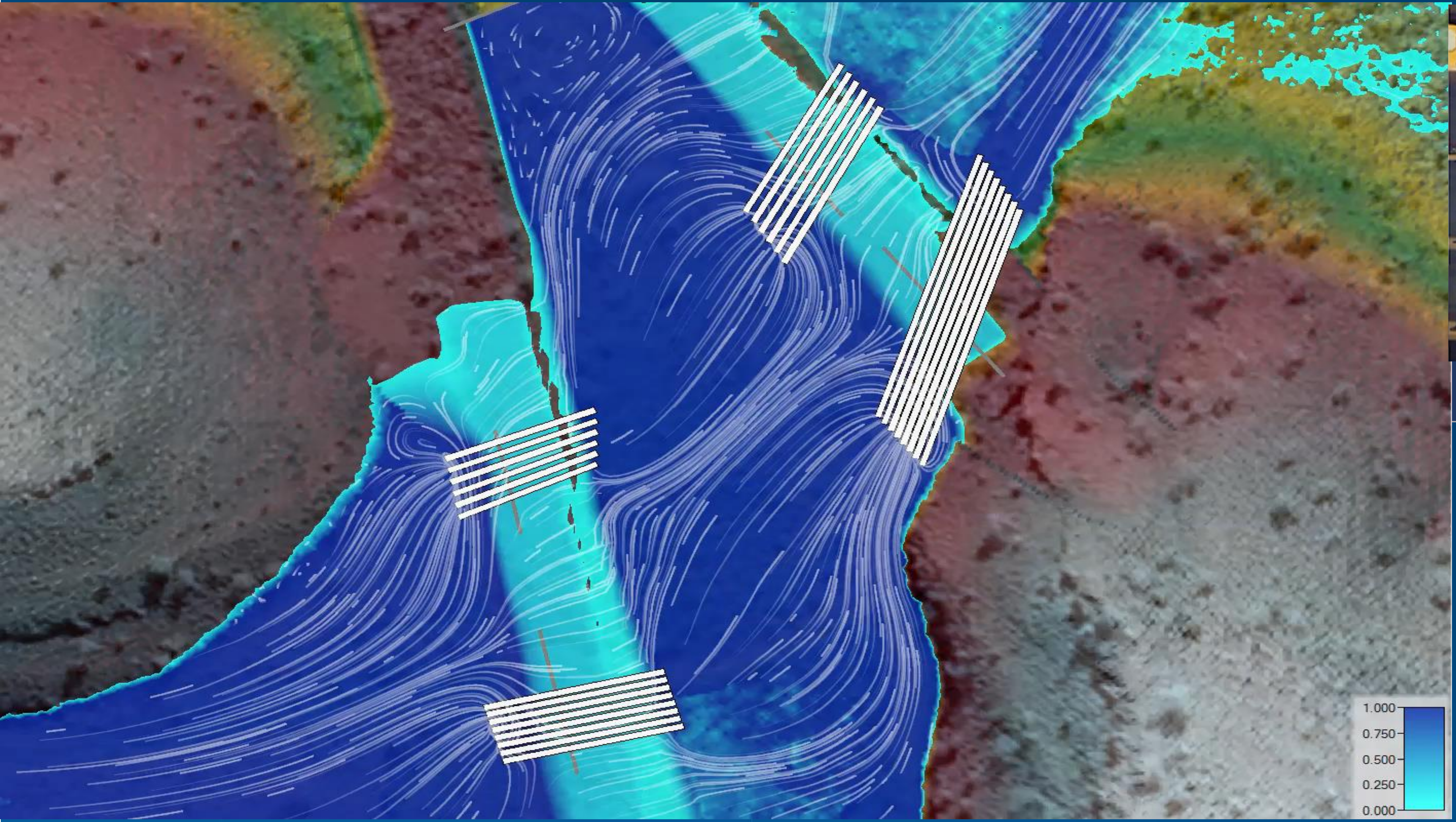
Krey Price

1D Assumptions:

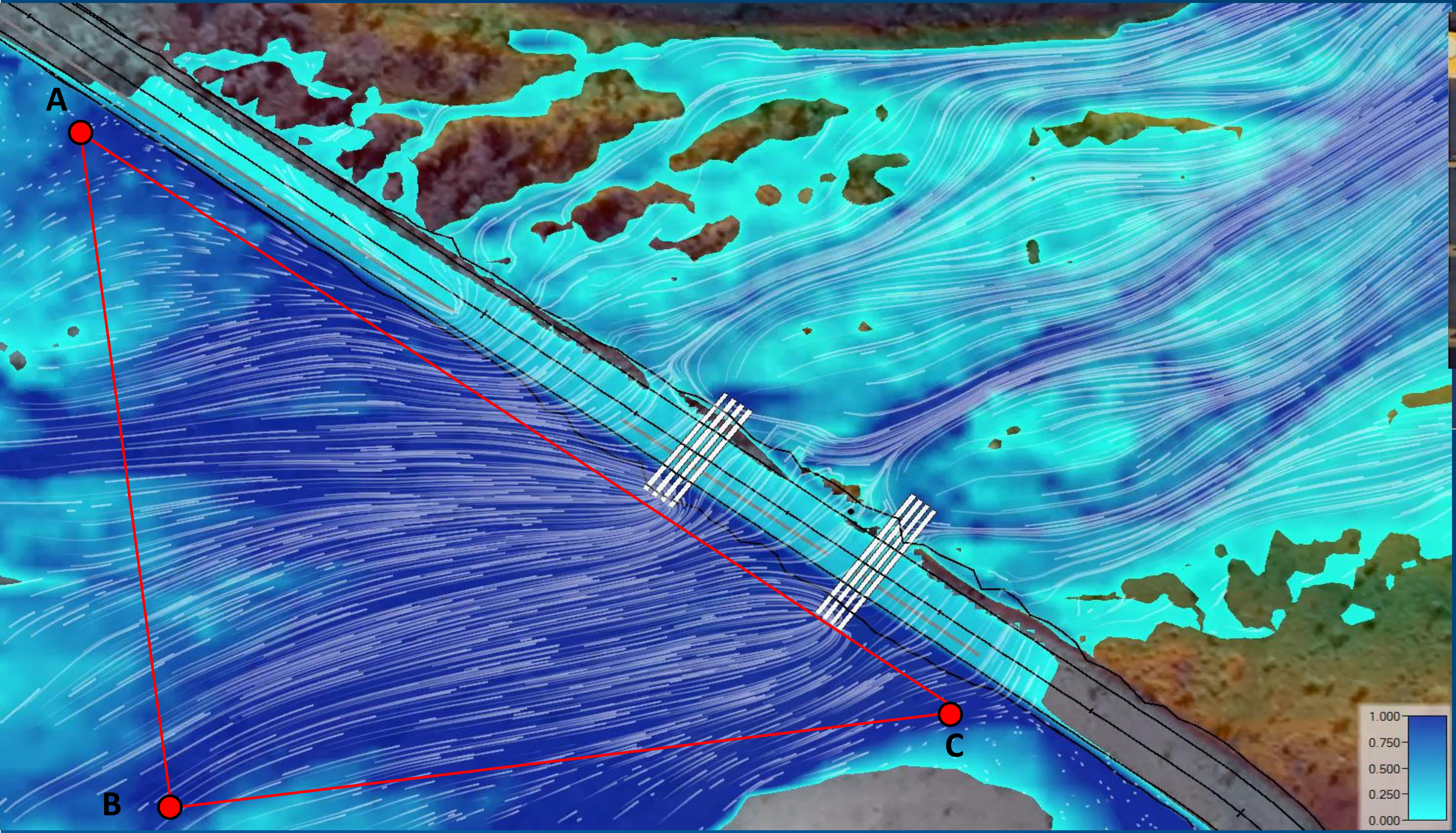
- Water surface elevations are flat across a cross section
- Velocities are flat across a cross section
- Energy gradient gradient levels are flat across a cross section
- Velocities are depth-averaged
- Normal (perpendicular) depth = vertical depth
- Horizontal length = slope length



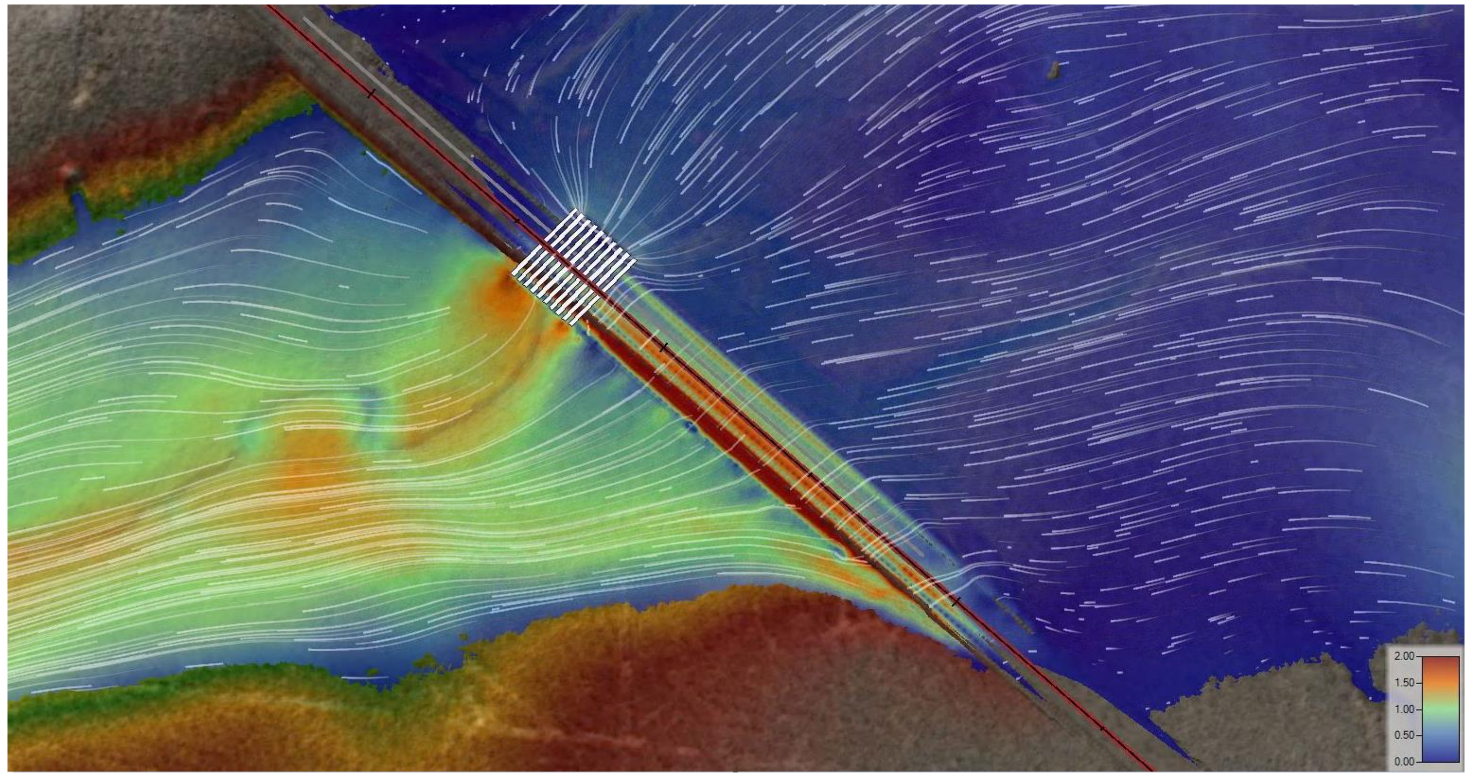
Krey Price

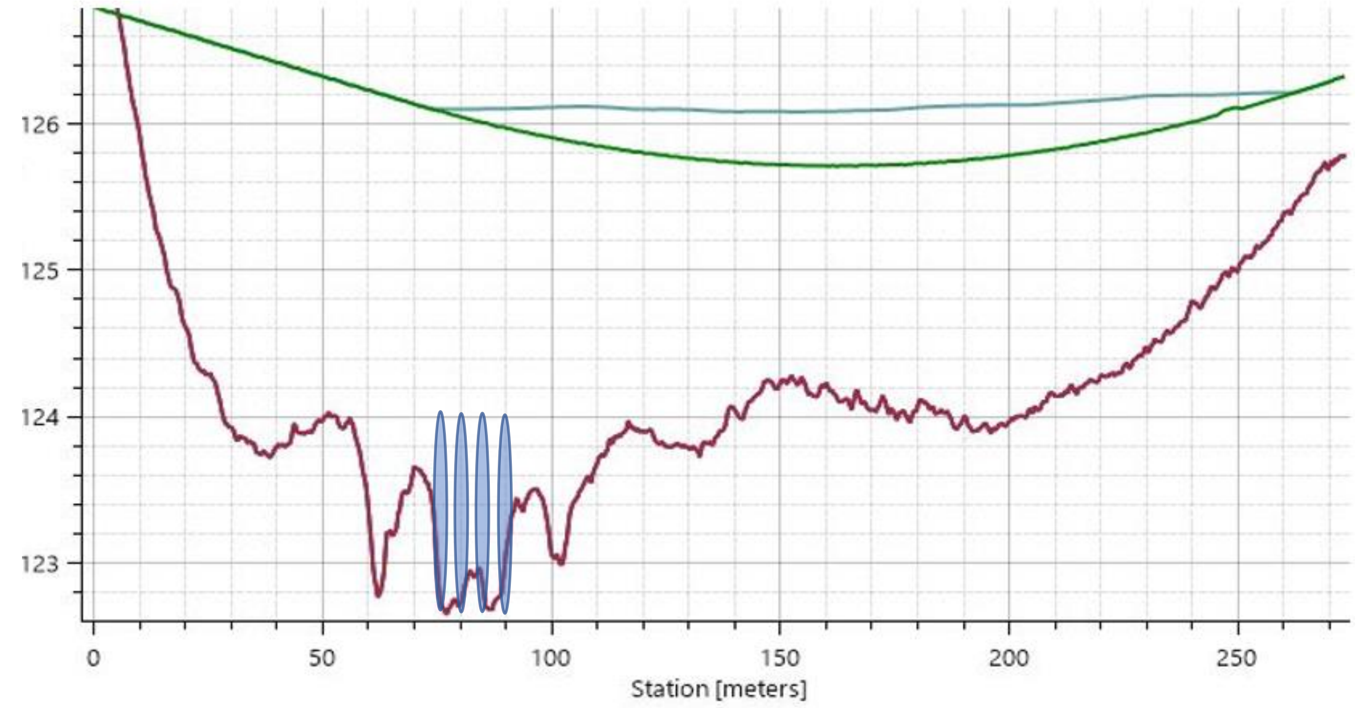


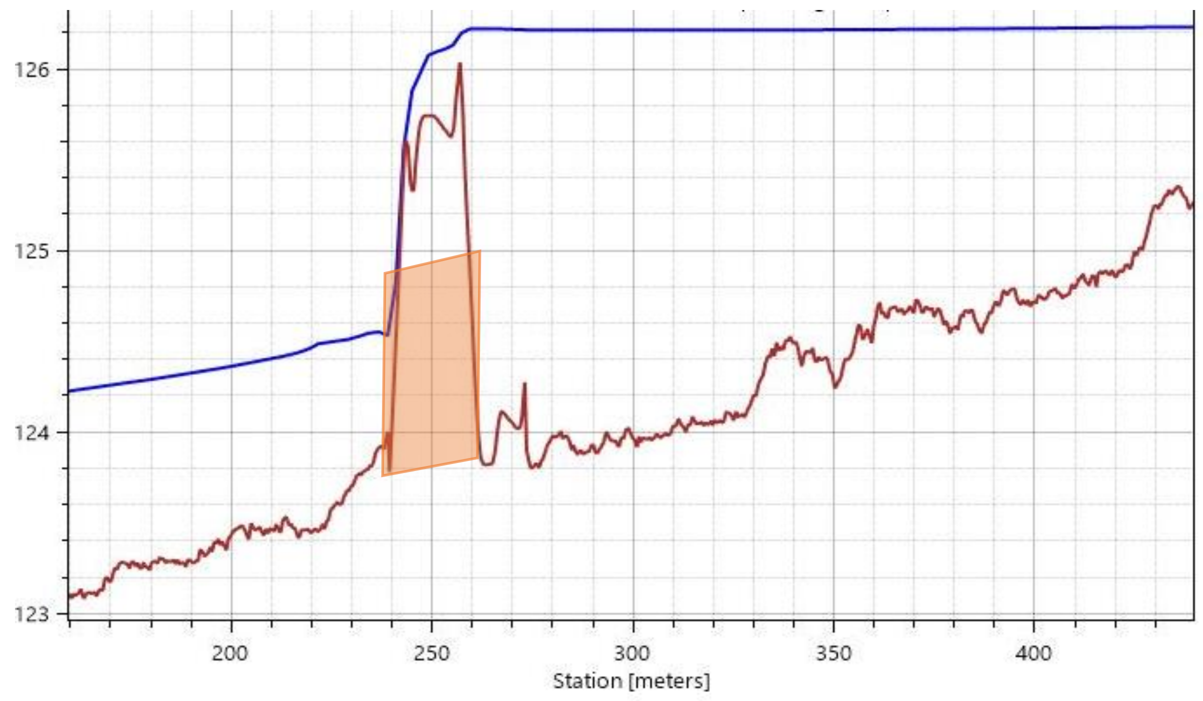
Krey Price



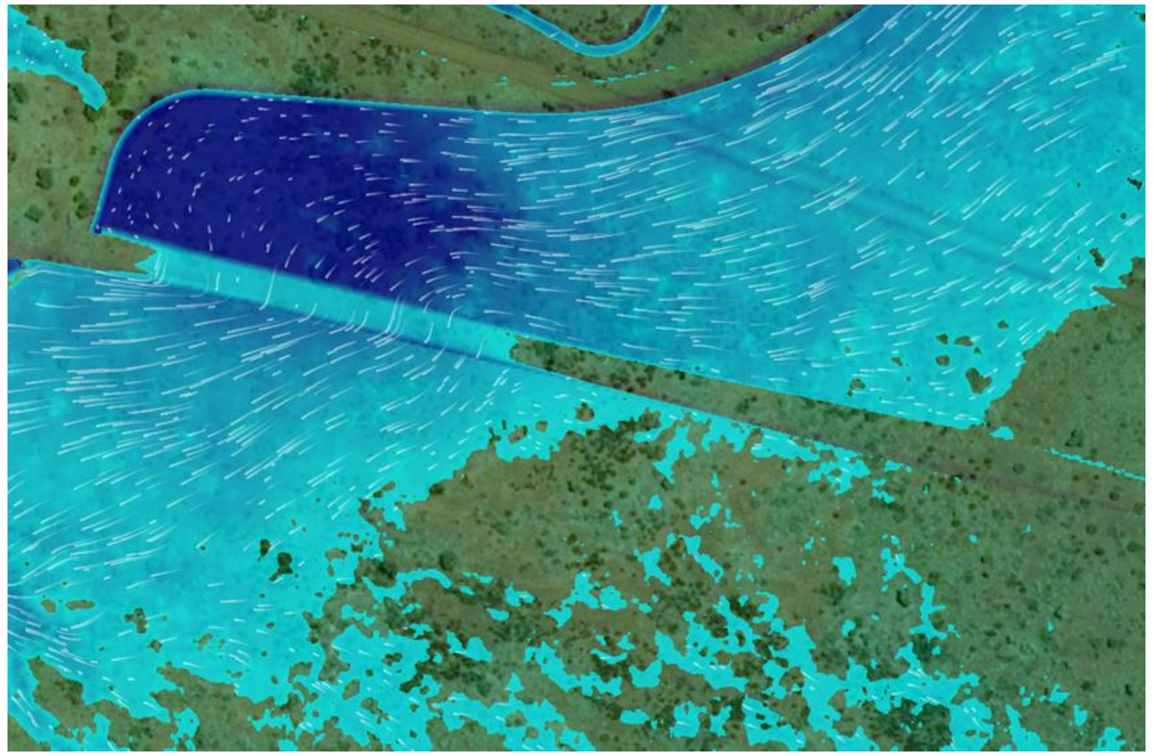
Krey Price

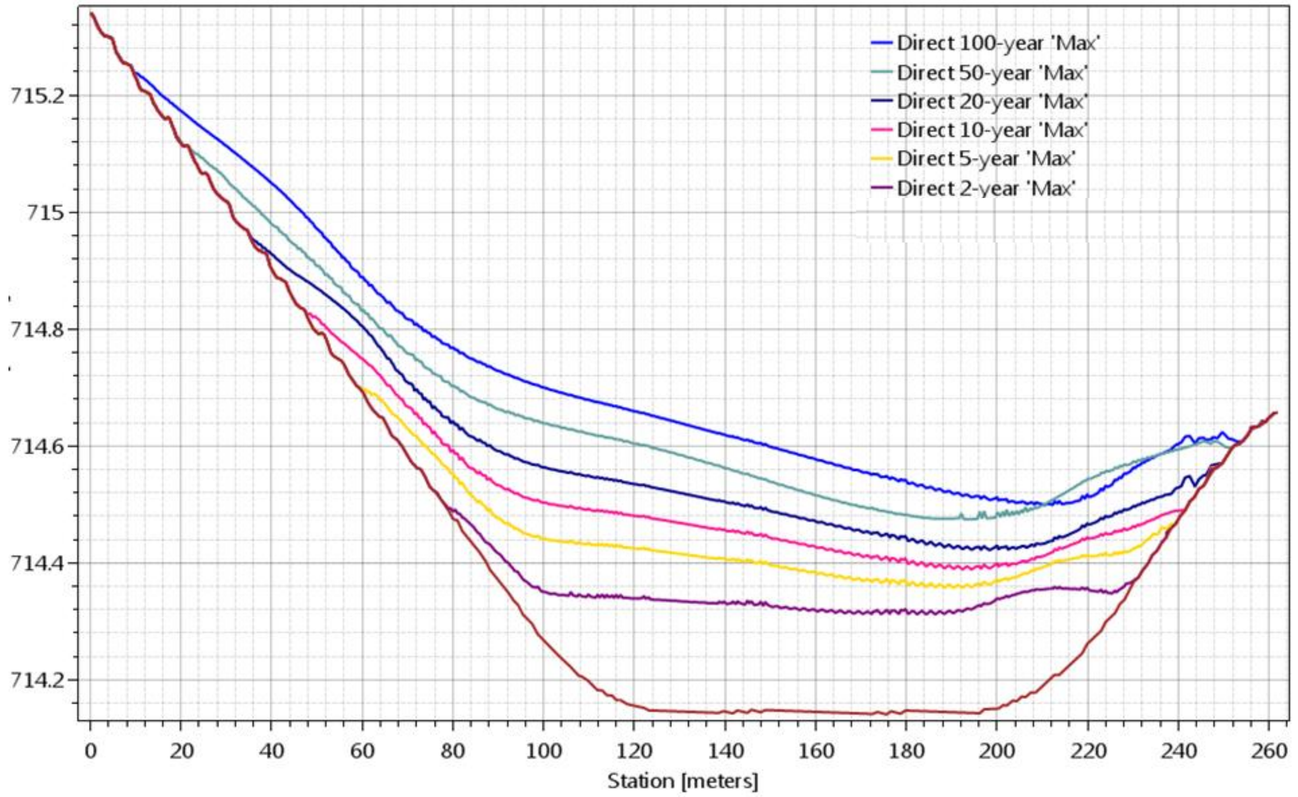


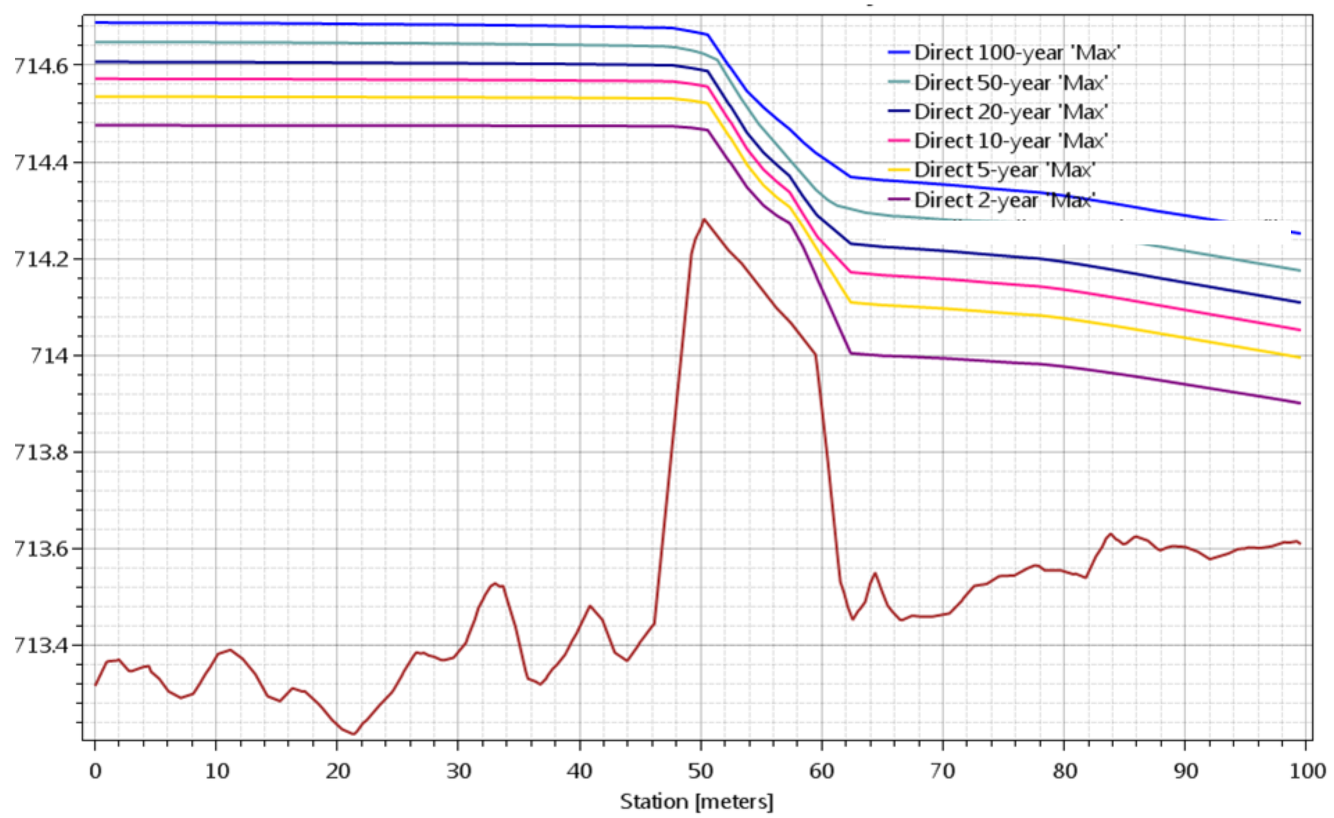

126
125
124
123
0
50
100
150
200
250
Station [meters]


126
125
124
123
200
250
300
350
400
Station [meters]

Krey Price

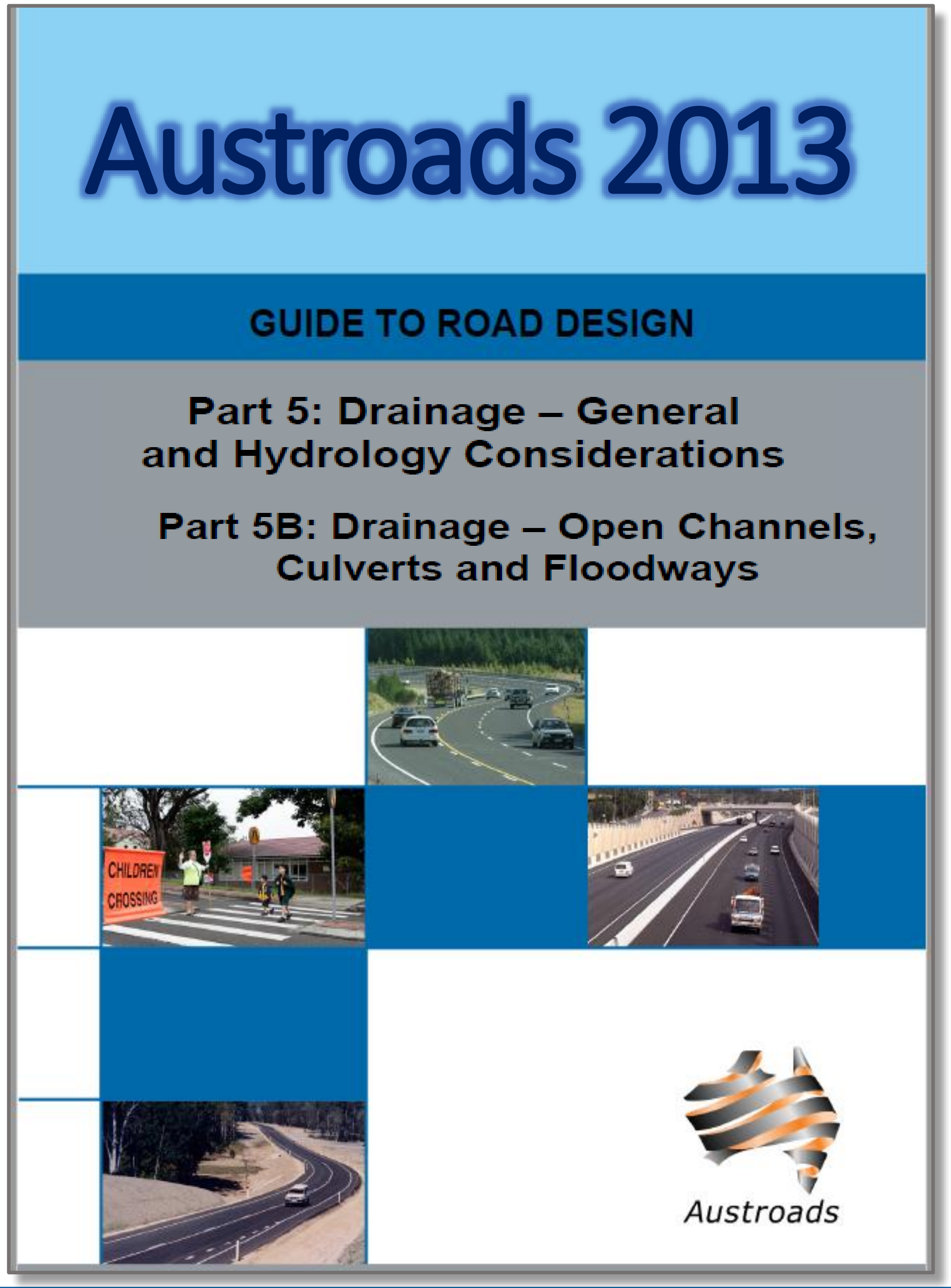


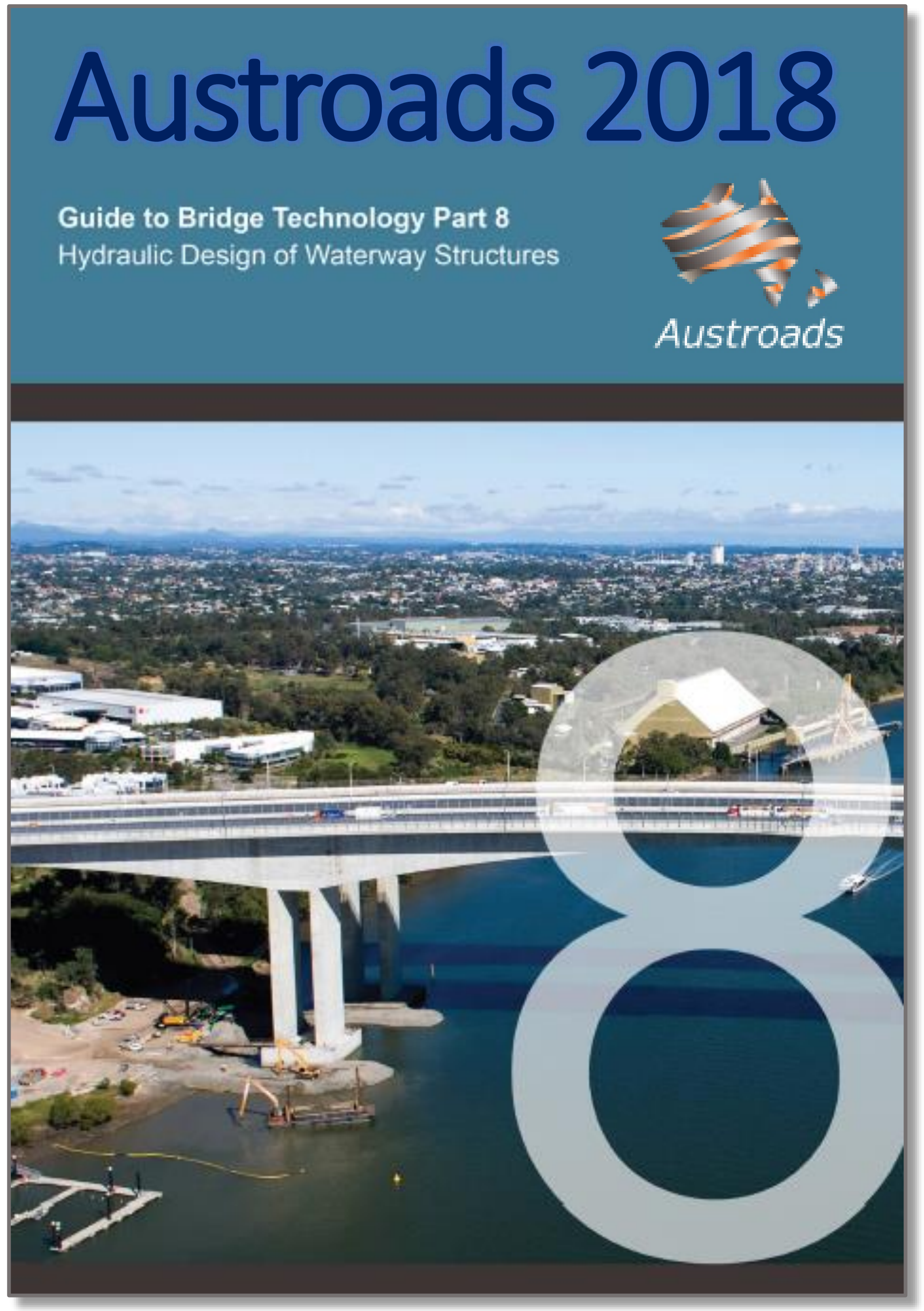

Direct 100-year 'Max'
Direct 50-year 'Max'
Direct 20-year 'Max'
Direct 10-year 'Max'
Direct 5-year 'Max'
Direct 2-year 'Max'
715.2
715
714.8
714.6
714.4
714.2
0
20
40
60
80
100
120
140
160
180
200
220
240
260
Station [meters]


Direct 100-year 'Max'
Direct 50-year 'Max'
Direct 20-year 'Max'
Direct 10-year 'Max'
Direct 5-year 'Max'
Direct 2-year 'Max'
714.6
714.4
714.2
714
713.8
713.6
713.4
0
10
20
30
40
50
60
70
80
90
100
Station [meters]

Krey Price

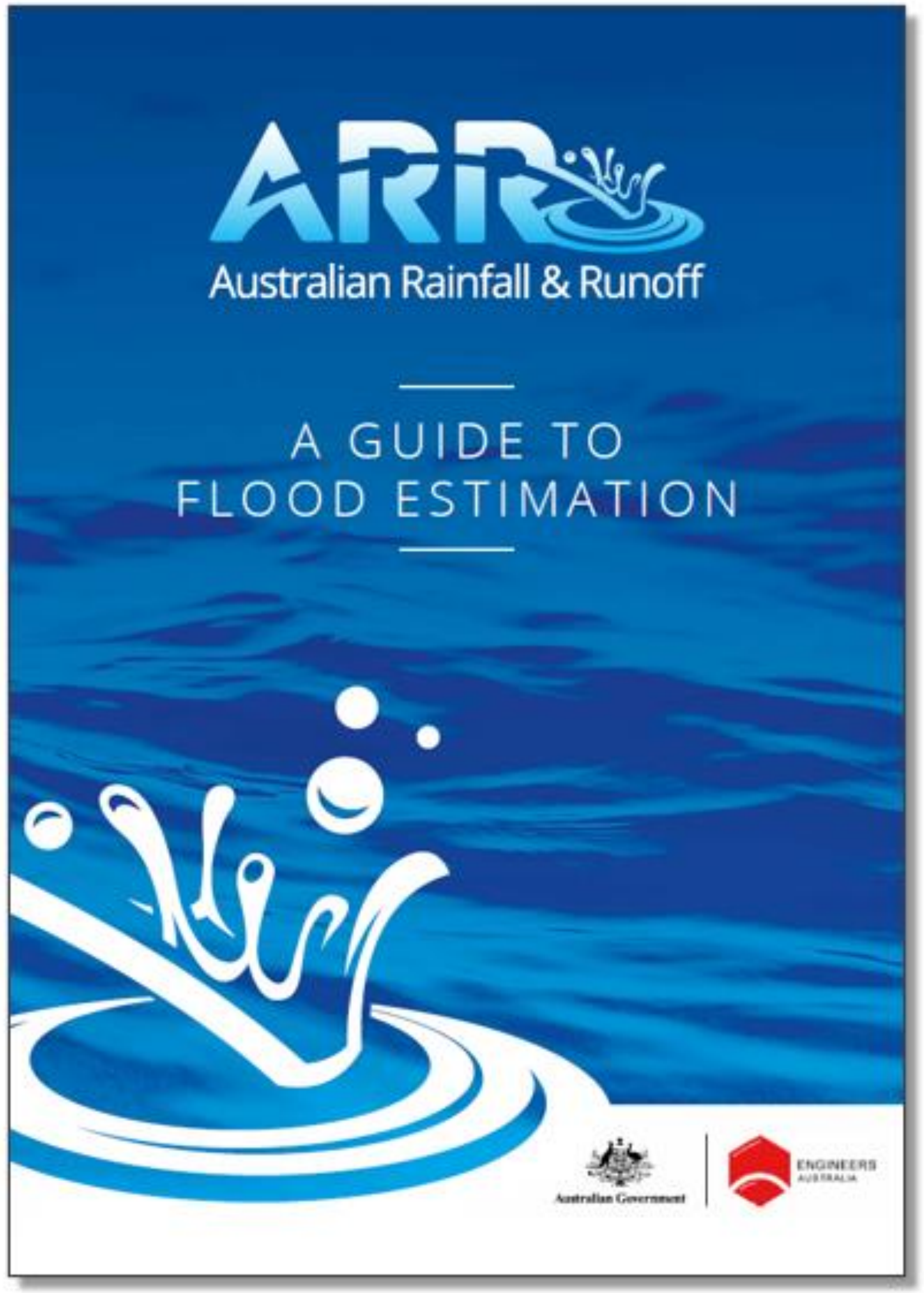
Australian national guidance for rock sizing





Krey Price

Australian national guidance for rock sizing



ARR 2019

Australian Rainfall and Runoff

A Guide to Flood Estimation

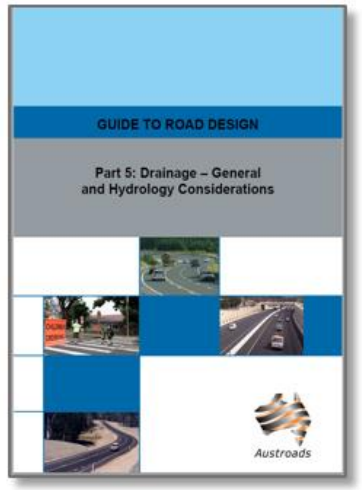
ISBN 978-1-925848-36-6

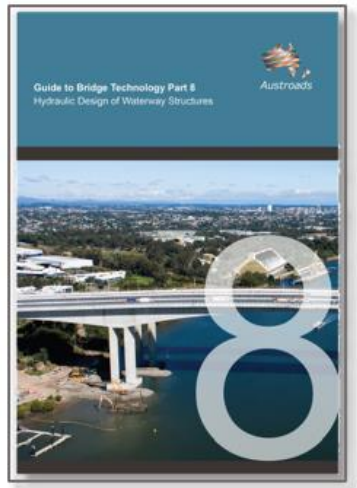
How to reference this book:
Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors) Australian Rainfall and Runoff: A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia), 2019.

How to reference Book 9: Runoff in Urban Areas:
Coombes, P., and Roso, S. (Editors), 2019 Runoff in Urban Areas, Book 9 in Australian Rainfall and Runoff - A Guide to Flood Estimation, Commonwealth of Australia, © Commonwealth of Australia (Geoscience Australia), 2019.

Krey Price

Australian national guidance for rock sizing

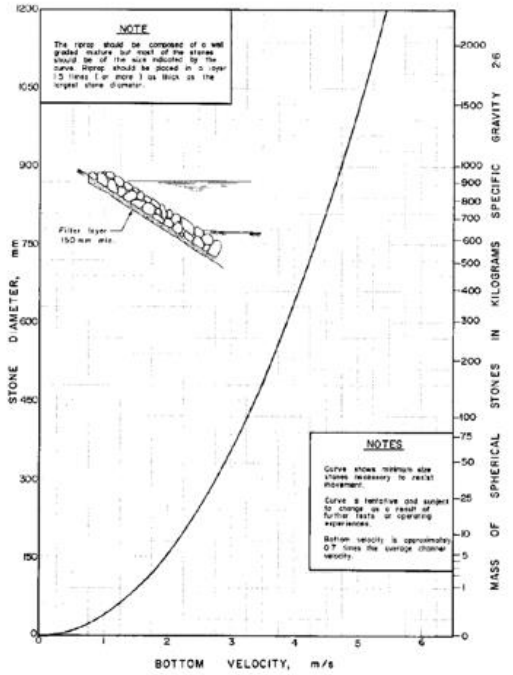




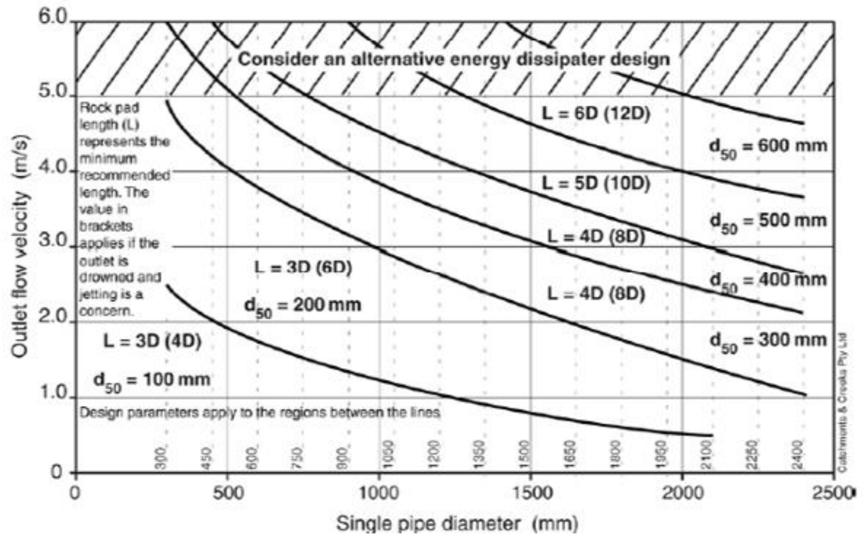
Bridges and Floodways

Velocity (m/s)	Class of rock protection (tonne)	Section thickness, *T* (m)
< 2	None	–
2.0–2.6	Facing	0.50
2.6–2.9	Light	0.75
2.9–3.9	¼	1.00
3.9–4.5	½	1.25
4.5–5.1	1.0	1.60
5.1–5.7	2.0	2.00
5.7–6.4	4.0	2.50
> 6.4	Special	–

Lined Channels



Culverts

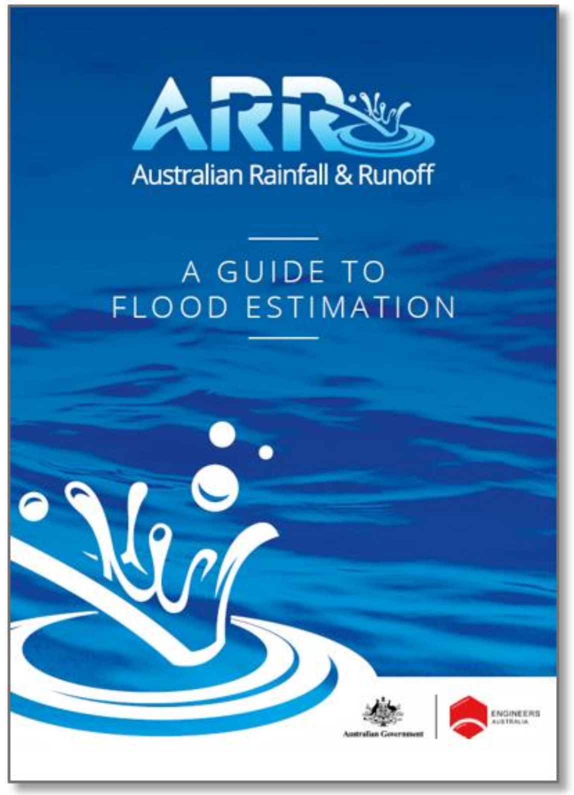


Natural Channels

Stream bed type		Velocity (m/s)
Silt		less than 0.3
Sand	Fine Coarse	less than 0.3 less than 0.3
Gravel	6 mm 25 mm 100 mm	0.6 to 0.9 1.3 to 1.5 2.0 to 3.0
Clay	Soft Stiff Hard	0.3 to 0.6 1.0 to 1.2 1.5 to 2.0
Rocks	150 mm 300 mm	2.5 to 3.0 3.5 to 4.0

Krey Price

Australian national guidance for rock sizing



Channels

Equation (6.2.21) applies to uniform flow, but it can be generalised to include gradually varying flow by replacing the slope, S by the friction slope, Sf. For gradually varying flow, the bed shear stress is given by:

$$\tau_o = \rho g R_h S_f \quad (6.2.25)$$

The bed shear stress is important when considering the flow velocities necessary for scour

Spillways

The surfaces of an earthen embankment and overflow spillway must be protected against damage by scour. The degree of protection required is subject to the calculated flow velocity.

The following treatments are recommended as a guide (NSW Government, 2004):

- $V \leq 2$ m/s a dense well-knit turf cover using for example kikuyu;
- 2 m/s < V < 7 m/s a dense well-knit turf cover incorporating a turf reinforcement system; and
- $V \geq 7$ m/s hard surfacing with concrete, riprap or similar.

Bridges

Riprap is one of the primary scour countermeasures to resist local scour forces at abutments of typical bridges. Riprap is generally abundant, inexpensive and requires no special equipment. However, proper design and placement is essential. Guidelines for proper grading and placement methods are included in QDTMR (2013).

Detailed descriptions of scour repair and protection for existing bridges is included in QDTMR (2013).

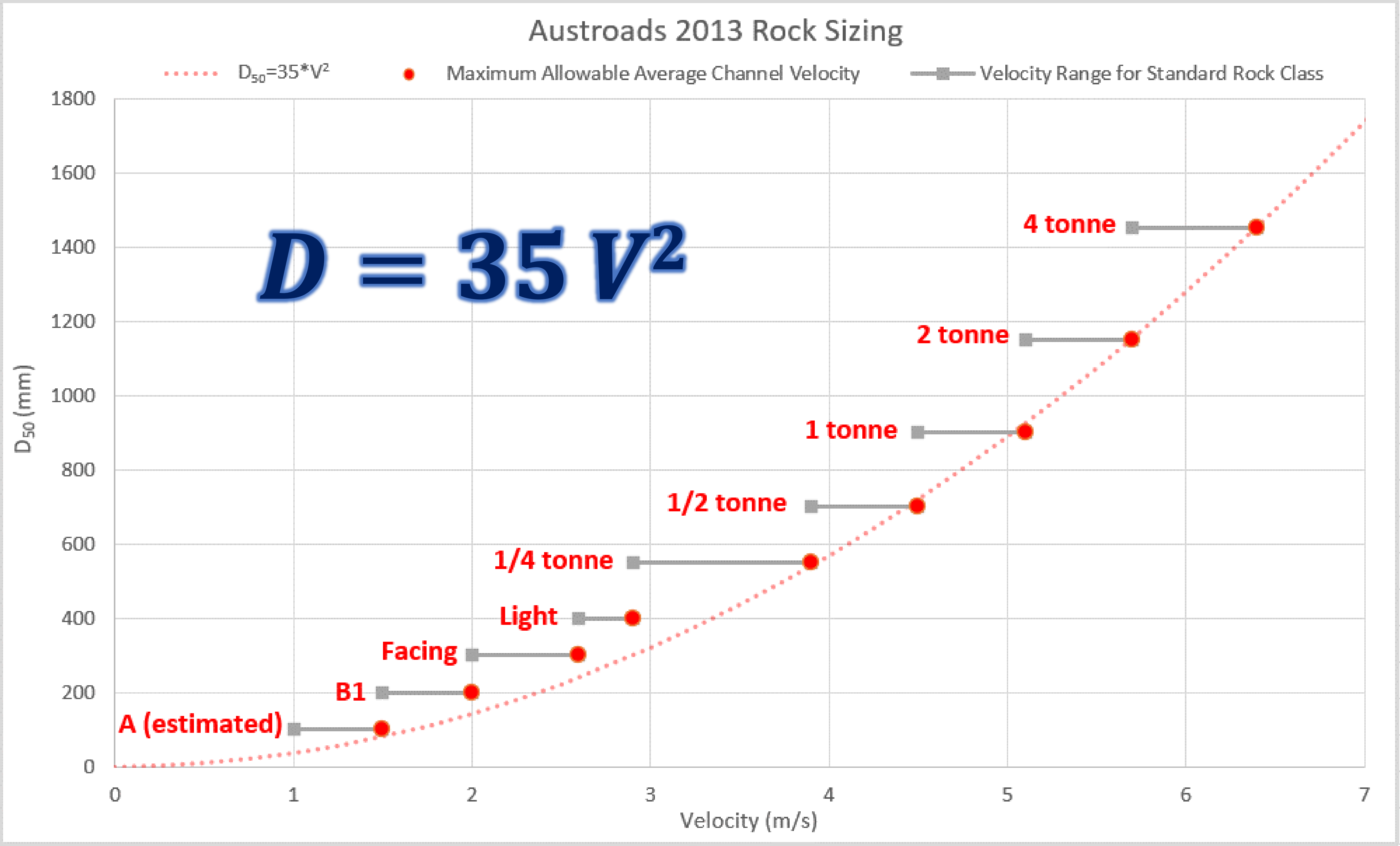
Culverts

If outlet velocities exceed the acceptable limits, it may be necessary to check for potential bed scour problems. Where the outlet flows have a Froude Number (*Fr*) less or equal to 1.7 and outlet velocities less than 5.0 m/s, an extended concrete apron or rock pad (commonly used) protection is recommended.

Design details are provided by Austroads (2013).

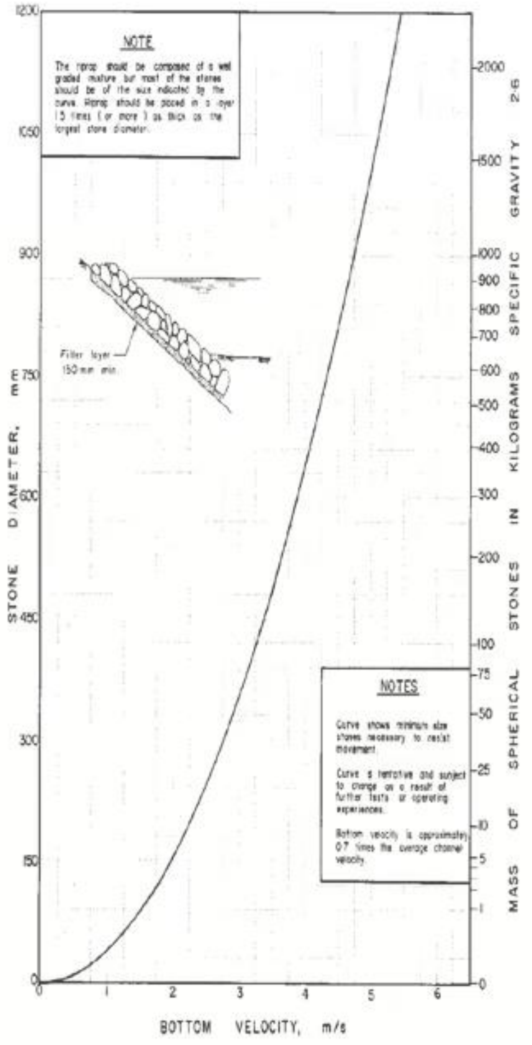
Krey Price

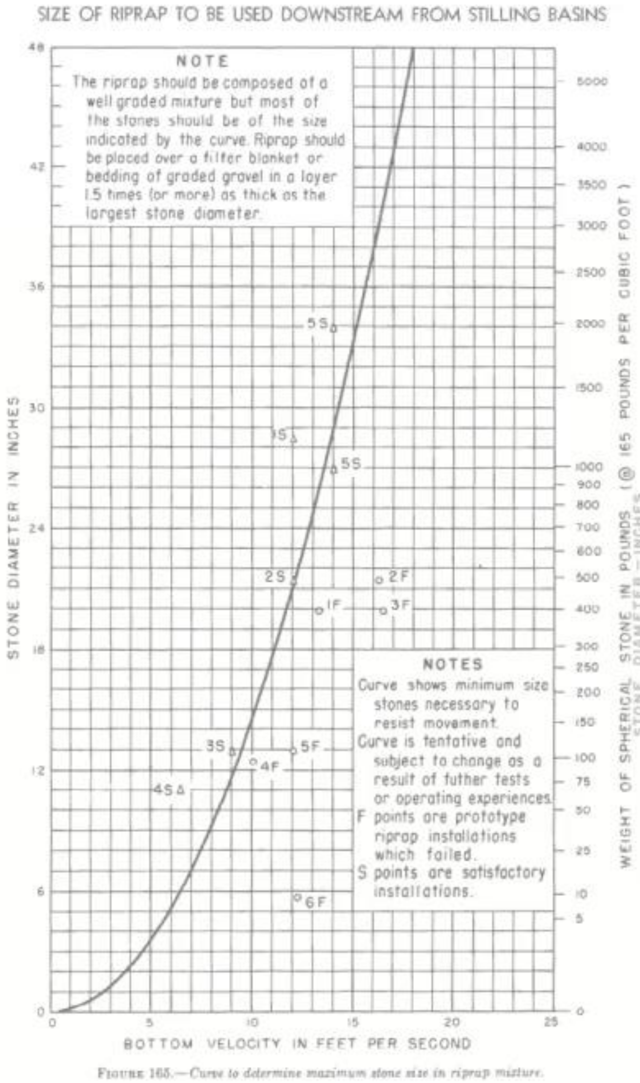
Australian national guidance for rock sizing

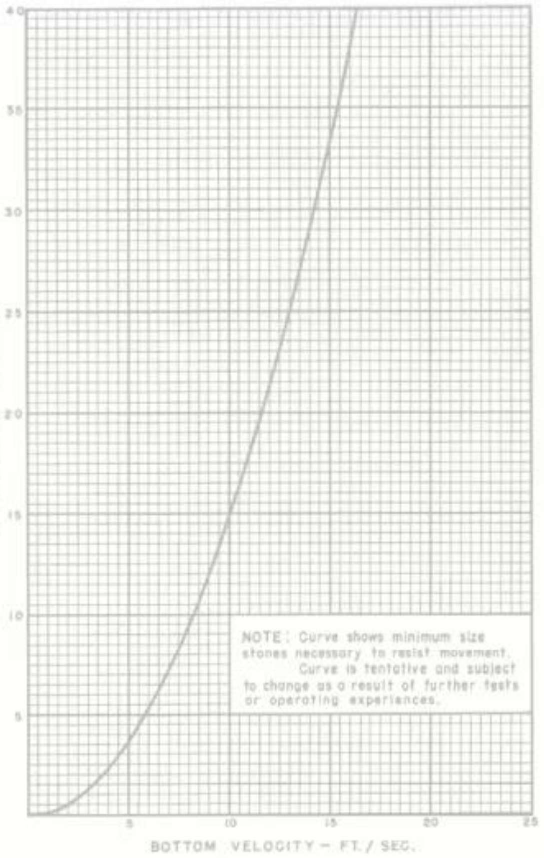


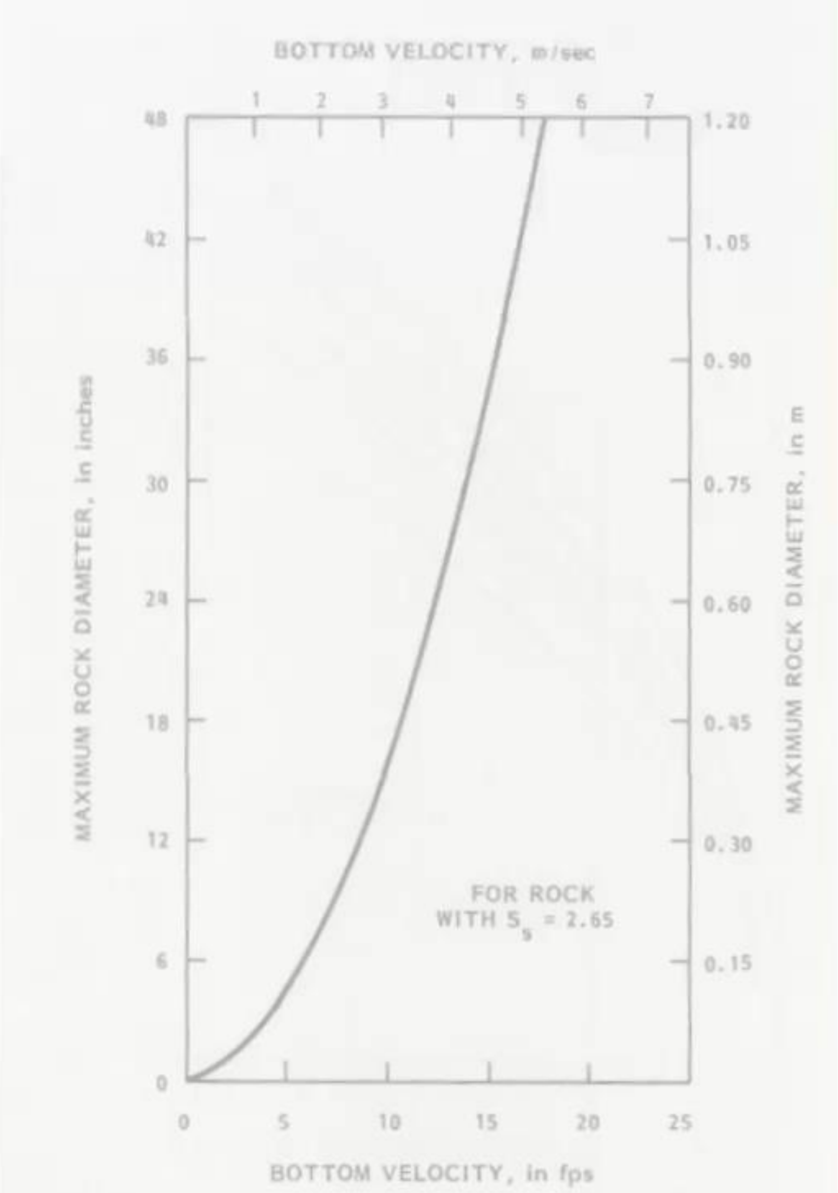
Krey Price

1D Assumptions: Horizontal Variation

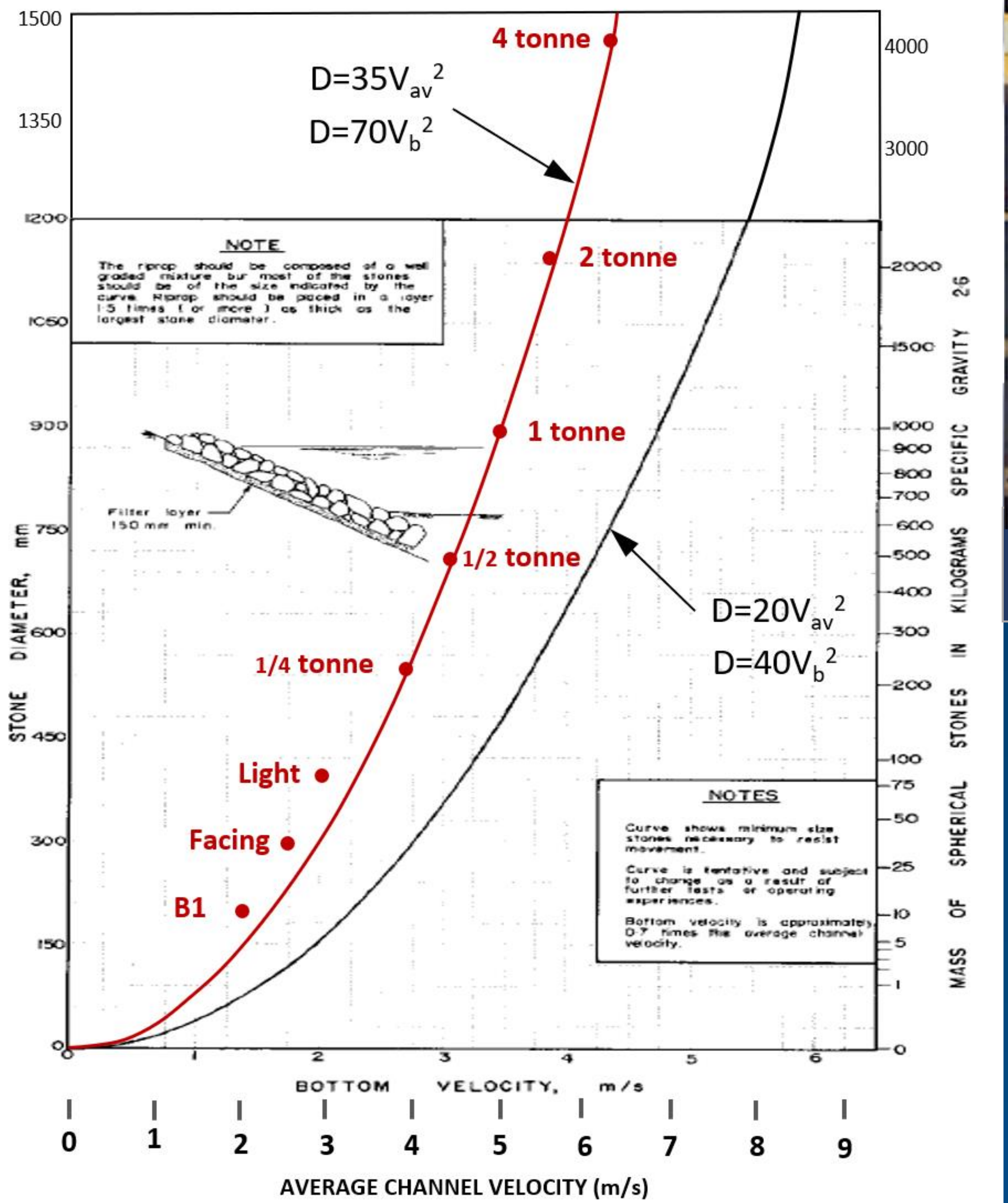






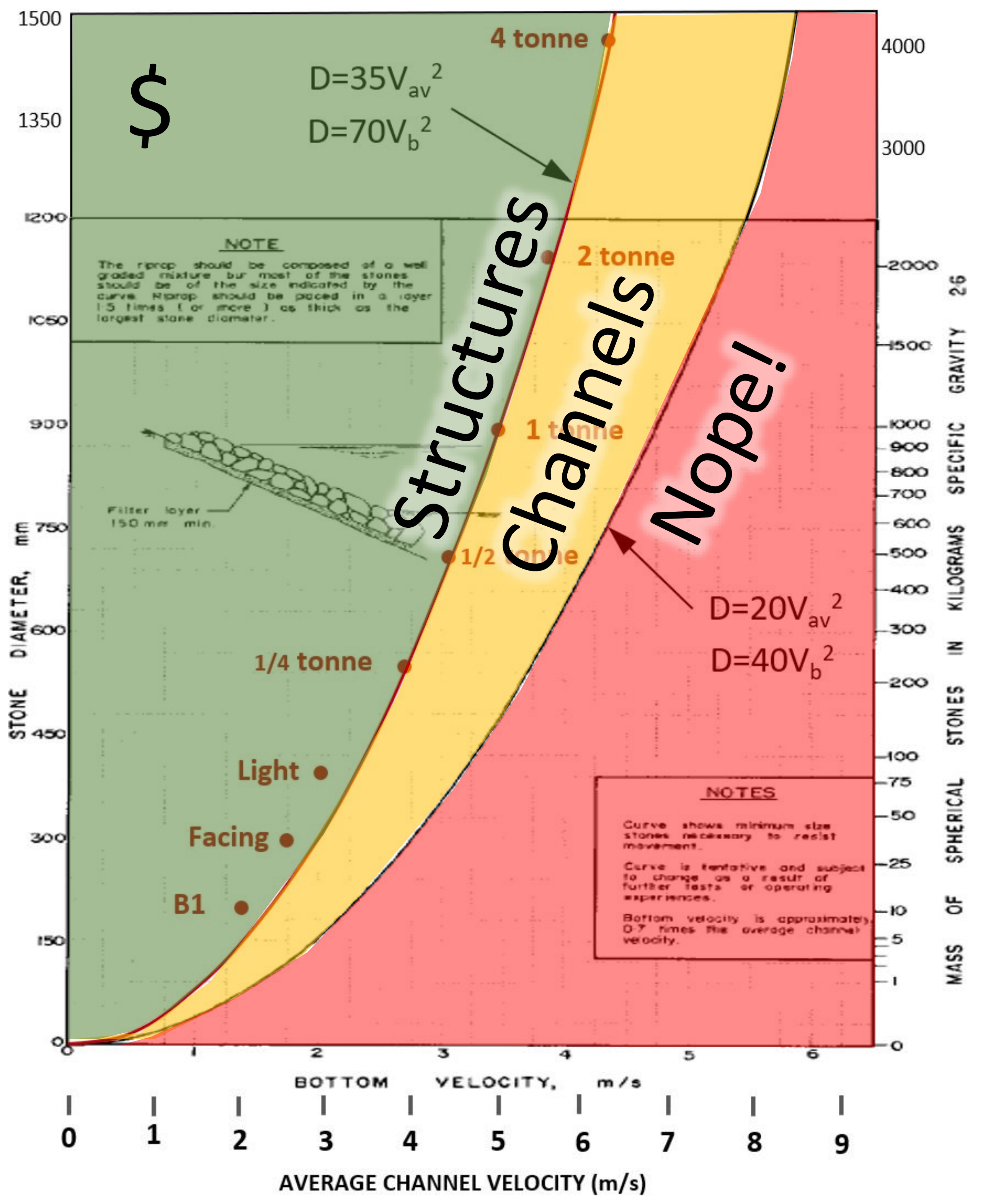


FMA
TOOWOOMBA REGION



4 tonne
D=35V_av^2
D=70V_b^2
2 tonne
1 tonne
1/2 tonne
1/4 tonne
Light
Facing
B1
D=20V_av^2
D=40V_b^2
NOTE
The riprop should be composed of a well graded mixture bur most of the stones should be of the size indicated by the curve. Riprop should be placed in a layer 1·5 times (or more) as thick as the largest stone diameter.
Filter layer 150 mm min.
NOTES
Curve shows minimum size stones necessary to resist movement.
Curve is tentative and subject to change as a result of further tests or operating experiences.
Bottom velocity is approximately 0·7 times the average channel velocity.
STONE DIAMETER, mm
BOTTOM VELOCITY, m/s
AVERAGE CHANNEL VELOCITY (m/s)
MASS OF SPHERICAL STONES IN KILOGRAMS SPECIFIC GRAVITY 2·6

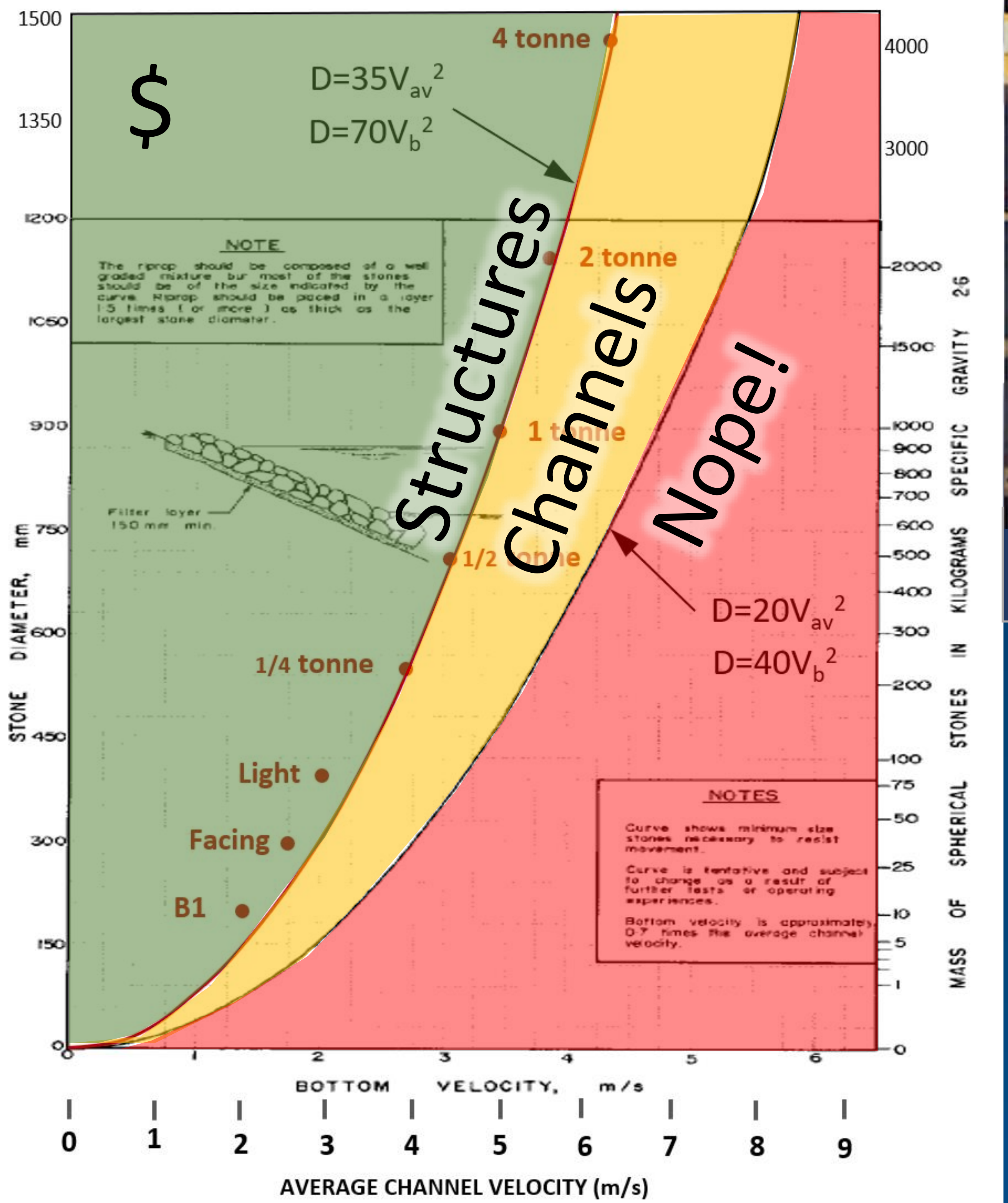
Krey Price


$
$D=35V_{av}^2$
$D=70V_b^2$
4 tonne
2 tonne
1 tonne
1/2 tonne
1/4 tonne
Light
Facing
B1
Structures
Channels
Nope!
$D=20V_{av}^2$
$D=40V_b^2$
NOTE
NOTES
Filter layer 150 mm min.
STONE DIAMETER, mm
MASS OF SPHERICAL STONES IN KILOGRAMS SPECIFIC GRAVITY 2.6
BOTTOM VELOCITY, m/s
AVERAGE CHANNEL VELOCITY (m/s)
0
1
2
3
4
5
6
7
8
9
1500
1350
1200
1050
900
750
600
450
300
150
4000
3000
2000
1500
1000
500
100

Krey Price

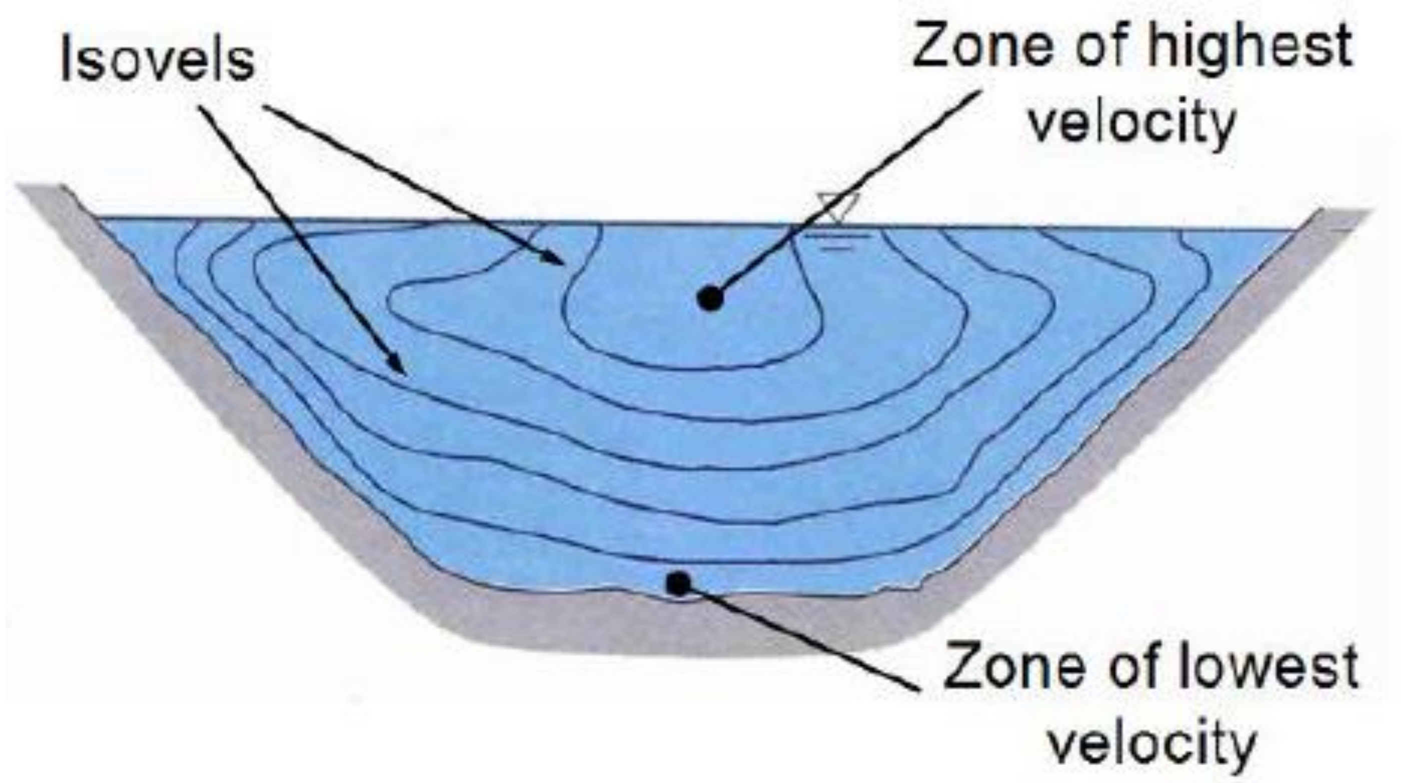
HWRS 2021 Recommendations

- Check using at least 3 methods:
  - Velocity $D_{50}=a*V^2$
  - Shear $D_{50} = S_f* \tau$
  - Velocity & Depth $D_{30}=S_f C_s C_v C_t d\left[\left(\frac{\gamma_w}{\gamma_s-\gamma_w}\right)^{0.5}\frac{V}{\sqrt{K_1 g d}}\right]^{2.5}$
- Clarifications needed:
  - Application:
    Channels vs. Structures
  - Gradation:
    D_{10}, D_{50}, D_{90} by total weight
  - Shear and Velocity Adjustments:
    1D vs 2D vs 3D
  - How to apply the USACE method



Krey Price

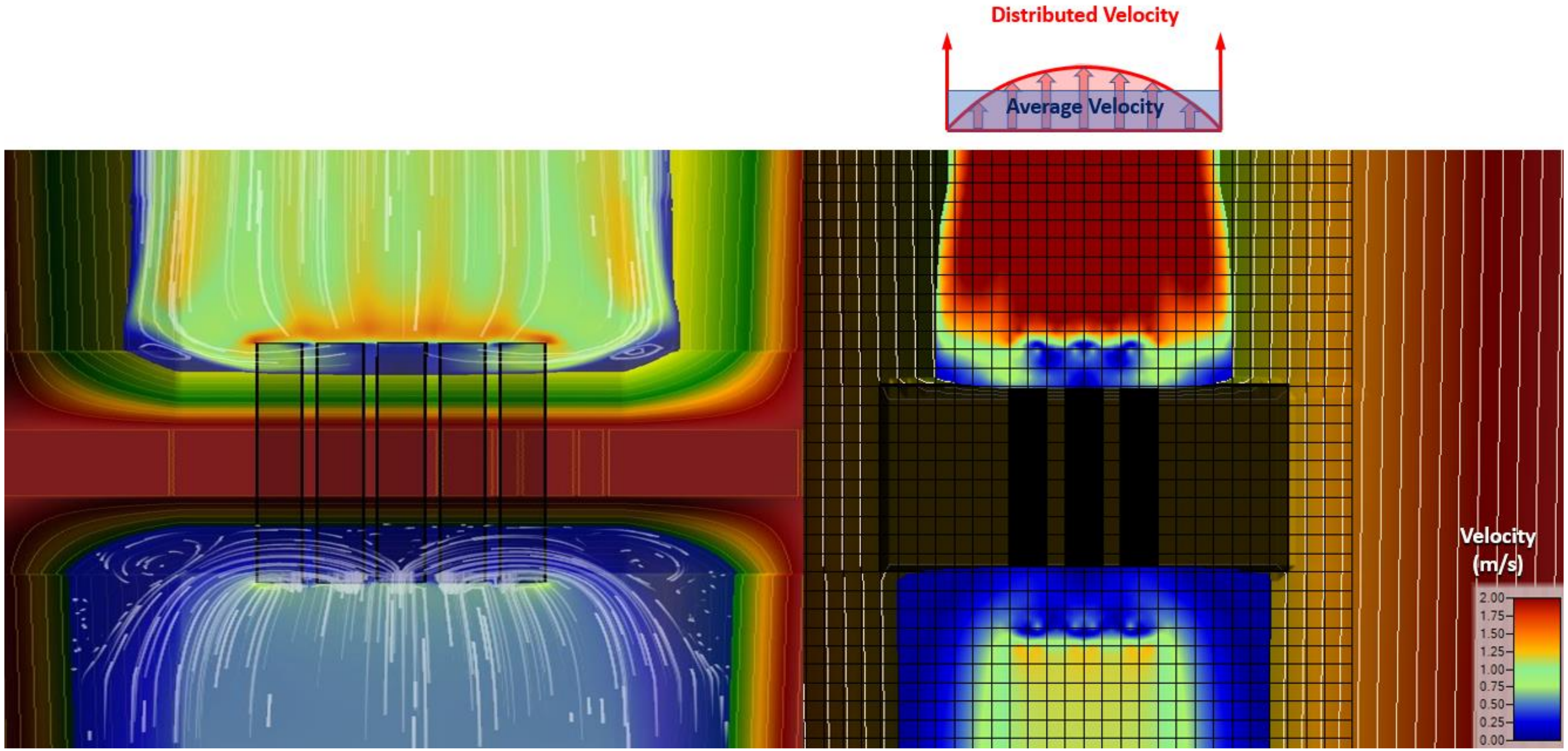
1D Assumptions: Horizontal Variation



Austroads 2013 and DTMR 2010

Krey Price

1D vs 2D Assumptions: Horizontal Variation



Krey Price

1D Assumptions: Horizontal Variation

$$W = \frac{0.00002V^6 \ sg_R \ \csc^3(\rho - \alpha)}{(sg_R - 1)^3}$$

W = Weight of critical stone in pounds; two thirds of stone should be heavier.

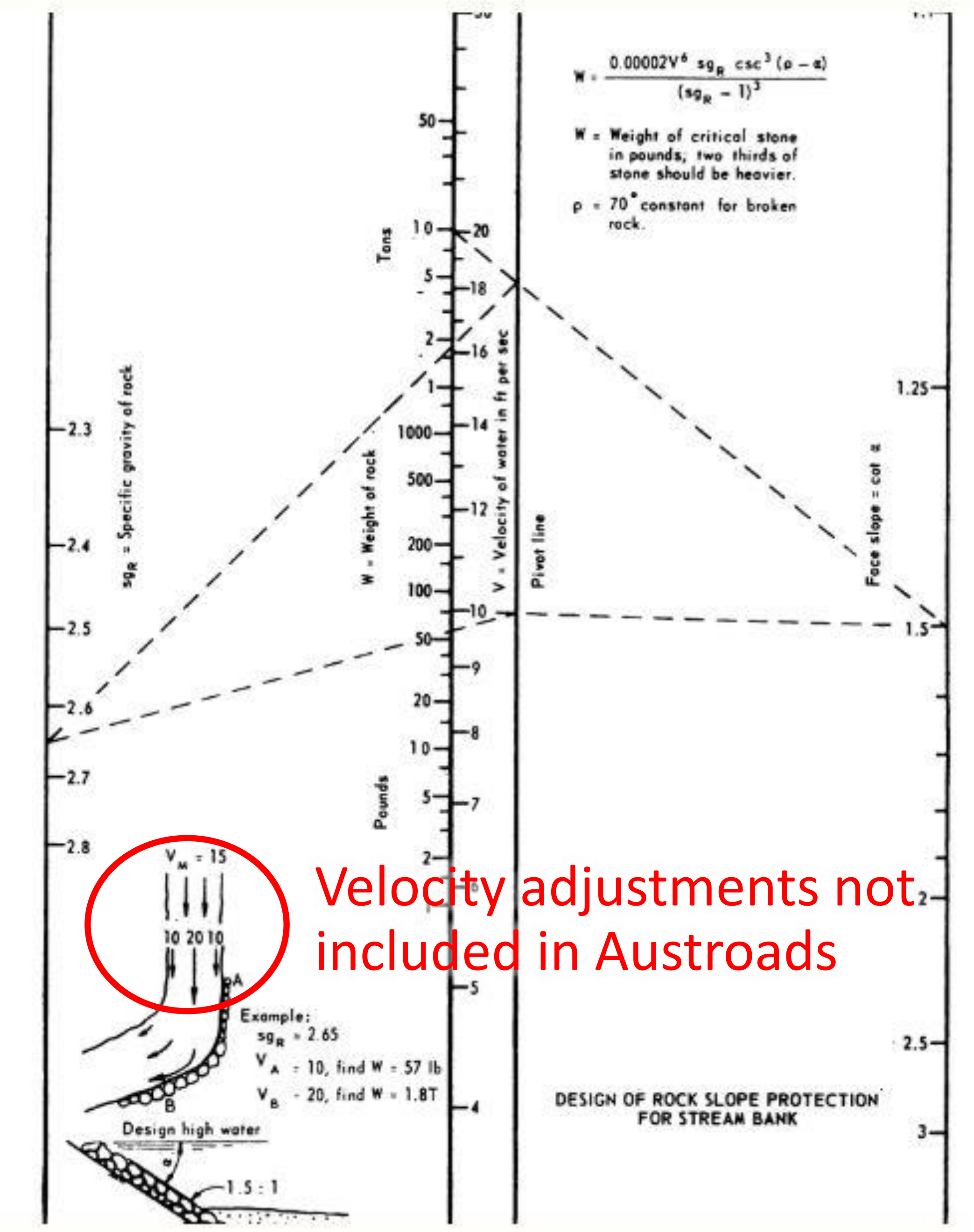
ρ = 70° constant for broken rock.

Basic data and assumptions: velocity ratios $V_A:V_M:V_B = 2{:}3{:}4$; specific gravity of rock is $sg_r = 2.65$; face slope of revetment is 1.5:1; stones grade uniformly between specified minima for class with two thirds heavier than minimum required on face; $T = \frac{1}{3}\sqrt[3]{W_c}$, plus 25% for Method B.

$$W = \frac{2 \times 10^{-5} \ V^6 \ sg_r}{(sg_r - 1)^3 \sin^3(\rho - \alpha)} = \frac{.00002 \ V^6 \cdot 2.65}{1.65^3 \quad .592^3} = .000057 \ V^6$$

V = Stream velocity to which bank is exposed, ft/s
= 4/3 the average stream velocity for impinging velocities (on outside of bends in line with the central thread), ft/s
= 2/3 the average velocity for tangent (parallel) velocity, ft/s

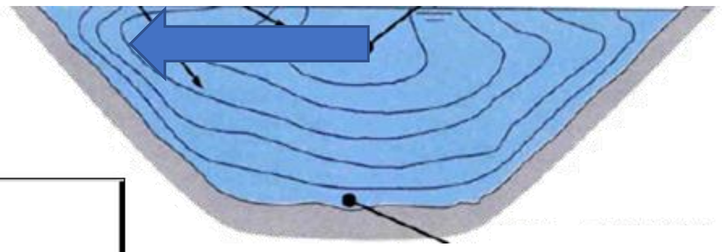
- 2/3 vs 4/3 = 64x Weight!

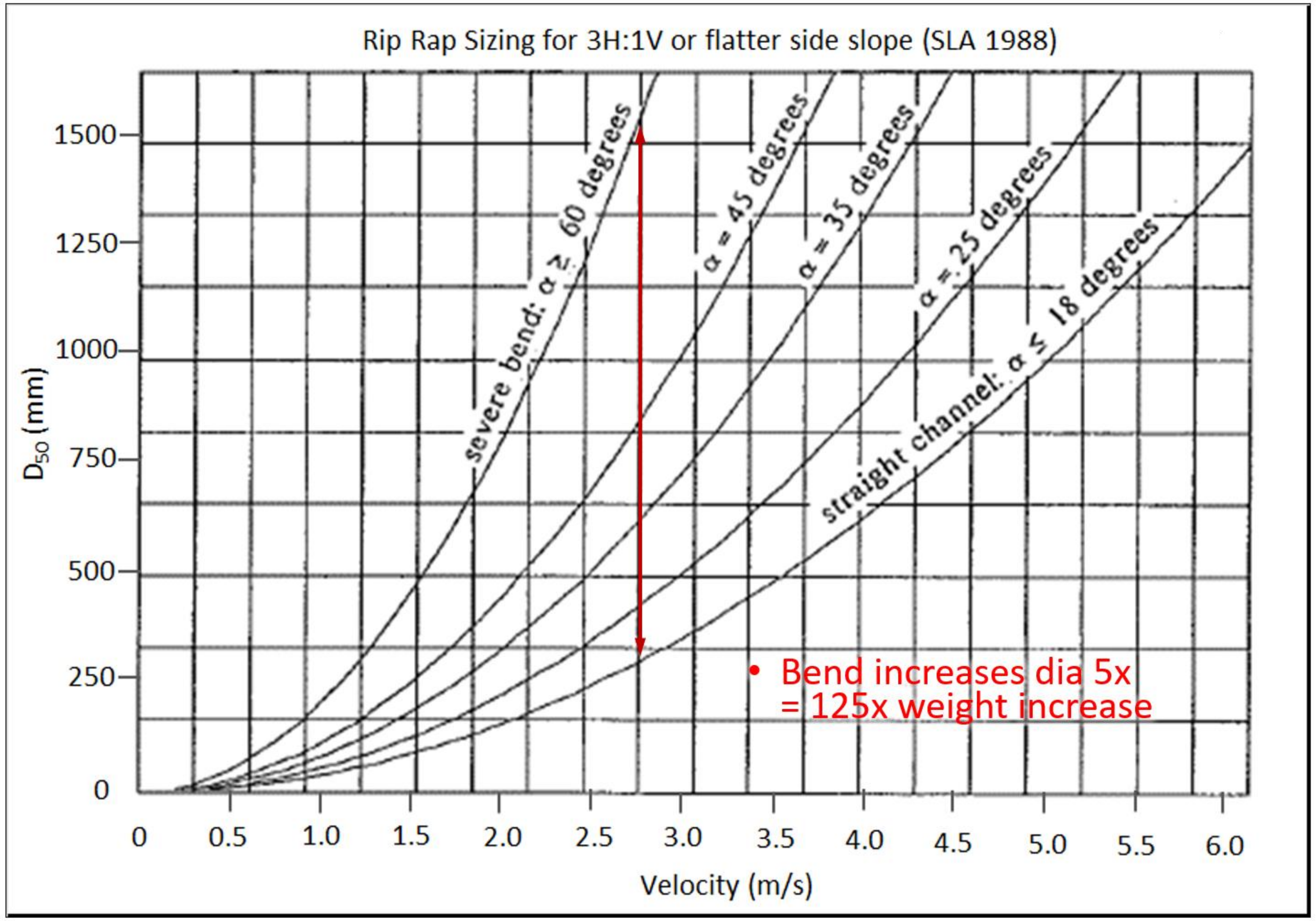


Velocity adjustments not included in Austroads

Krey Price

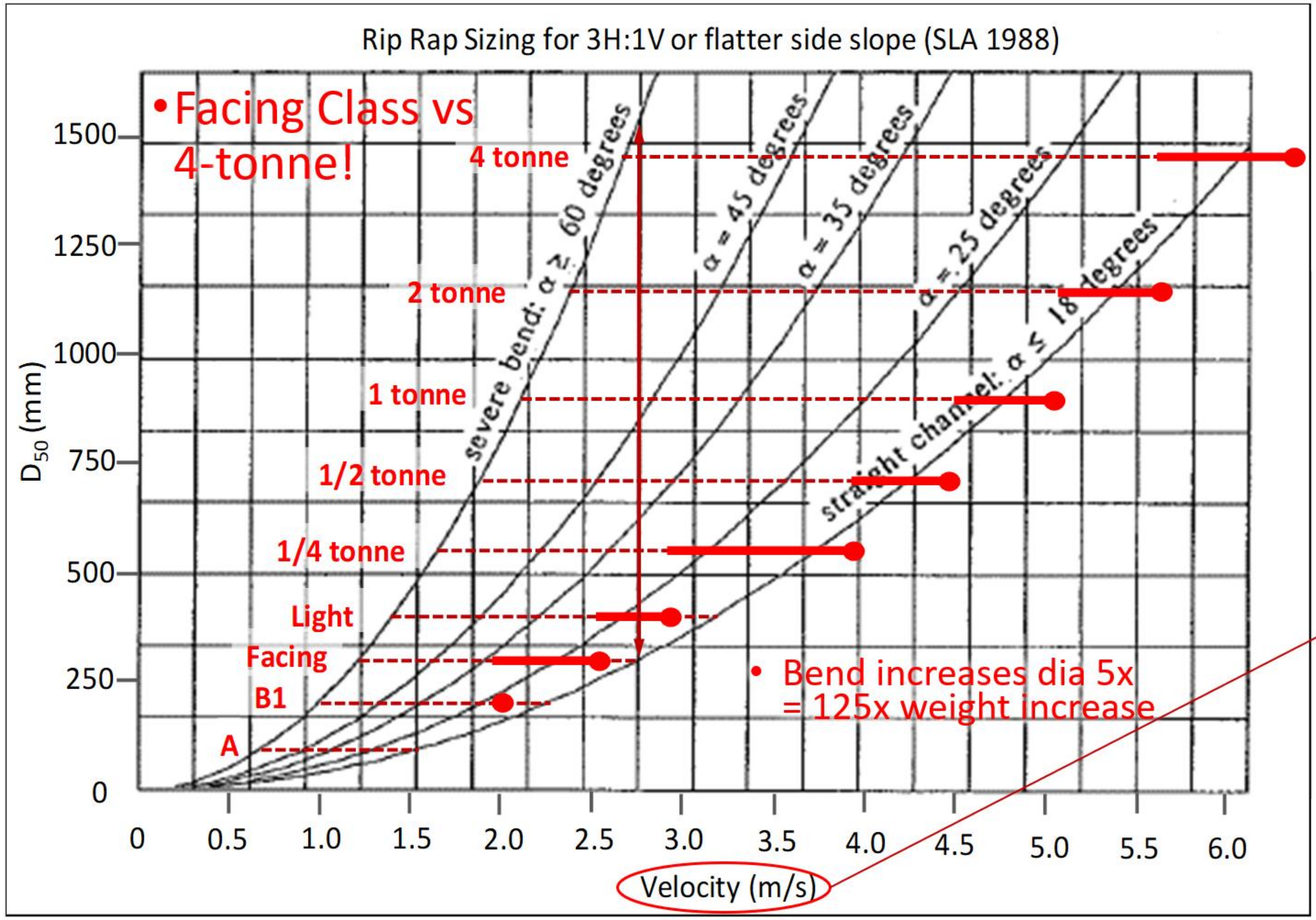
Effect of bends



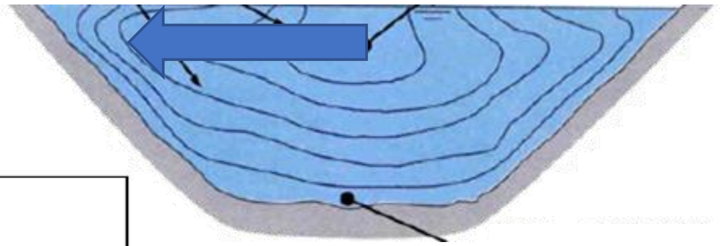


Krey Price

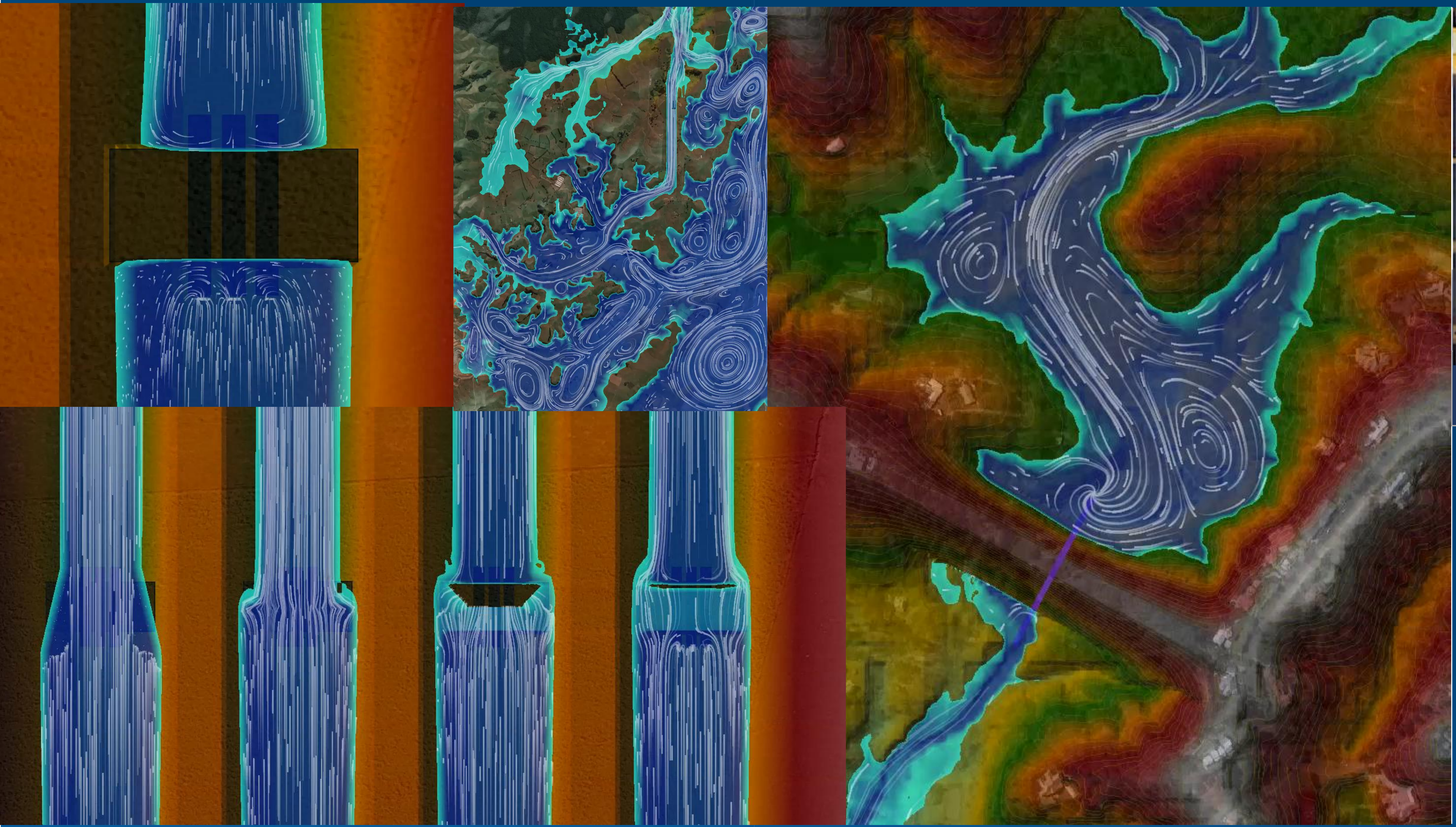
Effect of bends



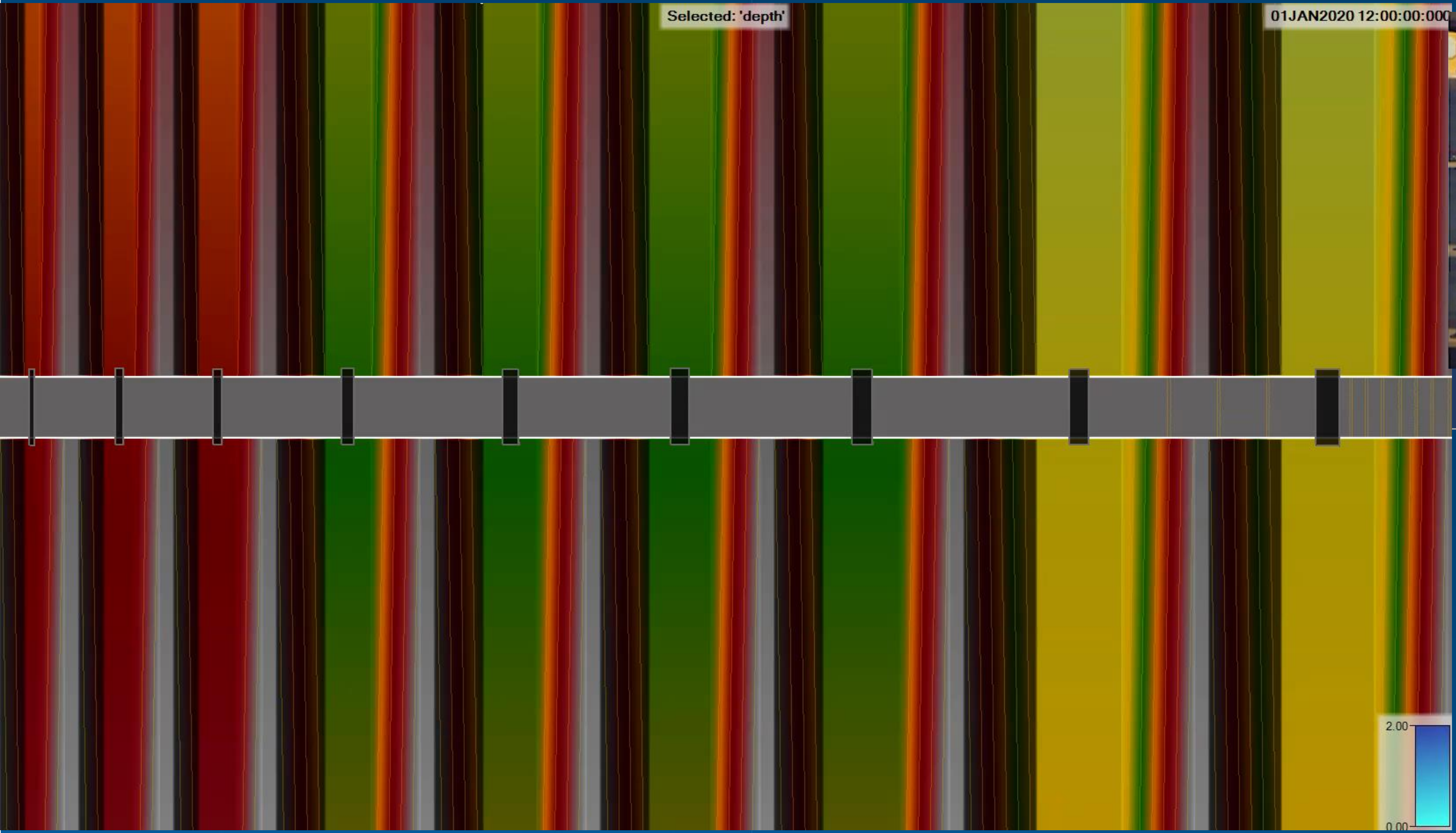
- Average velocity: Don't double count adjustment with localised 2D results!



Krey Price

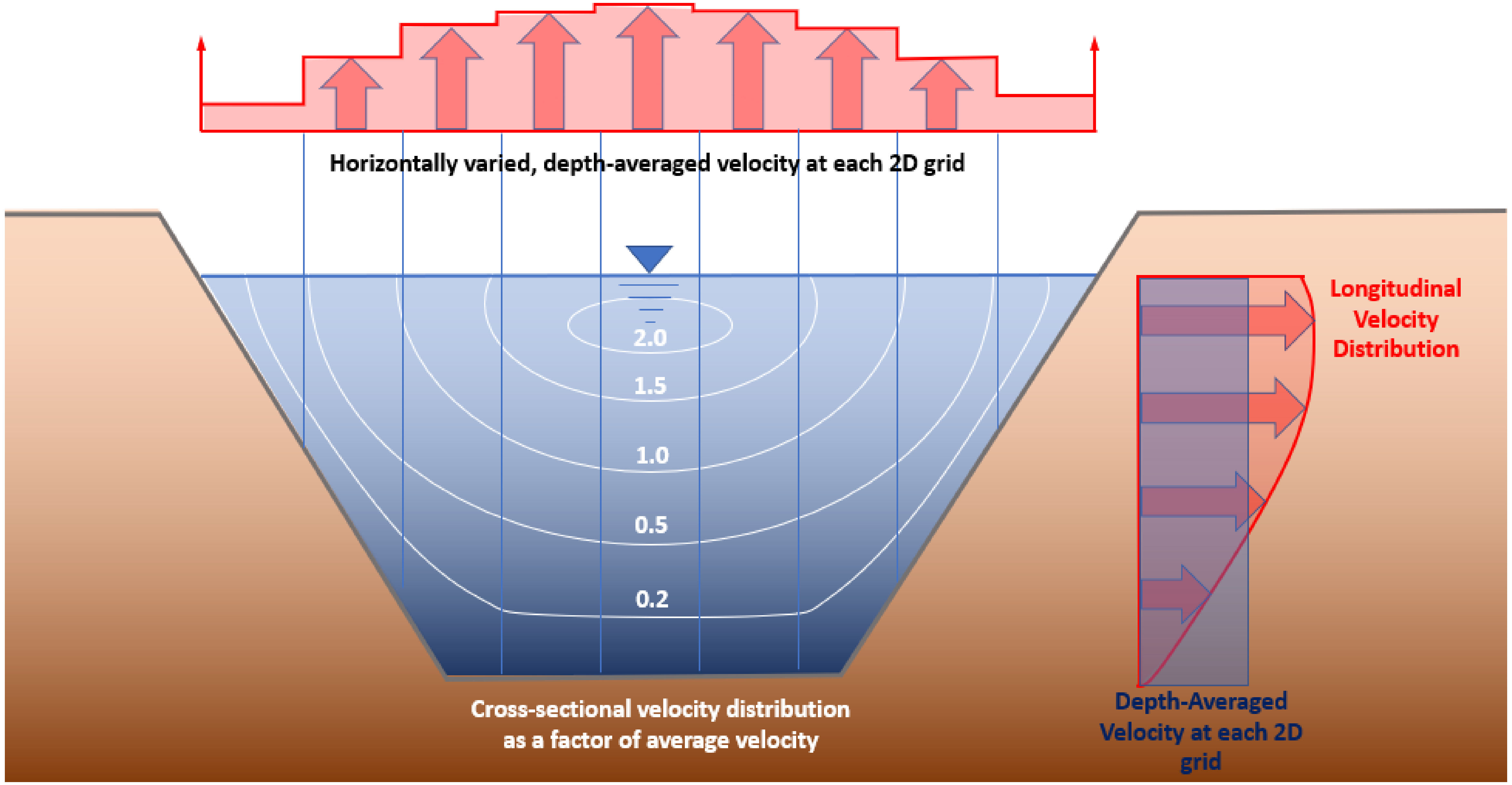


Krey Price

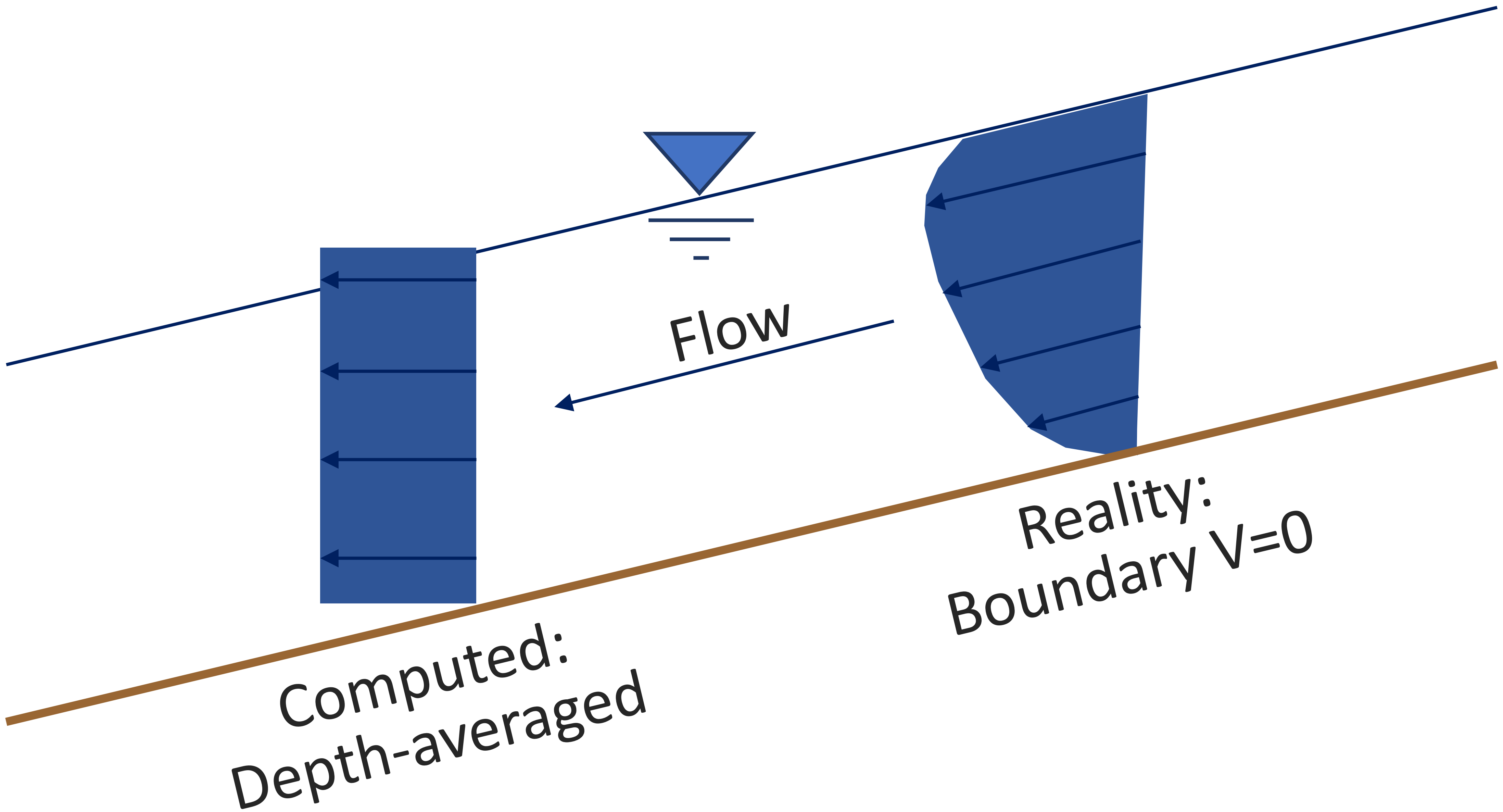


Krey Price

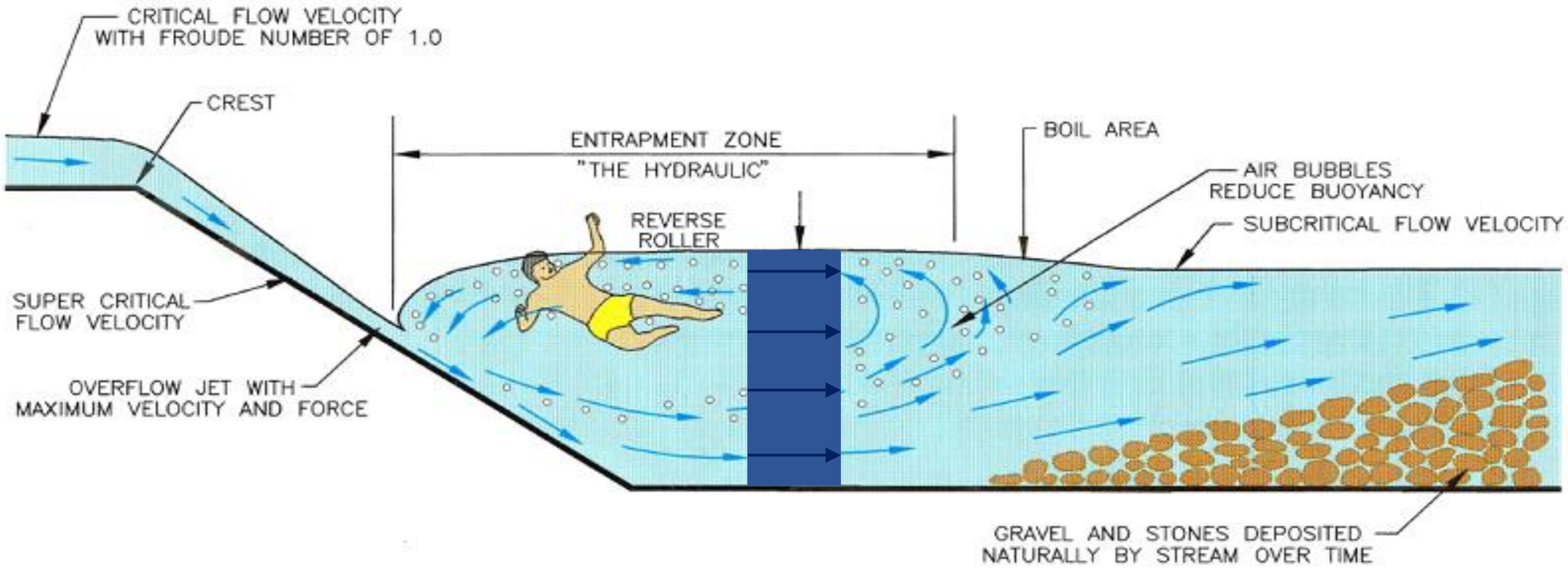
1D and 2D Assumptions: Vertical Variation



1D and 2D Assumptions: Depth-averaged



1D and 2D Assumptions: Depth-averaged

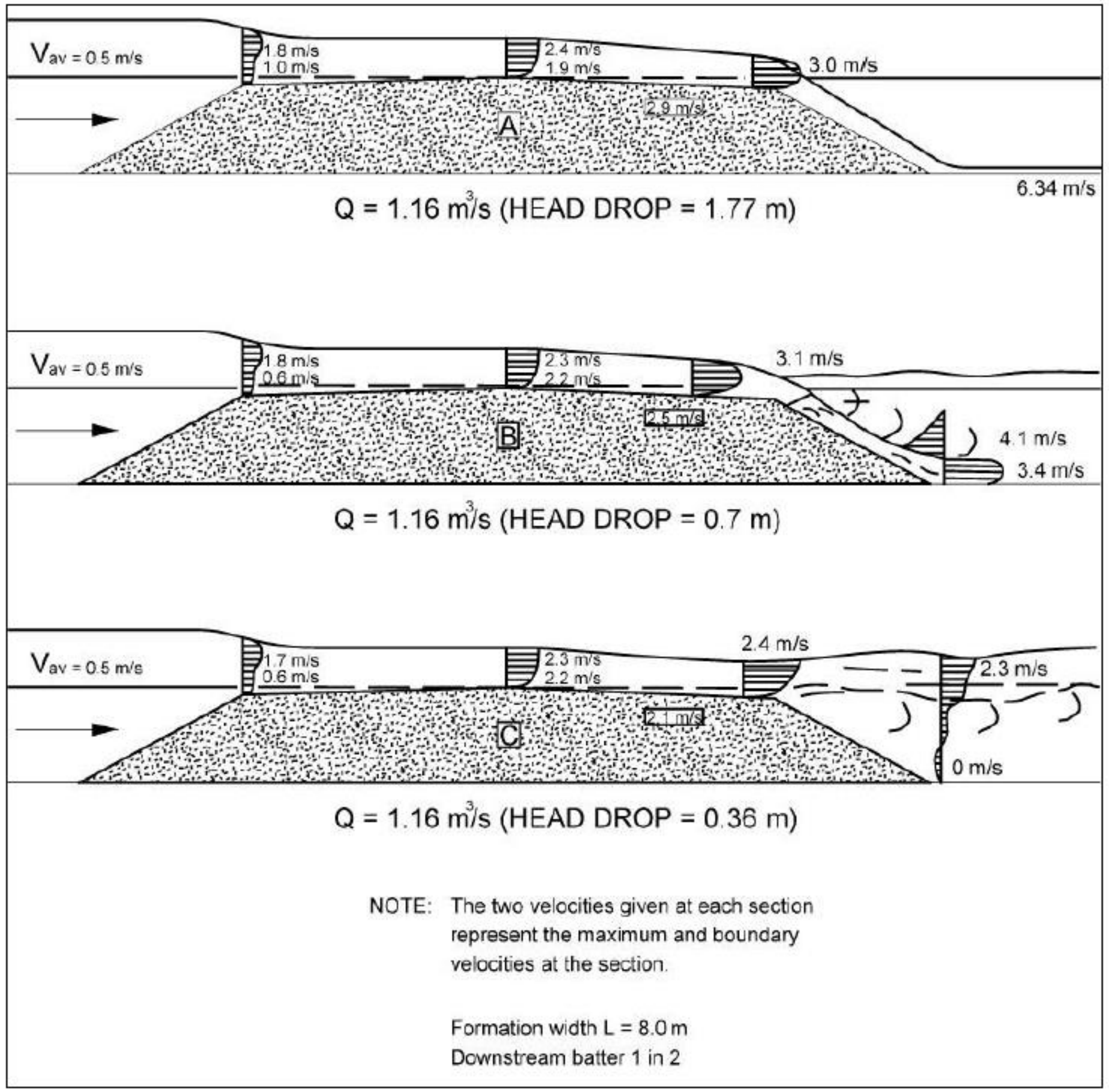


Courtesy of Wright Water Engineers, Inc. and ASDSO.
Source: Wright, Kenneth R., Kelly, Jonathan M., Houghtalen, Robert J., & Bonner, Mark R. "Emergency Rescues at Low-Head Dams." Paper presented at Dam Safety 1995, the 12th annual conference of the Association of State Dam Safety Officials, Atlanta, GA, September 1995.

Krey Price

Vertical Variation

Cameron and McNamara, Report on Model Investigation of Causeway Design for Commonwealth Department of Works, Darwin and Queensland Main Roads Department, 1966.



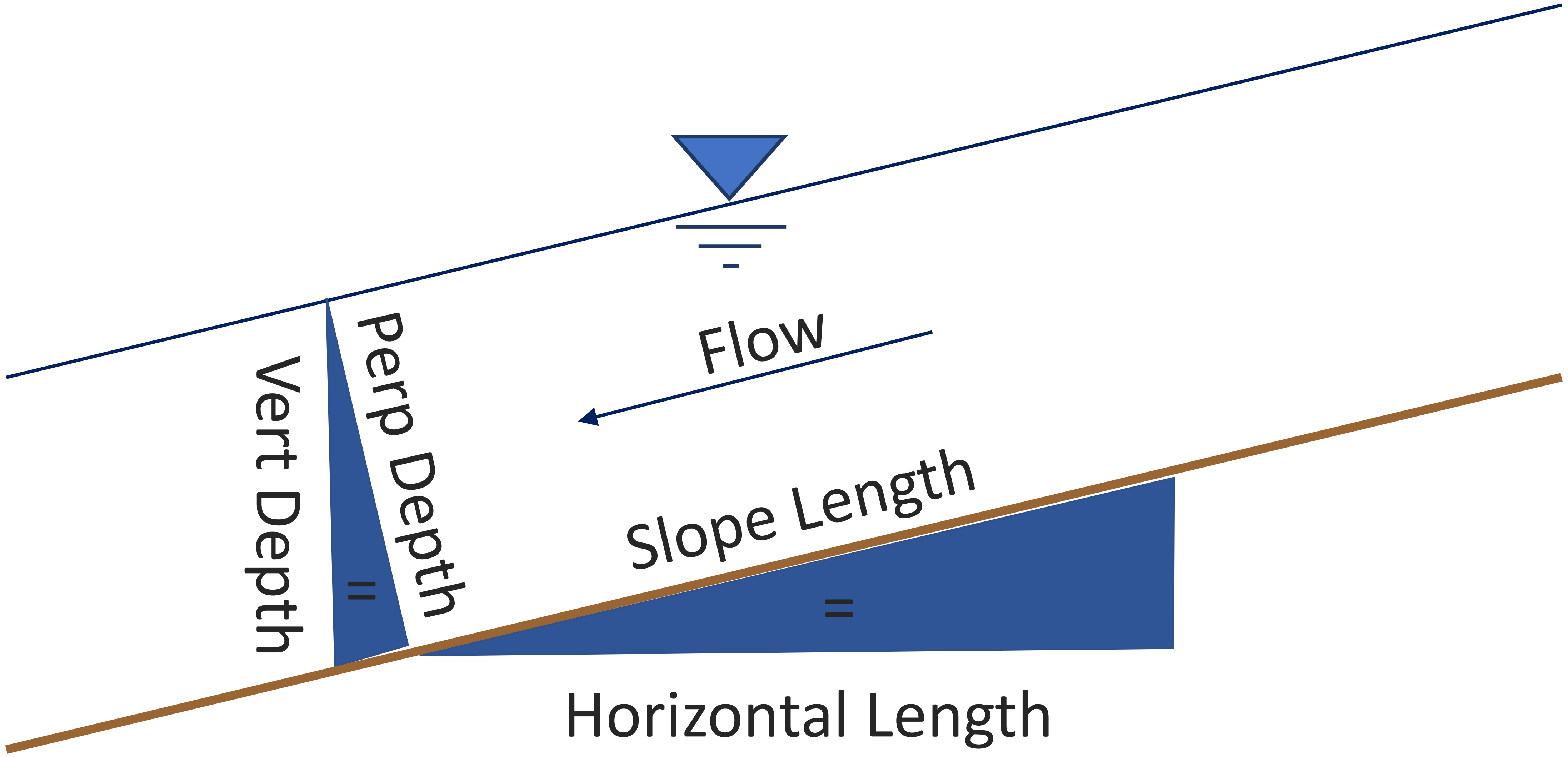
Source: DTMR (2010).

Source: Cameron and McNamara, 1966

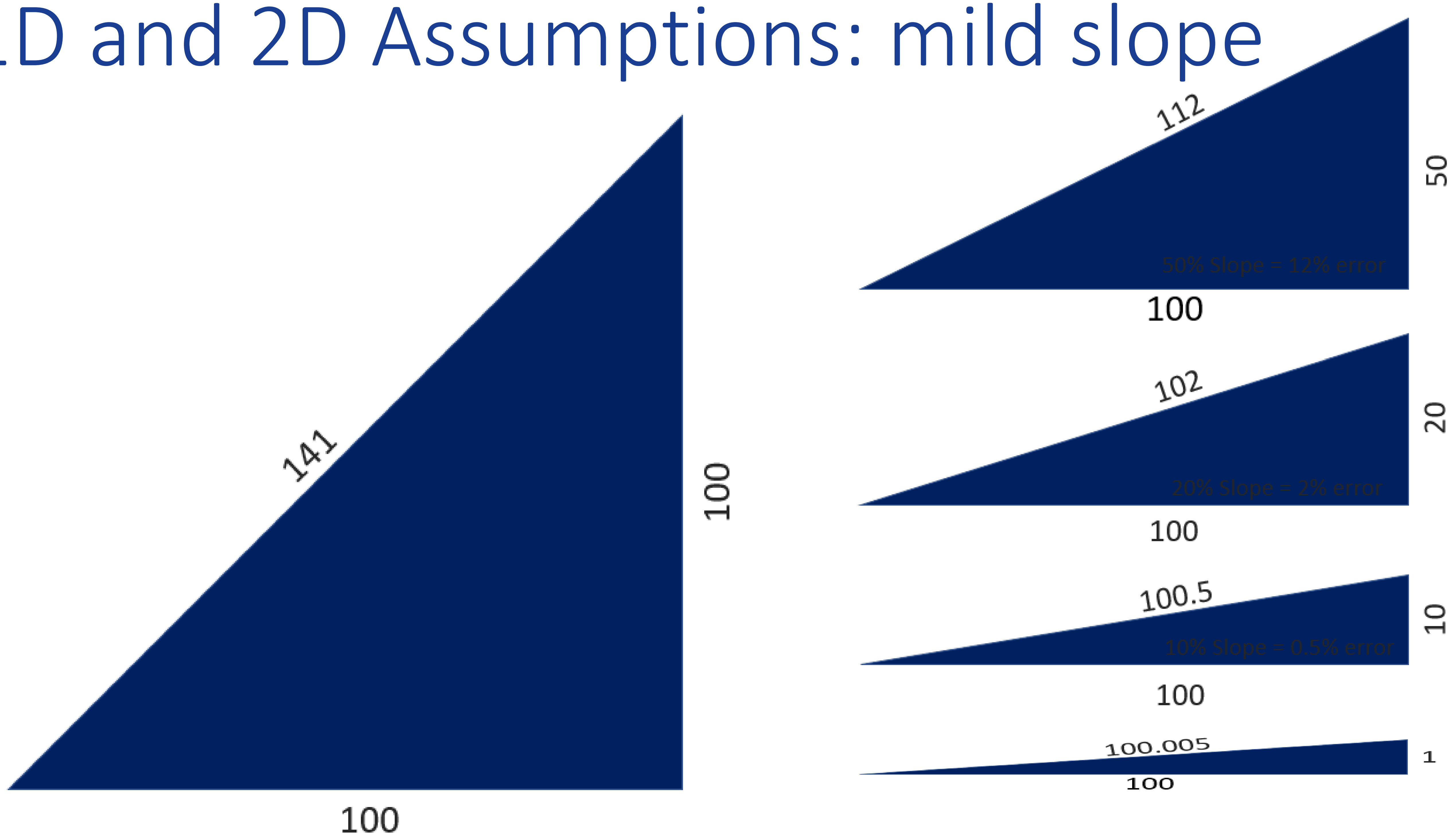
Figure 4.2: Indicative velocities of flow over a typical floodway

Krey Price

1D and 2D Assumptions: mild slope

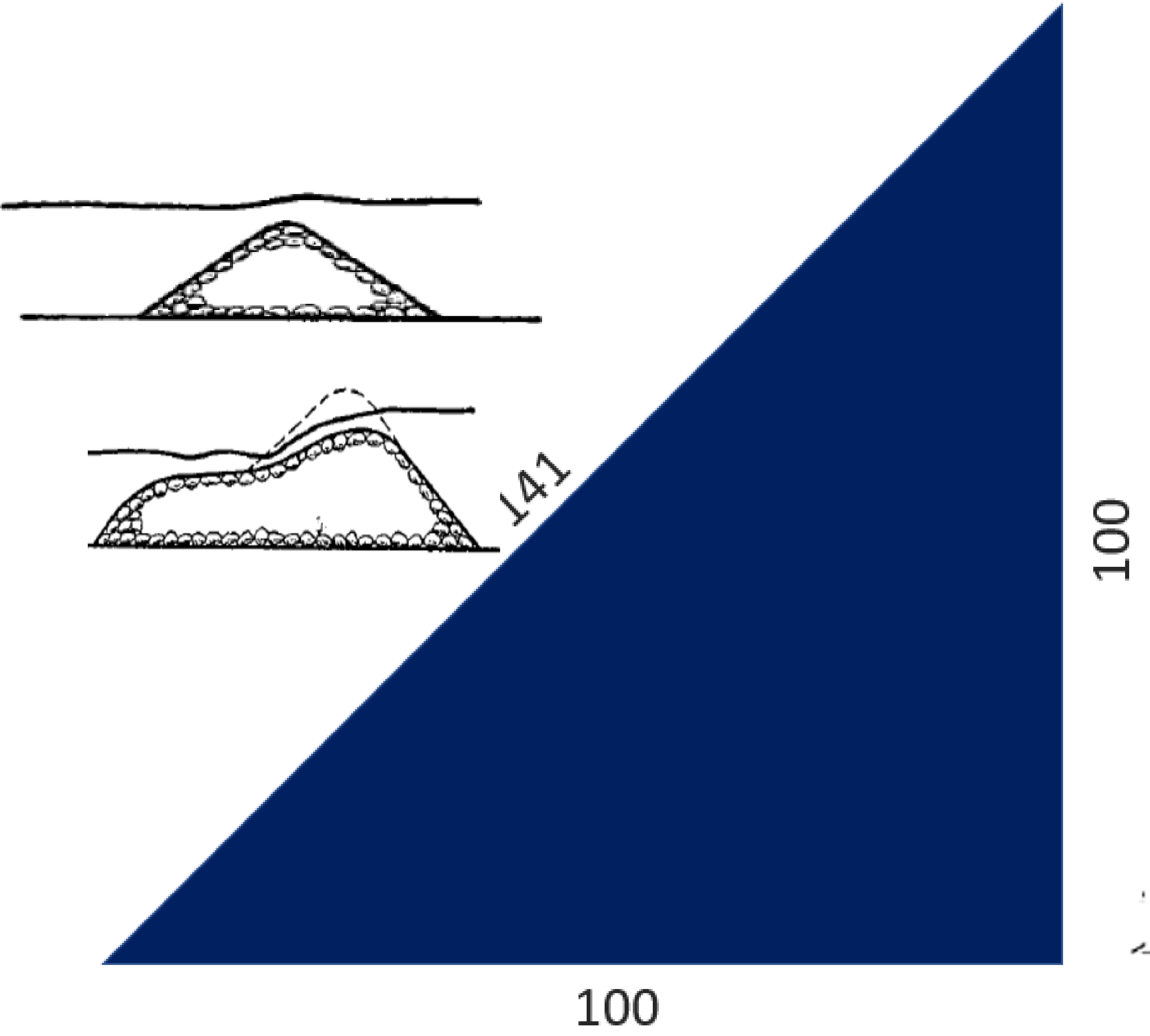


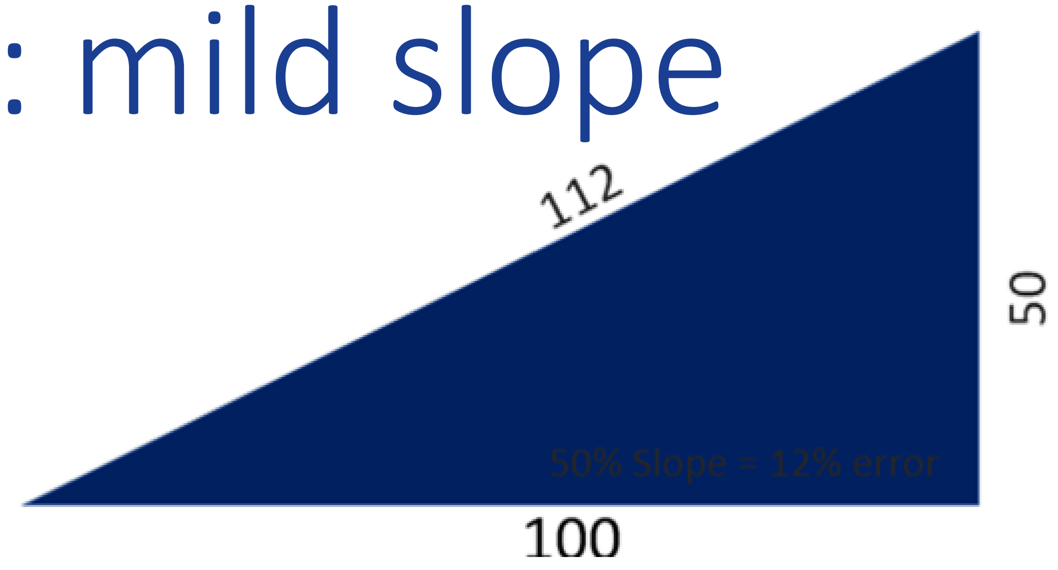
1D and 2D Assumptions: mild slope

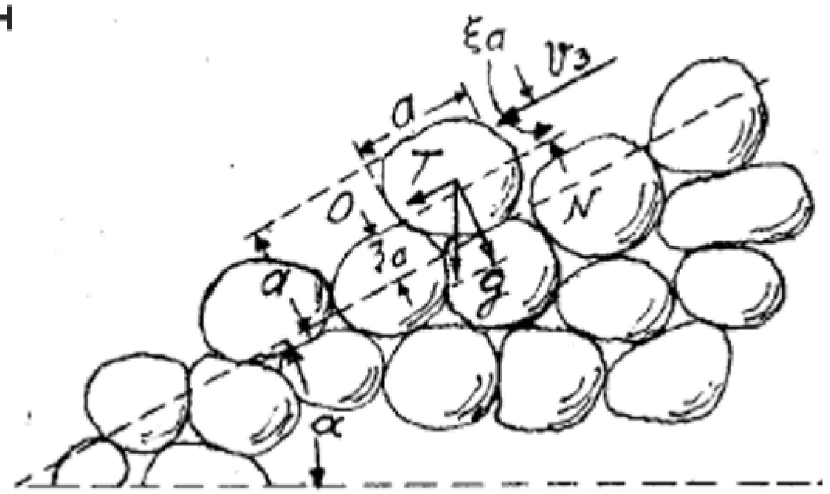


Krey Price

1D and 2D Assumptions: mild slope

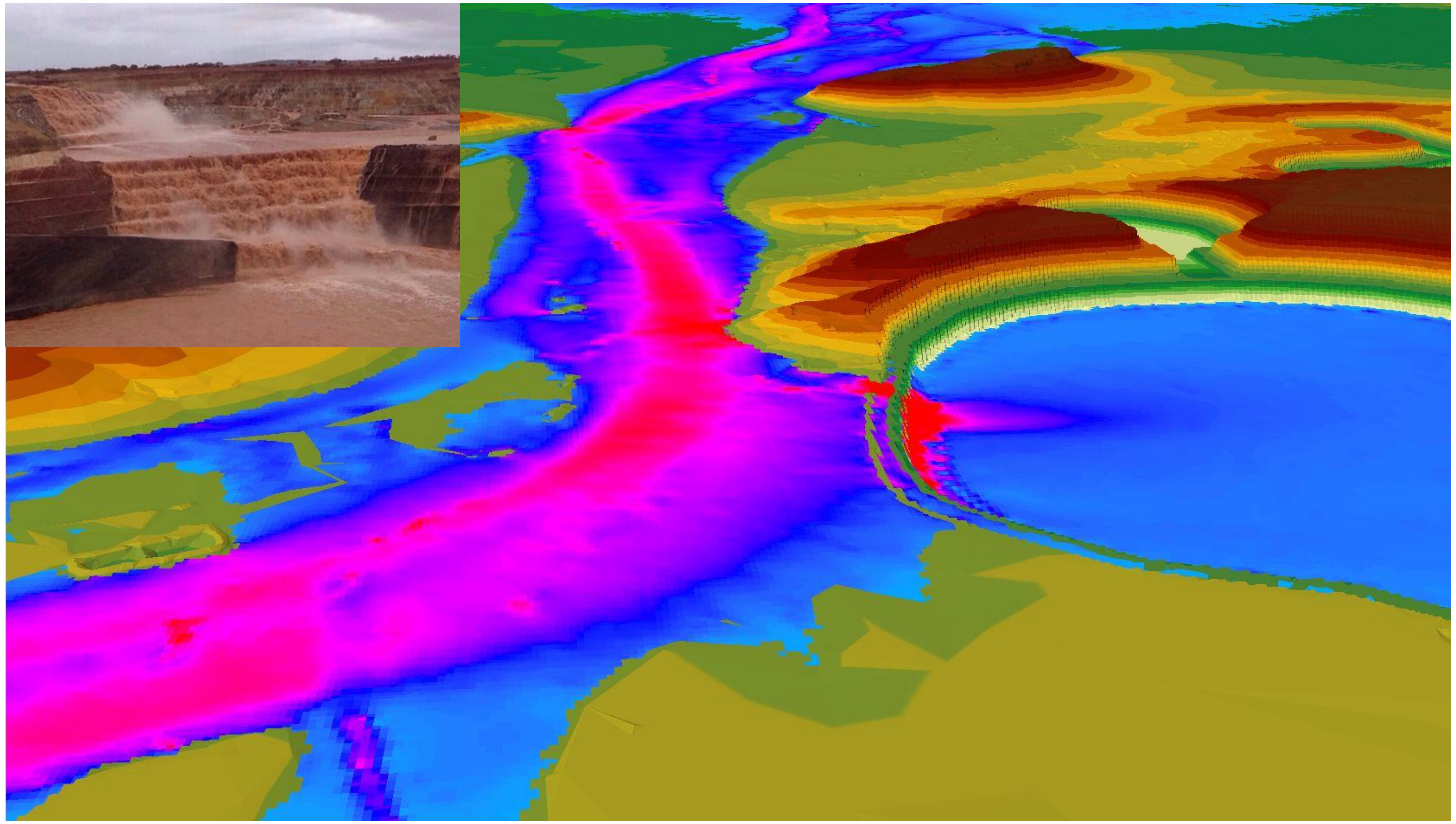






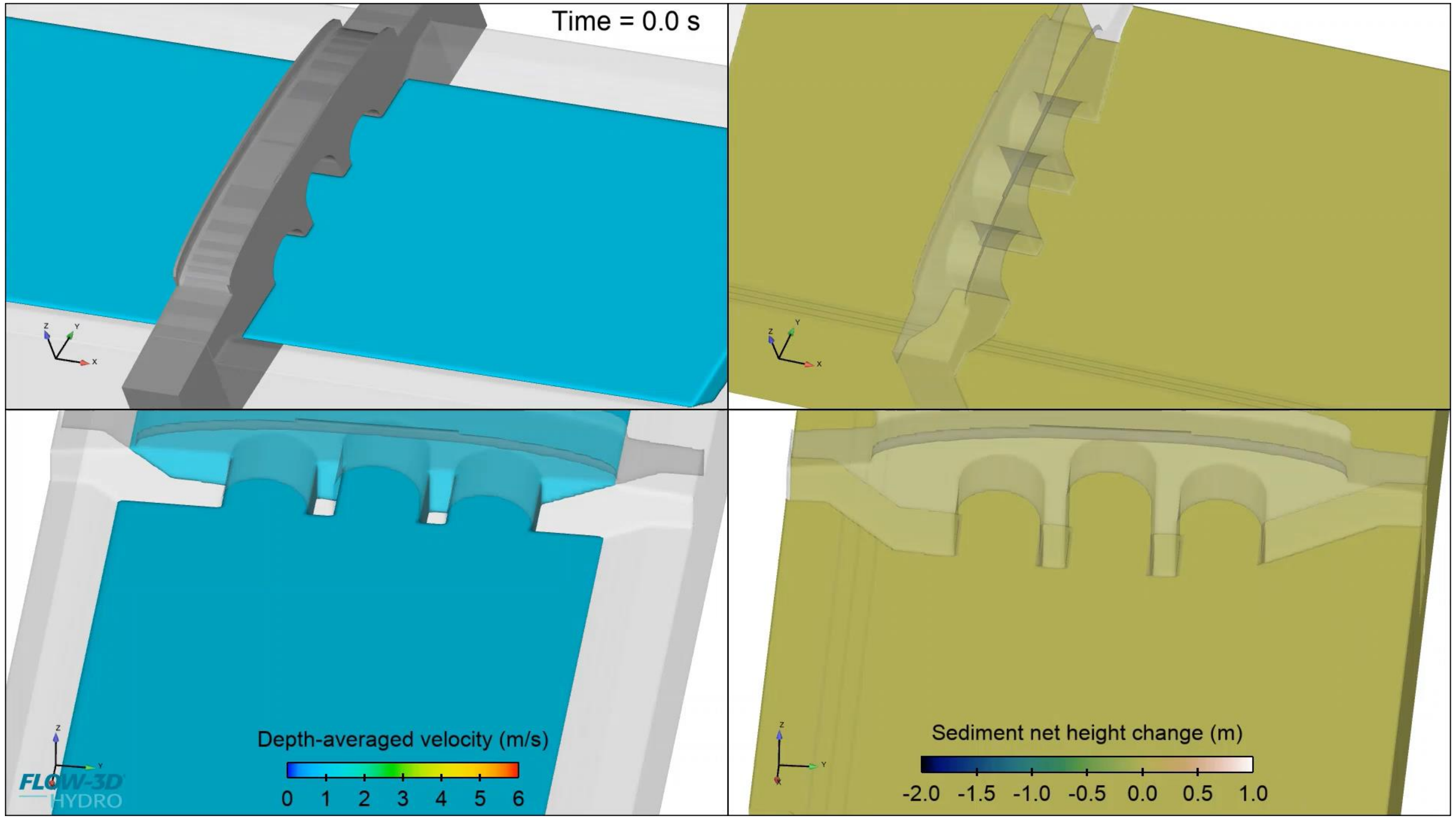
Krey Price

1D and 2D Assumptions: mild slope

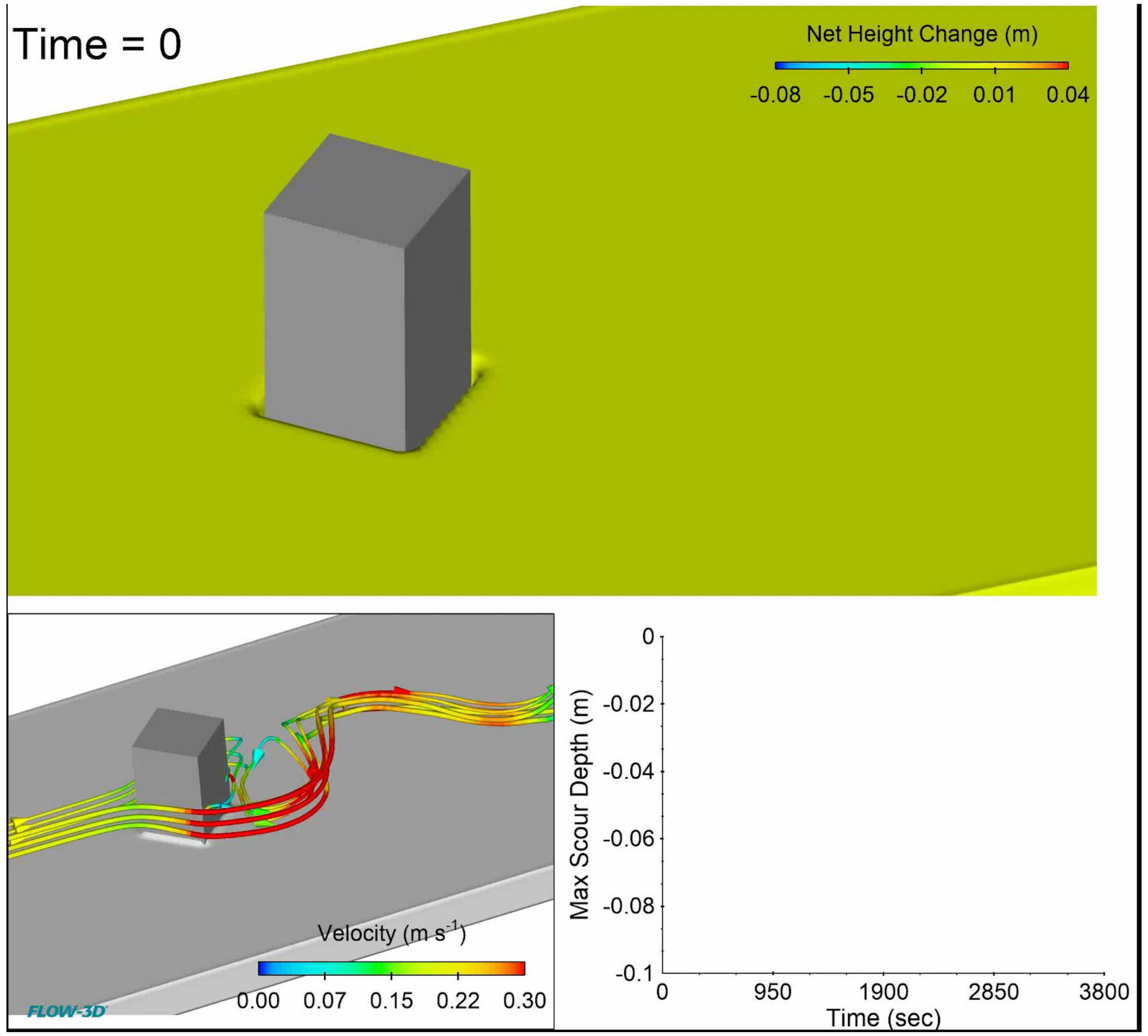


Krey Price

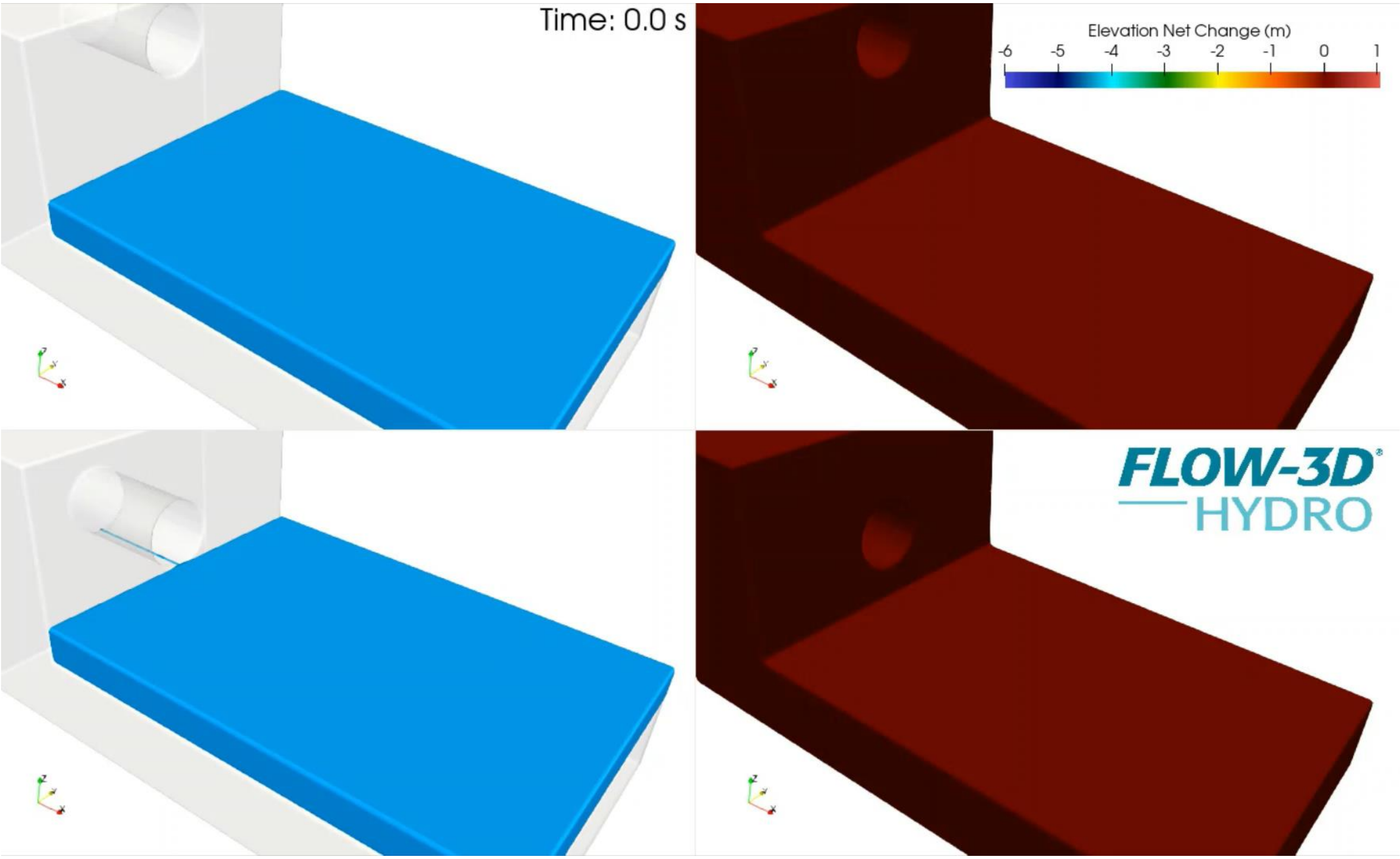
3D Scour Modelling



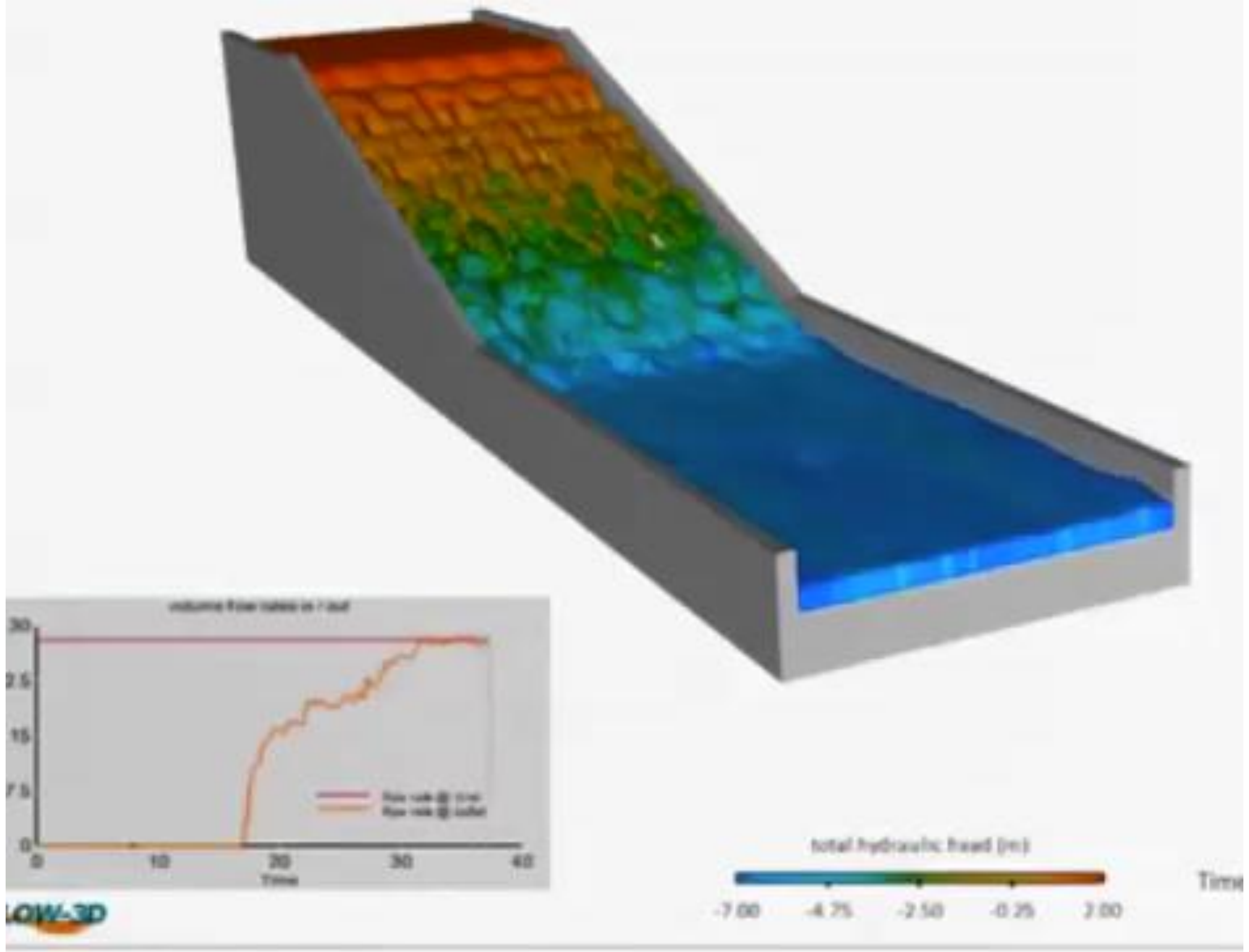
3D Scour Modelling



3D Scour Modelling

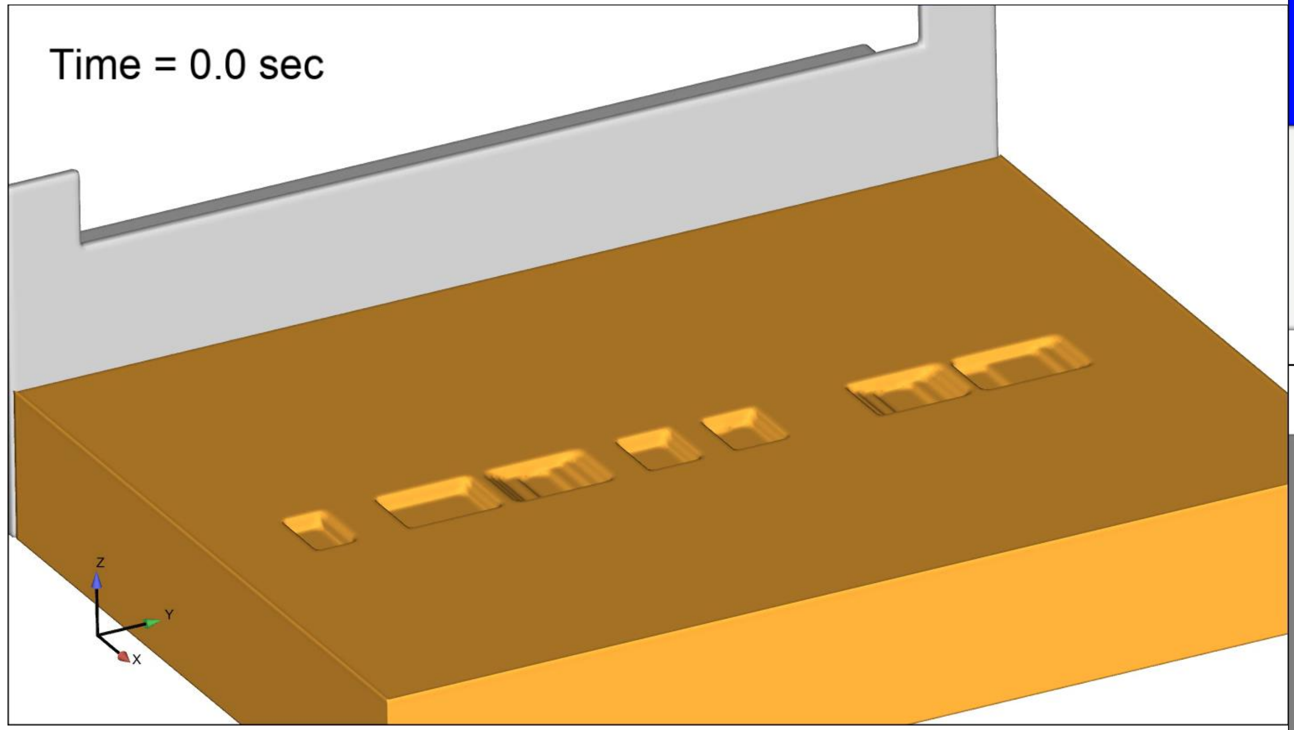


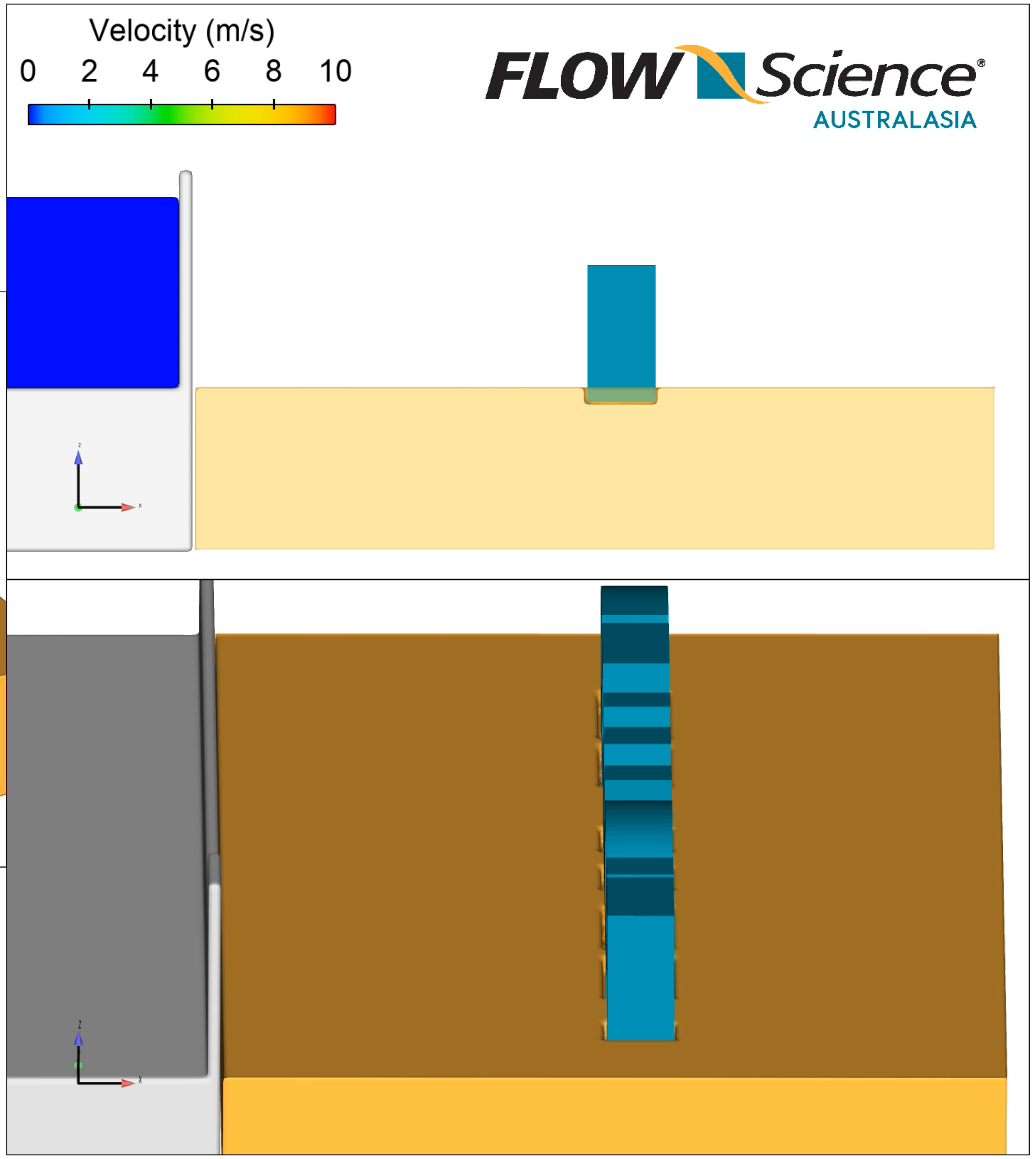
3D Energy Dissipation



Krey Price

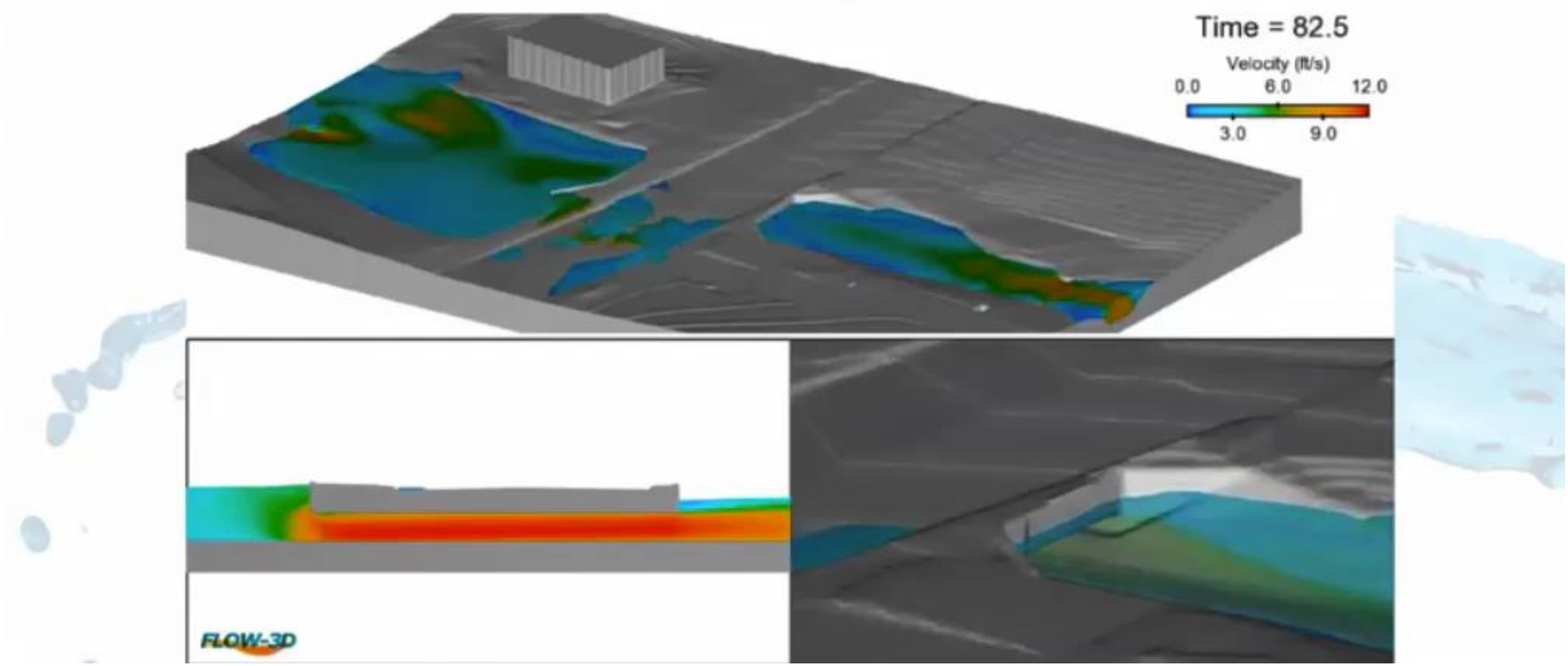
3D Scour Modelling



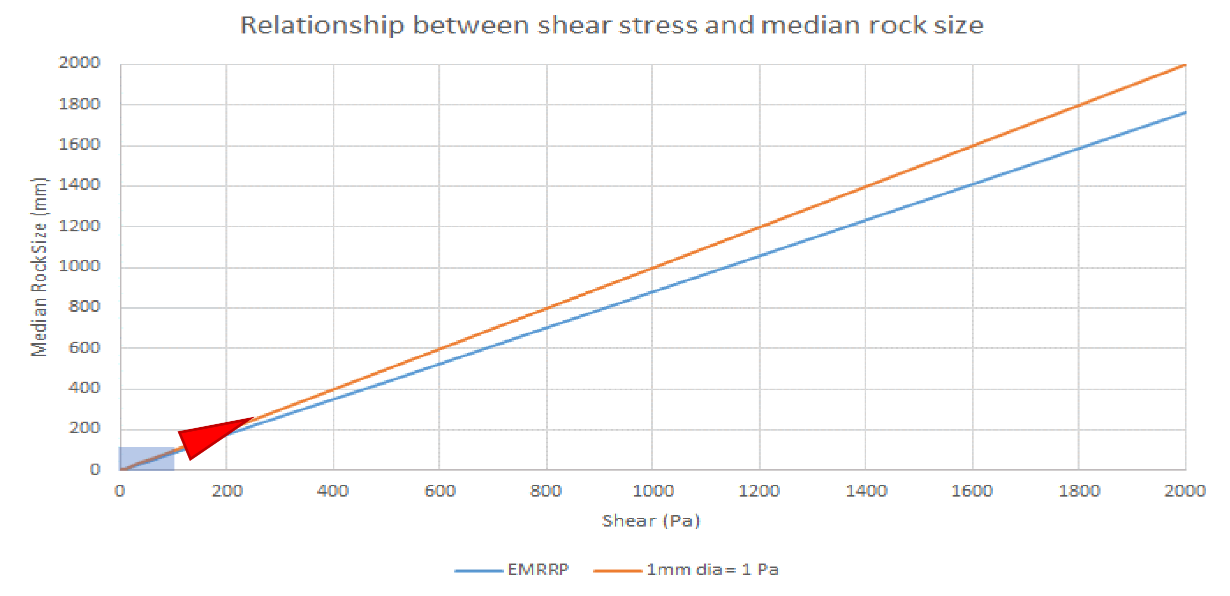


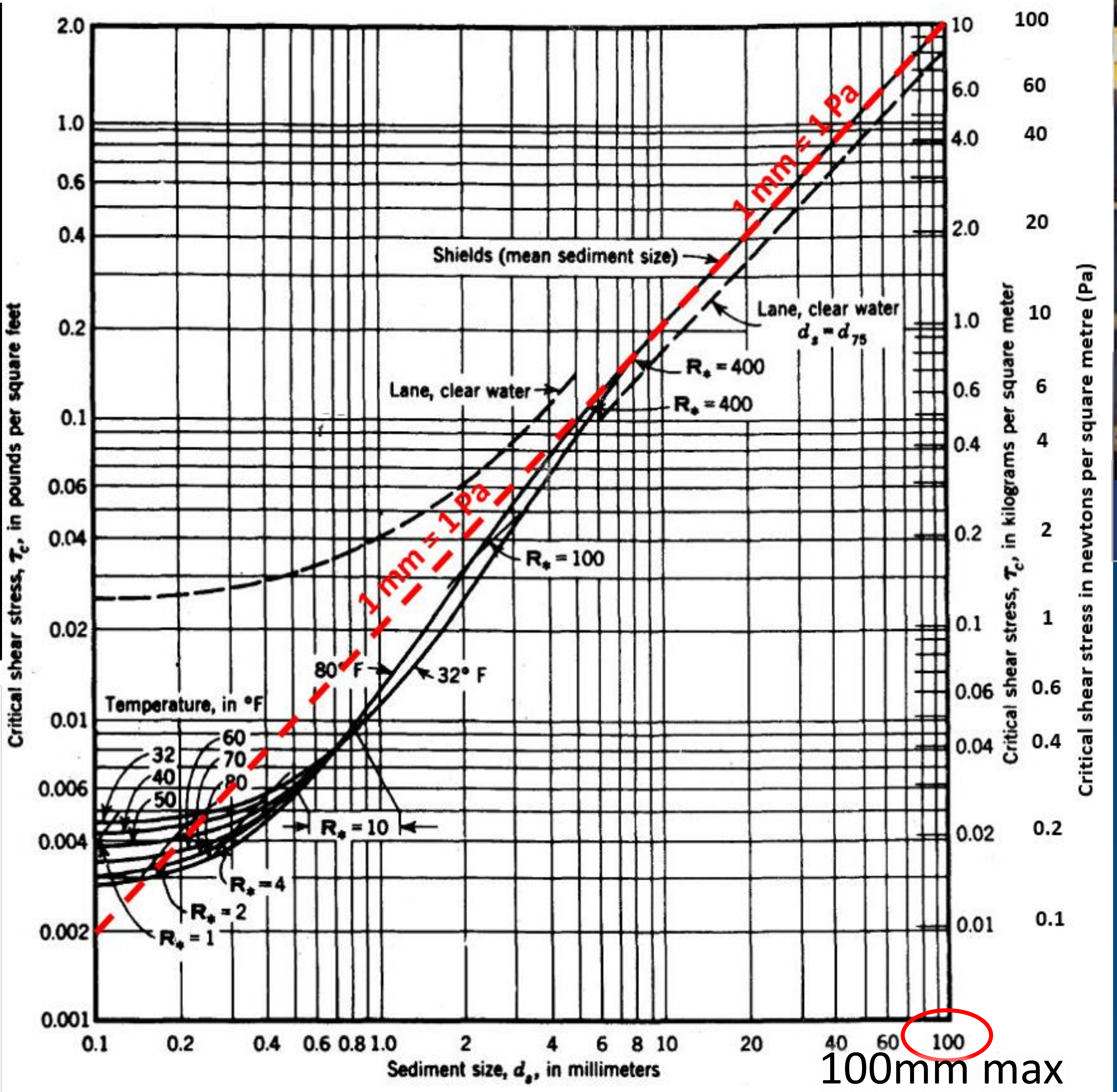
Krey Price

3D Weir flow vs orifice flow



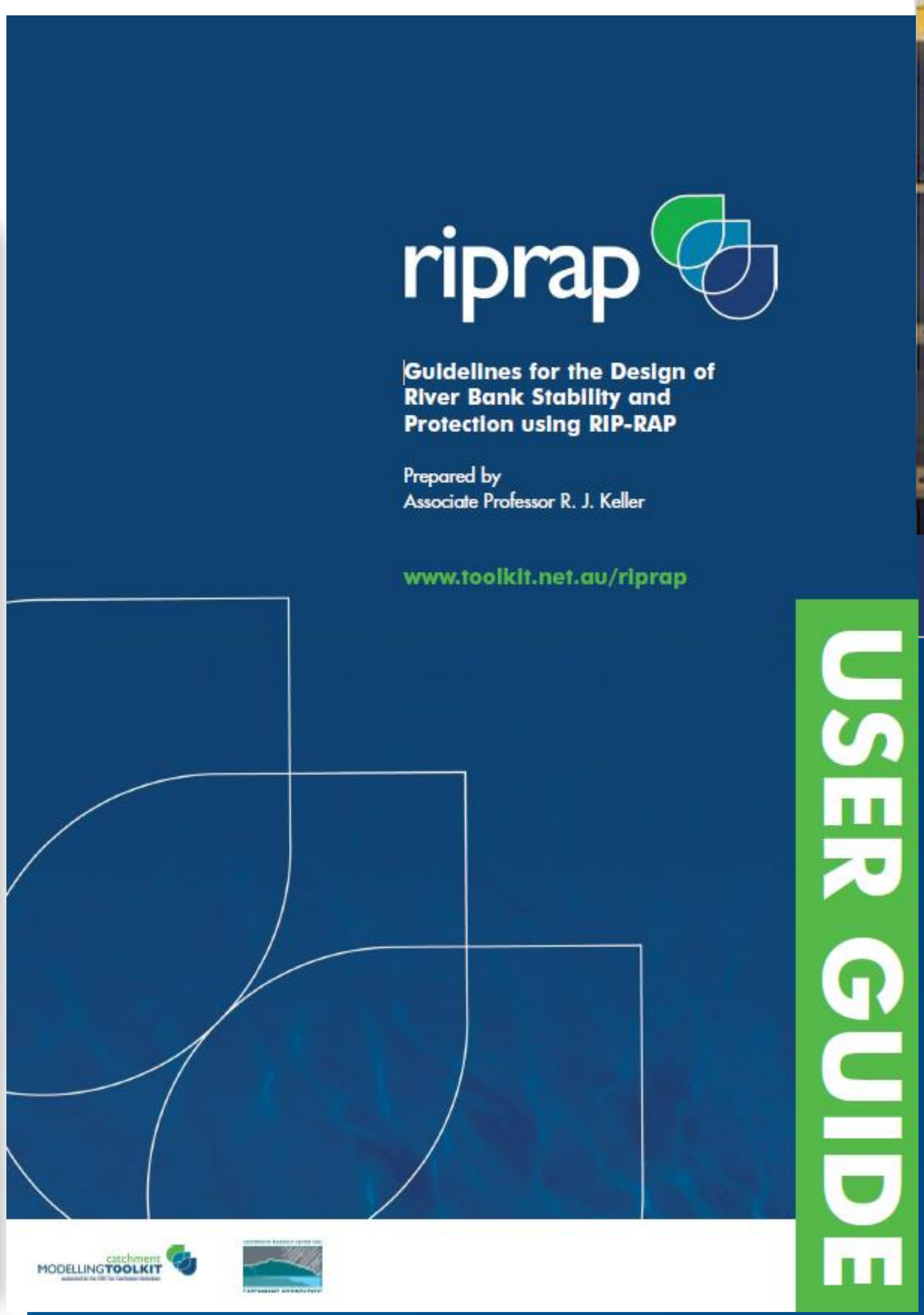
Rock class	Particle diameter	Angle of repose	Critical shear stress	Critical shear velocity	Particle diameter	Critical shear stress	Critical shear velocity
Class name	d_s (in)	ϕ (deg)	τ_c (lb/sf)	V_{*c} (ft/s)	(mm)	(Pa)	(m/s)
Boulder							
Very large	>80	42	37.4	4.36	2032	1791	1.33
Large	>40	42	18.7	3.08	1016	896	0.94
Medium	>20	42	9.3	2.20	508	445	0.67
Small	>10	42	4.7	1.54	254	225	0.47
Cobble							
Large	>5	42	2.3	1.08	127	110	0.33
Small	>2.5	41	1.1	0.75	64	53	0.23
Gravel							
Very coarse	>1.3	40	0.54	0.52	33	26	0.16
Coarse	>0.6	38	0.25	0.36	15	12	0.11
Medium	>0.3	36	0.12	0.24	8	6	0.07
Fine	>0.16	35	0.06	0.17	4	3	0.05
Very fine	>0.08	33	0.03	0.12	2	1	0.04
Sands							
Very coarse	>0.04	32	0.01	0.070	1.0	0.5	0.021
Coarse	>0.02	31	0.006	0.055	0.5	0.3	0.017
Medium	>0.01	30	0.004	0.045	0.3	0.2	0.014
Fine	>0.005	30	0.003	0.040	0.13	0.1	0.012
Very fine	>0.003	30	0.002	0.035	0.08	0.1	0.011
Silts							
Coarse	>0.002	30	0.001	0.030	0.05	0.05	0.009
Medium	>0.001	30	0.001	0.025	0.03	0.05	0.008



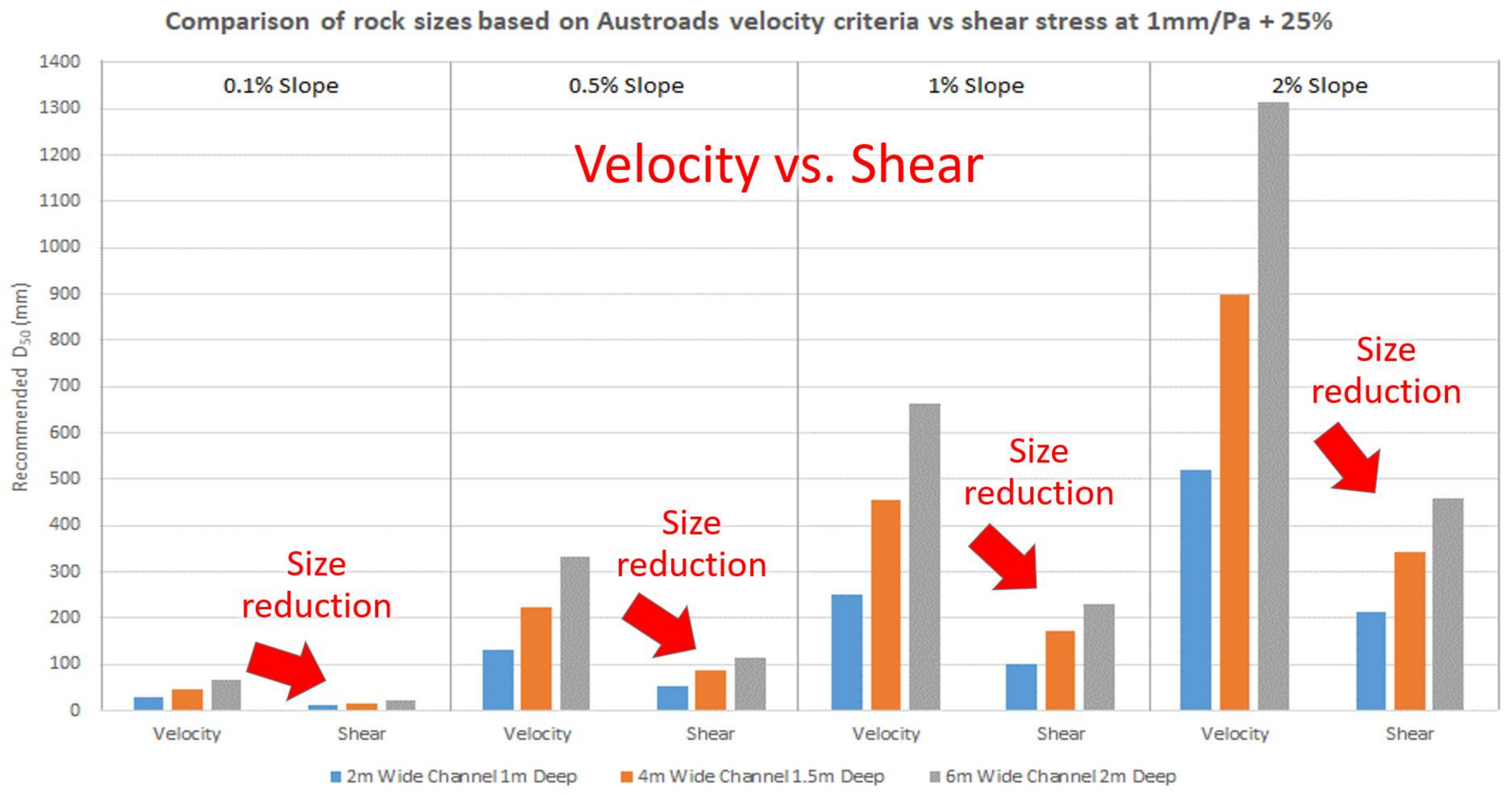


Krey Price

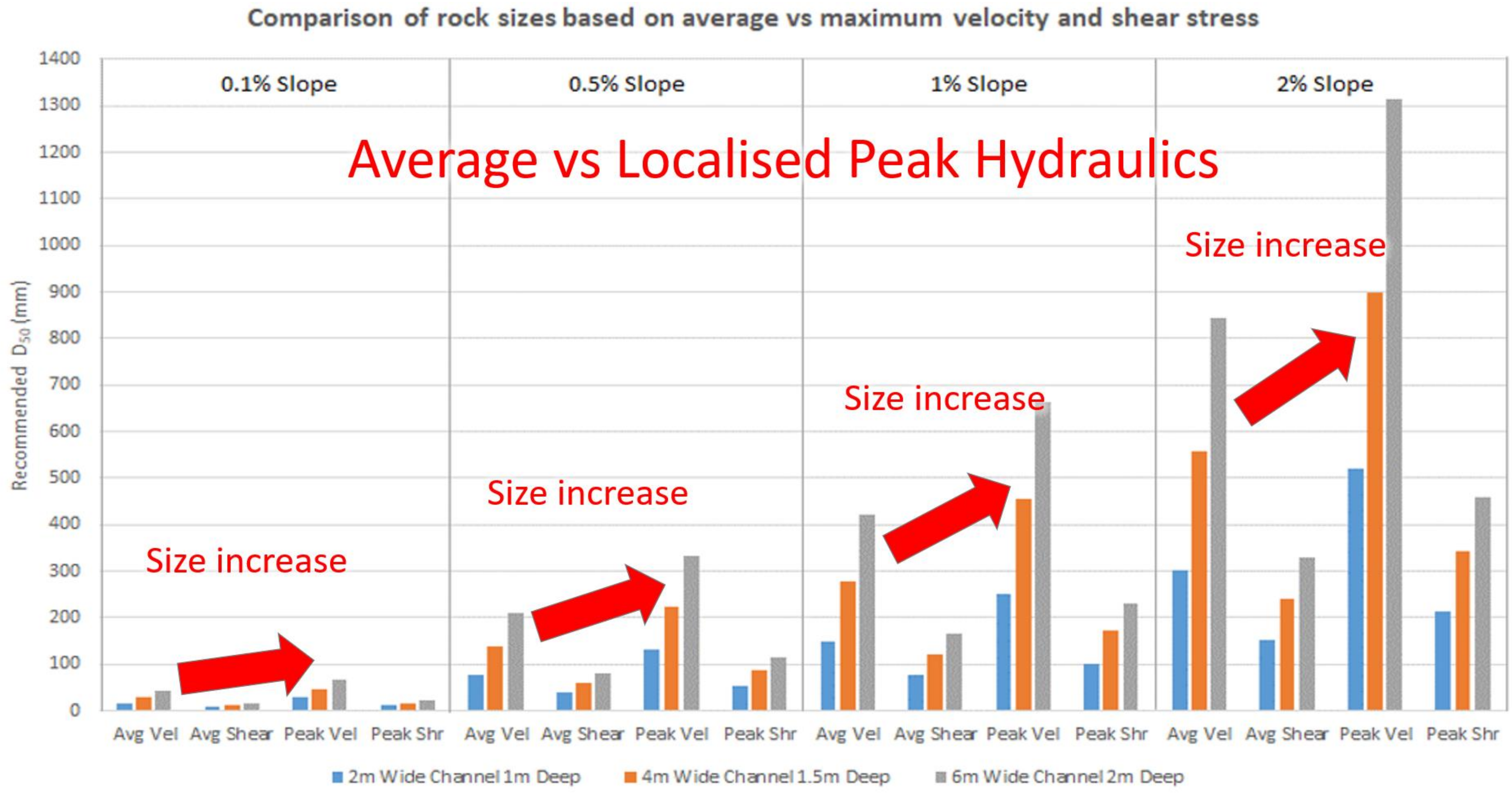

Catchment Modelling Toolkit - RIPRAP
riprap
A spreadsheet program for the design of rip-rap bank protection.
Rip-rap can be employed to provide protection to actively eroding or potentially eroding banks in rivers and channels.
https://toolkit.ewater.org.au/Tools/RIPRAP
catchment MODELLINGTOOLKIT
OK
CATCHMENT HYDROLOGY
The Catchment Modelling Toolkit is a suite of software designed to improve the standard and efficiency of catchment modelling. www.toolkit.net.au


riprap
Guidelines for the Design of River Bank Stability and Protection using RIP-RAP
Prepared by
Associate Professor R. J. Keller
www.toolkit.net.au/riprap
USER GUIDE

Krey Price

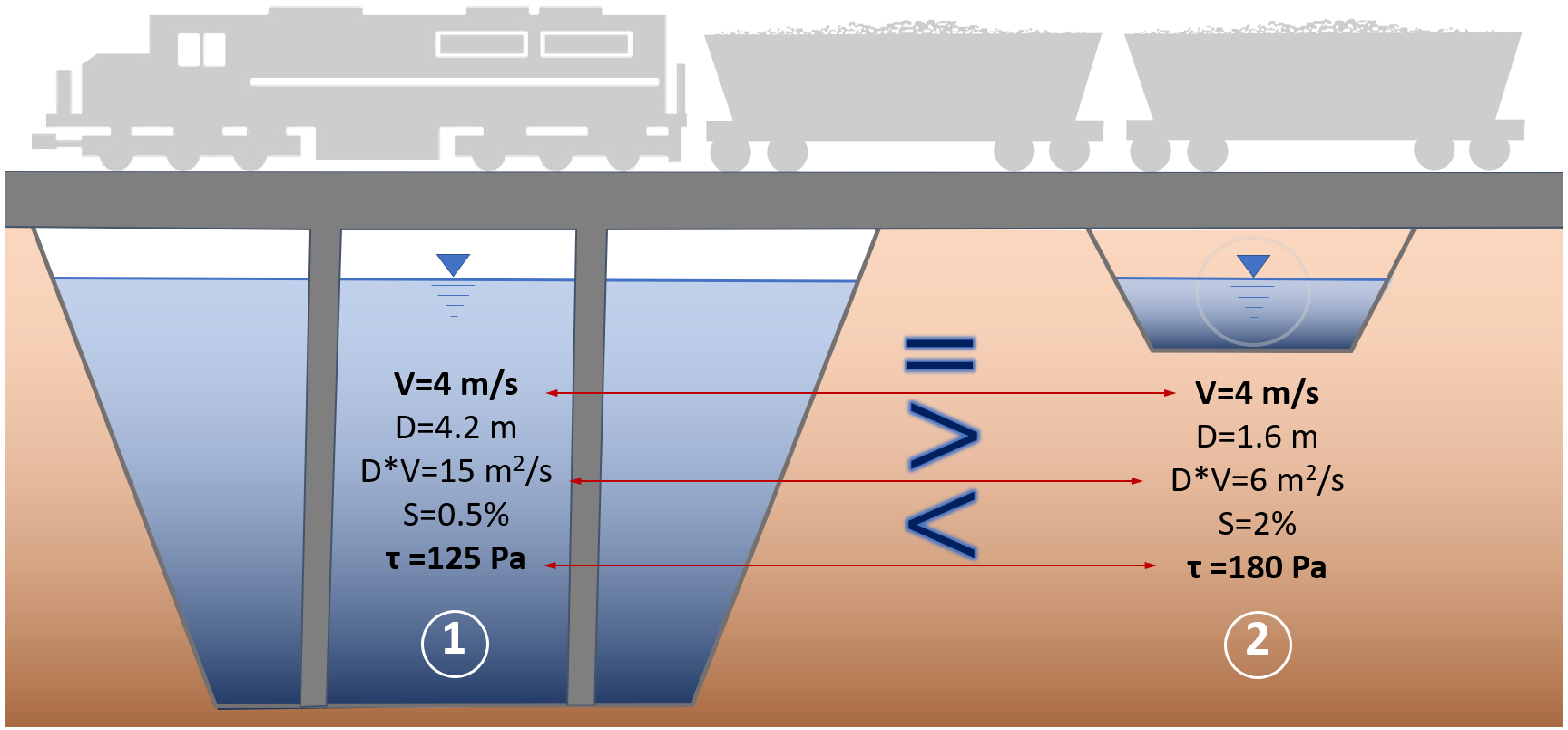


- From Price and Westwater, IMWA 2020



• From Price and Westwater, IMWA 2020

Krey Price



Krey Price

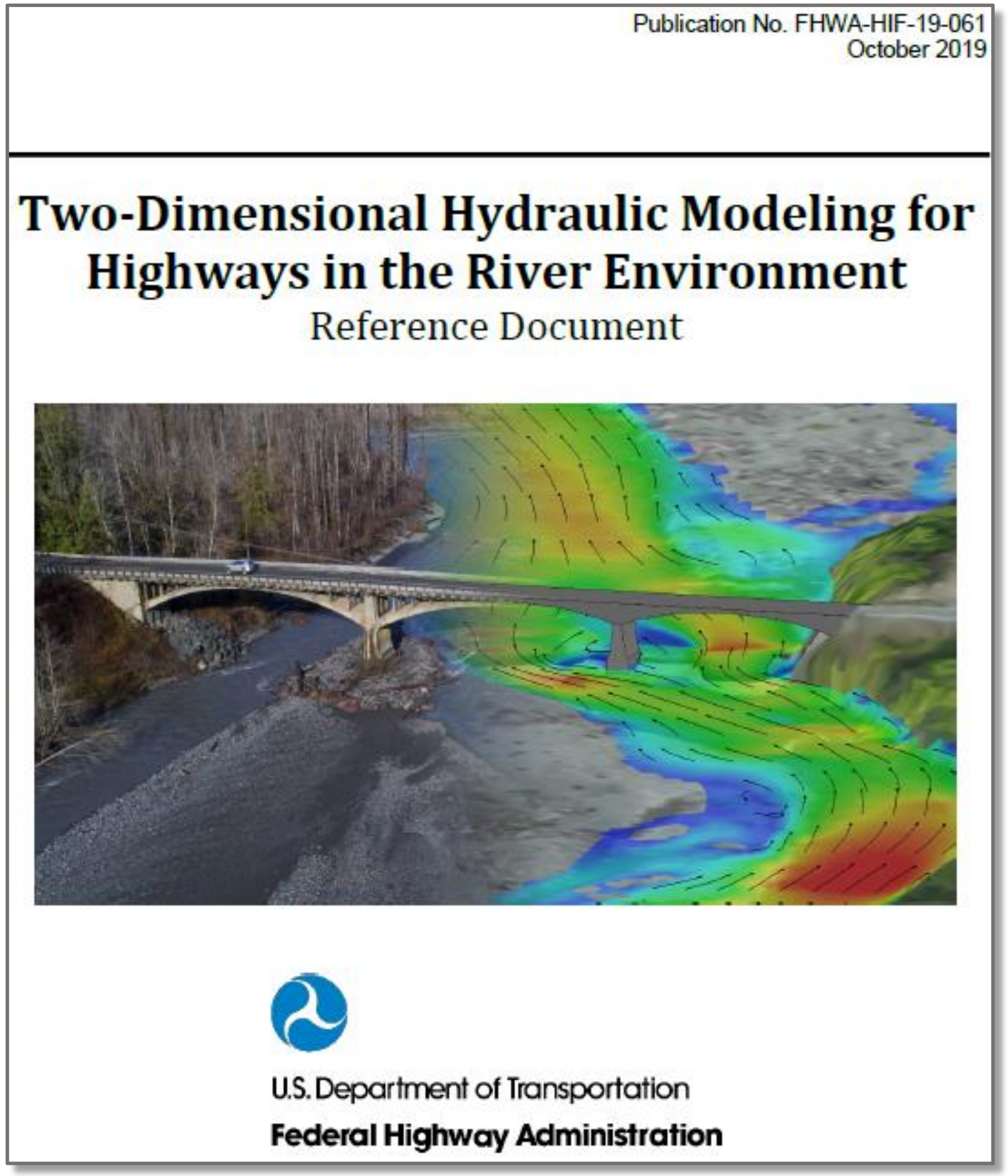
Limitations:

s<2%

F<0.8

$4<d:D_{30}<30$

Krey Price



- D_{50}= 4m, W_{50} = 40 tonne
- D_{90}= 6m, W_{50} =150 tonne

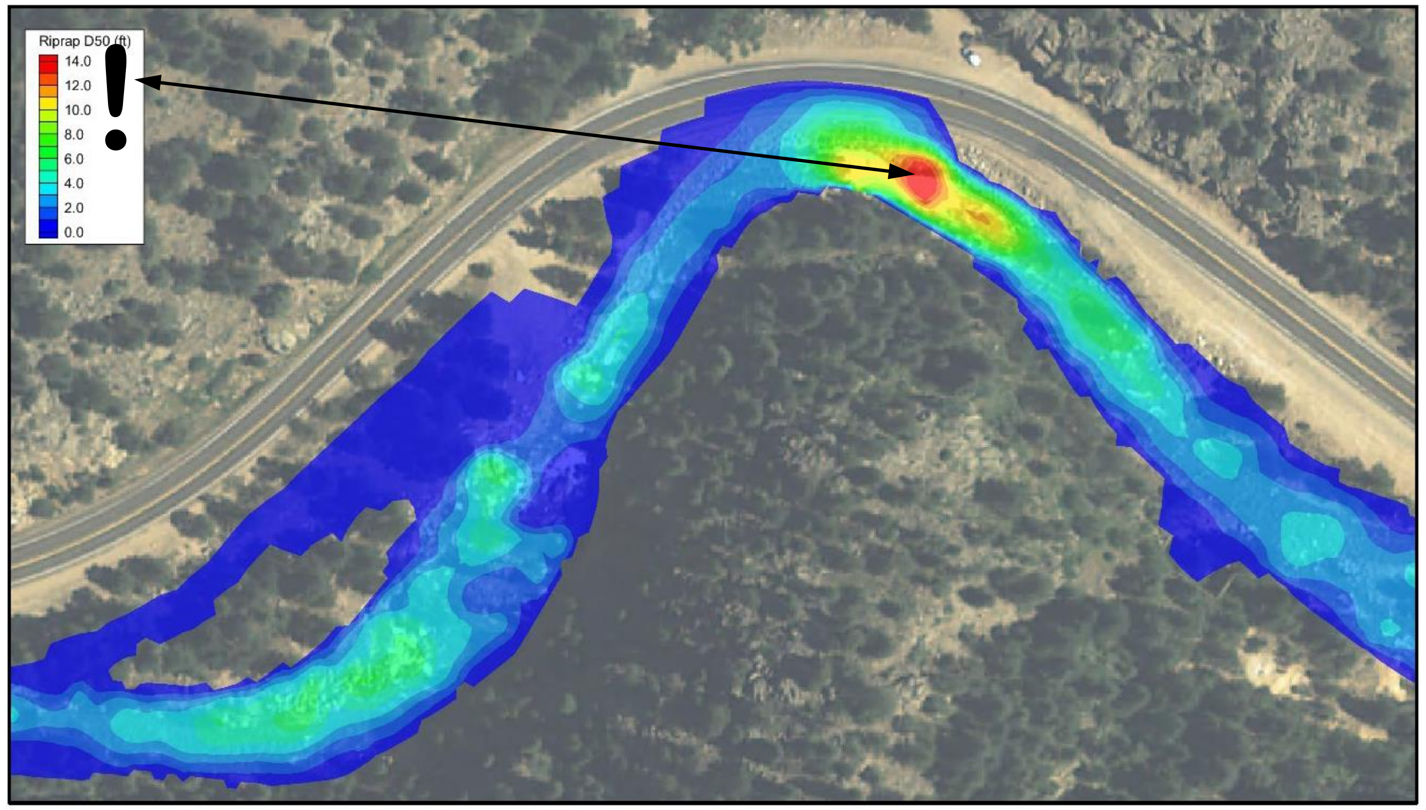
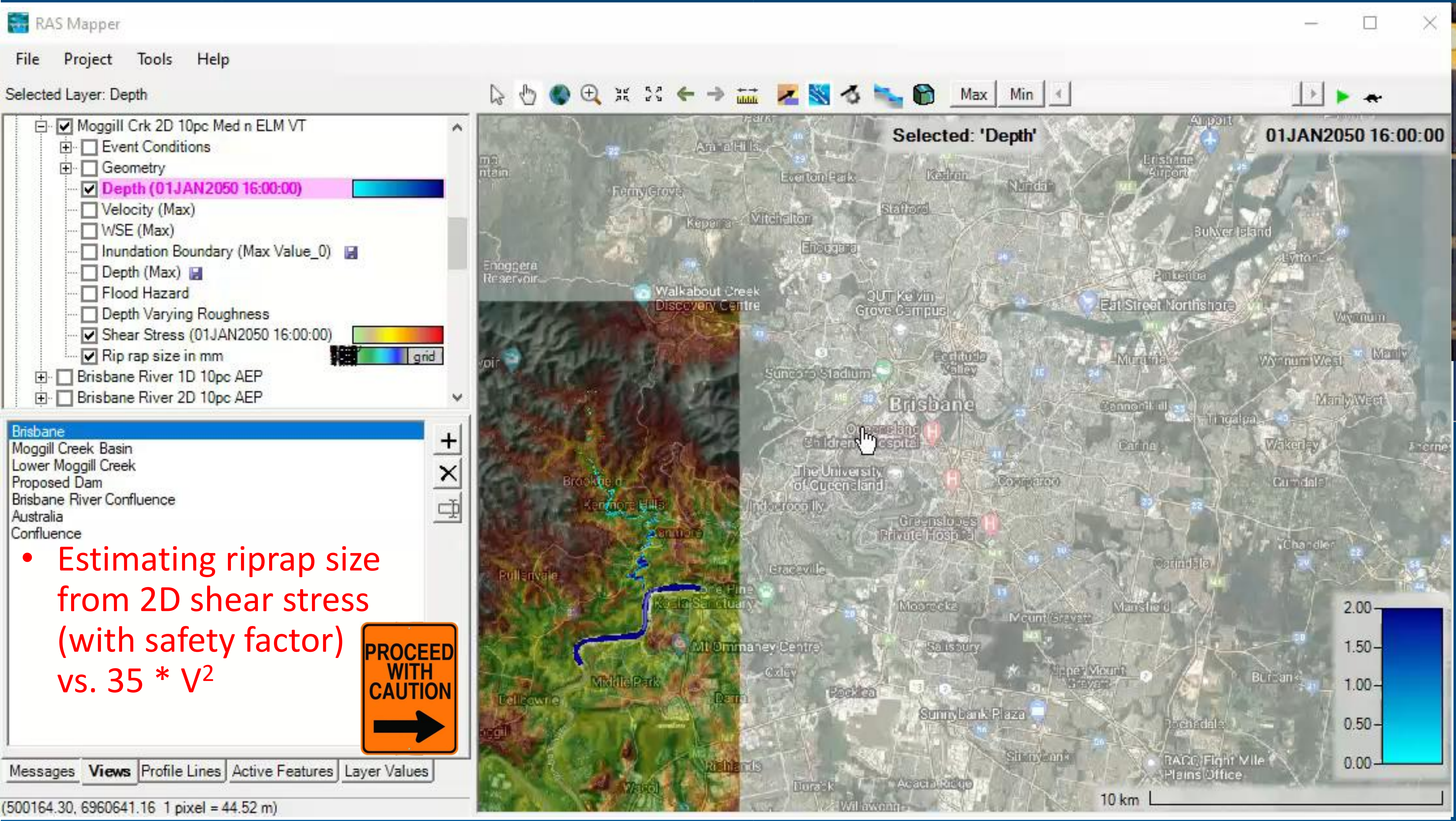


Figure 8.5. Riprap sizing contours based on 2D model depth and velocity results.

Krey Price



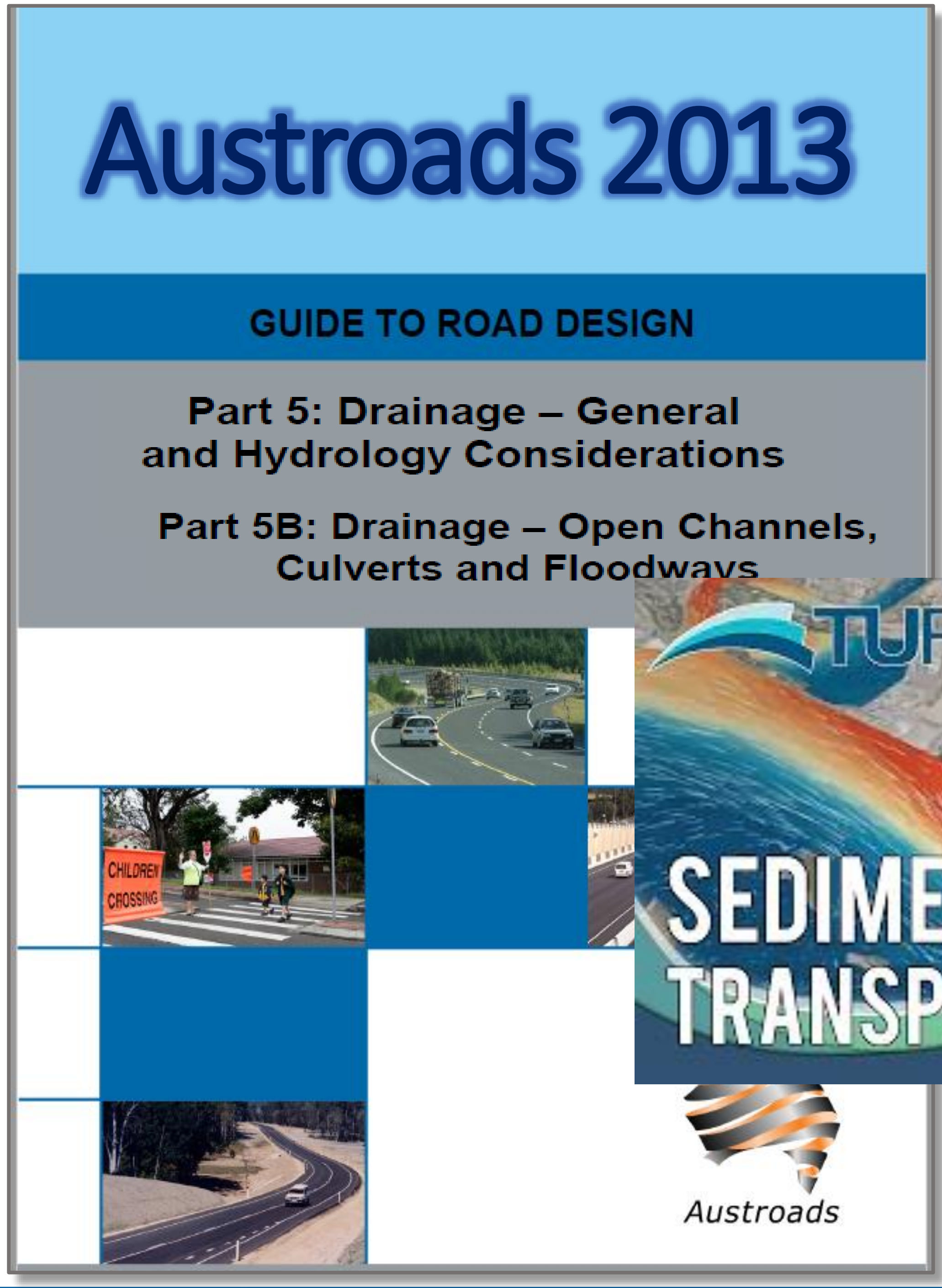
- Estimating riprap size from 2D shear stress (with safety factor) vs. $35 * V^2$

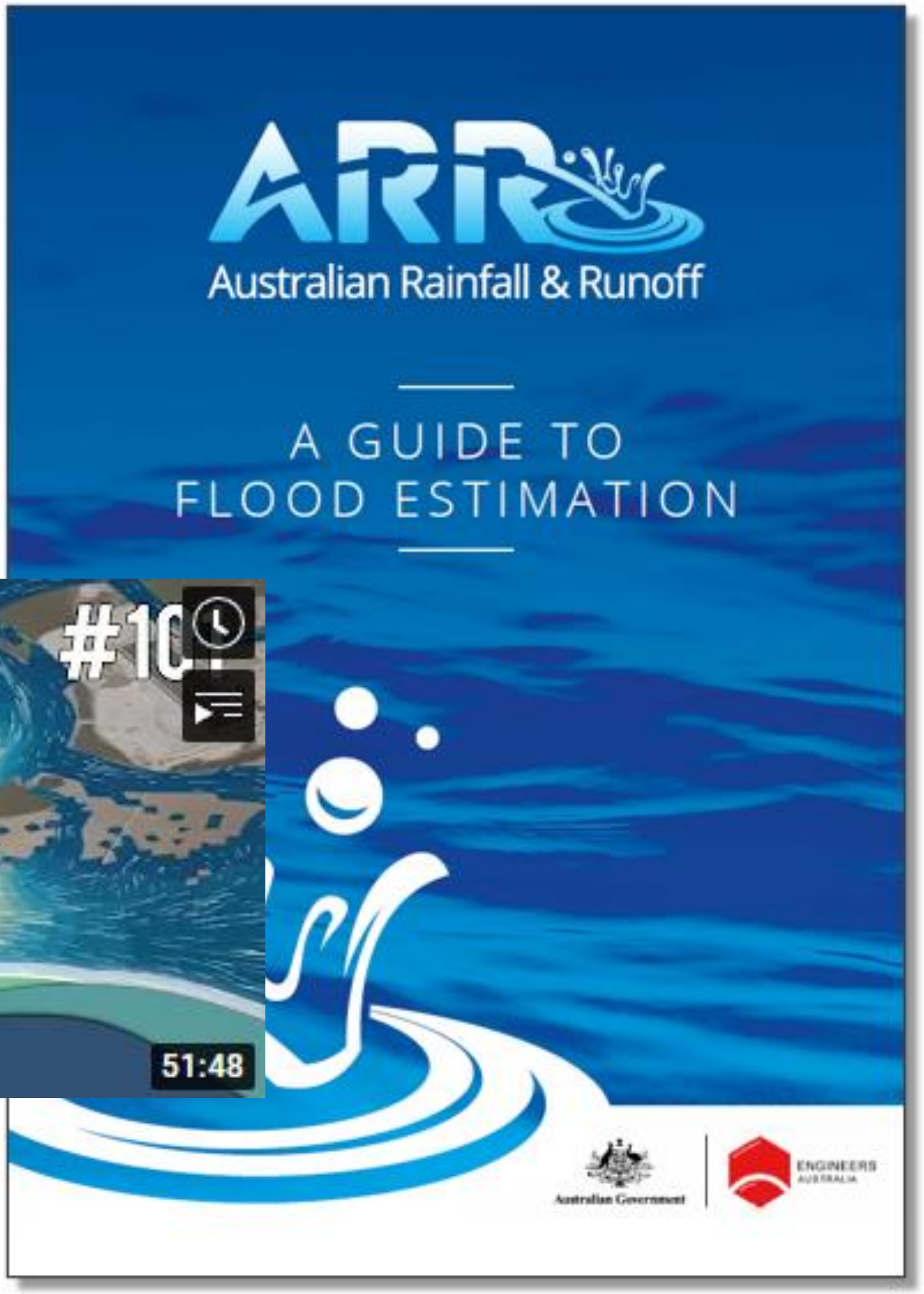
PROCEED
WITH
CAUTION

Krey Price

2022 FLOODPLAIN MANAGEMENT AUSTRALIA NATIONAL CONFERENCE

Numerical sediment transport modelling





Krey Price

Recommendations

- Check using at least 3 methods:

13.2 Sizing Riprap

The basis of designing a riprap revetment is sizing the rock. Methods presented here are applicable to all bank hardening methods presented in succeeding chapters. There are many methods available and this presentation is not all-inclusive, however a sensitivity analysis has been provided on the presented methods to aid in selecting an appropriate riprap sizing equation for the site. The recommended approach is to use a minimum of three methods to define the range in values. Selection of the riprap size could be based on an average value from the range, or it may be a high or low value depending on site specific characteristics such as the geomorphic factors. There are spreadsheets and software available for computing riprap size, but the designer should be familiar with the individual riprap sizing methods to ensure they are applied correctly.

RECLAMATION
Managing Water in the West

Bank Stabilization Design Guidelines

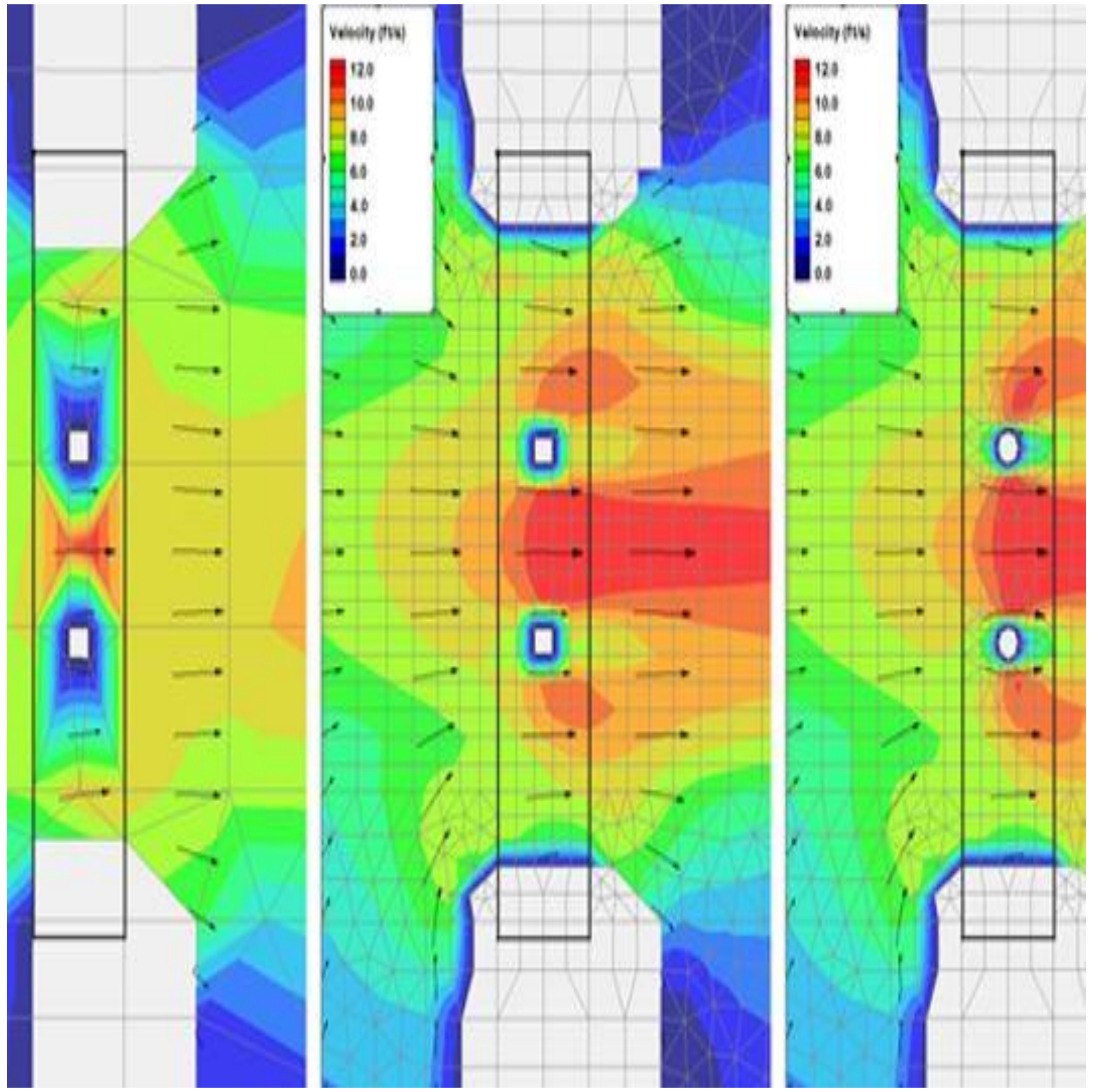
Report No. SRH-2015-25
Albuquerque Area Office
Science and Technology
Policy and Administration (Manuals and Standards)
Yuma Area Office

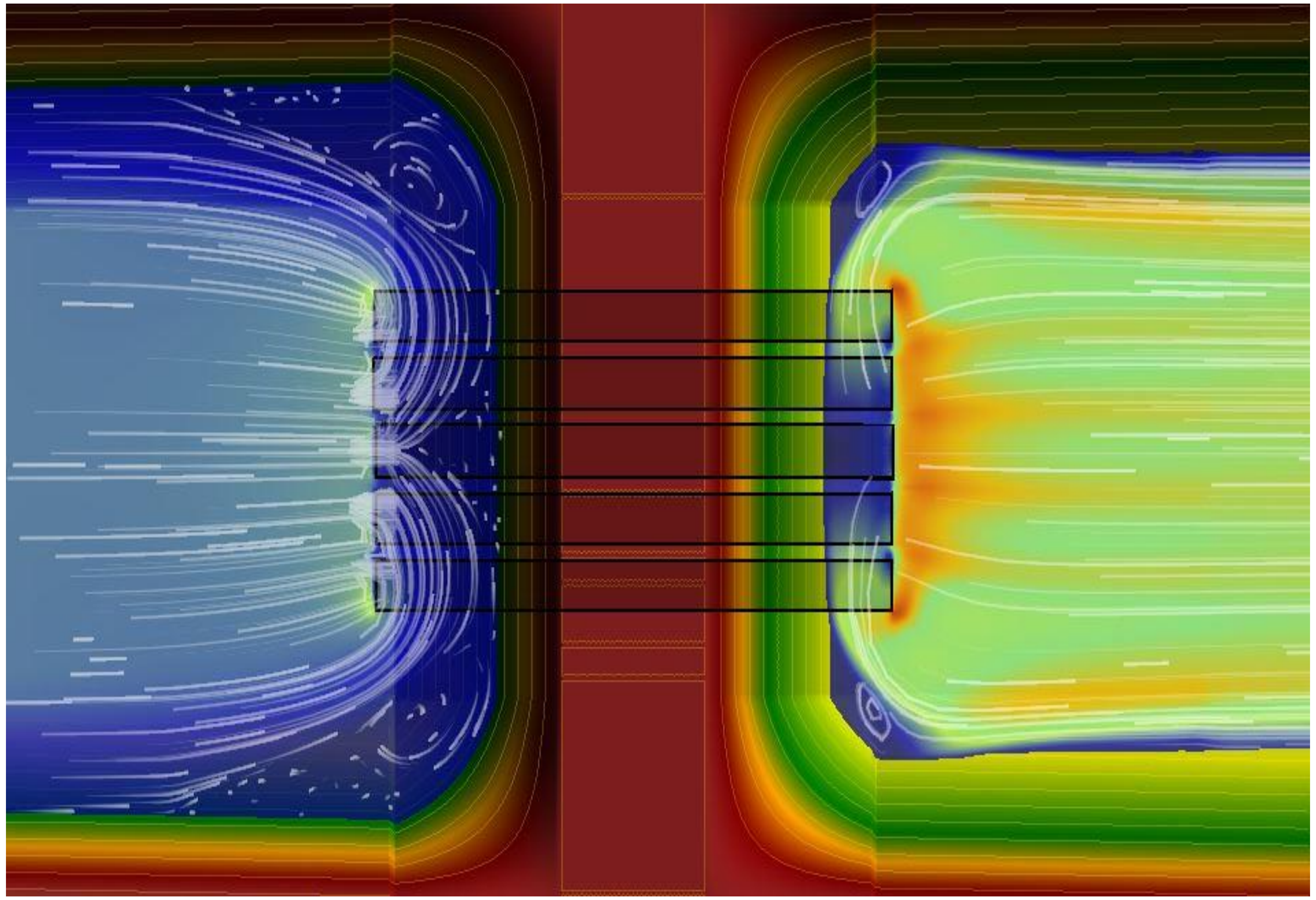
U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

June 2015

Krey Price

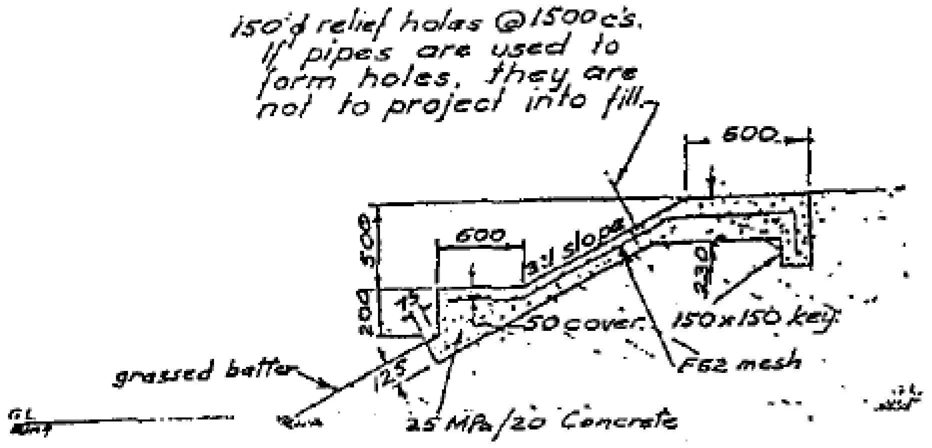
Applying 2D and 3D results to 1D methods



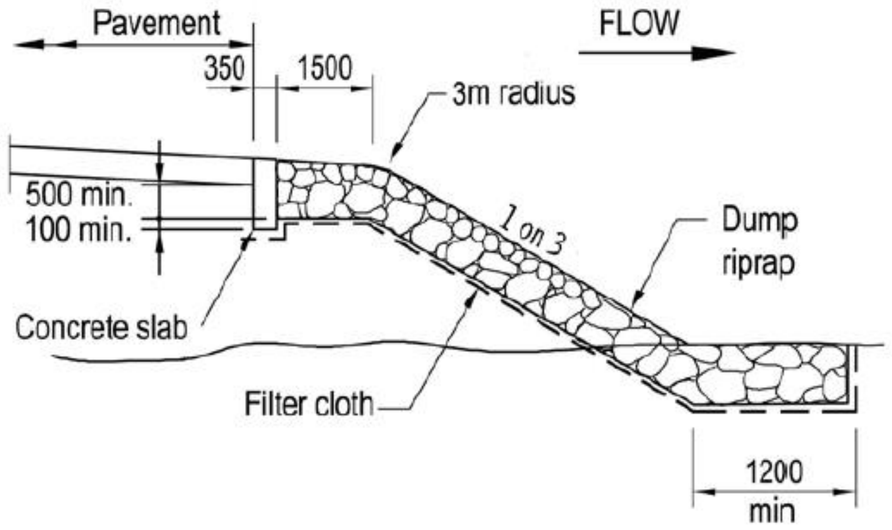


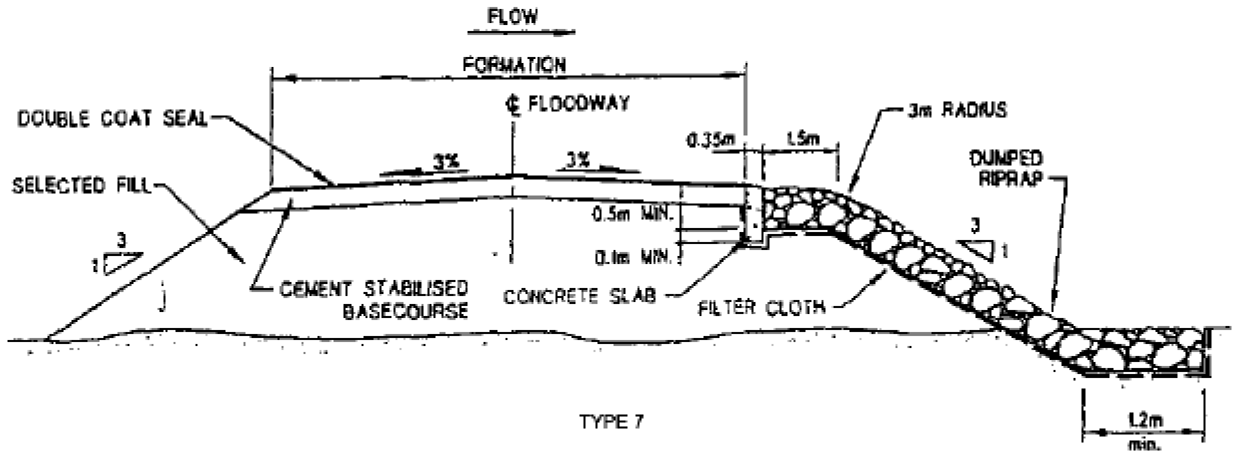
Krey Price

Extent of Protection



NAASRA, Bridge Waterways Hydrology and Design, 1989.





Poll Question

Floodwaters moved this particle 2km downstream in less than 6 hours. Guess its weight:

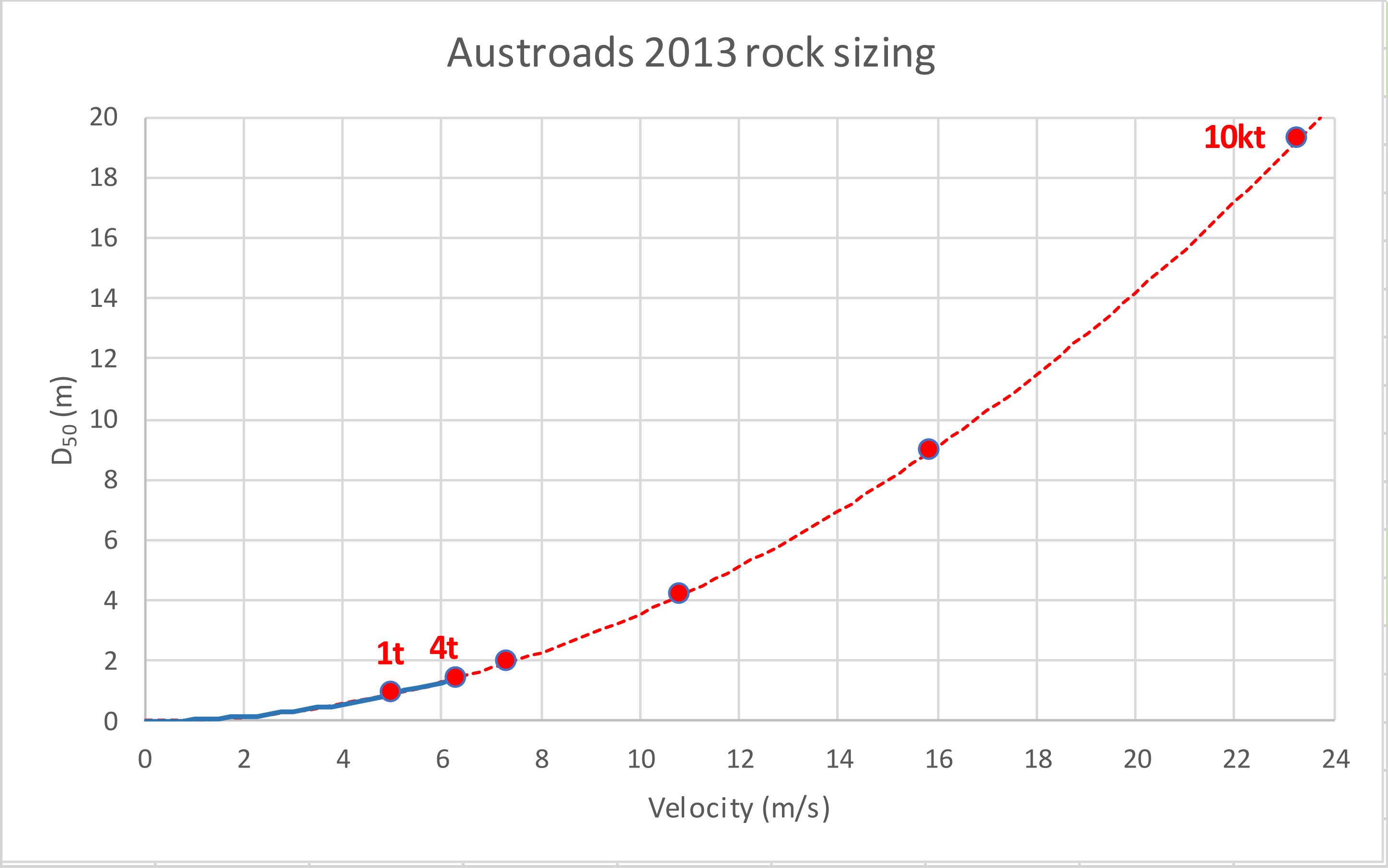
- 1 t
- 10 t
- 100 t
- 1,000 t
- 10,000 t

Krey Price

Poll Question

Floodwaters moved this particle 2km downstream in less than 6 hours. Guess its weight:

- 1 t
- 10 t
- 100 t
- 1,000 t
- 10,000 t

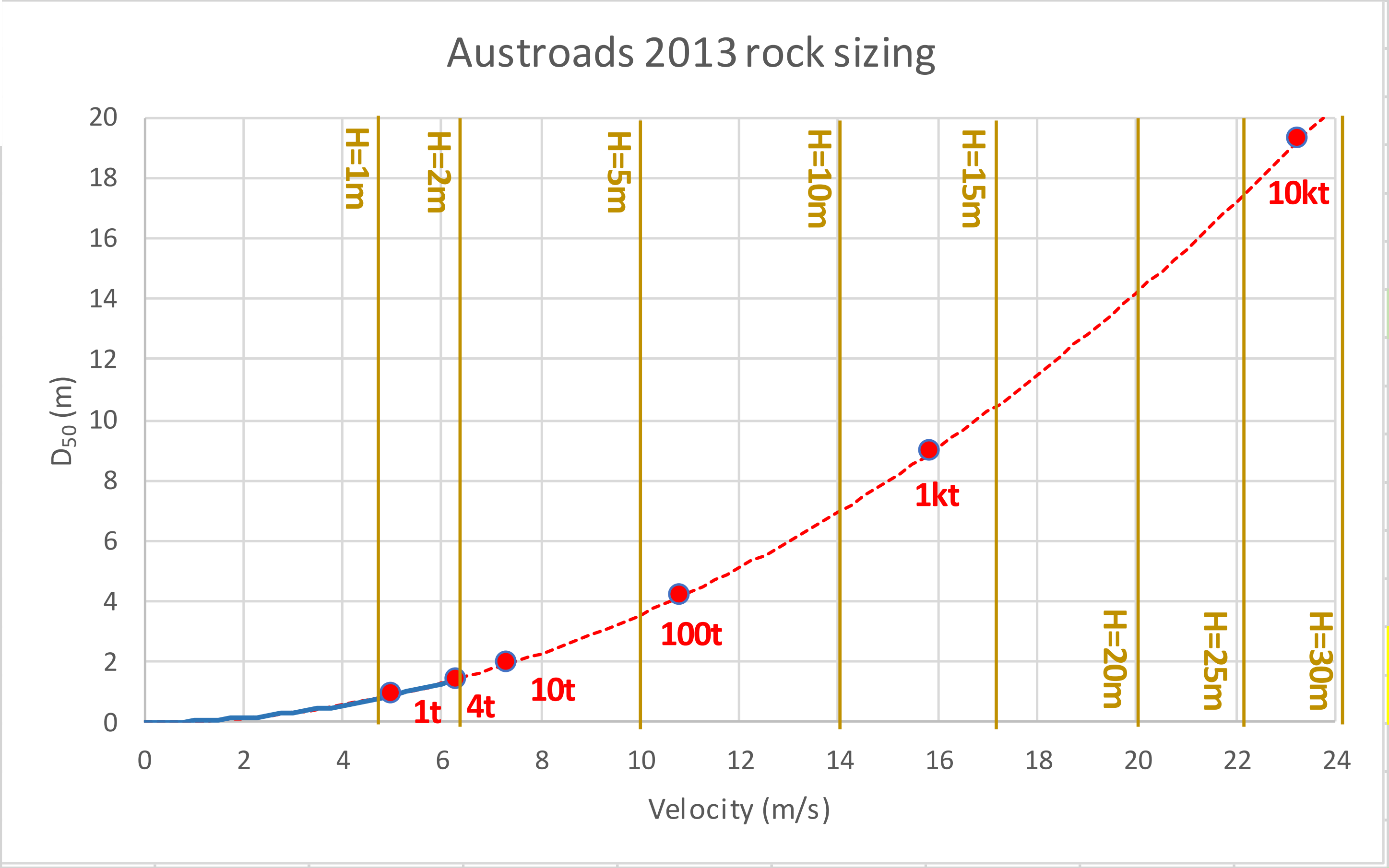


Krey Price

Poll Question

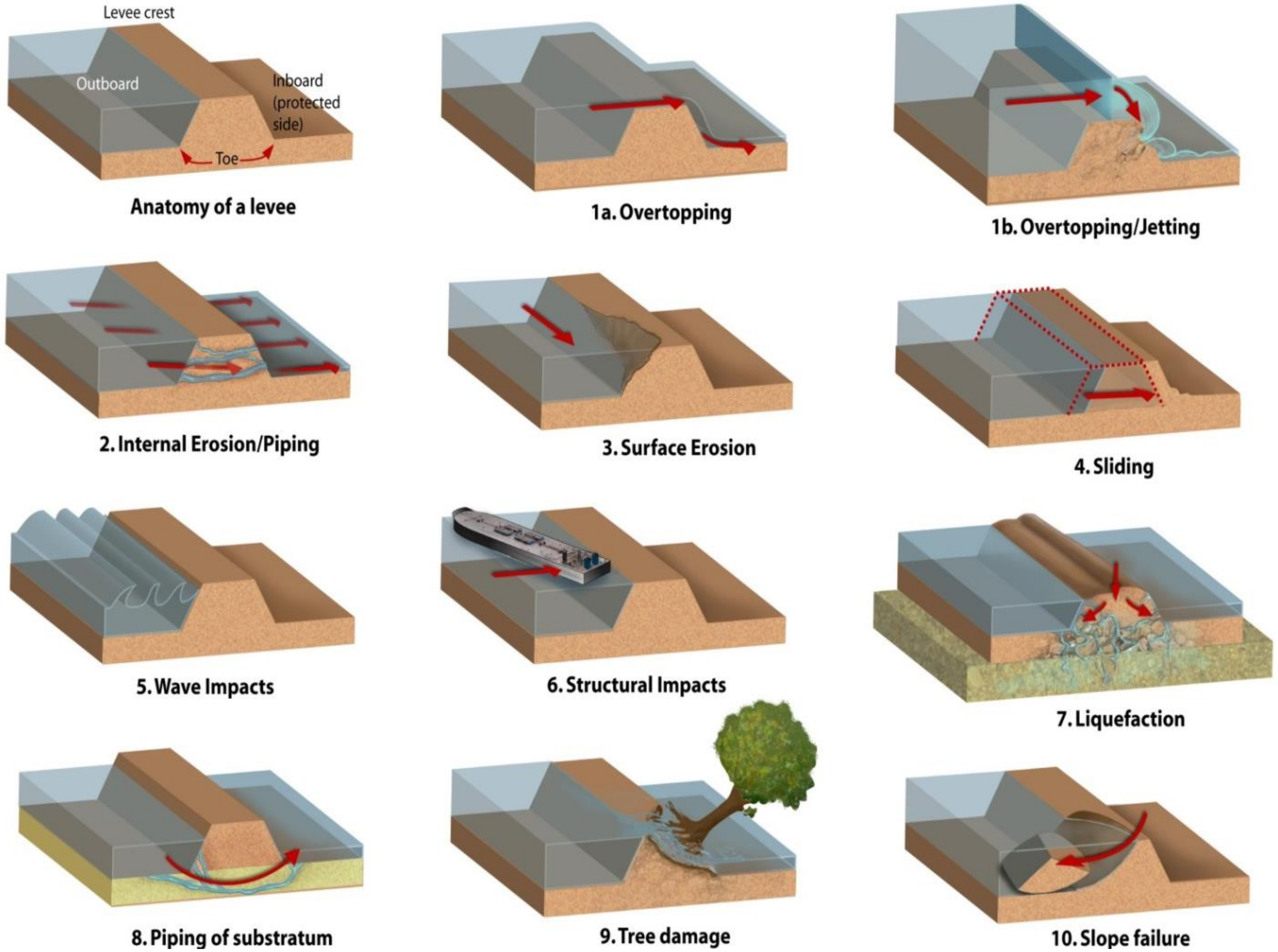
Floodwaters moved this particle 2km downstream in less than 6 hours. Guess its weight:

- 1 t
- 10 t
- 100 t
- 1,000 t
- 10,000 t



Krey Price

Erosion mechanisms



Krey Price

Additional resources

ISBN number for HWRS 2021 is 978-1-925627-53-4

Advancing Australian Riprap Sizing Approaches

Krey Price
Surface Water Solutions
krey.price@surfacewater.biz

ABSTRACT

The placement of riprap is the most commonly implemented scour countermeasure in Australia. Nationwide guidance for riprap sizing is provided in Austroads and Australian Rainfall and Runoff (ARR) documents. ARR guidance generally defers to Queensland Department of Transport and Main Roads (QDTMR) publications that, in turn, defer to Austroads guidance for riprap sizing. Austroads riprap sizing procedures fall back on methods developed by the United States Bureau of Reclamation (USBR), the U.S. Army Corps of Engineers (USACE), and the Federal Highways Administration (FHWA). The cited procedures generally relate the recommended riprap size to flow velocity because alternative parameters such as shear stress have historically been difficult to visualise, compute, and measure.

Austroads and ARR guidance manuals cite different methods for sizing riprap associated with bridges, culverts, floodways, energy dissipation structures, and channel lining applications; in some cases, the cited methods provide conflicting guidance. Some of the references that serve as a basis for Australian riprap sizing guidance have been superseded by more recent publications that should be incorporated into future editions of Australian guidance documents.

Both Austroads and ARR manuals recommend computing shear stress to determine the potential for mobilising material, but no guidance for applying shear-based rock sizing design criteria is presented. Recent advances in computational methods allow shear-based analyses to be more readily developed for previously impractical applications, leading to the potential introduction of standardised, shear-based, Australian riprap design approaches.

The increasing prevalence of 2D and 3D flood modelling relative to 1D modelling warrants a reappraisal of previously adopted riprap sizing criteria that have traditionally been based on 1D approaches. 2D and 3D results used for riprap sizing are subject to the proper selection of grid sizes, computational methods, turbulence coefficients, and other modelling parameters. A recommended interim approach for estimating stable design riprap size is presented using hydraulic modelling results for velocity, depth, and shear stress.

BACKGROUND

The Use of Riprap in Australia

Relative to other scour countermeasures, the installation of riprap in Australia is a primary scour protection option because it is "abundant, inexpensive, and requires no special equipment" (ARR 2019). Nationwide guidance for the application of hydraulic modelling results to scour protection designs is provided by Austroads and ARR. This paper provides a literature review of the sources that serve as a basis for Australian riprap sizing approaches and recommends selected adjustments to those approaches. Guidance provided by local jurisdictions is only included in this review where referenced in the national guidelines.

Velocity vs Shear

Both Austroads and ARR guidance documents cite velocity-based criteria for sizing riprap. In simplest terms, flow velocities are extracted from measurements or hydraulic models and converted directly into a recommended stone size. In general, the velocity refers to a depth-averaged channel velocity, and the stone size refers to the median diameter (D_{50}) of an individual riprap stone based on total weight of the rock classes. Figure 1 shows an example of a riprap sizing chart based on tabulated values in Austroads (2013a and 2013b).

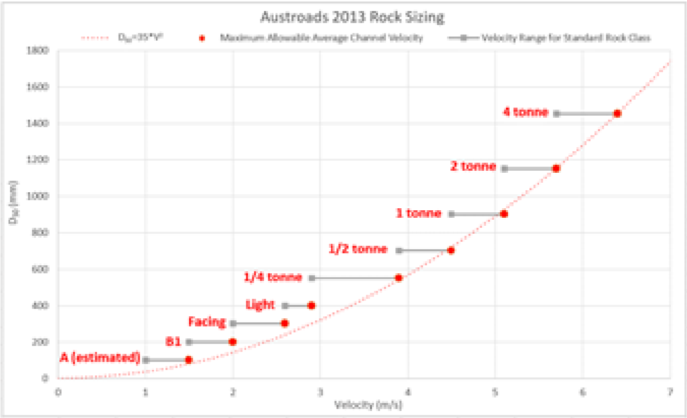


Figure 1. Riprap sizing chart (based on Austroads 2013a, 2013b).

Velocity-based riprap sizing methods can generally be summarised by stating the required rock diameter in terms of a coefficient "a" that is multiplied by the velocity raised to an exponent "b":

$$D_{50} = a*V^{b} \quad \text{(Equation 1)}$$

The coefficient "a" can vary with side slope, bend angle, density, angularity, safety factor, and other elements. The exponent "b" generally ranges between a value of 2 and 3 among the various available methods. The applicable velocity ranges associated with standard Australian rock classes are shown in Figure 1 against a relationship curve with a value of 35 for "a" and 2 for "b", where the median rock size (measured in milimetres) is 35 times the square of the velocity (measured in metres per second).

Figure 2 shows an alternative relationship where the velocity on the x axis is taken as the bottom velocity rather than a depth-averaged velocity (Austroads 2013b). The maximum allowable average channel velocities from Figure 1 are shown in red for comparison. The effective "a" values range from 20 to 35 for average channel velocities, and from 40 to 70 for bottom velocities, with the exponent "b" held constant at 2 for both curves.

Increasing the applied velocity has an exponential effect on the computed stone weight. Because the

Krey Price

www.hydroschool.com/riprap/

www.catchmentsandcreeks.com.au

Home | Services | Course Locations | Registration | Articles | About Us | Contact

Home › Rock sizing resources

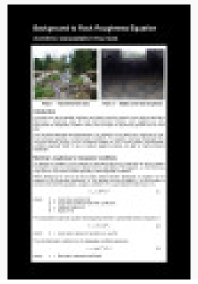
Rock sizing resources

We recently hosted the Australian Water School's 100th webinar, "Rocking It!" which covered using hydraulic modelling results for rock sizing. Watch the recording here:

Catchments & Creeks

About Us | Training | Field Guides | Fact Sheets | Drawings

Fact Sheets: Rock Sizing

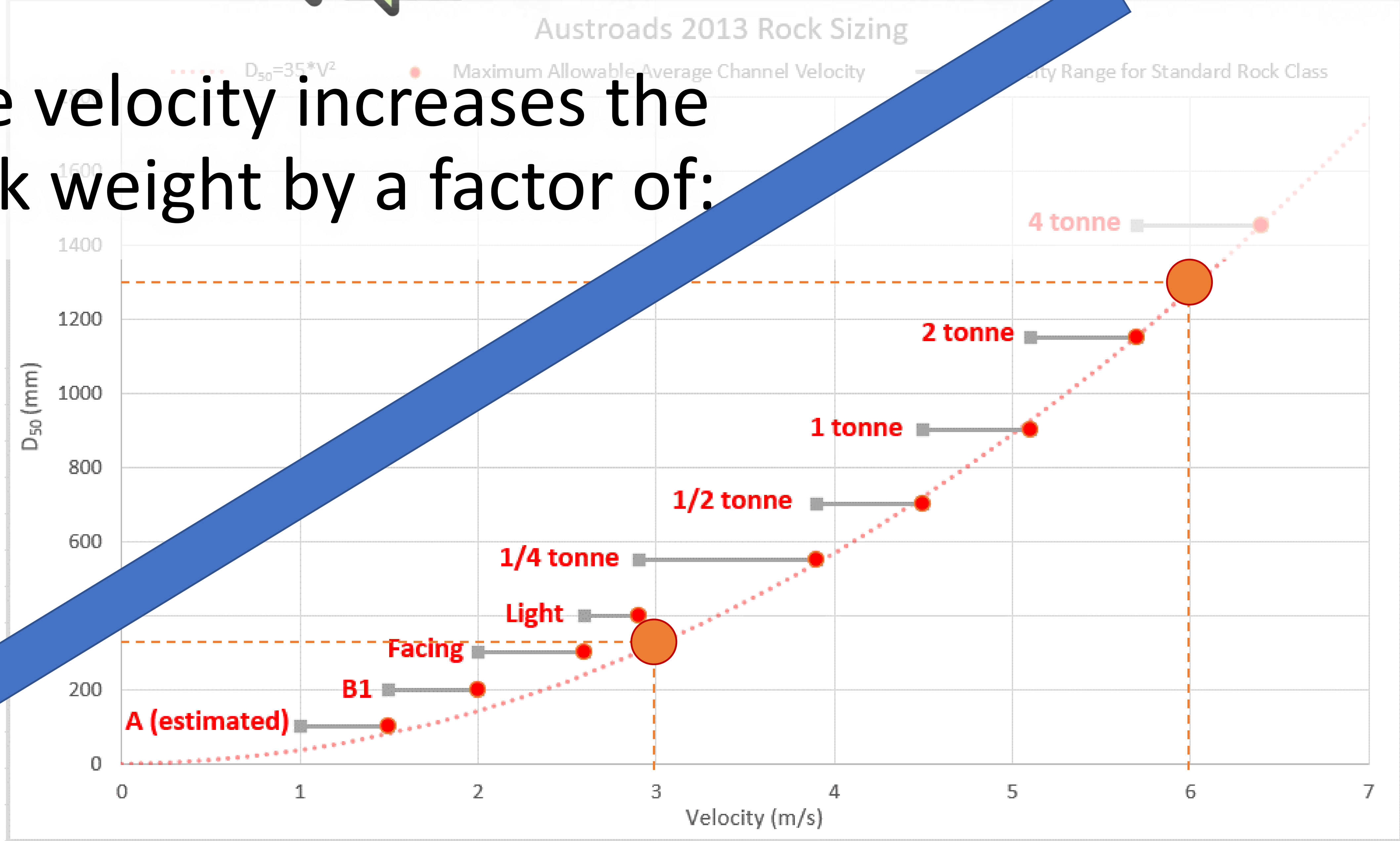
Preview	Title & Description	Specs	File
	Background to Rock Roughness Equation *5 pages*	N/A	PDF 185.75 KB
	Background to Rock Sizing Equations *52 pages*	N/A	PDF 992.40 KB

Krey Price

Poll Question

- $V = 3$ m/s $D_{50} = 315$mm $W_{50} = 43$ kg
- $V = 6$ m/s $D_{50} = 1260$mm $W_{50} = 2775$ kg

- Doubling the velocity increases the required rock weight by a factor of:
  - 2
  - 4
  - 8
  - 16
  - 32
  - 64



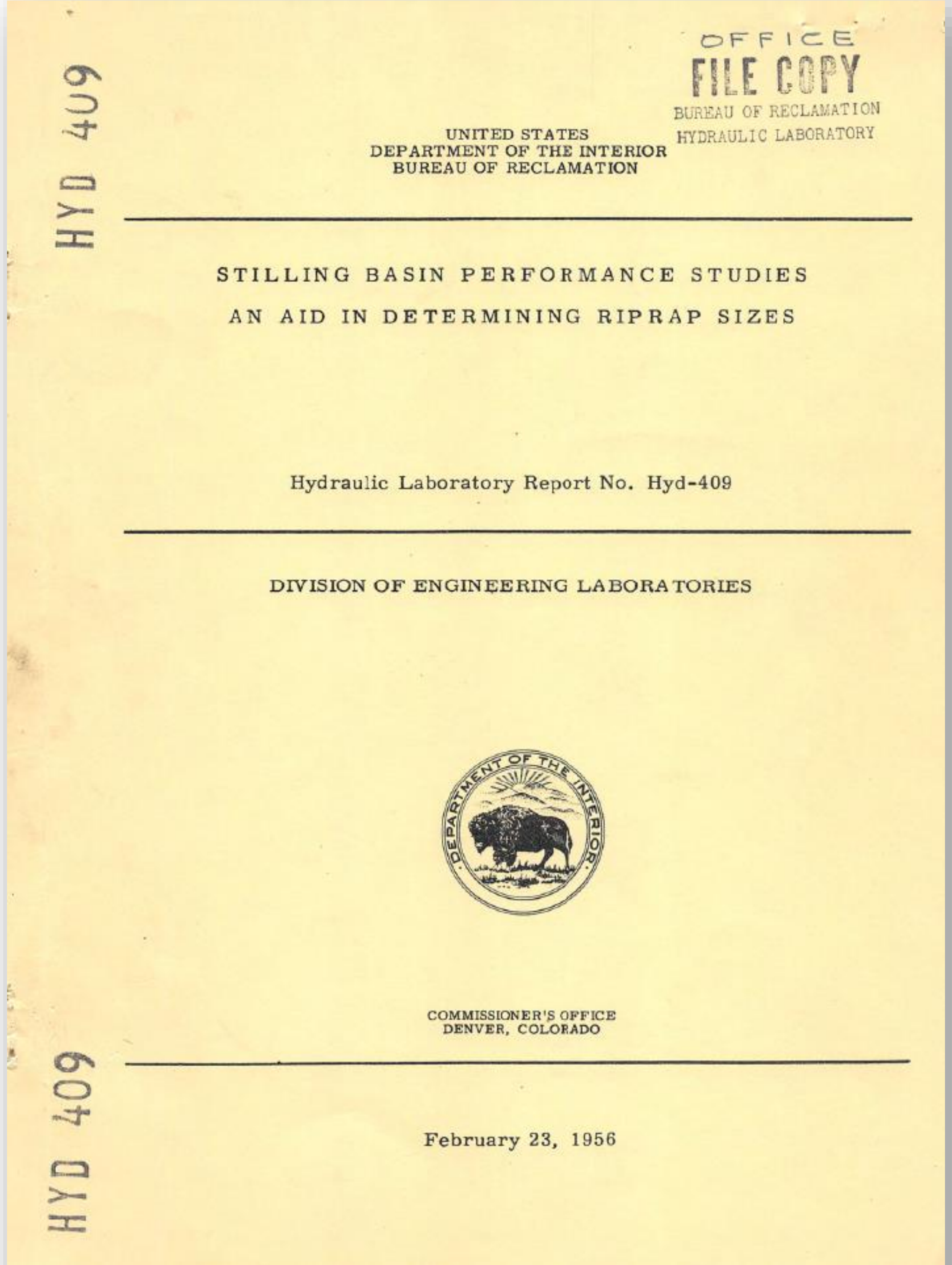
Krey Price

$$D \propto V^2 \qquad W \propto V^6$$

9. Je stärker diese Bewegung ist, je grössere Cörper können durch das Wasser gewältiget und mit fortgerissen werden. Die eigentlichen Schweren solcher Cörper verhalten sich untereinander, wie die Cubii der Höhen solcher Wasser-Säulen, oder wie die Cubic-Quadrate deren Geschwindigkeiten des bewegten Gewässers. §. 21. 116. 159. sqq.

W (Schweren) — V (Geschwindigkeiten) — 3 x 2 = 6 (Cubic-Quadrate)

Krey Price


OFFICE
FILE COPY
BUREAU OF RECLAMATION
HYDRAULIC LABORATORY

HYD 409

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

STILLING BASIN PERFORMANCE STUDIES
AN AID IN DETERMINING RIPRAP SIZES

Hydraulic Laboratory Report No. Hyd-409

DIVISION OF ENGINEERING LABORATORIES

COMMISSIONER'S OFFICE
DENVER, COLORADO

February 23, 1956

HYD 409

USBR 1956

RIPRAP SIZE DETERMINATION

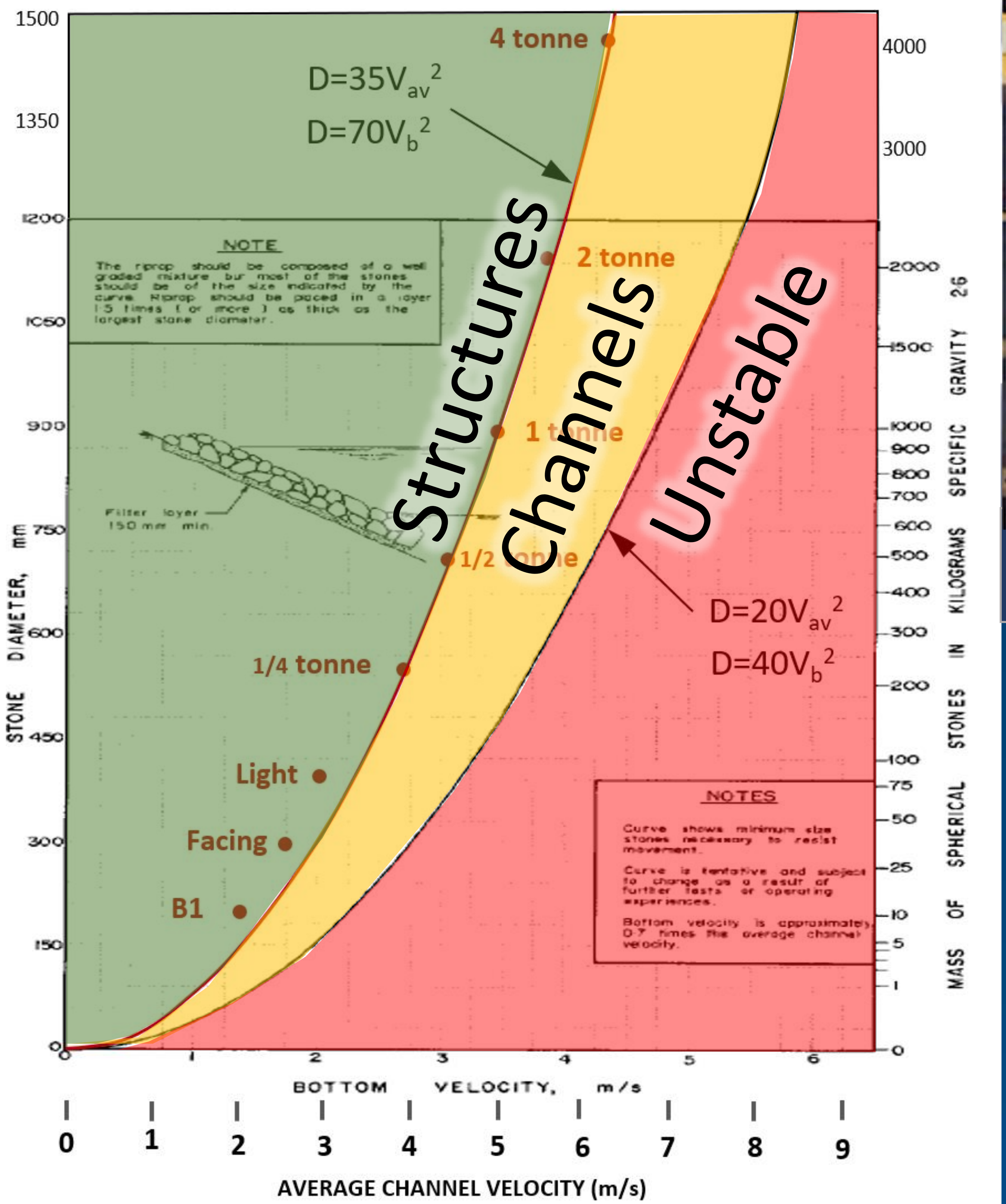
A suggested minimum size for riprap is given by the curve in Figure 11. The curve indicates, over most of its range, that doubling the flow velocity leaving a structure makes it necessary to provide riprap about 4 times larger in nominal diameter or 16 times larger in volume or weight.

Wrong by a factor of 4!

Krey Price

Recommendations

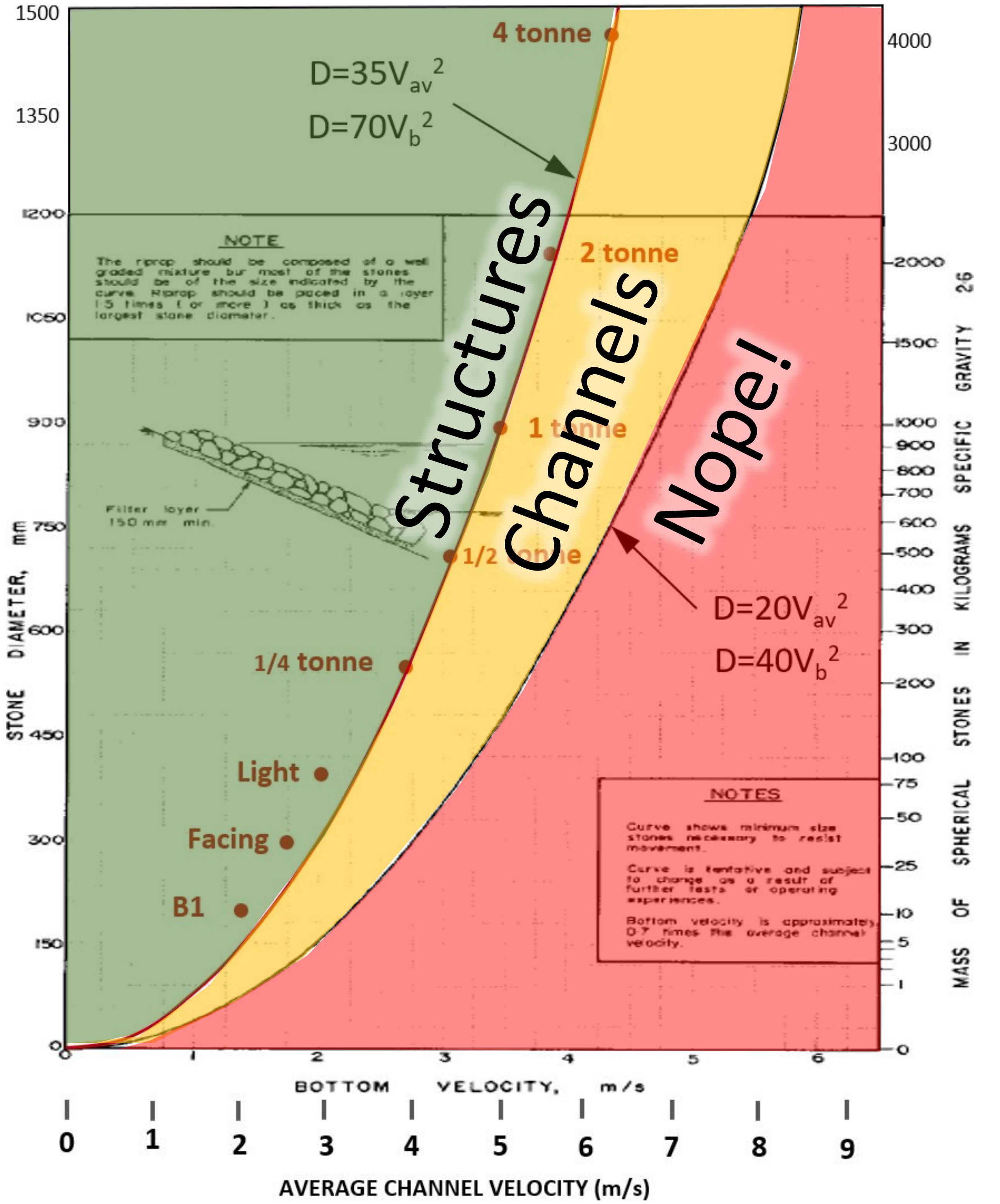
- Check stability using at least three 1D methods:
  - Velocity $D_{50}=a*V^2$
  - Shear $D_{50} = S_f * \tau$
  - Velocity & Depth $D_{30} = S_f C_s C_v C_t d \left[\left(\frac{\gamma_w}{\gamma_s - \gamma_w}\right)^{0.5} \frac{V}{\sqrt{K_1 g d}}\right]^{2.5}$
- Clarifications needed:
  - Application:
    Channels vs. Structures
  - Gradation:
    D_{10}, D_{50}, D_{90} by total weight
  - Shear and Velocity Adjustments:
    1D vs 2D vs 3D
  - How to apply the USACE method



Krey Price

Recommendations

- Gradation:
  D_{10}, D_{50}, D_{90} by total weight
- Shear and Velocity Adjustments:
  1D vs 2D vs 3D
- How to apply the USACE method



Estimating scour risks from 1D, 2D, and 3D flood model results

Krey Price
Surface Water Solutions

FMA National Conference
Toowoomba QLD
20 May 2022