AWS Free Webinar: 13 October 2021

Australian Riprap Sizing Approaches

Incorporating the USACE method

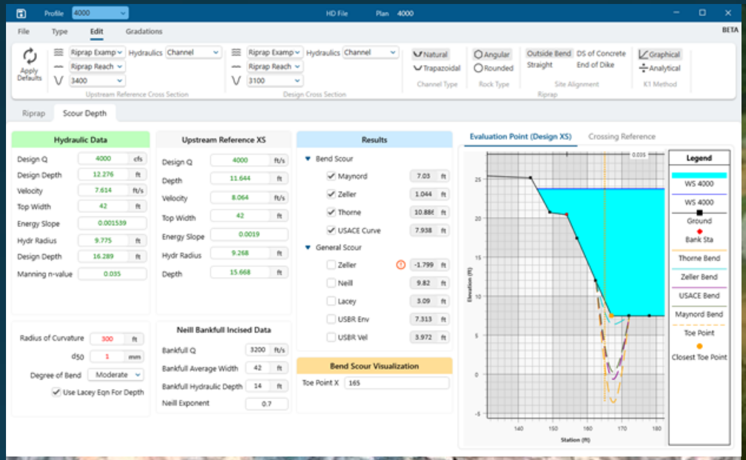
Presented by:

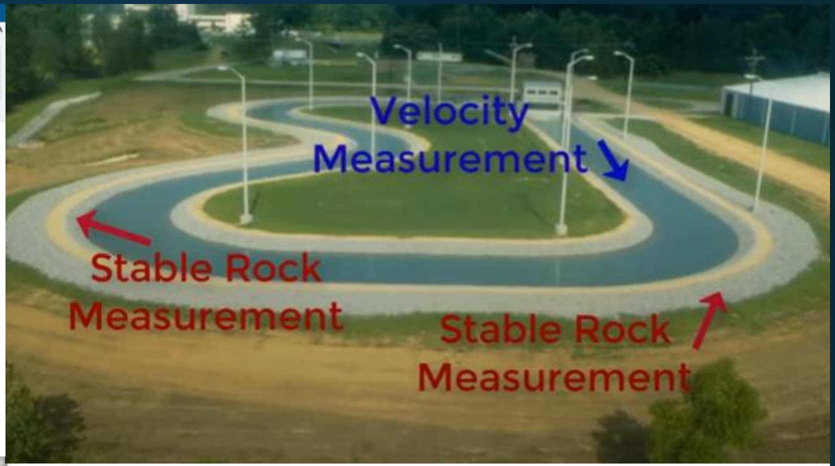
Krey Price

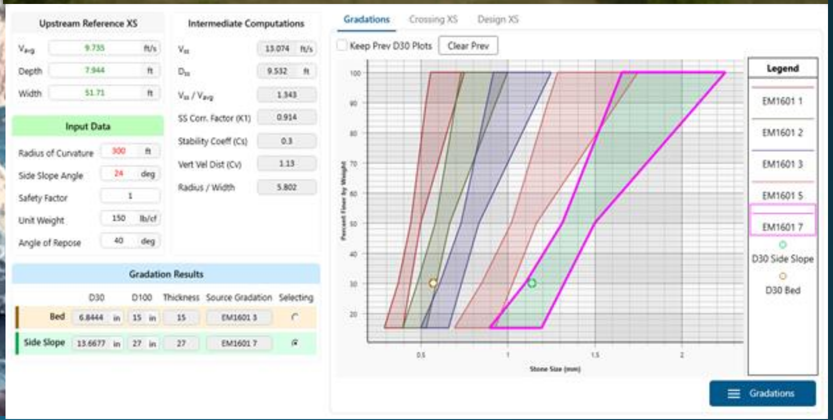
Surface Water Solutions

Stanford Gibson

USACE







Australian Water School

Rockin' it with riprap!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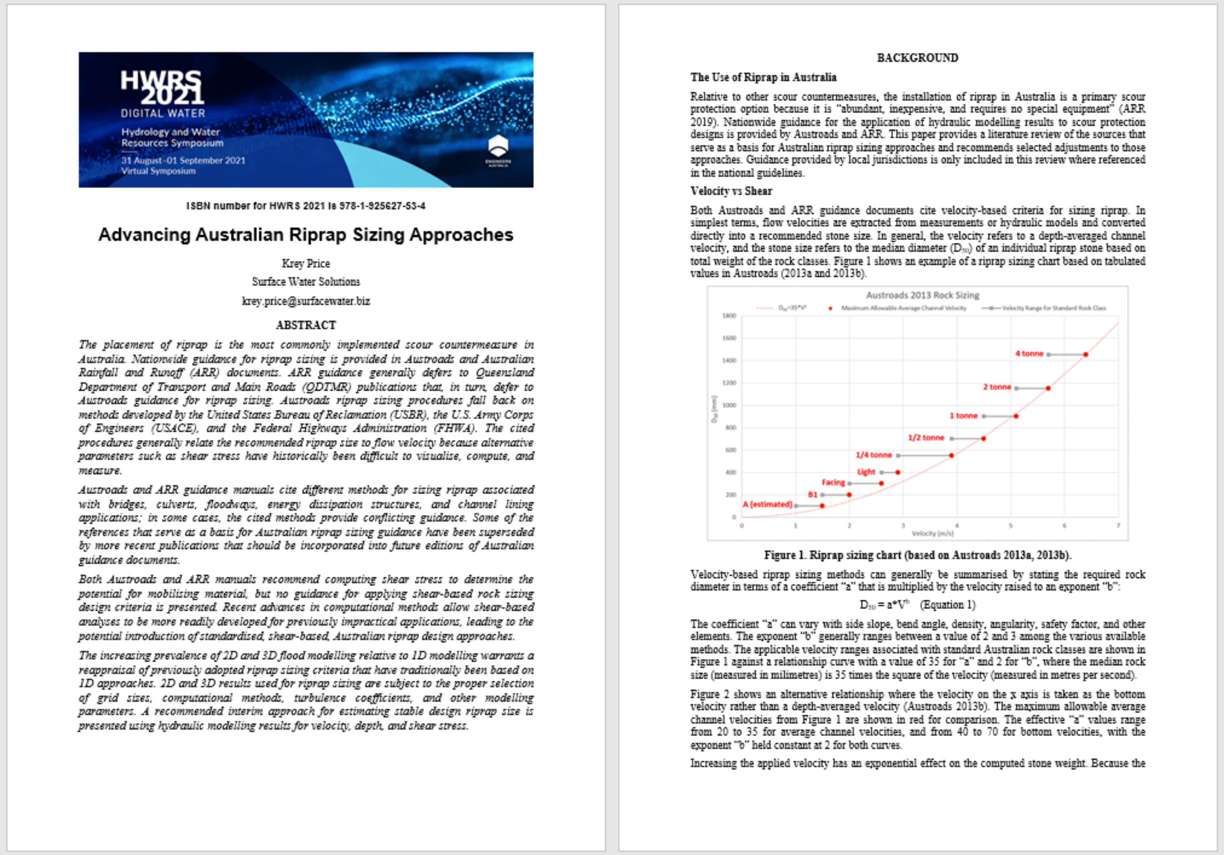
Background resources for today's webinar:

surfacewater.biz/riprap/



HWRS 2021
DIGITAL WATER
Hydrology and Water Resources Symposium
31 August -01 September 2021
Virtual Symposium

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

Advancing Australian Riprap Sizing Approaches

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Surface Water Solutions
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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).

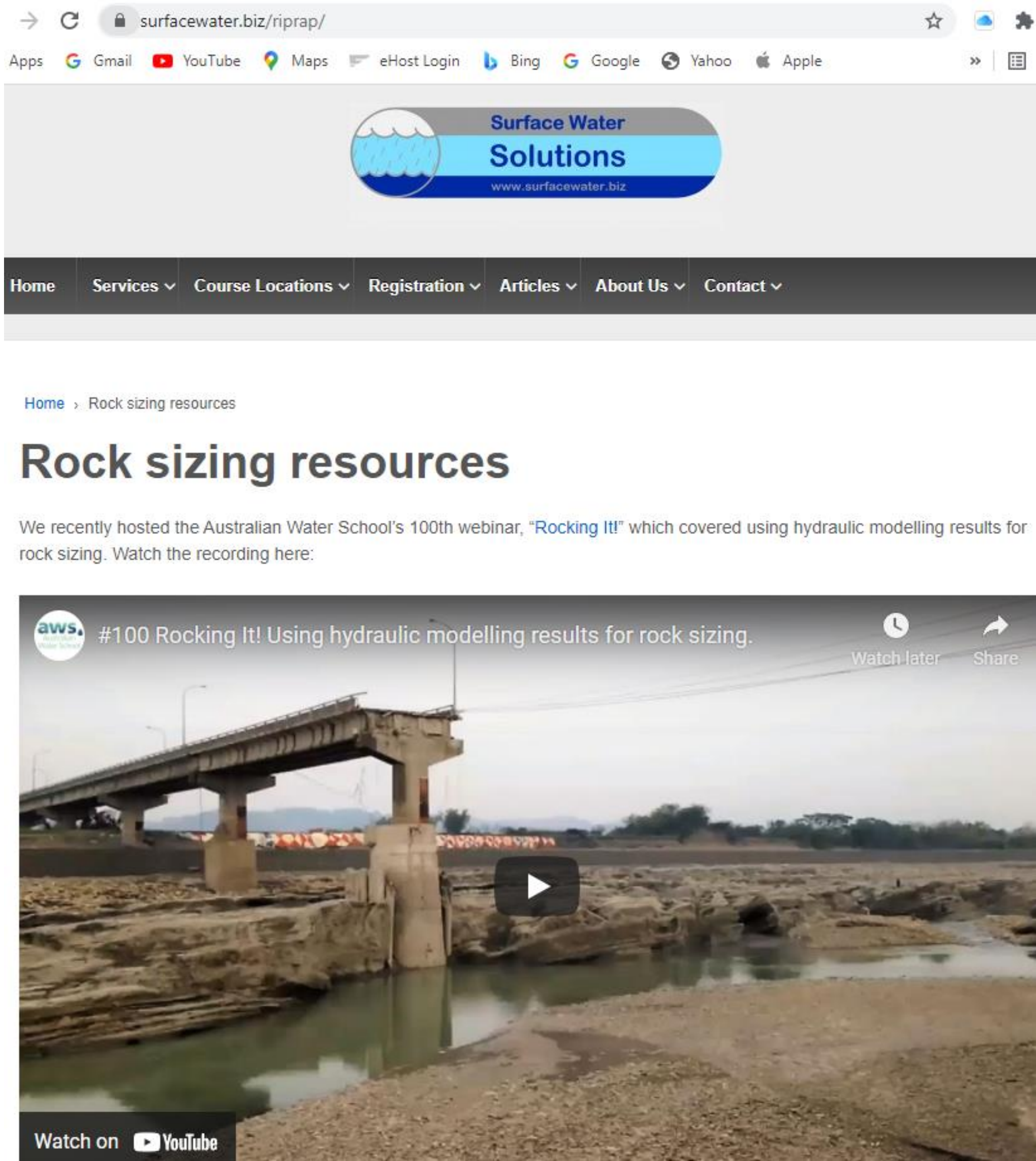
Velocity-based riprap sizing methods can generally be summarised by stating the required rock diameter in terms of a coefficient "a" that is multiplied by the velocity raised to an exponent "b":

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

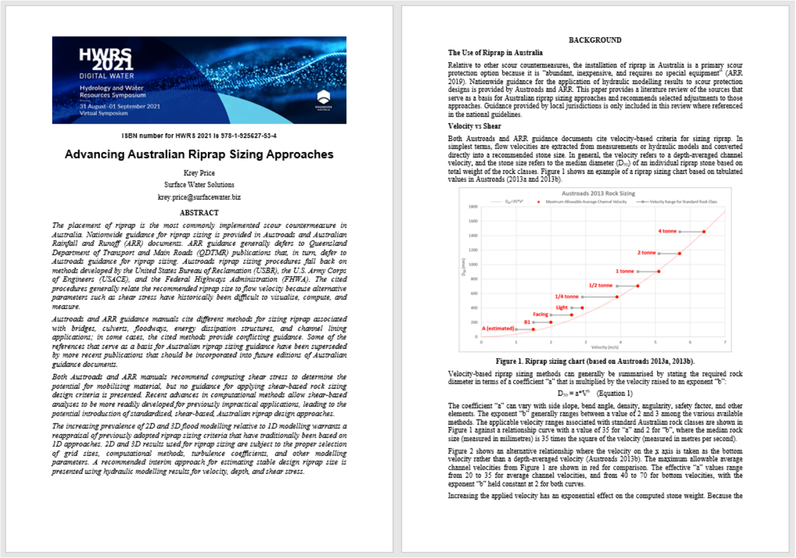
The coefficient "a" can vary with side slope, bend angle, density, angularity, safety factor, and other elements. The exponent "b" generally ranges between a value of 2 and 3 among the various available methods. The applicable velocity ranges associated with standard Australian rock classes are shown 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



- Research conducted for Rio Tinto
- Initial results published in IMWA 2020
- Expanded paper submitted to HIWE 2020
- Hydraulics session added to HWRS 2021



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Austroads 2013 Rock Sizing
$D_{50}=35*V^2$
Maximum Allowable Average Channel Velocity
Velocity Range for Standard Rock Class
4 tonne
2 tonne
1 tonne
1/2 tonne
1/4 tonne
Light
Facing
B1
A (estimated)
D_{50} (mm)
Velocity (m/s)

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":

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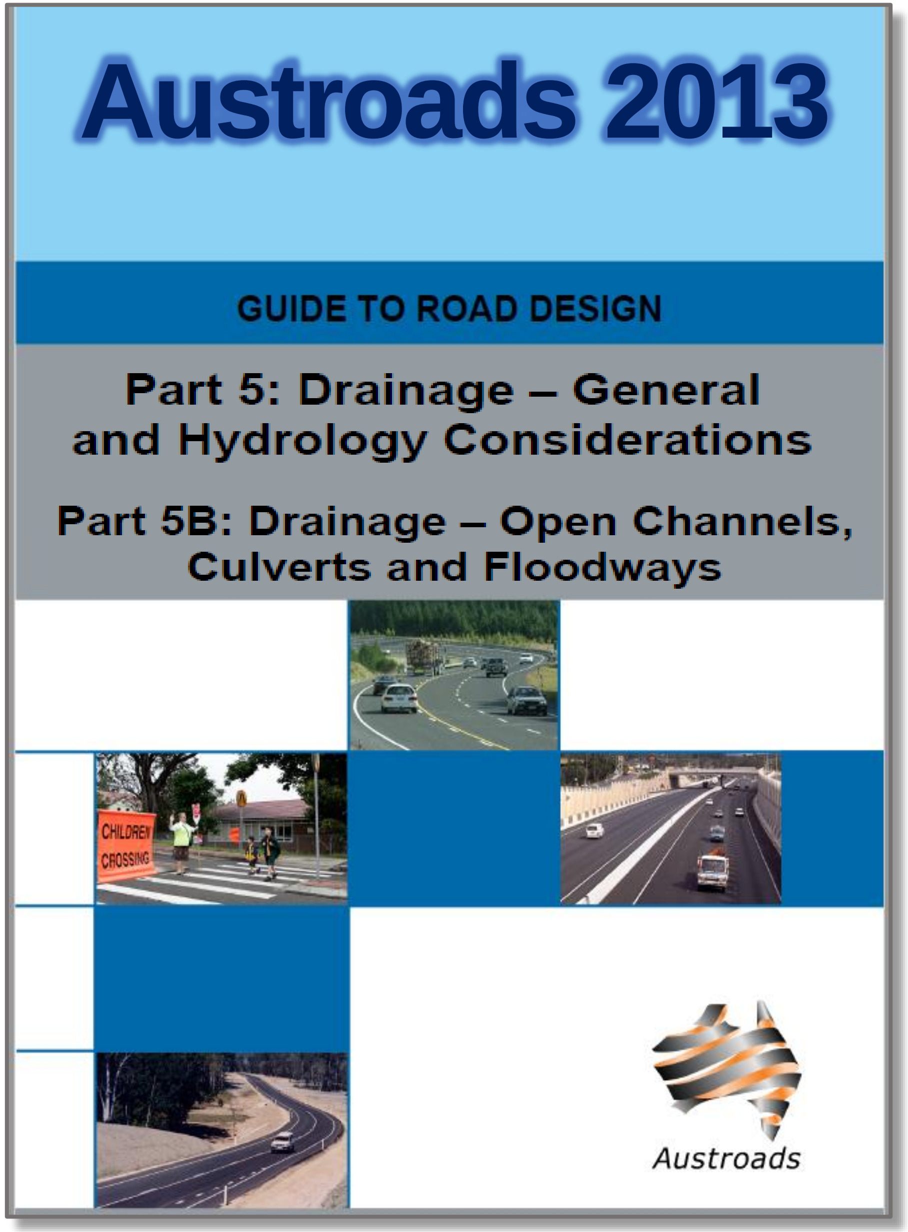
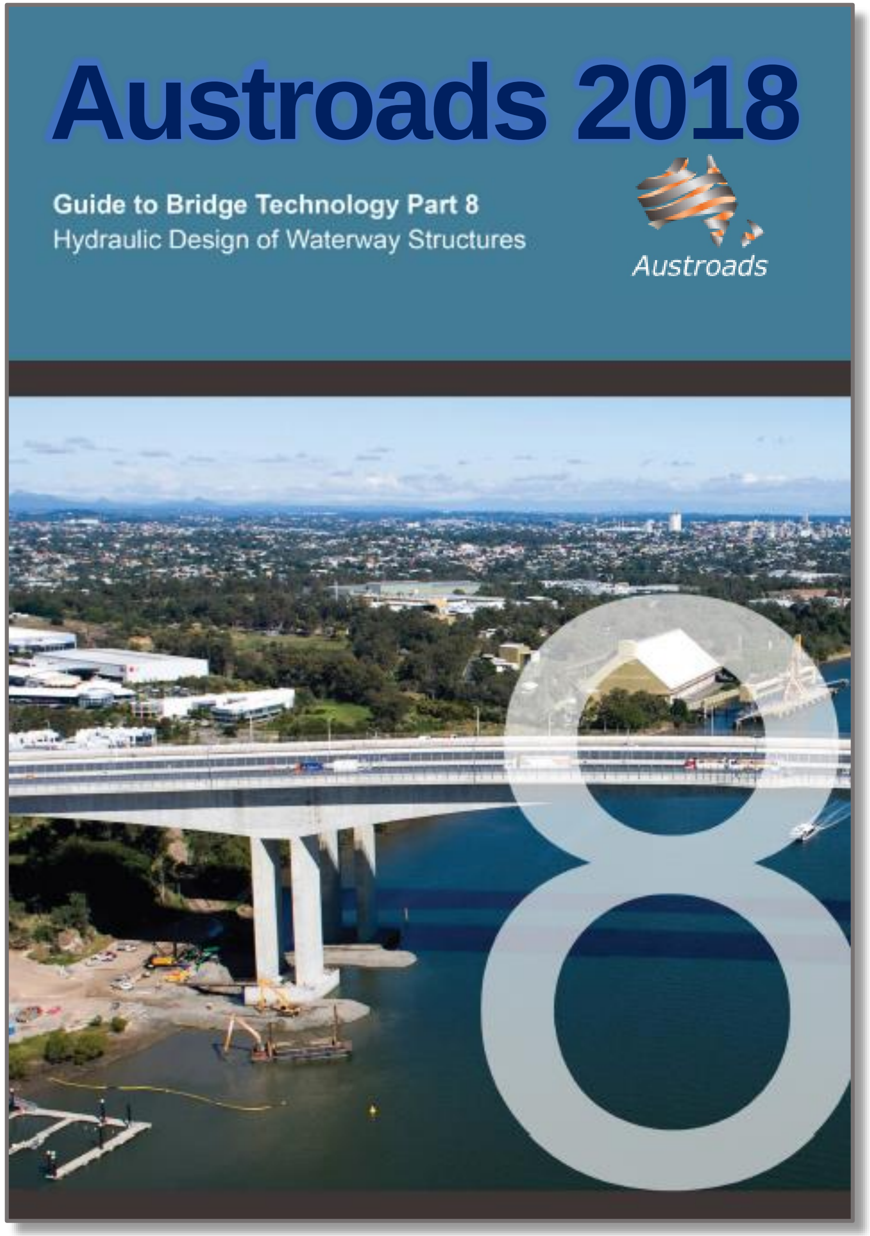
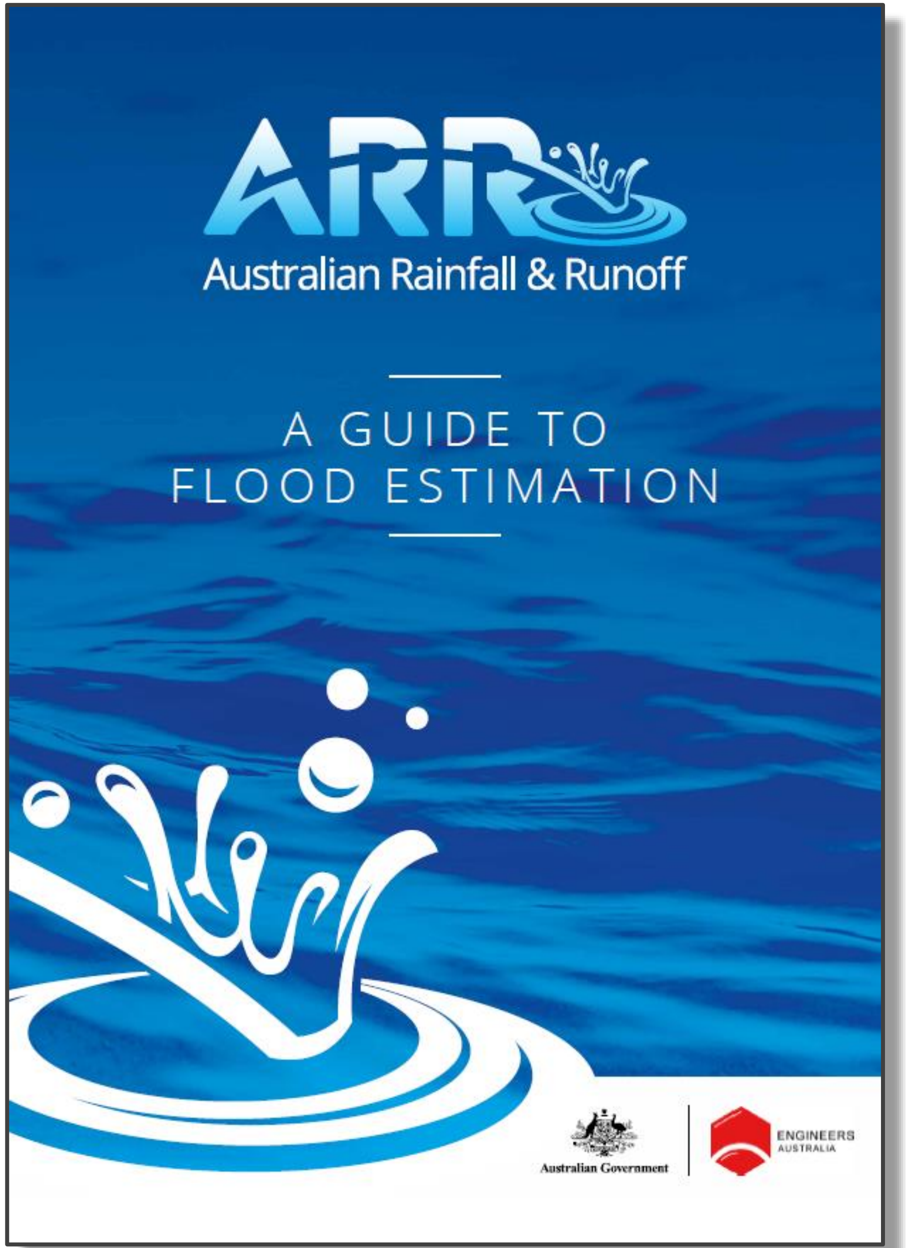
Australian national guidance for rock sizing





Australian national guidance for rock sizing



ARR 2019

Australian Rainfall and Runoff

A Guide to Flood Estimation

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Barton, ACT

ISBN 978-1-925848-36-6

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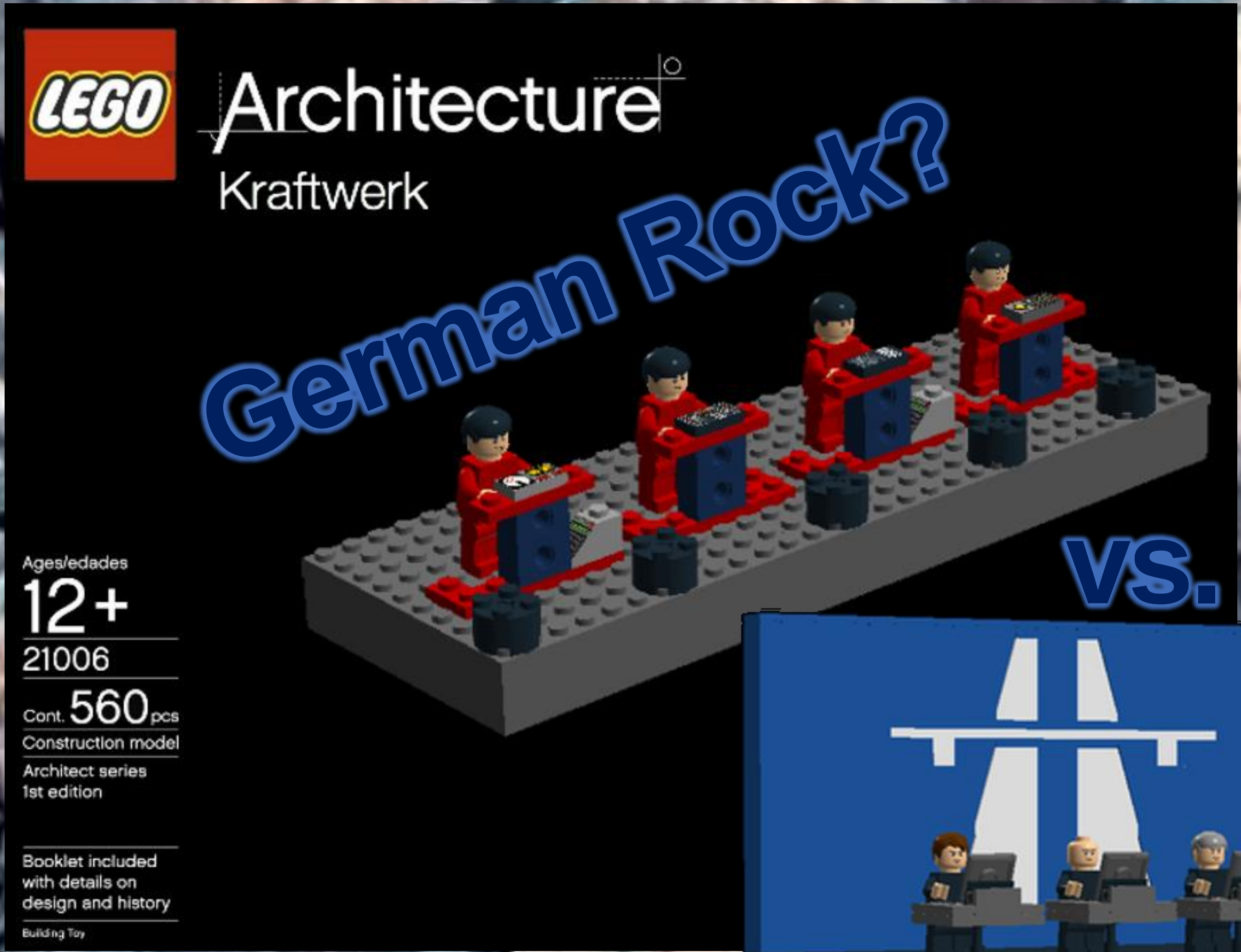
How to reference Book 9: Runoff in Urban Areas:
Coombes, P., and Roso, S. (Editors), 2019 Runoff in Urban Areas, Book 9 in Australian Rainfall and Runoff - A Guide to Flood Estimation, Commonwealth of Australia, © Commonwealth of Australia (Geoscience Australia), 2019.

Australian Rock vs. American Rock



German Rock?

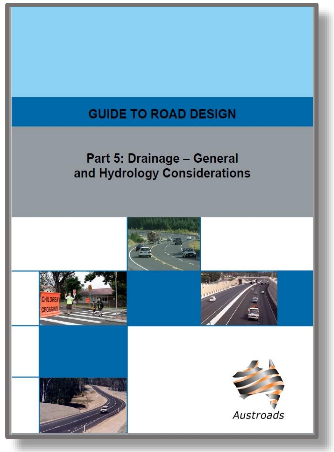
vs.

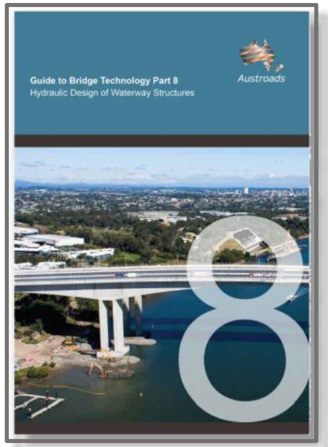
French Rock?

Australian riprap sizing ancestry

Australian riprap sizing ancestry

Rock/riprap references in Austroads

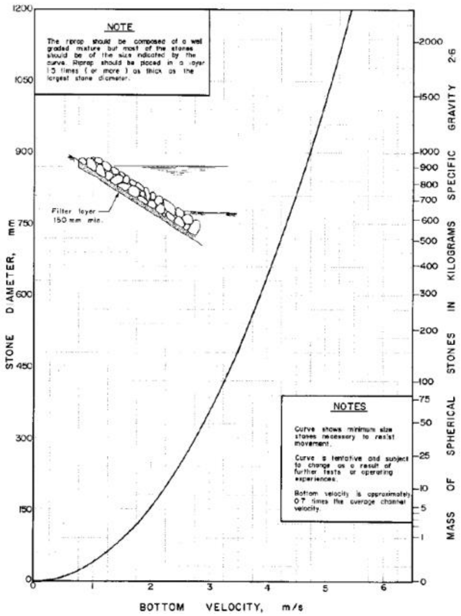




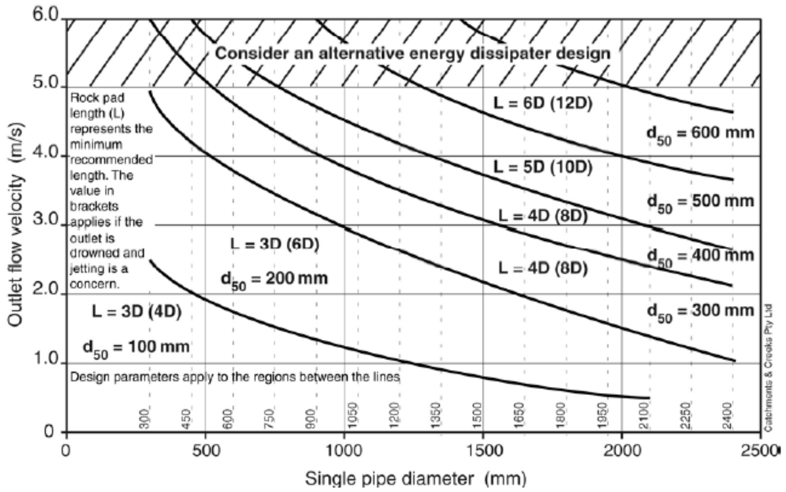
Bridges and Floodways

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



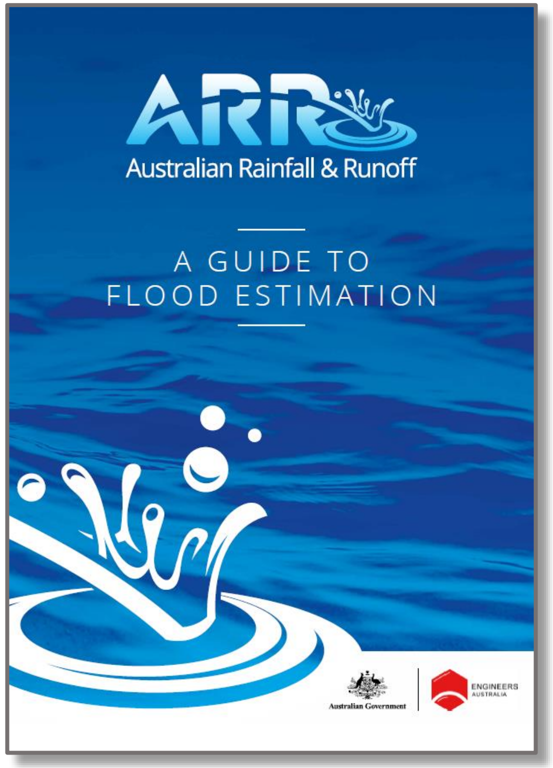
Culverts



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

Rock/riprap references in ARR



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):

- $V \le 2$ 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
- $V \ge 7$ 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).

Australian Rock Sizing Ancestry Applications:

1. Channel Bed and Bank Lining
2. Bridge Scour Countermeasures (Piers and Abutments)
3. Culvert Outlet Aprons
4. Floodways, Spillways, Rock Chutes, and Dissipation Structures

1 Australian Rock Sizing Ancestry: Channel Bed and Bank Lining

$$\tau_o = \rho g R_h S_f$$

ARR 2019

Austroads 2013

QDTMR 2019

Compute bed shear stress (uncited)[1]

QDTMR 2010

QDTMR 2015

[1] Bed shear stress is "important" for sediment motion in alluvial channels and scour at bridges

QDTMR 2002[2]

incorrect

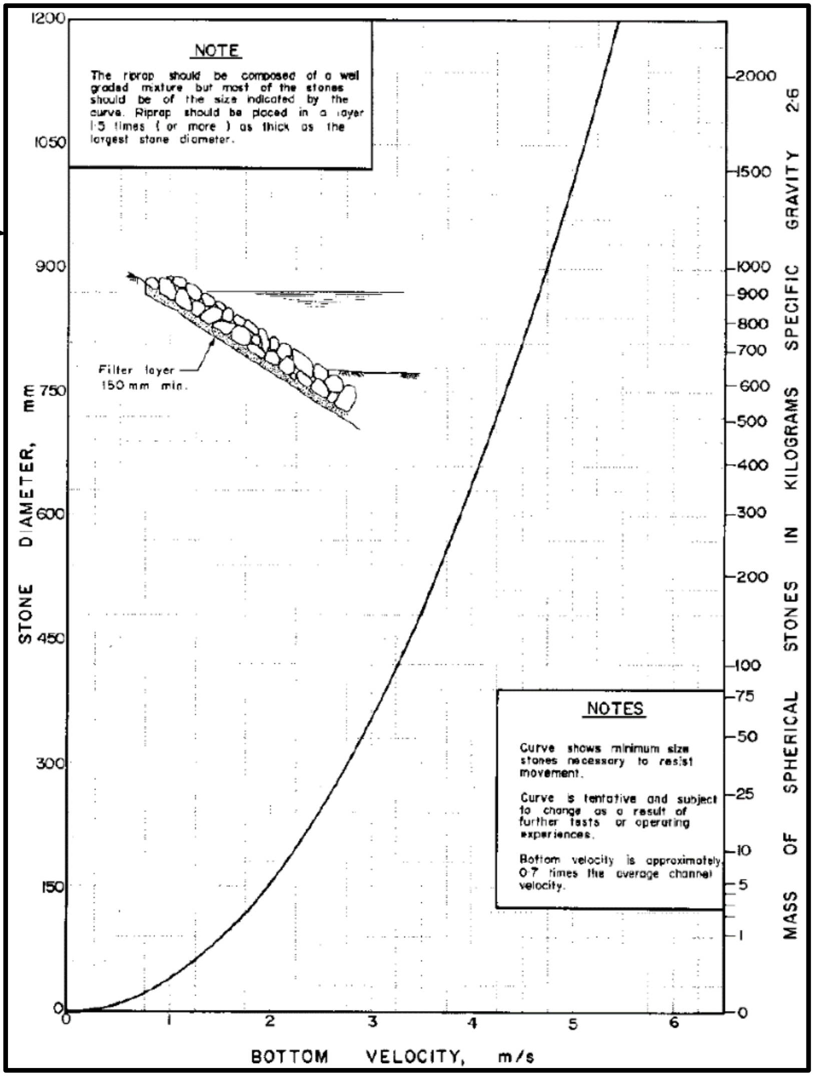
[2] Rock size should be based on channel velocity or "more accurately" to boundary shear stress

USBR 1956-1984[3]

[3] USBR charts based on "bottom velocity" but experimental validation used average channel velocities

Berry 1948[4]

[4] Berry used average of values from flume experiments conducted between 1786 and 1914



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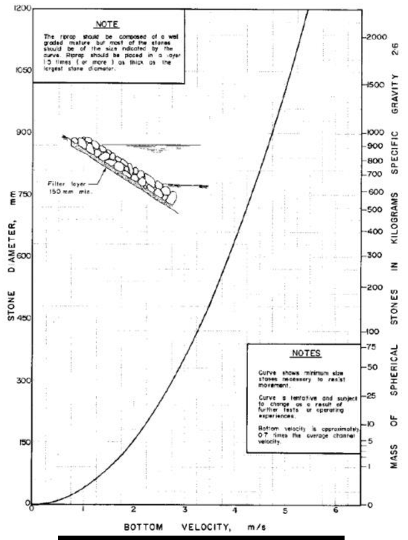

Berry 1948[4]

Gilbert 1914	Suchier 1874	Sainjon 1871
Blackwell 1857	Du Buat 1786	Bouniceau 1845

Brahms 1753

2 Australian Rock Sizing Ancestry: Bridge Scour Countermeasures (Piers and Abutments)

ARR 2019[1]

QDTMR 2019

Austroads 2019[2]

MRWA 2017

QDTMR 2013

FHWA 2009

MRWA 2006

Austroads 1994

USACE 1994[3]

Superseded!

Isbash 1936

CDPW 1960

Airy 1885[3]

[1] Use models to identify bed shear stress increase locations for scour protection (uncited)

[2] Use FHWA 2009 (HEC 23) for pier riprap sizing, MRWA 2006 and HEC 23 for abutment riprap sizing

[3] Maynord cites Bogardi 1968, Neill 1967, and Straub 1953. Caltrans 2020 dismisses CDPW 1960 in favour of USACE 1994

[4] "Airy's Law" as cited by Isbash was a response to Shelford 1885, same as developed by Brahms 1753 but not cited

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
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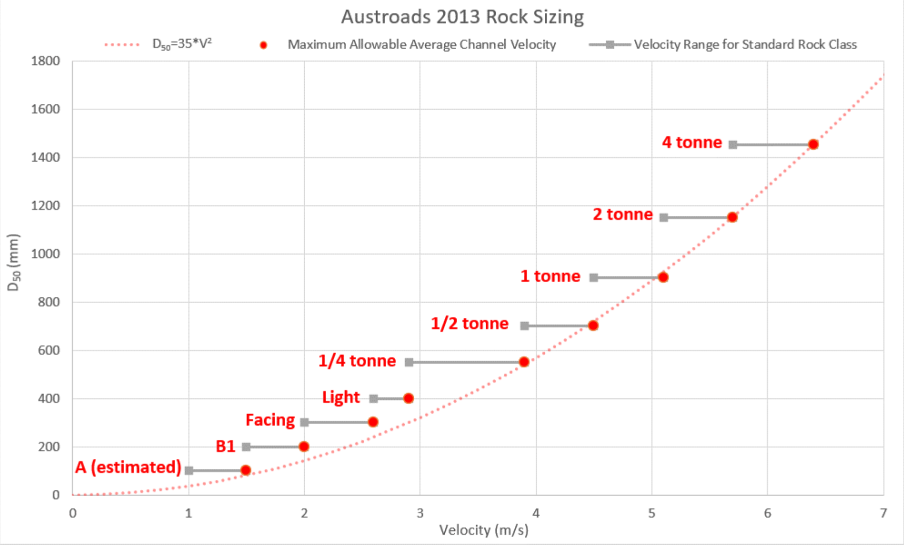


3 Australian Rock Sizing Ancestry: Culvert Outlet Aprons

ARR 2019[1,2]

Austroads 2013[1,3,4]

C&C 2017[6]

PCA 1964

Alderson 2006[5]

QDTMR 2010

VicRoads 2003

MRWA 2006

C&C 2011[7]

Neill 1973

USACE 1994[8]

Superseded!

Austroads 1994

ASCE 1992

CDPW 1960

OC 1989

Isbash 1936

Bohan 1970

Airy 1885

[1] Only use riprap or concrete apron for Fr<1.7 (ARR and Austroads) and V<5m/s (ARR only)

[2] Use PCA for erosive velocity limits of natural soils: "treat with caution"

[3] Use QDTMR 2010 and VicRoads 2003 for maximum velocity in "unprotected stream beds" only

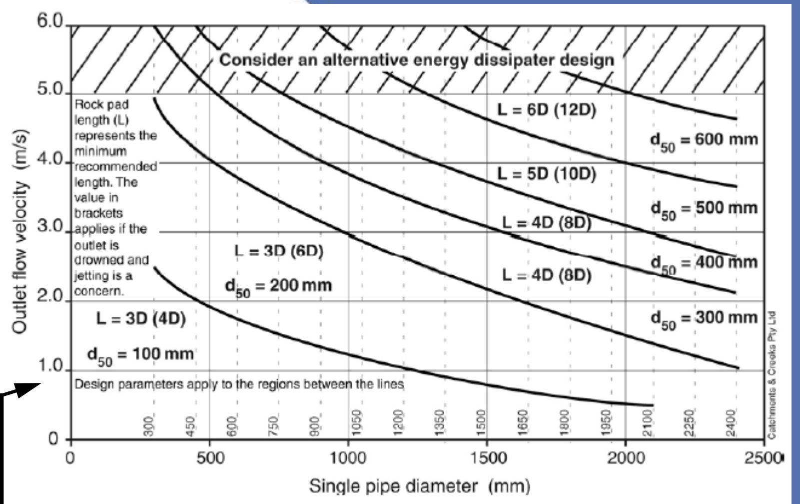
[4] Use MRWA 2006 for gradation, "refer to relevant jurisdiction" for rock size

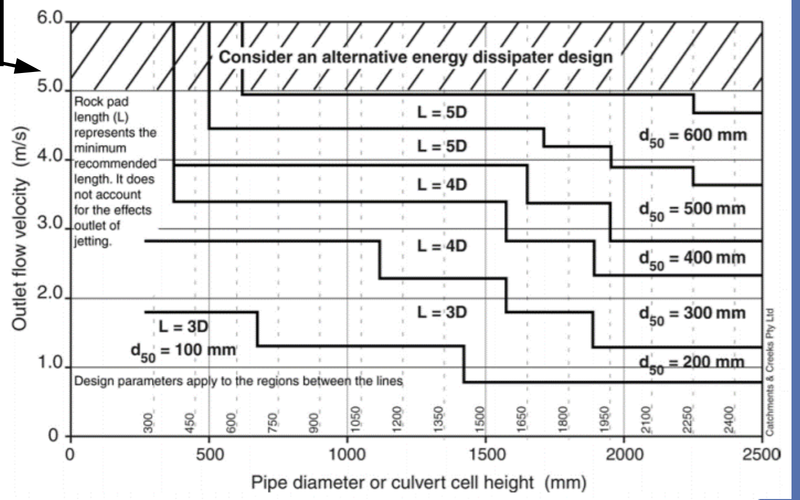
[5] Compute d_{50} from Q, S_0, R, P based on Alderson 2006, but standard MRWA 2006 rock classes recommended as "more accurate method"

[6] Maximum Isbash D_{50} sizing "arbitrarily limited" to culvert diameter

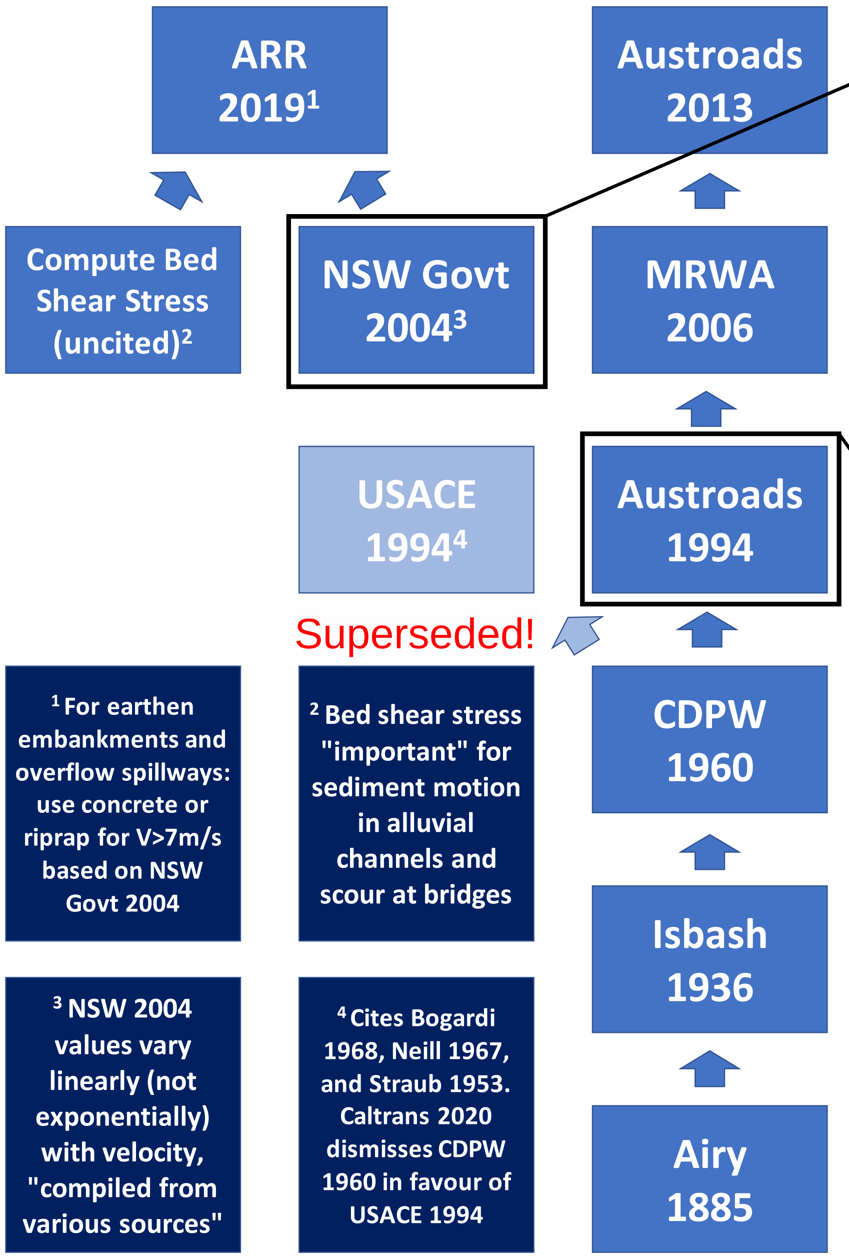
[7] Average of Bohan 1970, OC 1989, and ASCE 1992 for single culverts, Isbash and "complex derivation" for multi-pipe

[8] Cites Bogardi 1968, Neill 1967, and Straub 1953. Caltrans 2020 dismisses CDPW 1960 in favour of USACE 1994





4 Australian Rock Sizing Ancestry: Floodways, Spillways, Rock Chutes, and Dissipation Structures



Material			Critical velocity (m/second)	
Type	Thickness (m)	Aggregate size (mm)		
Gabions and reno mattresses	0.50	120-250	6.4	
	0.50	100-200	5.8	
	0.30	100-150	5.0	
	0.30	70-120	4.2	
	0.25	70-100	3.6	
	0.17	70-100	3.5	
	Weight each (kg)		Turbulent flow	Normal flow
Loose rock (assume 100 percent soil cover)	1,000		4.8	6.6
	500		4.2	5.7
	100		3.3	4.5
	50		2.8	3.8
	10		2.3	3.0

Velocity (m/s)	Class of rock protection (tonne)	Section thickness, *T* (m)
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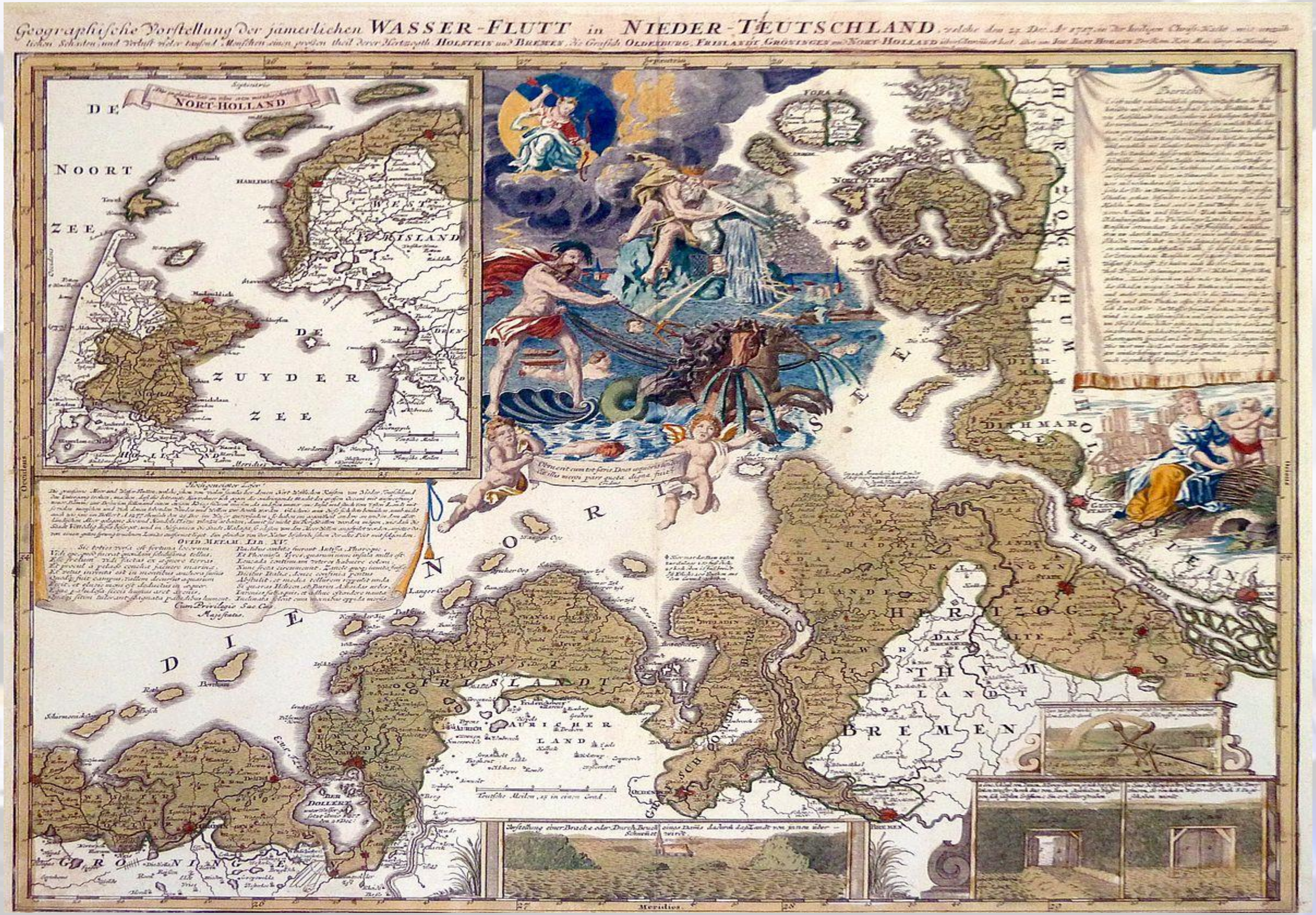
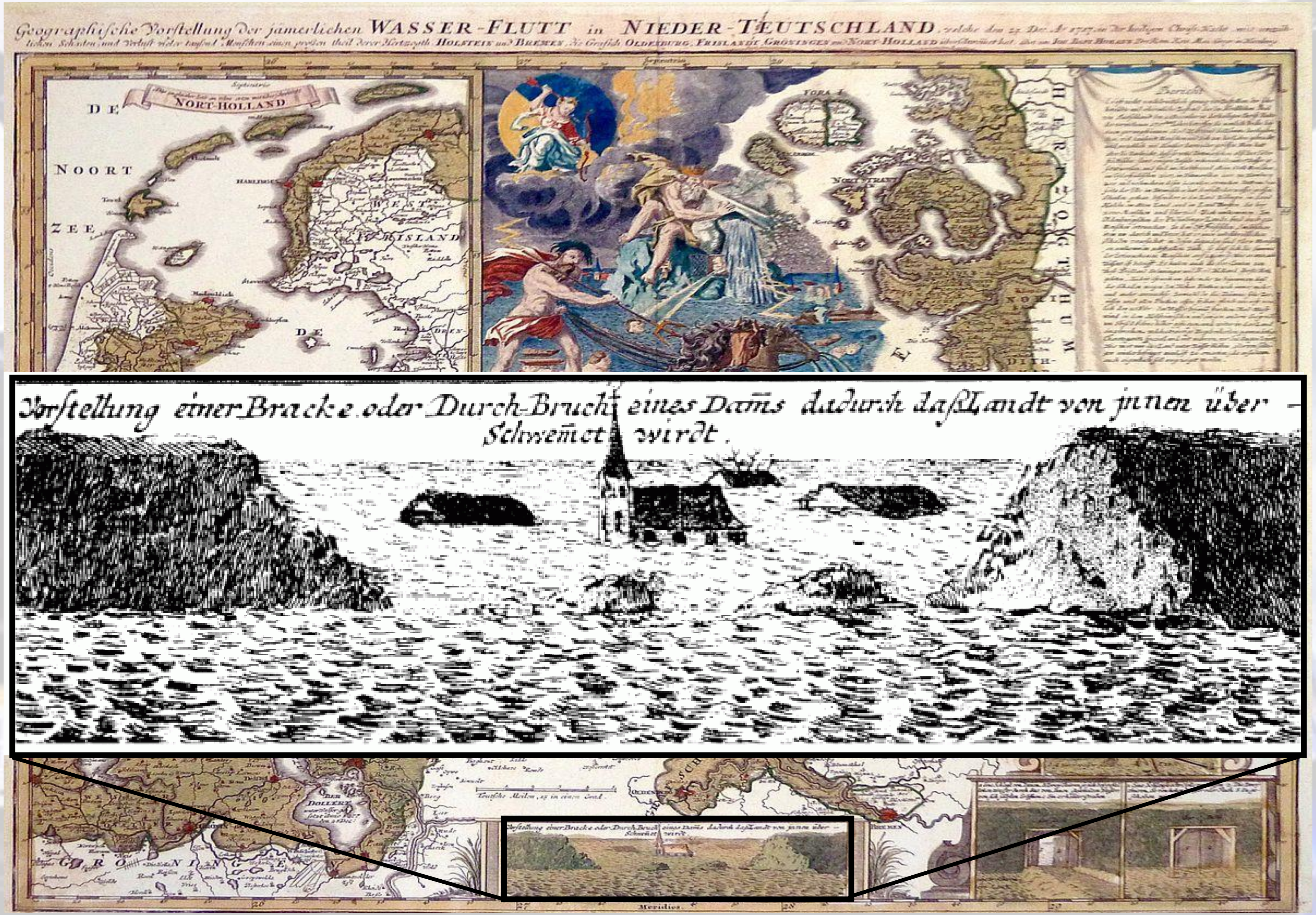
BACKINTIME

Christmas 1717



Christmas 1717



Christmas 1717

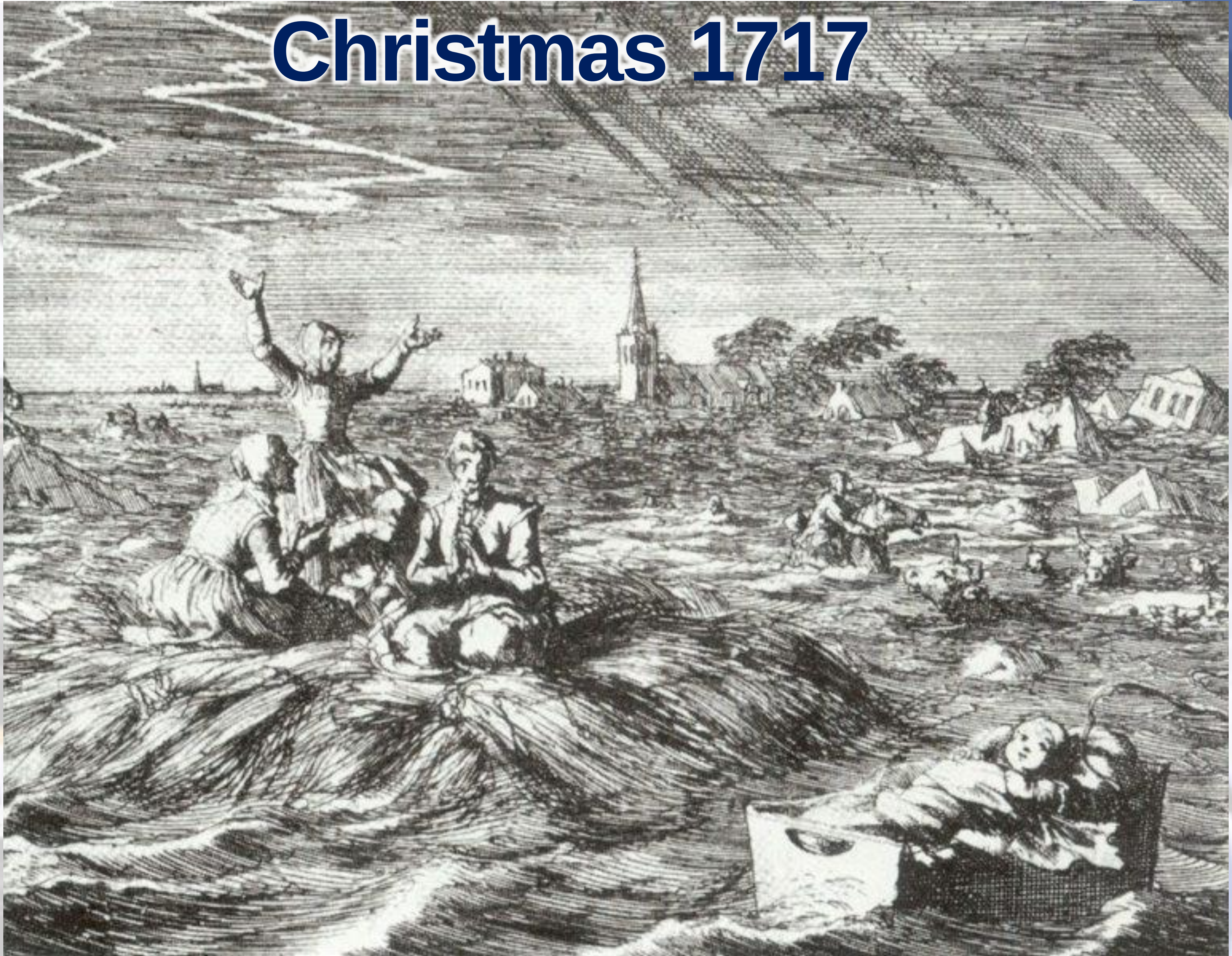
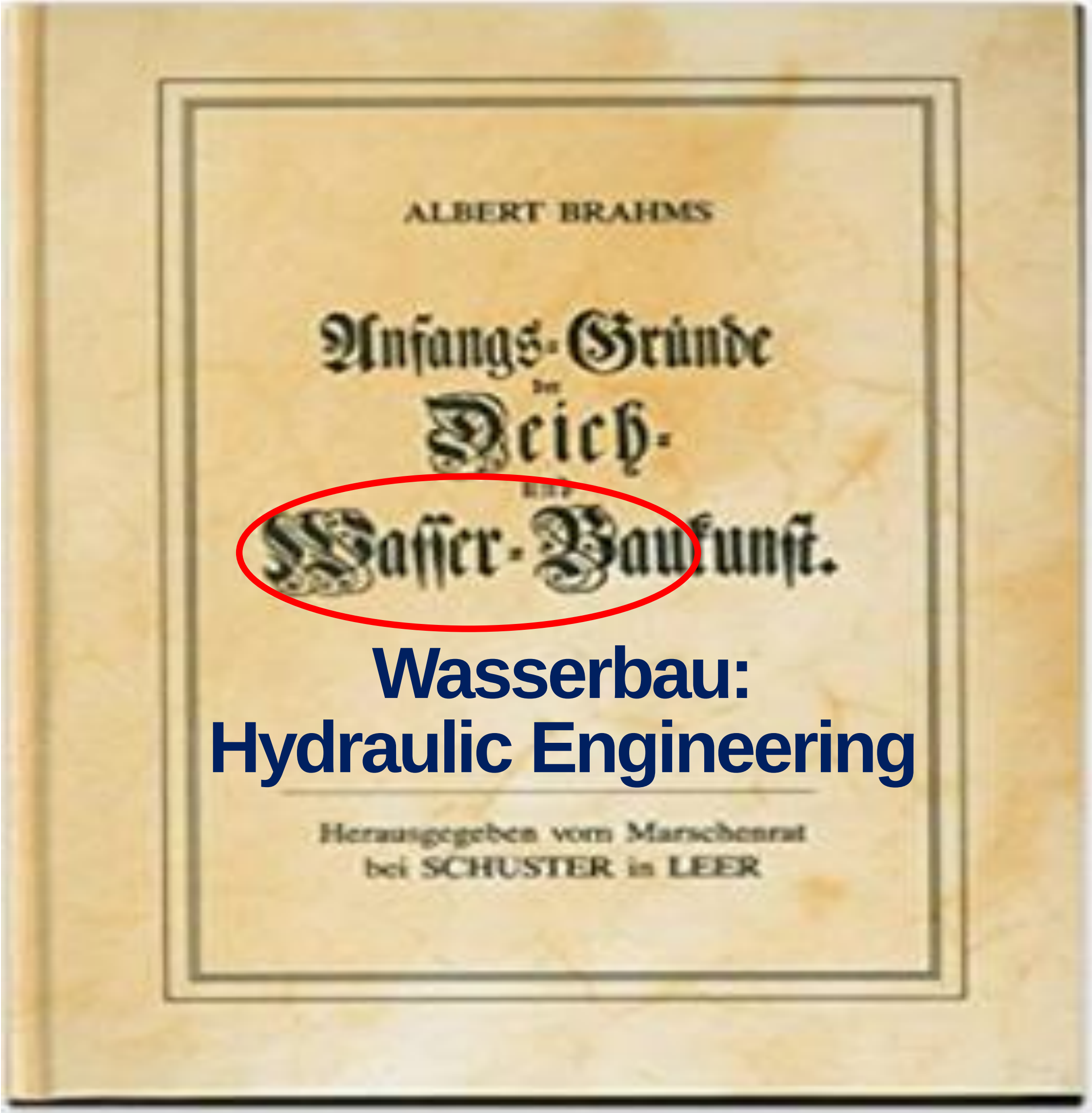



Abbildung der fast übernatürlich-hohen Wasser-
flut am H. Christ-Tag 1717 und am 25.
Hornung 1718.



Wasserbau:
Hydraulic Engineering

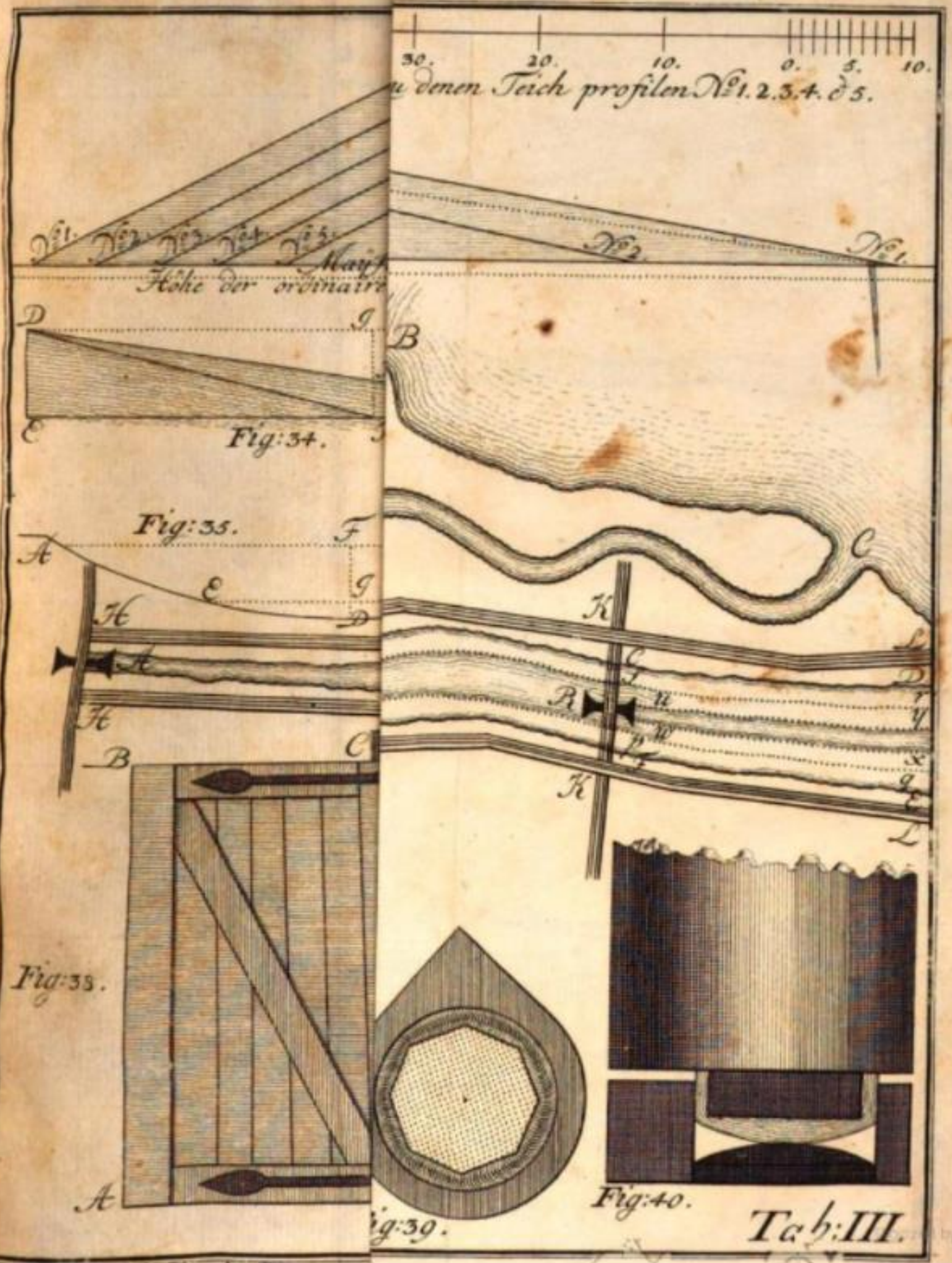
Anfangs-Gründe
der
Deich-
und
Wasser-Baukunst,
oder
Gründliche Anweisung, wie man tüchtige haltbare Dämme wider die Gewalt der grössesten See-Fluthen bauen, auch dieselbe jederzeit im unvergeringerten Zustande erhalten könne, damit das Land für verderblichen Einbrüchen und Ueberschwemmungen verwahret sey;
und was mehr bey
Anlegung der Schleusen, Schlengen, Holzungen, Canäle und andern Wasser-Werken zu wissen nöthig und nützlich damit alles wohl besorget, und zugleich unnöthige Kosten vermieden werden, nebst dazu gehörigen Berechnungen und Kupfern erläutert.
Dem gemeinen Wesen zu Dienste, und weiterer Verbesserung dieser so sehr nutzbaren Wissenschaft entworfen und ans Licht gegeben von
Albert Brahms.

Aurich, gedruckt, verlegt und zu finden bey Hermann Tapper, Königlich-Preussischen Ostfriesischen privilegirtem Buchdrucker.


ALBERT BRAHMS
Anfangs-Gründe der Deich- und Wasser-Baukunst.
Herausgegeben vom Marschenrat
bei SCHUSTER in LEER

Kunst = “art”


Anfangs-Gründe der Deich- und Wasser-Baukunst,
oder
Gründliche Anweisung, wie man tüchtige haltbare Dämme wider die Gewalt der grössesten See-Fluthen bauen, auch dieselbe jederzeit im unvergeringerten Zustande erhalten könne, damit das Land für verderblichen Einbrüchen und Ueberschwemmungen verwahret sey;
und was mehr bey
Anlegung der Schleusen, Schlengen, Holzungen, Canäle und andern Wasser-Werken zu wissen nöthig und nützlich damit alles wohl besorget, und zugleich unnöthige Kosten vermieden werden, nebst dazu gehörigen Berechnungen und Kupfern erläutert.
Dem gemeinen Wesen zu Dienste, und weiterer Verbesserung dieser so sehr nutzbaren Wissenschaft entworfen und ans Licht gegeben von
Albert Brahms.
Aurich, gedruckt, verlegt und zu finden bey Hermann Tapper, Königlich-Preussischen Ostfriesischen privilegirtem Buchdrucker.



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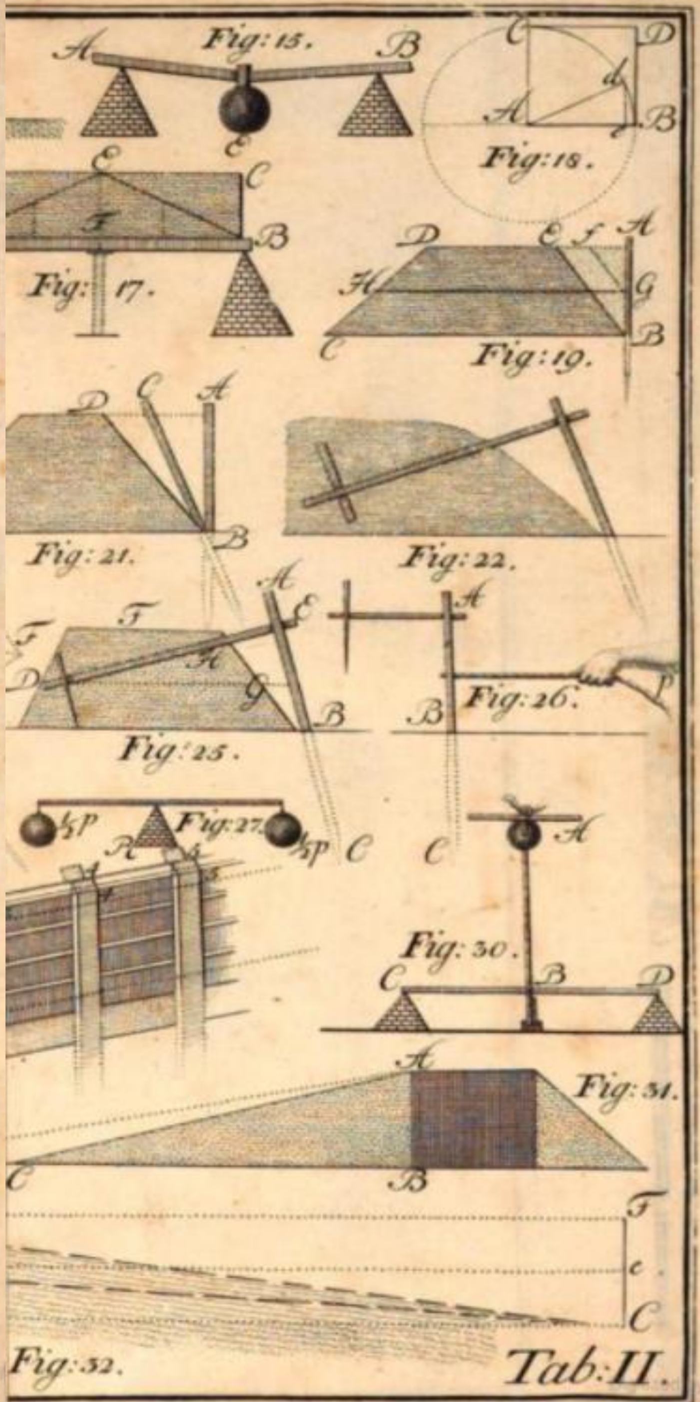

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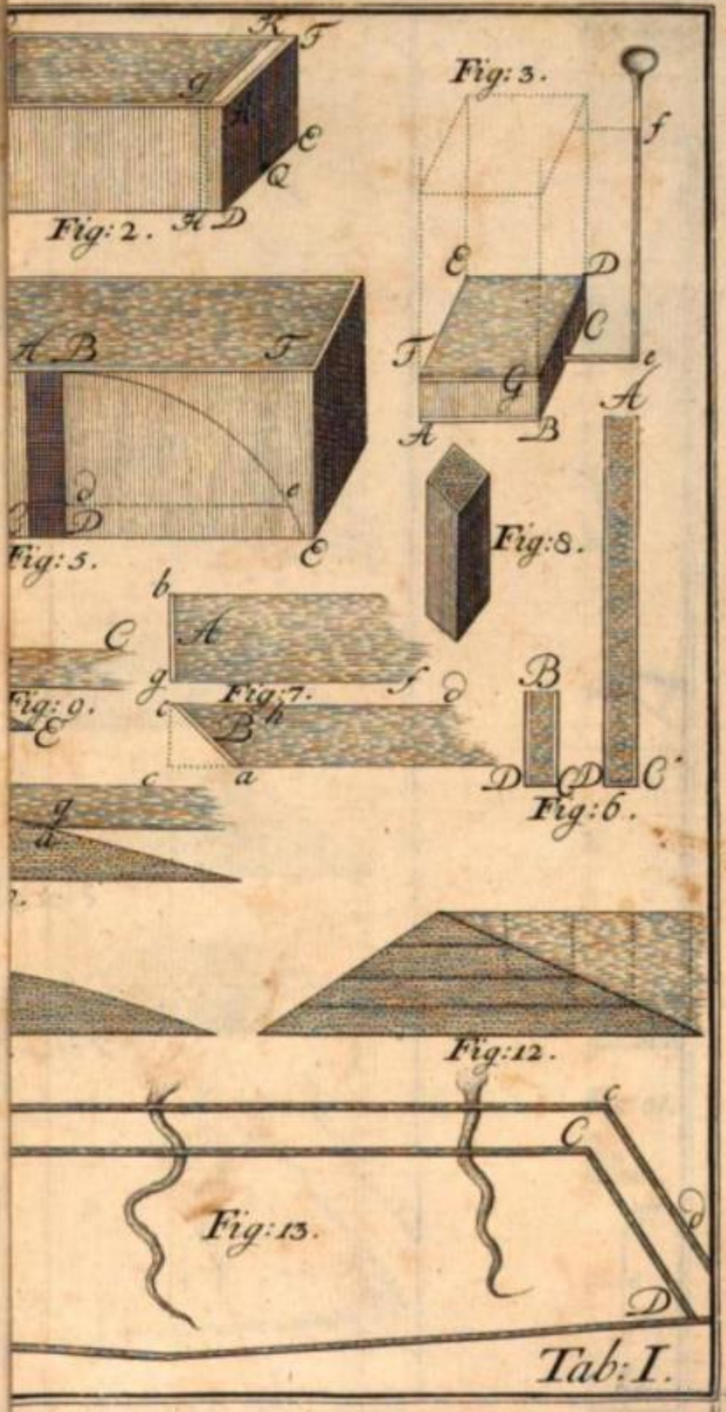


Tab:I.

das Quadrat der Geschwindigkeiten, womit diese Kugeln in Bewegung gesetzet werden können, die Höhe derjenigen Säulen gleich seyn müssen, die derselben das Gleich-Gewicht machen, mithin erhellet die Wahrheit des obigen Satzes, daß die Grössen der Cörper von einerley Materie und Form, die durch ein in Bewegung gesetztes Gewässer hinweggerissen und fortgeführet werden, sich untereinander verhalten, oder verhalten können, wie die Cubi Quadrate der Geschwindigkeiten des bewegten Gewässers, oder wie die Cubi der Höhen derjenigen Wasser-Säulen, woraus diese Geschwindigkeiten erzeuget werden, klärlich. Alle Wirkungen und Gefolgen, so sich aus diesem wichtigen Satz gründlich erklären und herleiten lassen, an- oder auszuführen, leidet Zeit und Raum alhier nicht, alle Veränderungen, so durch die Bewegung des Gewässers, es seyn Abbrüche und Vertieffungen der Gründe, Anwächse, und Zuschlickungen, oder was es sonst mehr seyn mögte, verursachet werden, lassen sich sehr leicht daraus finden.

W

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.

3 x 2 = 6

V

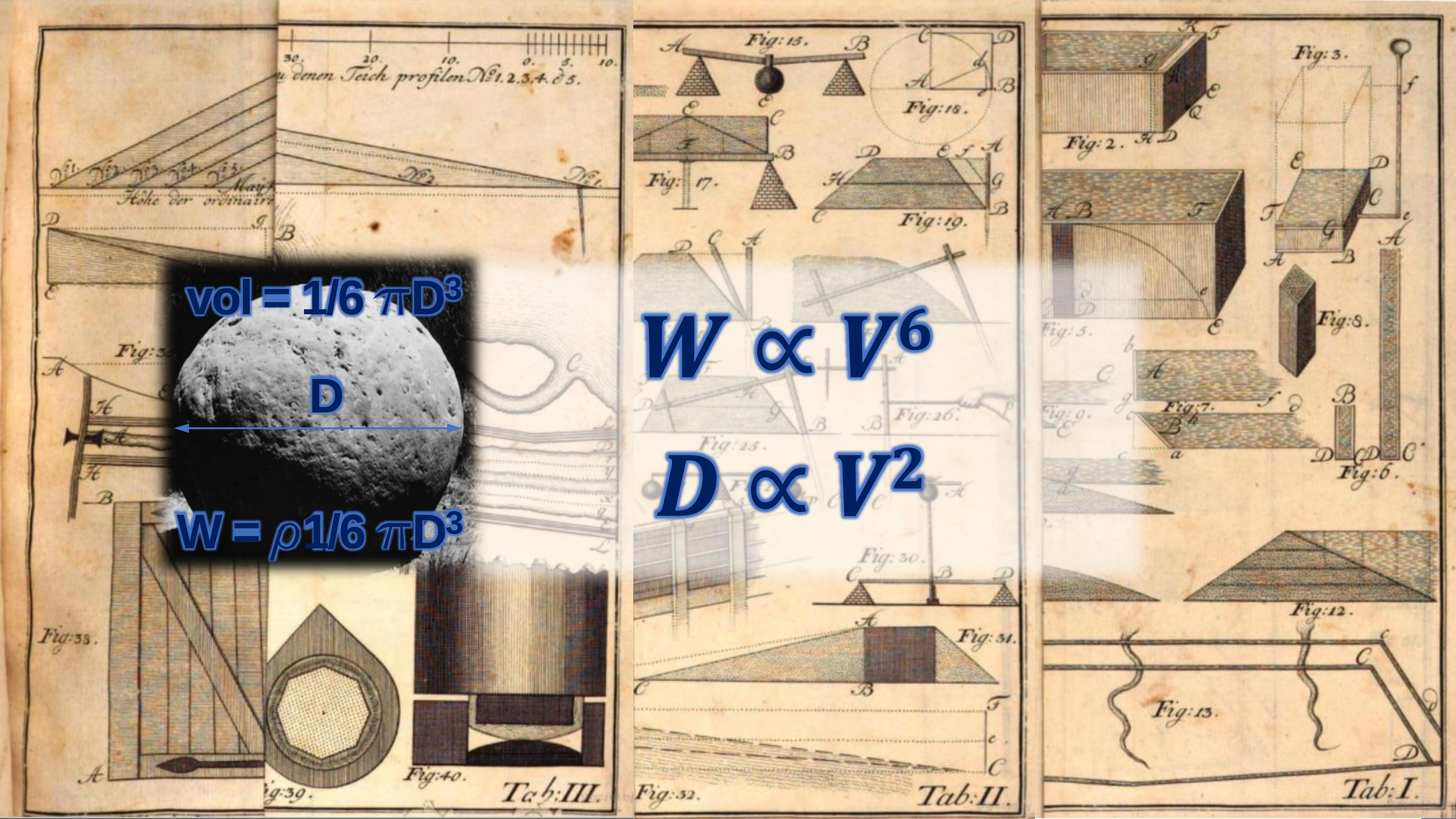
das Quadrat der Geschwindigkeiten, womit diese Kugeln in Bewegung gesetzet werden können, die Höhe derjenigen Säulen gleich seyn müssen, die derselben das Gleich-Gewicht machen, mithin erhellet die Wahrheit des obigen Satzes, daß die Grössen der Cörper von einerley Materie und Form, die durch ein in Bewegung gesetztes Gewässer hinweggerissen und fortgeführet werden, sich untereinander verhalten, oder verhalten können, wie die Cubi Quadrate der Geschwindigkeiten des bewegten Gewässers, oder wie die Cubi der Höhen derjenigen Wasser-Säulen, woraus diese Geschwindigkeiten erzeuget werden, klärlich. Alle Wirkungen und Gefolgen, so sich aus diesem wichtigen Satz gründlich erklären und herleiten lassen, an- oder auszuführen, leidet Zeit und Raum alhier nicht, alle Veränderungen, so durch die Bewegung des Gewässers, es seyn Abbrüche und Vertieffungen der Gründe, Anwächse, und Zuschlickungen, oder was es sonst mehr seyn mögte, verursachet werden, lassen sich sehr leicht daraus finden.

$\propto$ W

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.

$3 \times 2 = 6$

V



vol = 1/6 πD³
D
W = ρ1/6 πD³
W ∝ V⁶
D ∝ V²
zu denen Teich profilen No.1.2.3.4. & 5.
Höhe der ordinaire
Fig:15.
Fig:17.
Fig:18.
Fig:19.
Fig:25.
Fig:26.
Fig:30.
Fig:31.
Fig:32.
Fig:38.
Fig:39.
Fig:40.
Fig:2.
Fig:3.
Fig:5.
Fig:6.
Fig:7.
Fig:8.
Fig:9.
Fig:12.
Fig:13.
Tab:III.
Tab:II.
Tab:I.

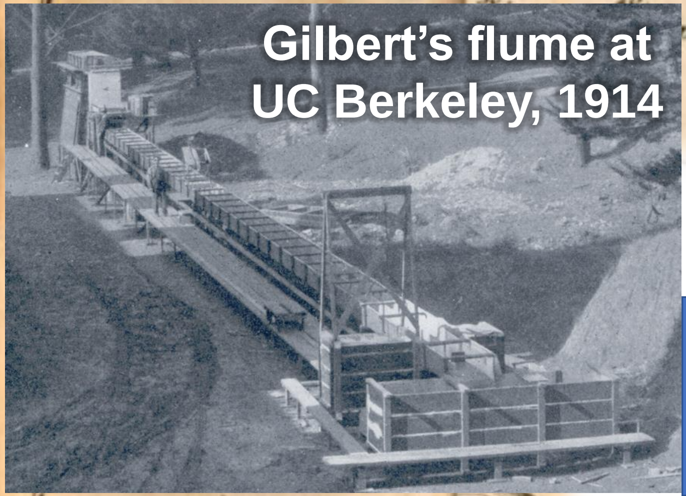
Austroads Ancestry

Gilbert 1914	Suchier 1874	Sainjon 1871
Blackwell 1857	Du Buat 1786	Bouniceau 1845

Airy 1885
Shelford 1885

Brahms 1753

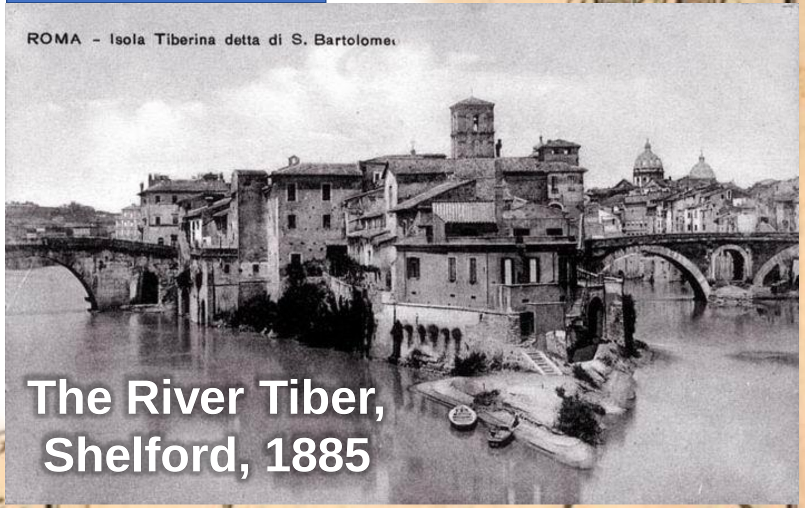
Austroads Ancestry



Gilbert's flume at UC Berkeley, 1914

Gilbert 1914	Suchier 1874	Sainjon 1871	Airy 1885
Blackwell 1857	Du Buat 1786	Bouniceau 1845	Shelford 1885

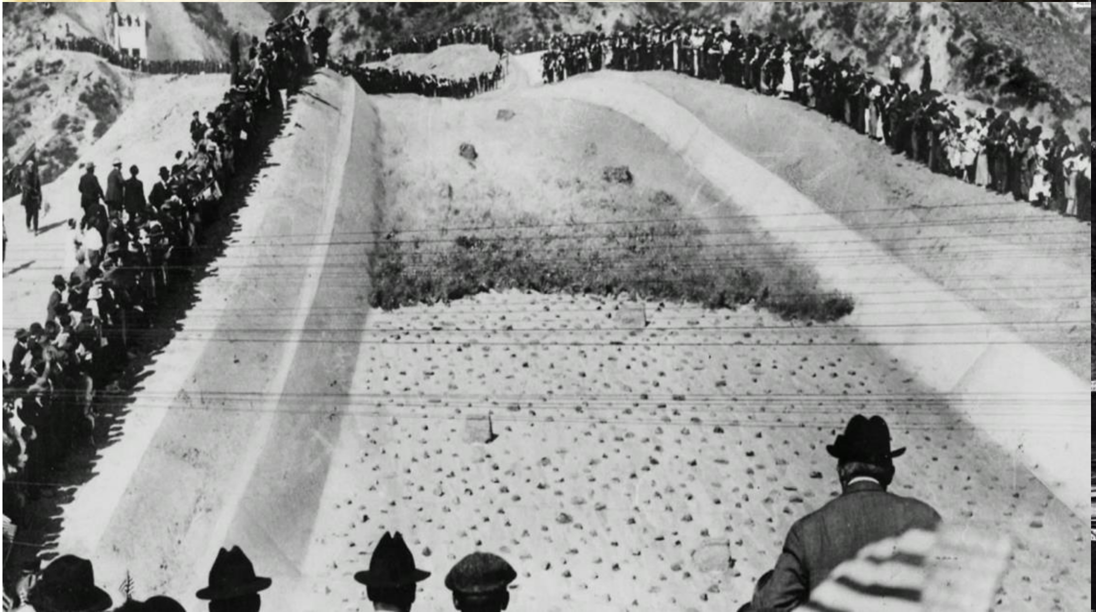
Brahms 1753



The River Tiber, Shelford, 1885

American West 1920s-30s

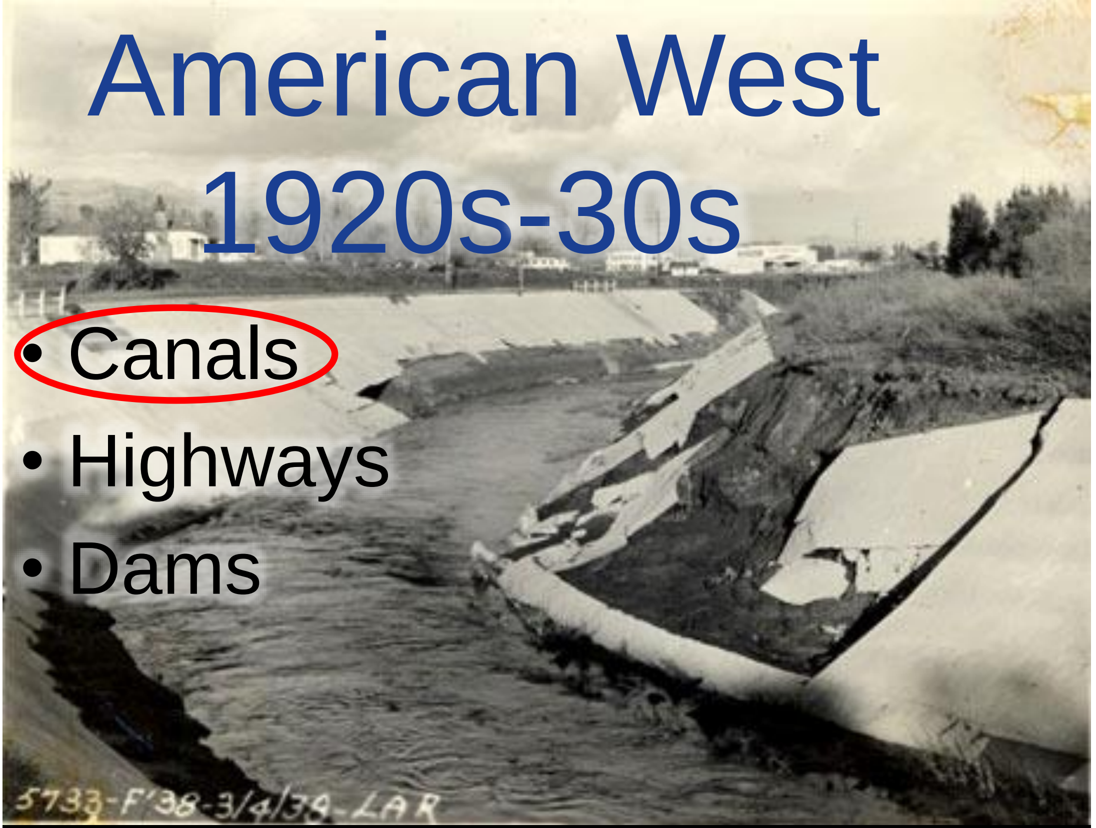
- Canals
- Highways
- Dams



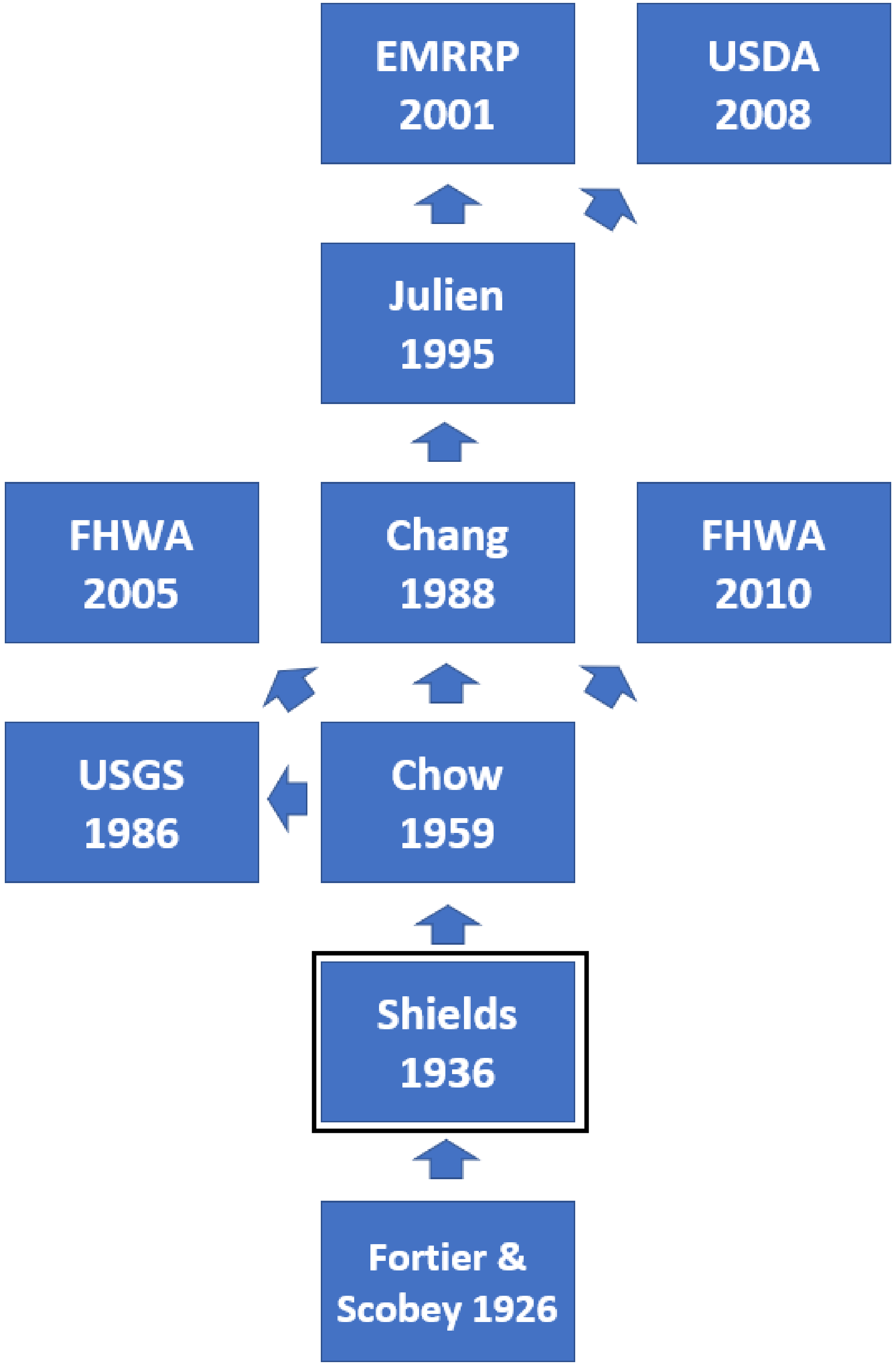
American West 1920s-30s

- Canals
- Highways
- Dams

American West 1920s-30s

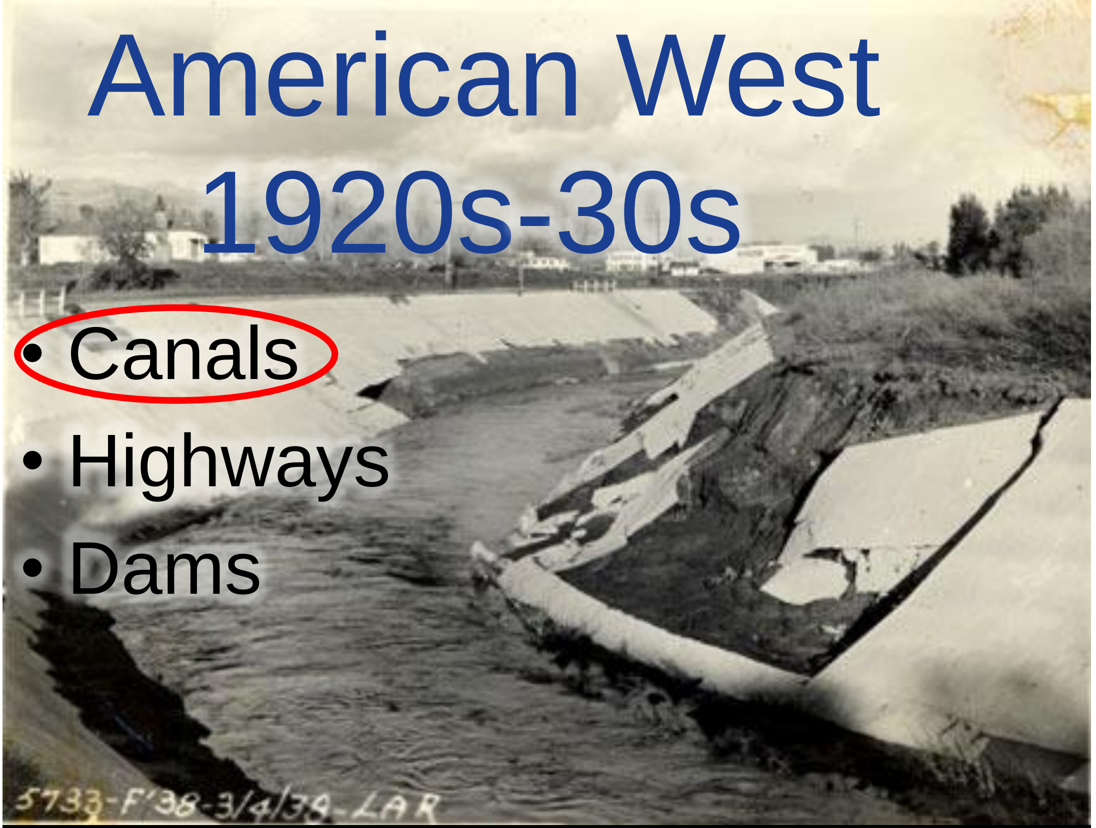


- Canals
- Highways
- Dams



American West 1920s-30s

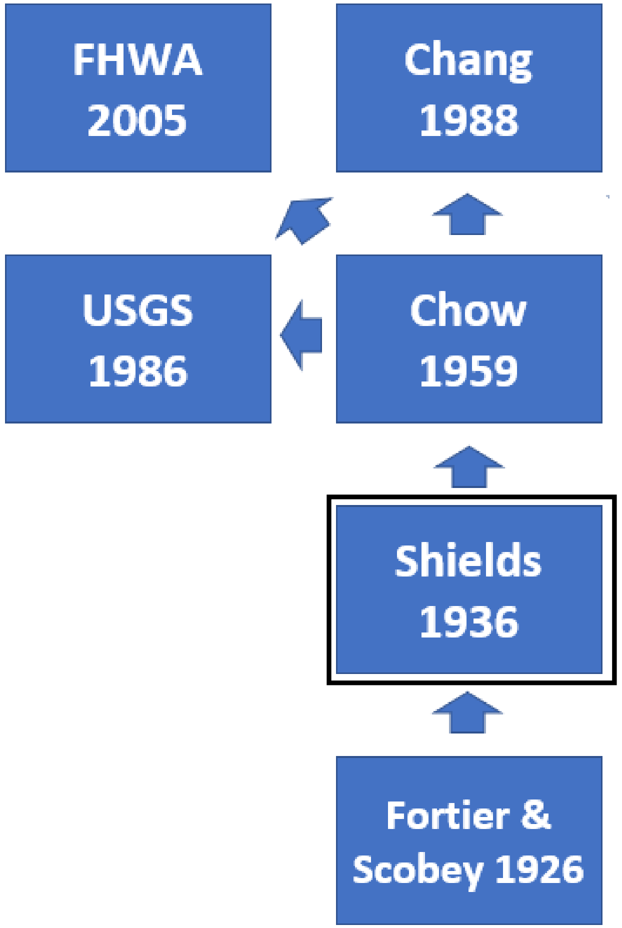
- Canals
- Highways
- Dams



The Albert Shields Story

By John F. Kennedy,[1] Member, ASCE

Abstract: In the vast literature on sediment transport, rivers, and related topics, few if any names are more frequently cited than Albert F. Shields (1908–1974). Yet all of these citations are to a single publication: his doctoral thesis submitted to the Technischen Hochschule Berlin in 1936 in which he developed his ideas on *Aenlichkeitsmechanik* (similarity mechanics) for application to riverine sediment transport, ripple formation, and initiation of motion. Shields' most famous results are his graph for critical tractive force (initiation of particle motion), and secondarily, his sediment-transport formula. Presented here is the story of the many difficulties Shields encountered in conducting his research in Nazi Germany; his inability to find employment in hydraulics following his return to his native United States; the chance encounter with and promulgation of his work by Rouse; and his eventual relinquishment of hydraulics for a long and successful career in machine design.



Shields 1936). In fact, it was not until a few years before his death that he learned that his name and work had become famous in engineering hydraulics.

This is the story of Shields' sediment research, and of his abdication of hydraulics for machine design.

SHIELDS' HYDRAULICS INTERLUDE

Albert Frank Shields was born in Cleveland, Ohio, on June 26, 1908, the son of Frank Shields, a machinist. Following graduation from high school, he worked for 1 year to earn money to support his further education. In 1927 he enrolled at Cornell University and remained there for two semesters before transferring to Stevens Institute of Technology, where he obtained his bachelor's and master's degrees, both in mechanical engineering, in 1931 and 1933, respectively. In 1933 he was named a *Stipendiat* (fellowship recipient) of the Deutschen Akademischen Austauschdienstes E.V. (German Academic Exchange Service) of the Technischen Hochschule Berlin (TH Berlin). His plans included pursuit of research at the Preussischen Veruschsanstalt für Wasserbau und Schiffhau (Prussian Research Institute for Hydraulic Engineering and Shipbuilding; herein, PRI) that would serve as the basis for his dissertation, which would be submitted to TH Berlin for the degree *Doktor-Ingenieurs* (Doctor of Engineering).

In 1933 the world economy was wracked by the Great Depression. Shields had no personal resources, nor was his family in a position to assist him financially. Moreover, his stipend did not provide funds for any travel expenses. After pursuing several other possibilities, he finally gained passage to Germany by working on a freighter.

American West 1920s-30s

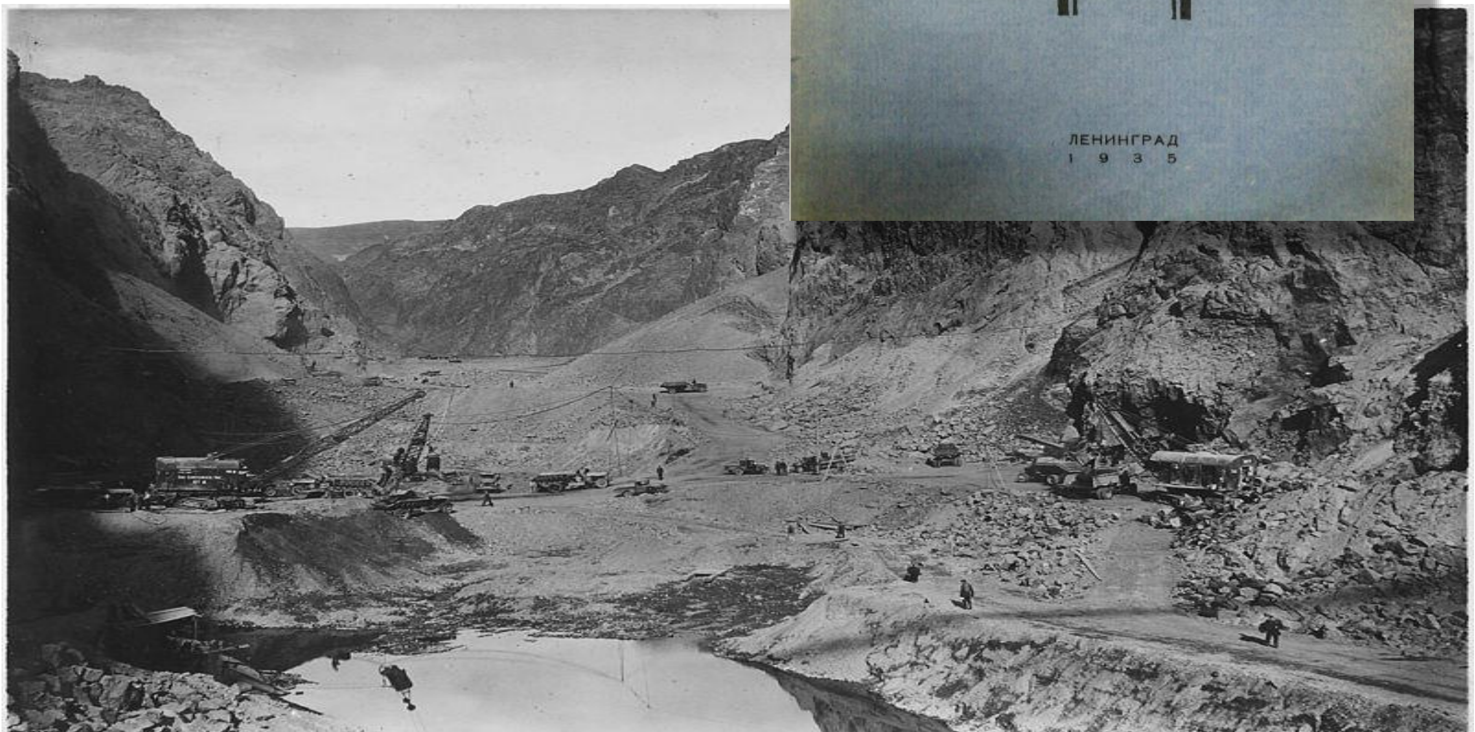
- Canals
- Highways
- Dams

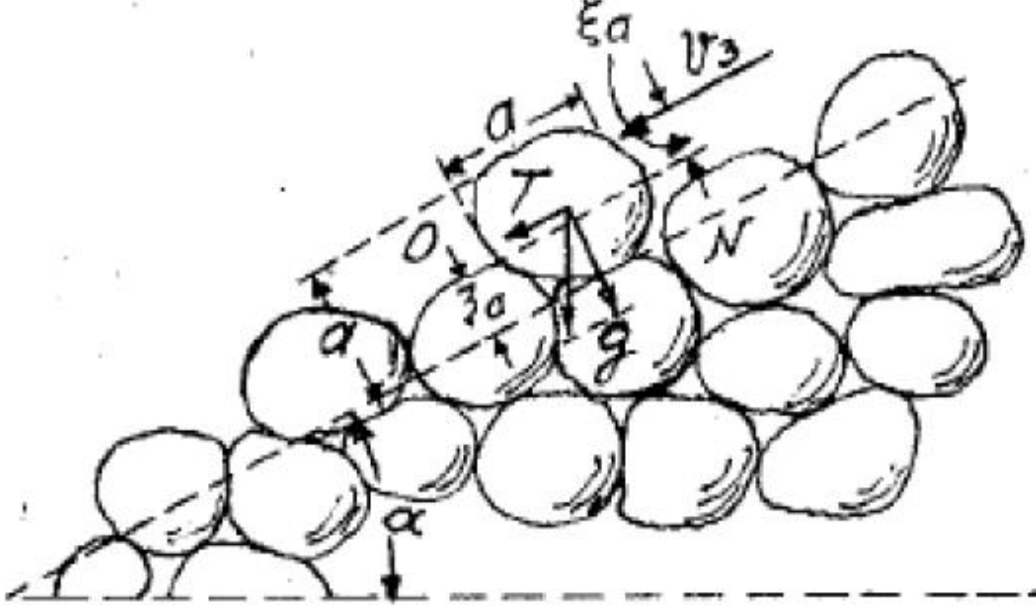
Trial and Error:

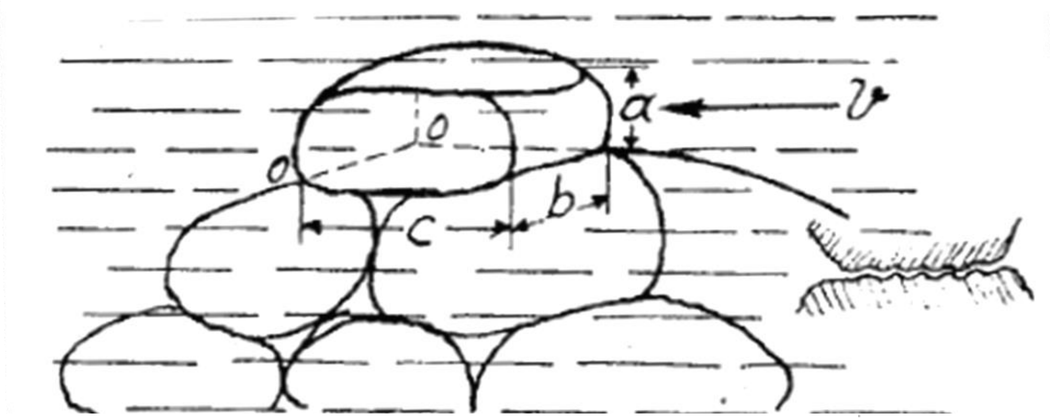
- 1921-22: California Floods
- 1922-27: Bank protection installed
- 1927: Floods, bank protection failed
- 1928-37: Withycombe studies failures, improvements implemented
- 1937 NoCal floods, 1938 SoCal floods: better results, but some problems with rigid solutions
- 1937-49: Riprap widely implemented
- 1949: California Joint Bank Protection Committee organised
- 1960: California Bank and Shore Protection Manual published (CABS)
- 1970: Errata and revisions published
- 2000: CABS updated by CPDW
- 2006: NCHRP review of CABS vs. USACE
- 2020: Caltrans recommends USACE

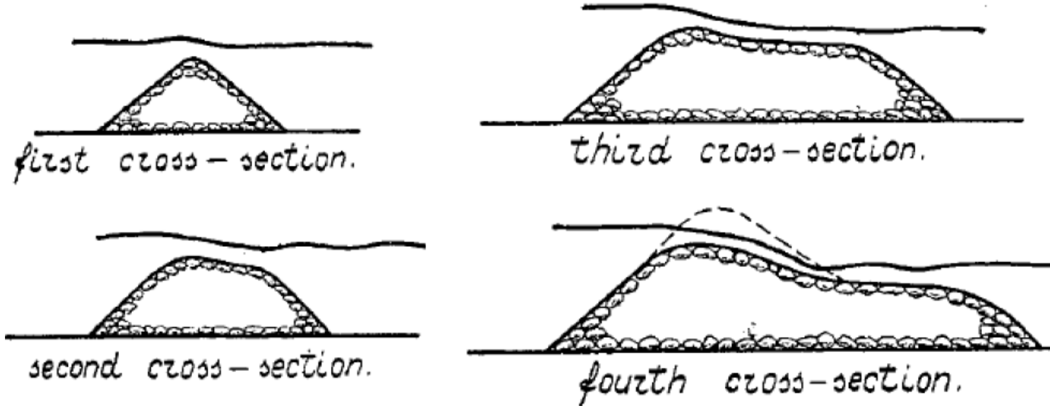
Leningrad 1930-1936

- Canals
- Highways
- Dams





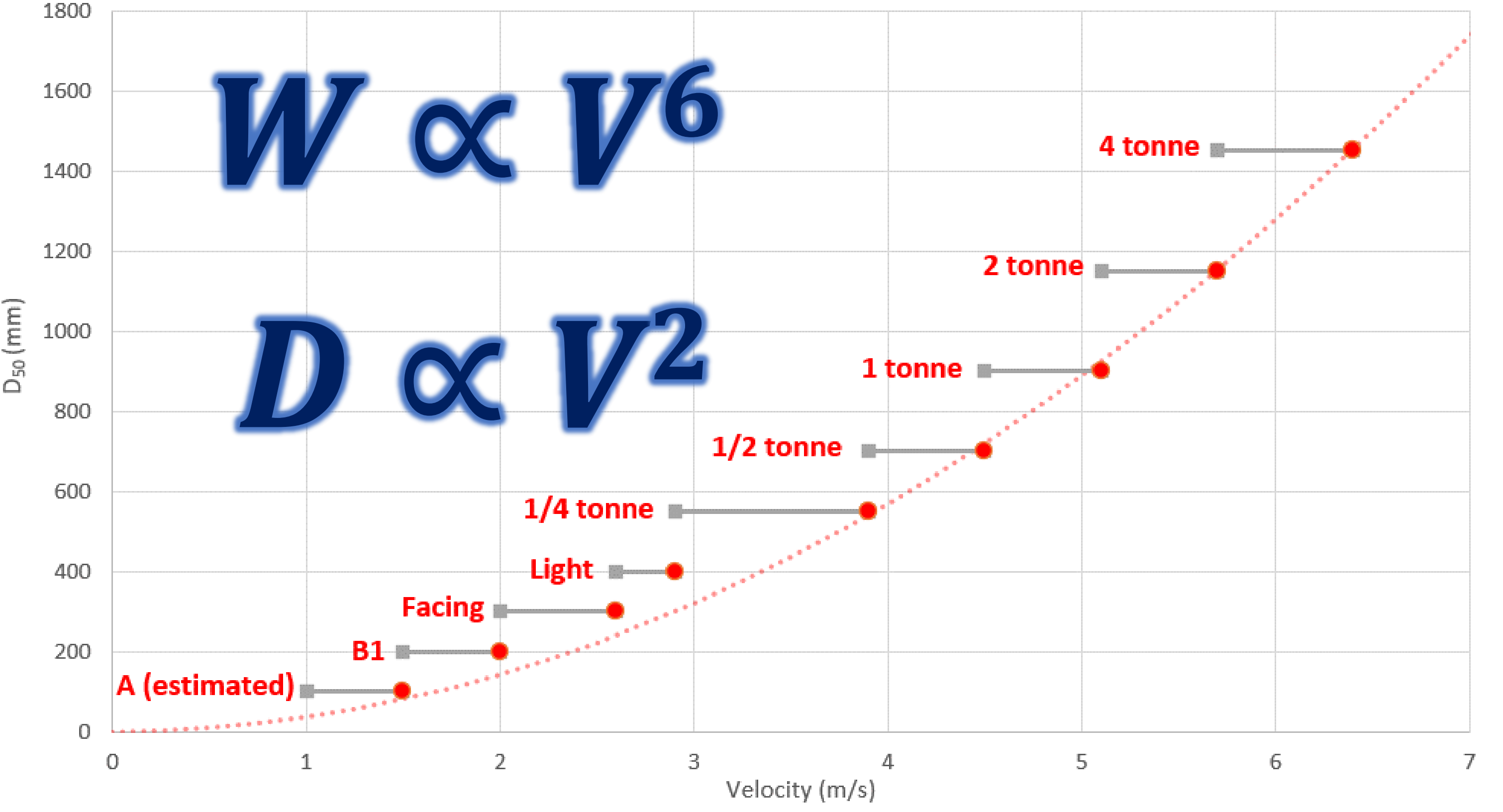


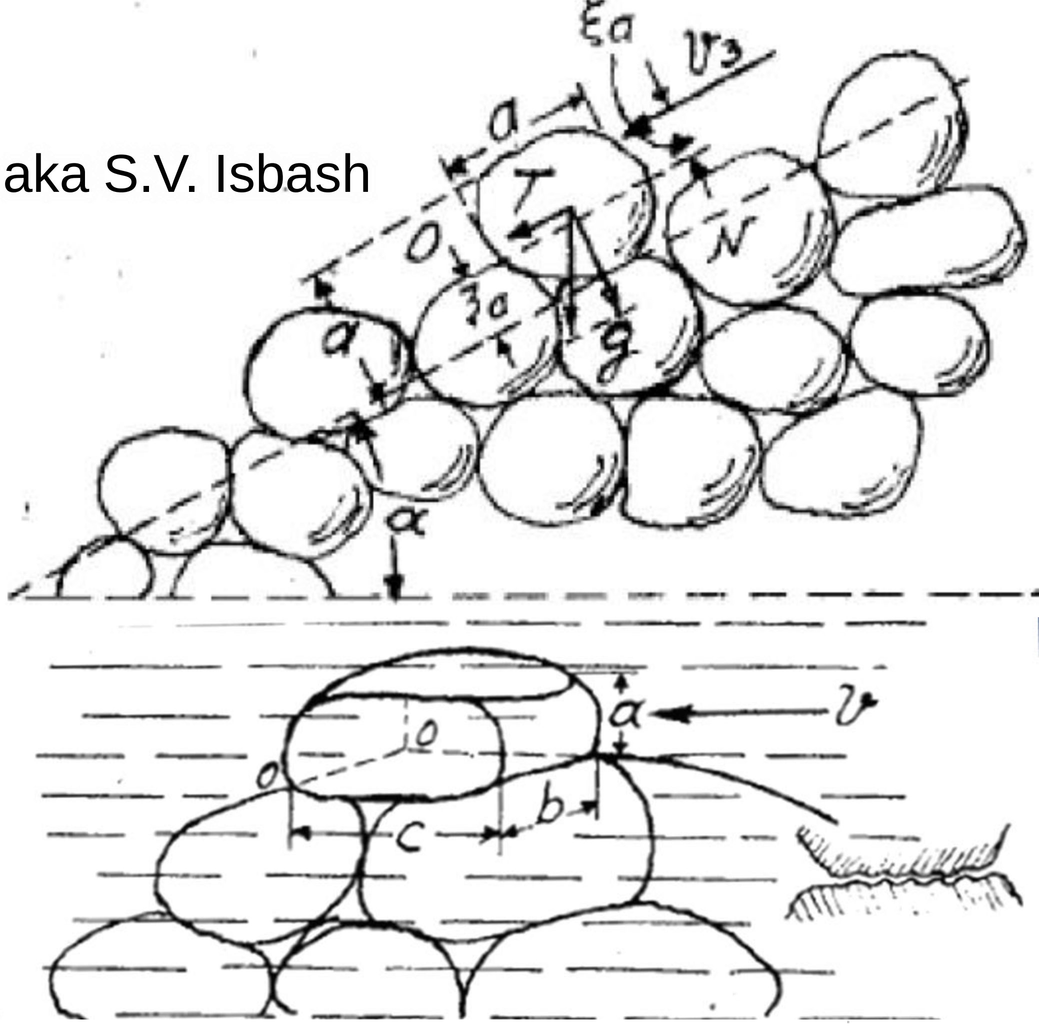


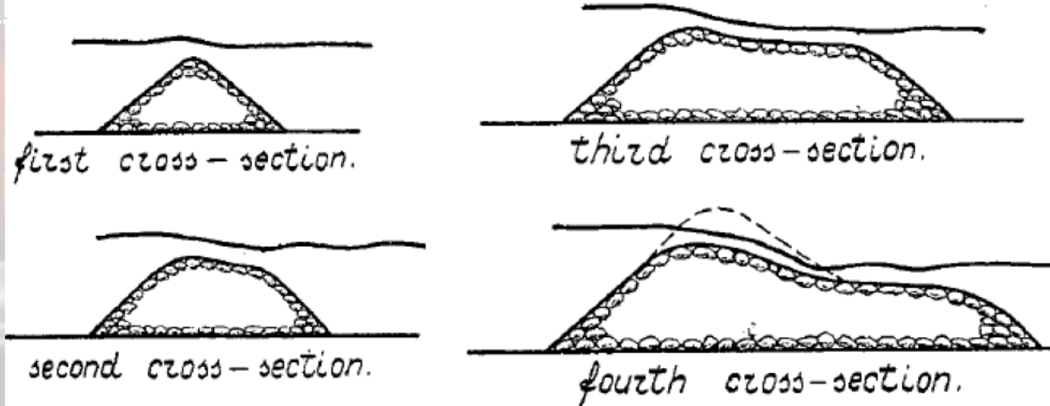
Isbash 1936

Сергей Владимирович Избаш

aka Sergey Vladimirovich Izbash aka S.V. Isbash







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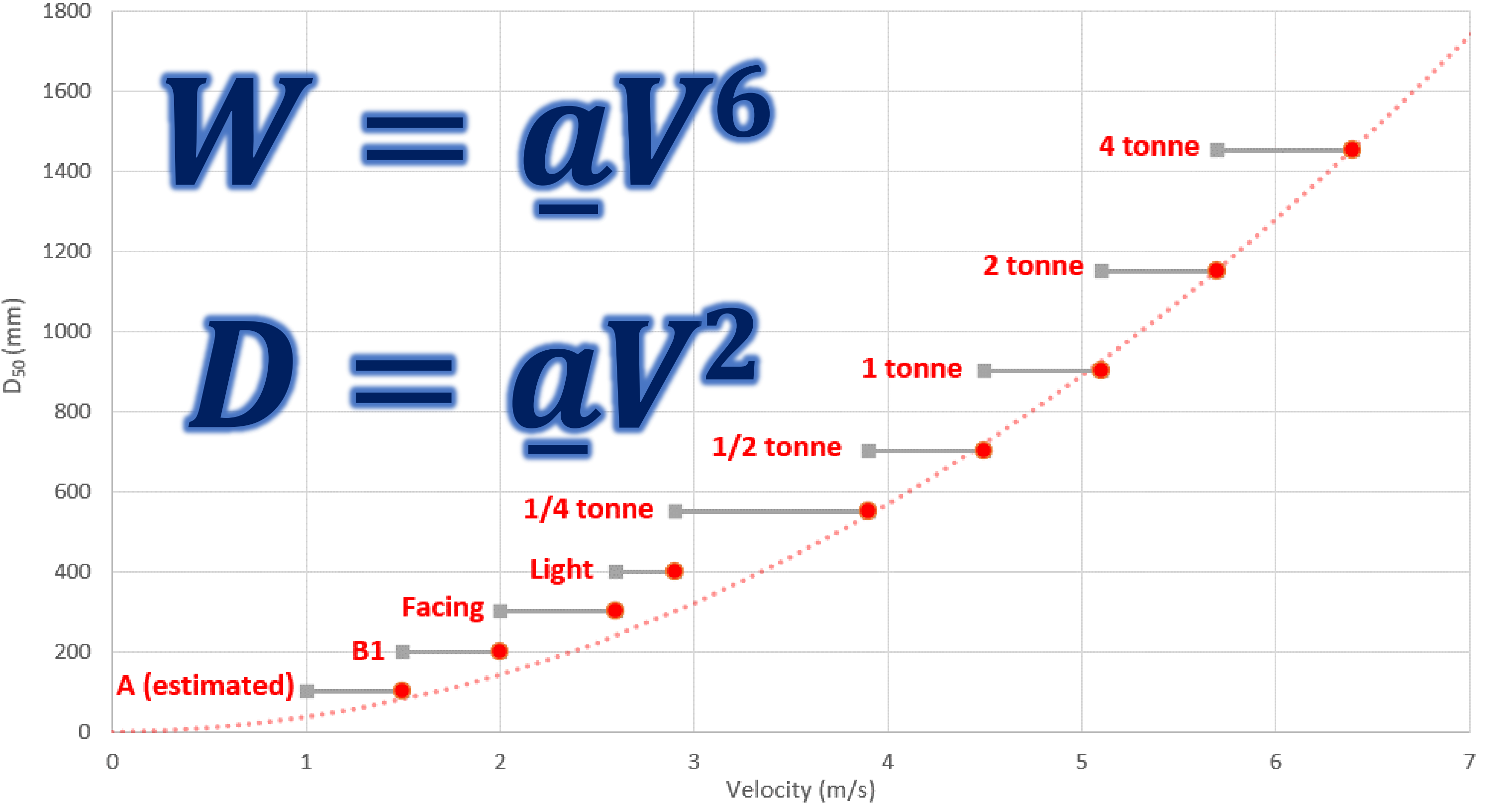
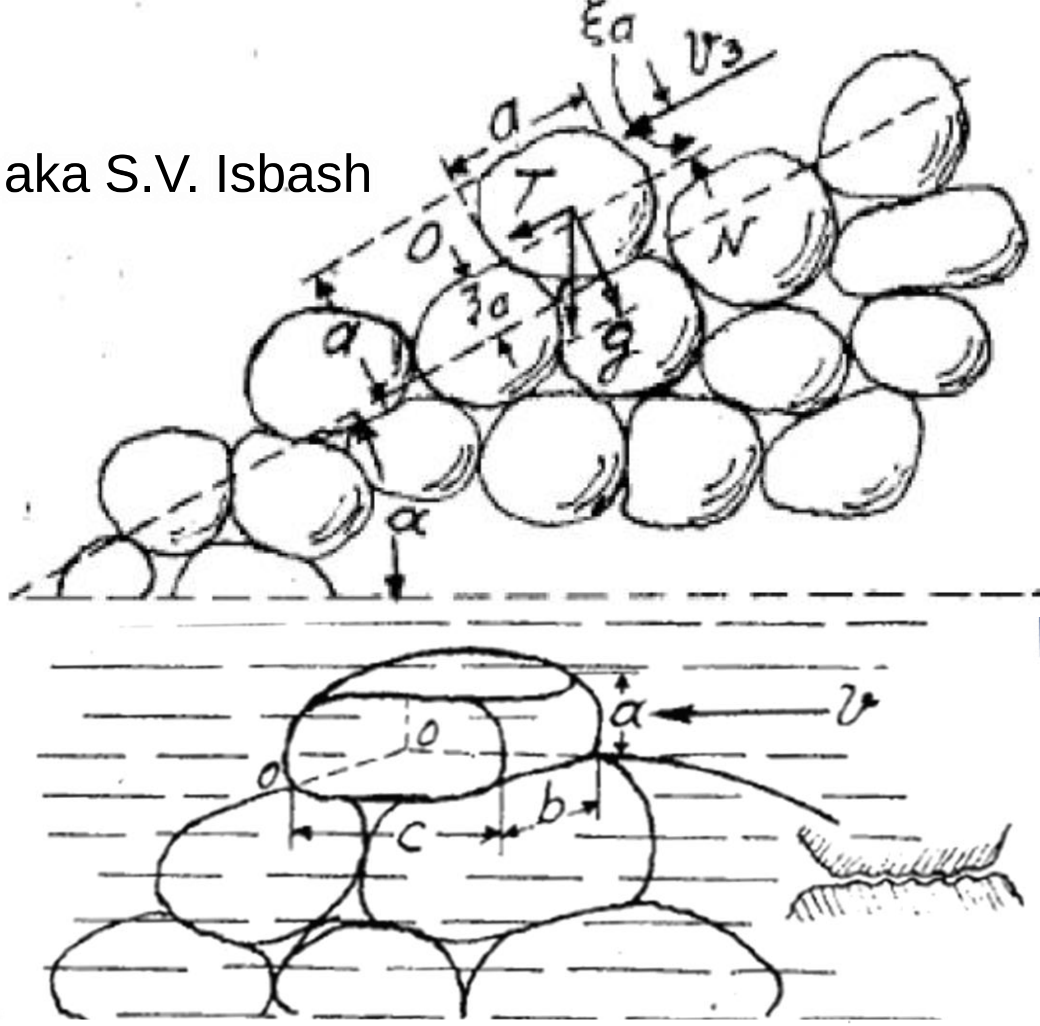
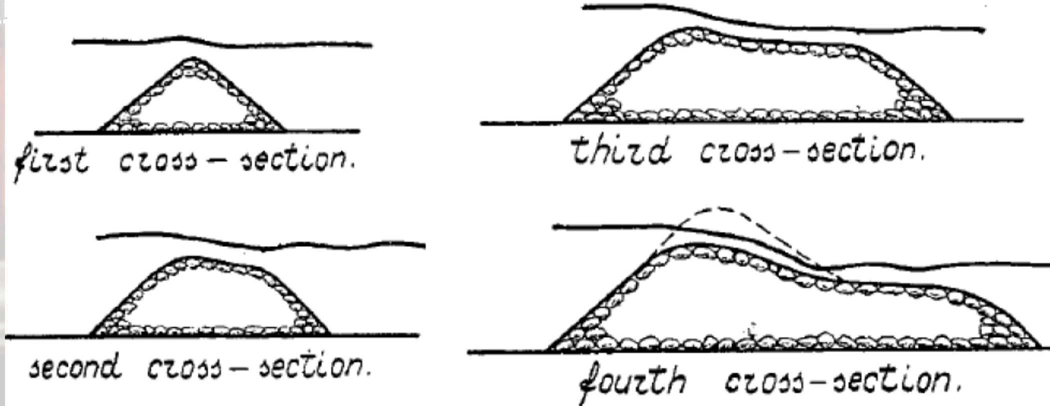
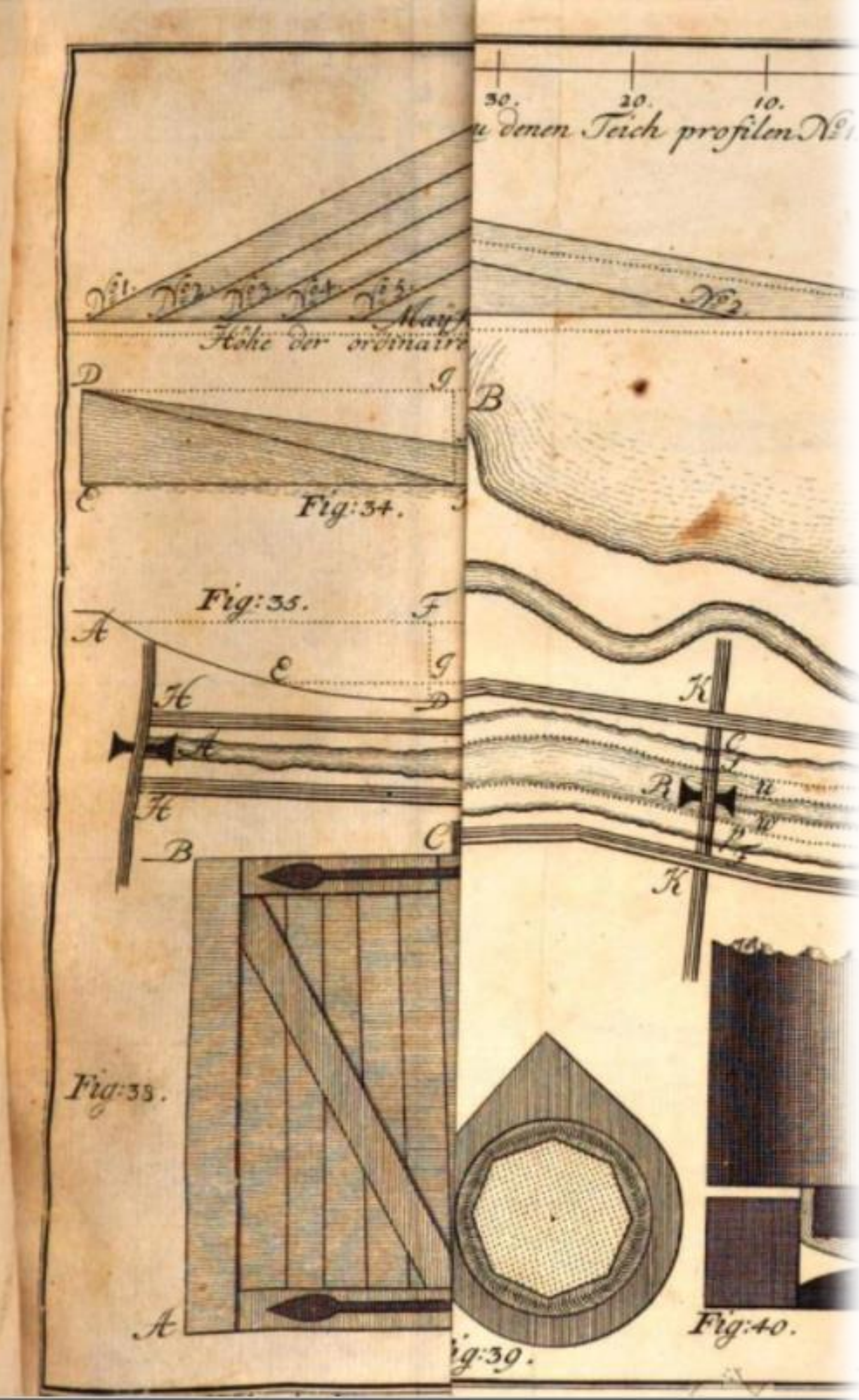








$$D = \underline{a}V^2$$

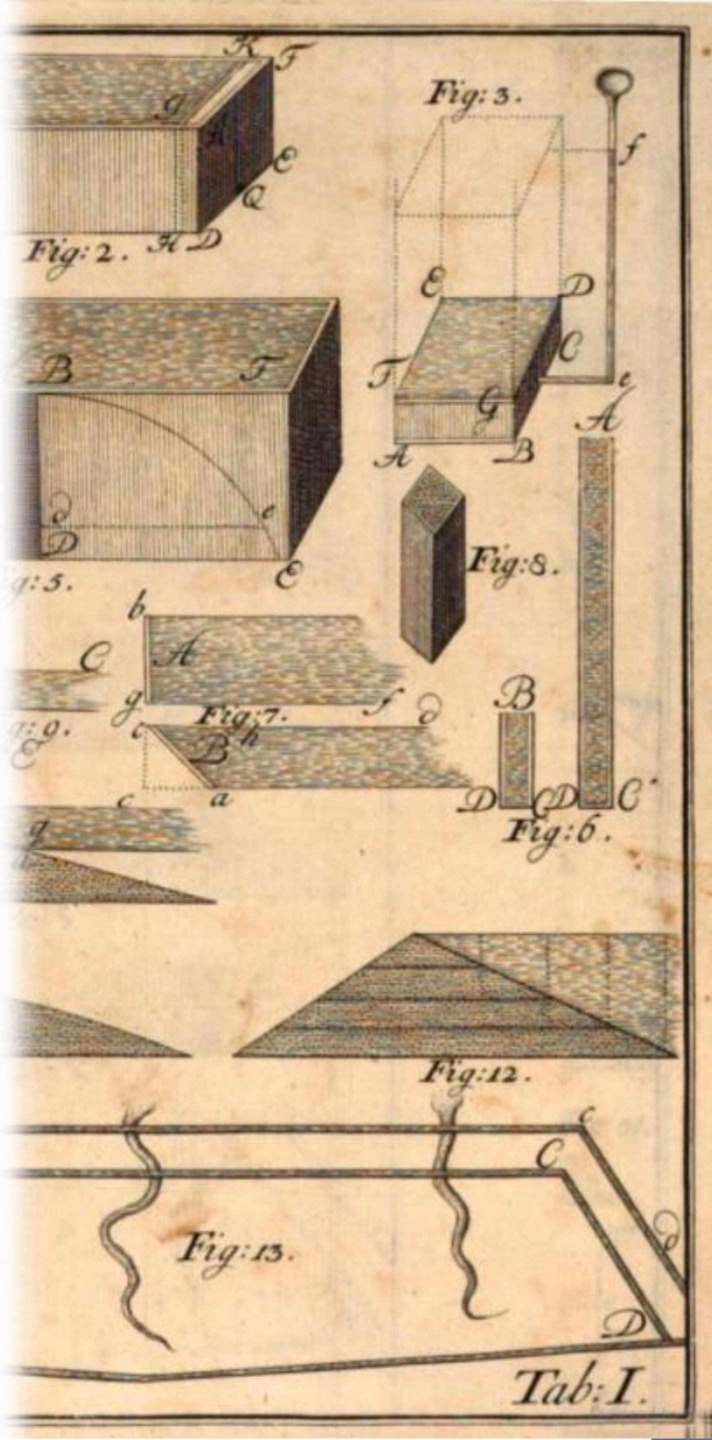
Berry
1948[4]

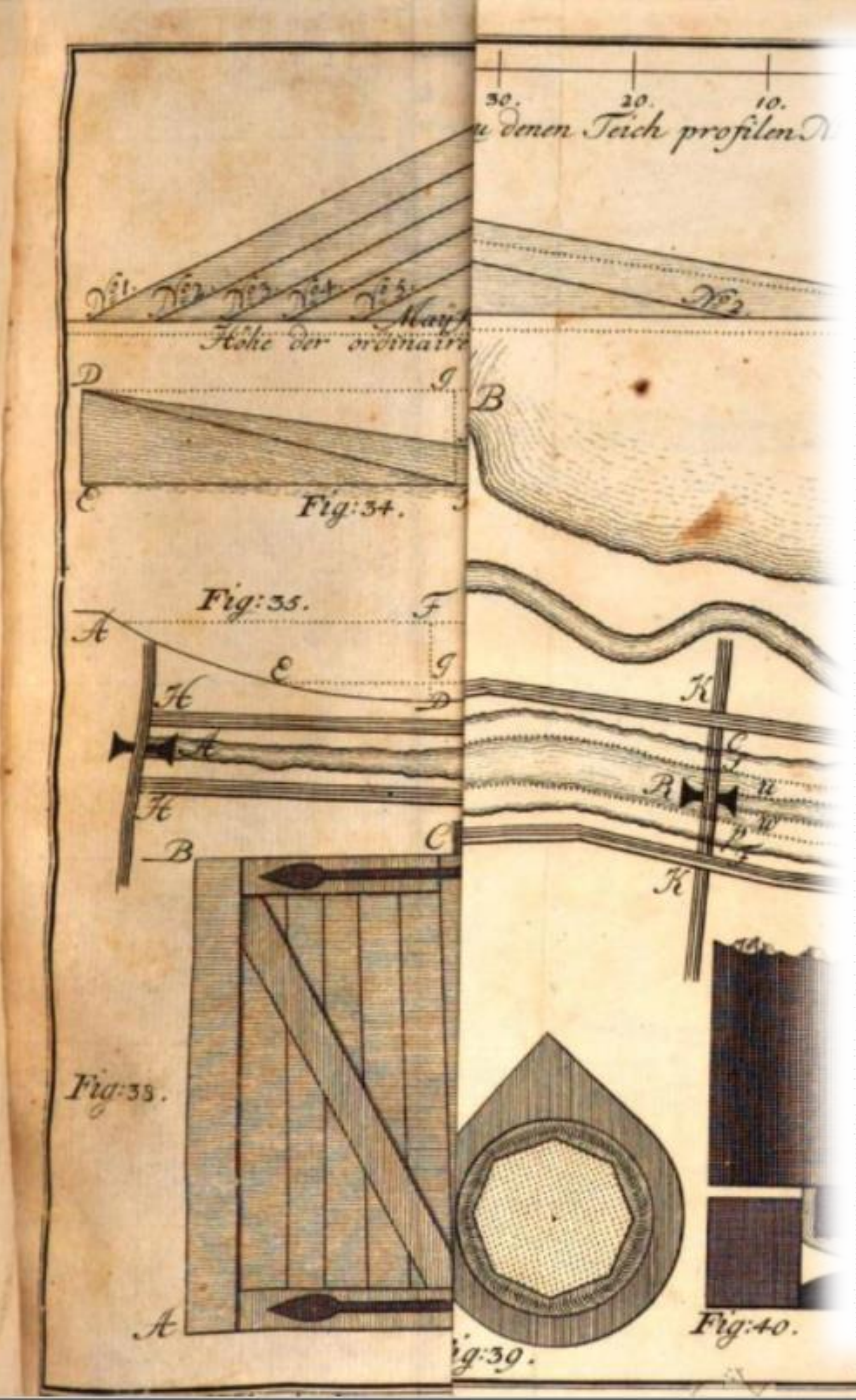
↑

Gilbert 1914	Suchier 1874	Sainjon 1871
Blackwell 1857	Du Buat 1786	Bouniceau 1845

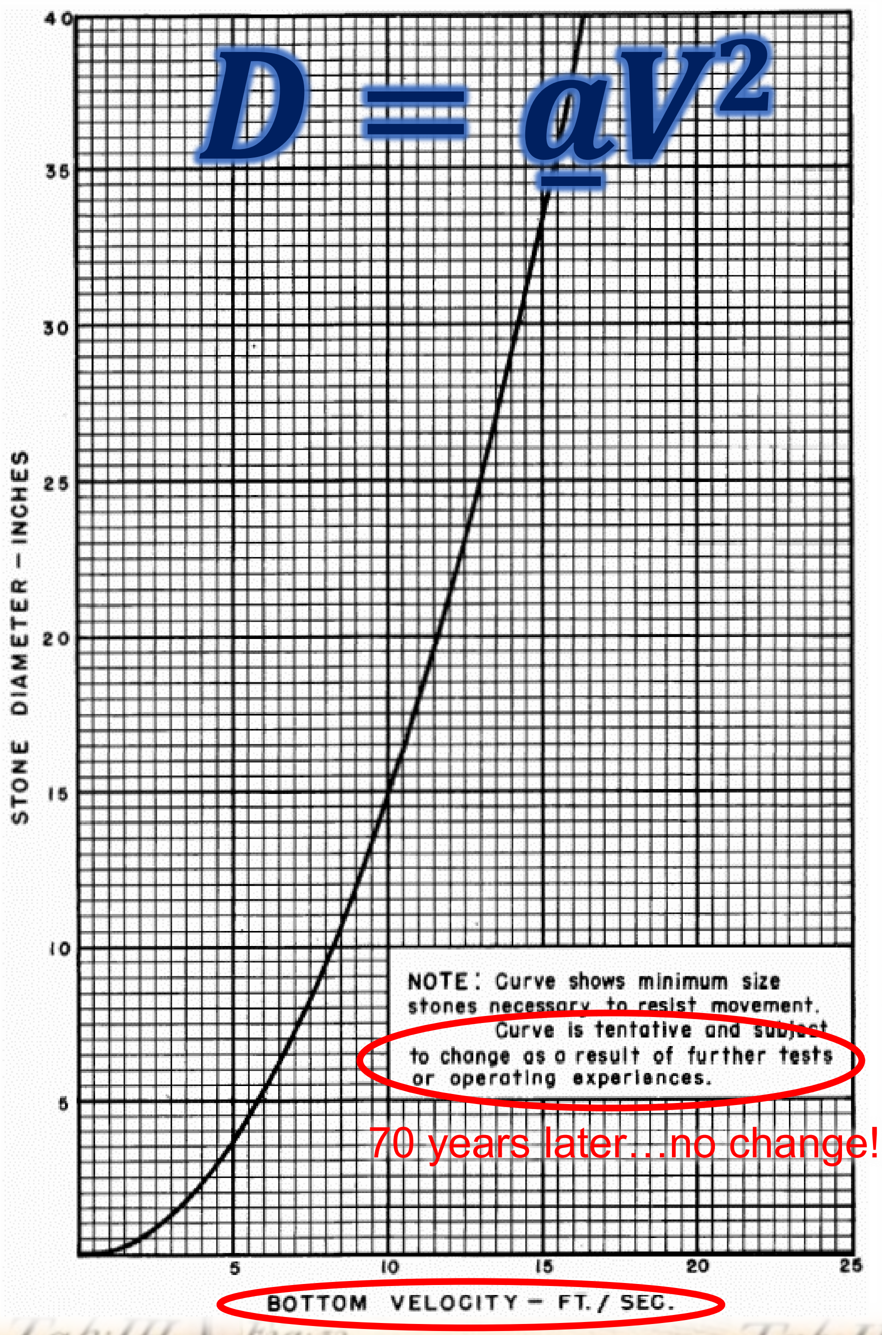
↑

Brahms
1753

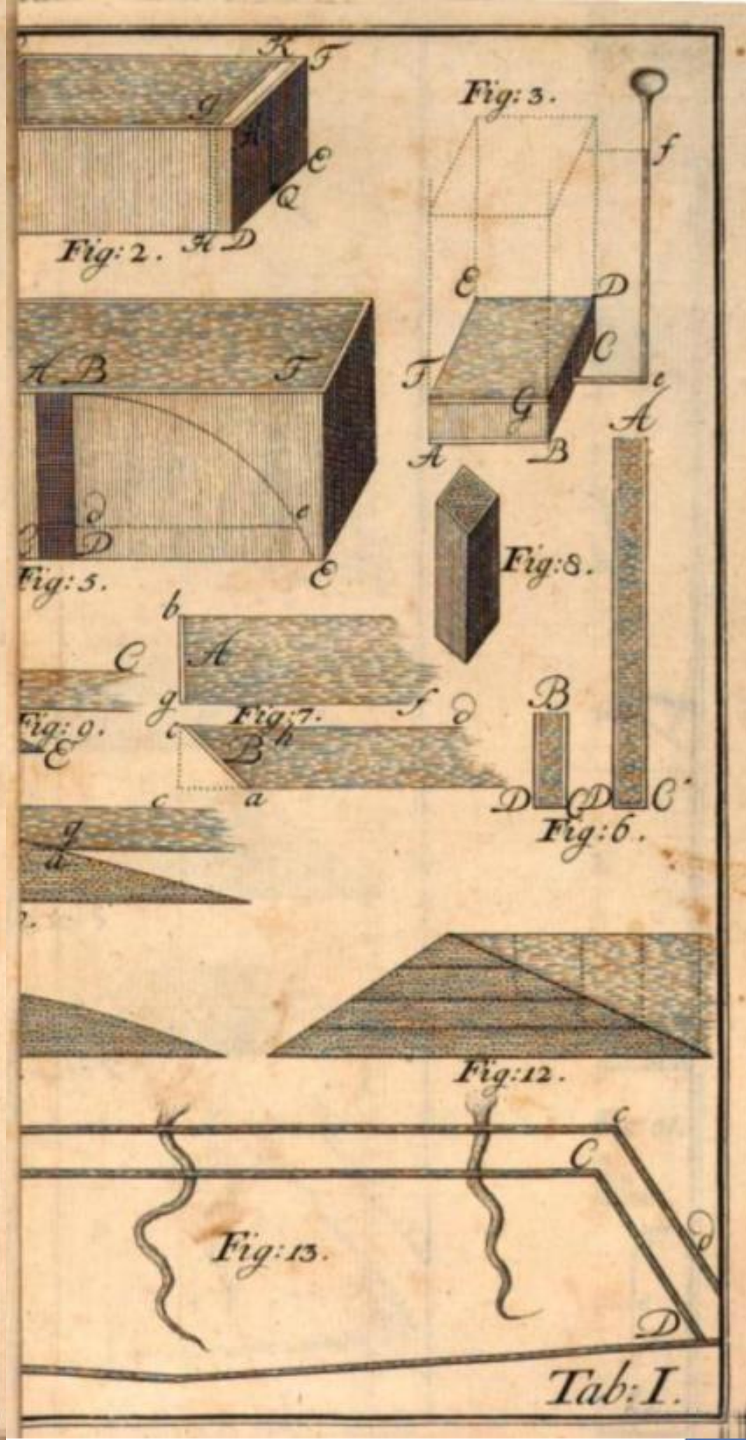


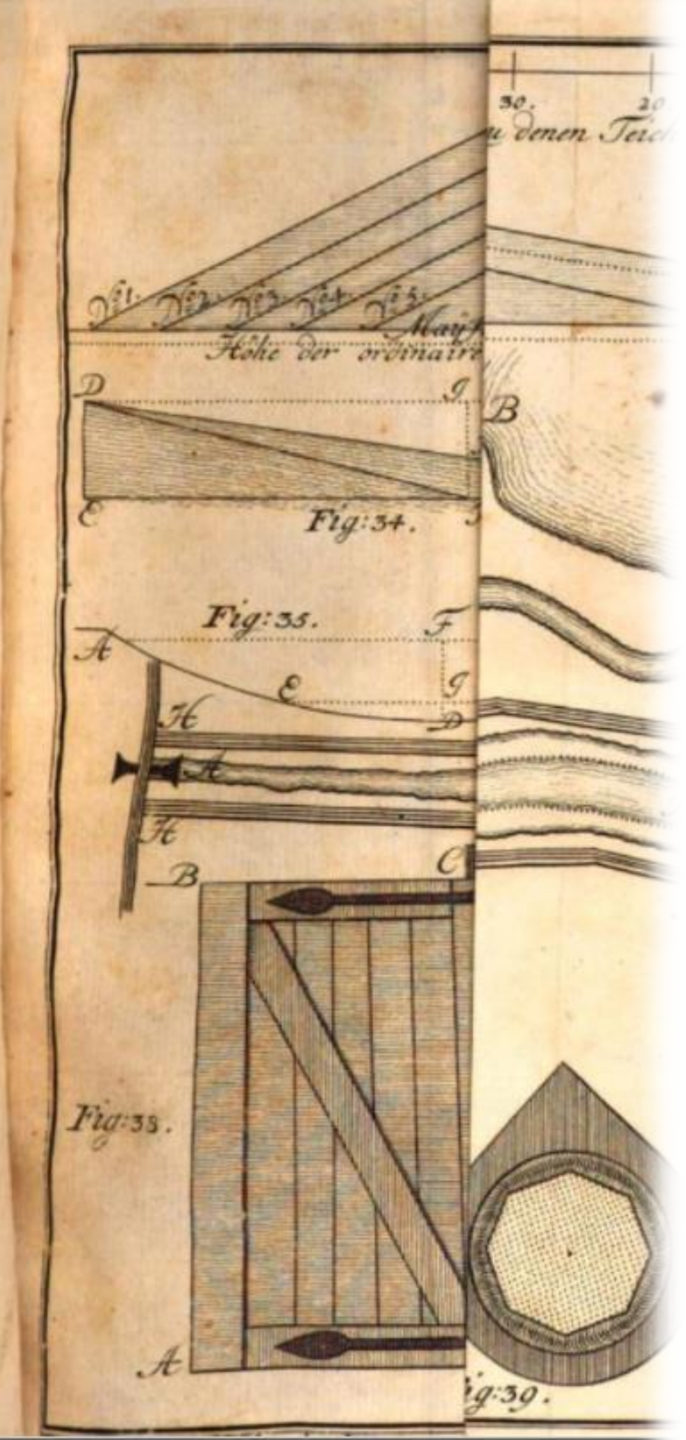


$$D = \underline{a}V^2$$



70 years later…no change!





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!

The lower portion of the curve is an average of data reported by Du Buat in 1786, Bouniceau in 1845, Blackwell in 1857, Sainjon in 1871, Suchier in 1874, and Gilbert in 1914. It checks well with results of tests made at the State University of Iowa by Chitty Ho, Yun-Cheng Tu, Te Yun Liu, and Edward Soucek. The data were assembled and discussed in a paper "A Reappraisal of the Beginnings of Bed Movement-Competent Velocity" by F. T. Mavis and L. M. Laushey, for the International Association for Hydraulic Structures Research, 1948, Stockholm, Sweden. In a thesis by N. K. Berry, University of Colorado, 1948, an identical curve was determined and an equation for it presented.

$$V_b = 2.57\sqrt{d}$$

where

$D = 40 V^2$ Matches Austroads

V_b = bottom velocity in channel in feet per second
d = diameter of particle in inches

In this case the specific gravity of the particle is 2.65.

Mavis and Laushey proposed an ~~identical~~ equation for use with particles of any specific gravity

$$V_b = 1/2.\sqrt{d},\ \sqrt{s - 1}$$

where

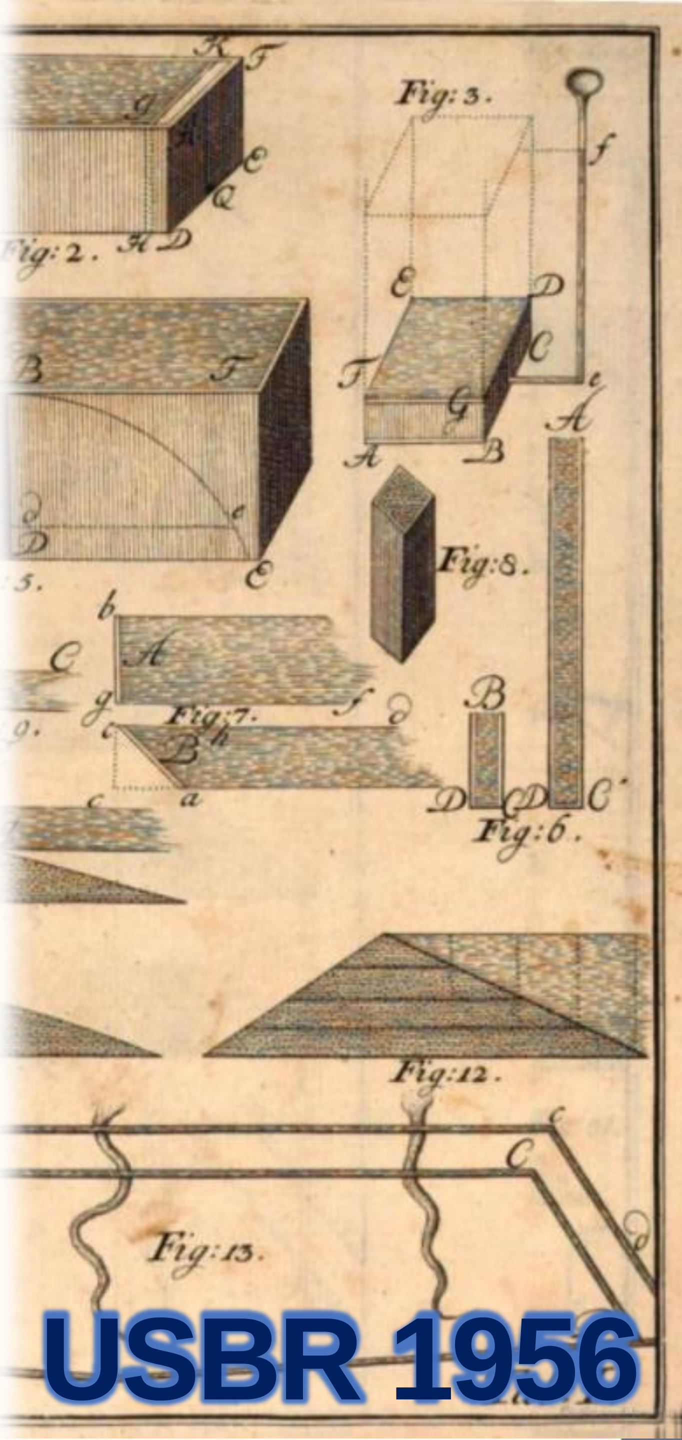
$D = 26 V^2$ Unstable!

s = specific gravity of the particle
d, = particle diameter in millimeters

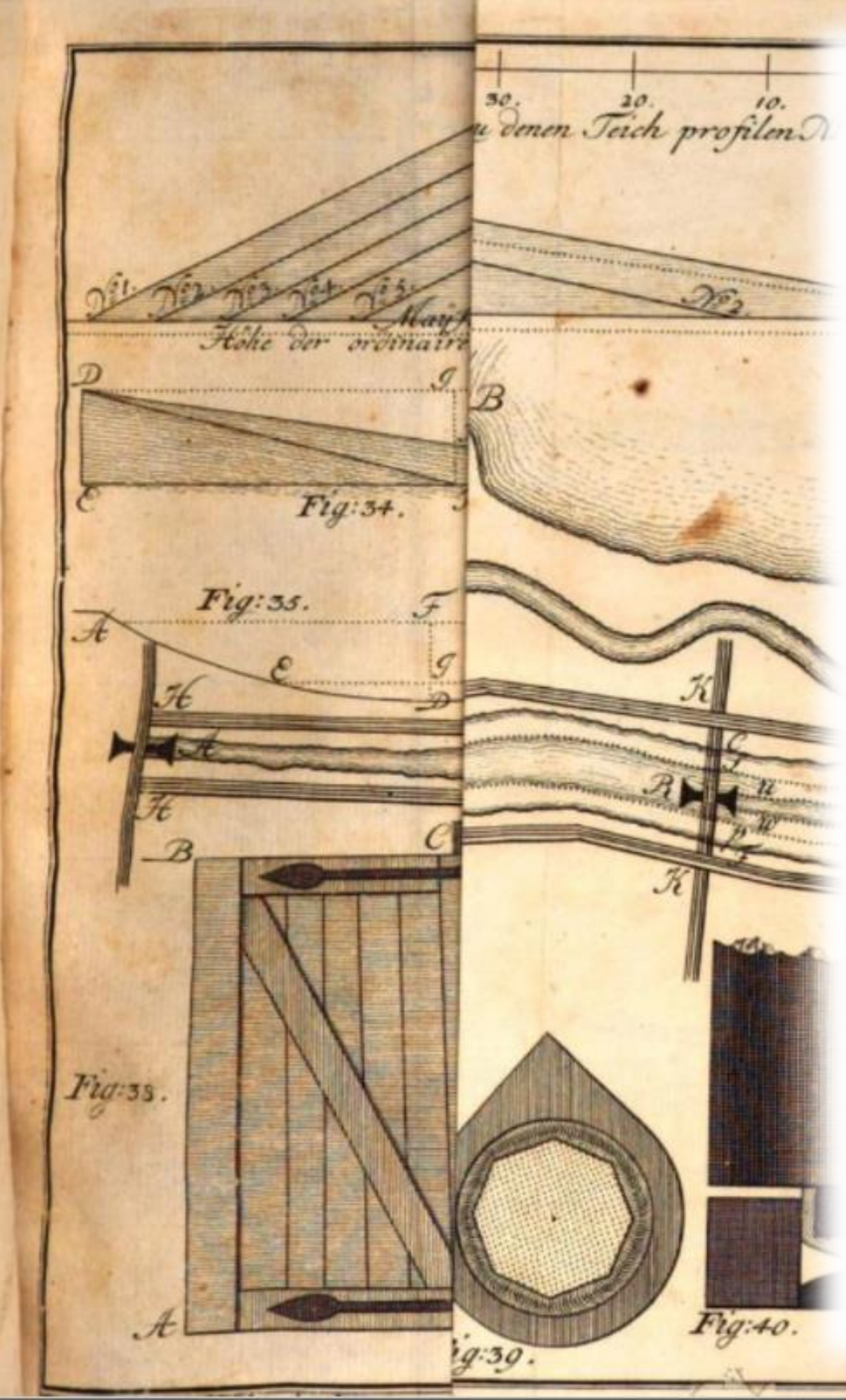
V_{ave}, not V_{bed}!

Rationalization of all the known factors indicates that the curve may be directly applicable for the determination of riprap sizes, particularly since it indicates larger stone sizes for the North Dam outlet than were used and agrees reasonably well with general laboratory experience. Until more data and experience with this curve are available, the velocity, determined by dividing discharge by flow area at the end sill, may be used. Until the interlocking effect of the rock pieces can be determined, most of the riprap should consist of the size indicated by the curve.

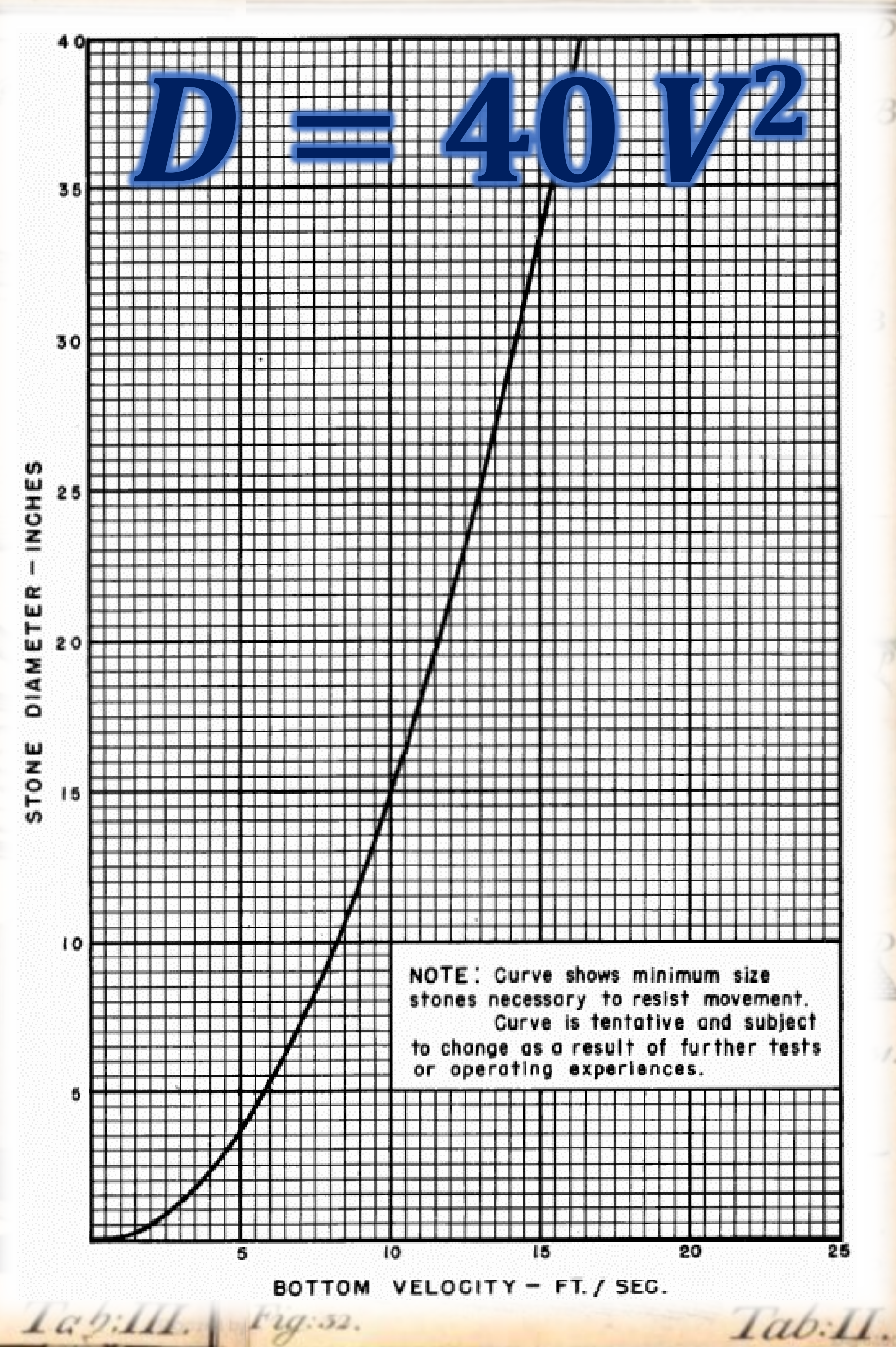
undefined gradation



USBR 1956



30.
20.
10.
zu denen Teich profilen
Höhe der ordinaire
Fig:34.
Fig:35.
Fig:38.
Fig:39.
Fig:40.
Tab:III.



D = 40 V²
STONE DIAMETER – INCHES
BOTTOM VELOCITY – FT. / SEC.
NOTE: 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.
Fig:32.
Tab:II.

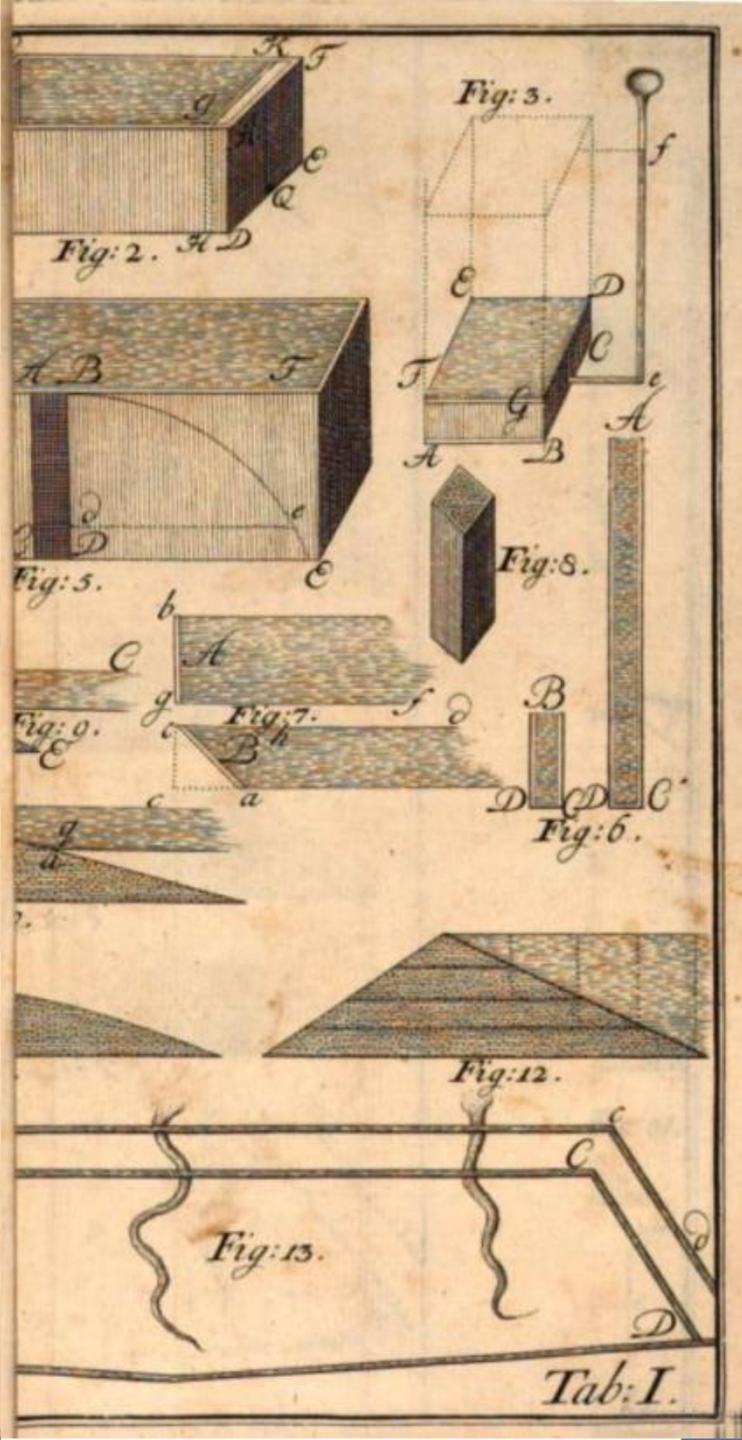
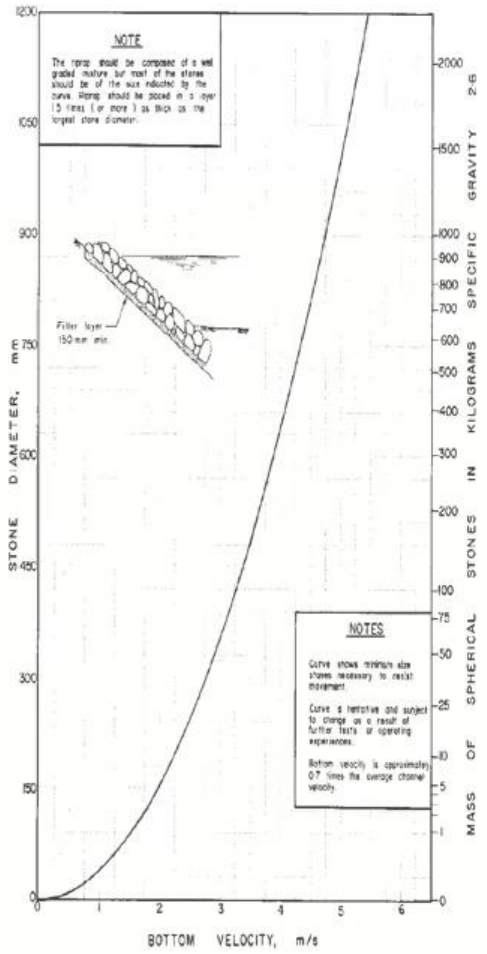


Fig:2.
Fig:3.
Fig:5.
Fig:6.
Fig:7.
Fig:8.
Fig:9.
Fig:12.
Fig:13.
Tab:I.



SIZE OF RIPRAP TO BE USED DOWNSTREAM FROM STILLING BASINS

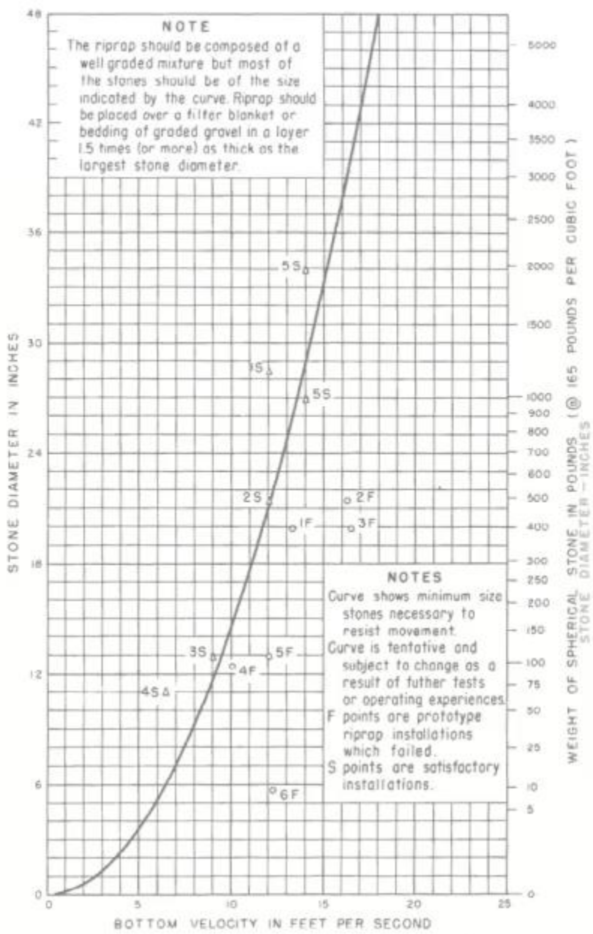
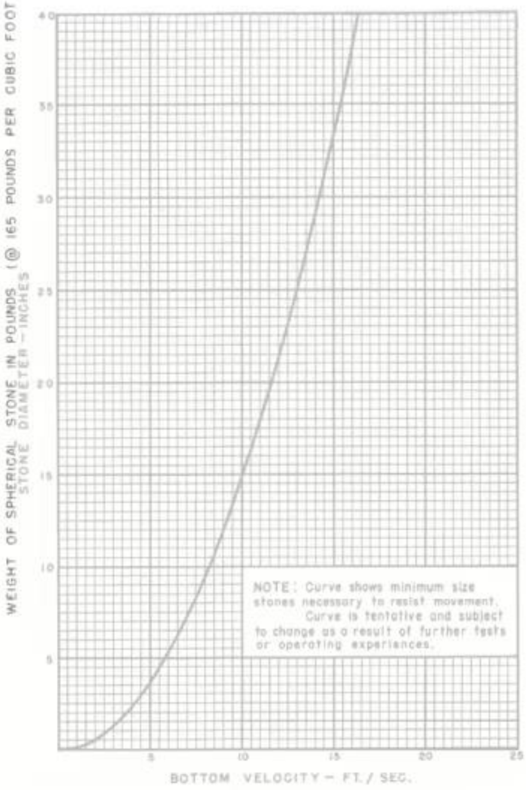
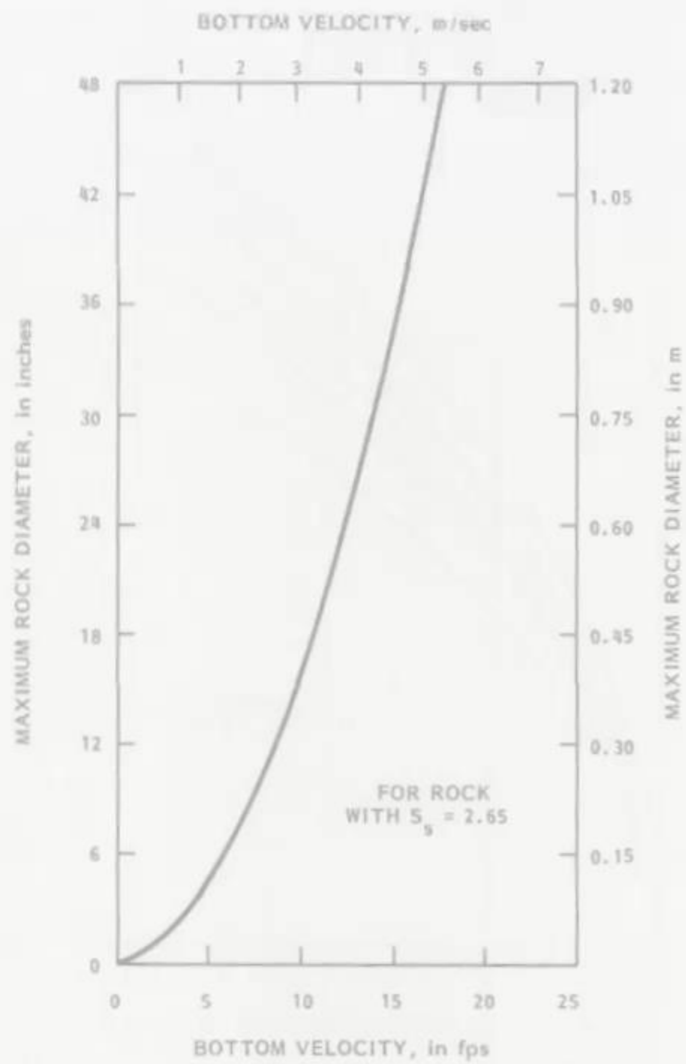
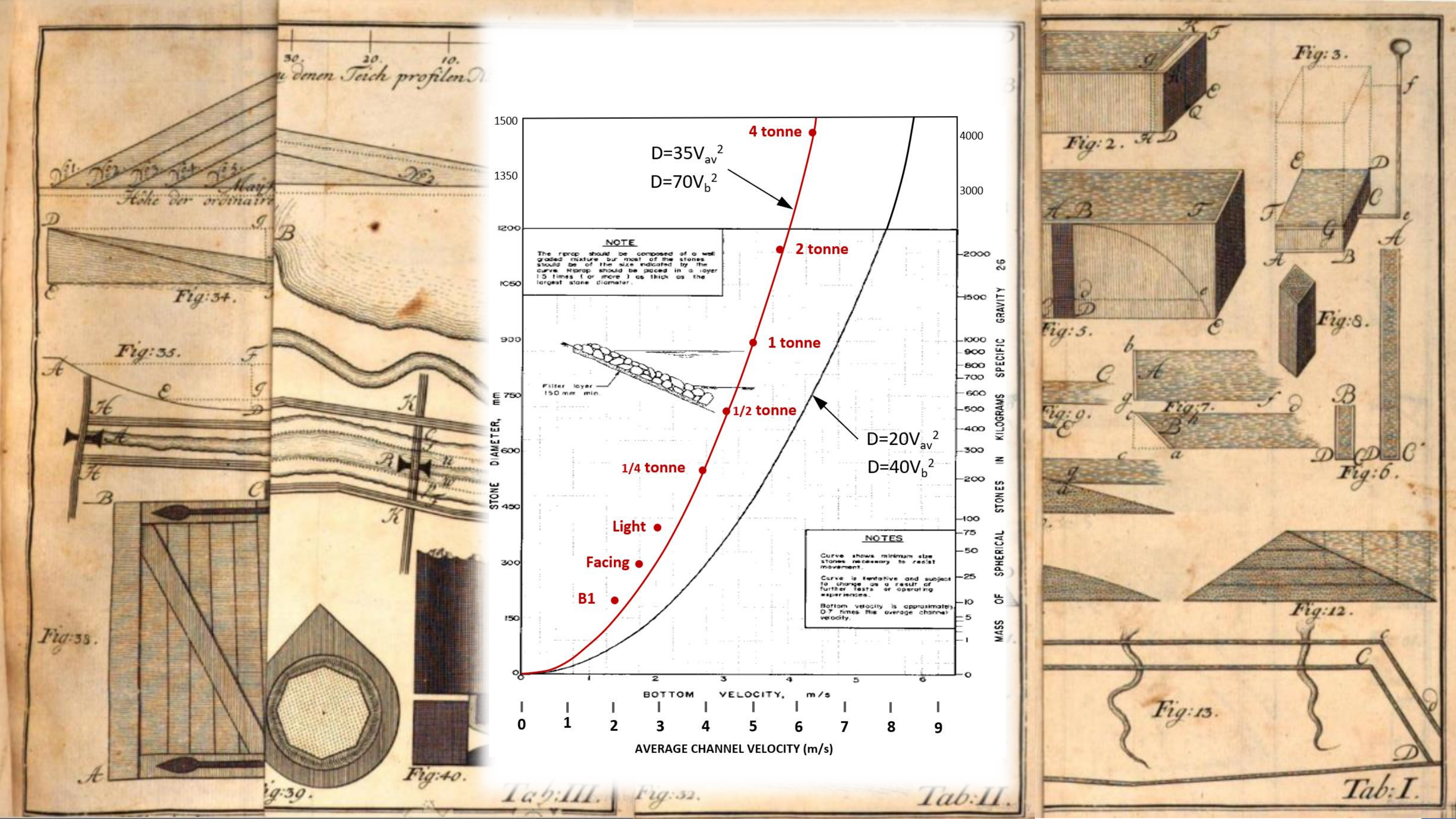


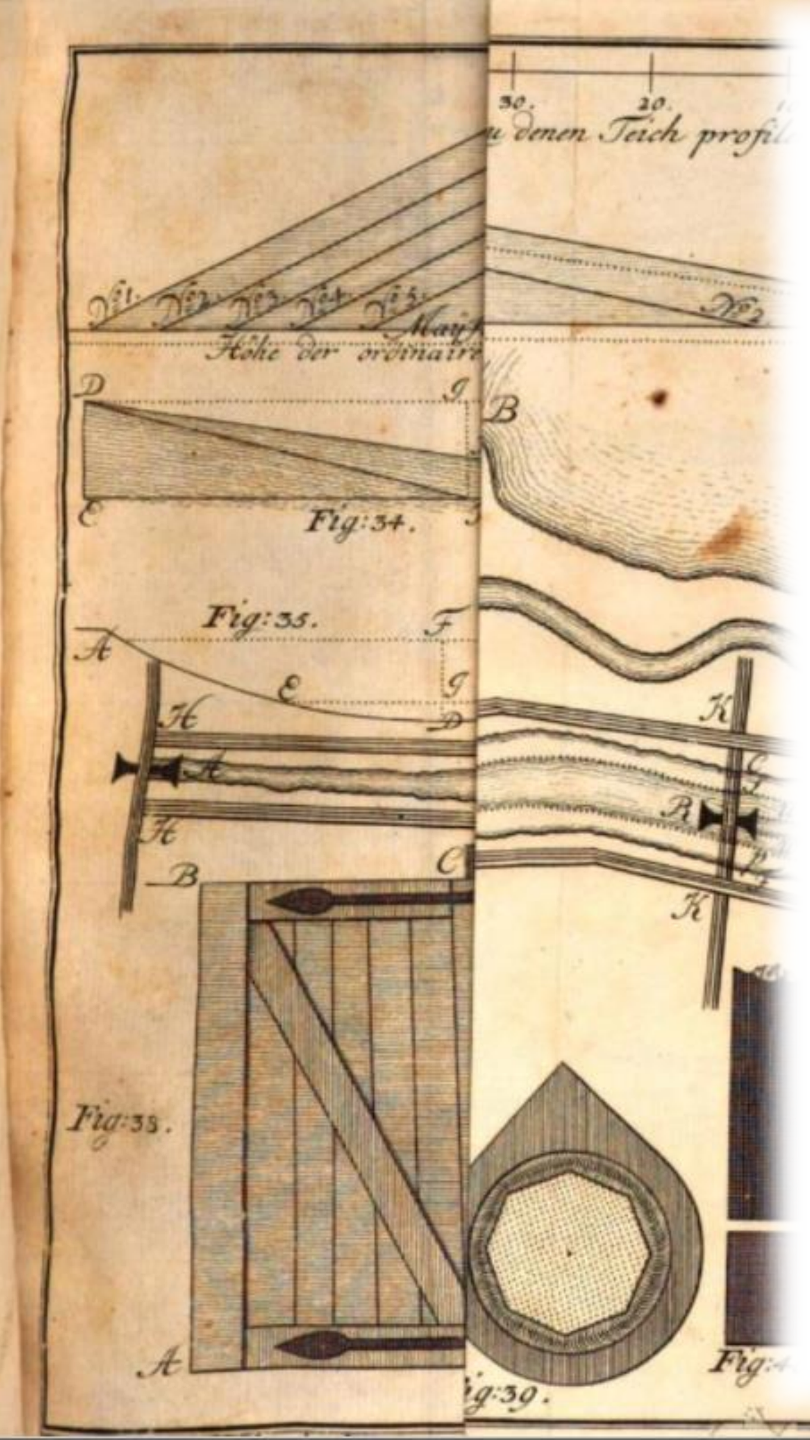
FIGURE 165.—*Curve to determine maximum stone size in riprap mixture.*







4 tonne
2 tonne
1 tonne
1/2 tonne
1/4 tonne
Light
Facing
B1
D=35V_av^2
D=70V_b^2
D=20V_av^2
D=40V_b^2
NOTE
The riprap should be composed of a well graded mixture bur most of the stones should be of the size indicated by the curve. Riprap 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
MASS OF SPHERICAL STONES IN KILOGRAMS SPECIFIC GRAVITY 2·6
BOTTOM VELOCITY, m/s
AVERAGE CHANNEL VELOCITY (m/s)
Fig:34.
Fig:35.
Fig:38.
Fig:39.
Fig:40.
Tab:III.
Fig:32.
Tab:II.
Fig:2.
Fig:3.
Fig:5.
Fig:6.
Fig:7.
Fig:8.
Fig:12.
Fig:13.
Tab:I.



1 Australian Rock Sizing Ancestry: Channel Bed and Bank Lining

ARR 2019

Austroads 2013 ← **QDTMR 2019**

↑ Compute bed shear stress (uncited)[1]

↑ **QDTMR 2010** → **QDTMR 2015** ↑

↑ **QDTMR 2002**[2]

↑ **USBR 1956-1984**[3]

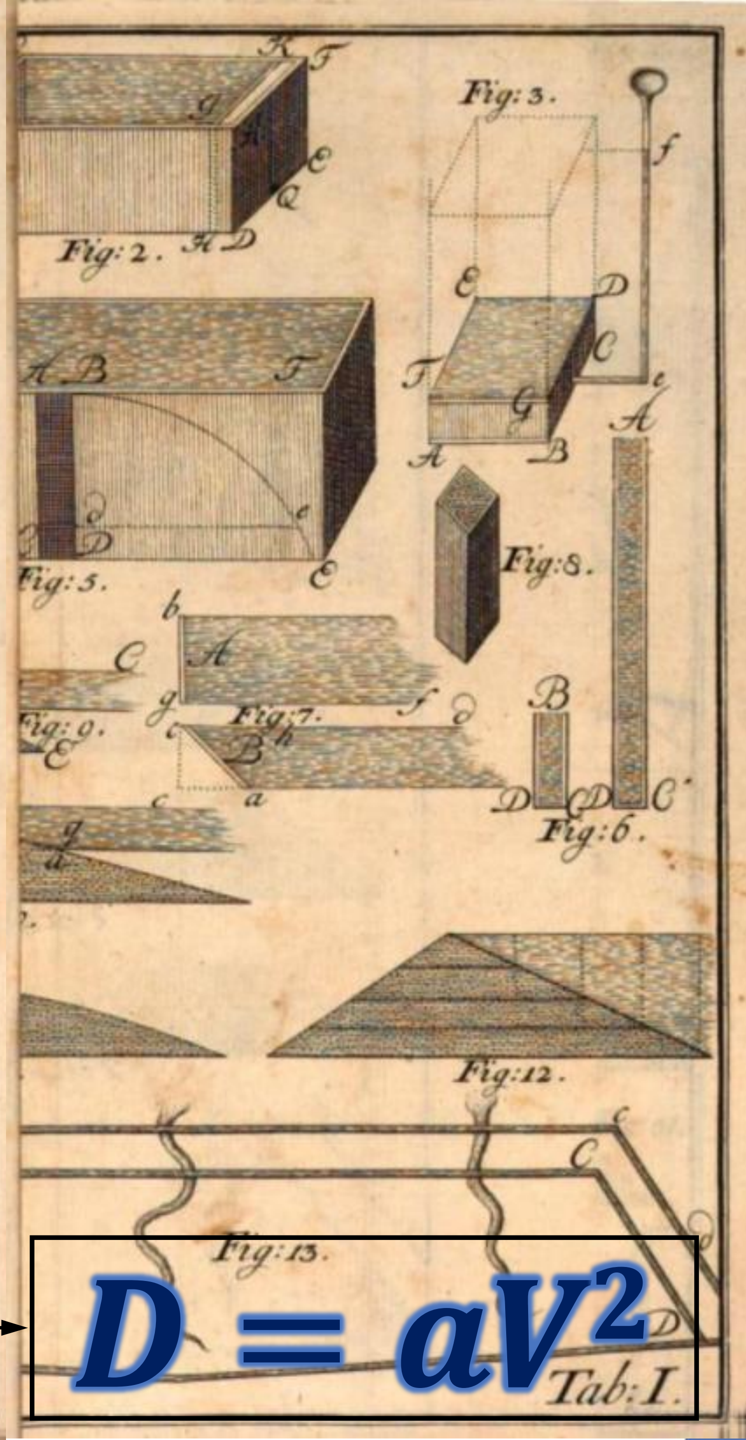
↑ **Berry 1948**[4]

[1] Bed shear stress is "important" for sediment motion in alluvial channels and scour at bridges

[2] Rock size should be based on channel velocity or "more accurately" to boundary shear stress

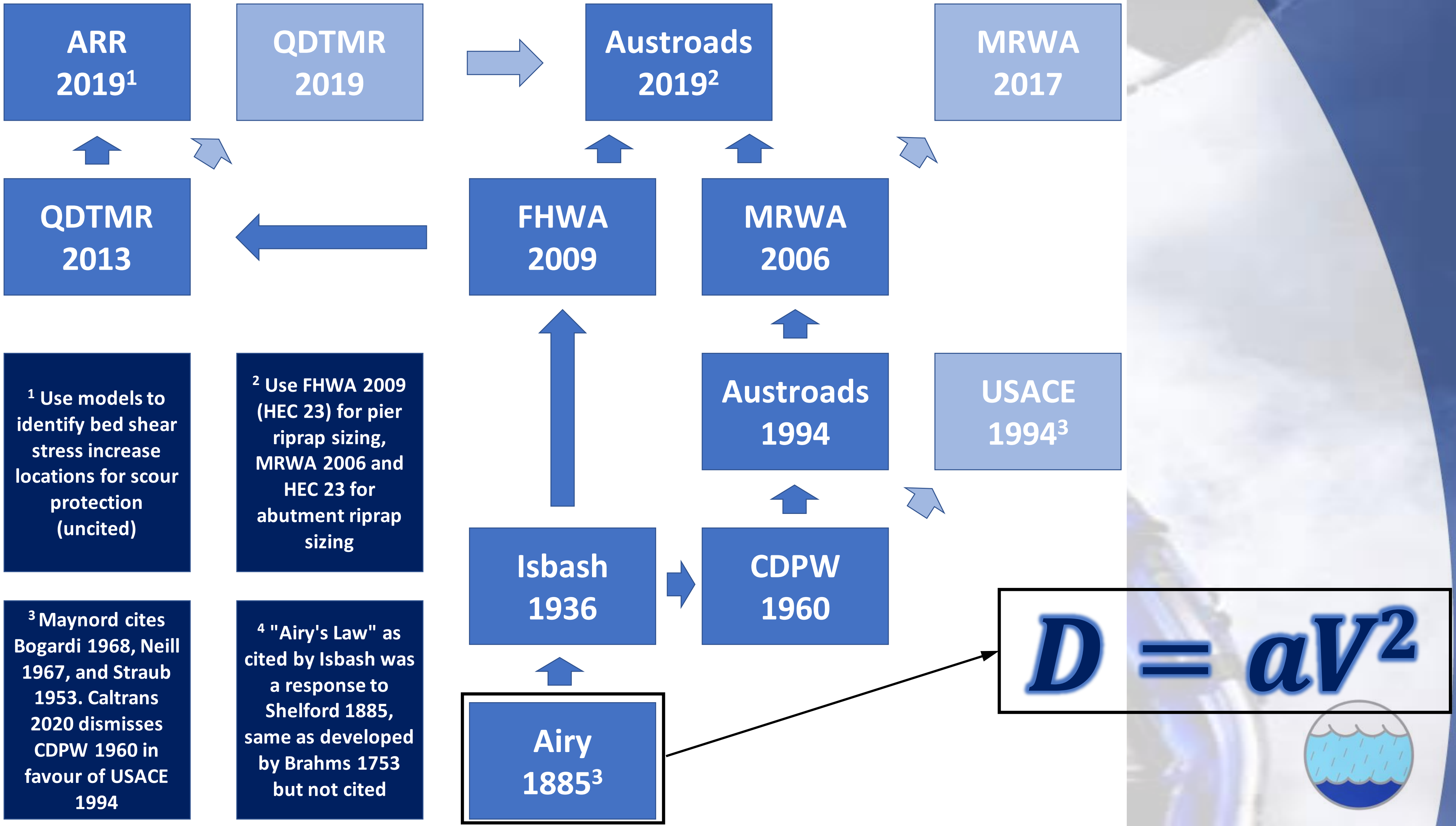
[3] USBR charts based on "bottom velocity" but experimental validation used average channel velocities

[4] Berry used average of values from flume experiments conducted between 1786 and 1914

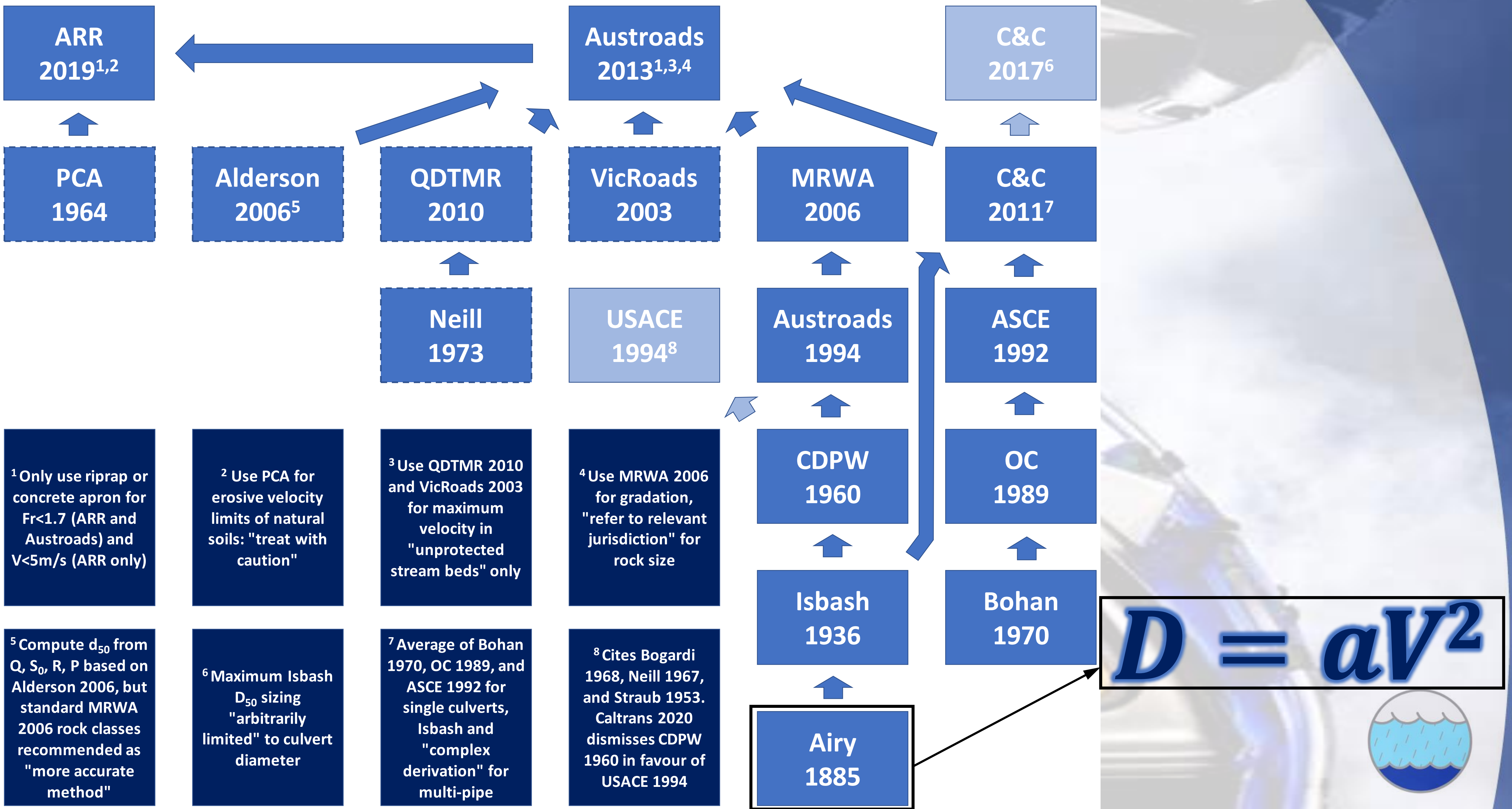


$$D = aV^2$$

2 Australian Rock Sizing Ancestry: Bridge Scour Countermeasures (Piers and Abutments)



3 Australian Rock Sizing Ancestry: Culvert Outlet Aprons



4 Australian Rock Sizing Ancestry: Floodways, Spillways, Rock Chutes, and Dissipation Structures

ARR 2019[1]

Austroads 2013

Compute Bed Shear Stress (uncited)[2]

NSW Govt 2004[3]

MRWA 2006

USACE 1994[4]

Austroads 1994

CDPW 1960

Isbash 1936

Airy 1885

[1] For earthen embankments and overflow spillways: use concrete or riprap for V>7m/s based on NSW Govt 2004

[2] Bed shear stress "important" for sediment motion in alluvial channels and scour at bridges

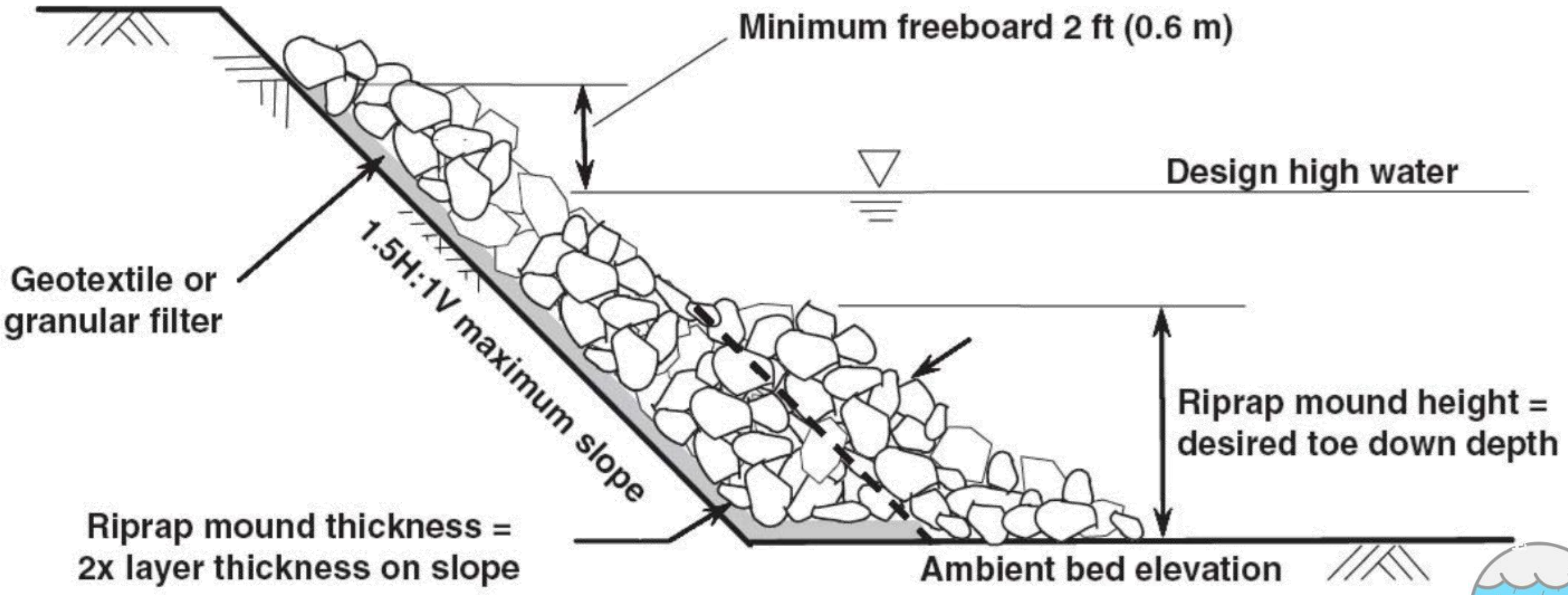
[3] NSW 2004 values vary linearly (not exponentially) with velocity, "compiled from various sources"

[4] Cites Bogardi 1968, Neill 1967, and Straub 1953. Caltrans 2020 dismisses CDPW 1960 in favour of USACE 1994

$$D = aV^2$$

Riprap design considerations and discrepancies

- Velocity distribution
- Shape
- Angle of repose
- Gradation



Velocity Distribution

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

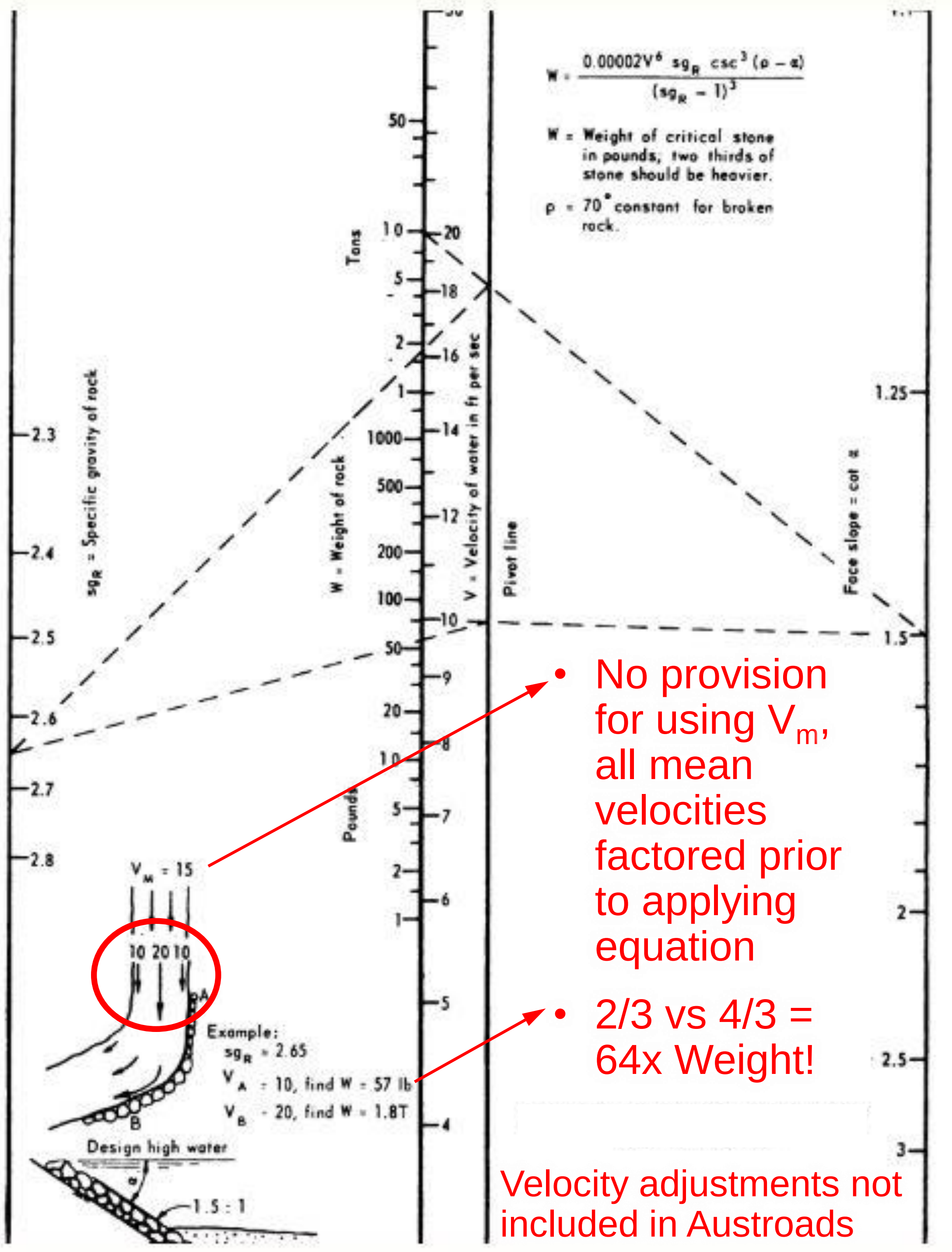
W = Weight of critical stone in pounds; two thirds of stone should be heavier.

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.

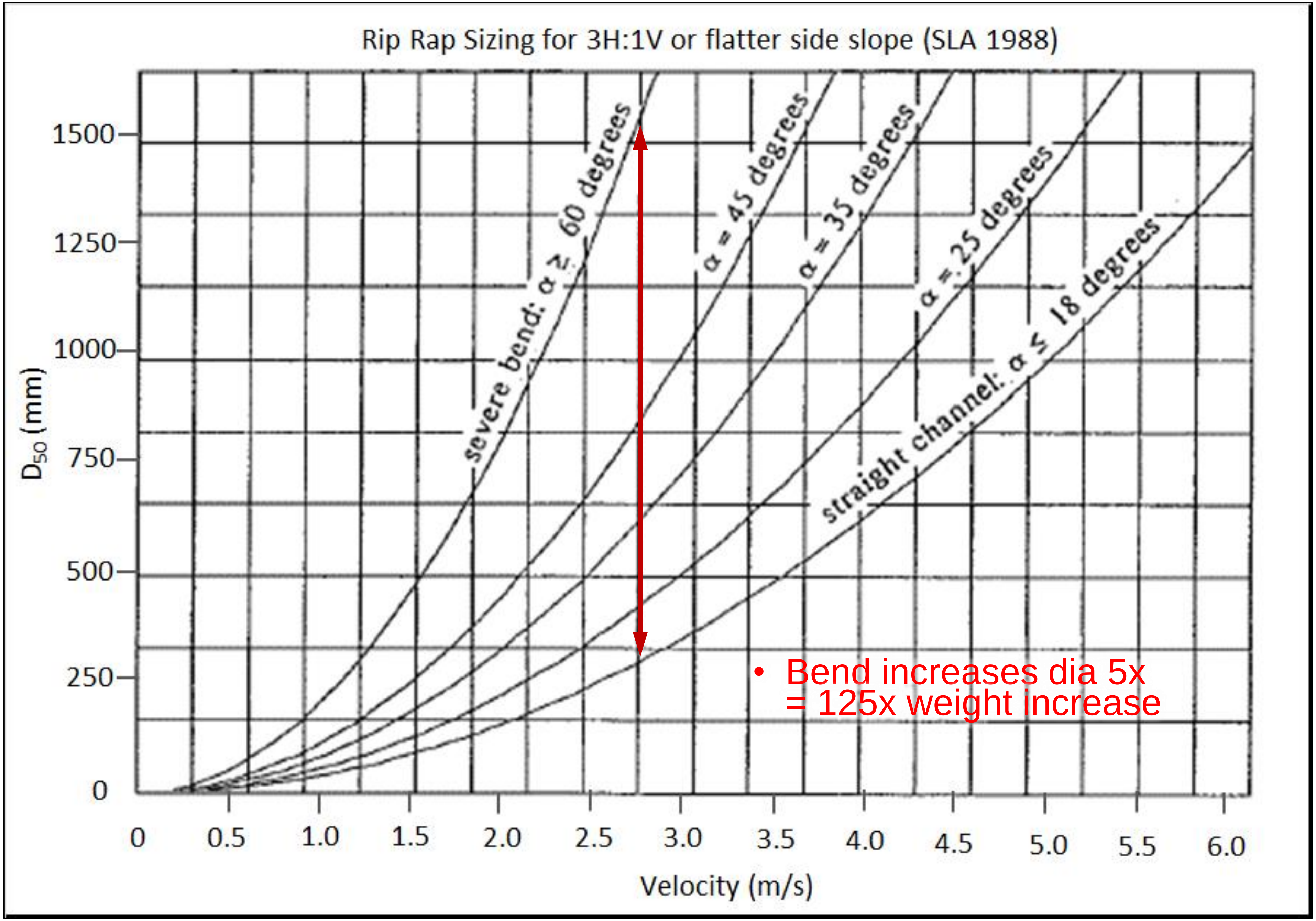
$$W = \frac{2 \times 10^{-5} \, V^6 \, sg_r}{(sg_r - 1)^3 \sin^3(\rho - \alpha)} = \frac{.00002 \; V^6 \cdot 2.65}{1.65^3 \quad .592^3} = .000057 \; V^6$$

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

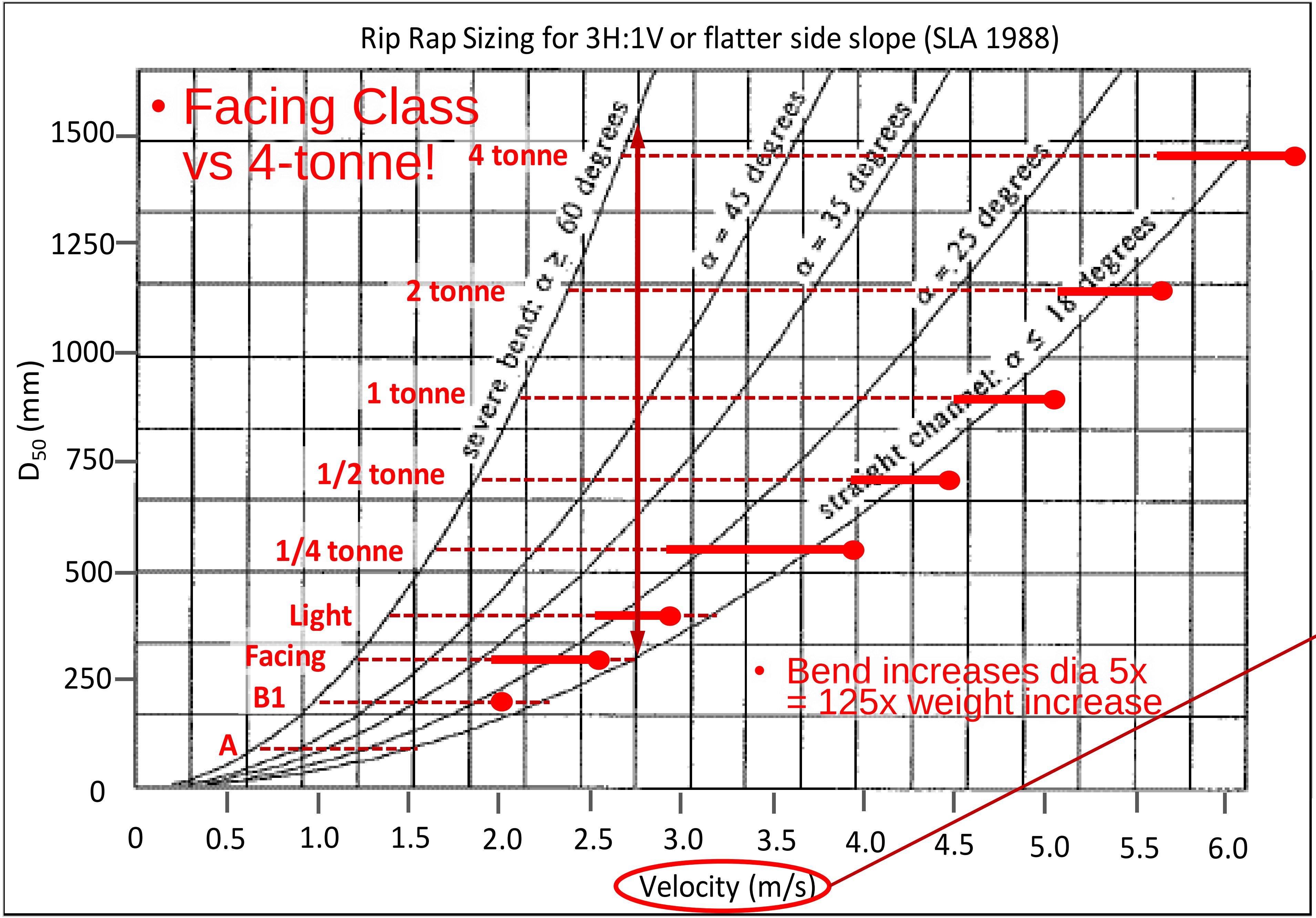


- No provision for using V_m, all mean velocities factored prior to applying equation
- 2/3 vs 4/3 = 64x Weight!

Velocity adjustments not included in Austroads

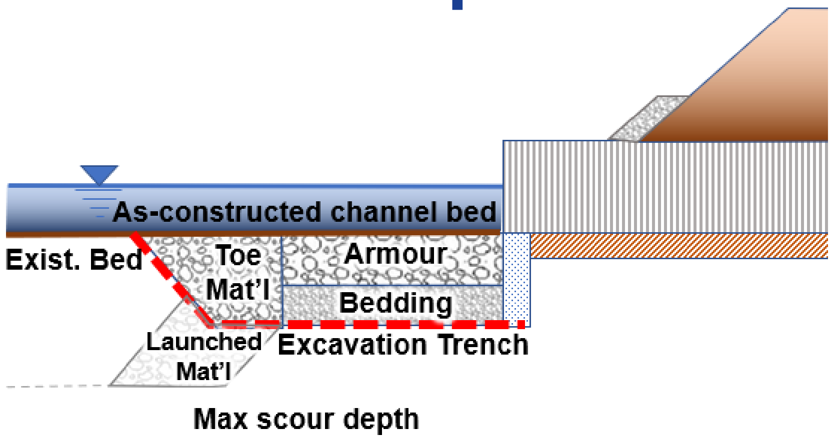


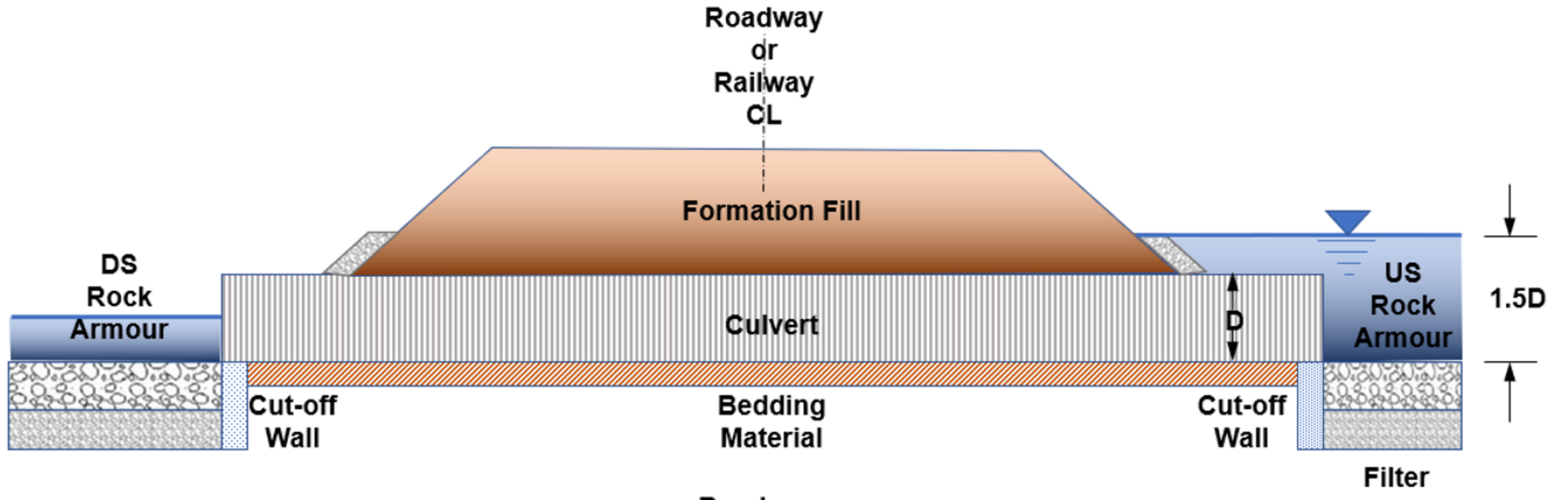
- Bend increases dia 5x = 125x weight increase



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

Culvert Aprons





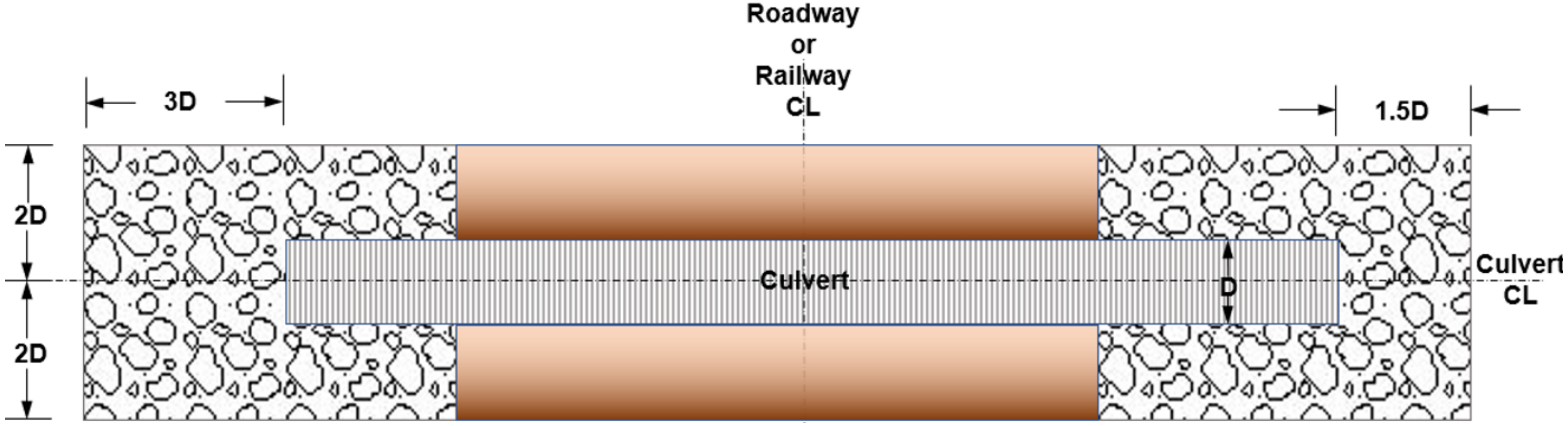
C&C 2011[7]

ASCE 1992

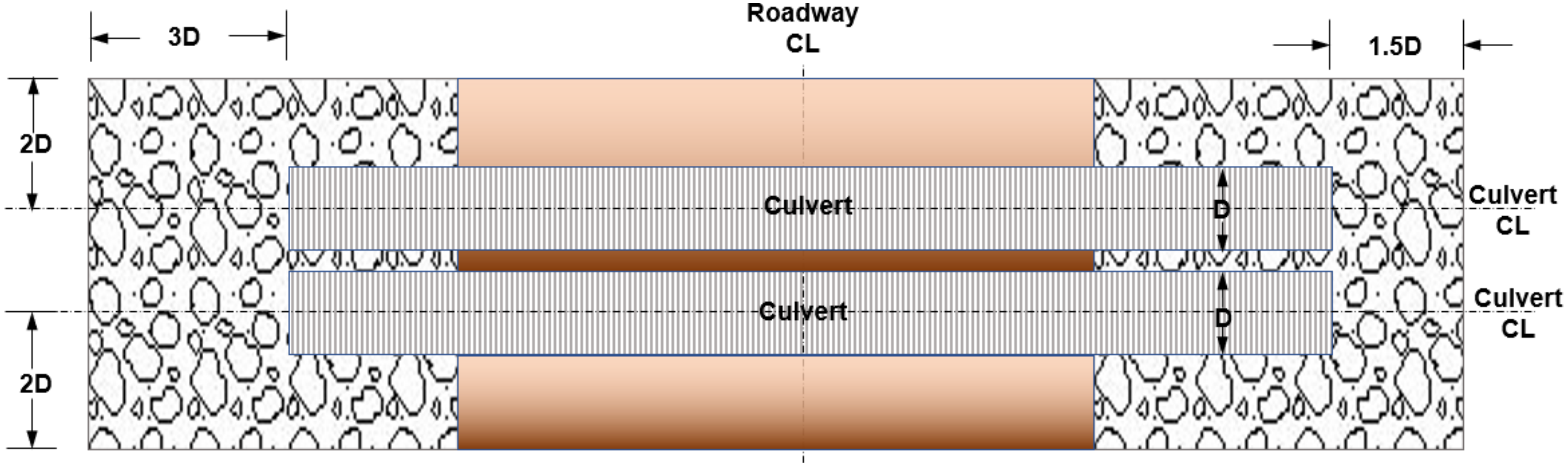
OC 1989

Bohan 1970

- Single barrel



- Multi barrel



Catchments & Creeks (cited in Austroads 2013)

www.catchmentsandcreeks.com.au

C&C 2017[6]

↑

C&C 2011[7]

↑

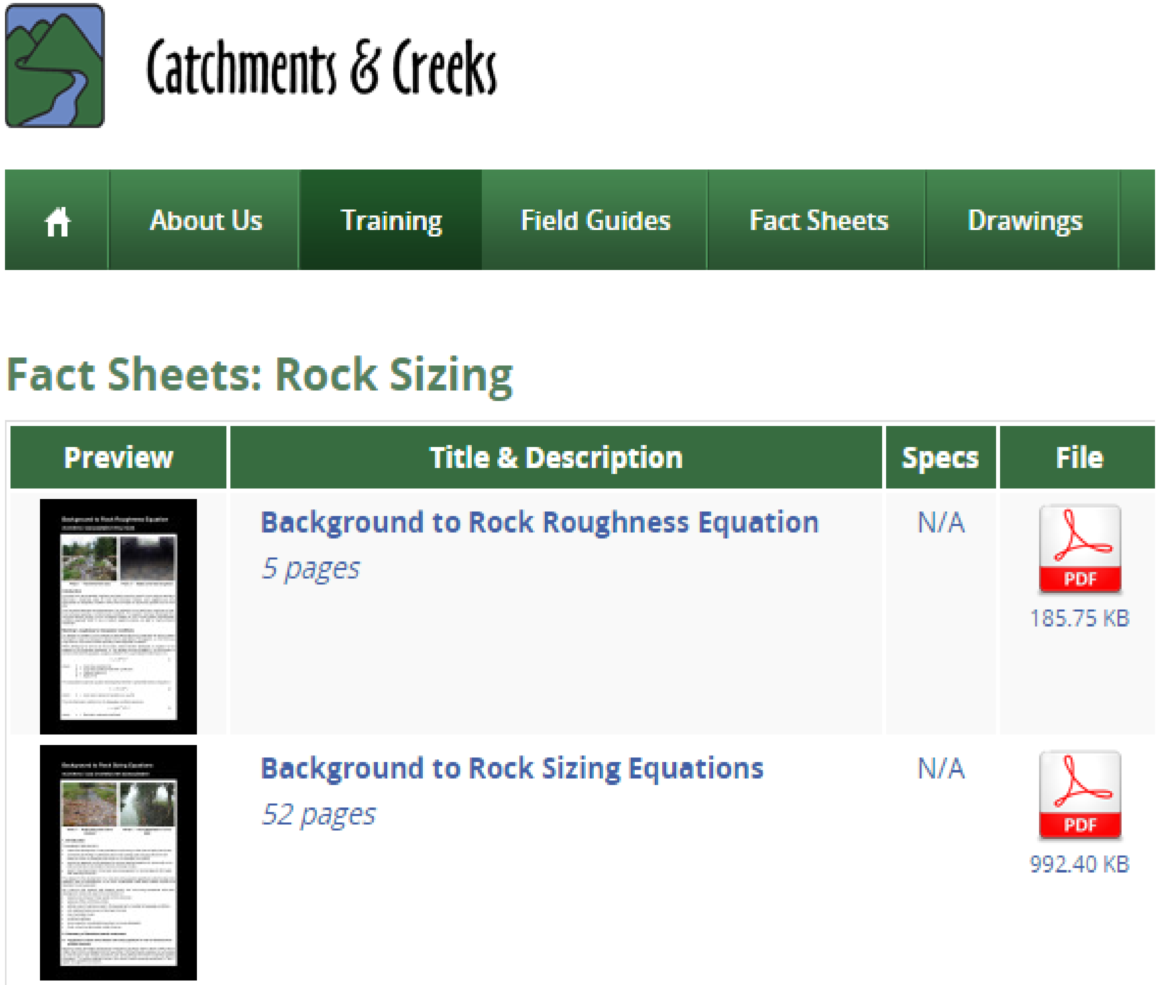
ASCE 1992

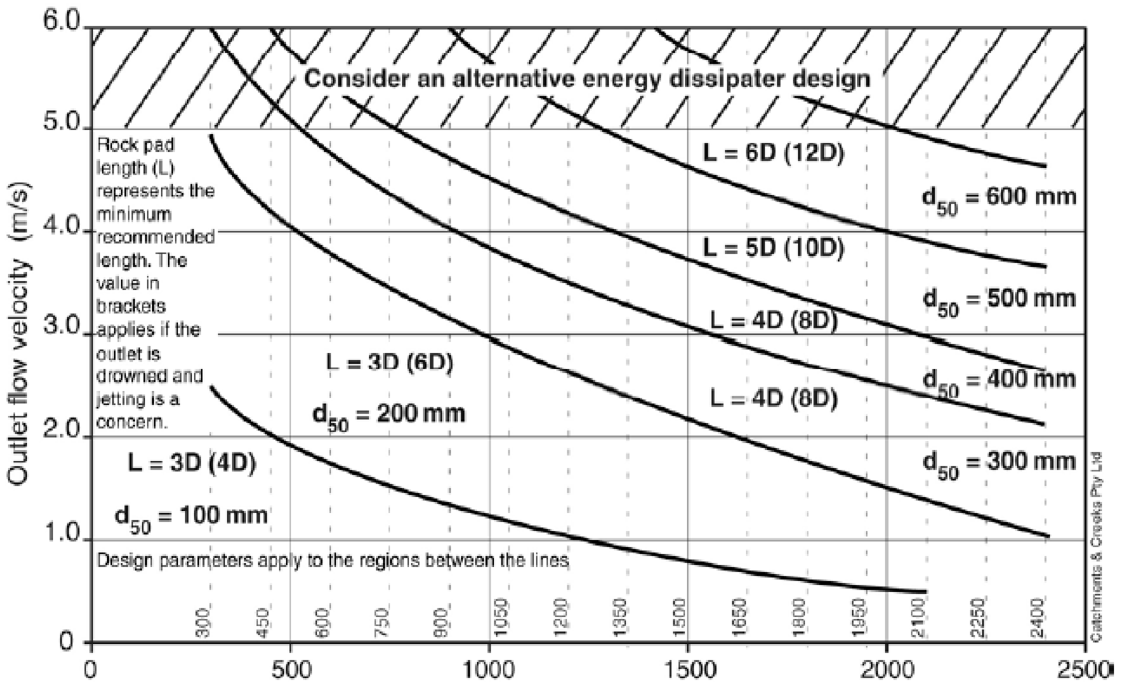
↑

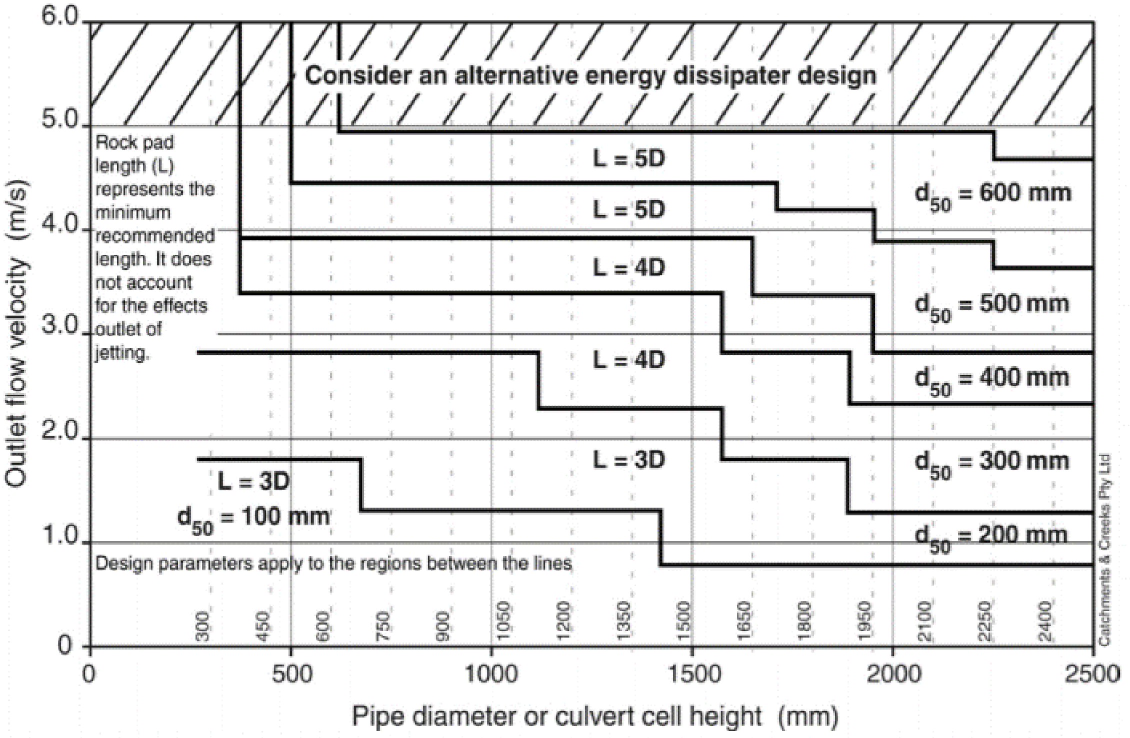
OC 1989

↑

Bohan 1970





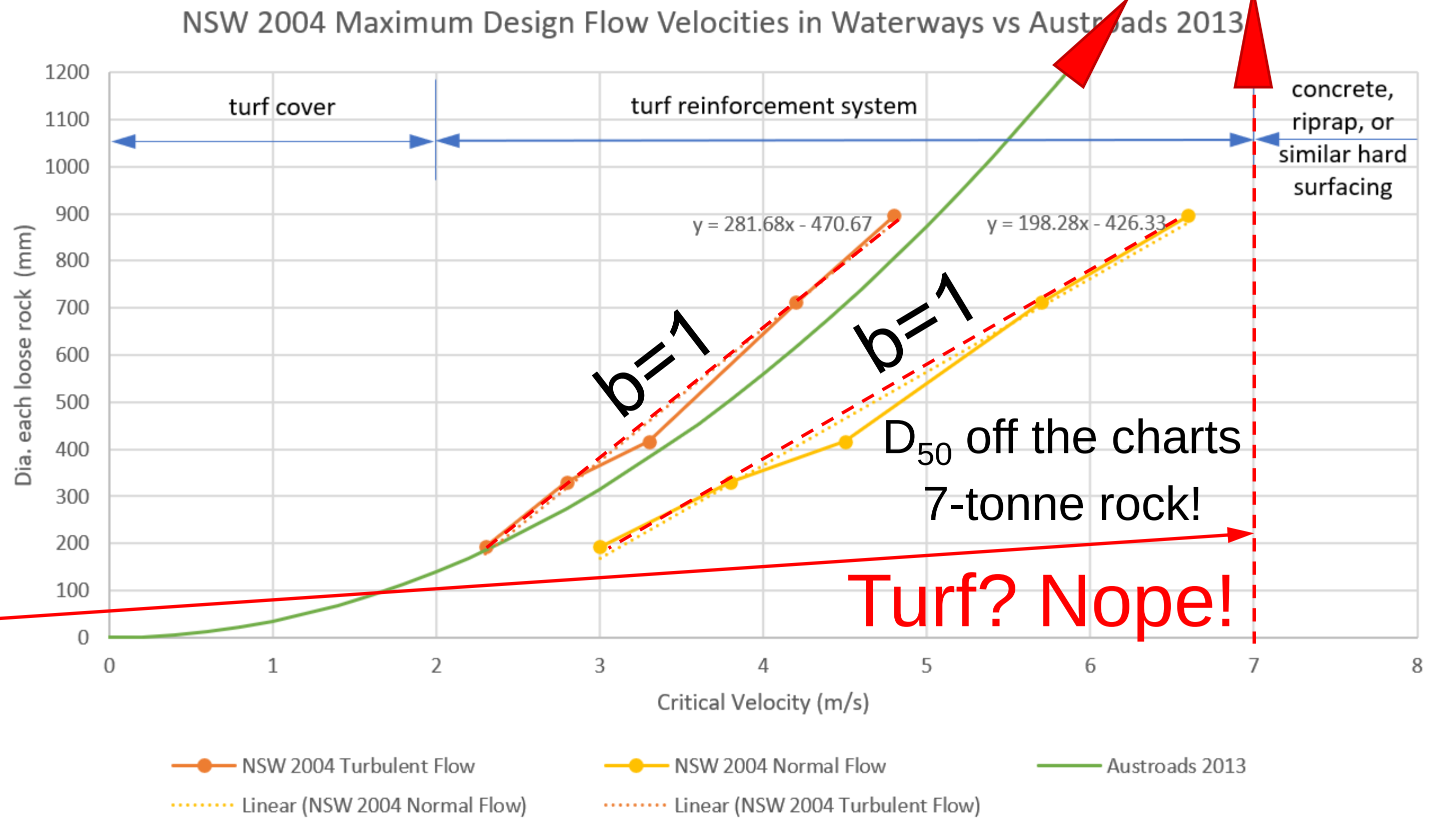


NSW 2004 (cited in ARR 2019)

- No citations, compiled from “various sources”
- For $D=a*V^b$, NSW 2004 shows linear relationship between D and V with b=1
- b varies between 2 and 3 (based on 200+ sources)
- b is never 1!

Material			Critical velocity (m/second)
Type	Thickness (m)	Aggregate size (mm)	
Gabions and reno mattresses	0.50	120-250	6.4
	0.50	100-200	5.8
	0.30	100-150	5.0
	0.30	70-120	4.2
	0.25	70-100	3.6
	0.17	70-100	3.5

Type	Weight each (kg)	Turbulent flow	Normal flow
Loose rock (assume 100 percent soil cover)	1,000	4.8	6.6
	500	4.2	5.7
	100	3.3	4.5
	50	2.8	3.8
	10	2.3	3.0



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

- V ≤ 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 ≥ 7 m/s hard surfacing with concrete, riprap or similar.

VicRoads 2003, DTMR 2010, Neill 1973 (Cited in ARR 2019)

Table 4.4 Erosive Velocities in Natural Streams

Stream Bed Type		Velocity (m/s)
Silt		less than 0.3
Sand	fine	less than 0.3
	coarse	0.4 to 0.6
Gravel	6 mm	0.6 to 0.9
	25 mm	1.3 to 1.5
	100 mm	2.0 to 3.0
Clay	soft	0.3 to 0.6
	stiff	1.0 to 1.2
	hard	1.5 to 2.0
Rocks	150 mm	2.5 to 3.0
	300 mm	3.5 to 4.0

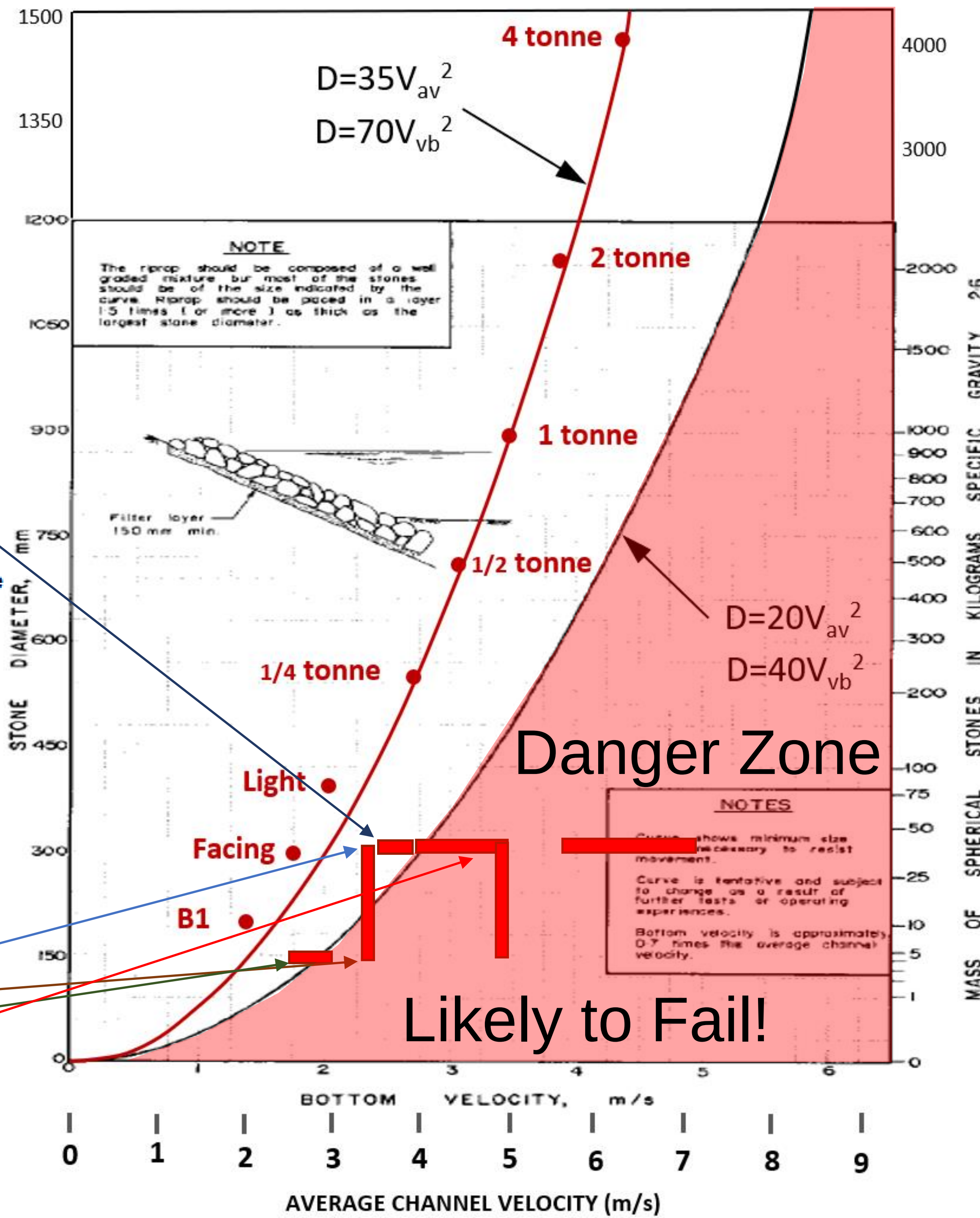
Table 2.5: Erosive velocities in natural streams

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

Table 3.10: Desirable maximum flow velocities in culverts or unprotected stream be

Stream bed soil type	Maximum advisable culvert velocity (m/s)	Maximum allowable stream velocity (m/s)
Silt	1.0–1.5	< 0.3
Clay, soft	1.0–1.5	0.3–0.6
Clay, stiff	1.2–2.0	1.0–1.2
Clay, hard	1.2–2.0	1.5–2.0
Sand, fine	1.0–1.5	< 0.3
Sand, coarse	1.0–1.5	0.4–0.6
Gravel, 6 mm	1.0–1.5	0.6–0.9
Gravel, 25 mm	1.2–2.0	1.3–1.5
Gravel, 100 mm	2.5	2.0–3.0
Rocks, 150 mm	3.5	2.5–3.0
Rocks, 300 mm	3.5	4.0–5.0

Source: Derived from DTMR (2010b) and VicRoads (2003).



Shape

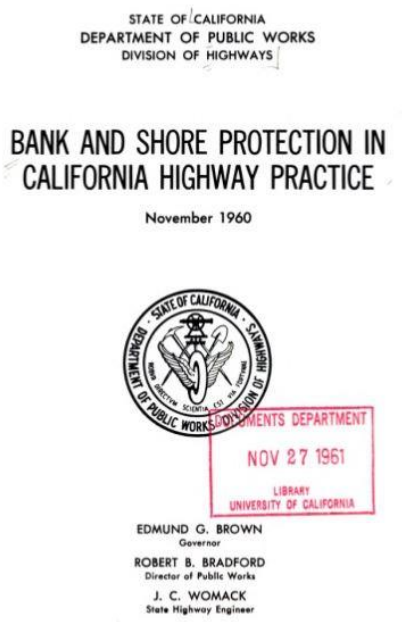
Assumed spherical for diameter-volume-weight calculations

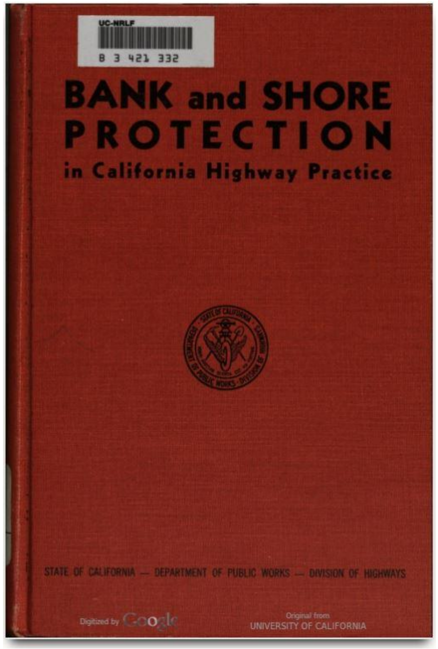
Assumed angular for calculations

FIG. 6. Large Sediment Particle Found on Streambed after Sizable Flood of Santa Clara River in California (Courtesy of Margaret Petersen, Honorary Member, ASCE)

- Volume of sphere is approximately half the volume of a cube with edges equal to sphere diameter
- Some methods recommend using a mid-way value of 75%-85% of the volume of an equivalent cube
- Austroads assumes spherical conversion and specific gravity of 2.65; some methods allow variation in s.g.

Angle of Repose





California Department of Transportation RSP
This technique was developed by the California Department of Transportation (CALTRANS) for designing rock slope protection (RSP) for streams and riverbanks. Unlike most of the other available techniques, it results in a recommended minimum weight of the stone. The equation is:

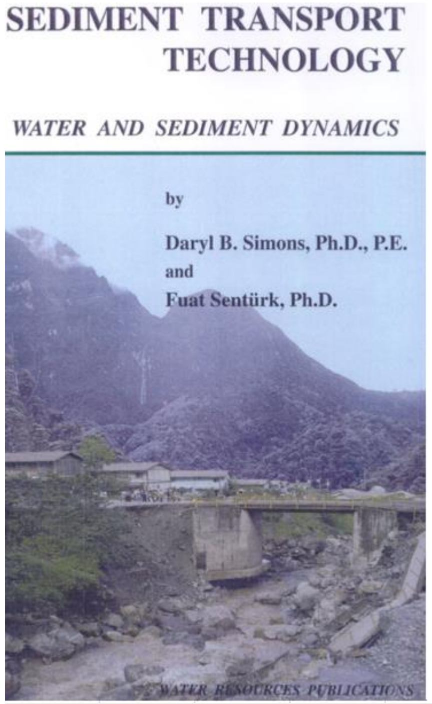
$$W = \frac{0.00002}{(G_S - 1)^3} \times \frac{VM \times V^6 \times G_S}{\sin^3(r - a)} \qquad \text{(eq. TS14C–18)}$$

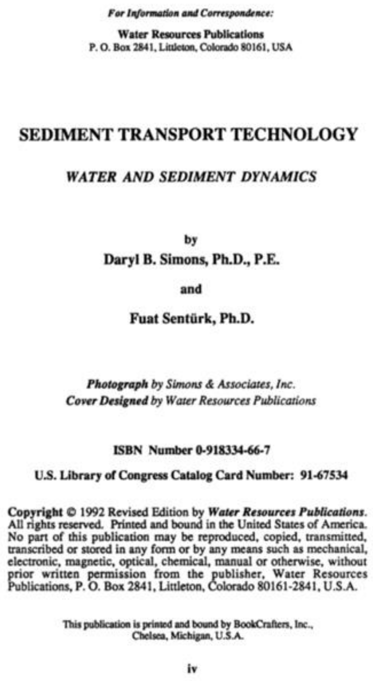
where:
- W = minimum rock weight (lb)
- V = velocity (ft/s)
- VM = 0.67 if parallel flow
- VM = 1.33 if impinging flow
- G_s = specific gravity of rock (typically 2.65)
- r = angle of repose (70° for randomly placed rock)
- a = outside slope face angle to the horizontal (typically a maximum of 33°)

- Nope!

The definition of r equals 70° (for randomly placed rubble, a constant). Neither the 1960 manual nor the 2000 manual discusses why the value of r is 70°. However, Blodgett and McConaughy (1986) refer to notes assembled by R.M. Carmany of Caltrans that discuss laboratory experiments conducted by the University of California to determine the minimum force to dislodge a stone from the bank. The University of California constructed a model streambank with small stones arranged as riprap and underlying stones cemented into a plaster base. The side slope was increased until the first outer stone was displaced. A maximum angle of 65° to 70° was attained before the first stone fell out. It is assumed that the value of r equals 70° is based on these tests.

- Cheat!

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SEDIMENT TRANSPORT TECHNOLOGY

WATER AND SEDIMENT DYNAMICS

by
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and
Fuat Sentürk, Ph.D.

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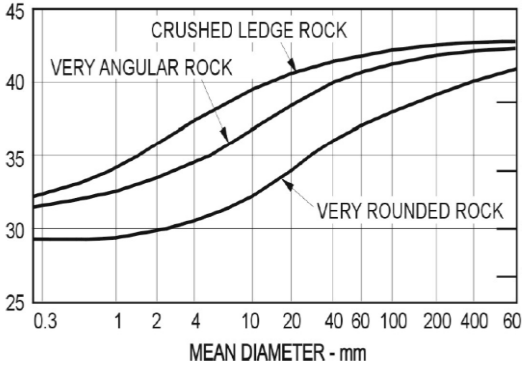
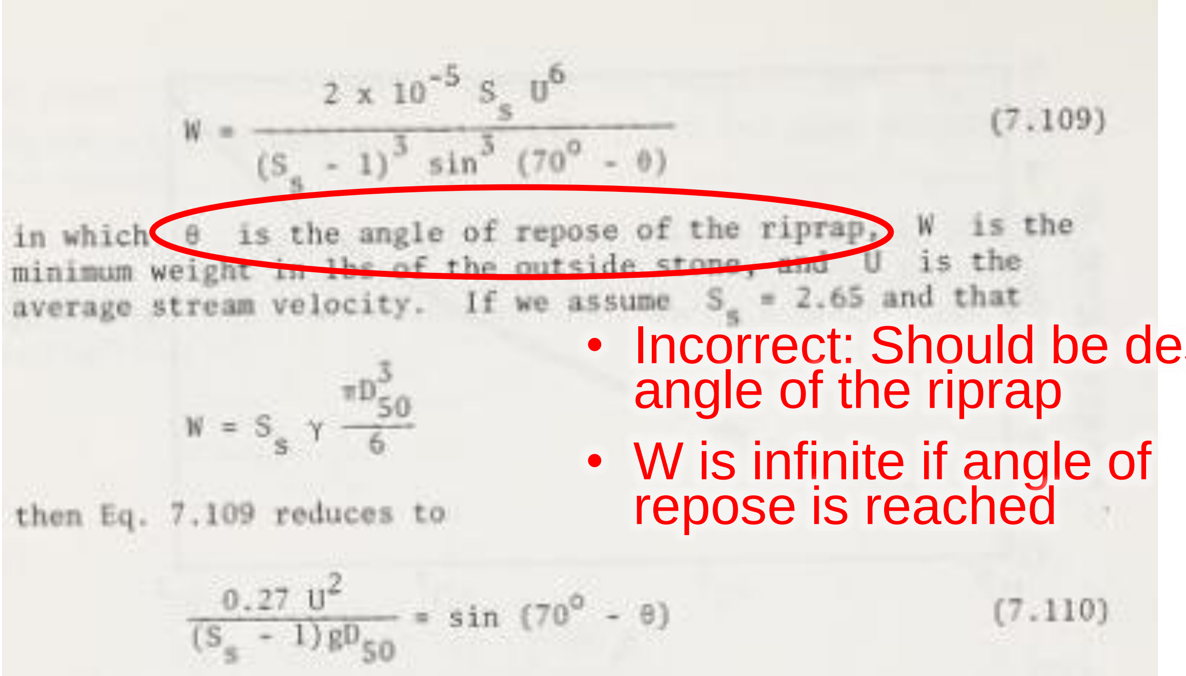



$$W = \frac{2 \times 10^{-5}\, S_s\, U^6}{(S_s - 1)^3 \sin^3 (70^\circ - \theta)} \qquad (7.109)$$

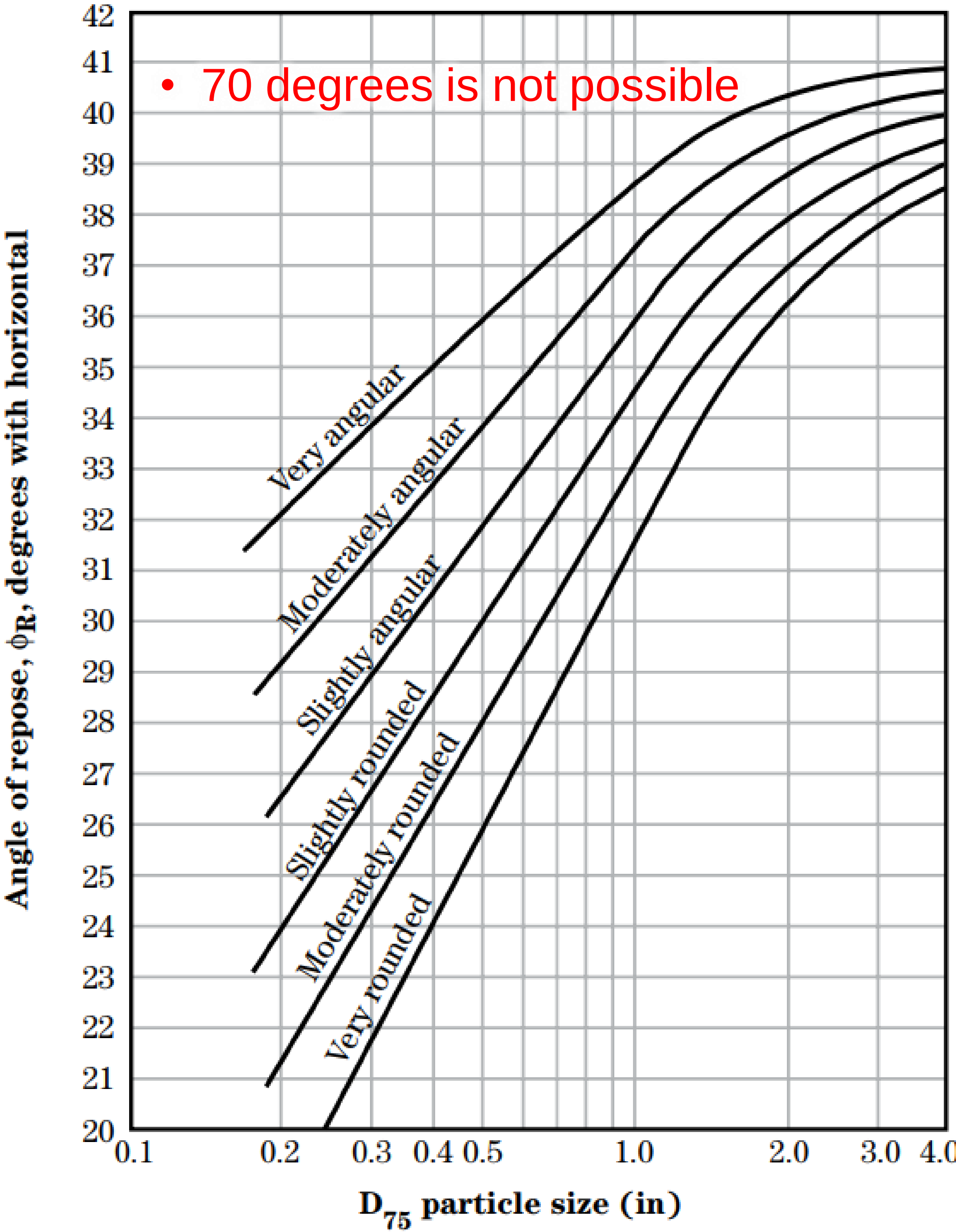
in which θ is the angle of repose of the riprap, W is the minimum weight in lbs of the outside stone, and U is the average stream velocity. If we assume $S_s = 2.65$ and that

$$W = S_s\, \gamma\, \frac{\pi D_{50}^3}{6}$$

then Eq. 7.109 reduces to

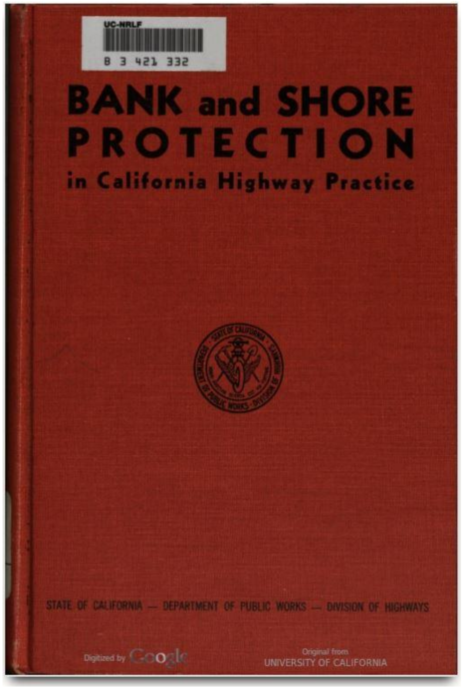
$$\frac{0.27\, U^2}{(S_s - 1) g D_{50}} = \sin (70^\circ - \theta) \qquad (7.110)$$

- Incorrect: Should be design angle of the riprap
- W is infinite if angle of repose is reached



- 70 degrees is not possible

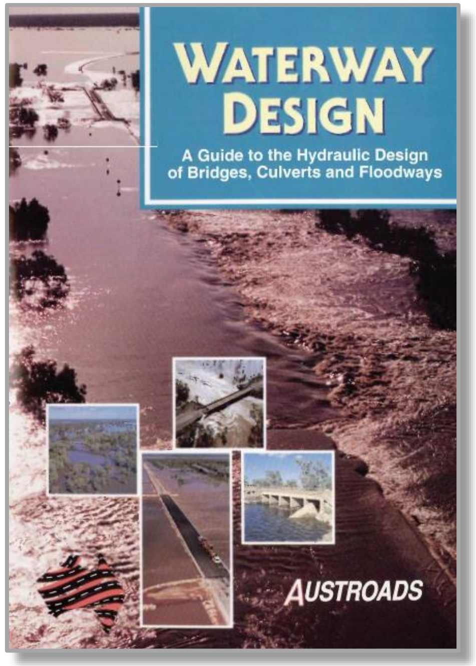
Gradation



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

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

ρ = 70° constant for broken rock.



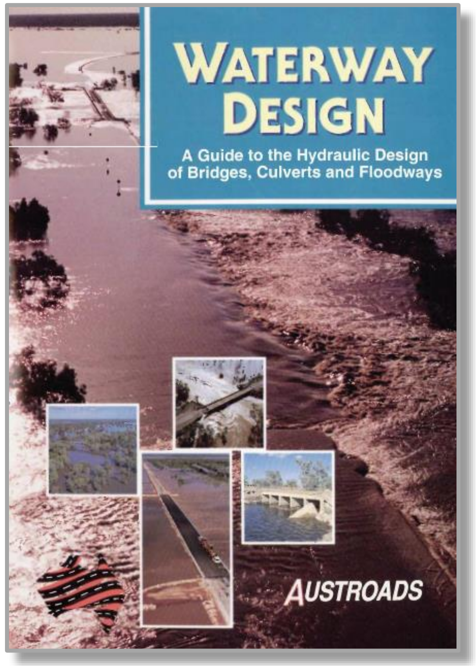
Note that the mass by which the Class of rock protection, W_c is designated does not correspond to the mass W. The Class of rock protection, W_c should be graded so that at least 2/3 of all rocks in the Class have a greater mass than W.

Rock

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

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

ρ = 70° constant for broken rock.



Note that the mass by which the Class of rock protection, W_c is designated does not correspond to the mass W. The Class of rock protection, W_c should be graded so that at least 2/3 of all rocks in the Class have a greater mass than W.

Rock

vs rocks

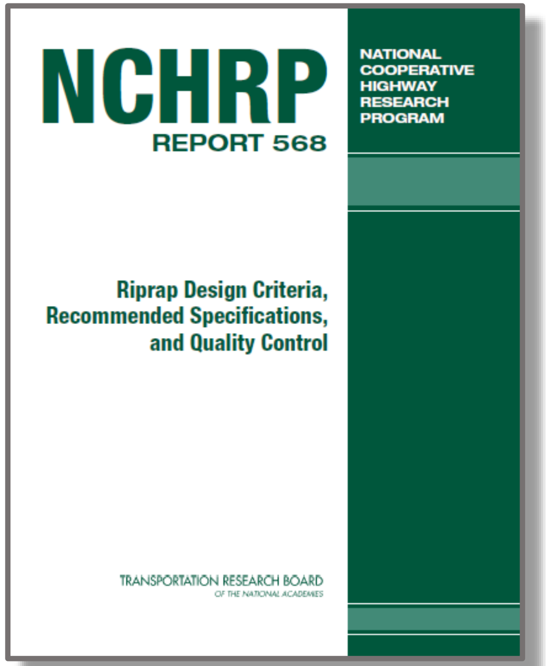
$$W = \frac{0.00002V^6 \, sg_R \, \csc^3(\rho - \alpha)}{(sg_R - 1)^3}$$

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

ρ = 70° constant for broken rock.

Note that the mass by which the Class of rock protection, W_c is designated does not correspond to the mass W. The Class of rock protection, W_c should be graded so that at least 2/3 of all rocks in the Class have a greater mass than W.

Gradation



CEN provides standard gradation classes for aggregates (five classes by size), light riprap (five classes by weight up to 300 kg), and heavy riprap (5 classes by weight up to 15,000 kg) (CEN, 2002). Particles with a length to thickness ratio A/C greater than 3.0 cannot be more than 20% by weight for aggregates and light riprap; for heavy riprap, the limit is 5% based on number of particles. Requirements for documenting the design, production, delivery, and placement of riprap are provided, as is guidance for general record-keeping procedures.

Size. Riprap design methods typically yield a required size of stone that will result in stable performance under the design loadings. Because stone is produced and delivered in a range of sizes and shapes, the required size of stone is often stated in terms of a minimum allowable representative size. For example, the designer may specify a minimum d_{50} or d_{30} for the rock composing the riprap, thus indicating the size for which 50% or 30% (by weight) of the particles are smaller. Stone sizes can also be specified in terms of weight (e.g., W_{50} or W_{30}) through the use of an equivalent spherical or cuboidal particle shape, and the known (or assumed) density of the particle.

Order of magnitude difference in W_{50}

The desired particle dimension or weight is typically expressed in the form of a size distribution curve. Such curves usually indicate the percentage of stones that are smaller than the indicated size, although the CABS (Racin et al., 2000) gradations are based on the percentage larger than the indicated size.

Whether expressed as a "larger than" or "smaller than" gradation, a size distribution curve represents the cumulative distribution function of the sample population of the various rocks that compose the matrix of particles. The d_{50} (or W_{50}) value represents the size for which half the particles are larger and half are smaller (i.e., the *median* size). The steepness of the distribution curve is a measure of the standard deviation of the particle sizes about the median and is referred to as the uniformity of the gradation. The probability function is not necessarily a normal ("bell-shaped" or Gaussian) distribution.

Once 100 particles have been measured, the frequency curve is developed by counting the number of particles less

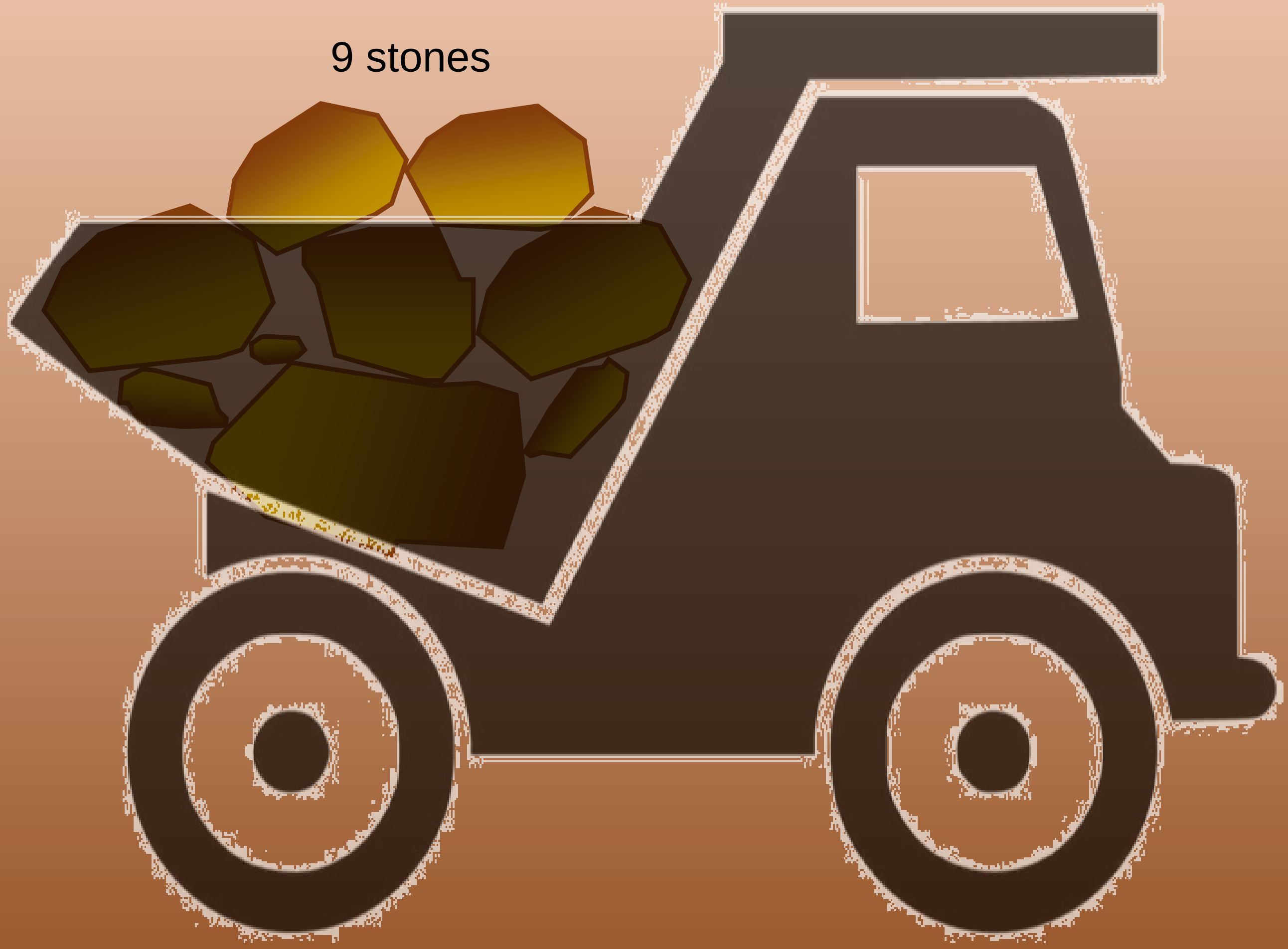
Gradation Specifications

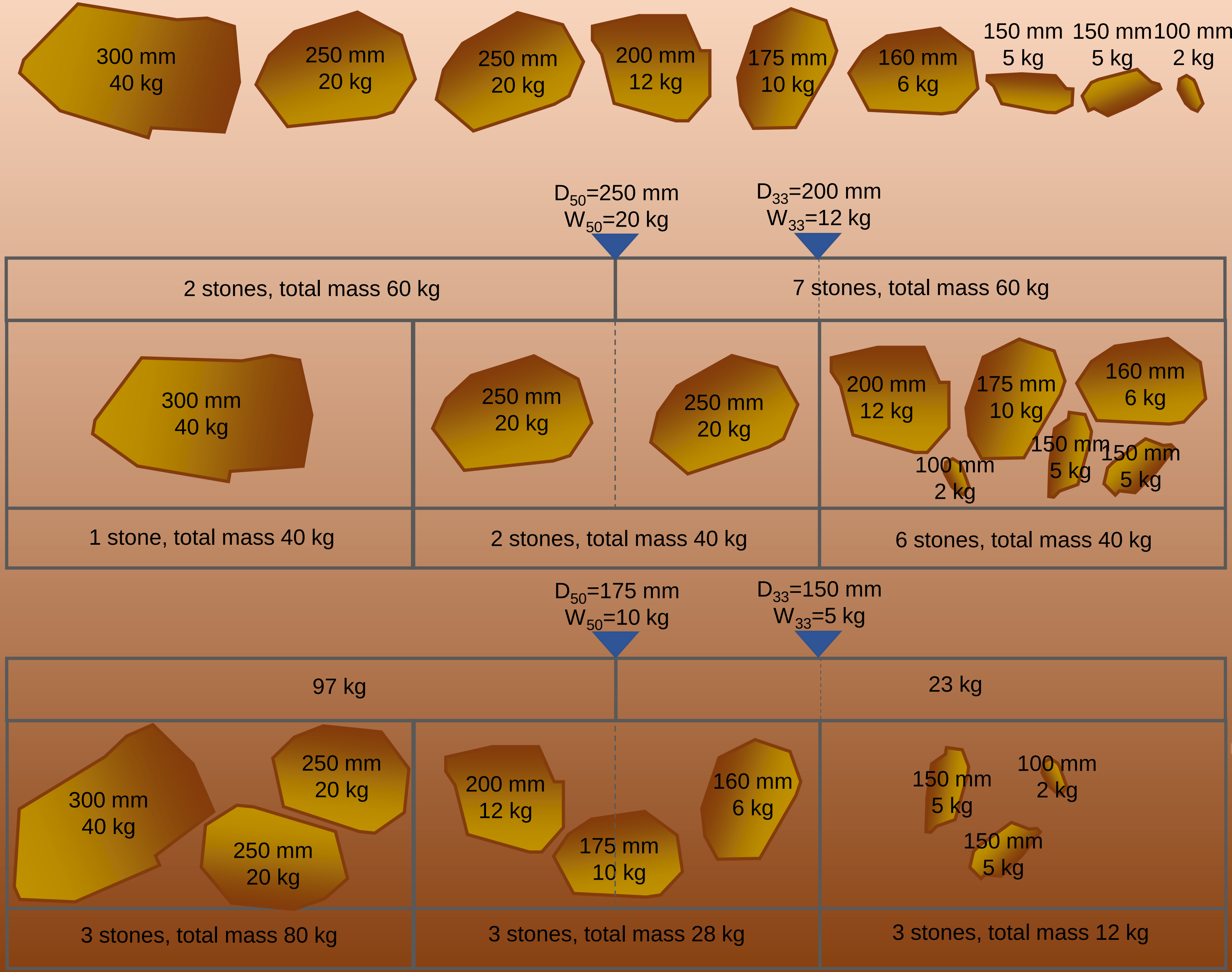
General. Gradation specifications for riprap prescribe a range of allowable sizes for a given riprap class. Sizes can be defined by weight or by a length dimension. Practical specification guidance must allow producers to supply rock with a range of sizes that allows reasonable, but not excessive, deviation from the "ideal" particle size distribution curve. The underlying principle in this regard is to achieve economy through standardization without sacrificing hydraulic stability. From this perspective, the specification should result in a matrix of rocks that has a majority of particles that are equal to, or larger than, the size required for stability at the design hydraulic loading. A certain amount of particles that are smaller than the stable size can be tolerated, but in much smaller proportion.

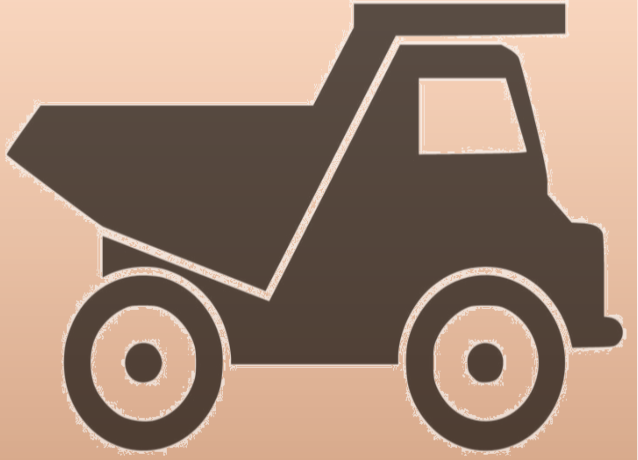
A specification that allows an excessive amount of undersized stones can result in failure by particle displacement. On the other hand, a specification that requires a large proportion of particles significantly greater than the stable stone size will result in unnecessarily high cost, both for the material itself, and for the transportation and placement of that material. Thus, there is a very real need to strike a balance between "too many small particles" on the one hand, versus "too many large particles" on the other.

- "Number of particles" implies "by weight" or count at regular intervals

What is the D_{33} and the D_{50}?

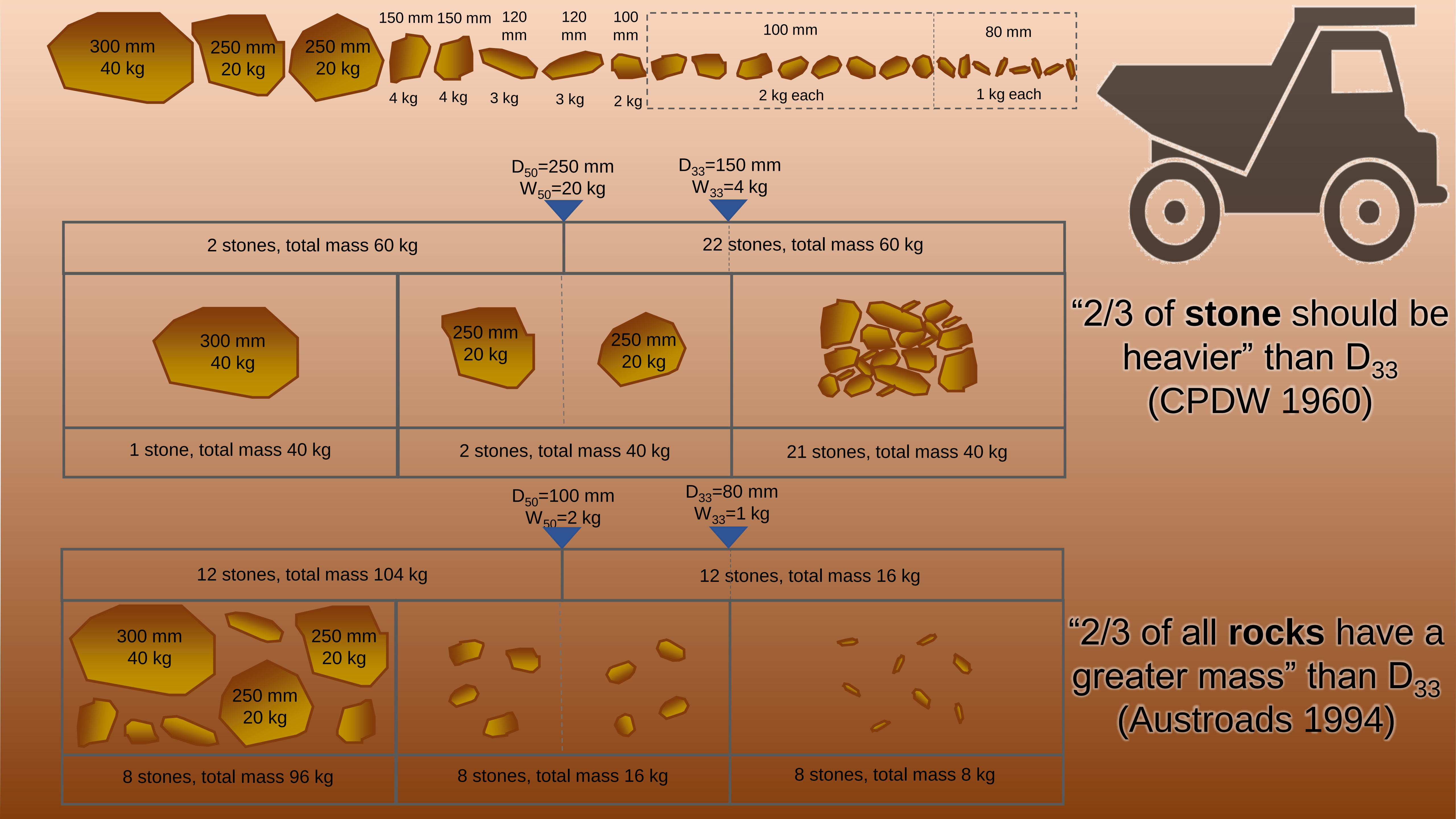






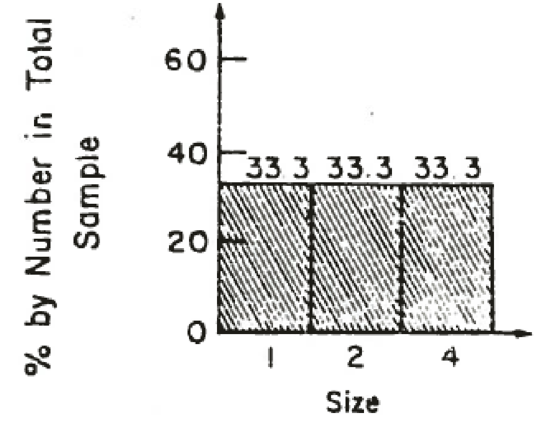
“2/3 of **stone** should be heavier” than D_{33} (CPDW 1960)

“2/3 of all **rocks** have a greater mass” than D_{33} (Austroads 1994)

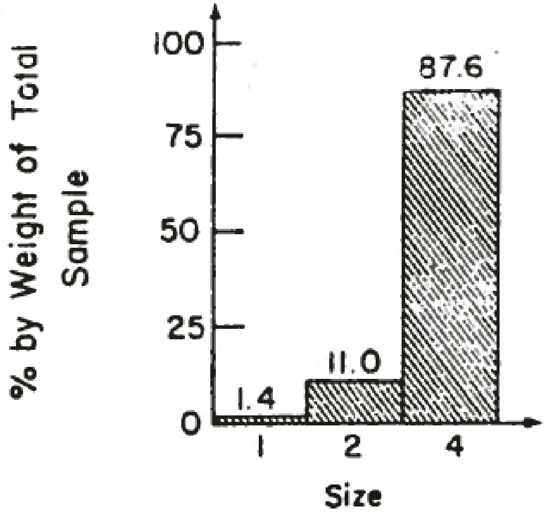


300 mm
40 kg
250 mm
20 kg
250 mm
20 kg
150 mm
4 kg
150 mm
4 kg
120 mm
3 kg
120 mm
3 kg
100 mm
2 kg
100 mm
2 kg each
80 mm
1 kg each
D_{50}=250 mm
W_{50}=20 kg
D_{33}=150 mm
W_{33}=4 kg
2 stones, total mass 60 kg
22 stones, total mass 60 kg
1 stone, total mass 40 kg
2 stones, total mass 40 kg
21 stones, total mass 40 kg
“2/3 of **stone** should be heavier” than D_{33} (CPDW 1960)
D_{50}=100 mm
W_{50}=2 kg
D_{33}=80 mm
W_{33}=1 kg
12 stones, total mass 104 kg
12 stones, total mass 16 kg
8 stones, total mass 96 kg
8 stones, total mass 16 kg
8 stones, total mass 8 kg
“2/3 of all **rocks** have a greater mass” than D_{33} (Austroads 1994)

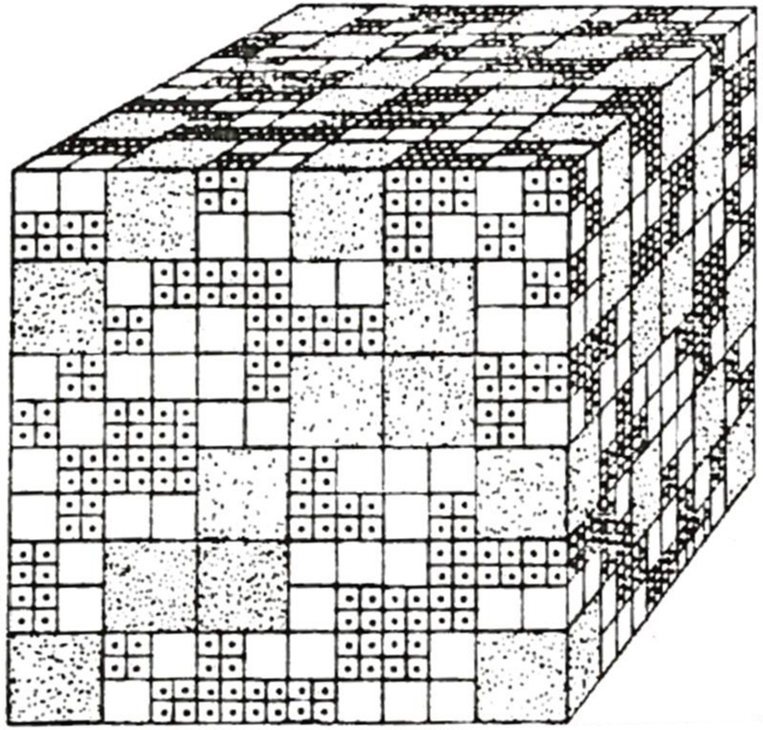
Cube Model



b) Grid-by-Number



d) Grid-by-Weight



Particle	Linear Size D	Weight W	Total No. in Sample Volume	Total No. in Sample Surface
	1	1	4608	192
	2	8	576	48
	4	64	72	12

Gradation

Table 4.2: Standard classes of rock slope protection

Rock class	Rock size (m)	Rock mass	Minimum percentage of rock larger than
Facing	0.4 0.3 0.15	100 35 2.5	0 50 90
Light	0.55 0.40 0.20	250 100 10	0 50 90
¼ tonne	0.75 0.55 0.30	500 250 35	0 50 90
½ tonne	0.90 0.70 0.40	1000 450 100	0 50 90
1 tonne	1.15 0.90 0.55	2000 1000 500	0 50 90
2 tonne	1.45 1.15 0.75	4000 [illegible] 500	0 50 90
4 tonne	1.80 1.45 0.90	8000 4000 1000	0 50 90

- Error
- Error

Rock Class	Rock Size (m)	Rock mass (kg)	Minimum Percentage of Rock Larger Than
Facing	0.40 0.30 0.15	100 35 2.5	0 50 90
Light	0.55 0.40 0.20	250 100 10	0 50 90
¼ tonne	0.75 0.55 0.30	500 250 35	0 50 90
½ tonne	0.90 0.70 0.40	1000 450 100	0 50 90
1 tonne	1.15 0.90 0.55	2000 1000 250	0 50 90
2 tonne	1.45 1.15 0.75	4000 2000 500	0 50 90
4 tonne	1.80 1.45 0.90	8000 4000 1000	0 50 90

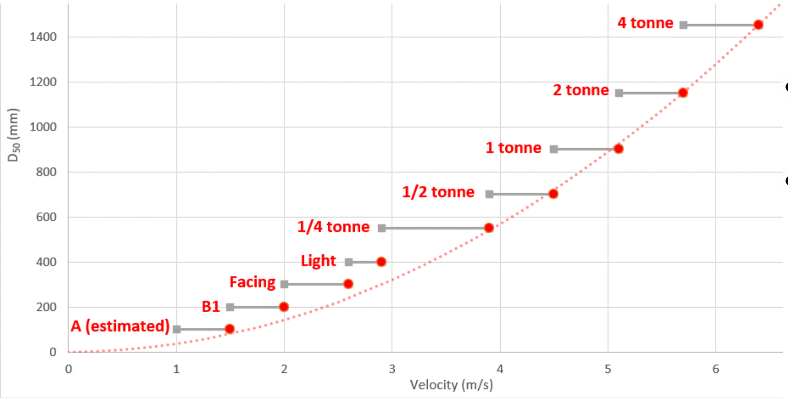
- Error

Table 5.2 – Standard Classes of Rock Slope Protection

Table 3.12: Standard classes of rock slope protection

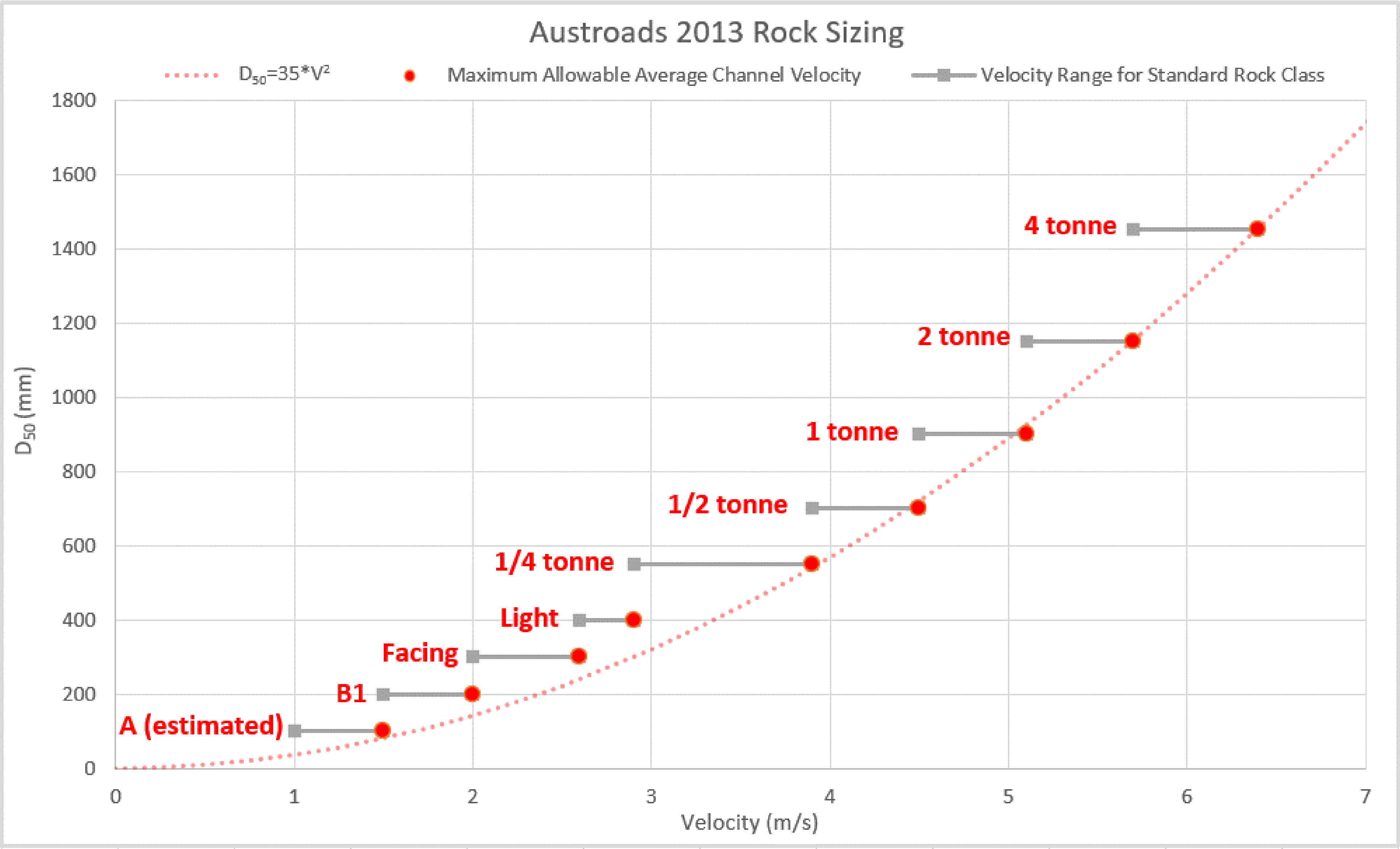
Rock class	Rock size[1] (m)	Rock mass (kg)	Minimum percentage of rock larger than
Facing	0.40 0.30 0.15	100 35 2.5	0 50 90
Light	0.55 0.40 0.20	250 100 10	0 50 90
¼ tonne	0.75 0.55 0.30	500 250 35	0 50 90
½ tonne	0.90 0.70 0.40	1000 450 100	0 50 90
1 tonne	1.15 0.60 0.55	2000 1000 250	0 50 90
2 tonne	1.45 1.15 0.75	4000 2000 500	0 50 90
4 tonne	1.80 1.45 0.90	8000 4000 100	0 50 90

- Error
- Error

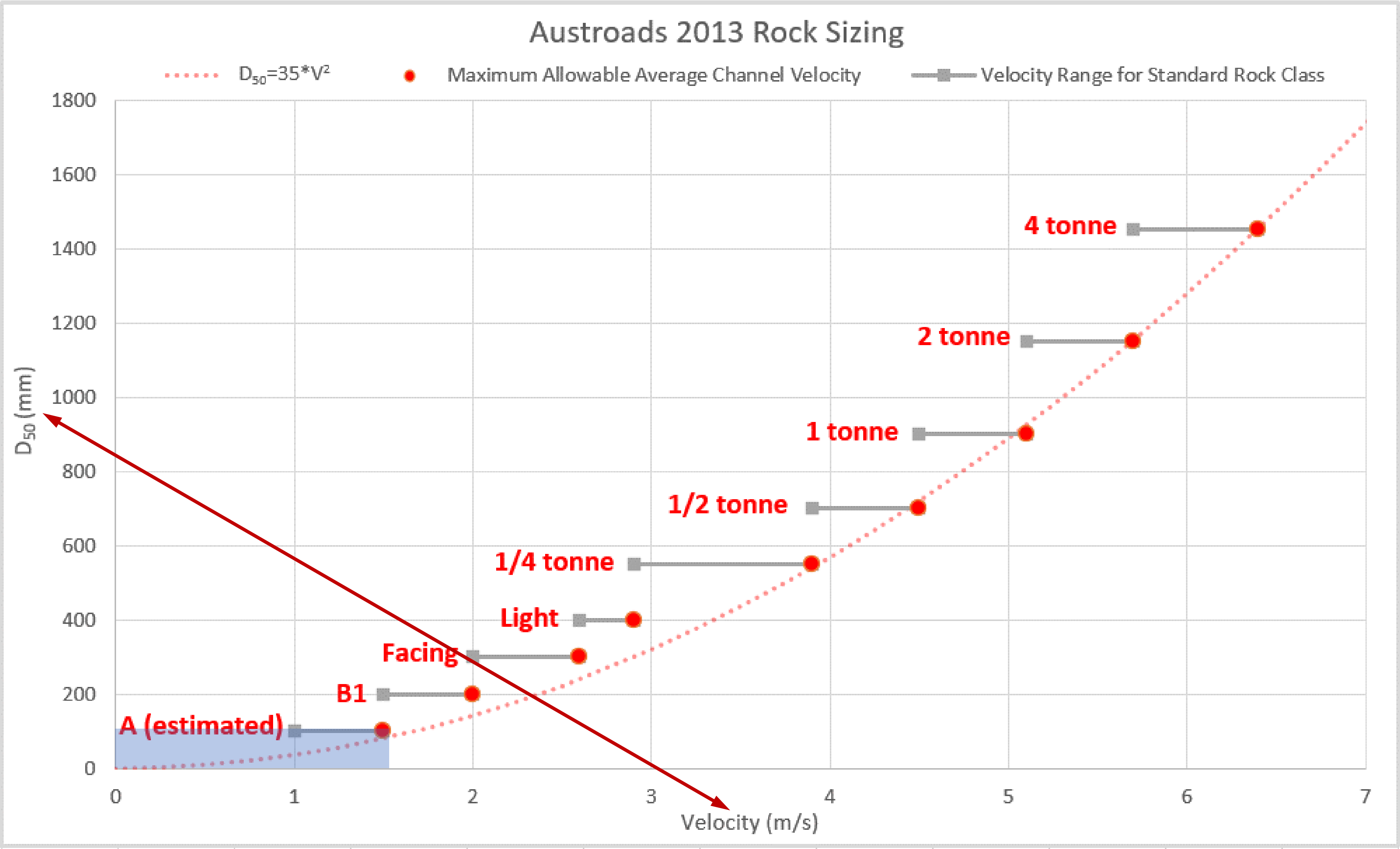


- Minimum zero percent larger is not helpful!
- Better to specify D_{85} or D_{90}

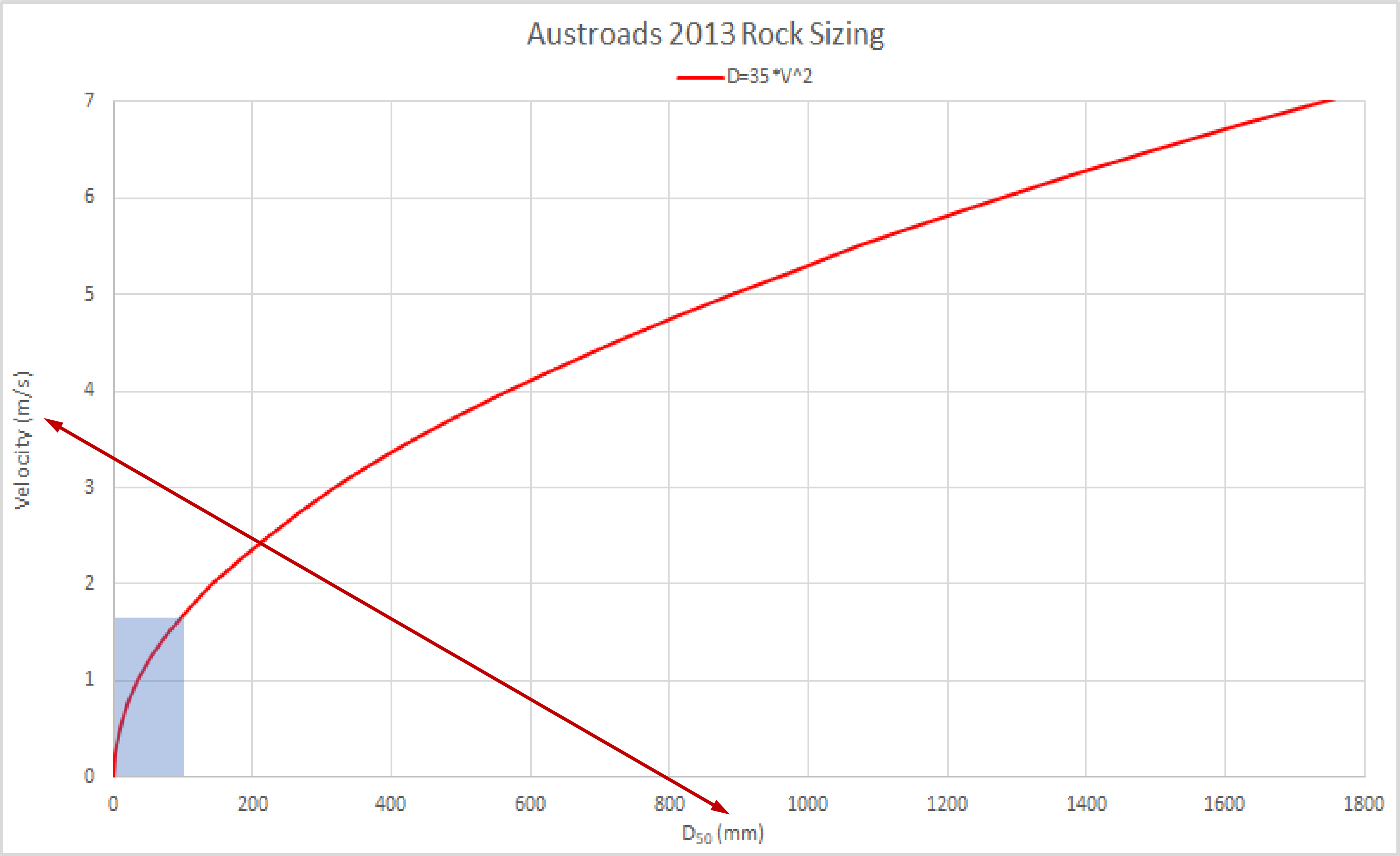
Velocity-based rock sizing



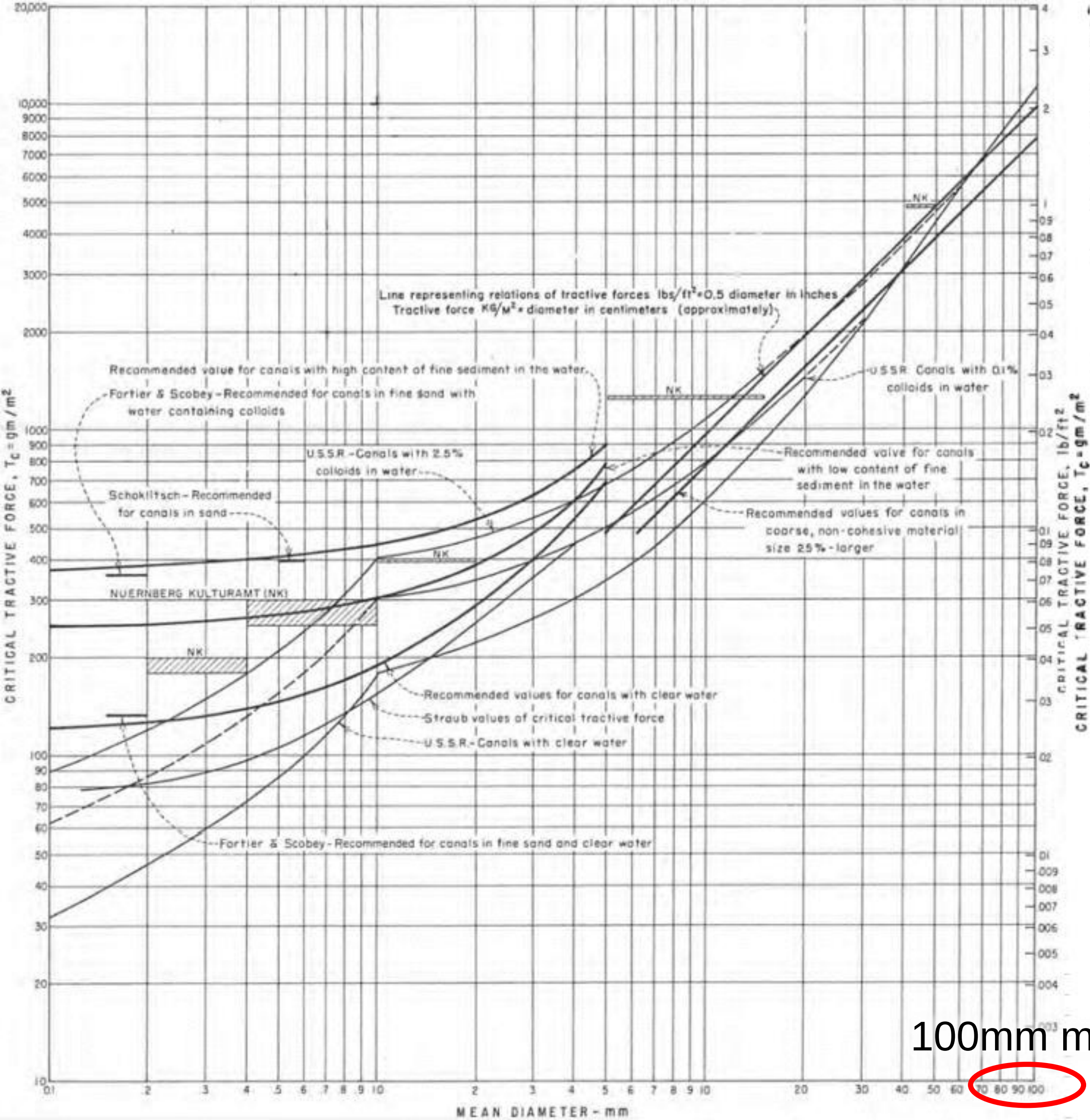
Shear-based rock sizing



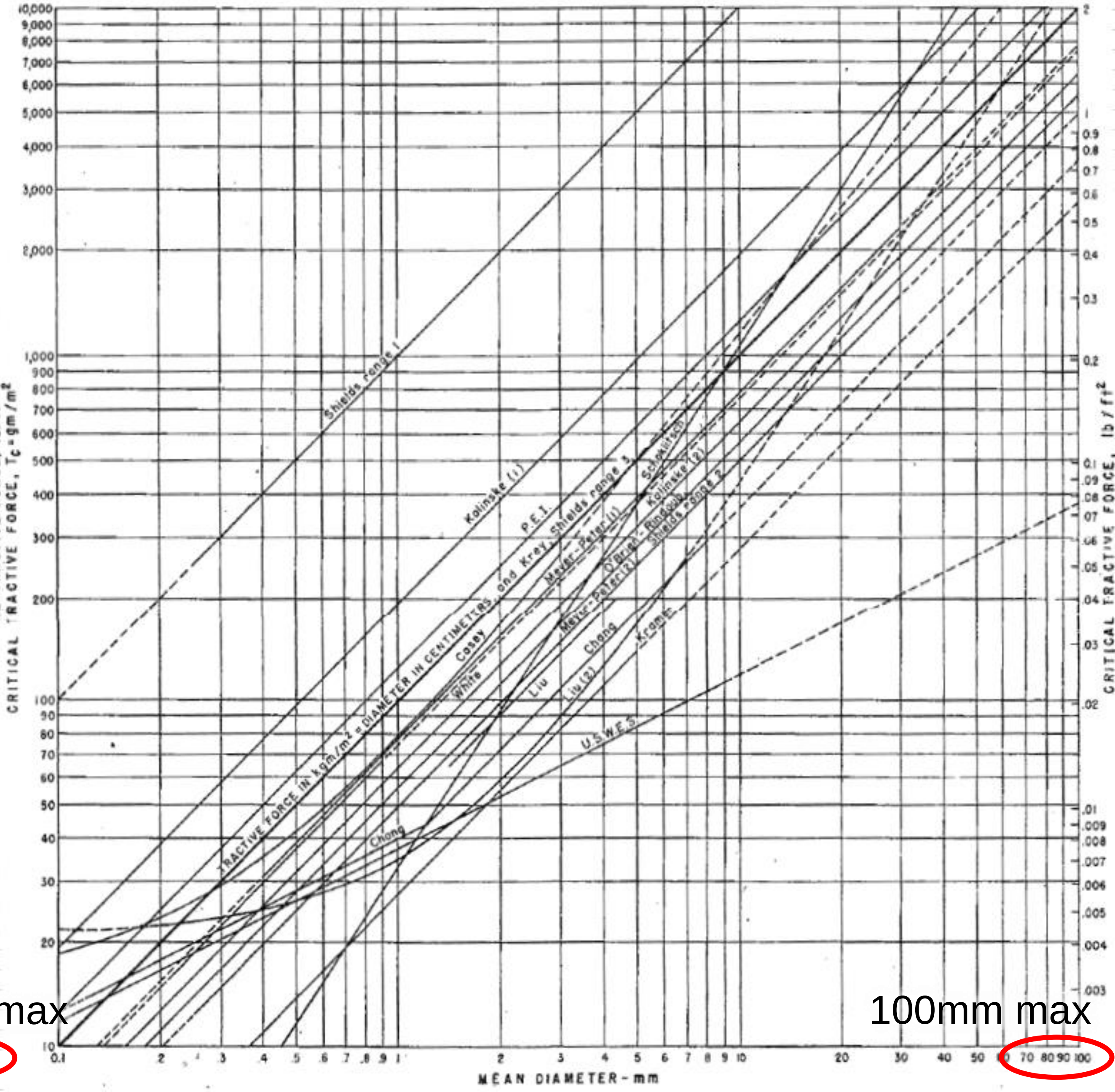
Shear-based rock sizing



Shear-based rock sizing

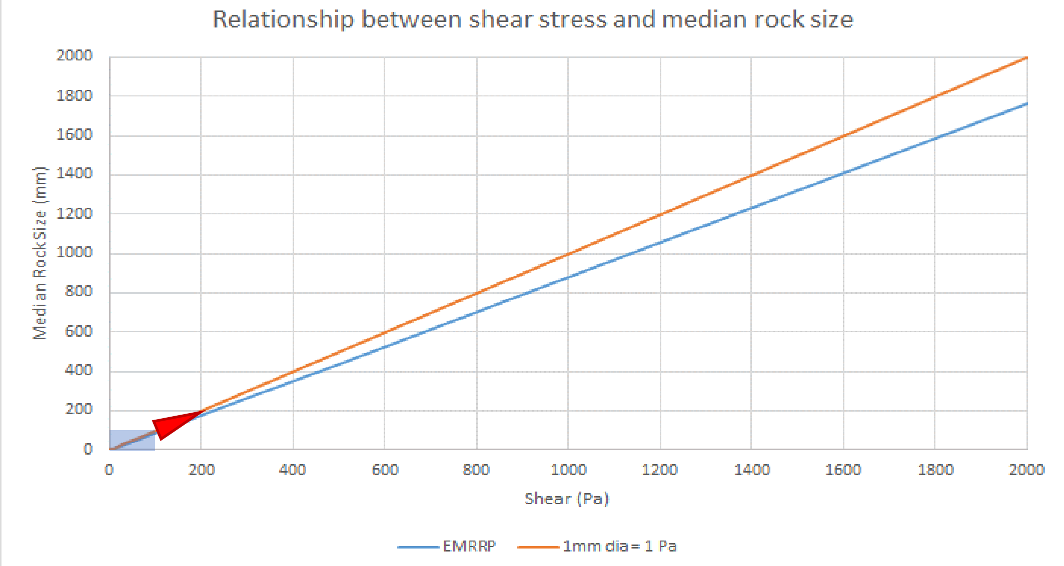


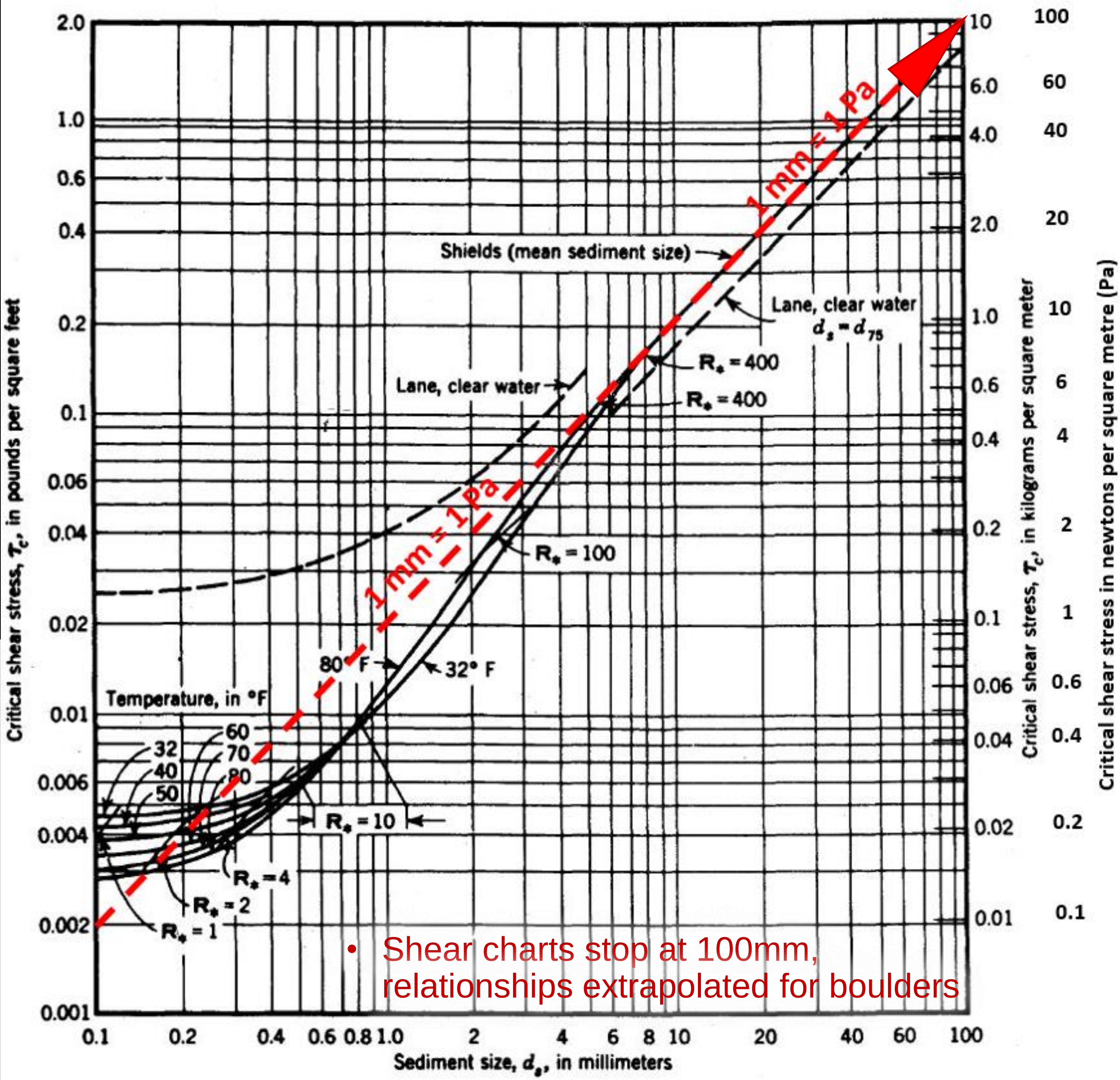
100mm max



100mm max

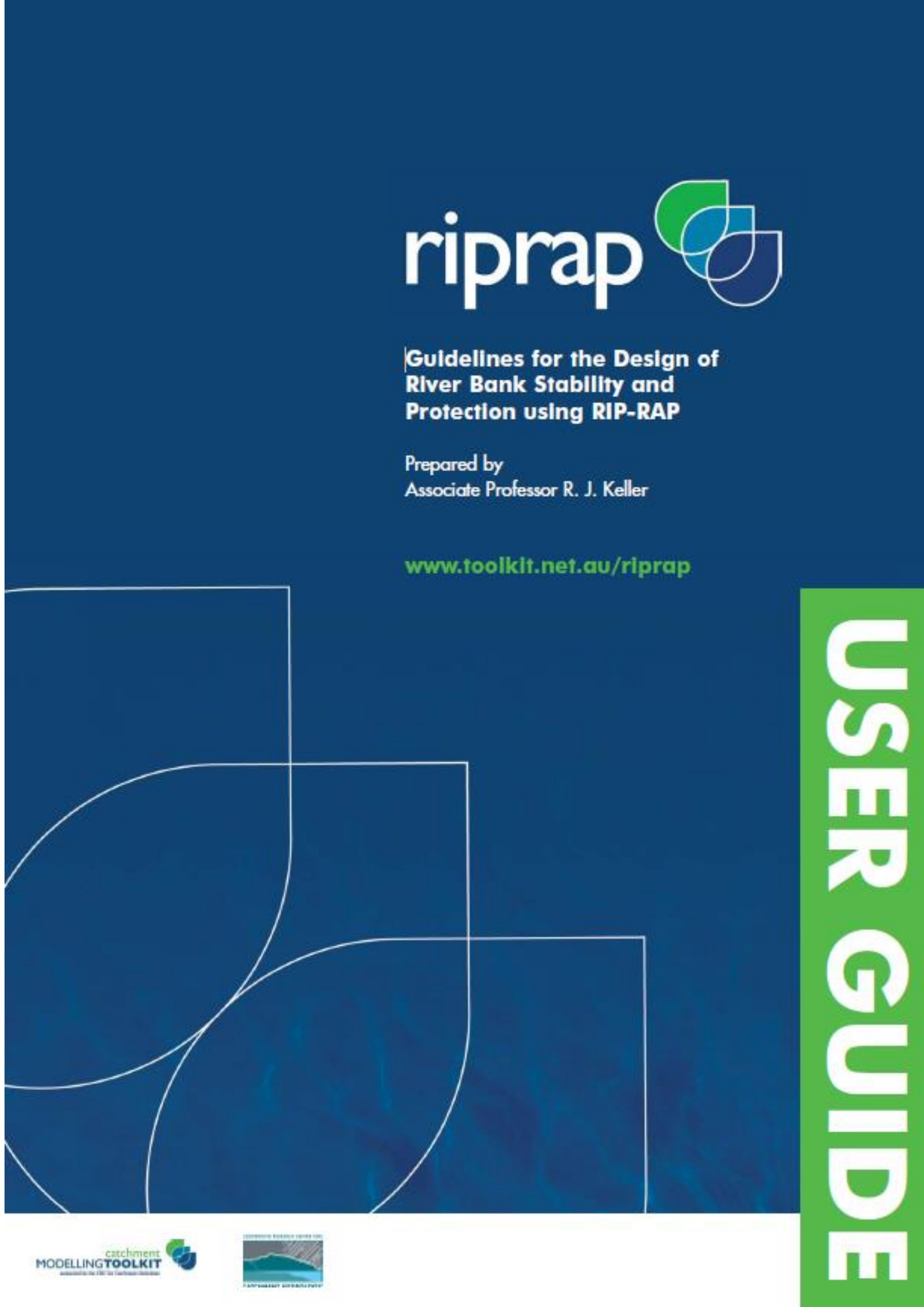
Rock class	Particle diameter	Angle of repose	Critical shear stress	Critical shear velocity	Particle diameter	Critical shear stress	Critical shear velocity
Class name	d_s (in)	ϕ(deg)	τ_{cr} (lb/sf)	V_{*c} (ft/s)	(mm)	(Pa)	(m/s)
Boulder							
Very large	>80	42	37.4	4.36	2032	1791	1.33
Large	>40	42	18.7	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





CRC for catchment hydrology riprap spreadsheet

https://toolkit.ewater.org.au/Tools/RIPRAP



Shear-based:

RIPRAP - Input Table			
A design program for stabilisation of river banks with rip- rap			About
Input Table			
Variable Name	Allowed Range	Value	Units
Energy Slope		2.10E-03	-
Bank Angle		22	degrees
Rock Specific Gravity	>1	2.65	-
Rock Angle of Repose	1-46	46	degrees
Maximum Depth		10	m
Depth of Interest		8	m
Factor of Safety	1-5	1.2	-
Maximum Safe Bank Angle	Calculated	40.7922861	degrees

Shields coefficient

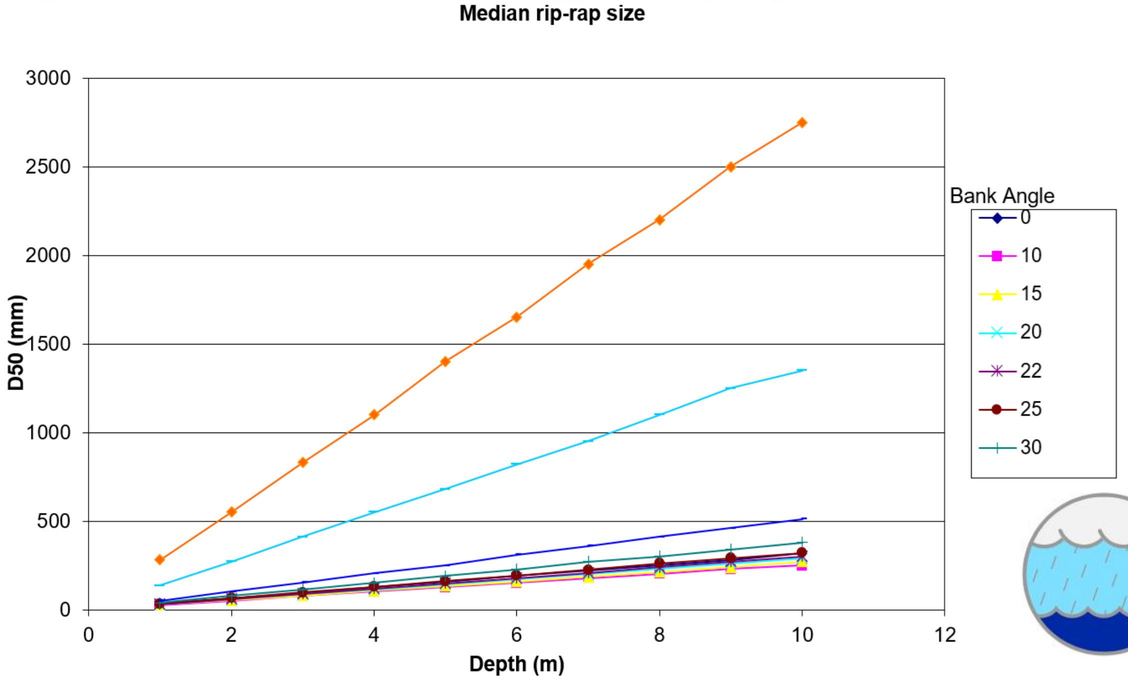
$$D_{50} = \frac{\left[\dfrac{0.75\, y S \tan\phi}{0.047 (S_s - 1)}\right]}{\sqrt{\left(\dfrac{\cos\theta \tan\phi}{F_S}\right)^2 - \sin^2\theta}}$$

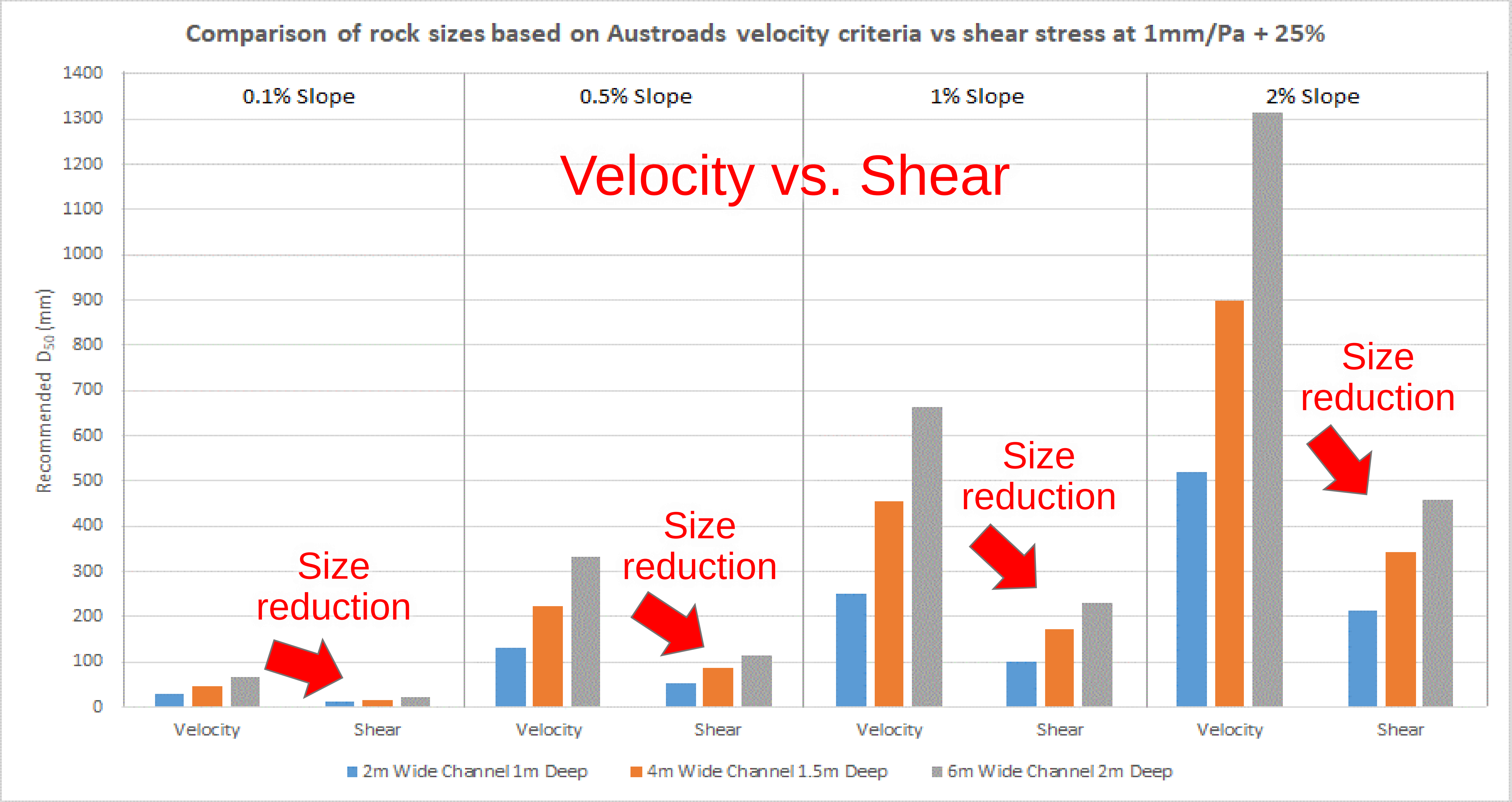
Output Table

Output Table D50 (mm)

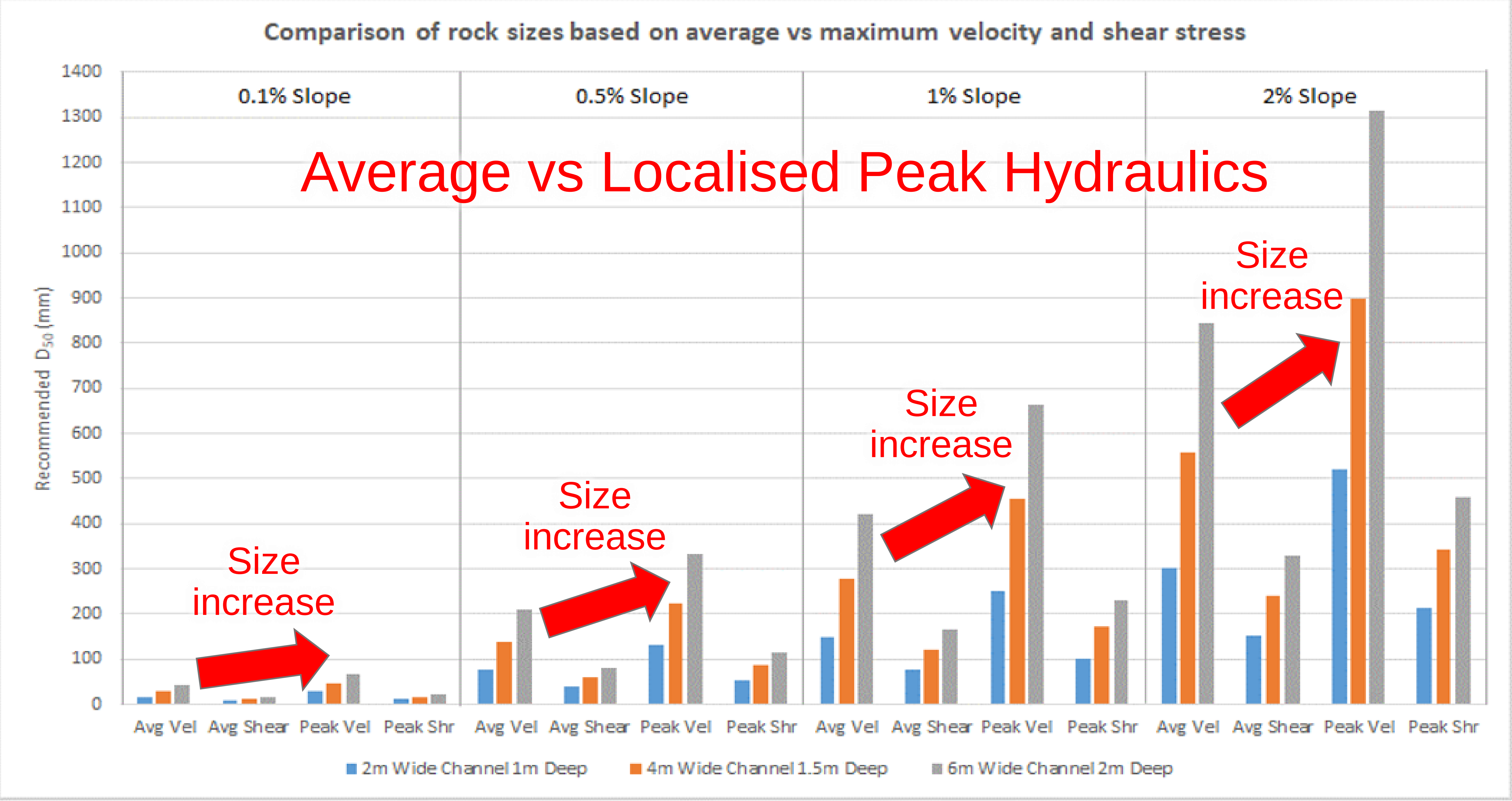
Depth (m)	Bank Angles: 0	10	15	20	22	25	30	35	40	40.6
1	32	25	27	29	30	32	38	51	136	280
2	63	51	53	57	59	64	76	102	270	550
3	95	76	80	86	89	96	114	153	410	830
4	126	101	106	114	119	128	151	204	550	1100
5	158	126	133	143	149	160	189	250	680	1400
6	189	152	159	172	178	192	227	310	820	1650
7	221	177	186	200	208	224	270	360	950	1950
8	250	202	212	229	238	260	300	410	1100	2200
9	280	228	239	260	270	290	340	460	1250	2500
10	320	250	270	290	300	320	380	510	1350	2750

Riprap size increases with depth (for constant energy slope)



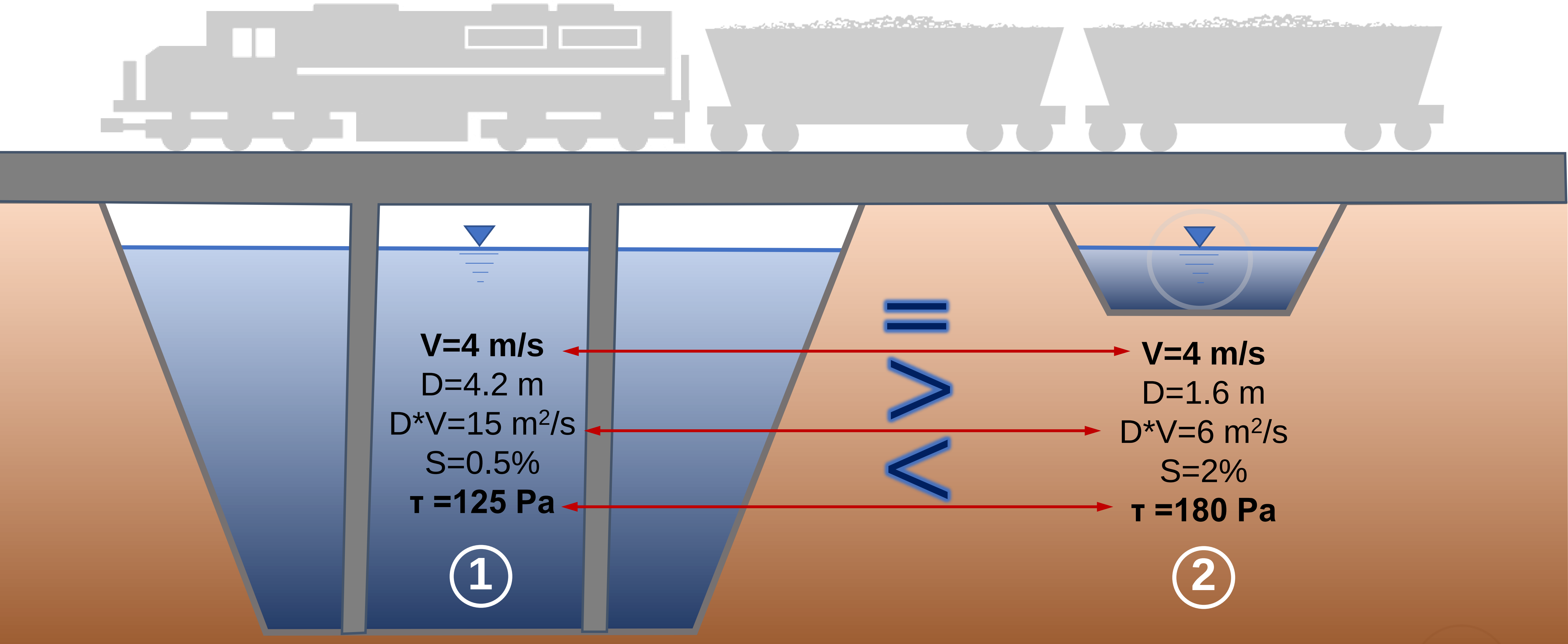


- From Price and Westwater, IMWA 2020

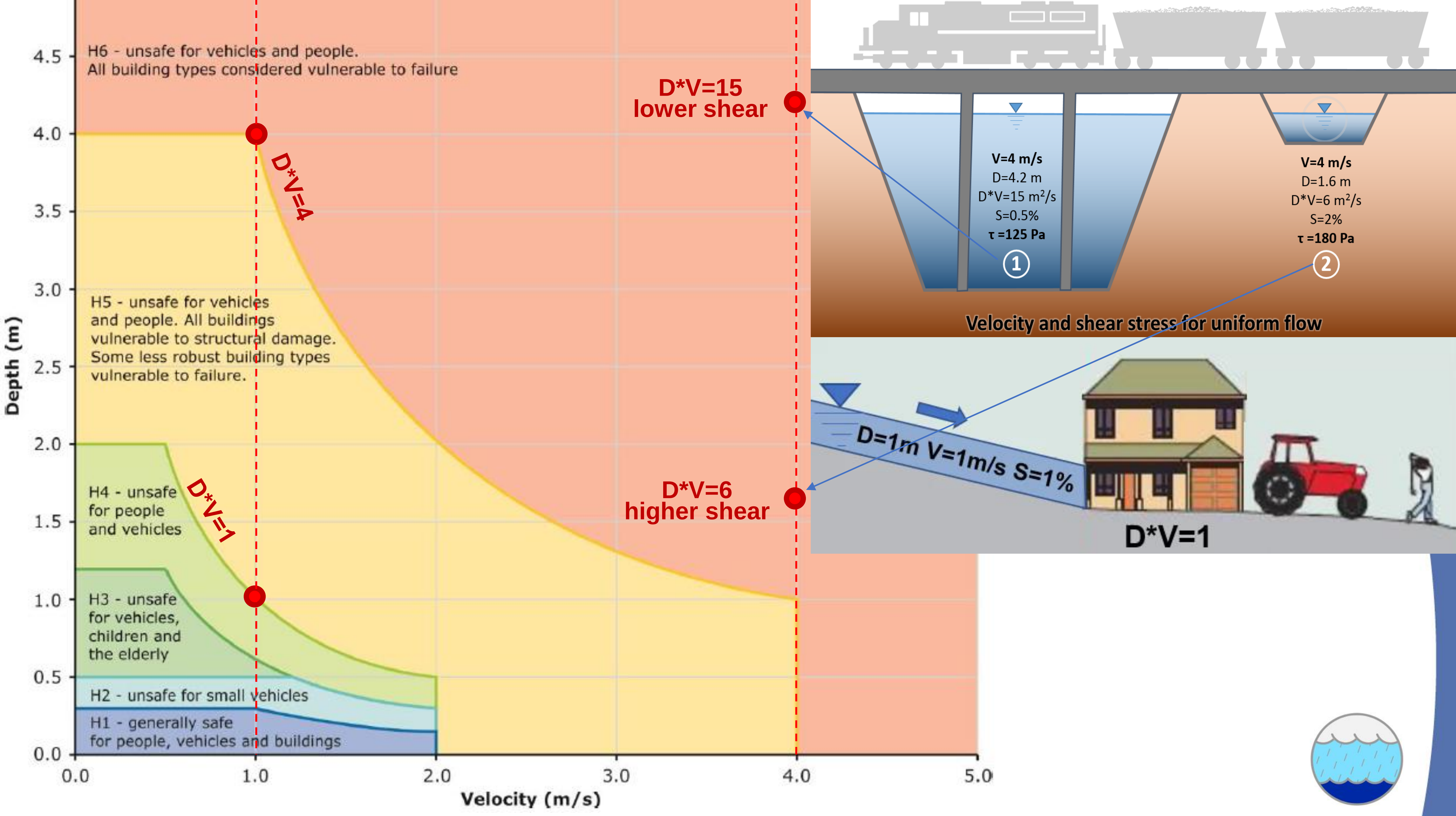


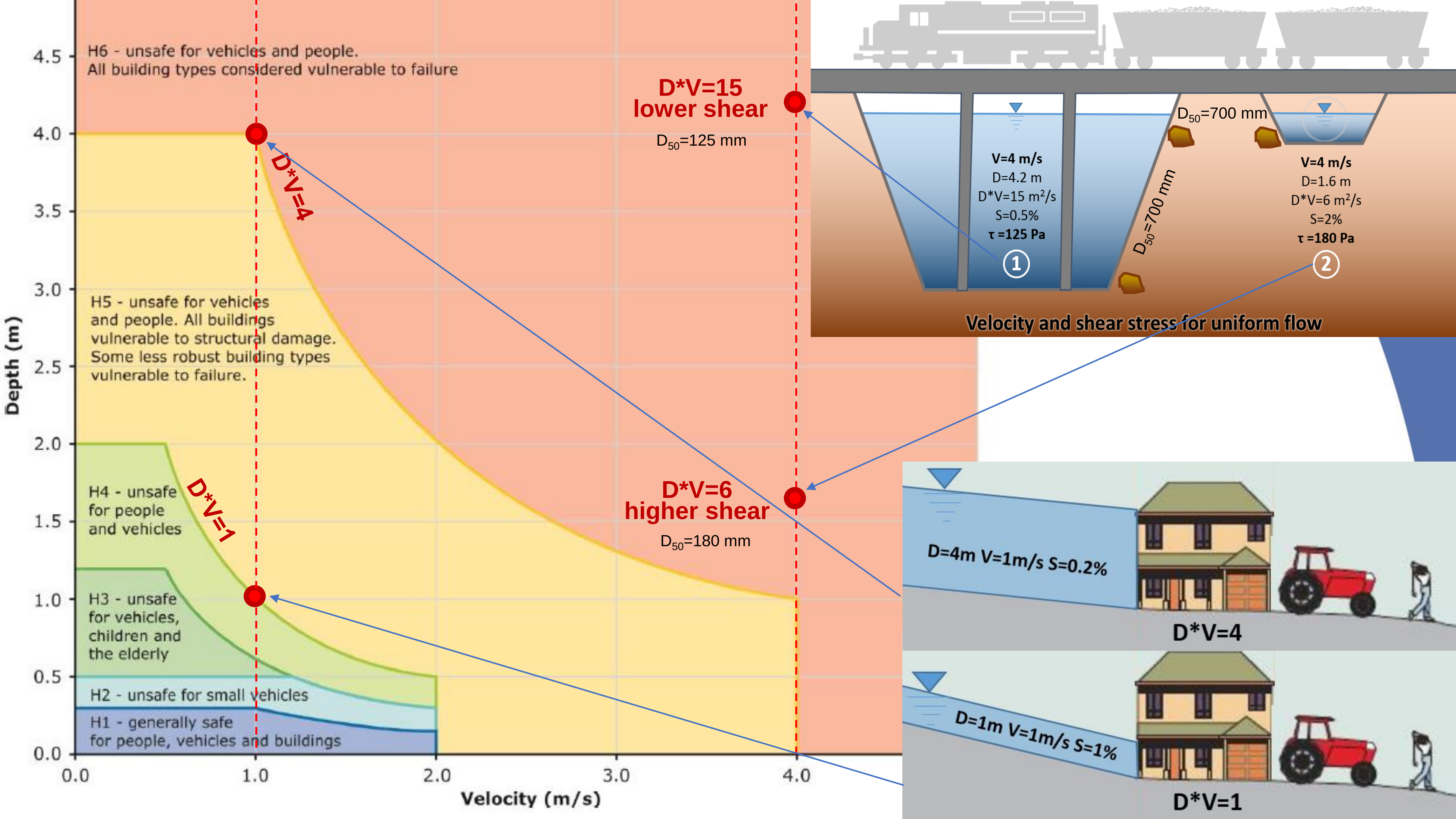
- From Price and Westwater, IMWA 2020

Velocity vs. Shear: Depth sensitivity



Velocity and shear stress for uniform flow


H6 - unsafe for vehicles and people.
All building types considered vulnerable to failure
D*V=15
lower shear
D*V=4
H5 - unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust building types vulnerable to failure.
H4 - unsafe for people and vehicles
D*V=1
H3 - unsafe for vehicles, children and the elderly
H2 - unsafe for small vehicles
H1 - generally safe for people, vehicles and buildings
D*V=6
higher shear
Depth (m)
Velocity (m/s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
0.0
1.0
2.0
3.0
4.0
5.0
V=4 m/s
D=4.2 m
D*V=15 m2/s
S=0.5%
τ =125 Pa
1
V=4 m/s
D=1.6 m
D*V=6 m2/s
S=2%
τ =180 Pa
2
Velocity and shear stress for uniform flow
D=1m V=1m/s S=1%
D*V=1



H6 - unsafe for vehicles and people.
All building types considered vulnerable to failure
H5 - unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust building types vulnerable to failure.
H4 - unsafe for people and vehicles
H3 - unsafe for vehicles, children and the elderly
H2 - unsafe for small vehicles
H1 - generally safe for people, vehicles and buildings
Depth (m)
Velocity (m/s)
D*V=4
D*V=1
D*V=15
lower shear
D50=125 mm
D*V=6
higher shear
D50=180 mm
D50=700 mm
D50=700 mm
V=4 m/s
D=4.2 m
D*V=15 m2/s
S=0.5%
τ =125 Pa
V=4 m/s
D=1.6 m
D*V=6 m2/s
S=2%
τ =180 Pa
1
2
Velocity and shear stress for uniform flow
D=4m V=1m/s S=0.2%
D*V=4
D=1m V=1m/s S=1%
D*V=1

USACE 1994: Experimental Flume

Limitations:

$s<2\%$

$F<0.8$

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

USACE 1994: D_{30} varies with depth

$$D_{30} = S_f C_s C_v C_t d \left(\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{0.5} \frac{V}{\sqrt{K_1 g d}} \right)^{2.5}$$

Riprap size is inversely proportional to depth:

$$D \propto d^{-0.25} V^{2.5}$$

Velocity exponent differs from Austroads, supersedes source material

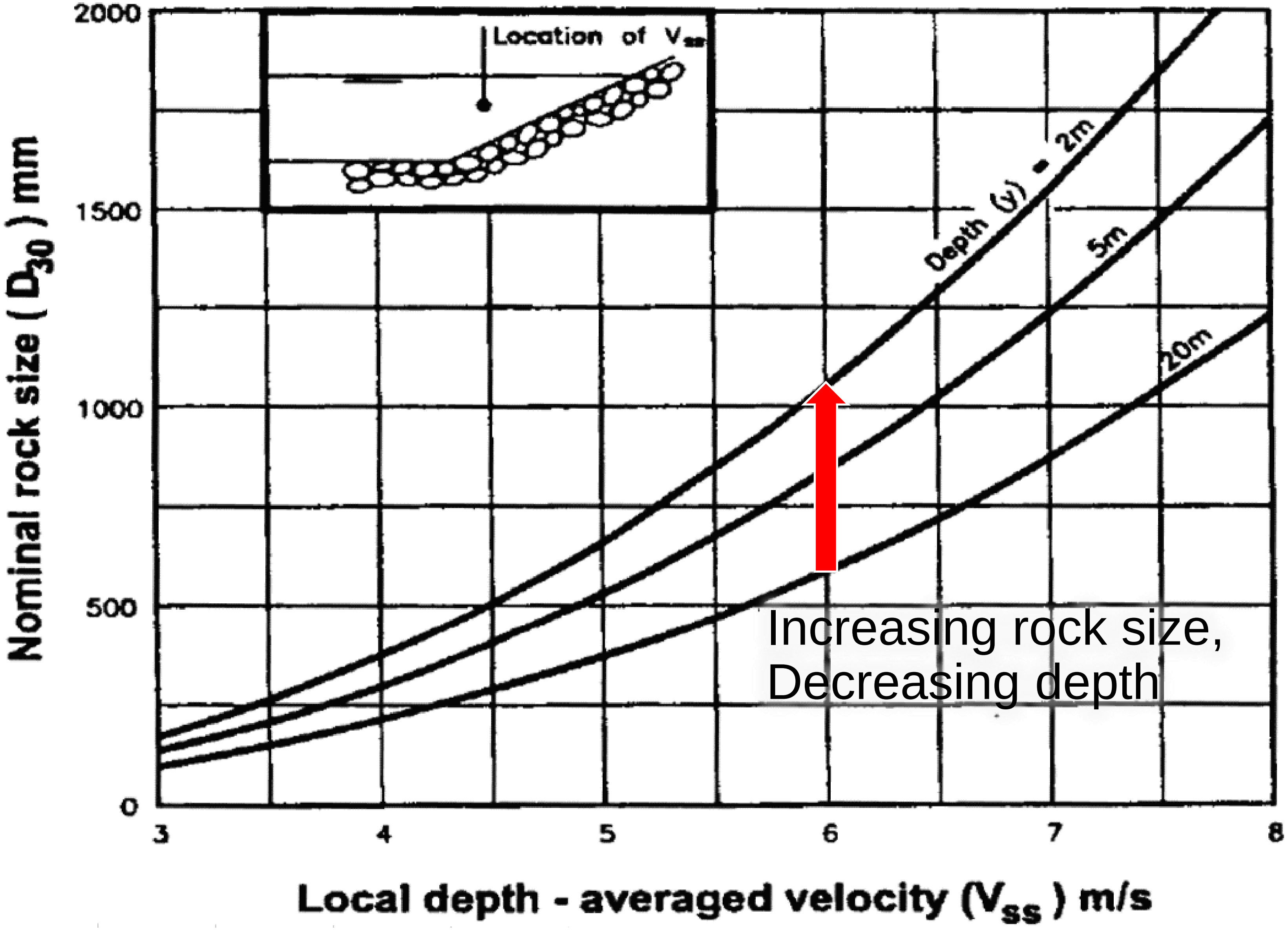
USACE 1994: D_{30} varies with depth

$$D_{30} = S_f C_s C_v C_t d \left(\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{0.5} \frac{V}{\sqrt{K_1 g d}} \right)^{2.5}$$

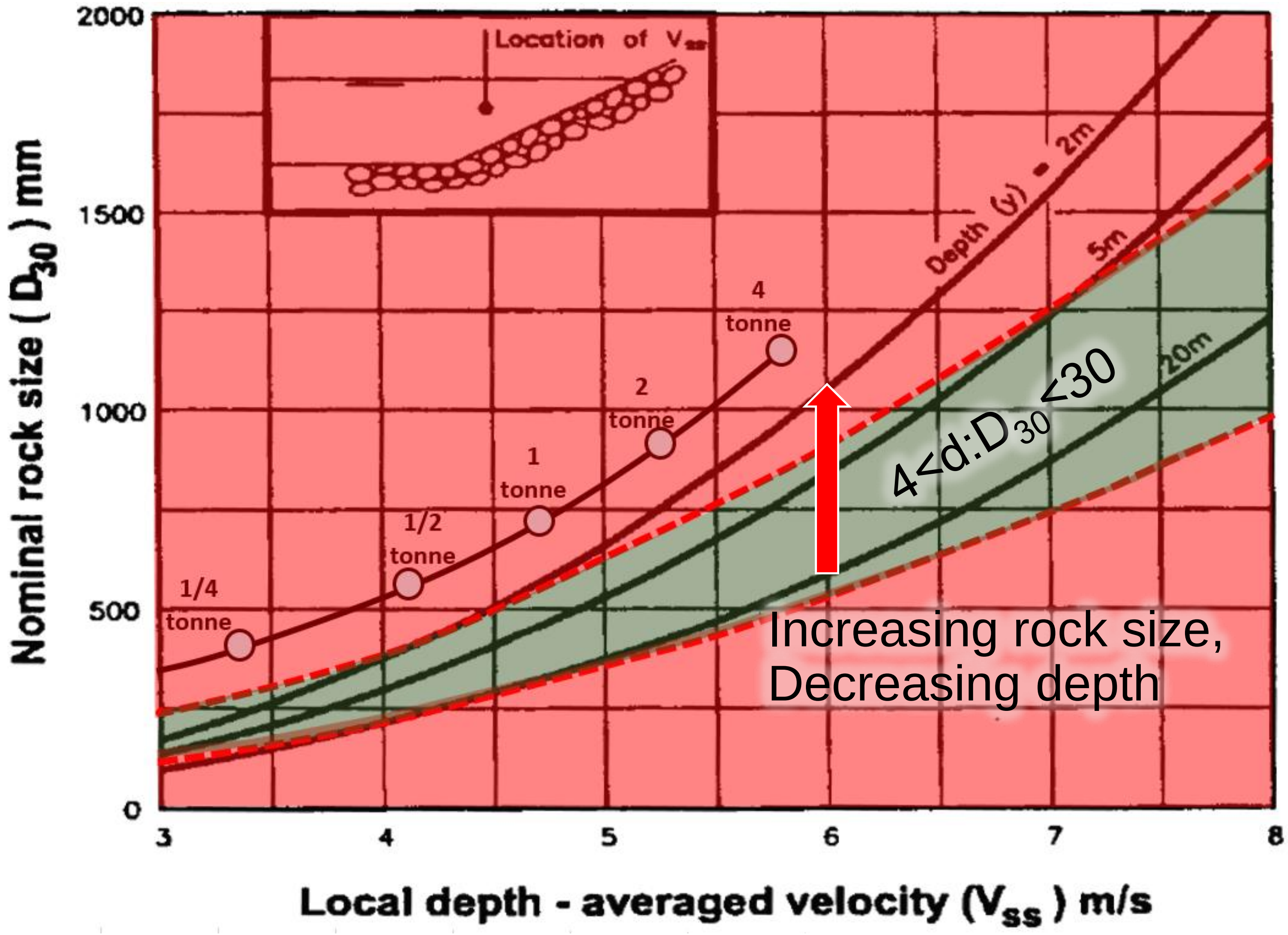
Coefficients are outside the exponents:

$$D=a(V^b) \neq D=(aV)^b$$

USACE 1994: D_{30} varies with depth



USACE 1994: Applicable range



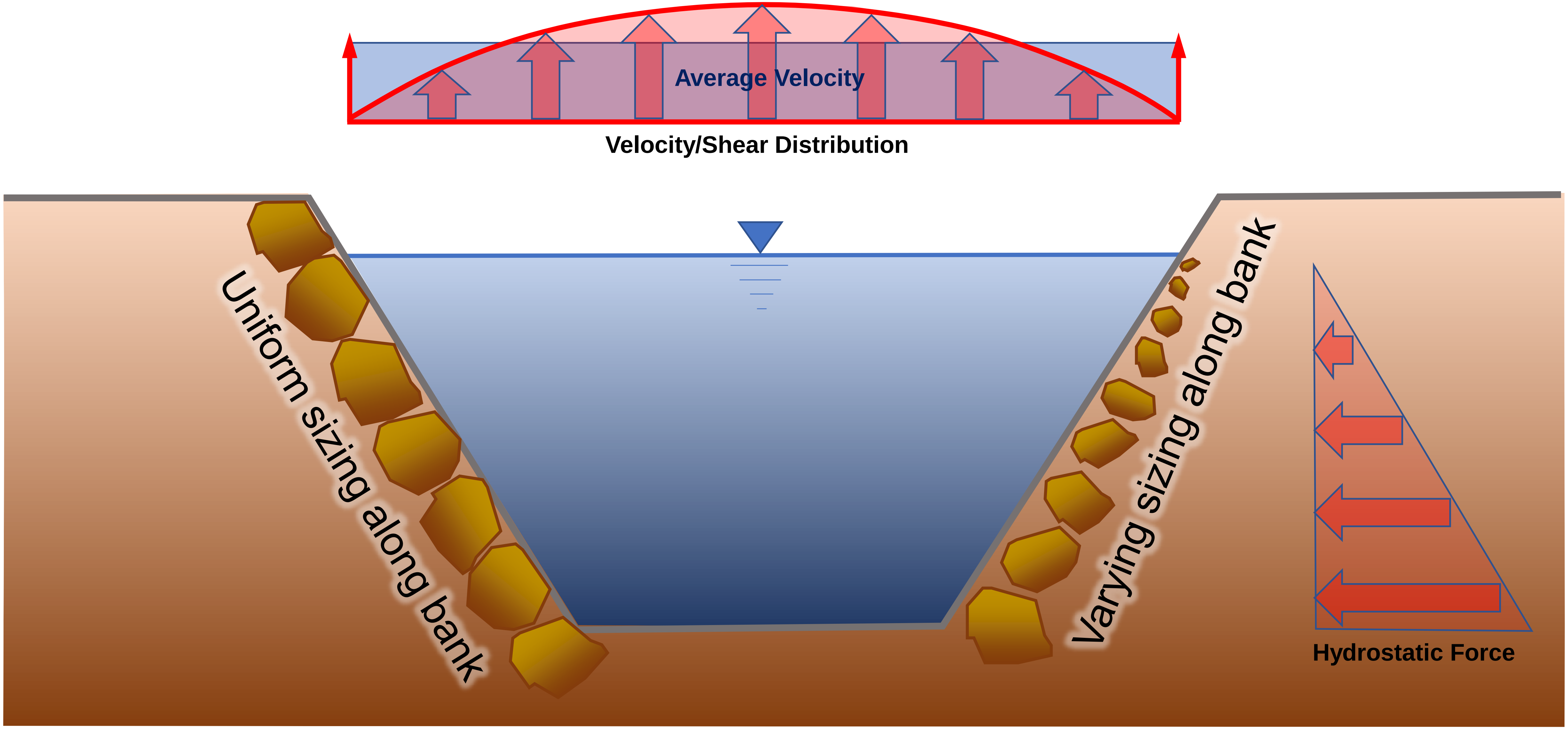
Limitations:

s<2%

F<0.8

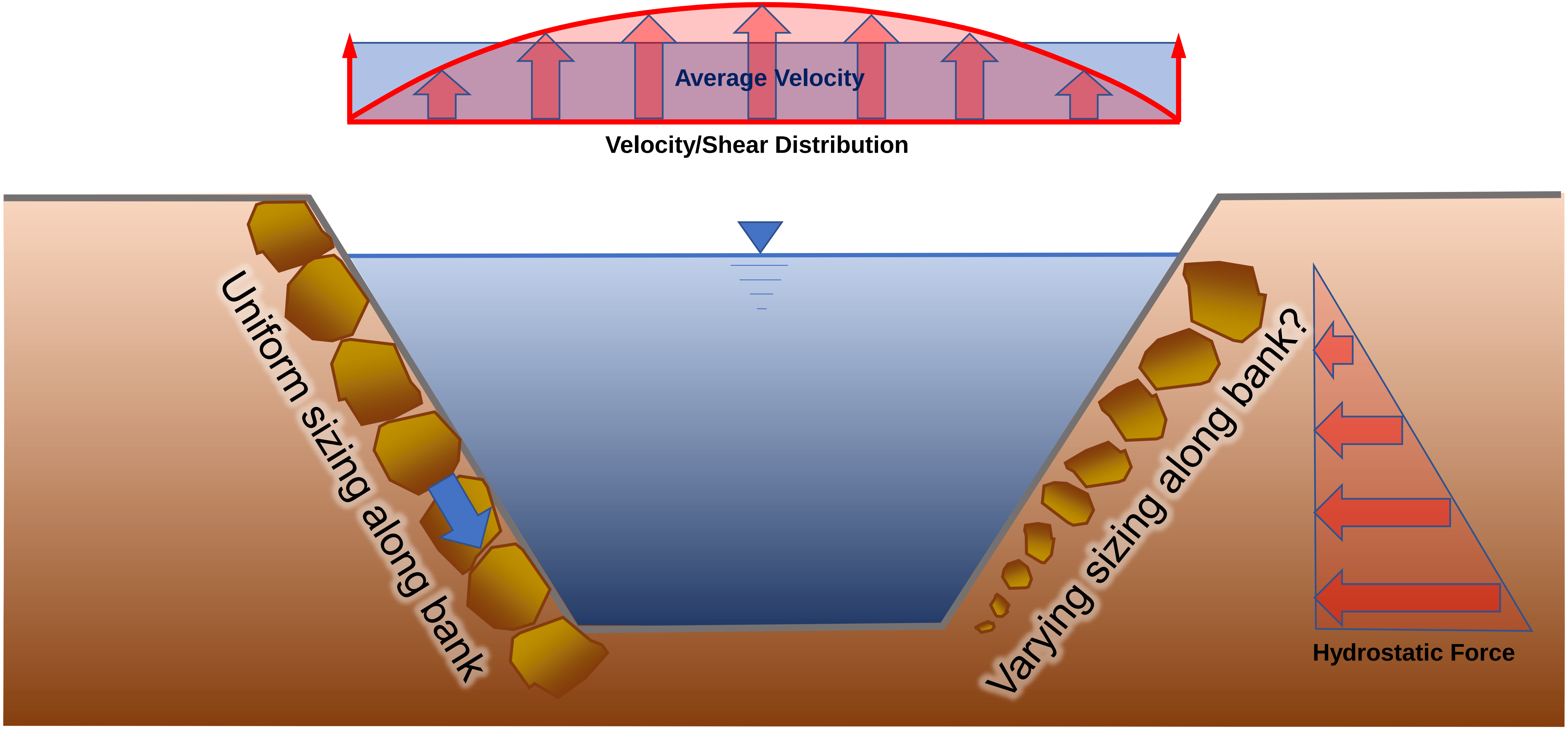
$4<d:D_{30}<30$

Variation of size with depth



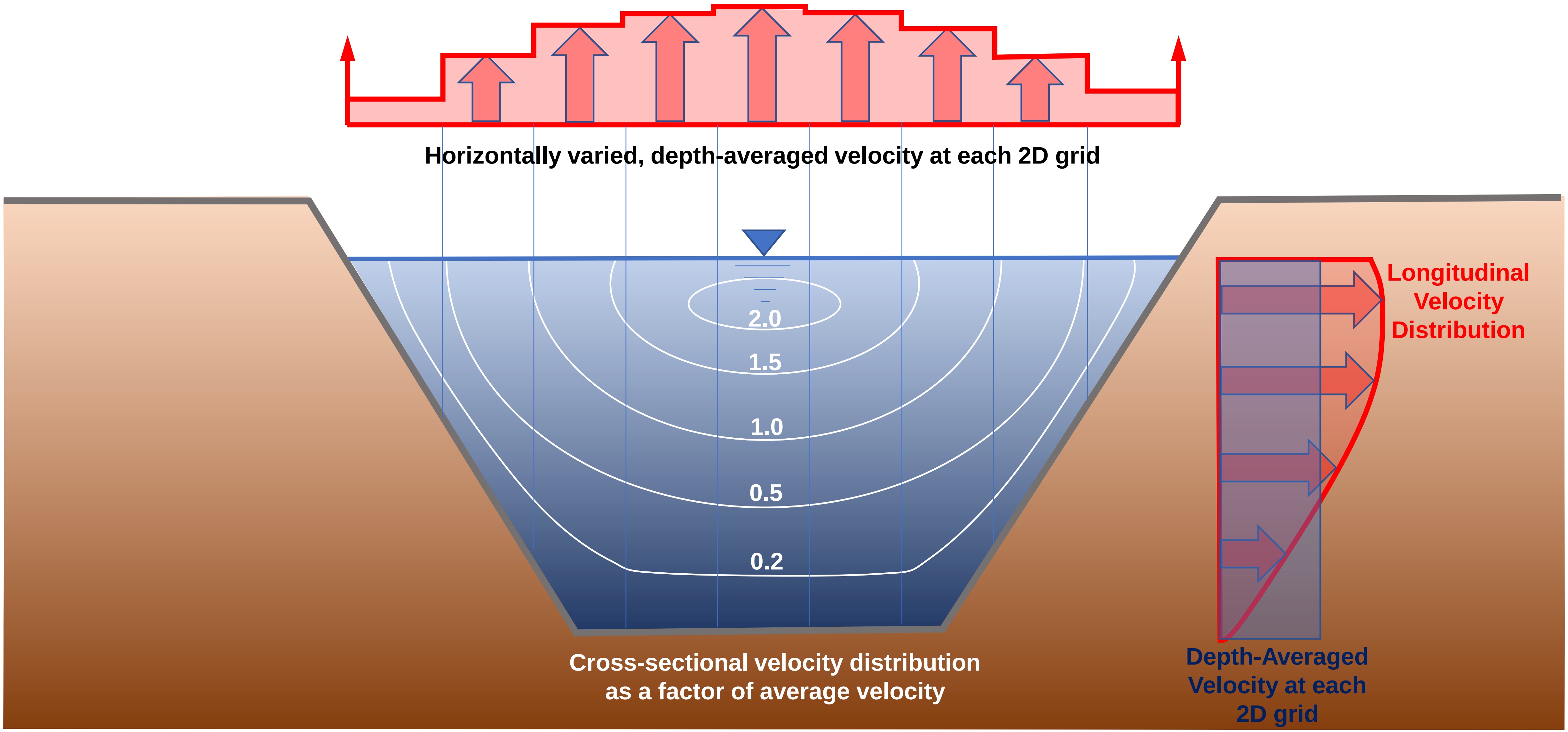
Distribution of tractive forces: shear increasing with depth

Variation of size with depth



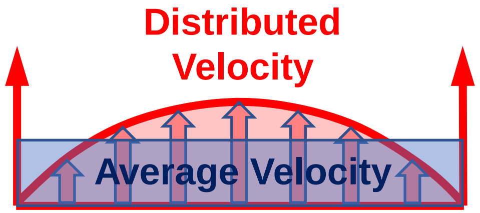
Distribution of forces: varying inversely with depth?

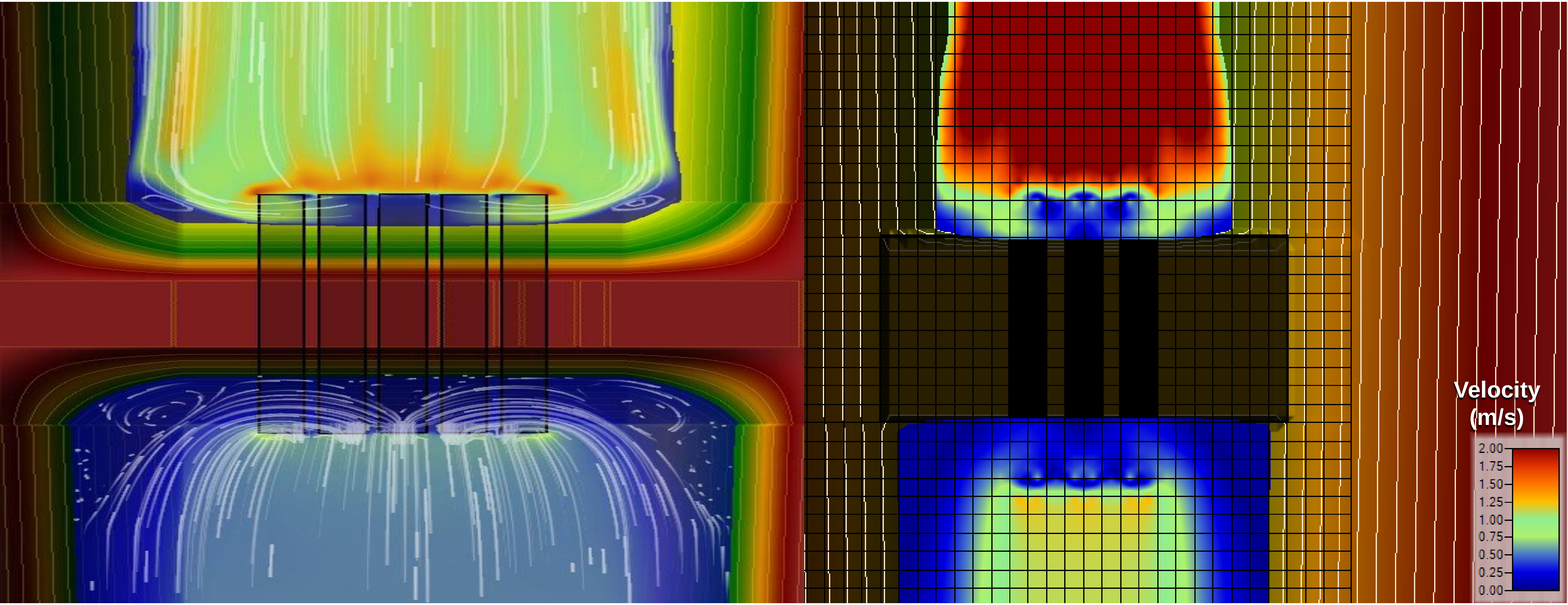
Horizontal and vertical variation



Typical distribution of velocities

Horizontal variation

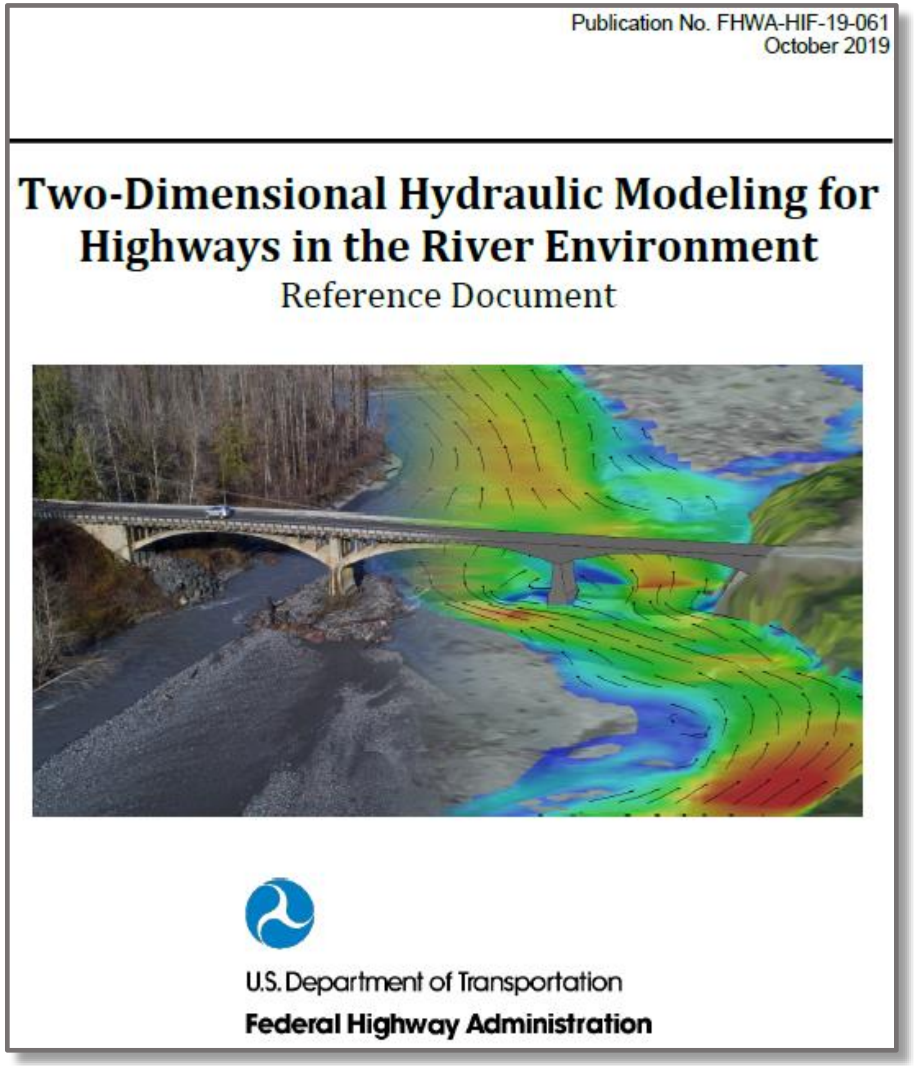




Horizontal distribution of depth-averaged velocities

Advancements: 2D Modelling Guidance

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



Publication No. FHWA-HIF-19-061
October 2019

Two-Dimensional Hydraulic Modeling for Highways in the River Environment

Reference Document

U.S. Department of Transportation

Federal Highway Administration

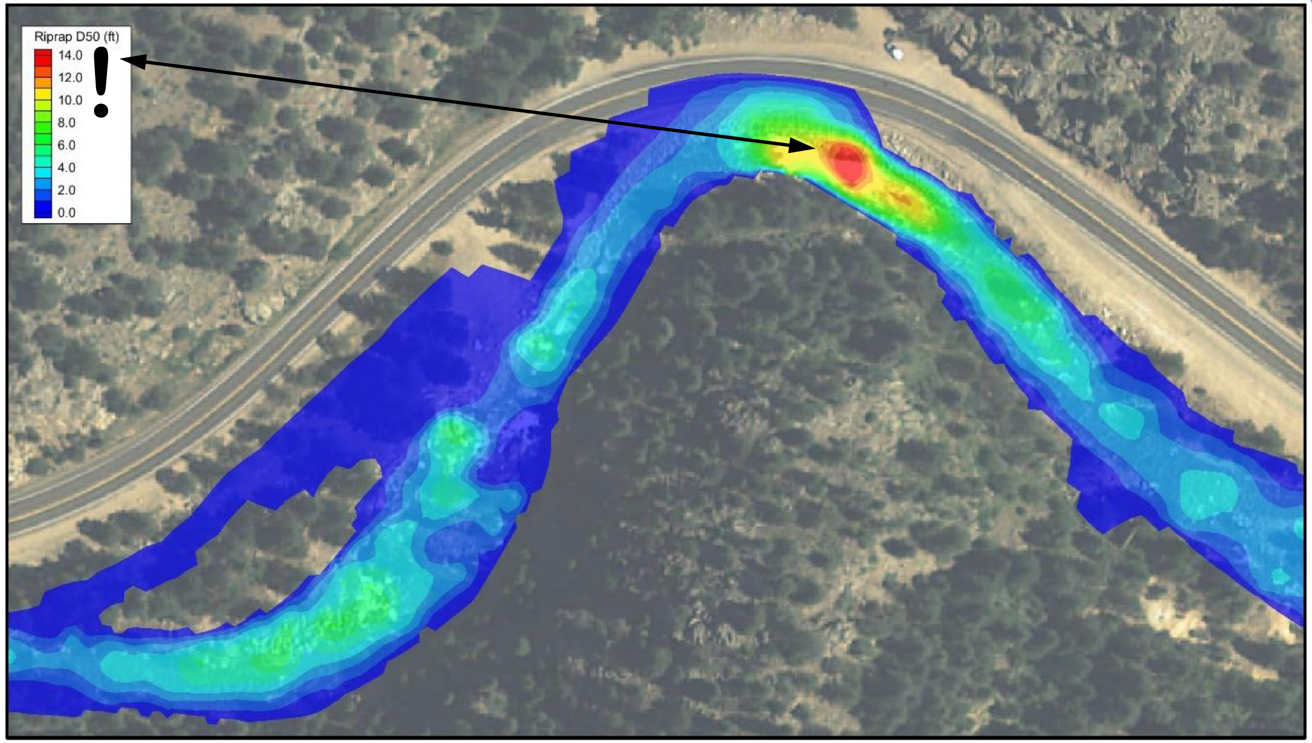
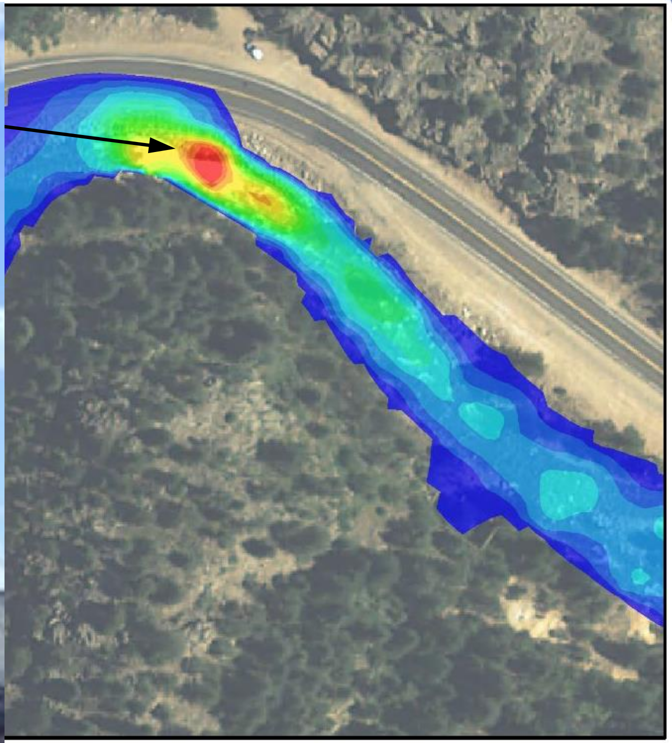


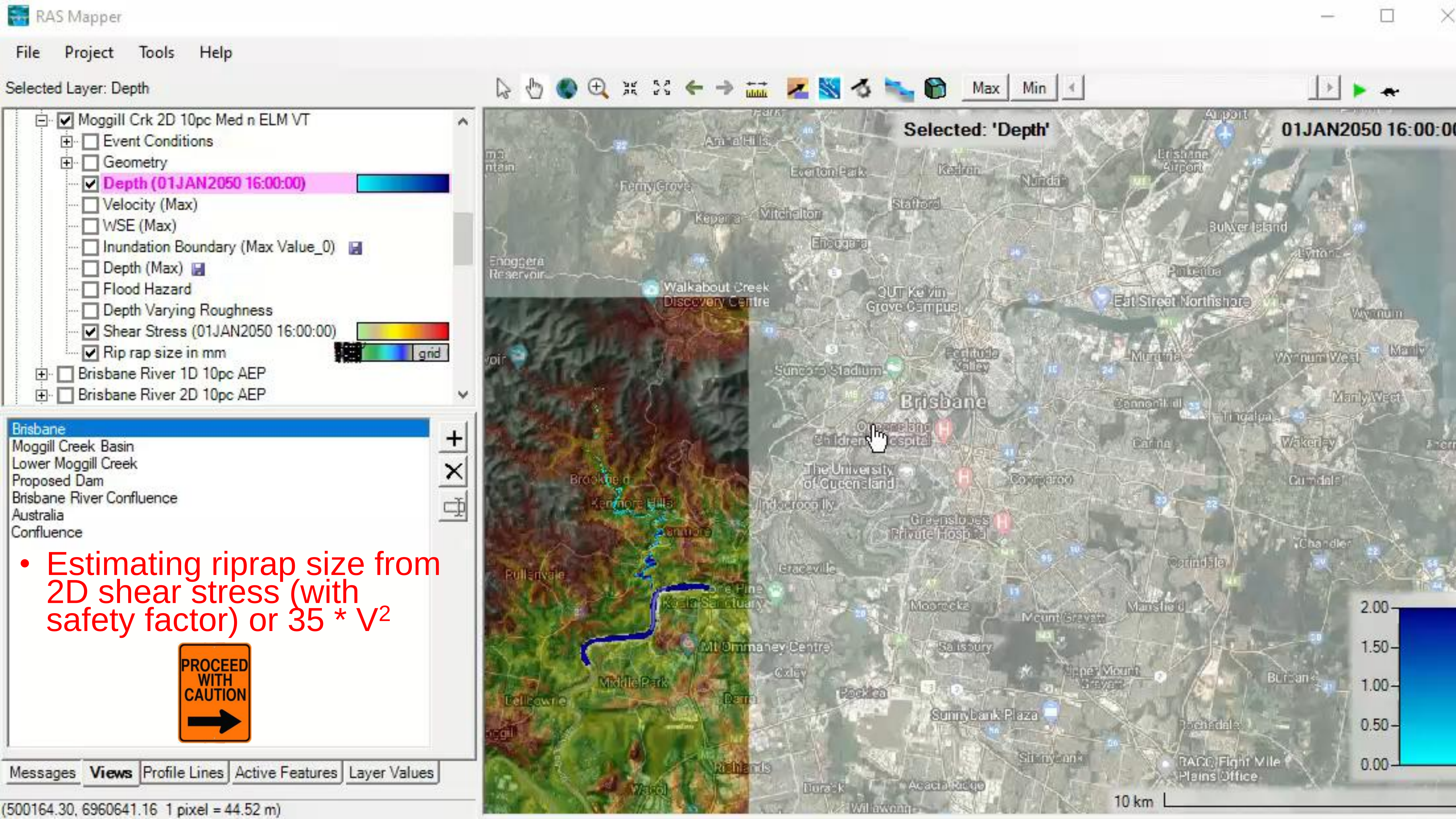
Figure 8.5. Riprap sizing contours based on 2D model depth and velocity results.

Advancements: 2D Modelling Guidance

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



d on 2D model depth and velocity results.


RAS Mapper
File
Project
Tools
Help
Selected Layer: Depth
Max
Min
Moggill Crk 2D 10pc Med n ELM VT
Event Conditions
Geometry
Depth (01JAN2050 16:00:00)
Velocity (Max)
WSE (Max)
Inundation Boundary (Max Value_0)
Depth (Max)
Flood Hazard
Depth Varying Roughness
Shear Stress (01JAN2050 16:00:00)
Rip rap size in mm
grid
Brisbane River 1D 10pc AEP
Brisbane River 2D 10pc AEP
Brisbane
Moggill Creek Basin
Lower Moggill Creek
Proposed Dam
Brisbane River Confluence
Australia
Confluence
• Estimating riprap size from 2D shear stress (with safety factor) or 35 * V²
PROCEED WITH CAUTION
Messages
Views
Profile Lines
Active Features
Layer Values
(500164.30, 6960641.16 1 pixel = 44.52 m)
Selected: 'Depth'
01JAN2050 16:00:0
Brisbane
2.00
1.50
1.00
0.50
0.00
10 km

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

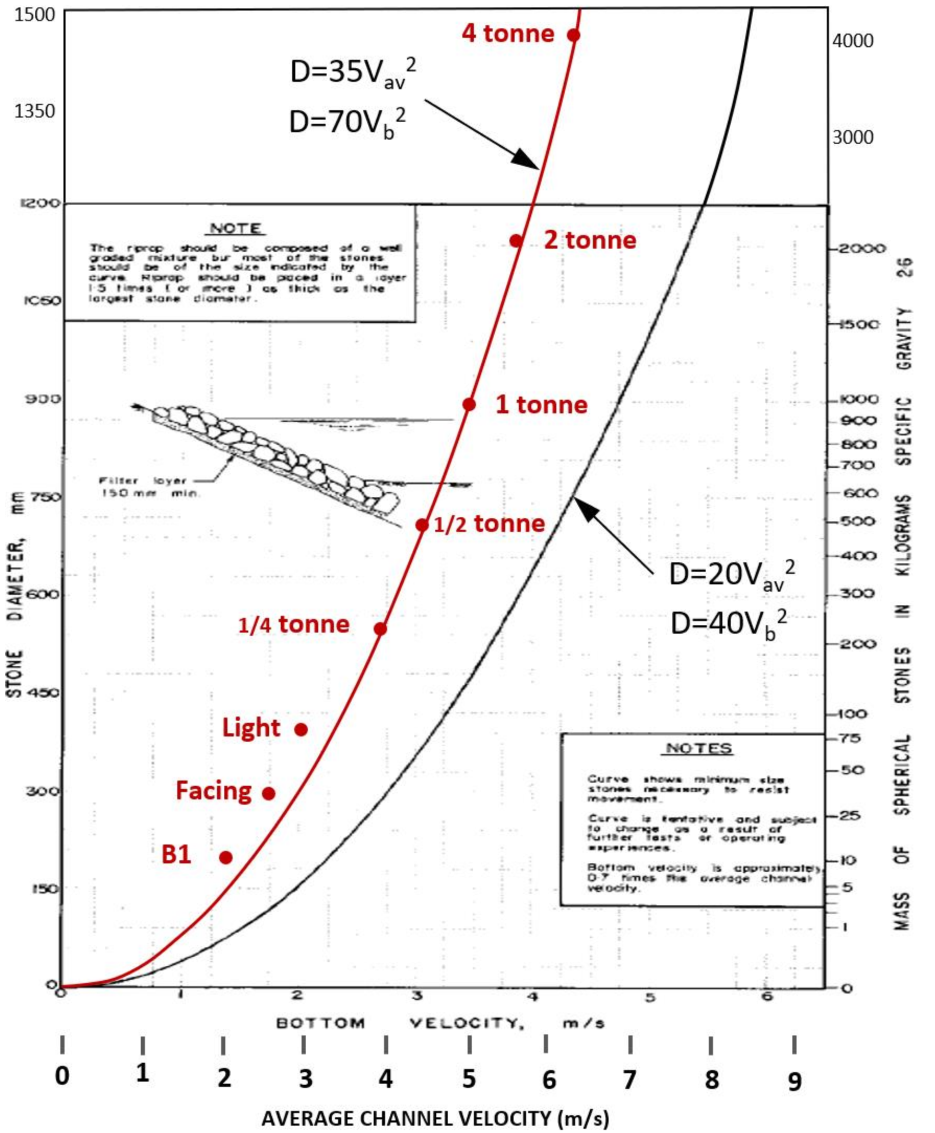
Report No. SRH-2015-25
Albuquerque Area Office
Science and Technology
Policy and Administration (Manuals and Standards)
Yuma Area Office

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

June 2015

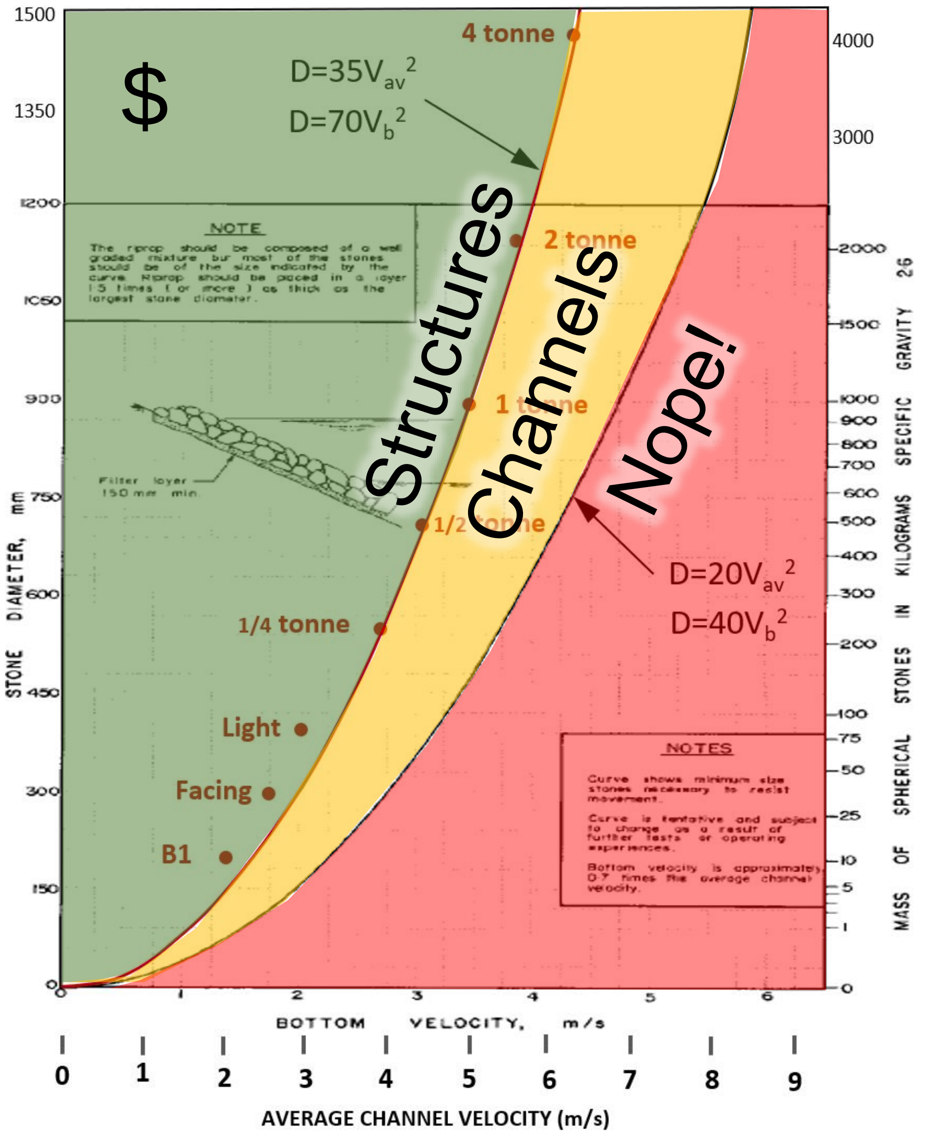
Recommendations

- 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
  - Velocity Adjustments:
    1D vs 2D vs 3D
  - How to apply the USACE method



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
  - Velocity Adjustments:
    1D vs 2D vs 3D
  - How to apply the USACE method



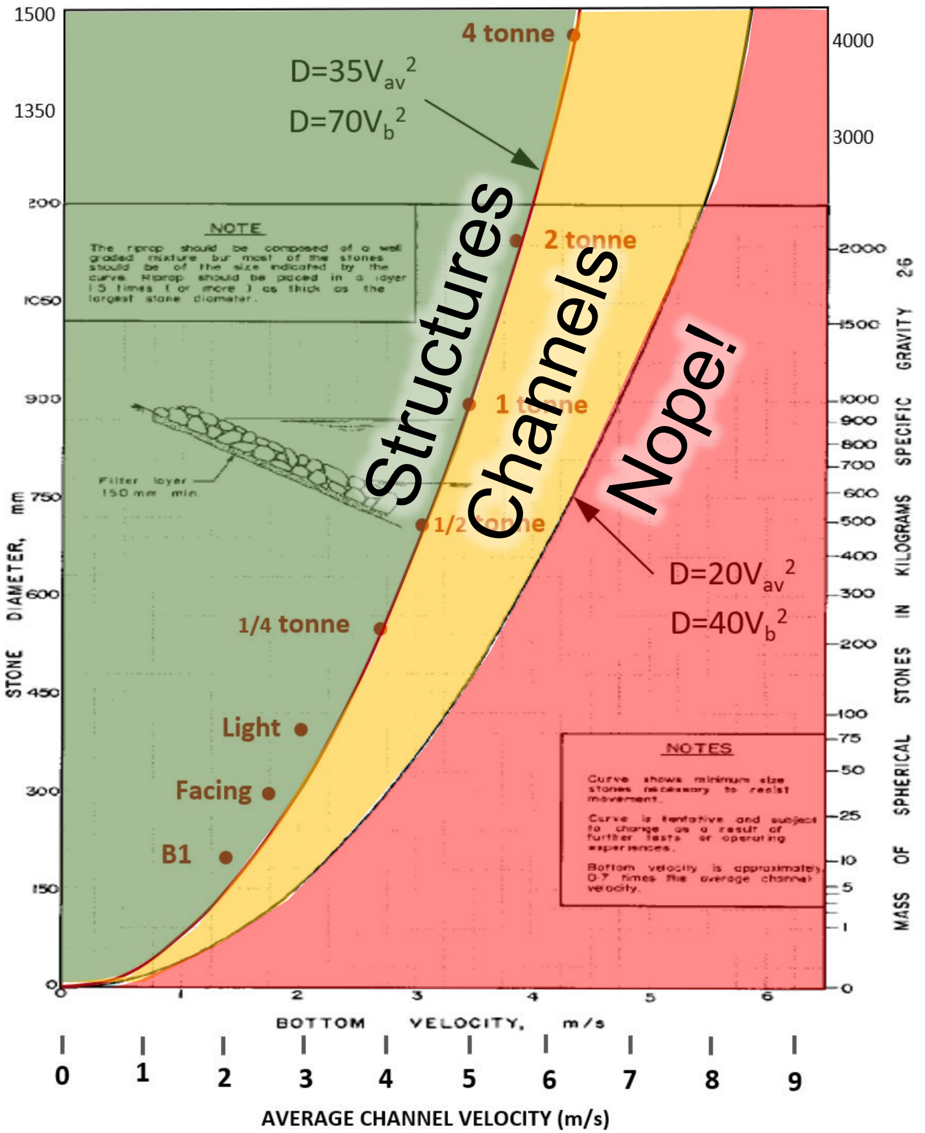
Recommendations

QDTMR 2019

'hard' solutions (such as riprap lining) or creek realignment (Option 3) is not favoured as changes to the creek at one location will often transfer problems to other nearby locations.

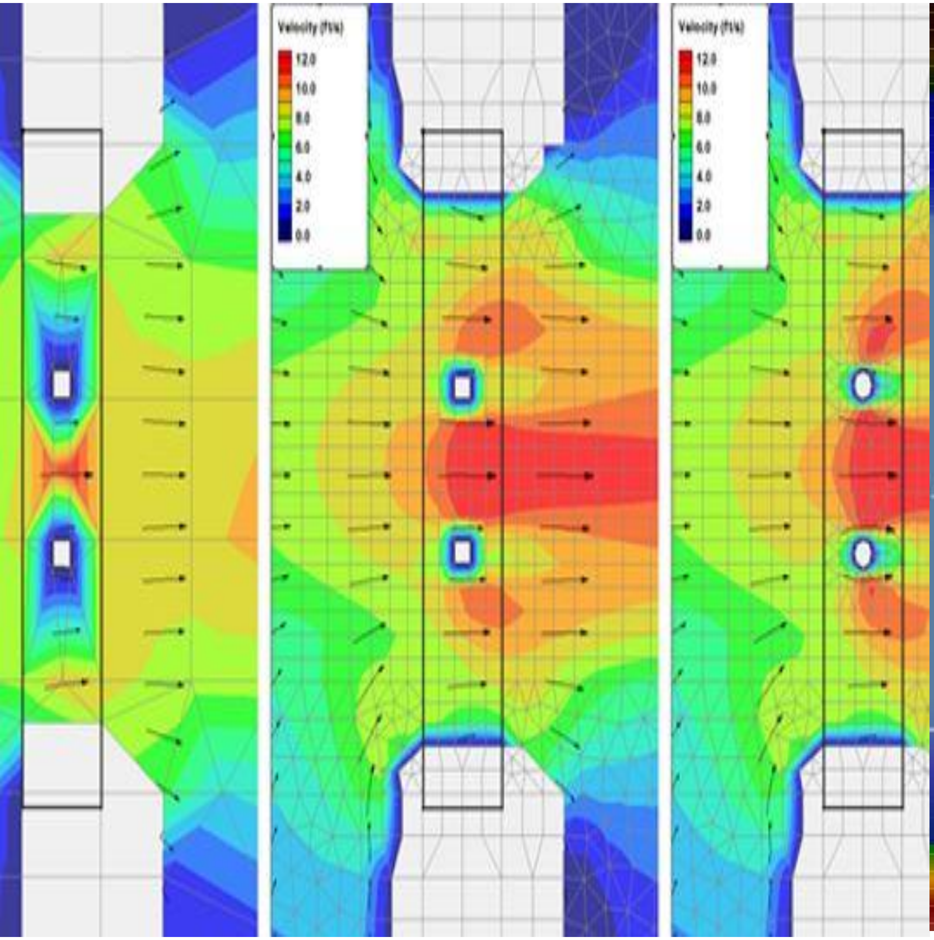
Austroads 2019

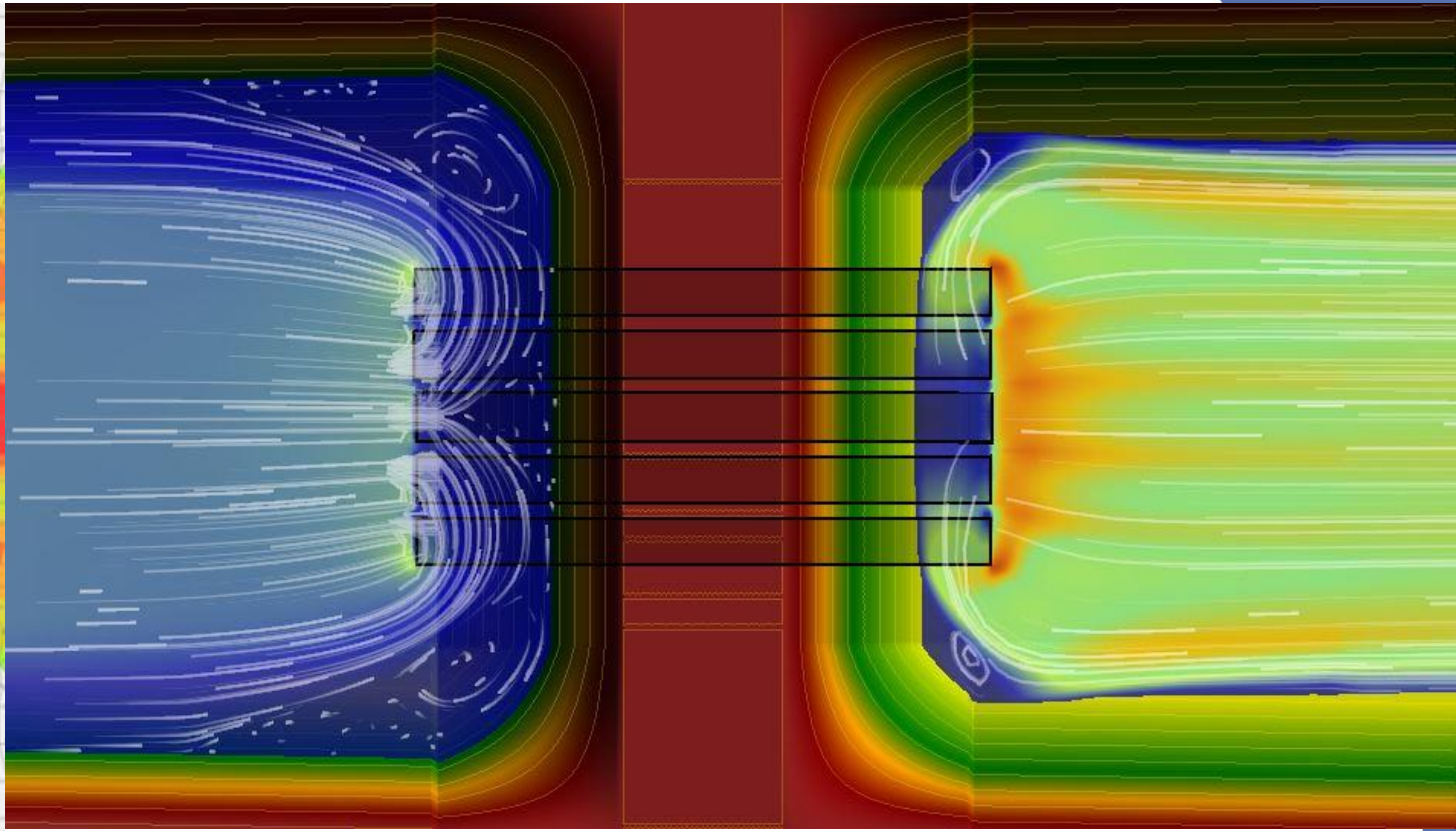
Riprap is, and will remain, one of the primary scour countermeasures to resist local scour forces at abutments of typical bridges. Riprap is generally abundant, inexpensive and requires no special equipment, but proper design and placement is still essential. An adequate hydraulic opening must be maintained when



Conclusions:

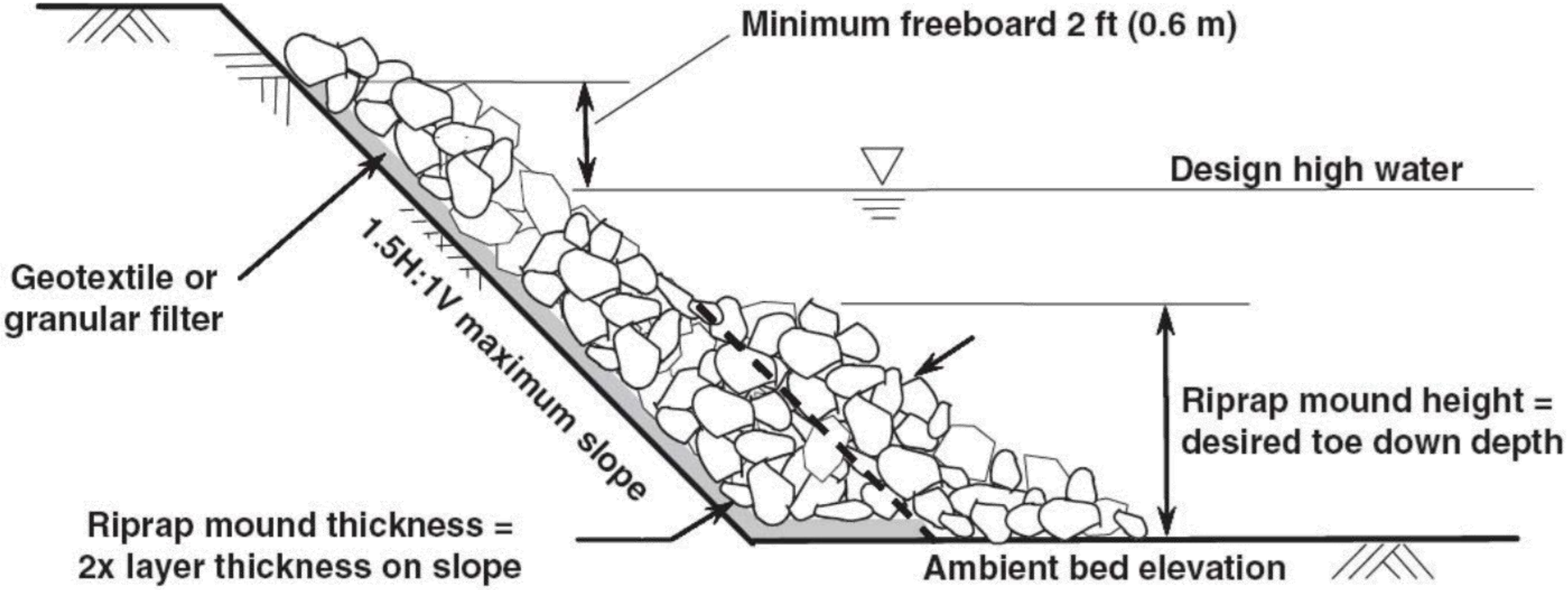
- Proper selection of 1D, 2D, or 3D modelling ✓





Conclusions:

- Appropriate sizing approach ✓
- Design parameters ✓
- Construction methods ✓



Conclusions:

- Remediation ?

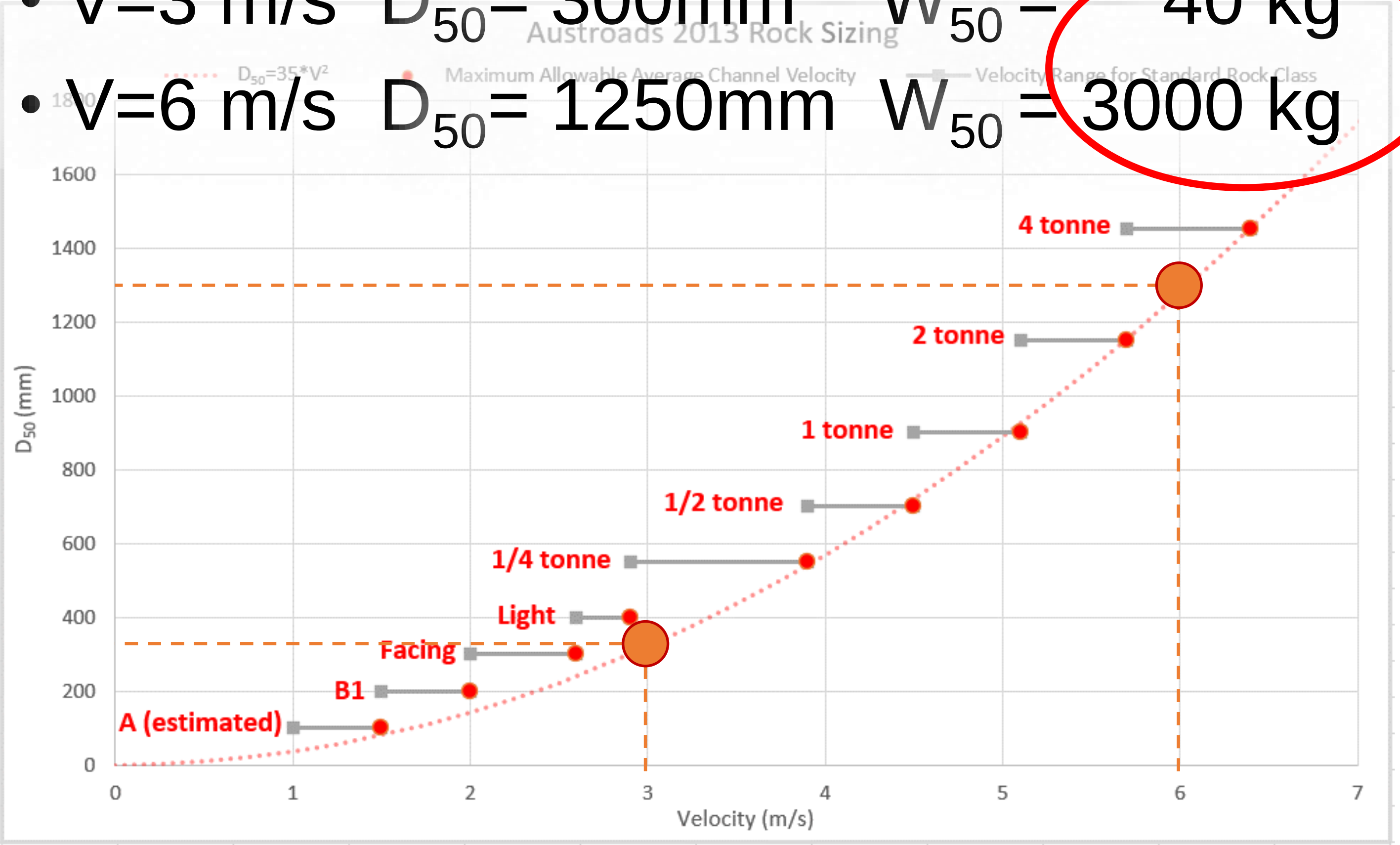
Pop Quiz

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

Pop Quiz

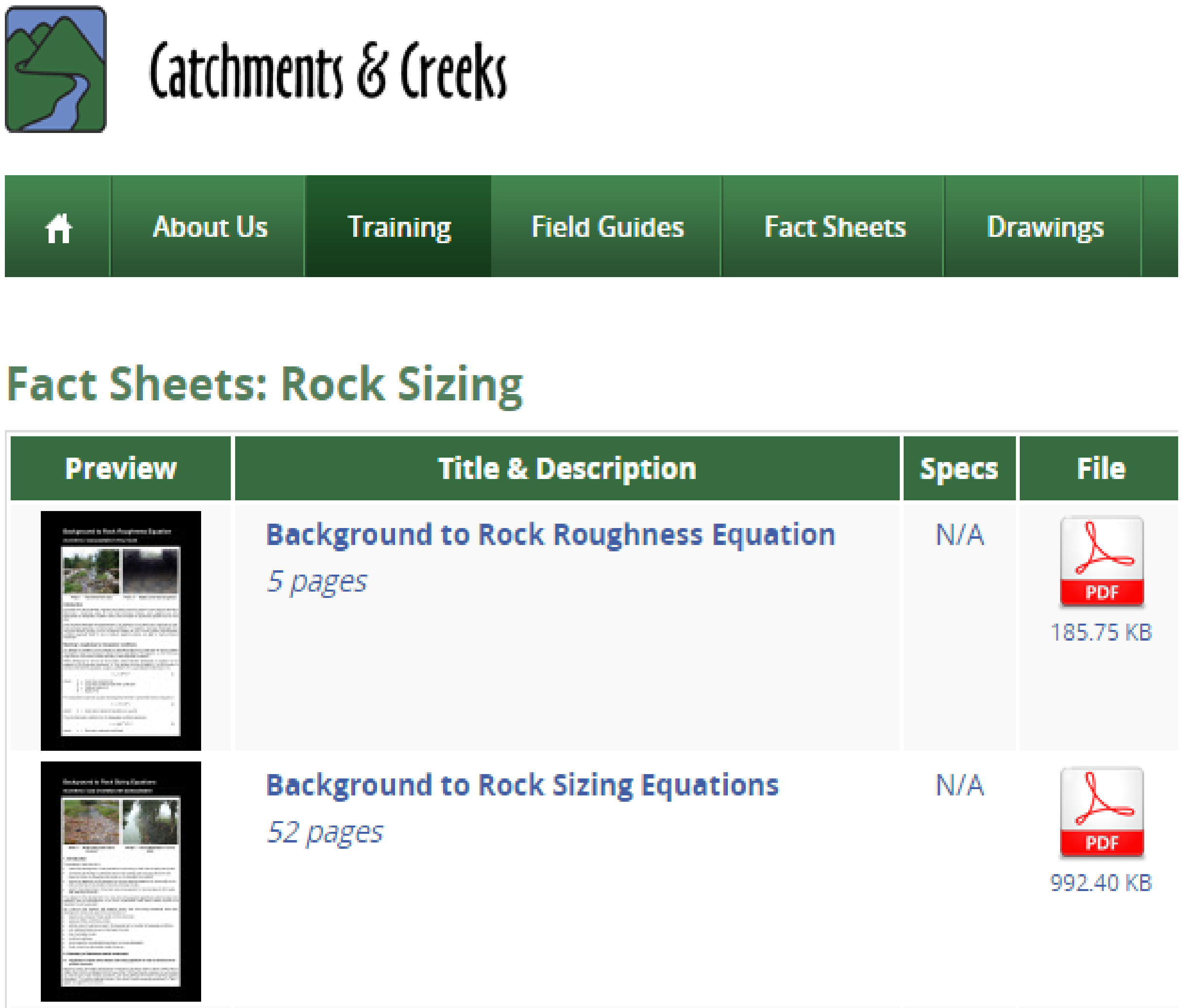
- Doubling the velocity increases the required rock weight by a factor of:
  - 2
  - 4
  - 8
  - 16
  - 32
  - 64

- V=3 m/s D_{50}= 300mm W_{50} = 40 kg
- V=6 m/s D_{50}= 1250mm W_{50} = 3000 kg

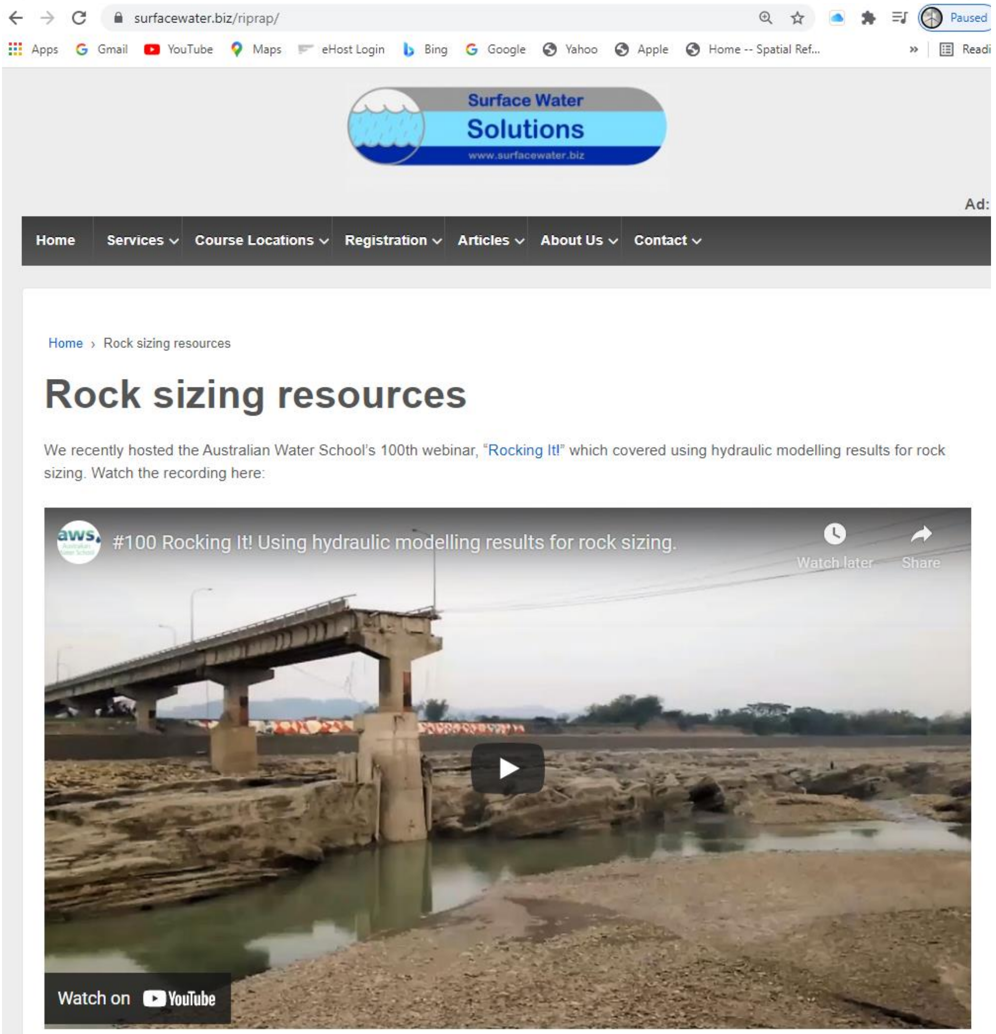


Additional Resources

www.catchmentsandcreeks.com.au

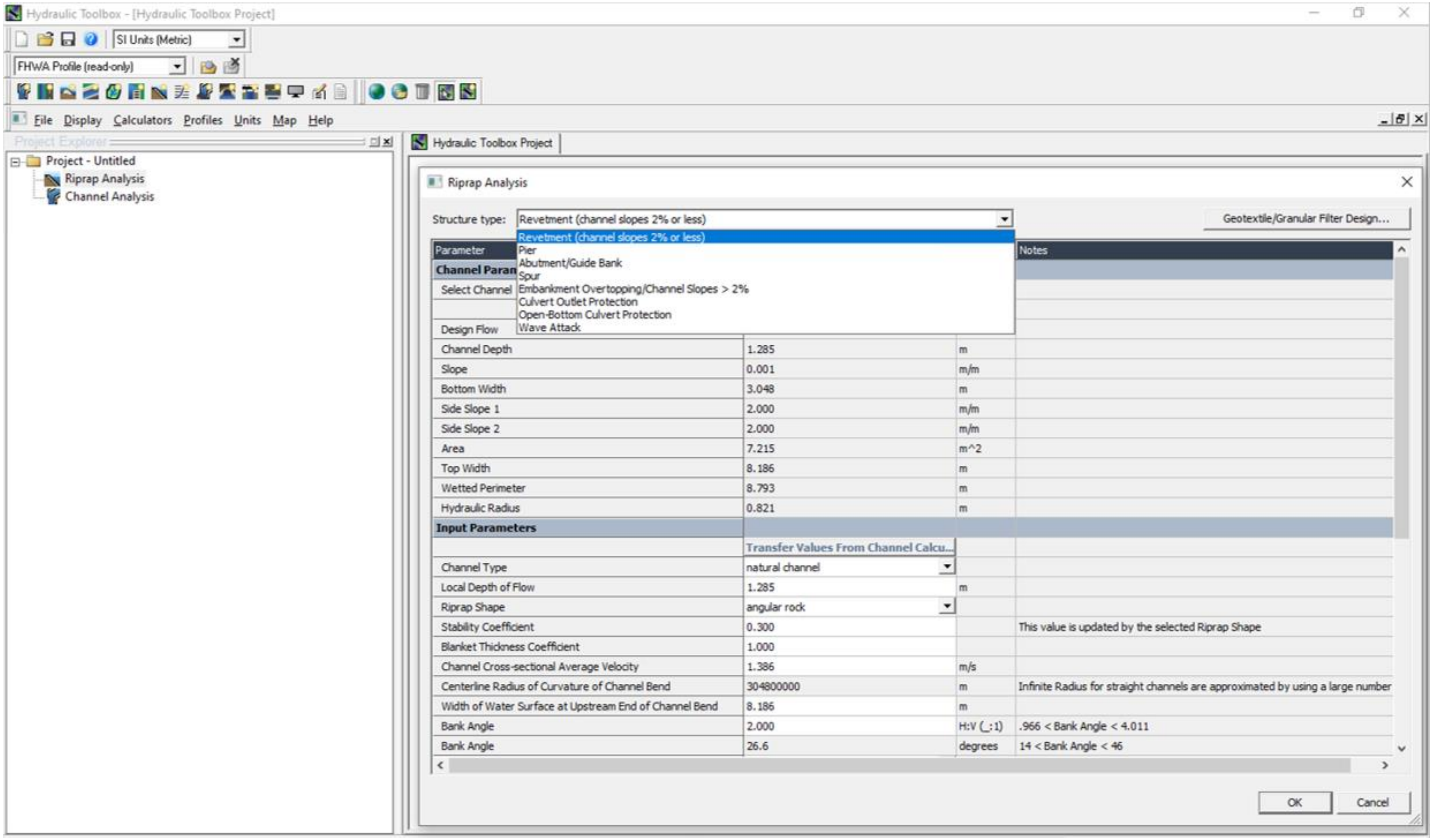


www.surfacewater.biz/riprap/



Additional Resources

FHWA Hydraulic Toolbox: www.fhwa.dot.gov/engineering/hydraulics/software/toolbox404.cfm



AWS Free Webinar: 12 October 2021

Australian Riprap Sizing Approaches

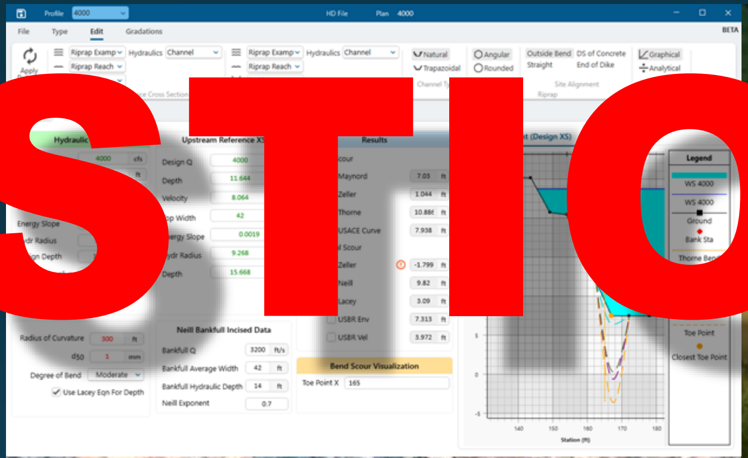
Incorporating the USACE method

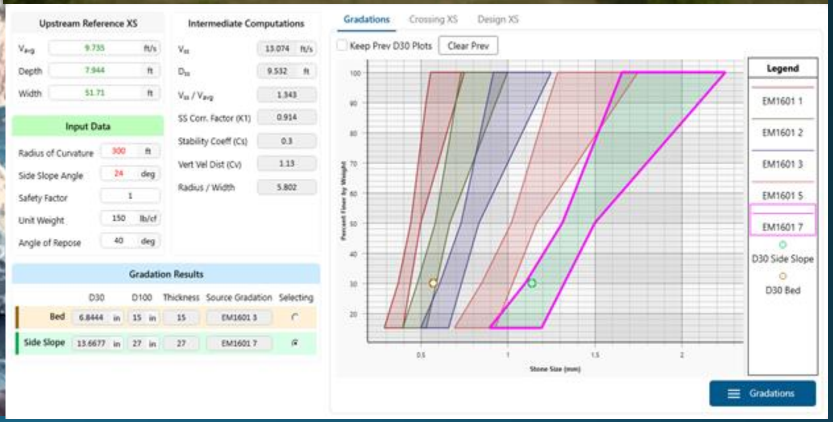
Presented by:

Stanford Gibson

USACE

Water Solutions





QUESTIONS?

Australian Water School