UNSW Spillway Erosion Project

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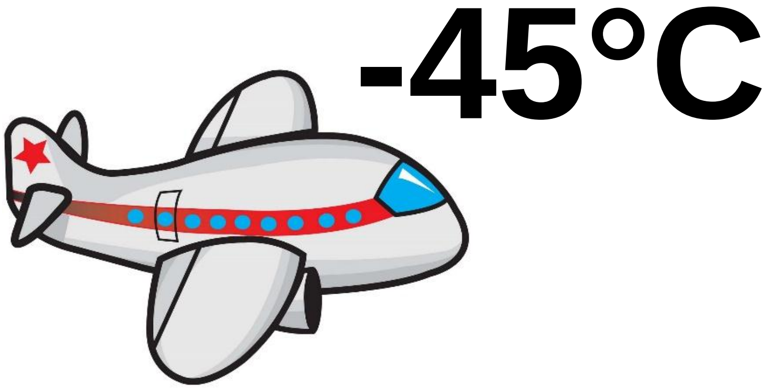
UNSW AUSTRALIA

Never Stand Still | Faculty of Engineering | School of Civil and Environmental Engineering



Dams Risk – Spillway Rock Erosion

- Backward erosion piping of dams and levees
- Global backward erosion piping in dams
- Prediction and numerical modelling of cracking in embankment dams
- Prediction of potential erosion in unlined spillways

The 'Dams Risk' Project

Australian Government
Australian Research Council

NSW Government | Public Works

Murray–Darling Basin Authority

ELFORSK

Melbourne Water

DSC New South Wales Dams Safety Committee

southern water

SMEC

URS

Water Corporation

GHD

Goulburn-Murray Water

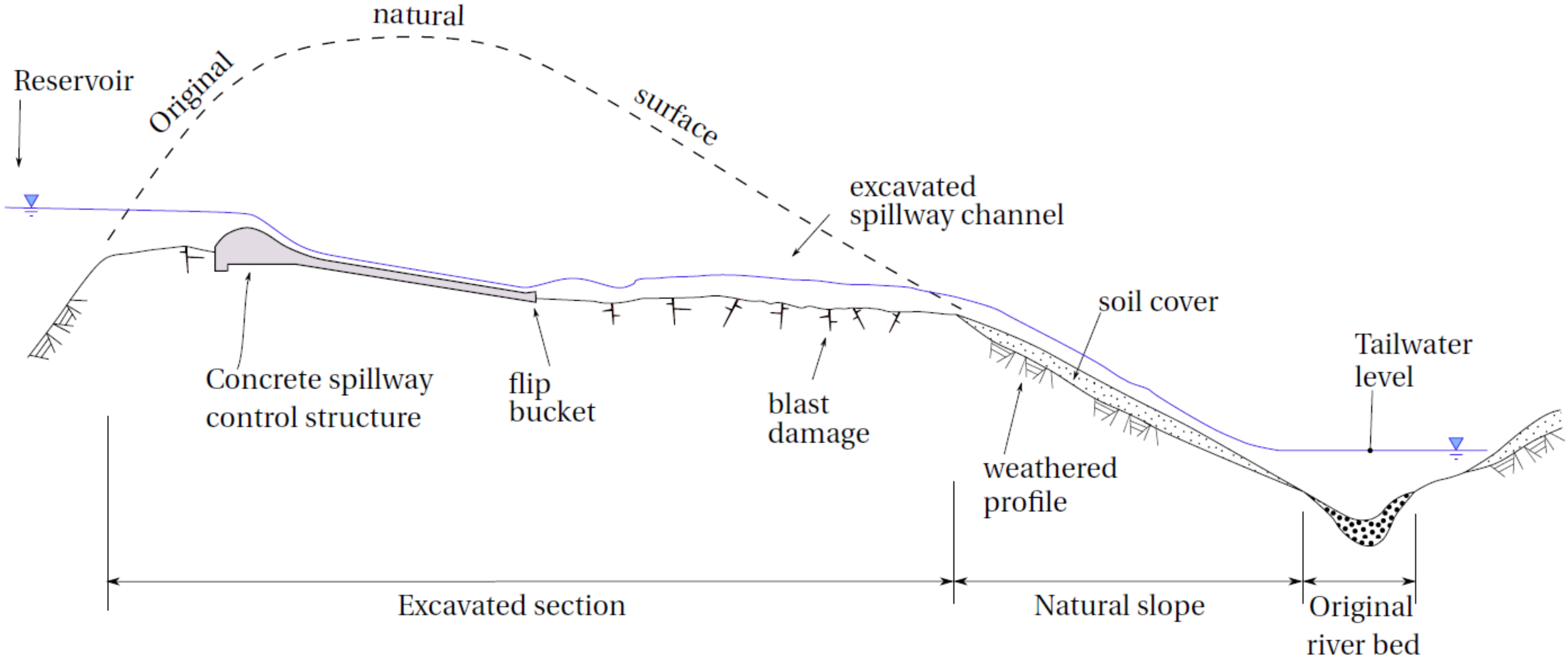
Hydro Tasmania
The power of natural thinking

SunWater
MAKING WATER WORK

Dams Risk – Spillway Rock Erosion

- Prediction of potential erosion in unlined spillways
  - Field studies of dam spillways from dams around Australia and South Africa (plus documented USA) with significant erosion and/or flows.
  - Laboratory flume studies focussing on potential pressure variations that can be induced in rock joints from parallel spillway flow.
  - New empirical and analytical methods of quantifying erosion created.

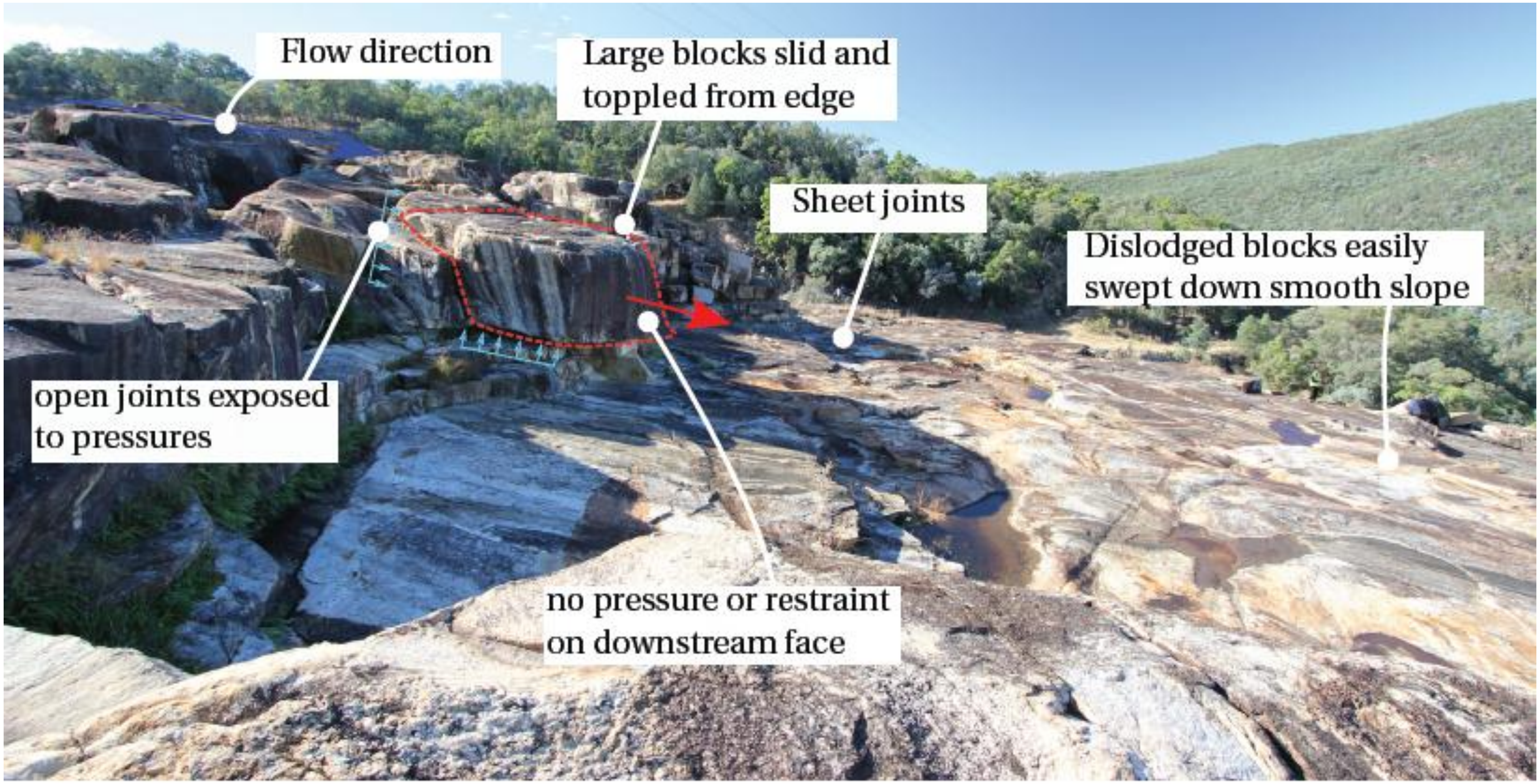
Erosion Mechanisms



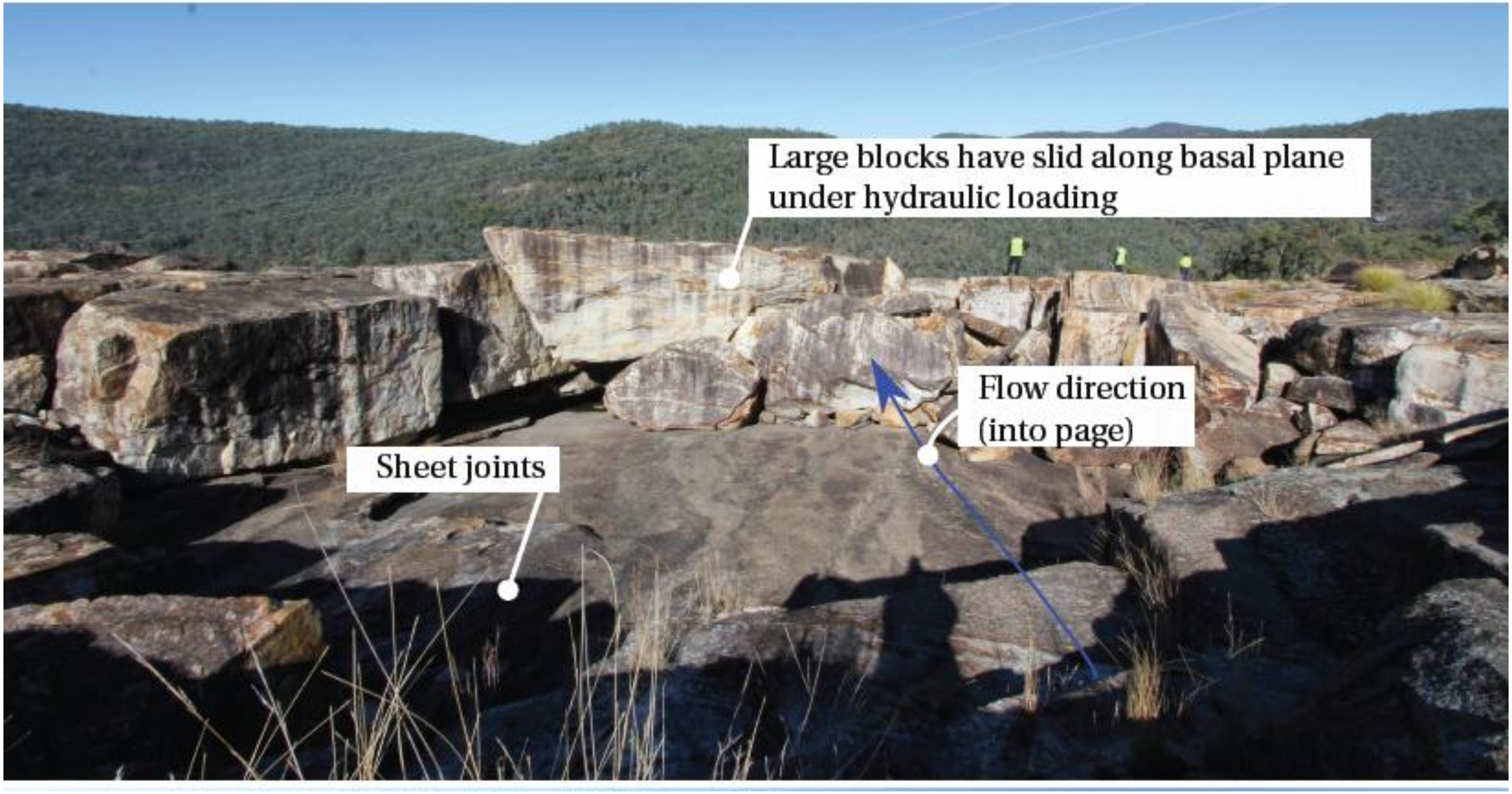
Erosion Mechanisms

- Requires consideration of BOTH the:
  - Geological Domains - primarily governed by the structural geology.
  - Hydraulics – primarily the spillway geometry and roughness and the direction of flow with respect to major defect orientations.
- Combined they are considered Erosion Domains
- Mechanisms are often very similar to slope instability mechanisms exacerbated by sub-horizontal water pressures.

Erosion Mechanisms – Copeton Dam

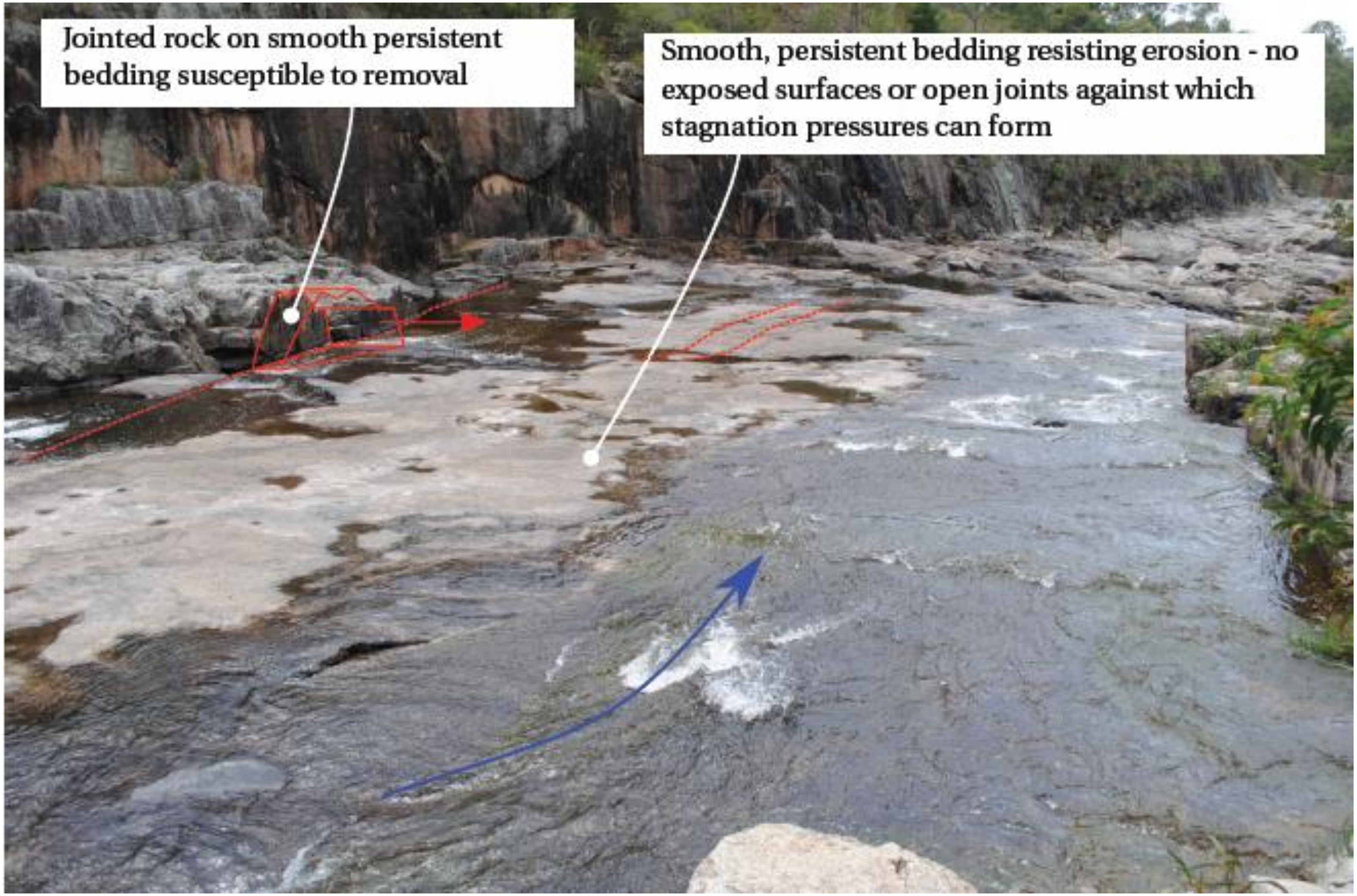


Erosion Mechanisms – Copeton Dam



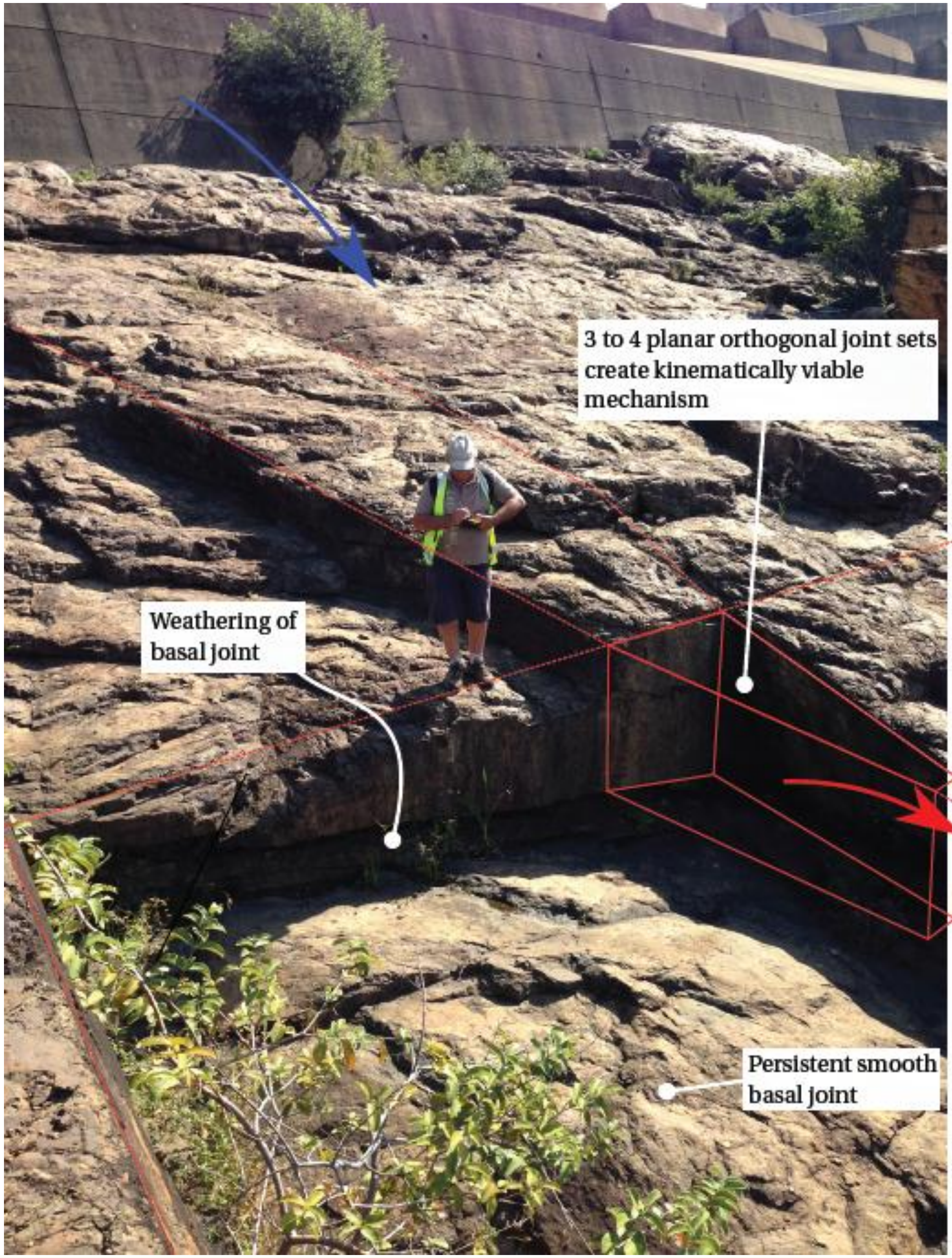
Erosion Mechanisms – Anthony Dam

Erosion Mechanisms - Brogo Dam

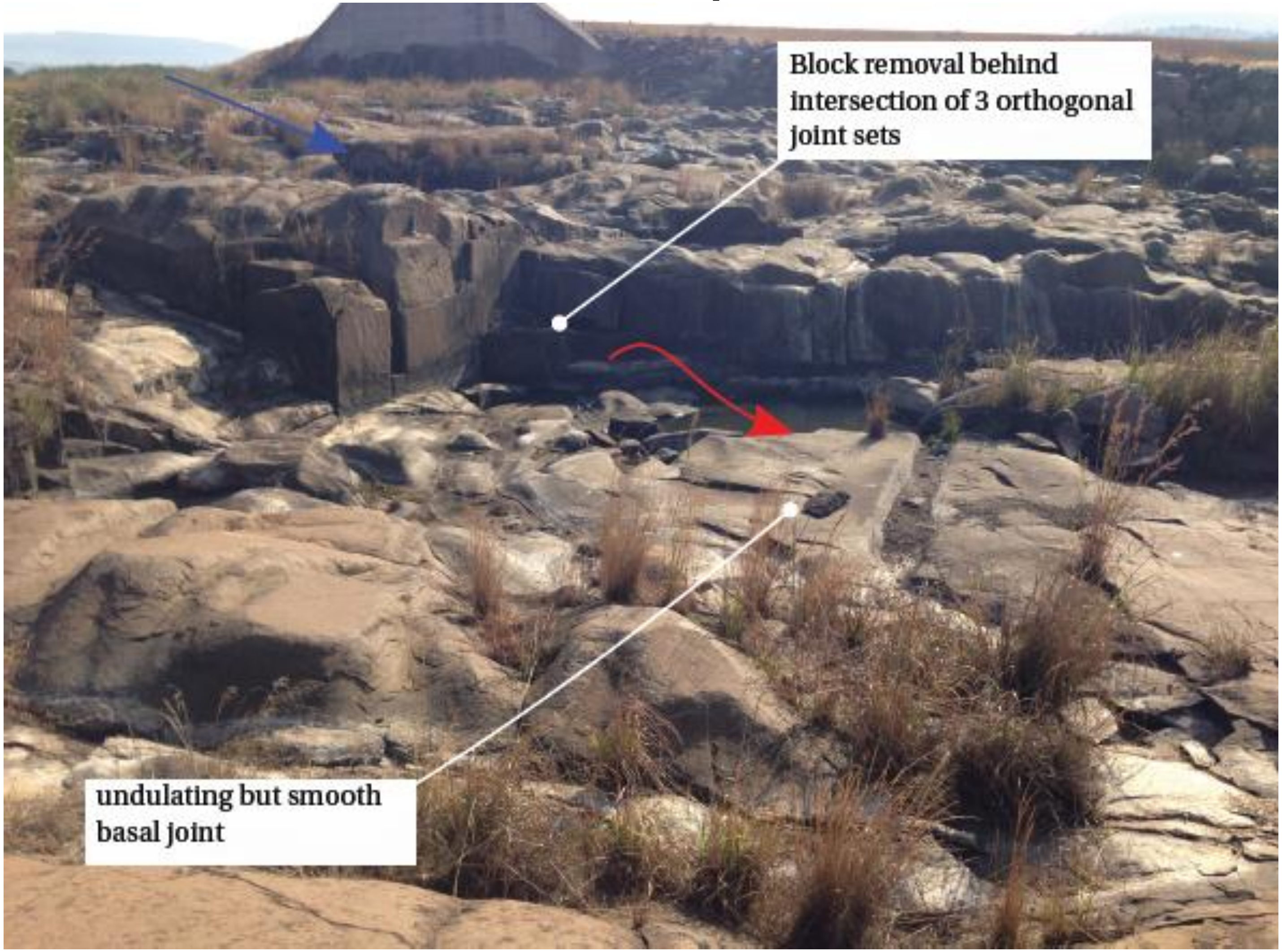


Erosion Mechanisms – Harding Dam

Erosion Mechanisms – Goedertrouw Dam

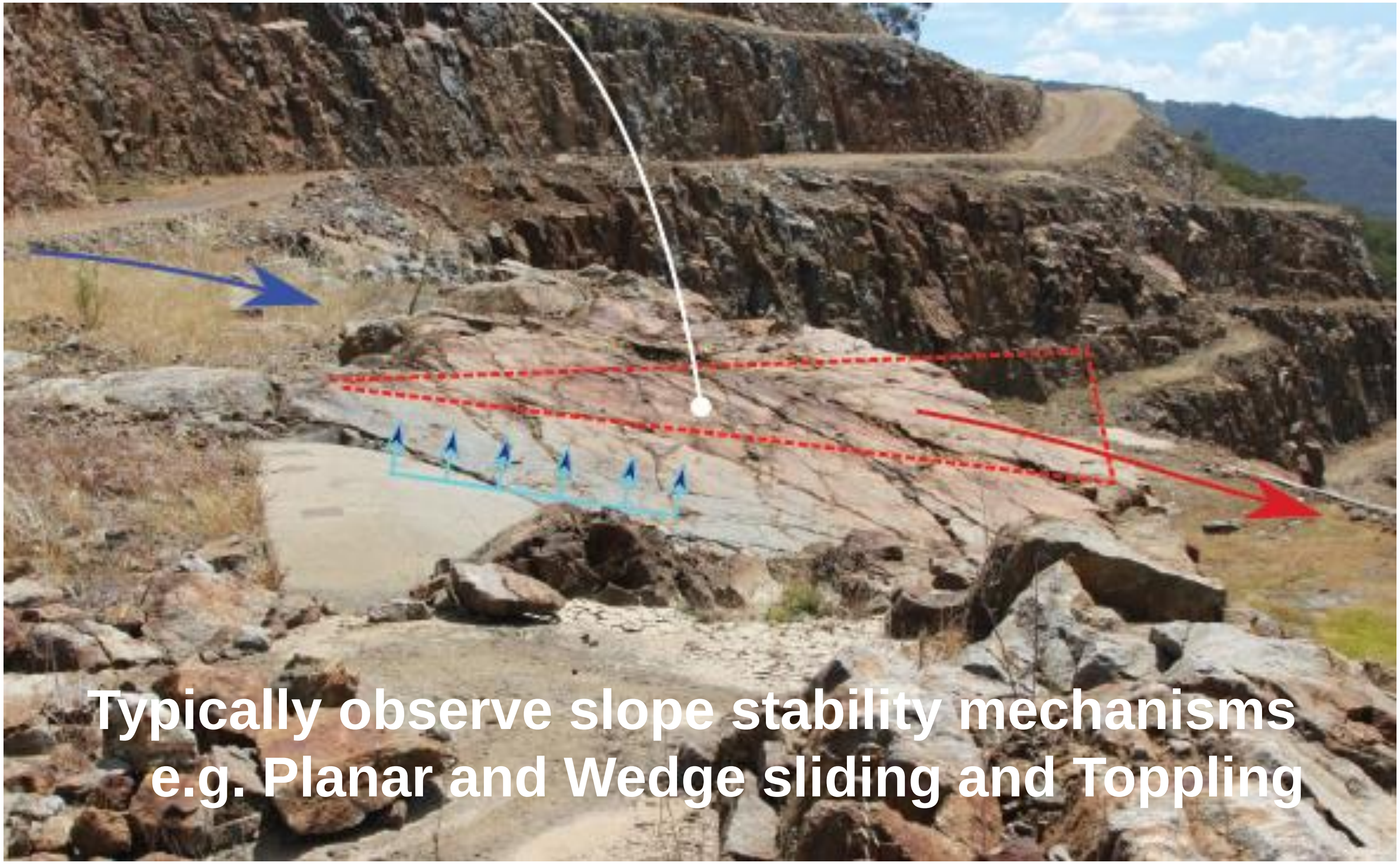


Erosion Mechanisms – Klipfontein Dam

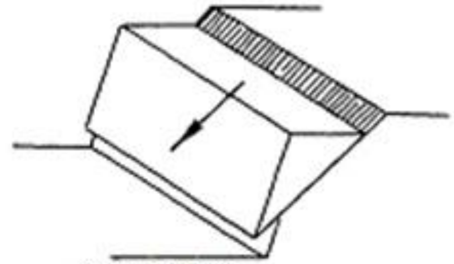


Erosion Mechanisms – Applethwaite Dam

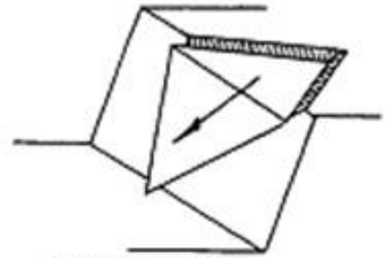
Erosion Mechanisms –Dartmouth Dam



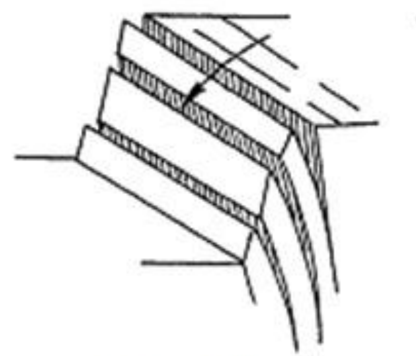
Simple slope stability mechanisms



Plane Failure

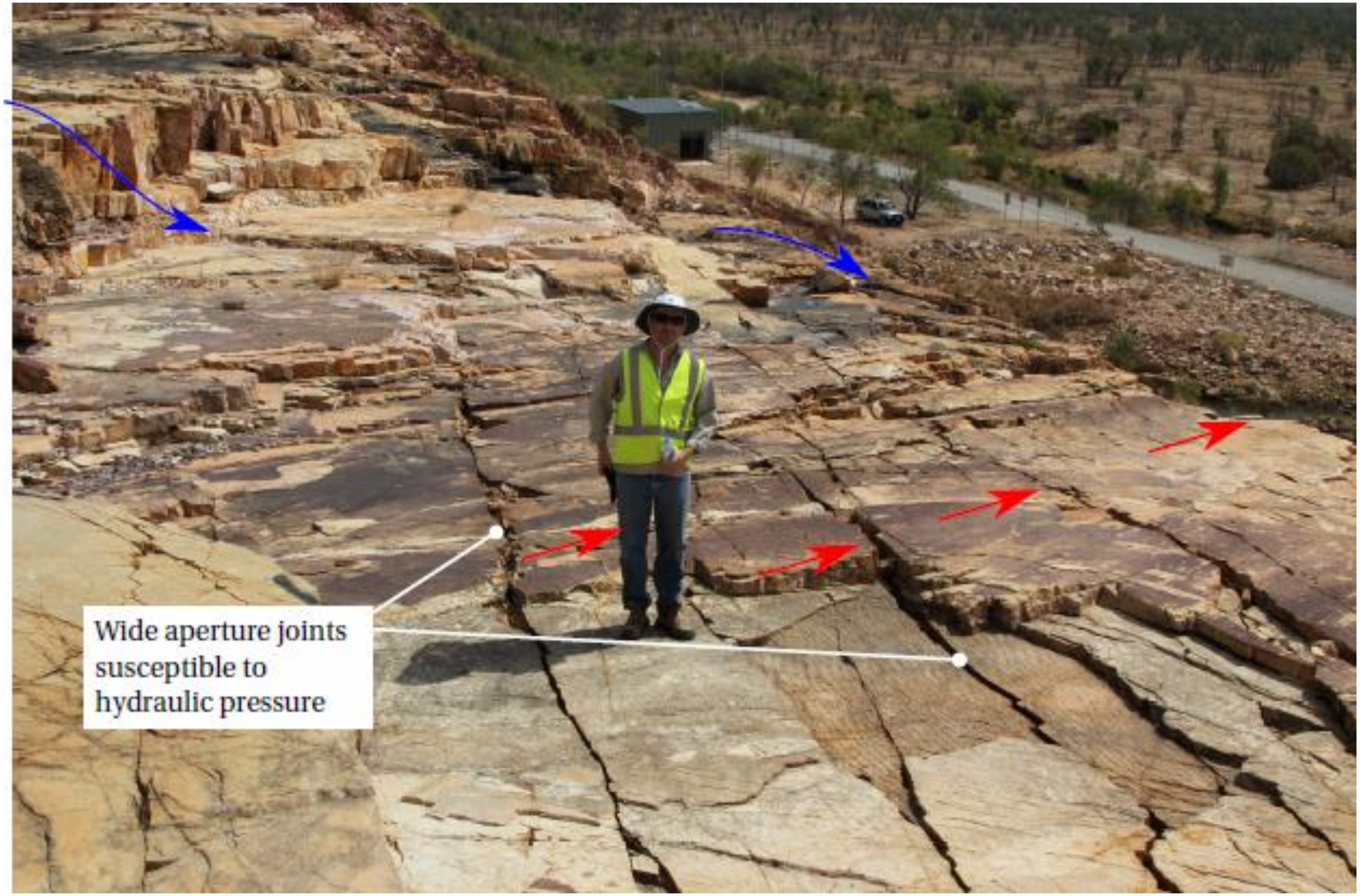


Wedge Failure



Toppling Failure

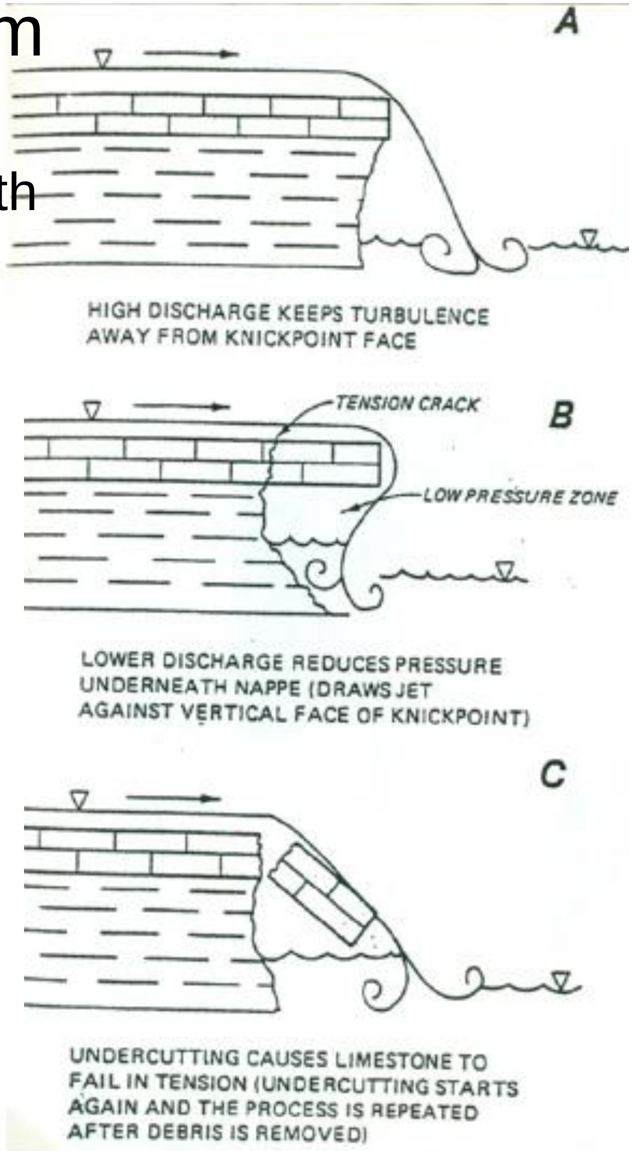
Erosion Mechanisms – Moochalabra Dam



Erosion Mechanisms – Moochalabra Dam

Erosion Mechanisms – Tuttle Ck Dam

Headcutting – erosion of weak shale beds beneath stronger limestone beds (courtesy USACE)

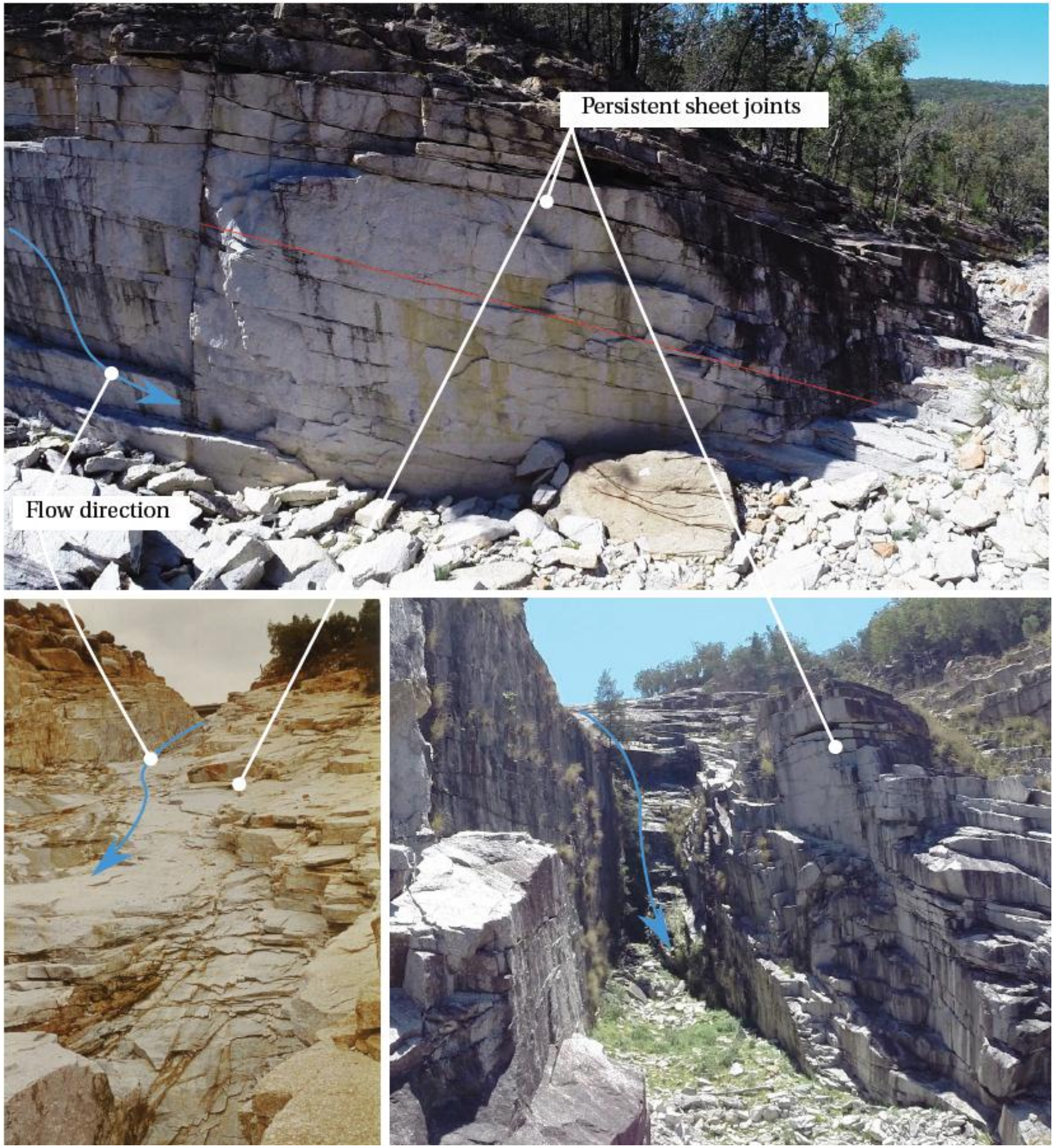


Erosion Mechanisms –Dartmouth Dam

Erosion Mechanisms – Pindari Dam

Erosion Mechanisms - Copeton Dam

Fault zone
+
Sheet joints
+
High stress
=
☹

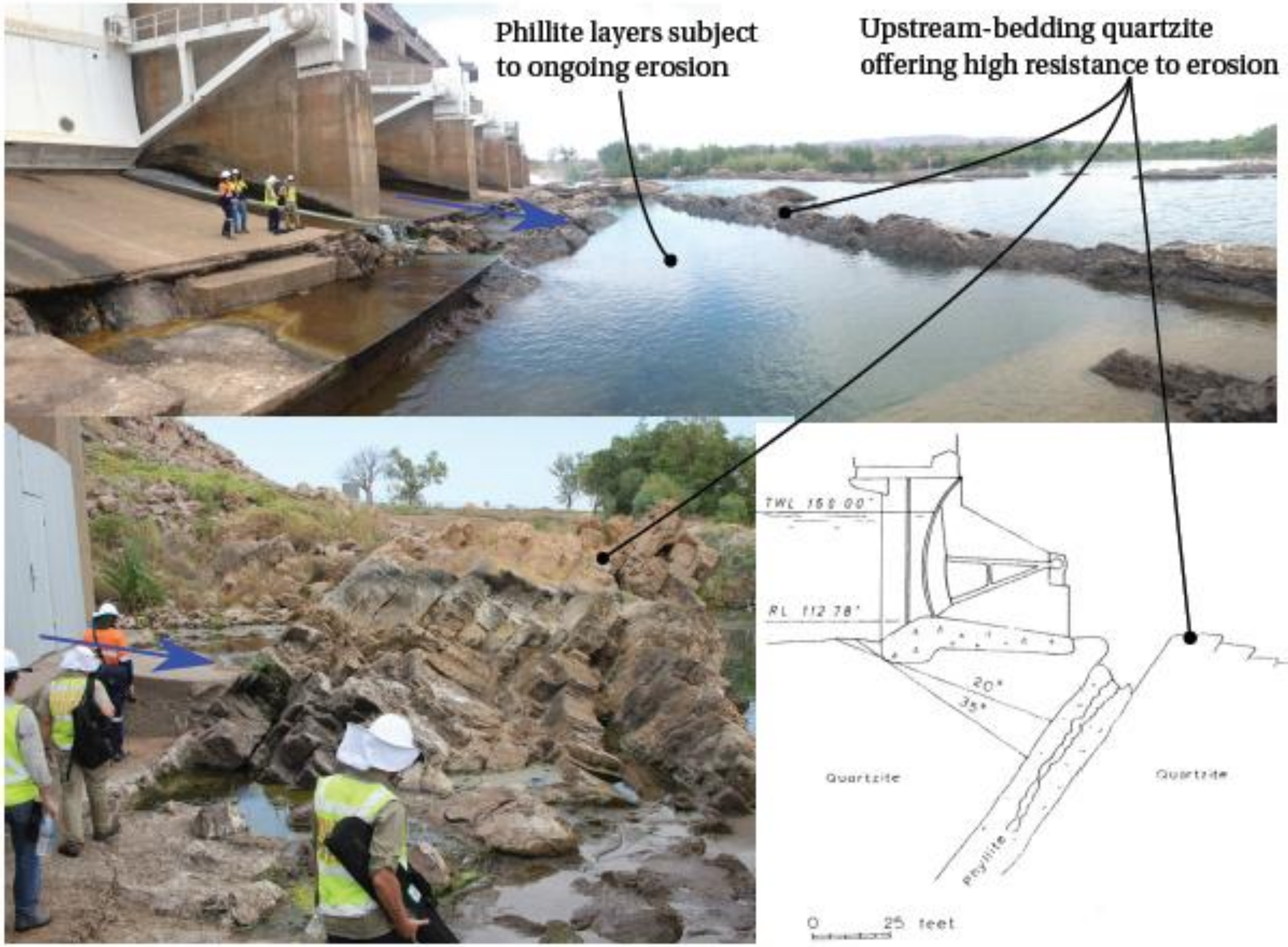


Erosion Mechanisms - Copeton Dam

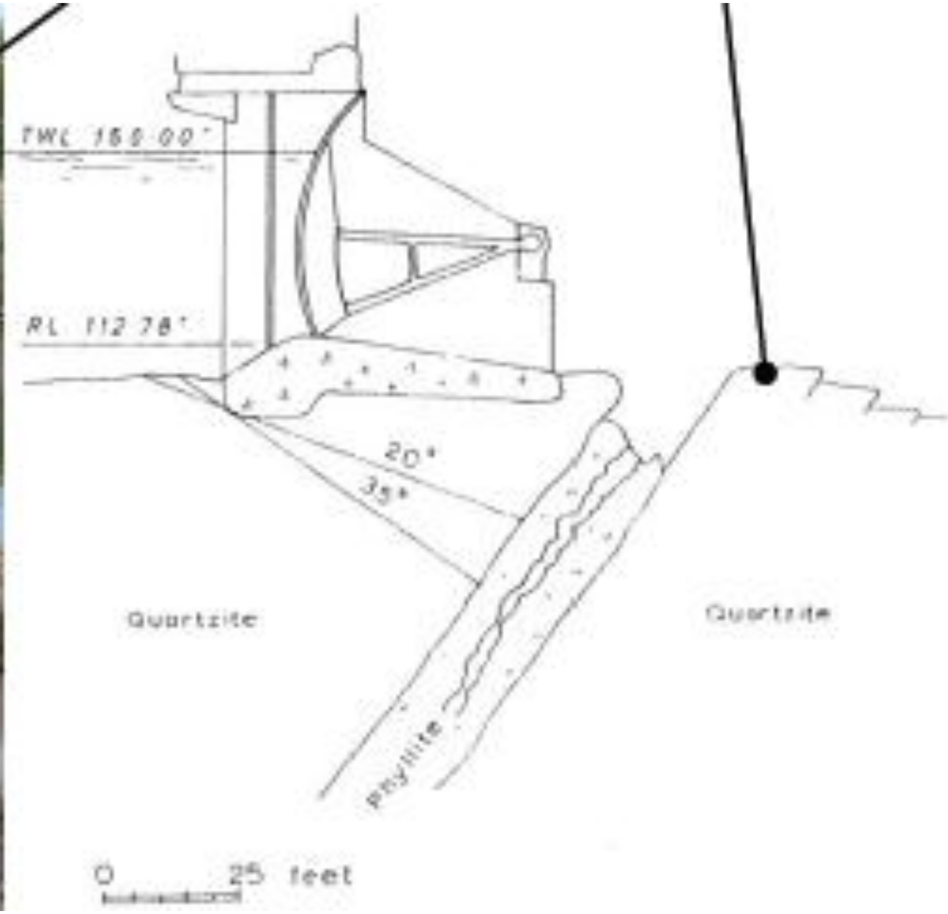
(Depth approx. 30m)

Erosion Mechanisms – Mokolo Dam

Erosion Mechanisms – Kununurra Diversion Dam

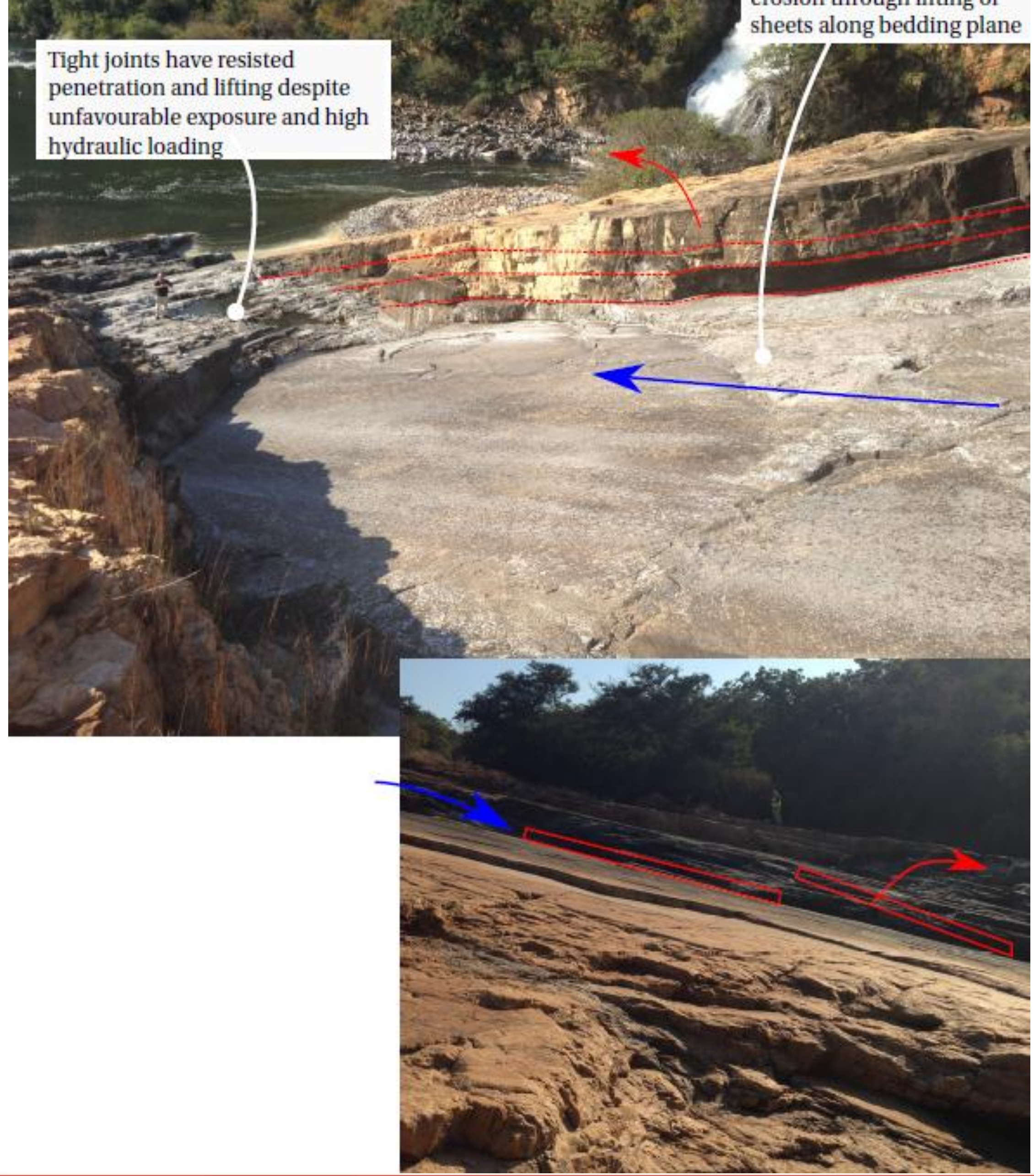


Erosion Mechanisms – Kununurra Diversion Dam



Erosion Mechanisms – Garden Route Dam

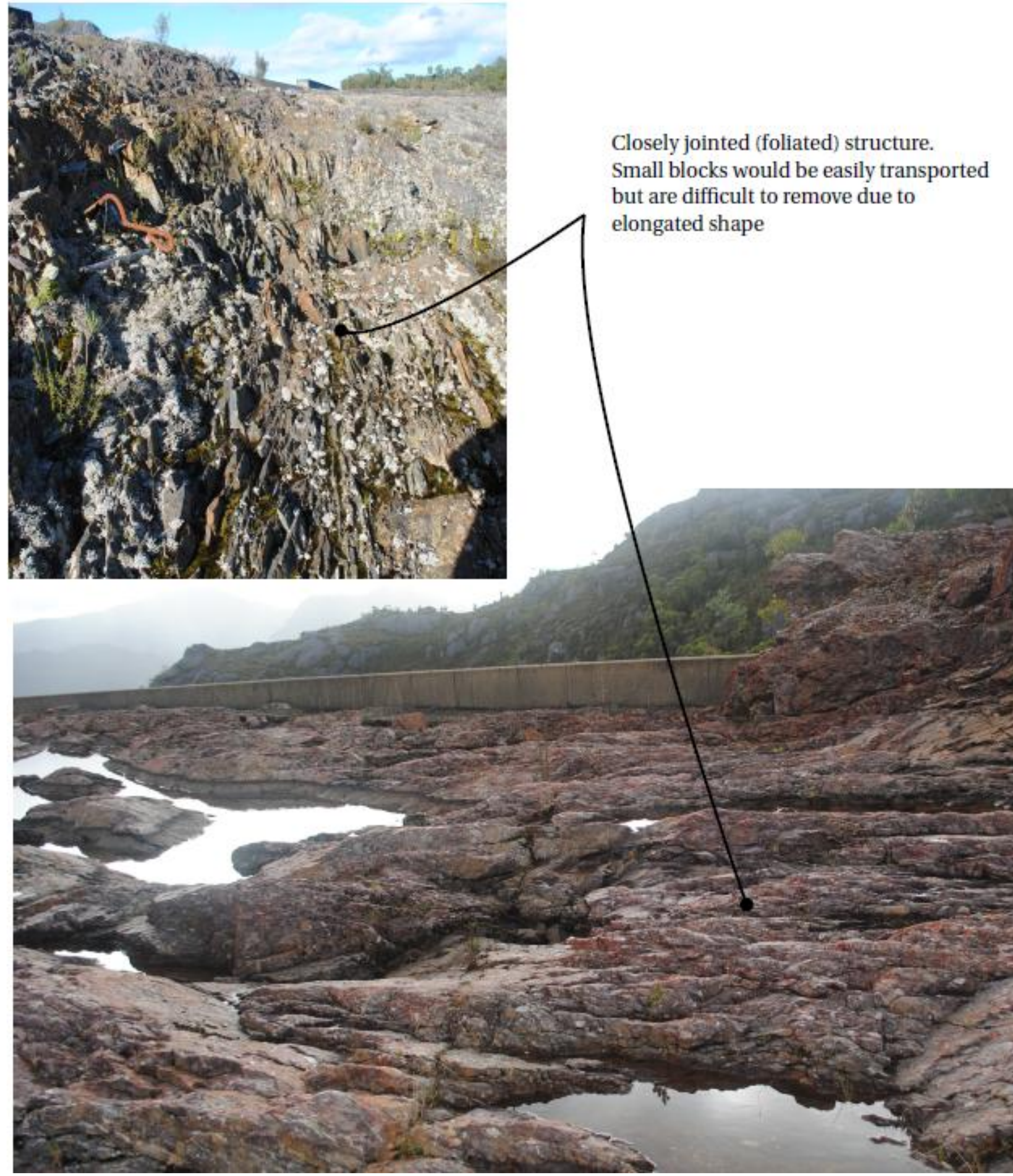
Erosion Mechanisms – Hartebeespoort Dam



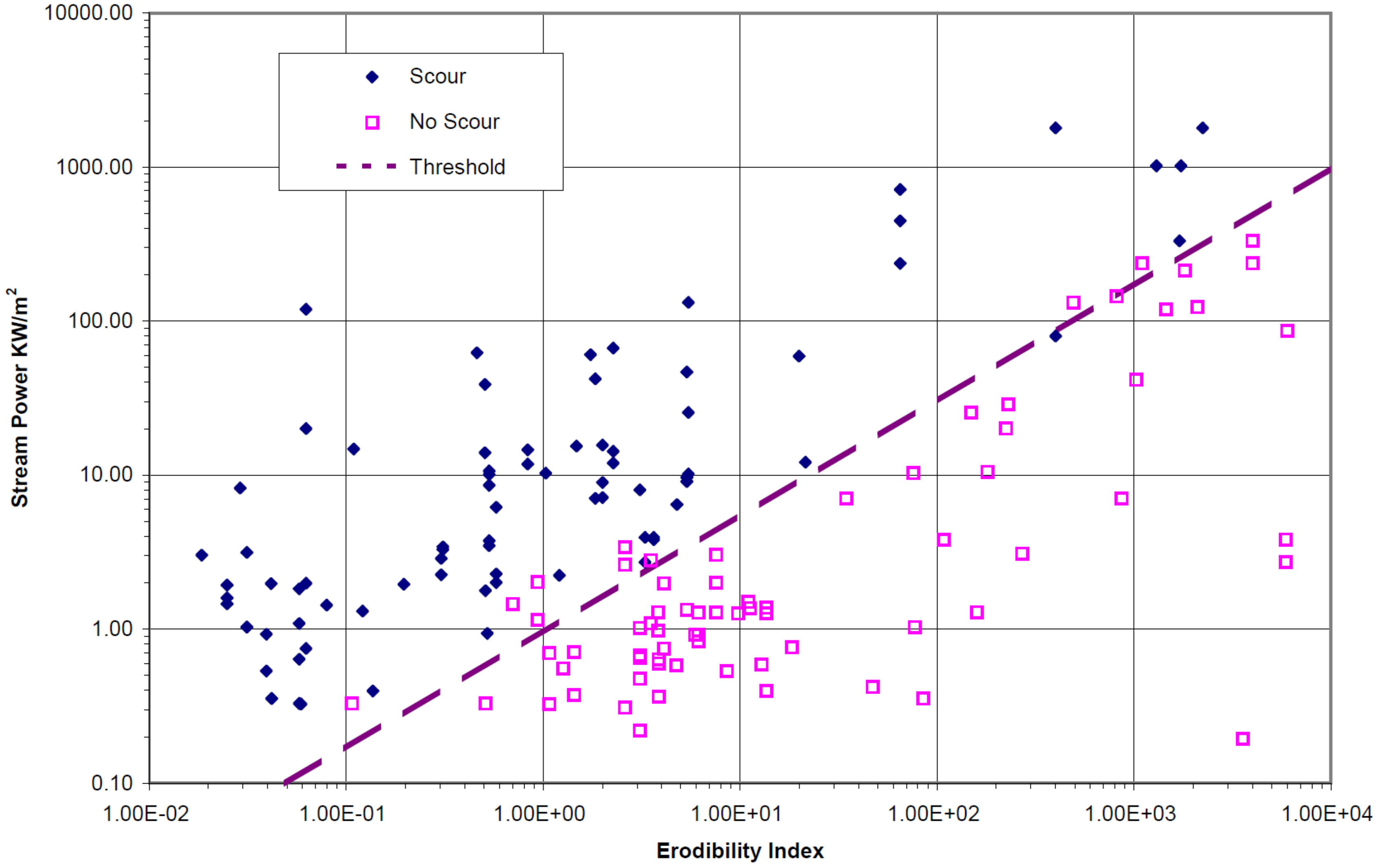
Erosion Mechanisms
Split Rock Dam

Persistent joins dipping upstream resist erosion (except where blast damaged)

Erosion Mechanisms – Mackenzie Dam (top) Anthony Dam (bottom)



Rowallan dam


Scour
No Scour
Threshold
Stream Power KW/m2
10000.00
1000.00
100.00
10.00
1.00
0.10
1.00E-02
1.00E-01
1.00E+00
1.00E+01
1.00E+02
1.00E+03
1.00E+04
Erodibility Index

Rock Mass Indices

Bieniawski 'RMR' (1974)

$$RMR = \sum(\text{classification parameters}) + \text{discontinuity orientation adjustment}$$

Barton (1974) 'Rock mass quality' ('Q-system')

$$Q = \left(\frac{RQD}{J_n}\right)\left(\frac{J_r}{J_a}\right)\left(\frac{J_w}{SRF}\right)$$

Hoek (1995) 'Geological Strength Index' ('GSI')

$$GSI = RMR'_{76} = F_1 + F_2 + F_3 + F_4 + 10$$

Kirsten (1982) 'excavatability' ('Kirsten Index')

$$K = \left(\frac{RQD}{J_n}\right)\left(\frac{J_r}{J_a}\right) M_s J_s$$

Rock Mass Indices

1.	ROCK QUALITY DESIGNATION	(*RQD*)
A.	Very poor	0—25
B.	Poor	25—50
C.	Fair	50—75
D.	Good	75—90
E.	Excellent	90—100

Note:
(i) Where *RQD* is reported or measured as ≦10 (including 0) a nominal value of 10 is used to evaluate *Q* in Eq. (1)
(ii) *RQD* intervals of 5, i. e. 100, 95, 90, etc. are sufficiently accurate

2.	JOINT SET NUMBER	(J_n)
A.	Massive, no or few joints	0.5—1.0
B.	One joint set	2
C.	One joint set plus random	3
D.	Two joint sets	4
E.	Two joint sets plus random	6
F.	Three joint sets	9
G.	Three joint sets plus random	12
H.	Four or more joint sets, random, heavily jointed, "sugar cube", etc.	15
J.	Crushed rock, earthlike	20

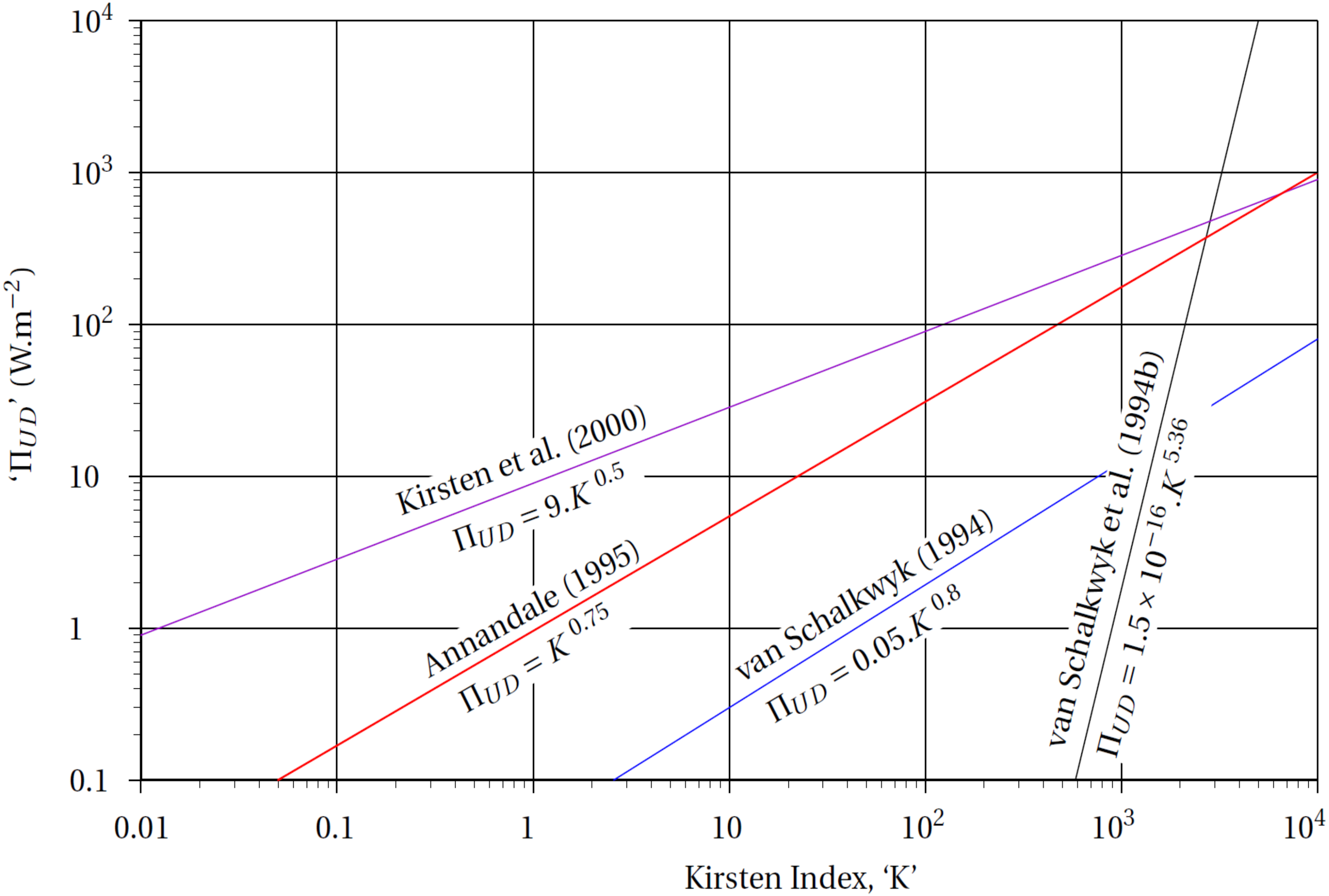
Note:
(i) For intersections use $(3.0 \times J_n)$
(ii) For portals use $(2.0 \times J_n)$

3.	JOINT ROUGHNESS NUMBER	(J_r)
	(a) *Rock wall contact* and (b) *Rock wall contact before 10 cms shear*	
A.	Discontinuous joints	4
B.	Rough or irregular, undulating	3
C.	Smooth, undulating	2
D.	Slickensided, undulating	1.5
E.	Rough or irregular, planar	1.5
F.	Smooth, planar	1.0
G.	Slickensided, planar	0.5
	(c) *No rock wall contact when sheared*	
H.	Zone containing clay minerals thick enough to prevent rock wall contact	1.0 (nominal)
J.	Sandy, gravelly or crushed zone thick enough to prevent rock wall contact	1.0 (nominal)

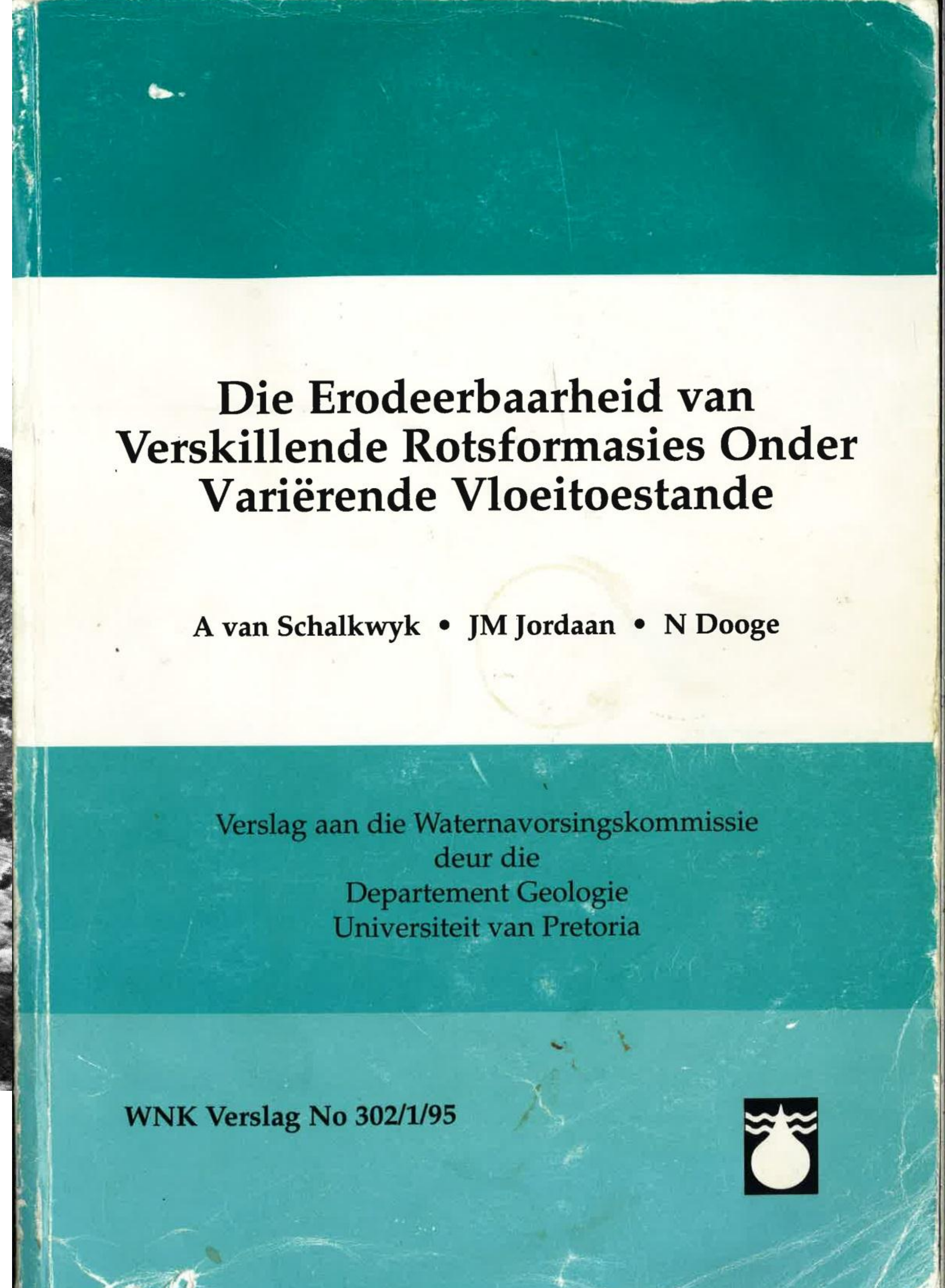
Note:
(i) Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m
(ii) $J_r = 0.5$ can be used for planar slickensided joints having lineations, provided the lineations are favourably orientated

4.	JOINT ALTERATION NUMBER	(J_a)	φ_r (approx.)
	(a) *Rock wall contact*		
A.	Tightly healed, hard, non-softening, impermeable filling i. e. quartz or epidote	0.75	(—)
B.	Unaltered joint walls, surface staining only	1.0	(25°—35°)
C.	Slightly altered joint walls. Non-softening mineral coatings, sandy particles, clay-free disintegrated rock etc.	2.0	(25°—30°)
D.	Silty-, or sandy-clay coatings, small clay-fraction (non-softening)	3.0	(20°—25°)
E.	Softening or low friction clay mineral coatings, i. e. kaolinite, mica. Also chlorite, talc, gypsum and graphite etc., and small quantities of swelling clays. (Discontinuous coatings, 1—2 mm or less in thickness)	4.0	(8°—16°)
	(b) *Rock wall contact before 10 cms shear*		
F.	Sandy particles, clay-free disintegrated rock etc.	4.0	(25°—30°)
G.	Strongly over-consolidated, non-softening clay mineral fillings (Continuous, < 5 mm in thickness)	6.0	(16°—24°)
H.	Medium or low over-consolidation, softening, clay mineral fillings. (Continuous, < 5 mm in thickness)	8.0	(12°—16°)
J.	Swelling clay fillings, i. e. montmorillonite (Continuous, < 5 mm in thickness). Value of J_a depends on percent of swelling clay-size particles, and access to water etc.	8.0—12.0	(6°—12°)
	(c) *No rock wall contact when sheared*		
K, L, M.	Zones or bands of disintegrated or crushed rock and clay (see G, H, J for description of clay condition)	6.0, 8.0 or 8.0—12.0	(6°—24°)
N.	Zones or bands of silty- or sandy clay, small clay fraction (non-softening)	5.0	
O, P, R.	Thick, continuous zones or bands of clay (see G, H, J for description of clay condition)	10.0, 13.0 or 13.0—20.0	(6°—24°)

Note:
(i) Values of $(\varphi)_r$ are intended as an approximate guide to the mineralogical properties of the alteration products, if present



10^4
10^3
10^2
10
1
0.1
'Π_{UD}' (W.m^{-2})
0.01
0.1
1
10
10^2
10^3
10^4
Kirsten Index, 'K'
Kirsten et al. (2000)
$\Pi_{UD} = 9.K^{0.5}$
Annandale (1995)
$\Pi_{UD} = K^{0.75}$
van Schalkwyk (1994)
$\Pi_{UD} = 0.05.K^{0.8}$
van Schalkwyk et al. (1994b)
$\Pi_{UD} = 1.5 \times 10^{-16}.K^{5.36}$

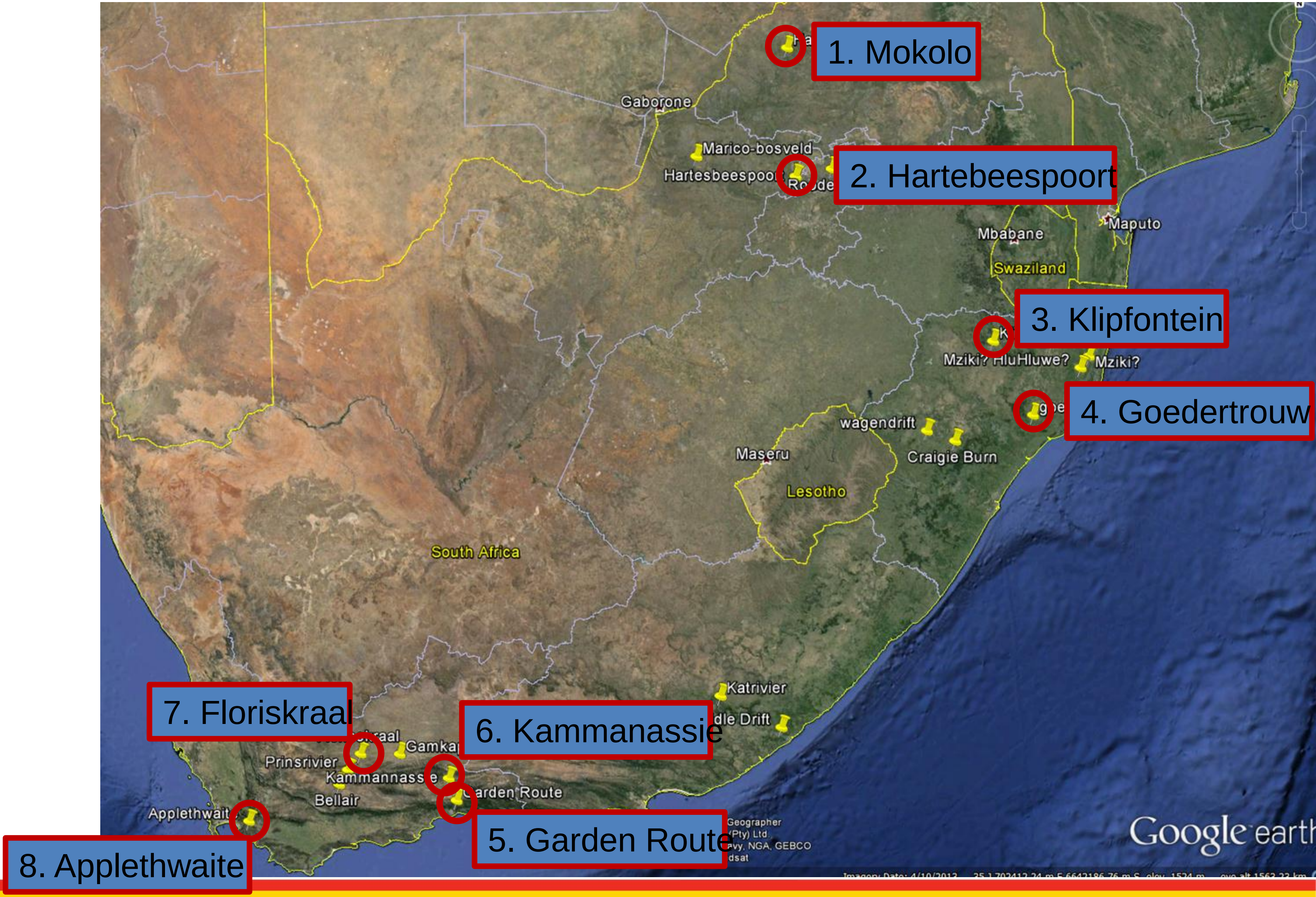


Die Erodeerbaarheid van Verskillende Rotsformasies Onder Variërende Vloeitoestande

A van Schalkwyk • JM Jordaan • N Dooge

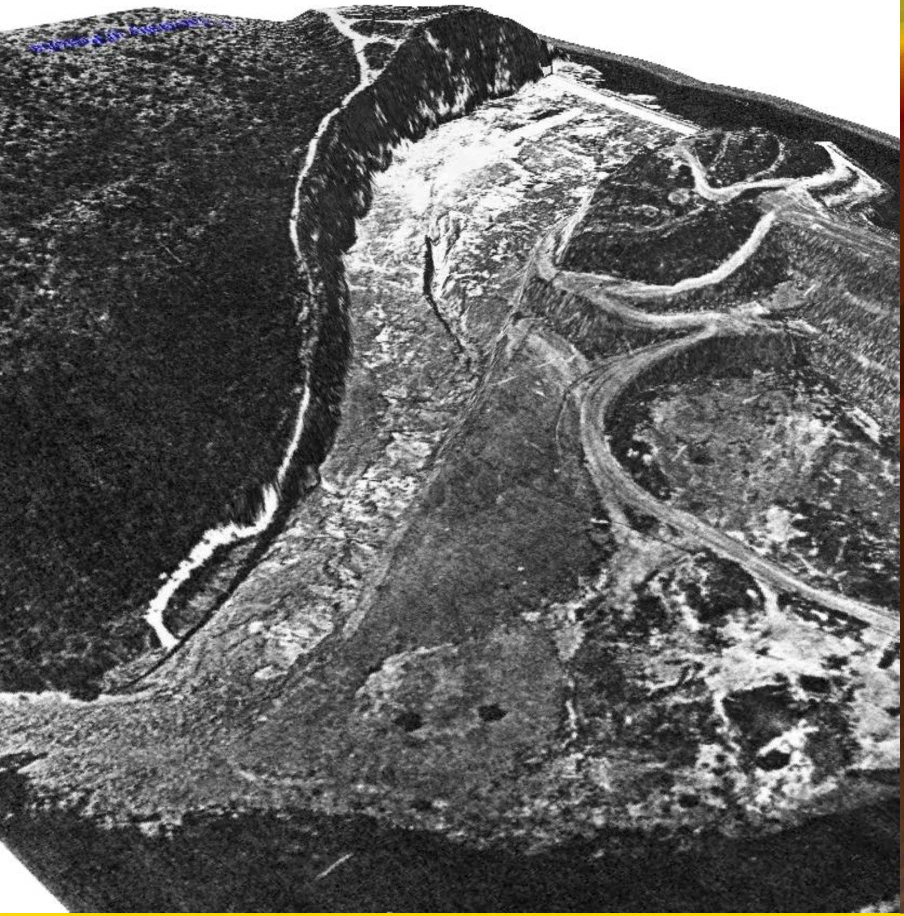
Verslag aan die Waternavorsingskommissie
deur die
Departement Geologie
Universiteit van Pretoria

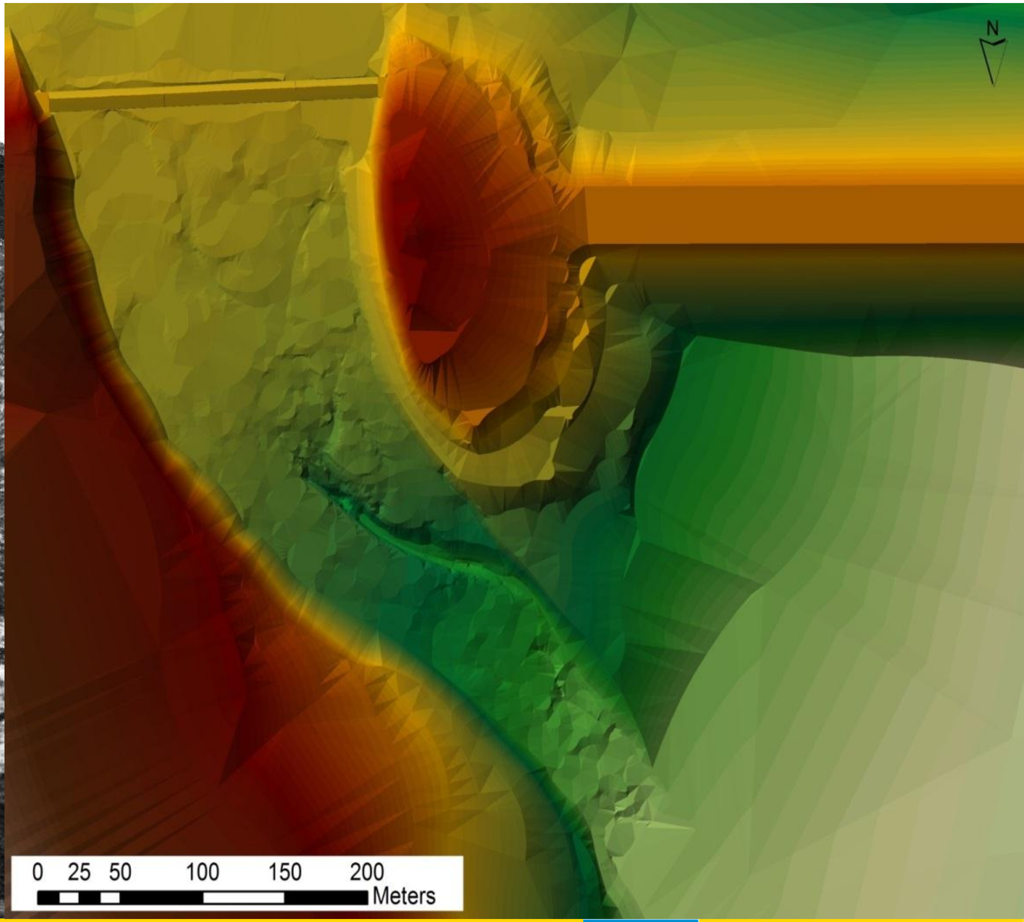
WNK Verslag No 302/1/95


1. Mokolo
2. Hartebeespoort
3. Klipfontein
4. Goedertrouw
5. Garden Route
6. Kammanassie
7. Floriskraal
8. Applethwaite
Gaborone
Marico-bosveld
Hartesbeespoort
Maputo
Mbabane
Swaziland
Mziki? HluHluwe?
Mziki?
wagendrift
Craigie Burn
Maseru
Lesotho
South Africa
Katrivier
Prinsrivier
Kammannassie
Gamka
Garden Route
Bellair
Applethwait
Google earth

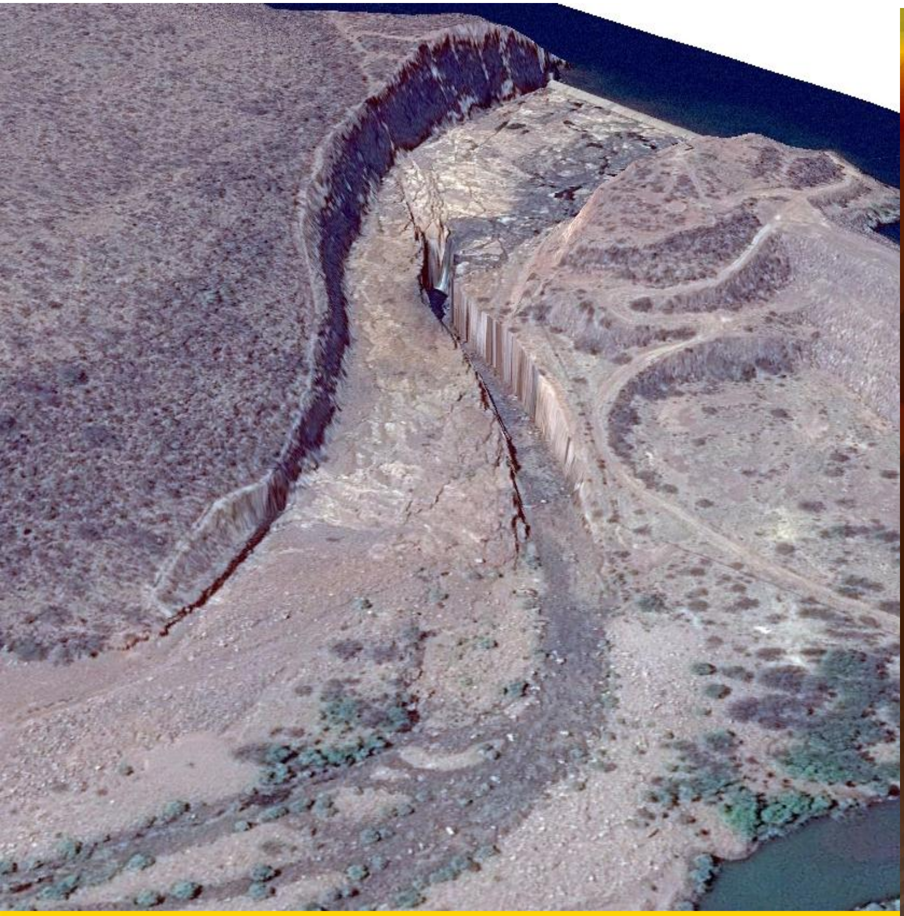
link

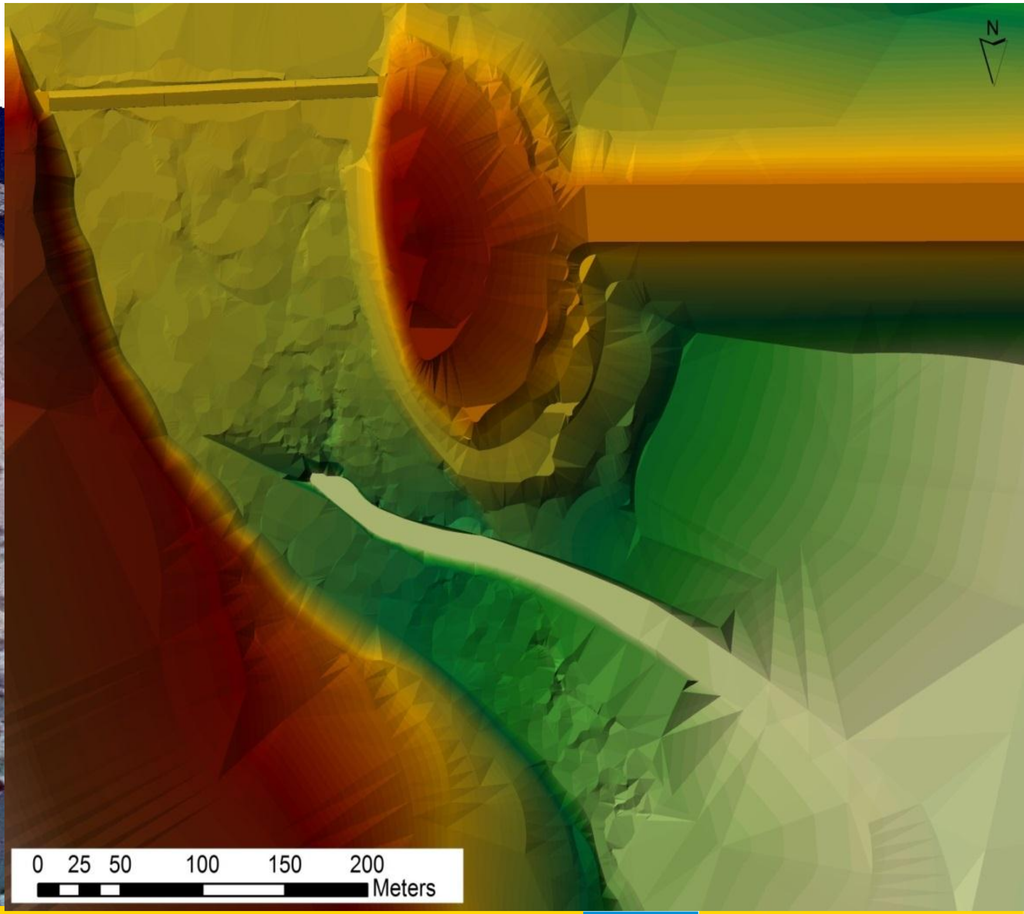
Mokolo Dam





Mokolo Dam





Flood of 12 March 2014

~ 2m above 200m wide crest

~920 m^3/s

Kammannasie

Erosion Assessment

Max Depth m	General extent m^3 per 100 m^2	Class	Descriptor
<0.3	< 10	I	Negligible
0.3 to 1	10 to 30	II	Minor
1 to 2	30 to 100	III	Moderate
2 to 7	100 to 350	IV	Large
>7	>350	V	Extensive

Interpreted extent of erosion

Interpretation of erosion mechanism

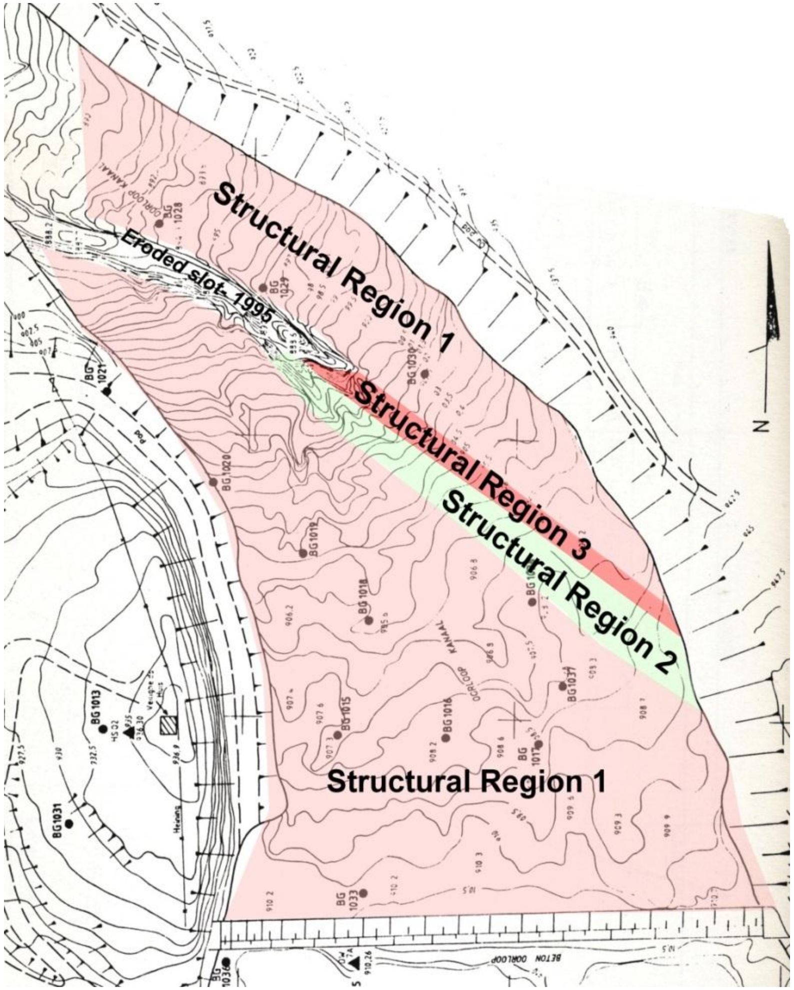
Assessed same 'erosion points' as van Schalkwyk

Interpreted erosion

Table D.8 Examination areas, South African dams

Dam	Exam.	Chart	Location of Examination Area		Erosion period		Erosion
No.	area	ID	Ch. [1.]	Description	Start [2.]	End	class
1	EA1	App1	25	near-level area upstream of bridge	C	2014	Negligible
	EA2	App2	60	cascade just downstream of bridge	C	2014	Minor
2	EA0	Flo1	40	stilling pool	C	2014	Moderate [3.]
	EA1	Flo2	40	stilling pool	C	2014	Moderate [3.]
3	EA1	Gar1	70	level area below gauge	C	Oct-85	Negligible
	EA2	Gar2	85	cascade (45^o), remaining material	C	Oct-85	Minor
	EA3	Gar3	85	cascade (45^o), eroded material	C	Oct-85	Moderate [4.]
	EA1	Gar4	70	level area below gauge	Oct-85	Nov-07	Negligible
	EA2	Gar5	85	cascade (45^o), remaining material	Oct-85	Nov-07	Minor
4	EA1	Goe1	40	right side slot	C	2014	Minor
	EA2	Goe2	40	island	C	2014	Moderate
	EA3	Goe3	60	base of central slot around island	C	2014	Negligible
	EA4	Goe4	40	left side slot	C	2014	Moderate
	EA5	Goe5	125	original creek bed	C	2014	Moderate
5	EA1	Haa1	45	low flow channel (LHS)	C	1996	Large
	EA2	Haa2	90	high flow channel (RHS)	C	1996	Moderate
	EA1	Haa3	45	low flow channel (LHS)	2010	2014	Large
	EA2	Haa4	90	high flow channel (RHS)	2010	2014	Large
6	EA1	Har1	250	left slot, remaining material	1947	2014	Negligible
	EA2	Har2	250	left slot, eroded material	C	1947	Moderate

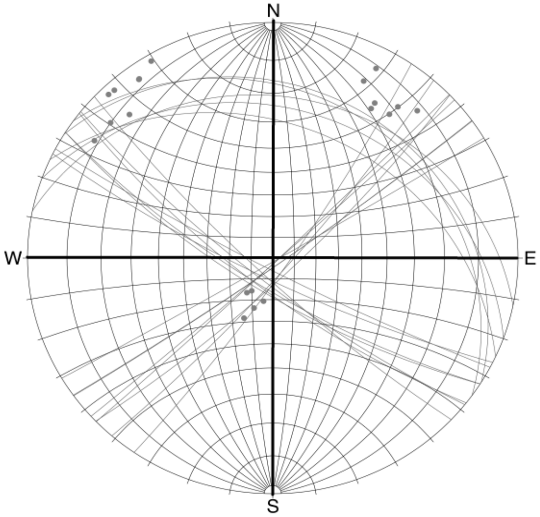
Geological Assessment



Structural regions

Geological mapping

Rock-mass indices



Interpreted rock mass indices

Table D.9 Interpreted rock mass indices - Q-system and Kirsten index, South African dams

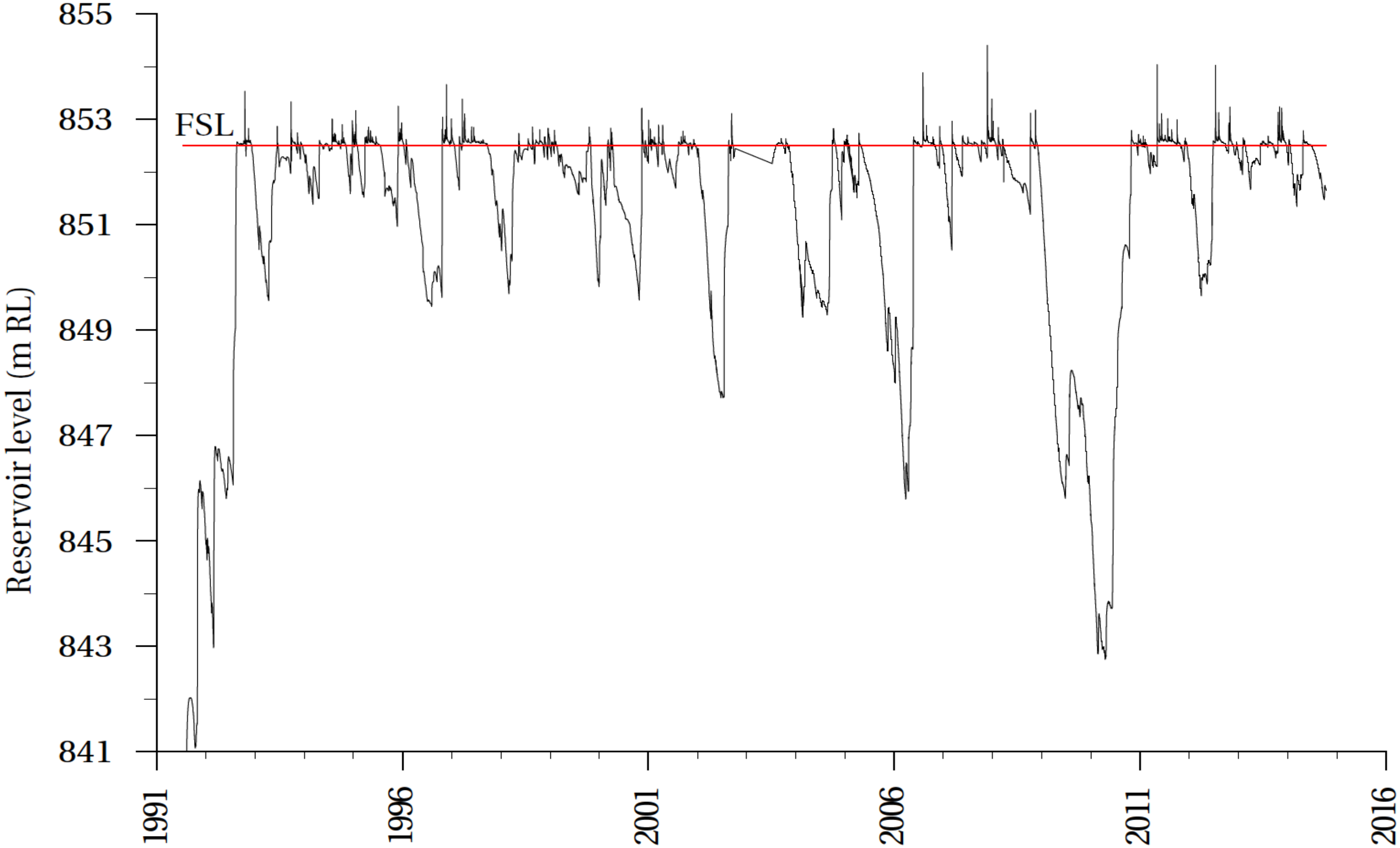
Chart	RQD	Q-rating				Kirsten index			
ID	%	J_n	J_r [1.]	J_a [1.]	Q'	J_n	J_s	M_S	K
App1	50	9	1.5	3 (4K)	2.78	2.73	0.6	50	206
App2	50	9	1.5	3 (4K)	2.78	2.73	0.6	50	206
Flo1	60	9	2.5	1	16.7	2.73	0.5	200	5495
Flo2	5	12	2	1.5	0.56	3.34	0.5	100	100
Gar1&4	30	3	1	2 (1K)	5.00	1.5	0.44	12	106
Gar2&5	30	3	1	2 (1K)	5.00	1.5	0.44	12	106
Gar3	10	3	1	4	0.83	1.5	0.44	4	2.9
Goe1	70	12	2	2	5.83	3.34	1	140	2934
Goe2	15	12	1	6	0.21	3.34	1	35	26
Goe3	70	12	2	2	5.83	3.34	1	140	2934
Goe4	15	12	1	6	0.21	3.34	1	35	26
Goe5	15	12	1	6	0.21	3.34	1	35	26
Haa1&3	20	12	1	3	0.56	3.39	0.48	12	11
Haa2&4	20	12	1	3	0.56	3.39	0.48	12	11
Har1	70	12	2.5	2	7.29	3.34	0.8	180	3772
Har2	40	12	1	4	0.83	3.34	0.8	15	36

Interpreted rock mass indices

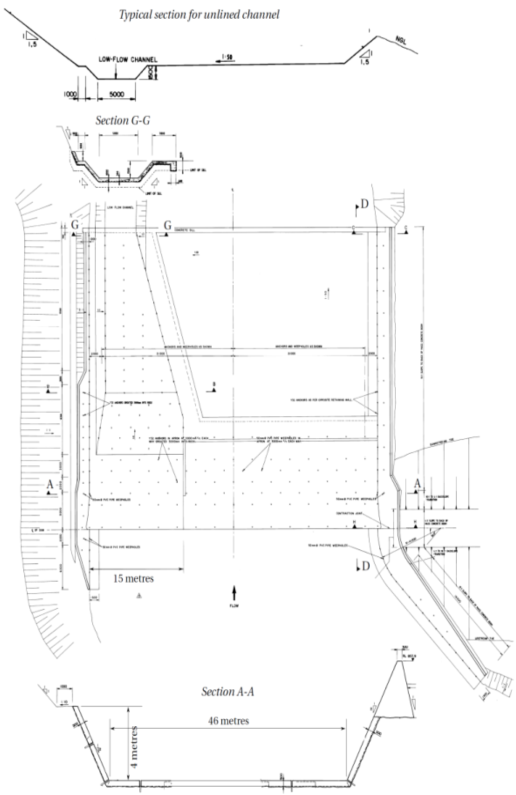
Table D.10 Interpreted rock mass indices - GSI, South African dams

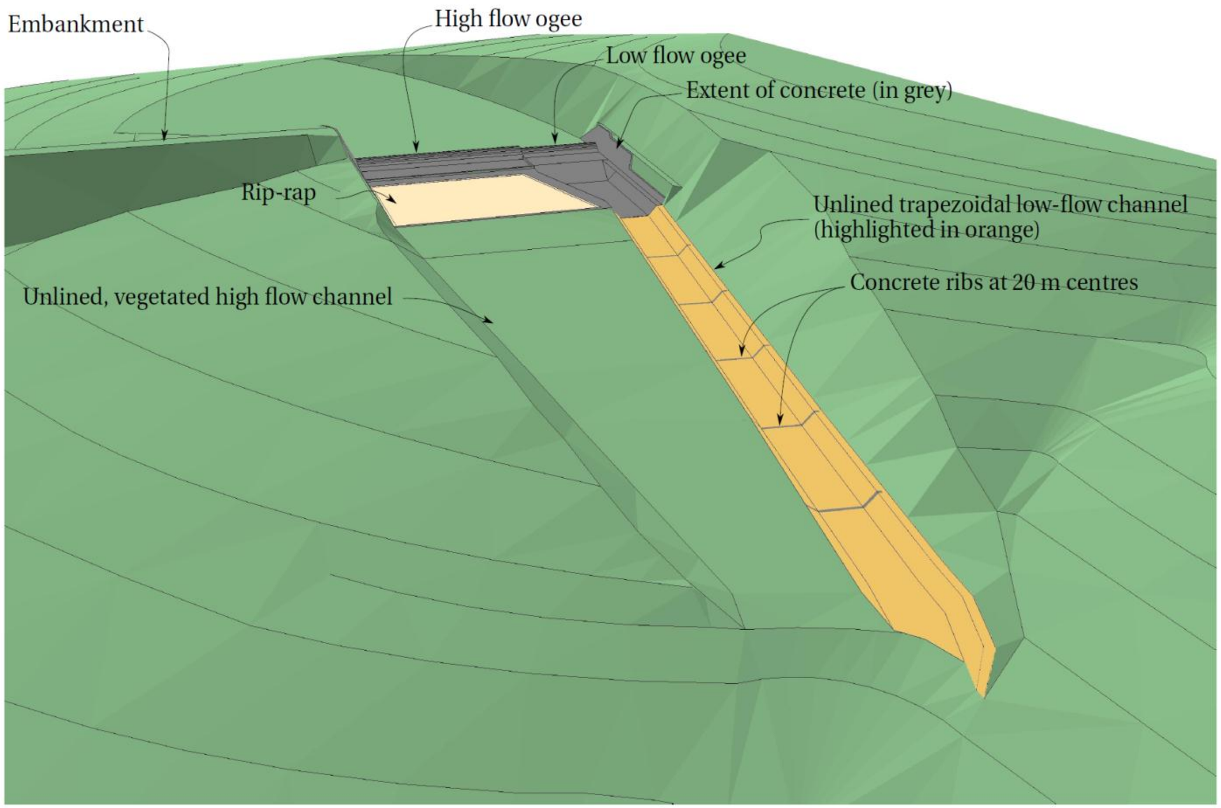
Chart ID	RMR_{76} parameters				GSI		Erosion GSI	
	Strength rating	RQD rating	Discont. spacing	Discont. cond.	GSI_{RMR}	GSI_{Chart}	E_{doa}	$eGSI$
App1	6	8	20	12	56	50	-5	45
App2	6	8	20	12	56	50	-8	43
Flo1	15	13	20	20	78	68	-25	43
Flo2	12	1	5	20	48	38	-25	13
Gar1&4	2	3	10	10	35	30	-5	25
Gar2&5	2	3	10	10	35	30	-8	23
Gar3	1	3	10	0	24	20	-18	3
Goe1	12	14	25	20	81	76	-8	69
Goe2	4	3	15	2	34	38	-8	31
Goe3	12	14	25	20	81	76	-8	69
Goe4	4	3	15	2	34	38	-8	31
Goe5	4	3	15	2	34	38	-8	31
Haa1&3	2	3	5	10	30	20	-15	5
Haa2&4	2	3	5	10	30	20	-15	5

Hydraulic Assessment

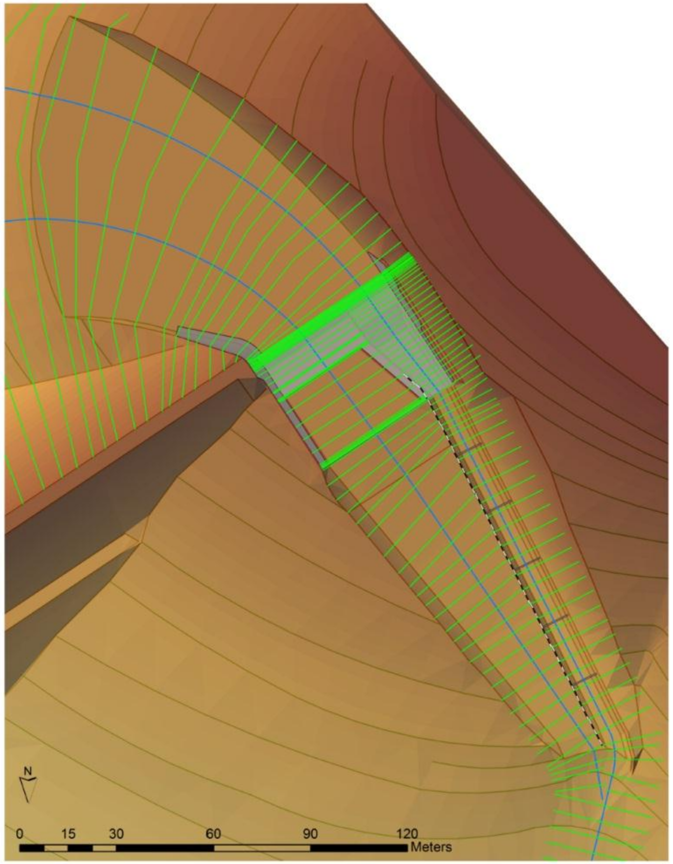


Hydraulic Assessment

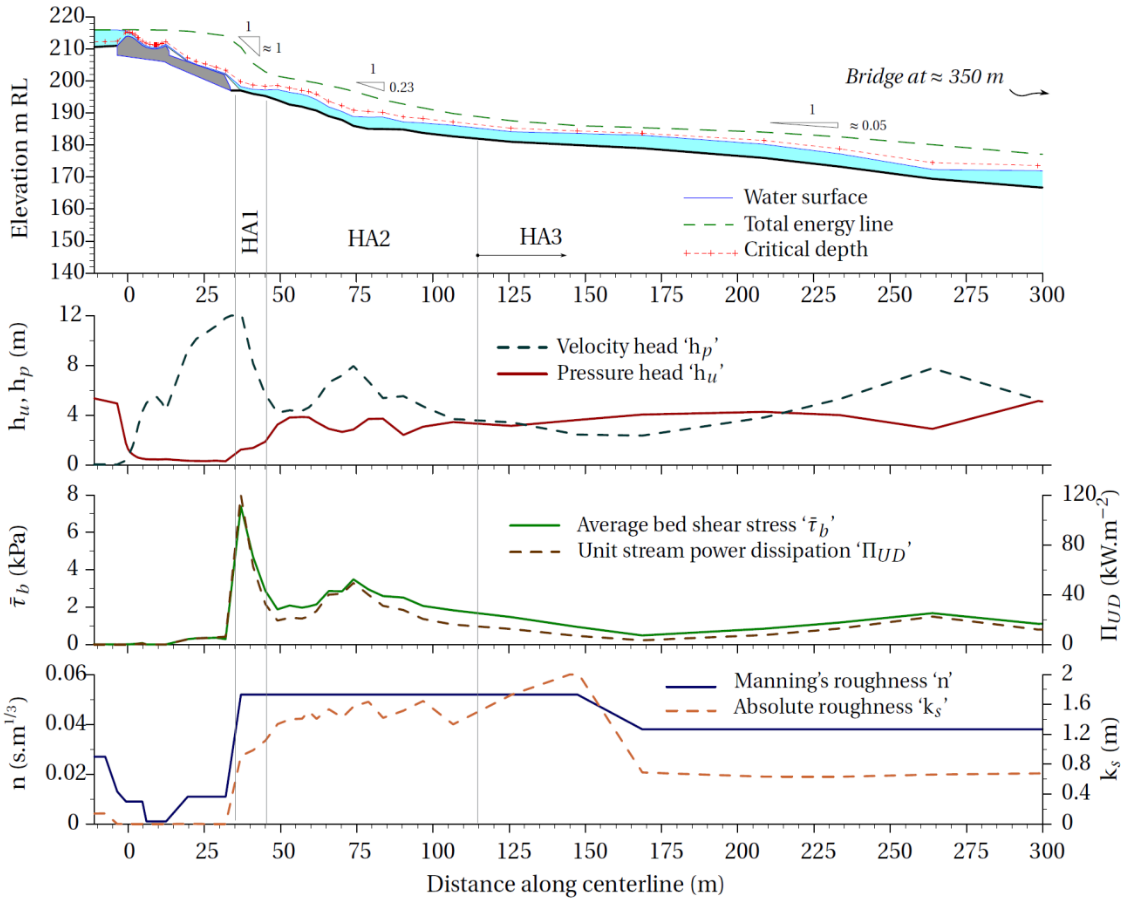


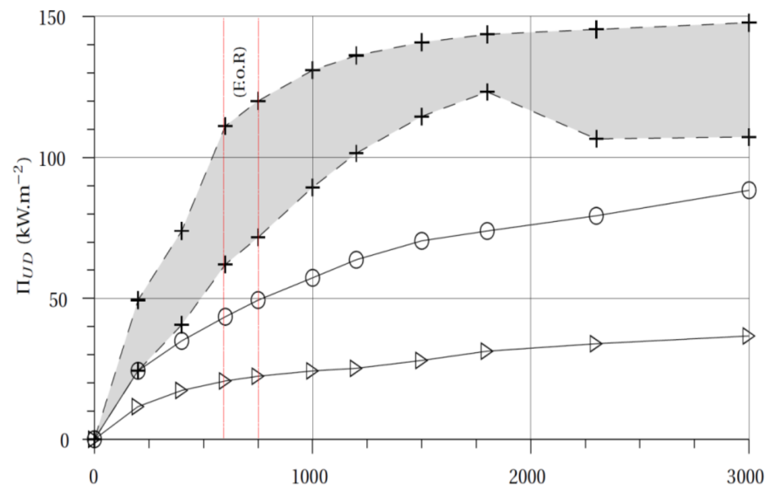


Hydraulic Assessment



Hydraulic Assessment





Discharge

Interpreted hydraulic indices

Table D.12 Hydraulic indices - South African dams

Chart ID	Hydraulic area	Peak Q $m^3.s^{-1}$	Analytical estimates: Peak q $m^2.s^{-1}$	Analytical estimates: S_o $tan\phi$ -	Analytical estimates: Peak Π_{UD} $kW.m^2$	HEC-RAS Estimates: Peak q $m^2.s^{-1}$	HEC-RAS Estimates: S_f -	HEC-RAS Estimates: Peak $\bar{u}$ $m.s^1$	HEC-RAS Estimates: Peak $\bar{\tau}_b$ kPa	HEC-RAS Estimates: Peak Π_{UD} $kW.m^2$	HEC-RAS Estimates: E_U $MJ.m^2$
App1	HA1	250	-	-	-	15.0	0.018	7.1	0.3	2.6	-
App2	HA2	250	-	-	-	10.9	0.142	8.5	1.72	15	-
Flo1	HA1	2200	-	-	-	41	0.298	22.5	4	120	3.30×10^5
Flo2	HA1	2200	-	-	-	41	0.298	22.5	4	120	3.30×10^5
Gar1	HA1	44	-	-	-	1.9	0.054	5.2	0.17	1	3.50×10^3
Gar2	HA2	44	-	-	-	2.1	0.680	12.6	1.1	14	1.60×10^4
Gar3	HA3	44	-	-	-	2	0.459	10.0	0.7	9	1.50×10^4
Gar4	HA1	127	-	-	-	4.3	0.031	6.8	0.18	1.3	5.50×10^4
Gar5	HA2	127	-	-	-	5.1	0.390	15.1	1.3	20	2.40×10^5
Goe1	HA1	750	-	-	-	9.3	0.986	15.6	7.5	90	1.45×10^6
Goe2	HA1	750	-	-	-	5	1.835	15.6	7.5	90	1.45×10^6
Goe3	HA2	750	-	-	-	21.9	0.233	12.5	3.6	50	1.10×10^6
Goe4	HA1	750	-	-	-	9.3	0.986	15.6	7.5	90	1.45×10^6
Goe5	HA3	750	-	-	-	15	0.152	12.3	1.68	22	5.00×10^5
Haa1	HA1LF	55	-	-	-	7.9	0.046	7.1	0.46	3.6	9.00×10^3
Haa2	HA1HF	55	-	-	-	1.44	0.020	2.6	0.11	0.3	1.00×10^3

Summary of interpreted indices

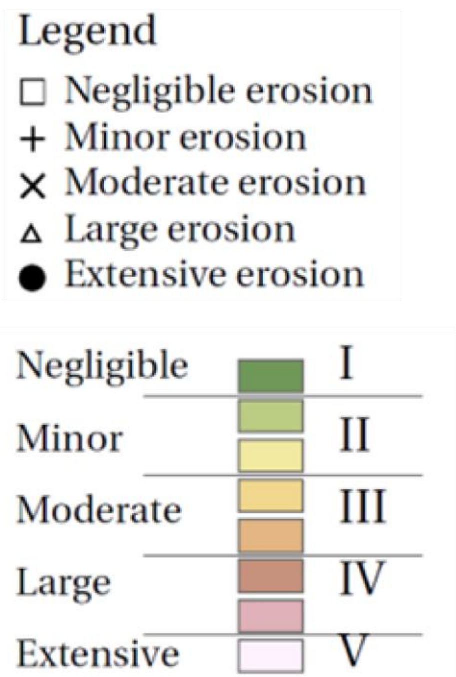
Over 30 dams

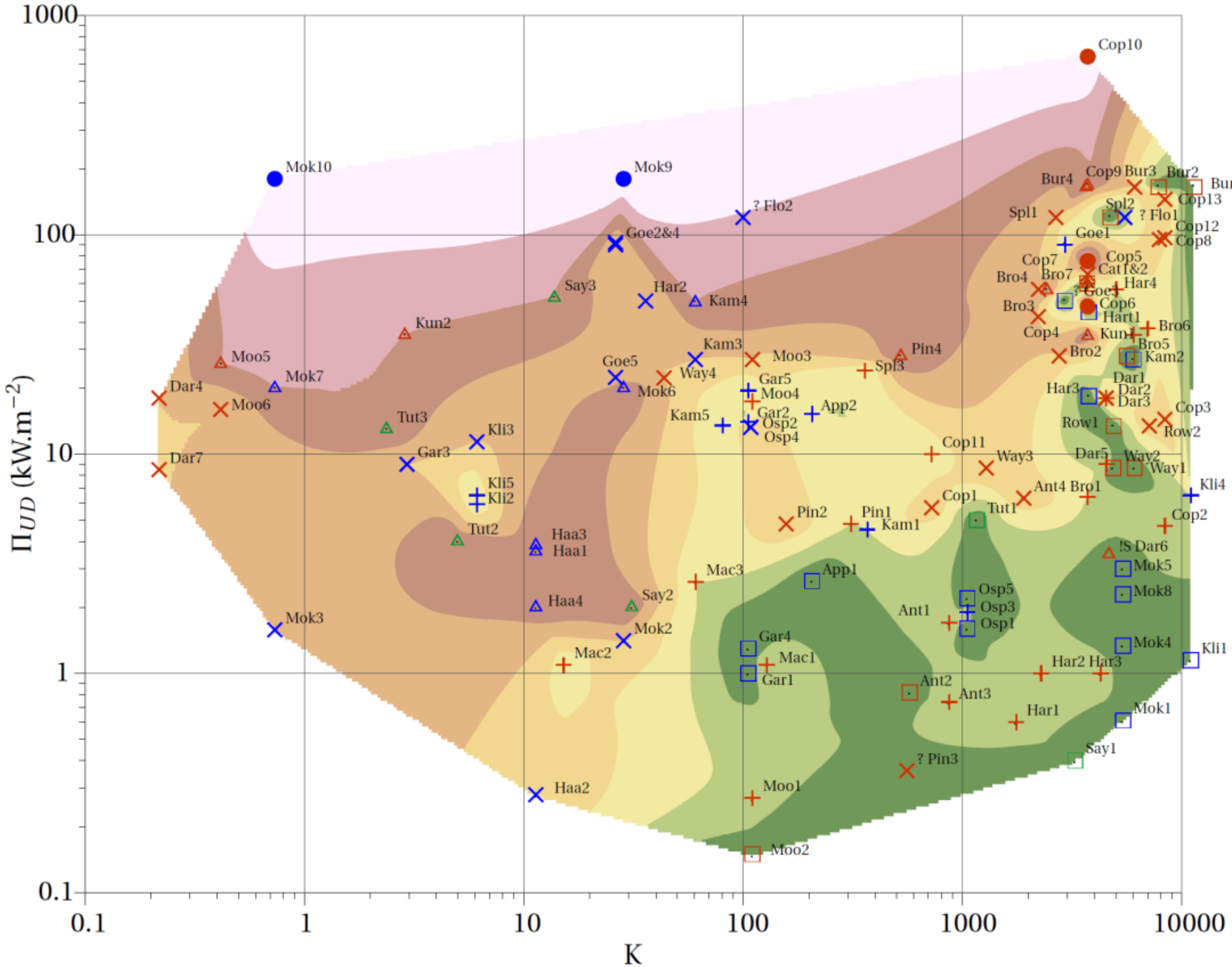
Australia (19)
South Africa (11)
USA (2)

~120 datapoints of erosion in fractured rock environments (vs. ~20 in previous publications)

Country	Dam Name	Inspection Date	Inspection Personnel[1.]	Reporting Hydraulics	Reporting Geology[2.]	Exam. areas
Australia	Anthony	18-Apr-13	SEP; RF	Appendix B.1	Ref. 1	4
	Brogo	4-Dec-14	RF	Appendix B.2	Ref. 1	7
	Burdekin Falls	2-Dec-08	RF	Appendix B.3	Ref. 1	4
	Catagunya	17-Apr-13	SEP; RF	Appendix B.4	Ref. 1	3
	Copeton	15-May-13	SEP; KD	Appendix B.5	Ref. 1	13
	Dartmouth	16-Dec-13	SEP; KD; RF	Appendix B.6	Ref. 1	7
	Harding	26-Sep-13	SEP; KD	Appendix B.7	Ref. 1	4
	Junction Reefs	15-Jan-14	SEP; PJNP	-	-	-
	Kununurra	24-Sep-13	SEP; KD	Appendix B.8	Ref. 1	2
	Mackenzie	18-Apr-13	SEP; RF	Appendix B.9	-	-
	Mackintosh	19-Apr-13	SEP; RF	Basic only	Ref. 1	3
	Moochalabra	23-Sep-13	SEP; KD	Appendix B.10	Ref. 1	6
	Murchison	19-Apr-13	SEP; RF	-	-	-
	Ord River	24-Sep-13	SEP; KD	-	-	-
	Pindari	15-May-13	SEP; KD	Appendix B.11	Ref. 1	4
	Rowallan	17-Apr-13	SEP; RF	Basic only	Ref. 1	2
	Split Rock	16-May-13	SEP; KD	Appendix B.12	Ref. 1	3
	Wayatina	17-Apr-13	SEP; RF	Appendix B.13	Ref. 1	4
	Wyangala	11-Jun-13	SEP	-	-	-
South Africa	Applethwaite	17-May-14	SEP; PJNP	Appendix B.14	Ref. 2	2
	Floriskraal	14-May-14	SEP; PJNP	Appendix B.15	Ref. 2	2
	Garden Route	12-May-14	SEP; PJNP	Appendix B.16	Ref. 2	5
	Goedertrouw	9-May-14	SEP; PJNP	Appendix B.17	Ref. 2	5
	Haarlem	11-May-14	SEP; PJNP	Appendix B.18	Ref. 2	4
	Hartbeespoort	4-May-14	SEP; PJNP	Appendix B.19	Ref. 2	3
	Kammanassie	12-May-14	SEP; PJNP	Appendix B.20	Ref. 2	5
	Klipfontein	8-May-14	SEP; PJNP	Appendix B.21	Ref. 2	5
	Koos Raubenheimer	13-May-14	SEP; PJNP	-	Ref. 2	-
	Mokolo	5-May-14	SEP; PJNP	Appendix B.22	Ref. 2	10
	Osplaas	14-May-14	SEP; PJNP	Appendix B.23	Ref. 2	5
USA	Saylorville	-	-	Basic only	Ref. 3	3
	Tuttle Creek	-	-	Appendix B.24	Ref. 3	3

Kirsten Index

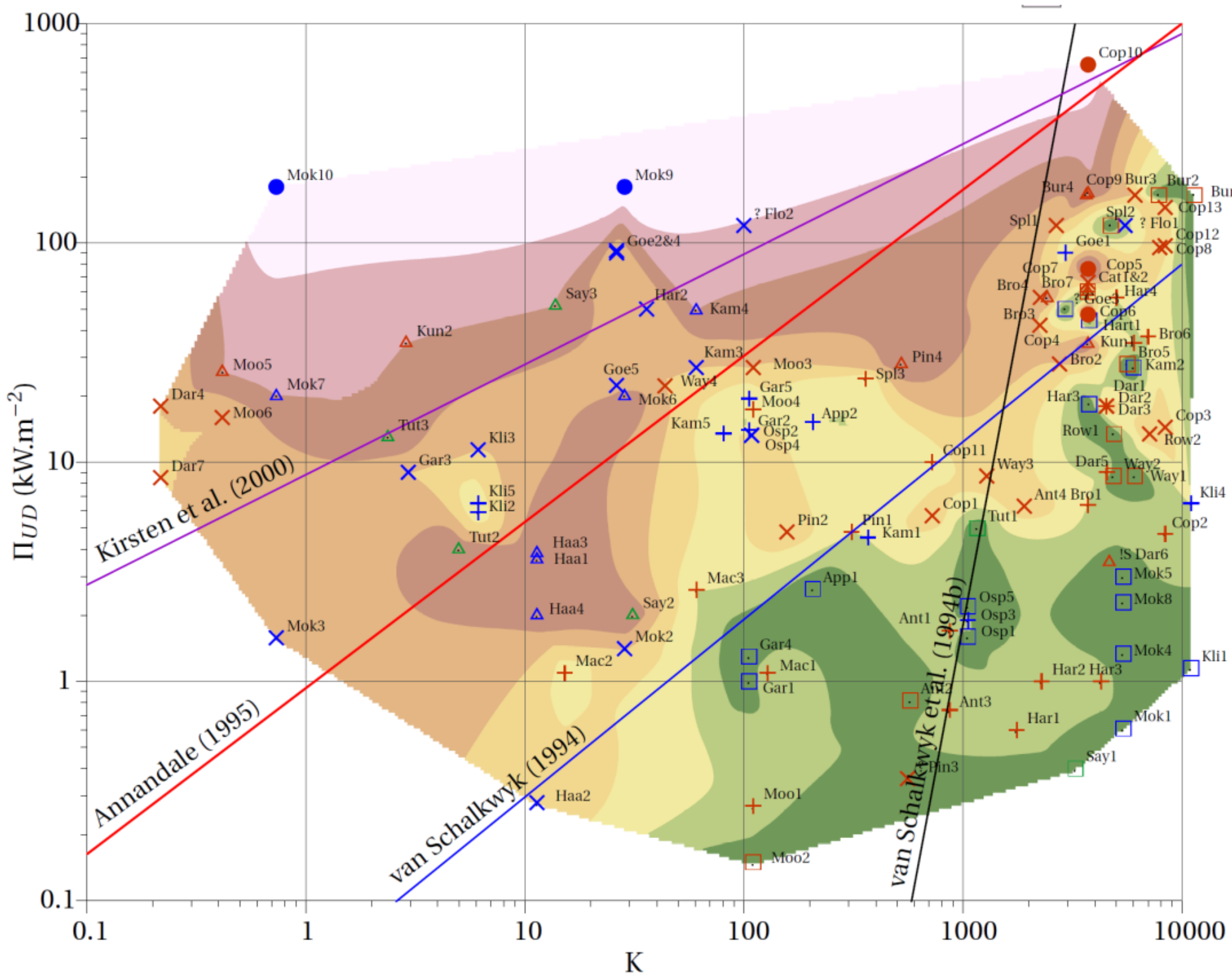




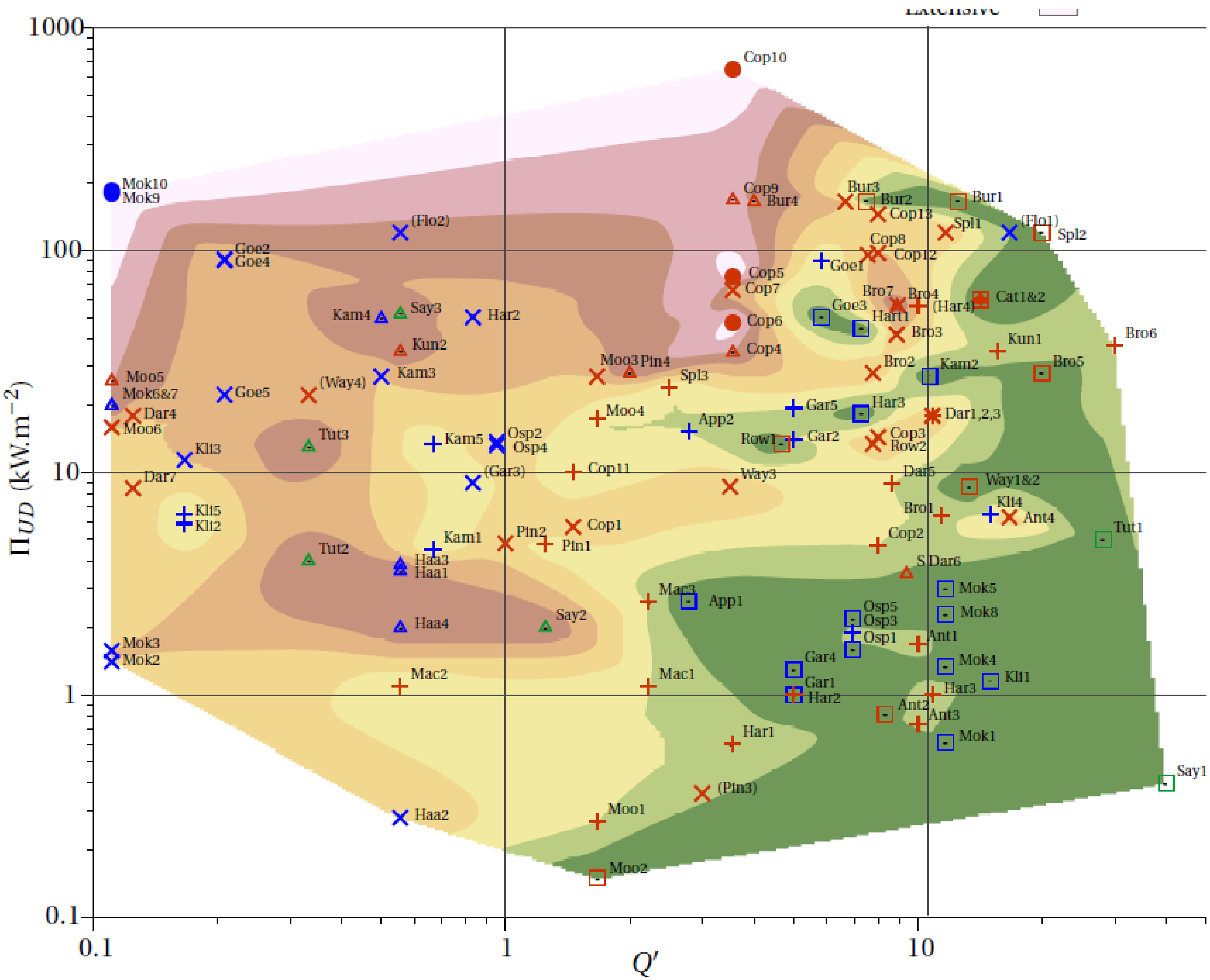
PSM

UNSW AUSTRALIA

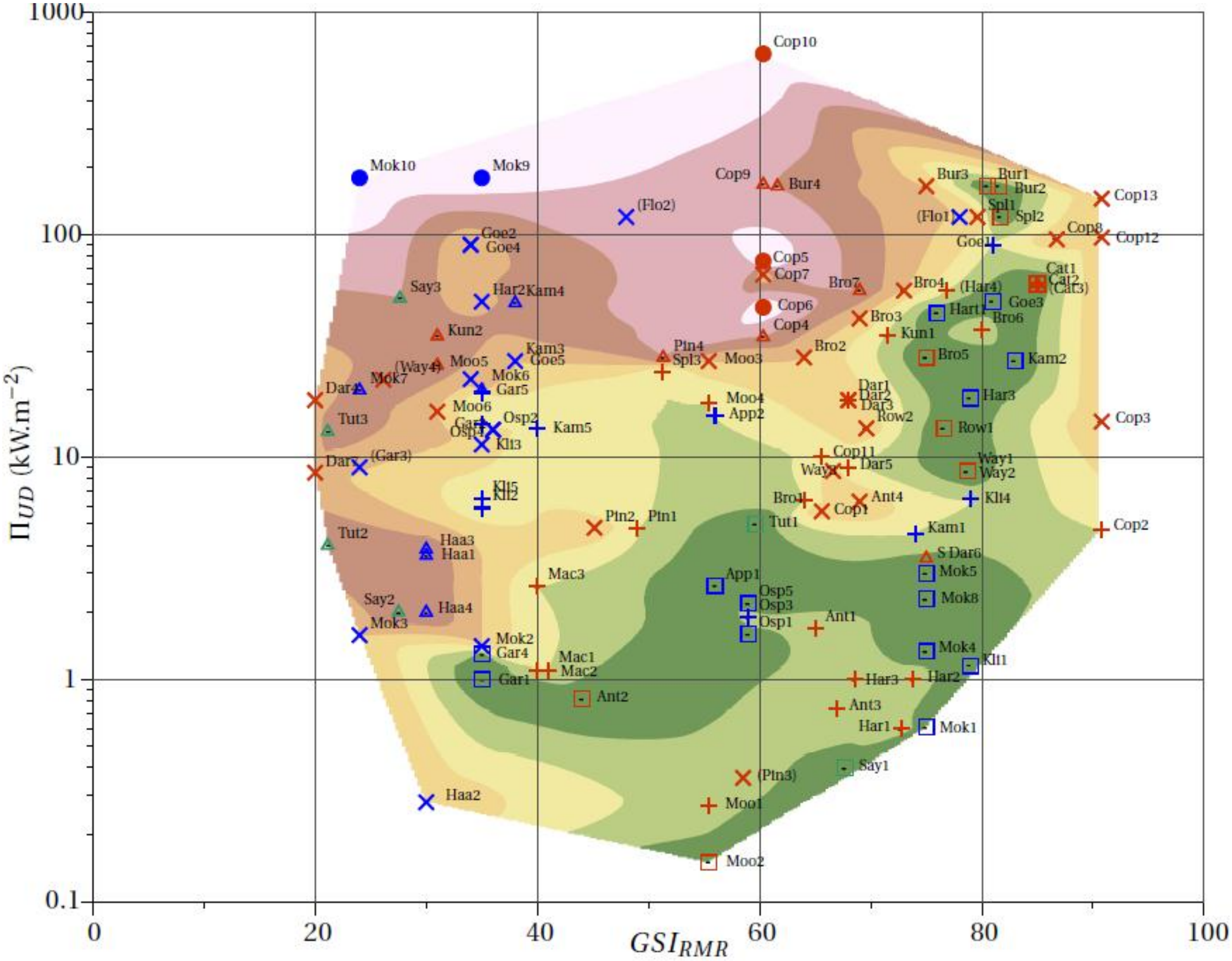
Kirsten Index



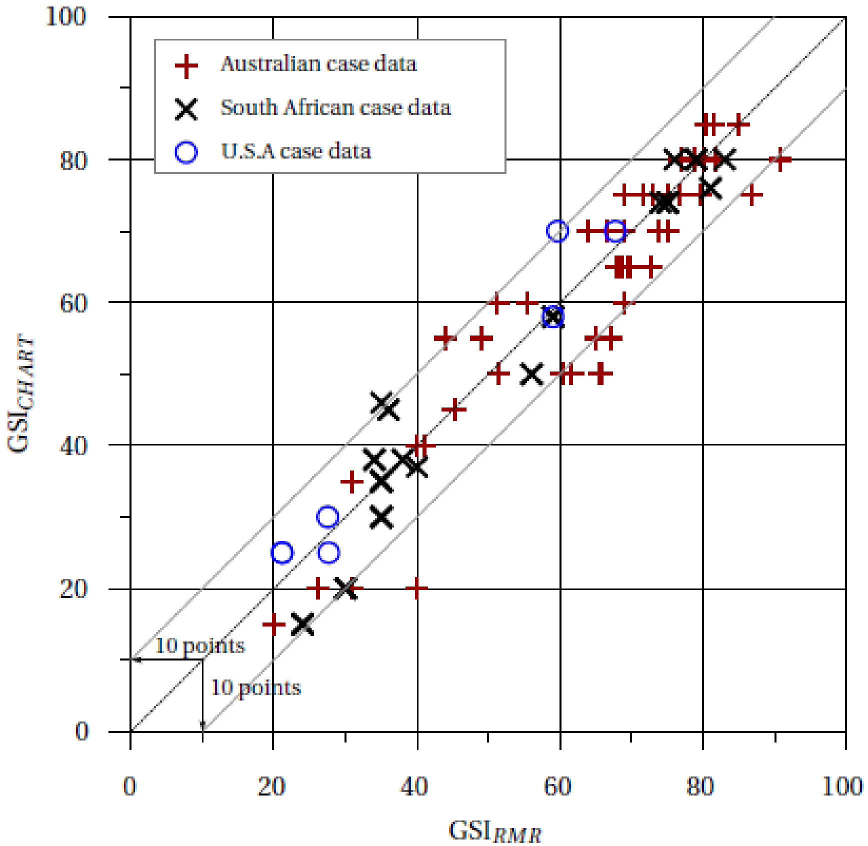
Q-system



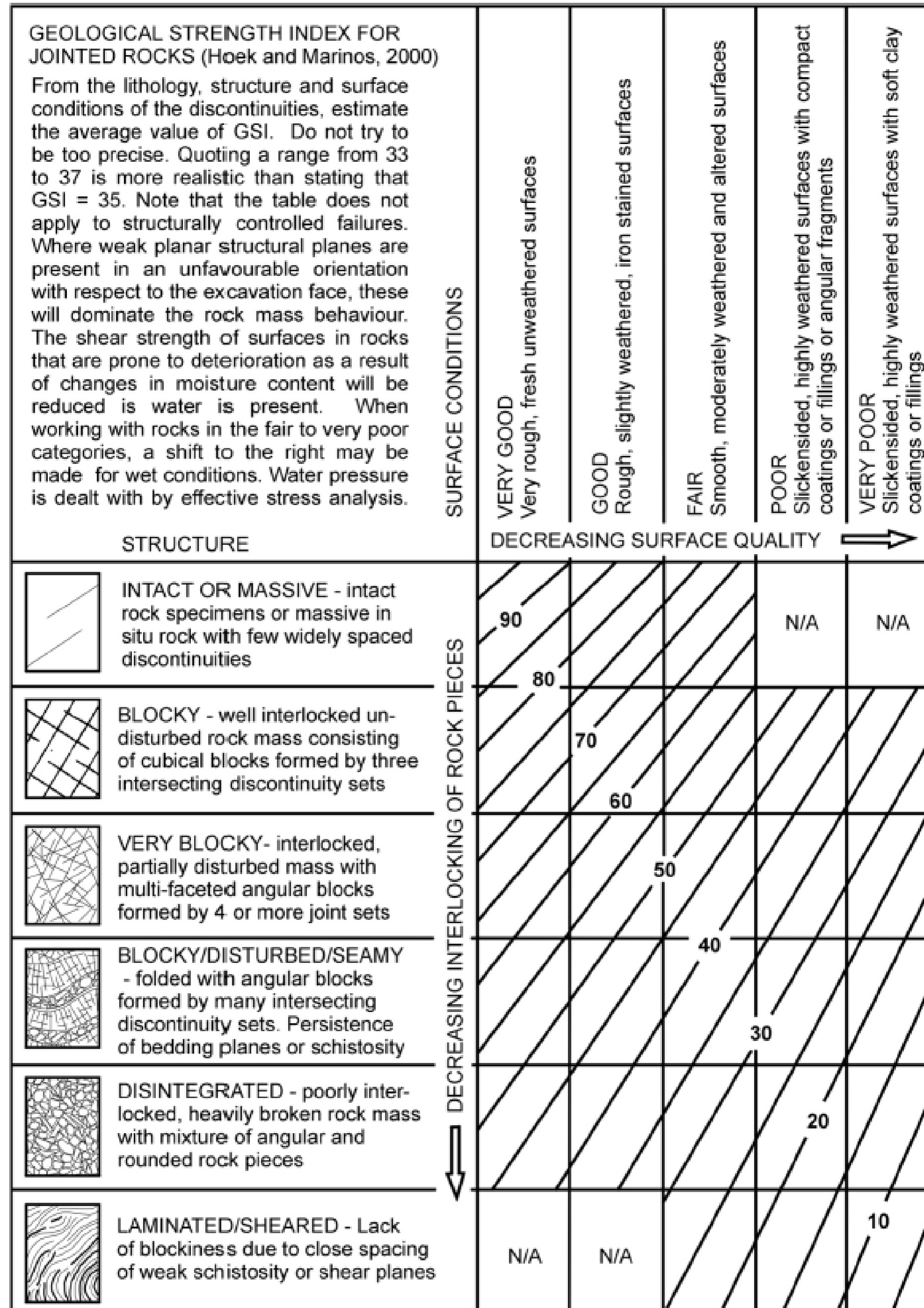
GSI



GSI chart

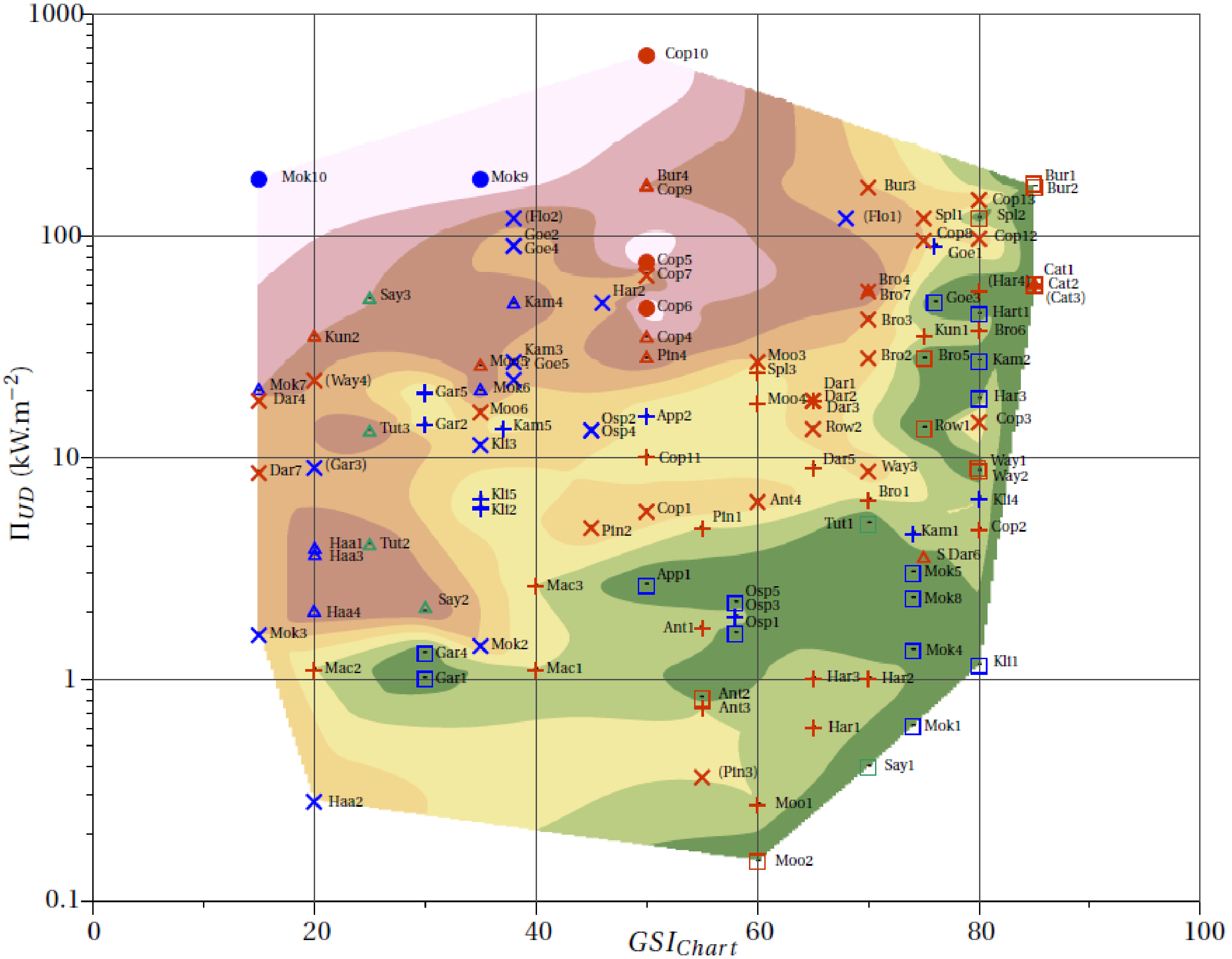


Australian case data
South African case data
U.S.A case data
10 points
10 points
0
20
40
60
80
100
GSI_{CHART}
GSI_{RMR}



GEOLOGICAL STRENGTH INDEX FOR JOINTED ROCKS (Hoek and Marinos, 2000)
From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced is water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.
SURFACE CONDITIONS
VERY GOOD
Very rough, fresh unweathered surfaces
GOOD
Rough, slightly weathered, iron stained surfaces
FAIR
Smooth, moderately weathered and altered surfaces
POOR
Slickensided, highly weathered surfaces with compact coatings or fillings or angular fragments
VERY POOR
Slickensided, highly weathered surfaces with soft clay coatings or fillings
DECREASING SURFACE QUALITY
STRUCTURE
INTACT OR MASSIVE - intact rock specimens or massive in situ rock with few widely spaced discontinuities
BLOCKY - well interlocked un-disturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets
VERY BLOCKY- interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets
BLOCKY/DISTURBED/SEAMY - folded with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity
DISINTEGRATED - poorly inter-locked, heavily broken rock mass with mixture of angular and rounded rock pieces
LAMINATED/SHEARED - Lack of blockiness due to close spacing of weak schistosity or shear planes
DECREASING INTERLOCKING OF ROCK PIECES
90
80
70
60
50
40
30
20
10
N/A
N/A
N/A
N/A

GSI chart



A new index: ‘eGSI’

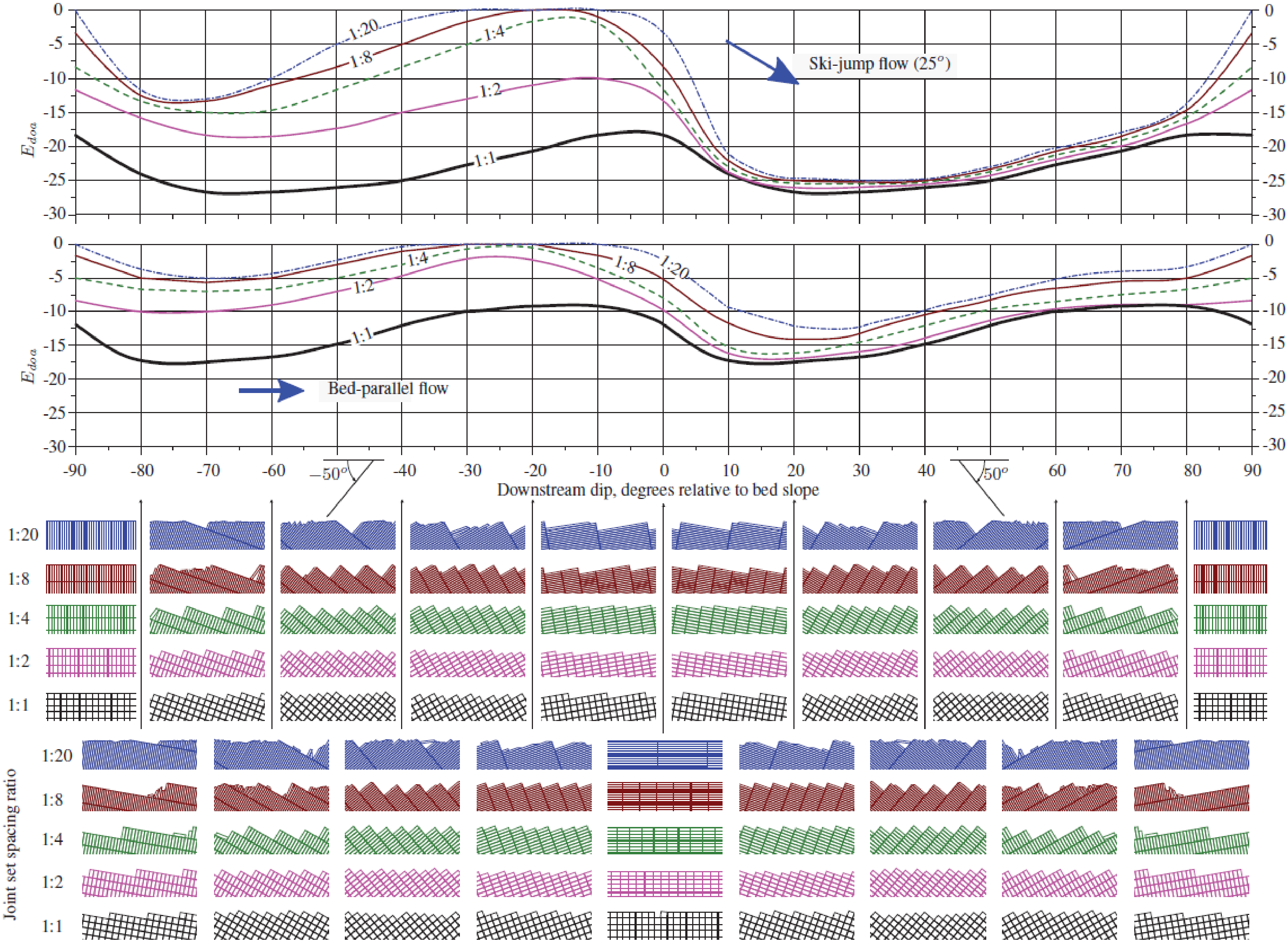
eGSI – adjustment of GSI to vulnerability of erosion from unfavourable orientation of defects

$$eGSI = \max \begin{cases} GSI + E_{doa} \\ 0 \end{cases}$$

where: $eGSI$ is an index of erodibility

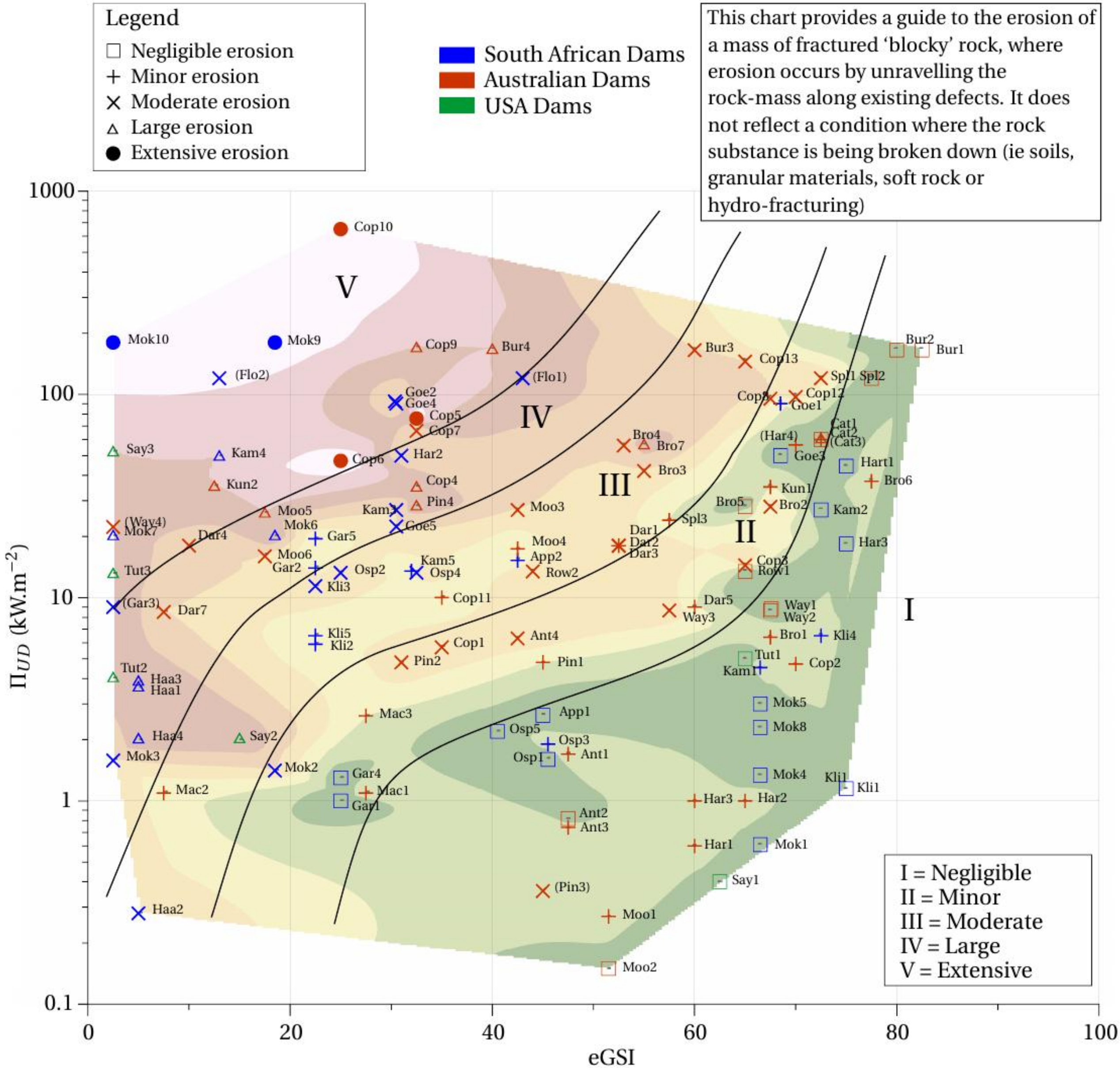
E_{doa} is a discontinuity orientation adjustment for erodibility

Defect orientation



The 'eGSI' method …

- Simpler
- Larger data set for rock
- Can trace case studies
- Gradation, not a 'threshold'
- GSI is current and credible
- No RQD
- No Mass Strength
- Appropriate inference of accuracy
- Reliable even when used by non-geologists

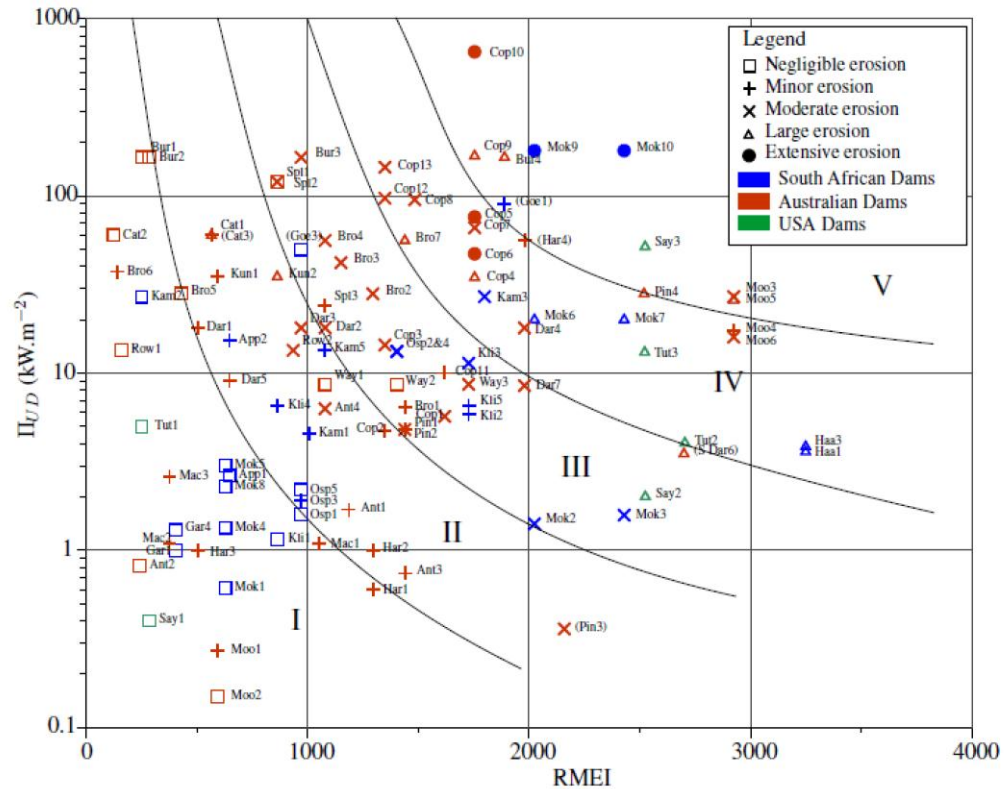


Rock Mass Erodibility Index "RMEI"

Table 3.3 Estimation of Rock Mass Erosion Index (RMEI)

Erosion vulnerability parameter	RF[1]	Likelihood Factor (**LF**) Very Unlikely 1	Unlikely 2	Likely 3	Highly Likely 4	Almost Certain 5
P1: Kinematically viable mechanism for detachment[2]	3	Rock with three defects, basal defect sub-parallel to spillway floor, and no day lighting basal release surface, or; Massive rock with effectively only two defect sets and no basal release surface.	Rock with three or more defects, with: basal defect sub-parallel to spillway floor, Joint 2 protruding from surface, or; basal defect inclined upstream or downstream at > 30 degrees relative to spillway floor.	Rock with three or more defects, with: persistent basal defect dip 10 to 30 degrees upstream relative to the spillway floor, or; Persistent basal defect dip 10 to 30 degrees downstream relative to the spillway floor.	Rock with three or more defects, with: persistent basal defect dip ≤ 10 degrees upstream relative to the spillway floor, or; persistent basal defect dip ≤10 degrees downstream relative to the spillway floor.	Persistent basal defect sub-parallel to the spillway floor, day lighting upstream or downstream, or; persistent shear and / or closely jointed rock which erodes readily forming a release surface into the shear.
P2: Nature of the potentially eroding surface	3	Smooth water or glacier worn, with no protrusions of joint 2, no opening of defects	Bedding surface with protrusions of joint 2 < 1mm, and little or no opening of defects	Relatively small protrusions and defect openings (eg pre-split, or ripped and bulldozed)	Irregular surface following defects, little opening of defects (eg. blasted rock).	Irregular surface following defects, extensive defect opening (eg. heavily blasted rock)
P3: Nature of the defects[3]	2	Very rough surfaces, eg JRC ≥ 12	Rough surfaces, e.g. JRC 8-10	Slightly rough surfaces e.g. JRC 4-8	Smooth surfaces e.g. JRC < 4	Smooth or slickensided surfaces
		No separation	Apperture < 1mm	Apperture 1-2mm	Apperture 2 to 5mm	Apperture > 5mm
		UCS > 50MPa	UCS 20MPa to 50 MPa	UCS 5MPa to 20MPa	UCS 1MPa to 5MPa	UCS < 1MPa, or Soft gouge > 5mm thick
P4: Spacing of basal defect[4]	1	>3m	1m to 3m	0.3m to 1m	0.1m to 0.3m	<0.1m
P5: Block shape[5]	1	≤0.5	0.5 to 1	1 to 2	2 to 5	>5

Notes:
1. 'Relative importance factor'
2. Defects include joints, bedding surfaces, shears, and foliation partings.
3. Select class which best fits the data taking into account the kinematically viable mechanism and which defects control the displacement of the block of rock from the spillway.
Use Table 3.4 to assist in making this assessment but use judgement to make the assessment.
4. Joint 1 is basal defect of a block or region (bedding or joint).
5. Block shape = Joint 2 spacing / Joint 1 spacing;
Joint 2 is sub-vertical defect normal to the flow in the spillway.

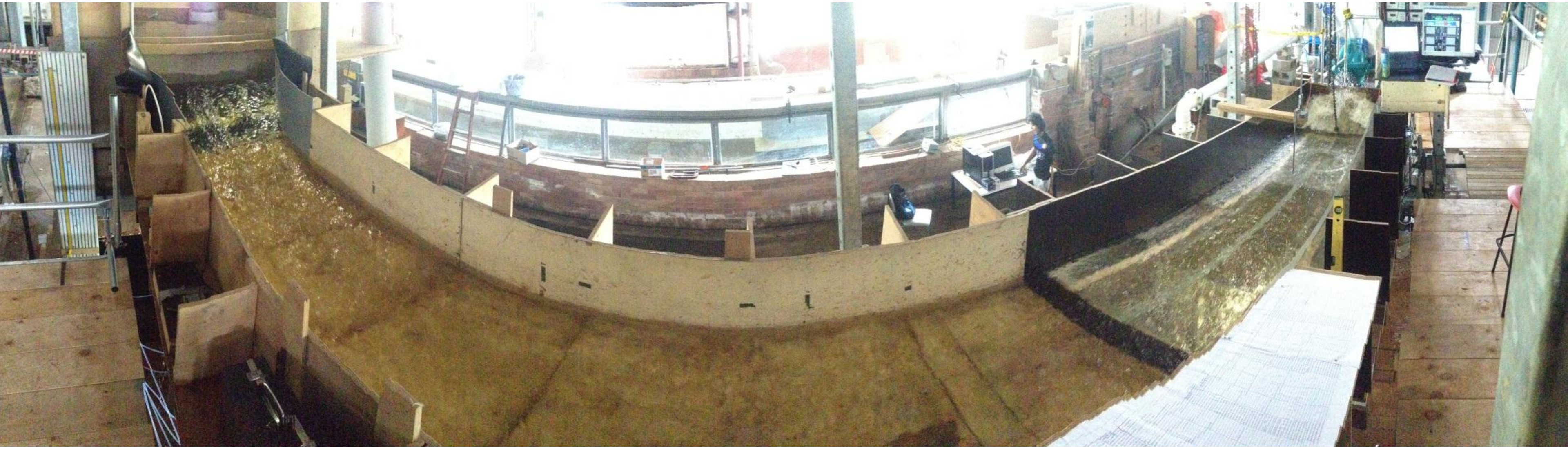


Summary of rock mass index approaches

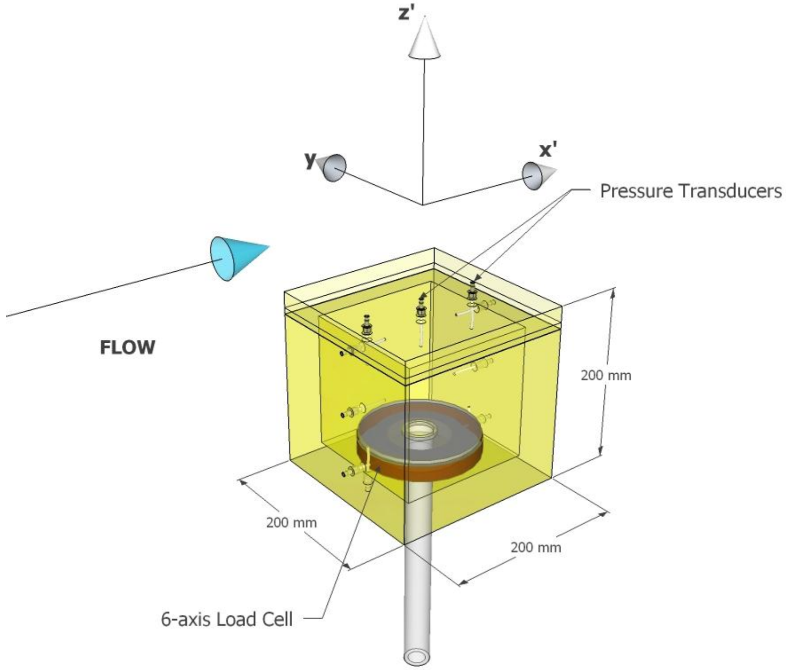
1. All rock mass indices are approximate representations of rock masses
2. Stream power dissipation is only an approximation of hydraulic loading
3. The method does not represent the mechanics of the problem
4. It is useful for 'first-pass' comparison to other case studies

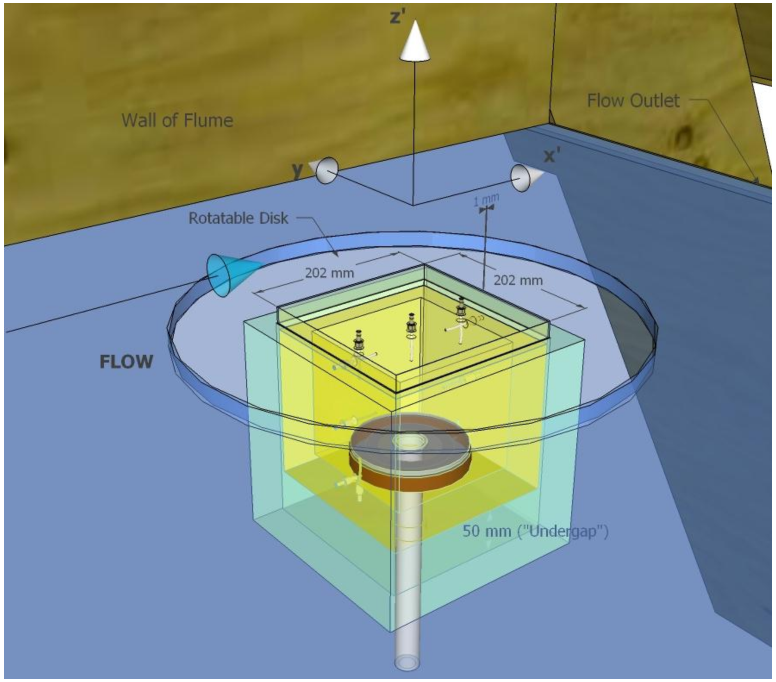
Beyond rock mass indices …

Flume



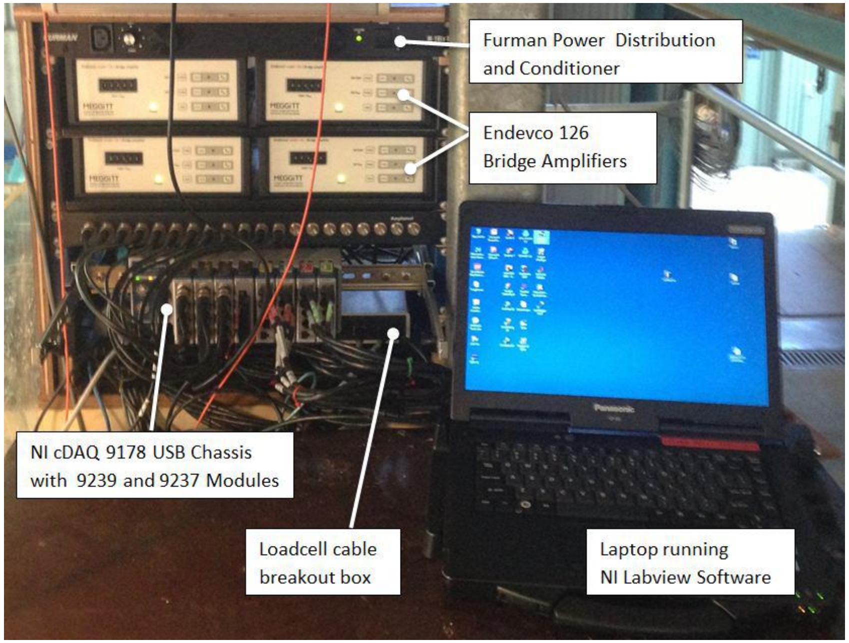
`The block'

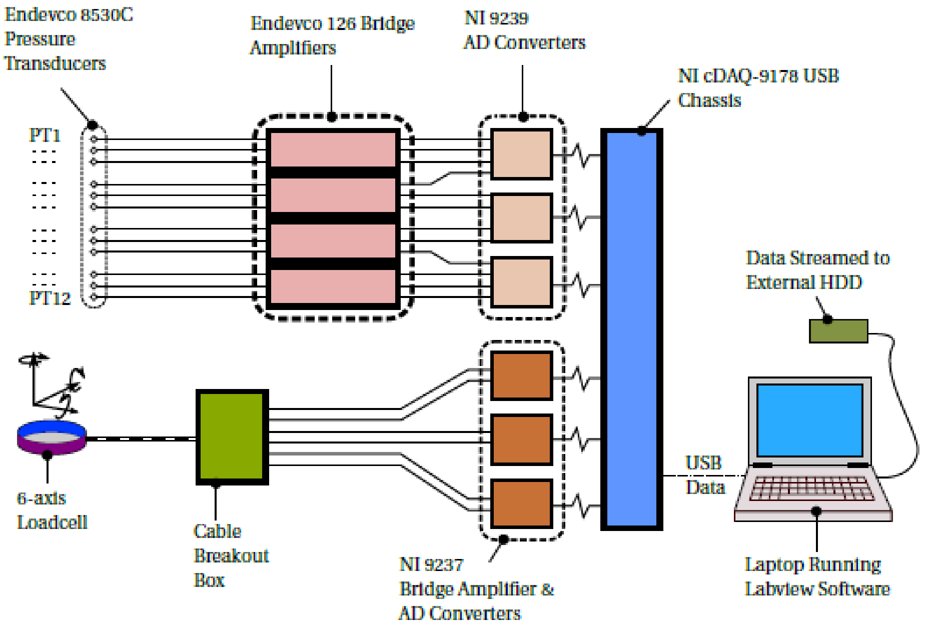

z'
y
x'
Pressure Transducers
FLOW
200 mm
200 mm
200 mm
6-axis Load Cell


z'
Wall of Flume
Flow Outlet
y
x'
1 mm
Rotatable Disk
202 mm
202 mm
FLOW
50 mm ("Undergap")

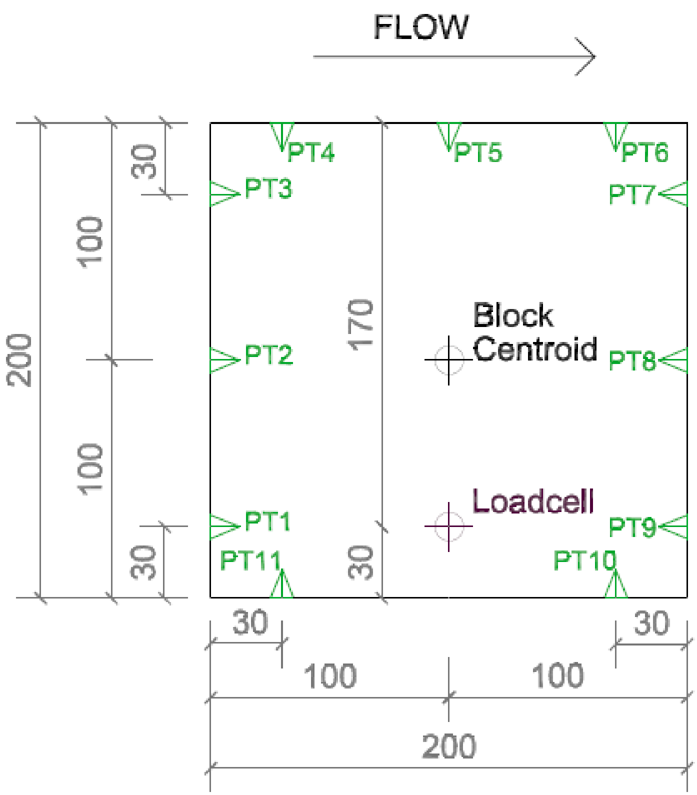
Instruments

Instruments





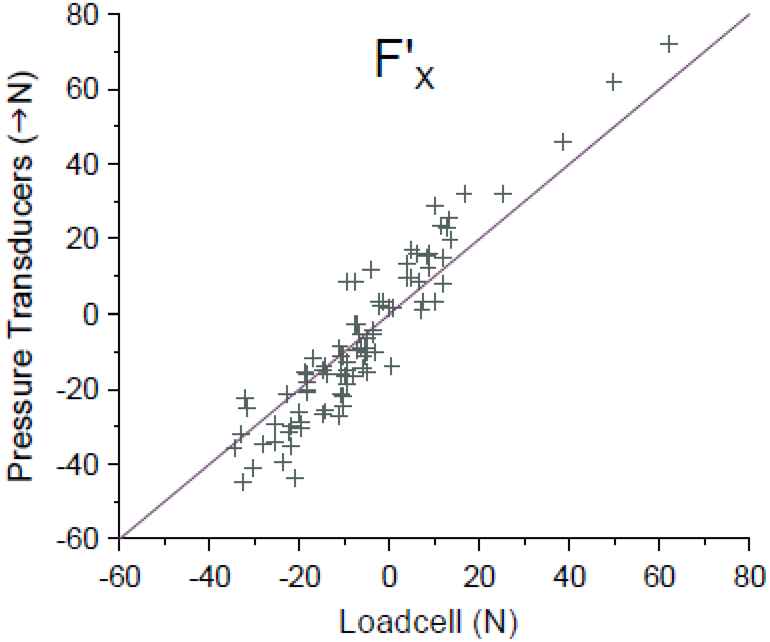
Instruments

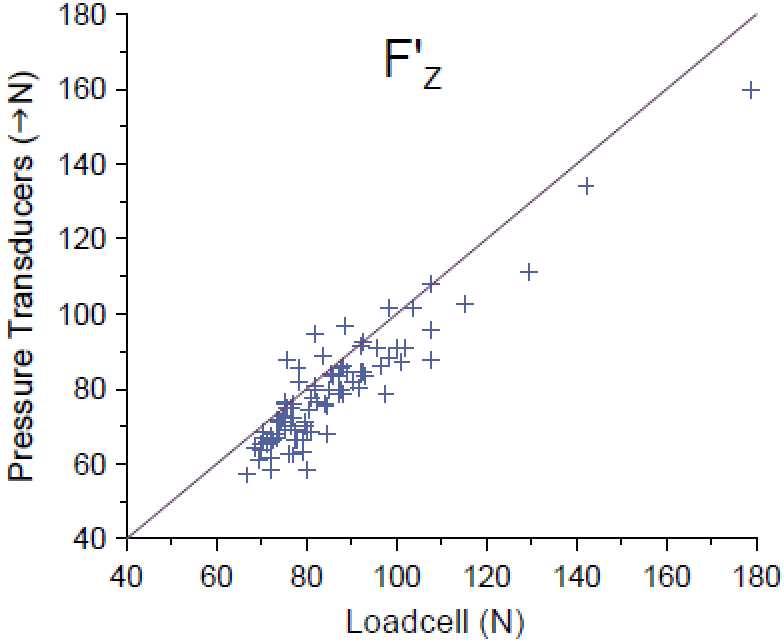


Pressure Transducer	Action Length (mm)	Width (mm)	Action Area (mm^2)	Lever Arm (mm)
PT1	60	200	12000	−70
PT2	80	200	16000	0
PT3	60	200	12000	70
PT4	60	200	12000	−70
PT5	80	200	16000	0
PT6	60	200	12000	70
PT7	60	200	12000	−70
PT8	80	200	16000	0
PT9	60	200	12000	70
PT10	100	200	19018*	−52*
PT11	100	200	19018*	52*

* These values include consideration of the area of the pole

Instruments



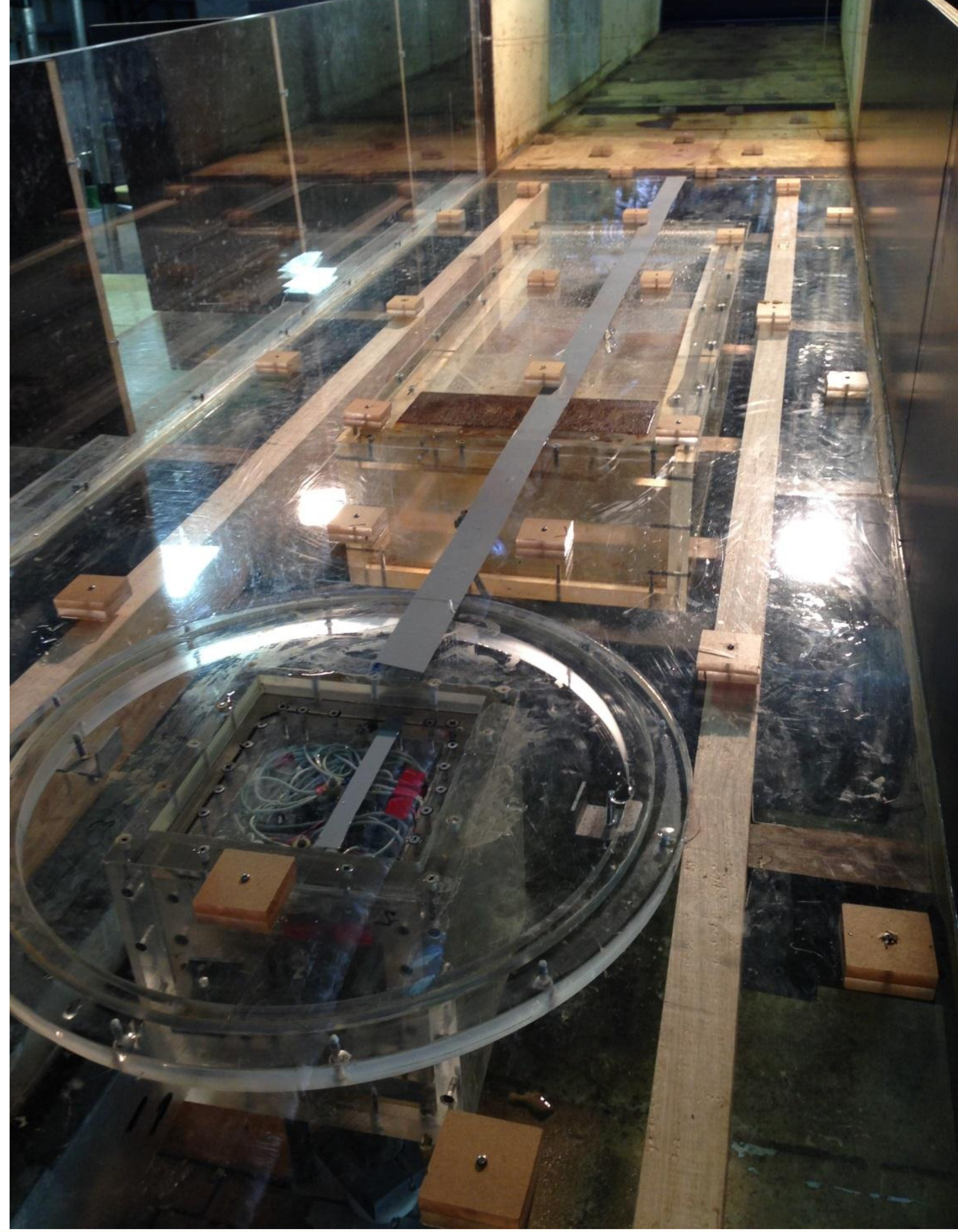


Base Tests

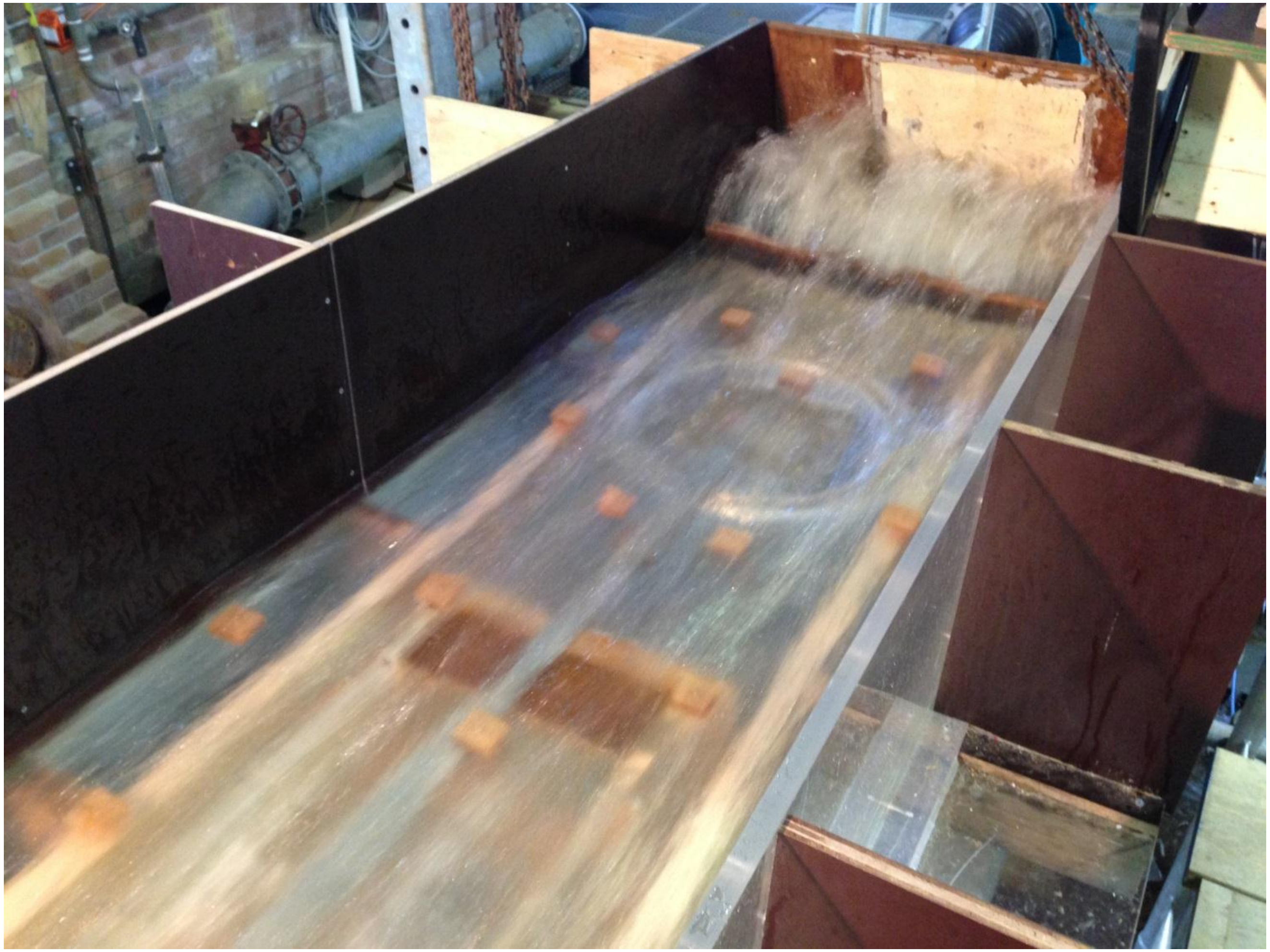
Base Tests

Base Tests, with varying protrusion

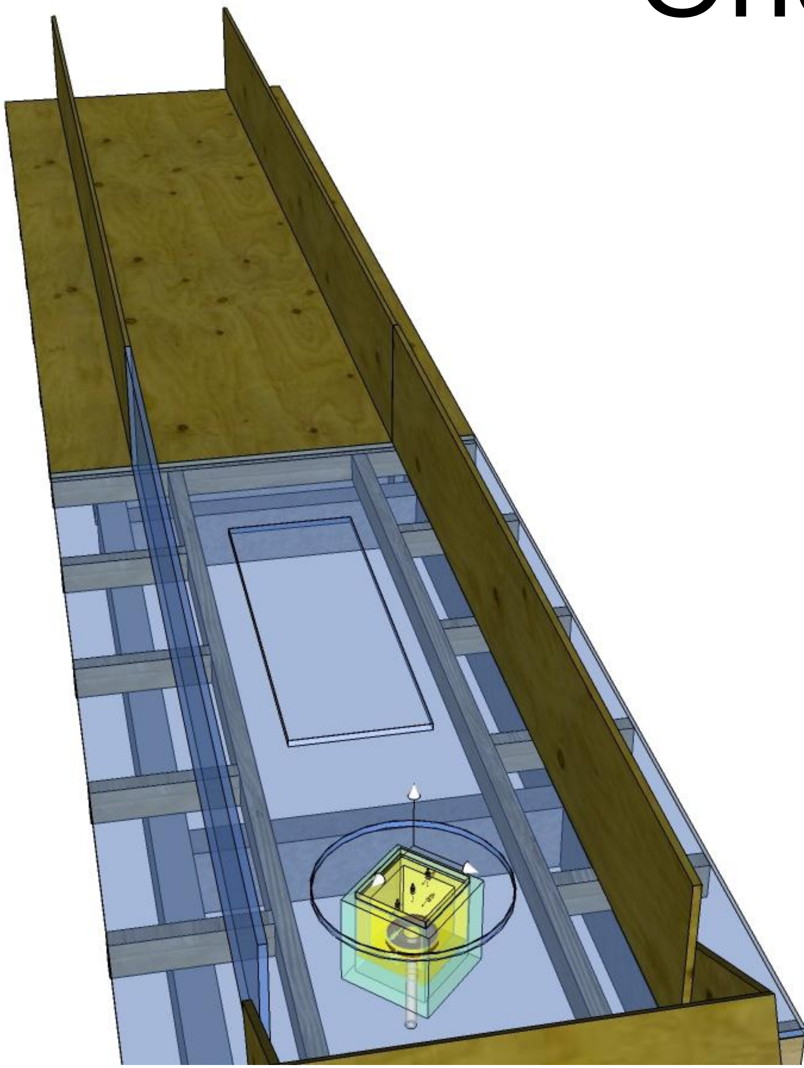
Varied roughness

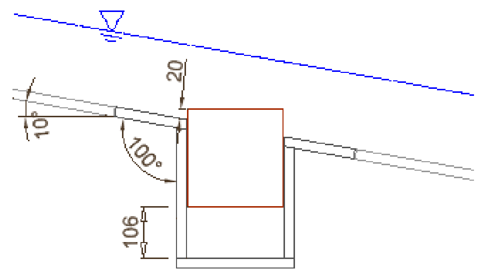


Varied roughness

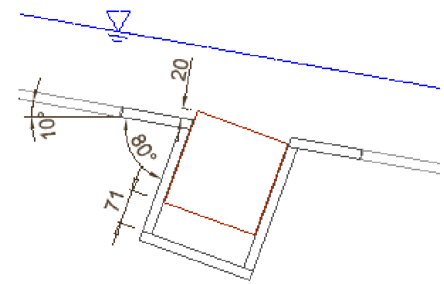


Orientation



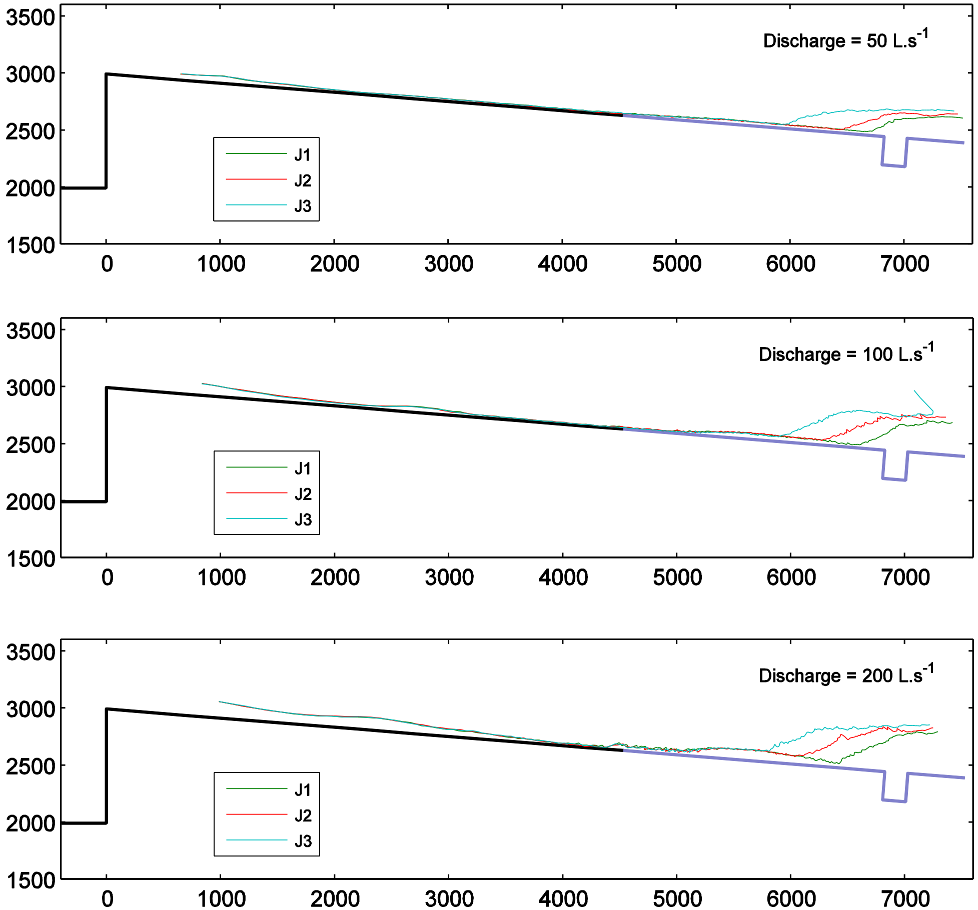


Test V1 at 10 degrees slope



Test V2 at 10 degrees slope

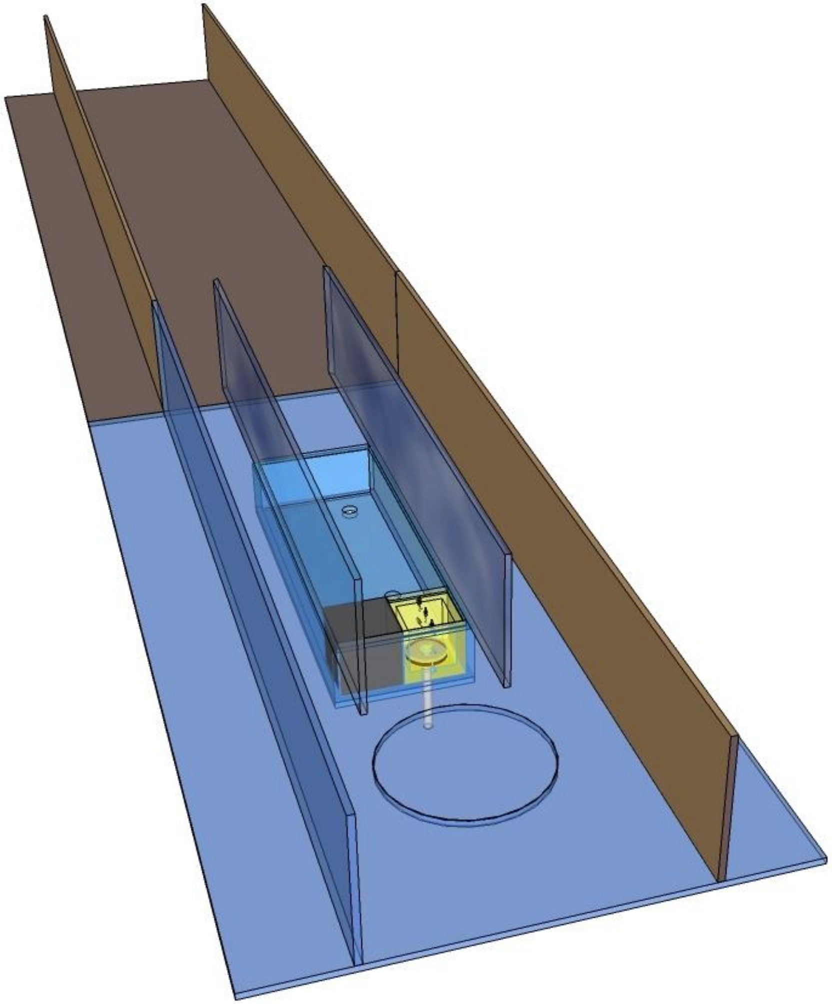
Tests with Hydraulic Jumps

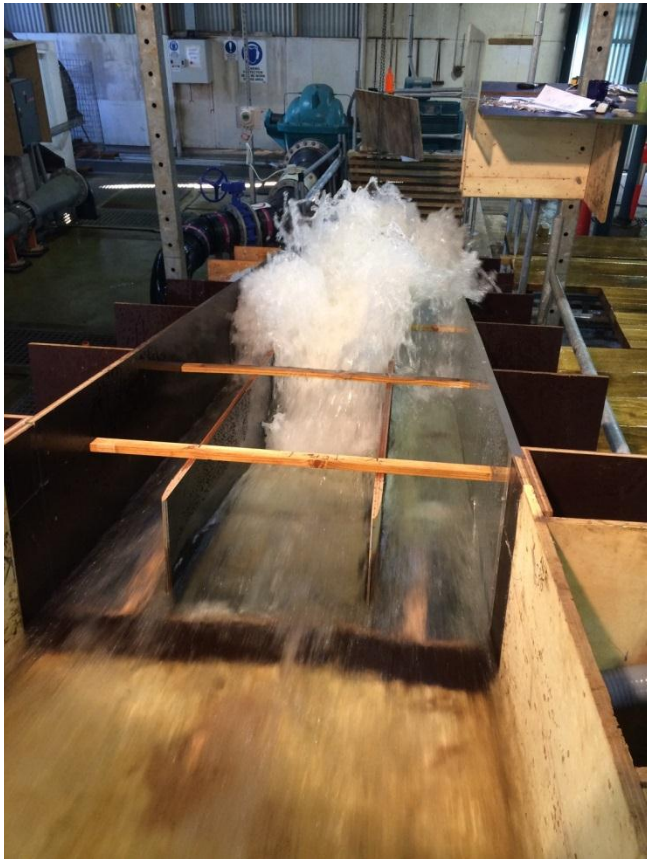


Plunging (ski-jump)

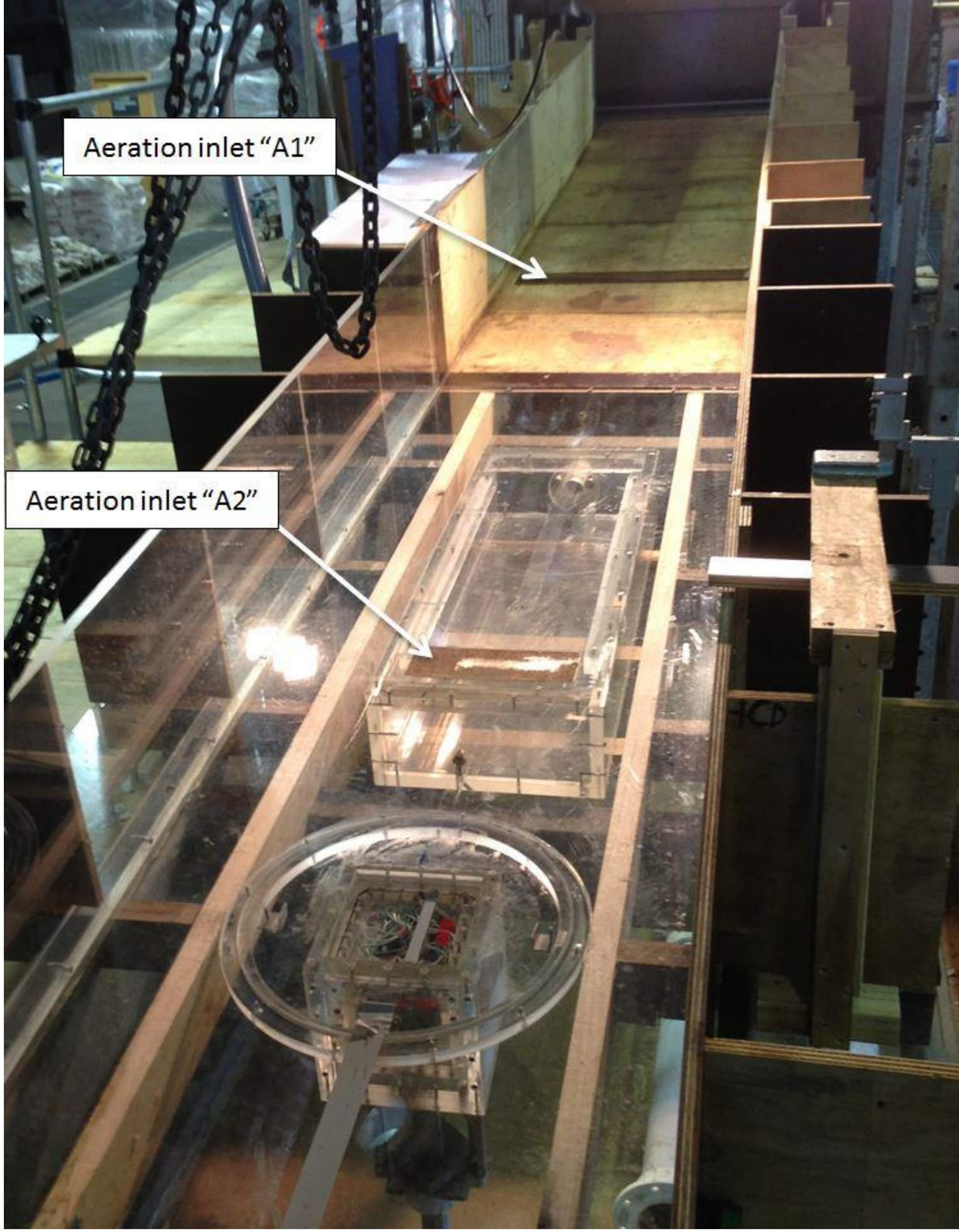
Top = u
Mid = 0.97u
Bot = 0.93u

Headcutting and Scour Holes

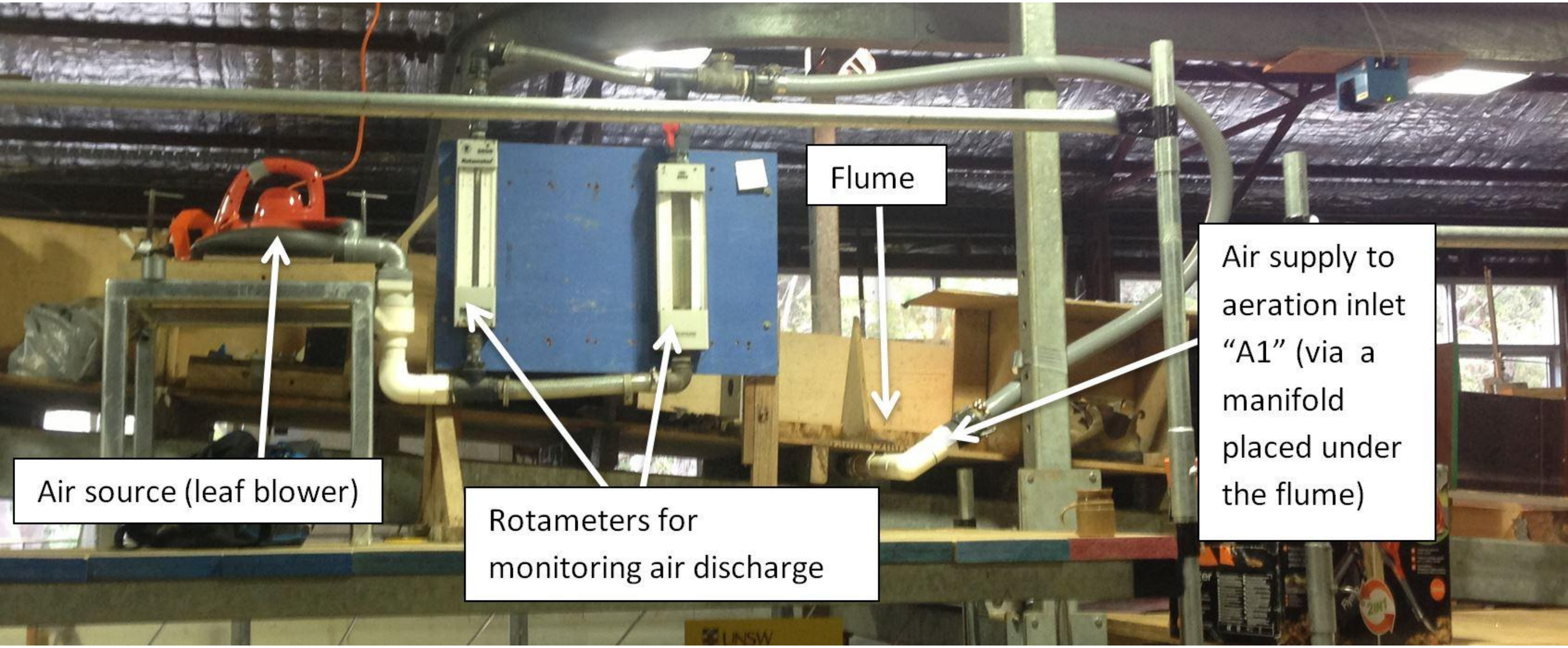




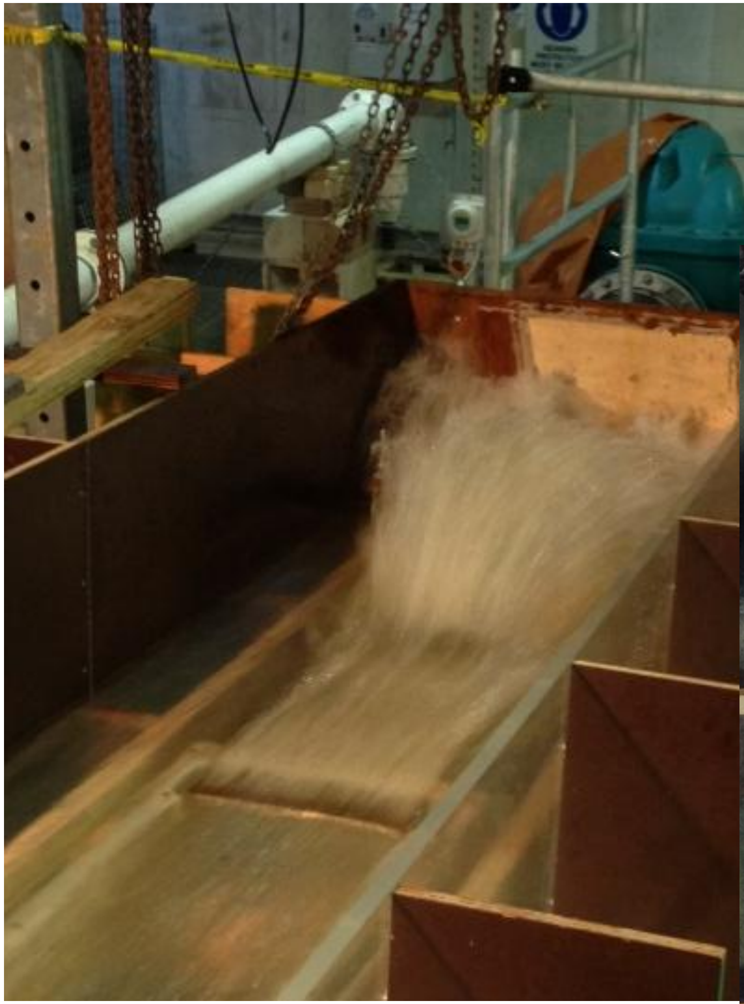
Tests with Aeration



Tests with Aeration

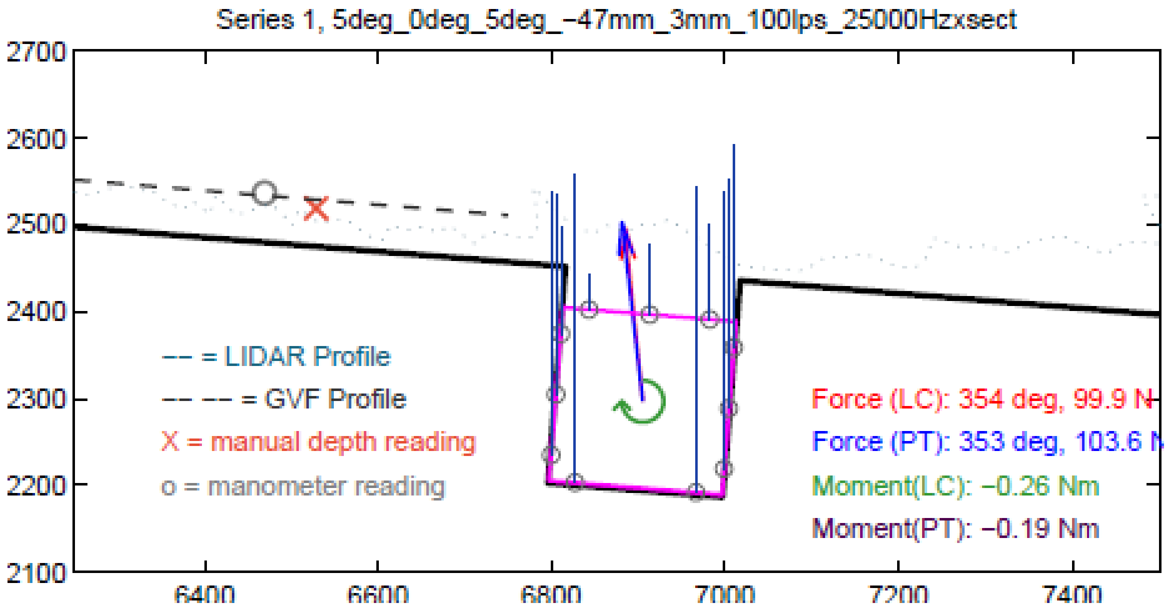


Tests with Aeration



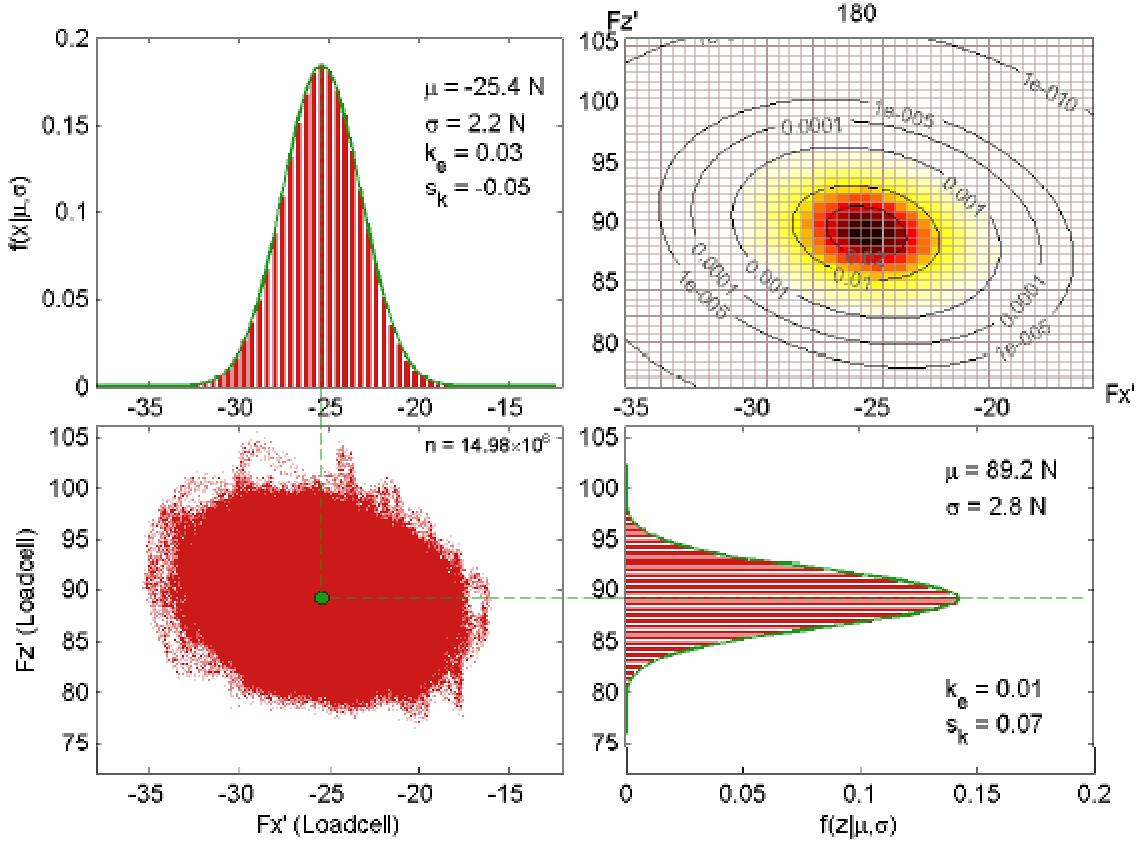
Tests with Aeration

Analysis
Statics



LINK

Analysis
Dynamics



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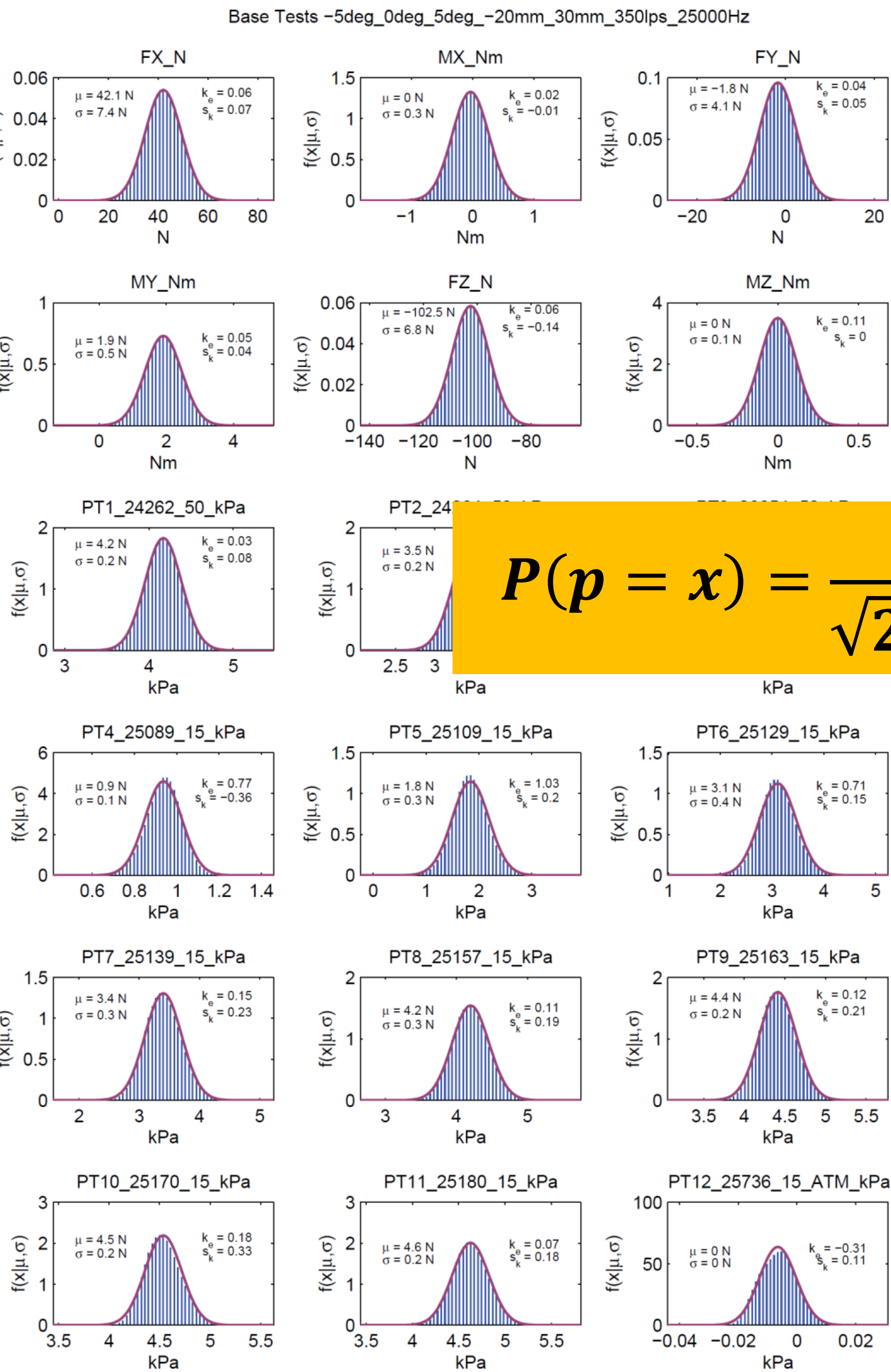
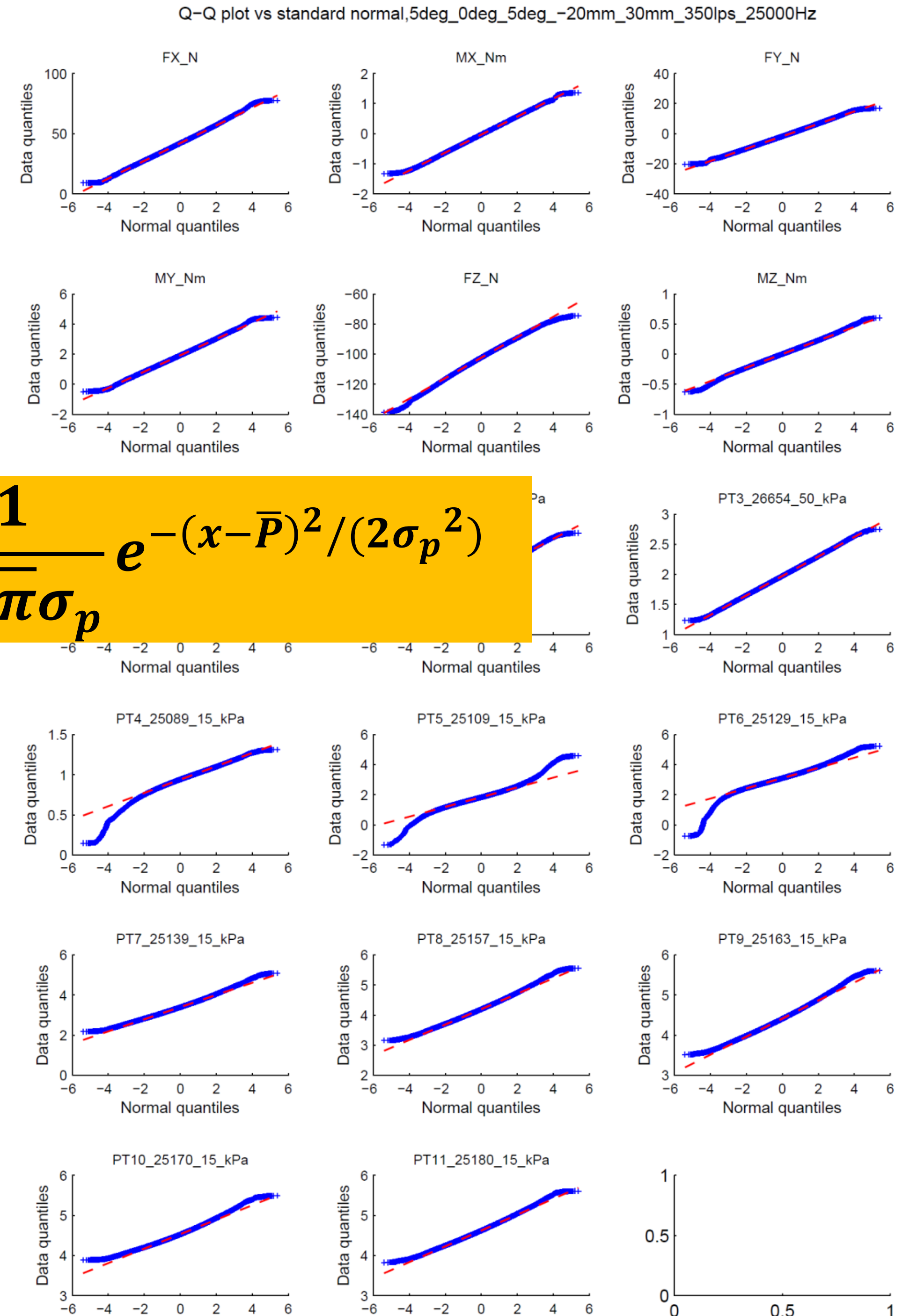


$$P(p = x) = \frac{1}{\sqrt{2\pi}\sigma_p} e^{-(x-\bar{P})^2/(2{\sigma_p}^2)}$$



What to do with it?

- Drag force equations
  - Traditional "C_D" values
  - A new drag equation
- Bed shear stress
- Slope stability
- Rip rap design equations
- Rock masses

Rock-mass stability

Closed analytical solution not appropriate

- Complex and unhelpful
- Rock masses cant be generalised

"Don't try to re-invent rock mechanics"

"give us pressures … we will roll our own vectors"

Dimensionless coefficients
Mean Pressure

Pressure (Pa) recorded in laboratory by transducer
(ie ***total*** pressure at that point)

Pressure head, assuming a hydrostatic profile

Inferred velocity head at transducer

$$\bar{C}_P = \frac{\left(\overline{P}/(\rho g) - H_P\right)}{\bar{u}^2/2g}$$

Mean velocity head of the flow

$$\bar{P} = \bar{C}_P \rho \frac{\bar{u}^2}{2} + H_p \rho g$$

Re-arrange to give design equation

Dimensionless coefficients
Fluctuating Pressure

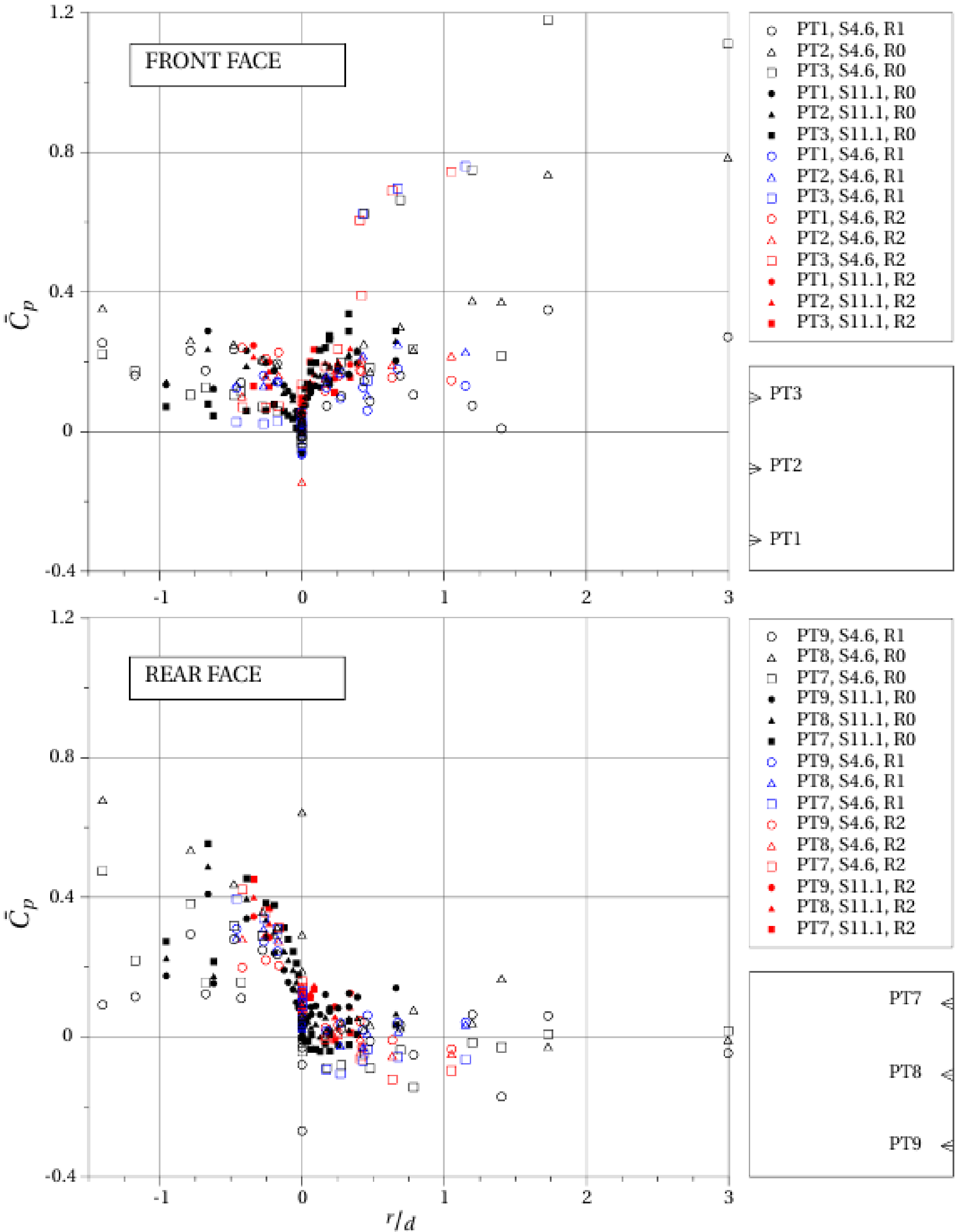
Standard deviation of pressure (Pa) recorded by transducer over 10 minute test

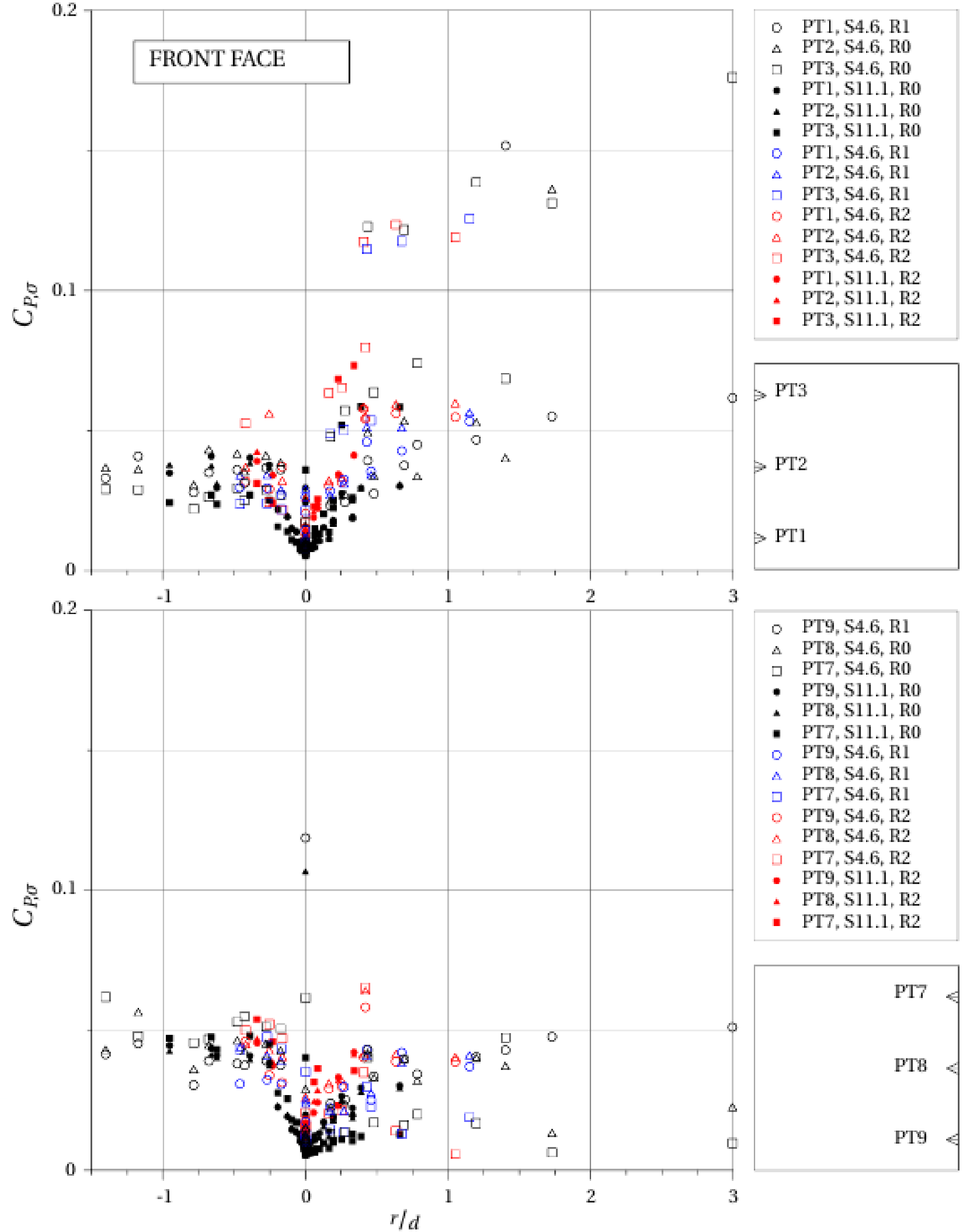
$$C_{P,\sigma} = \frac{\sigma_P / \rho g}{\bar{u}^2 / 2g} = \frac{2\sigma_P}{\rho \bar{u}^2}$$

Velocity head

$$\sigma_P = C_{P,\sigma} \rho \frac{\bar{u}^2}{2}$$

Re-arrange to give design equation

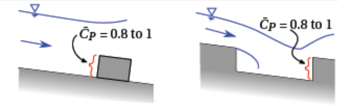
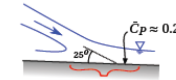
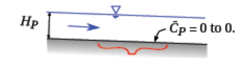
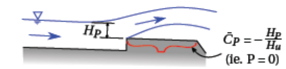
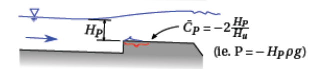
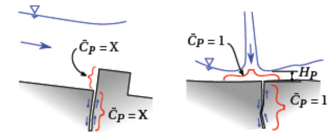
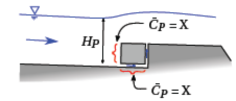
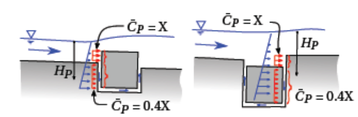
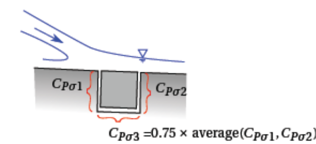
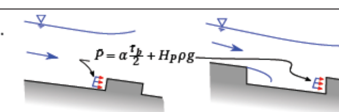
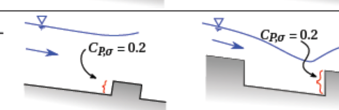
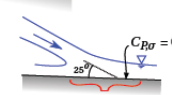
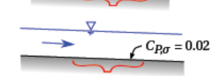

FRONT FACE
PT1, S4.6, R1
PT2, S4.6, R0
PT3, S4.6, R0
PT1, S11.1, R0
PT2, S11.1, R0
PT3, S11.1, R0
PT1, S4.6, R1
PT2, S4.6, R1
PT3, S4.6, R1
PT1, S4.6, R2
PT2, S4.6, R2
PT3, S4.6, R2
PT1, S11.1, R2
PT2, S11.1, R2
PT3, S11.1, R2
PT3
PT2
PT1
REAR FACE
PT9, S4.6, R1
PT8, S4.6, R0
PT7, S4.6, R0
PT9, S11.1, R0
PT8, S11.1, R0
PT7, S11.1, R0
PT9, S4.6, R1
PT8, S4.6, R1
PT7, S4.6, R1
PT9, S4.6, R2
PT8, S4.6, R2
PT7, S4.6, R2
PT9, S11.1, R2
PT8, S11.1, R2
PT7, S11.1, R2
PT7
PT8
PT9
$\bar{C}_p$
r/d
1.2
0.8
0.4
0
-0.4
-1
0
1
2
3

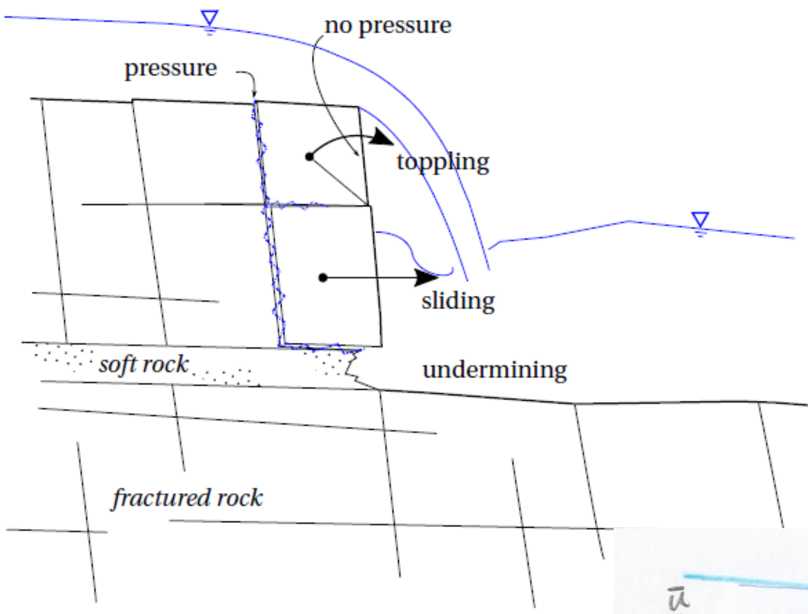


FRONT FACE
$C_{P,\sigma}$
0.2
0.1
0
-1
0
1
2
3
PT1, S4.6, R1
PT2, S4.6, R0
PT3, S4.6, R0
PT1, S11.1, R0
PT2, S11.1, R0
PT3, S11.1, R0
PT1, S4.6, R1
PT2, S4.6, R1
PT3, S4.6, R1
PT1, S4.6, R2
PT2, S4.6, R2
PT3, S4.6, R2
PT1, S11.1, R2
PT2, S11.1, R2
PT3, S11.1, R2
PT3
PT2
PT1
PT9, S4.6, R1
PT8, S4.6, R0
PT7, S4.6, R0
PT9, S11.1, R0
PT8, S11.1, R0
PT7, S11.1, R0
PT9, S4.6, R1
PT8, S4.6, R1
PT7, S4.6, R1
PT9, S4.6, R2
PT8, S4.6, R2
PT7, S4.6, R2
PT9, S11.1, R2
PT8, S11.1, R2
PT7, S11.1, R2
PT7
PT8
PT9
r/d

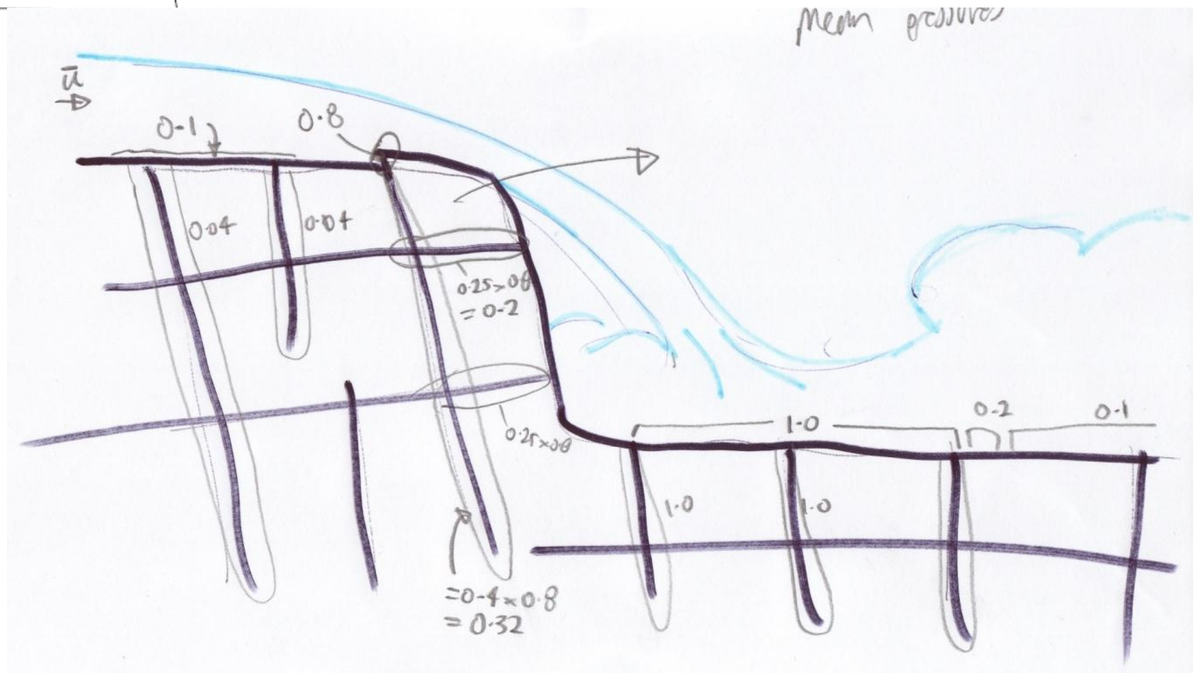
Design coefficients

Table 6.3 Design pressure coefficients

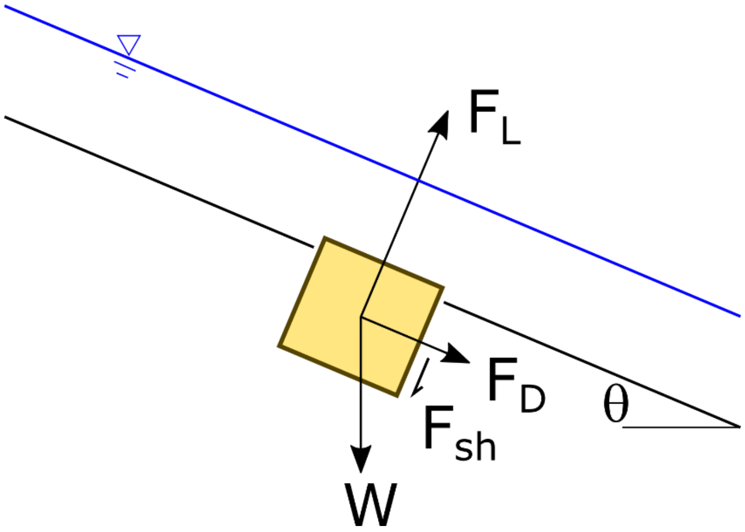
Hydraulic Action	Design Equation	Design coefficient	Basis	Examples
$\bar{P}$ (kPa)	$= \bar{C}_P \rho \frac{\bar{u}^2}{2} + H_P \rho g$	$\bar{C}_p = 0.8$ to 1 for surfaces protruding perpendicular to bed-parallel flow or jet impingment.	Figure 6.35 (PT3); Figure 6.37 (PT1, PT2, PT3 for scour hole cases)	
		$\bar{C}_p = 0.2$ for surfaces 25^o to flow direction or jet impingement.	Figure 6.38 (PT4, PT5, PT6 for r/d=0)	
		$\bar{C}_p = 0$ to 0.1 for surfaces parallel (streamlined) to flow, no detachment.	Figure 6.36 (PT4, PT5, PT6 for r/d=0)	
		$\bar{C}_p = -\frac{H_P}{H_u}$ (ie $\bar{P} = 0$) where flow fully detached from surface.	Section 6.3.2	
		$\bar{C}_p = -2\frac{H_P}{H_u}$ where flow detachment imminent.	Section 6.3.2; Figure 6.36 (PT4); Figure 6.40 (PT4)	
		Daylighting, single-ended defects adopt the surface $\bar{C}_p$ value.	not tested	
		Daylighting, thoughflowing, defects with dip parallel to impinging flow adopt the surface $\bar{C}_p$ value.	Figure 6.38 (PT10, PT11 for scour hole cases)	
		Daylighting, thoughflowing, defects with dip perpendicular to impinging flow adopt 0.4 × surface $\bar{C}_p$ value.	Figure 6.35 (PT1, PT2 for 0<r/d<1.5; PT8, PT9 for -1<r/d<0)	
		Buried (ie - non-daylighting) defects adopt 0.75 × average of connected defect $\bar{C}_p$ values.	Figure 6.37 (PT7, PT8, PT9 for scour hole cases), Figure 6.26 ($F_{z'}$ increase as two joints exposed due to rotation), Figure 6.36 (PT10 and PT11)	
$\bar{P}$ (kPa)	$= \alpha \frac{\tau_b}{2} + H_P \rho g$	for surfaces protruding perpendicular to bed-parallel flow (preferable for small protrusions).	α from Equation A.1.69. See Section 6.4.5	
σ_P (kPa)	$= C_{P\sigma} \rho \frac{\bar{u}^2}{2}$	$C_{P\sigma} = 0.2$ for surfaces protruding perpendicular to bed-parallel flow or jet impingment.[#1.]	Figure 6.41 (PT3); Figure 6.43 (PT1, PT2, PT3)	
		$C_{P\sigma} = 0.1$ for surfaces 25^o to flow direction or jet impingement. [#1.]	Figure 6.44 (PT4, PT5, PT6)	
		$C_{P\sigma} = 0.02$ for surfaces parallel (streamlined) to flow, no detachment.[#1.]	Figure 6.42 (PT4, PT5, PT6 for r/d=0)	

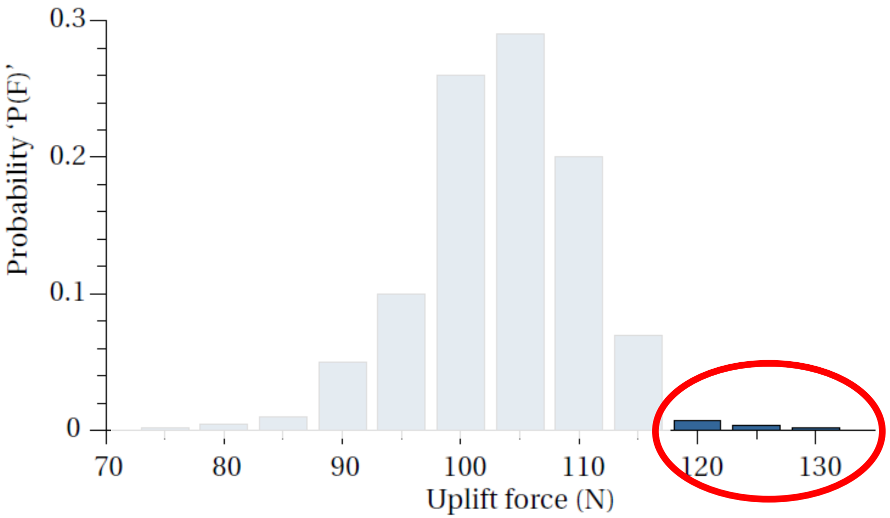


Practitioners need to perceive the problem and develop own force vectors …



Analytical block removal





Consider the case of lifting of the block.

For the purpose of illustration, assume:

F_L = hydraulic uplift force, fluctuating as per histogram shown

F_D = drag force = 30 N

F_{sh} = rock shear force, = $F_D \tan\phi$ = 17 N

W = mass of block = 10kg (98 N)

For movement, require:

$F_L > F_{sh} + W\cos\theta$

$F_L > 115$ N

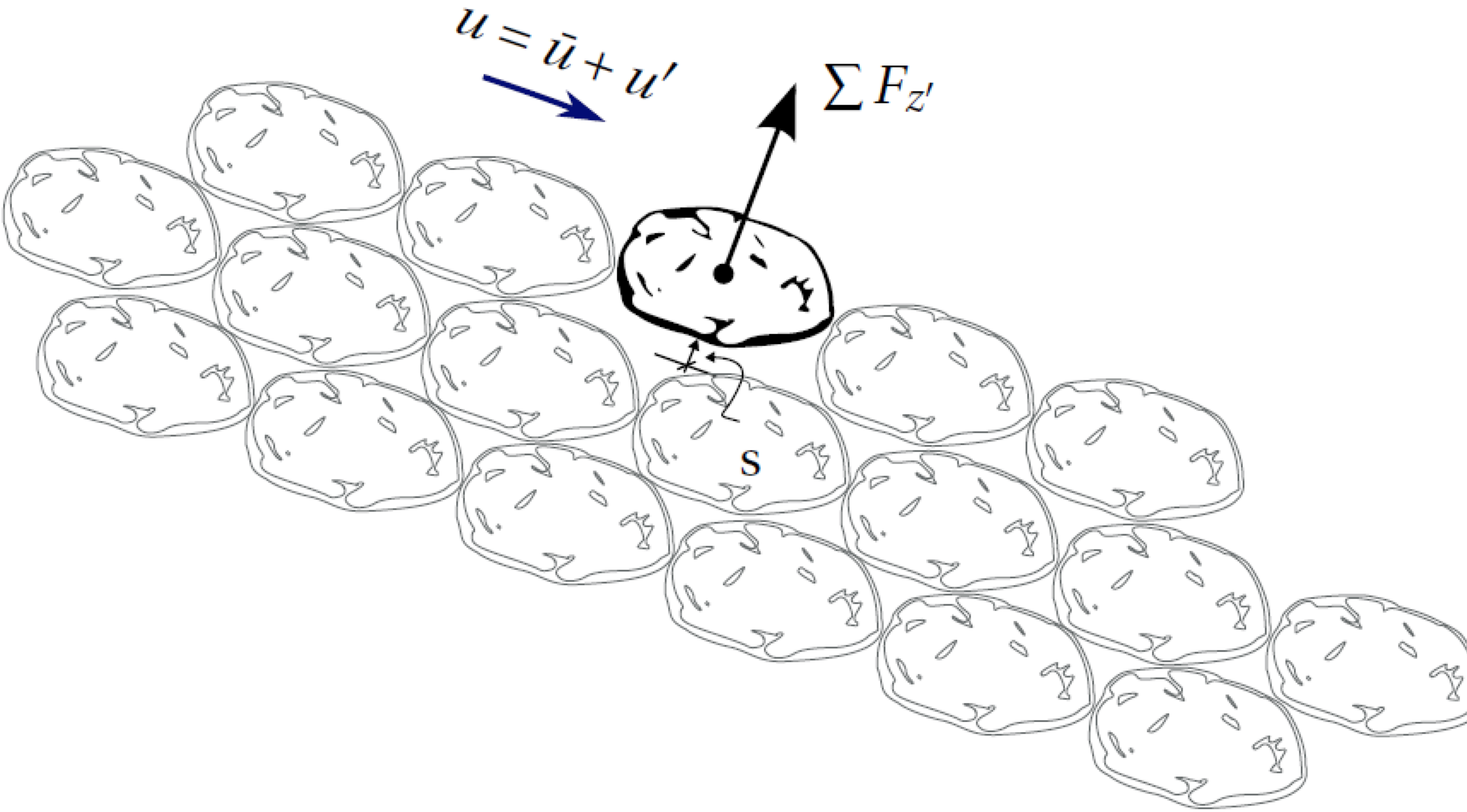
Lift Force (N)	P(F)	Force Duration (secs)	Net applied force $F_L - W$ (N)	Restraining force $F_D \tan\phi$ available (N)	Restraining force $F_D \tan\phi$ applied (N)	F_{net} (N)	Displacement Case 1 up/down (mm)	Displacement Case 2 up only (mm)
75	0.002	$= 0.002 \times 60 = 0.12$	-23.1	17.3	-17.3	-5.8	-4.2	0.0
80	0.005	$= 0.005 \times 60 = 0.3$	-18.1	17.3	-17.3	-0.8	-3.5	0.0
85	0.01	$= 0.01 \times 60 = 0.6$	-13.1	17.3	-13.1	0.0	0.0	0.0
90	0.05	$= 0.05 \times 60 = 3$	-8.1	17.3	-8.1	0.0	0.0	0.0
95	0.1	$= 0.1 \times 60 = 6$	-3.1	17.3	-3.1	0.0	0.0	0.0
100	0.26	$= 0.26 \times 60 = 15.6$	1.9	17.3	1.9	0.0	0.0	0.0
105	0.29	$= 0.29 \times 60 = 17.4$	6.9	17.3	6.9	0.0	0.0	0.0
110	0.2	$= 0.2 \times 60 = 12$	11.9	17.3	11.9	0.0	0.0	0.0
115	0.07	$= 0.07 \times 60 = 4.2$	16.9	17.3	16.9	0.0	0.0	0.0
120	0.007	$= 0.007 \times 60 = 0.42$	21.9	17.3	17.3	4.6	40.4	40.4
125	0.004	$= 0.004 \times 60 = 0.24$	26.9	17.3	17.3	9.6	27.6	27.6
130	0.002	$= 0.002 \times 60 = 0.12$	31.9	17.3	17.3	14.6	10.5	10.5
Total	1	$= 1.0 \times 60 = 60$					70.8	78.5

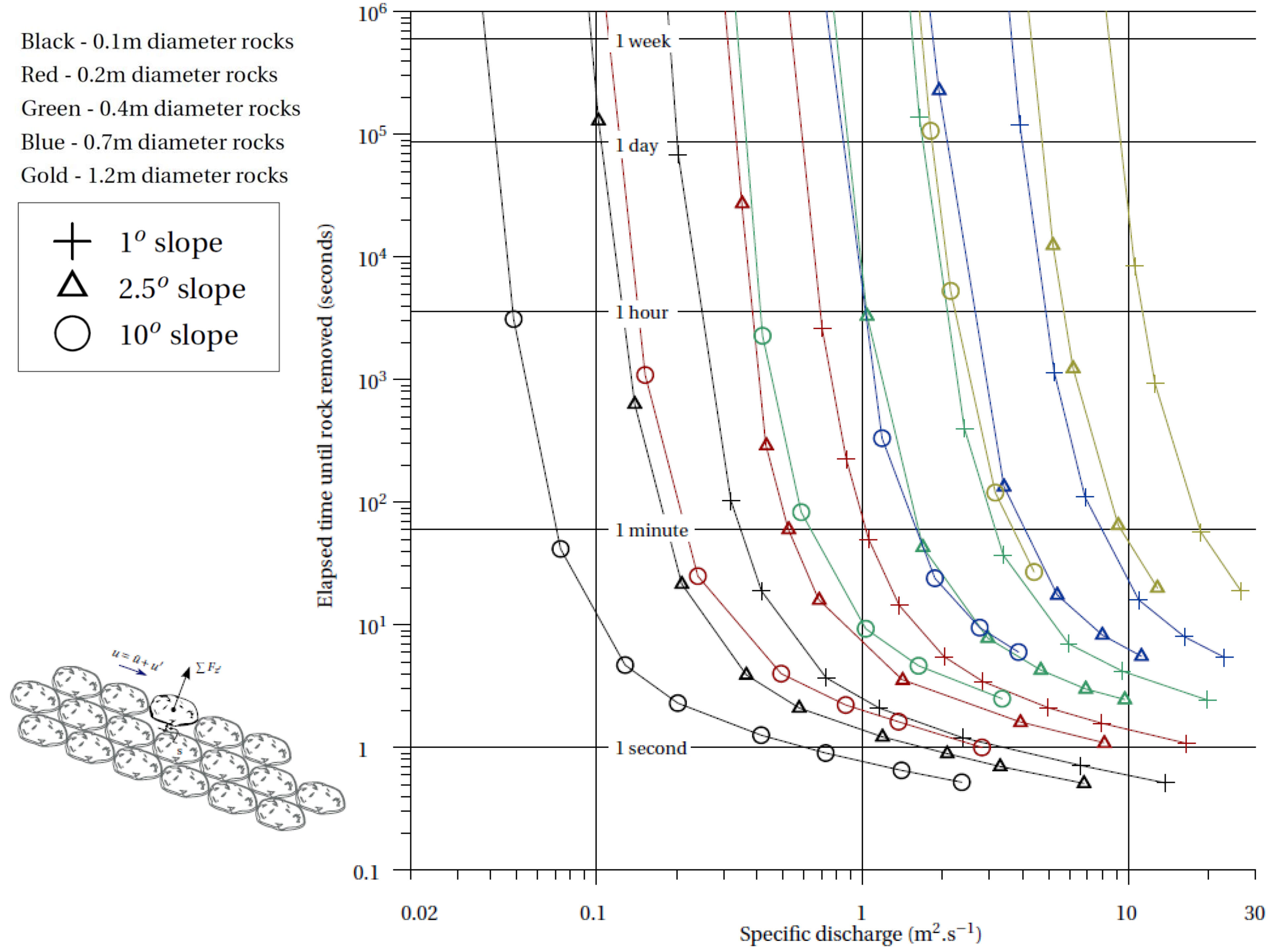
Displacement

Time

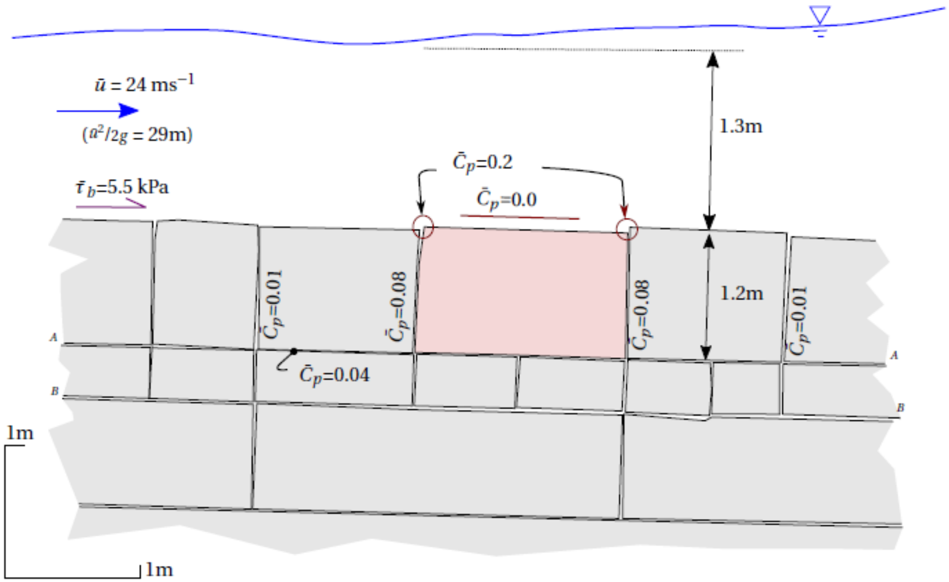
$$s_{\text{rock}} = \frac{F_{\text{net}}}{\forall_s . \rho_s} \frac{t^2}{2}$$

Displacement after 60 seconds

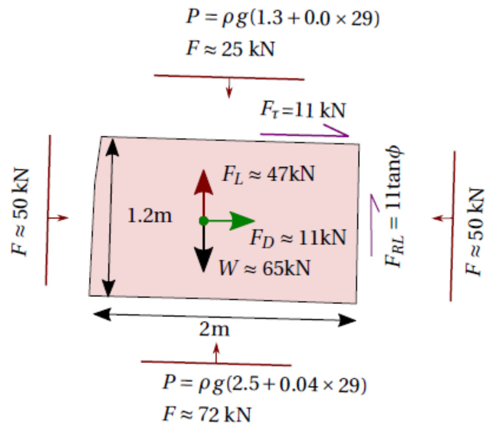

$u = \bar{u} + u'$
$\sum F_{z'}$
s



Black - 0.1m diameter rocks
Red - 0.2m diameter rocks
Green - 0.4m diameter rocks
Blue - 0.7m diameter rocks
Gold - 1.2m diameter rocks
1° slope
2.5° slope
10° slope
1 week
1 day
1 hour
1 minute
1 second
Elapsed time until rock removed (seconds)
10^6
10^5
10^4
10^3
10^2
10^1
1
0.1
0.02
0.1
1
10
30
Specific discharge (m².s⁻¹)

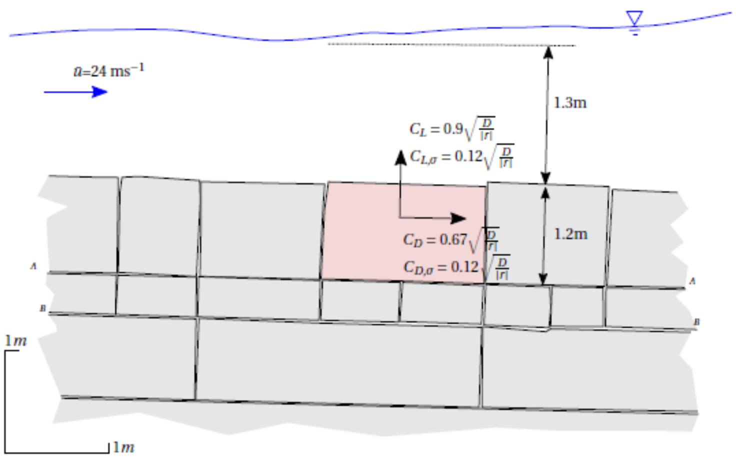


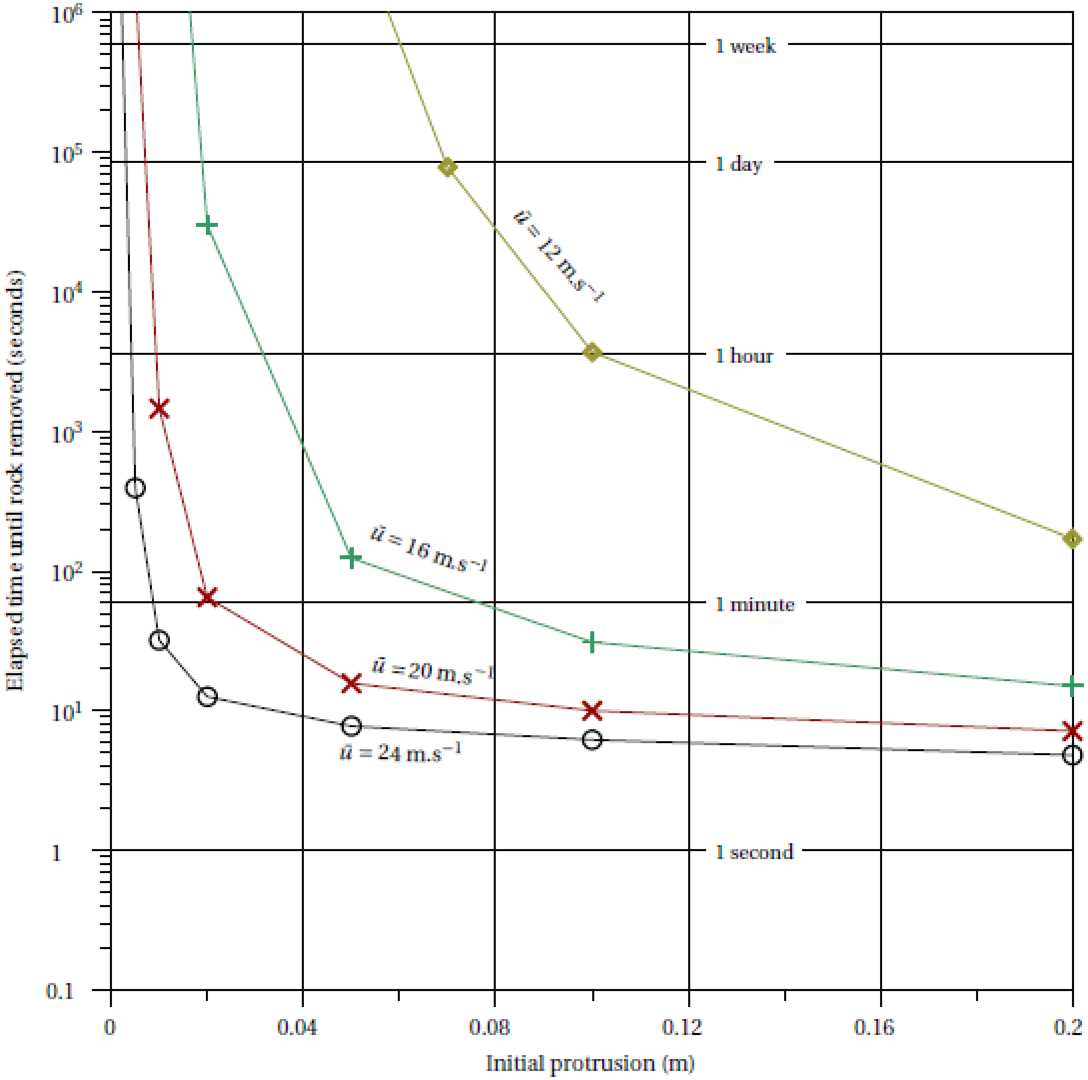
$\bar{u} = 24\ \mathrm{ms}^{-1}$
$(\bar{u}^2/2g = 29\mathrm{m})$
$\bar{\tau}_b$=5.5 kPa
$\bar{C}_p$=0.2
$\bar{C}_p$=0.0
1.3m
1.2m
$\bar{C}_p$=0.01
$\bar{C}_p$=0.08
$\bar{C}_p$=0.08
$\bar{C}_p$=0.01
$\bar{C}_p$=0.04
A
B
1m
1m

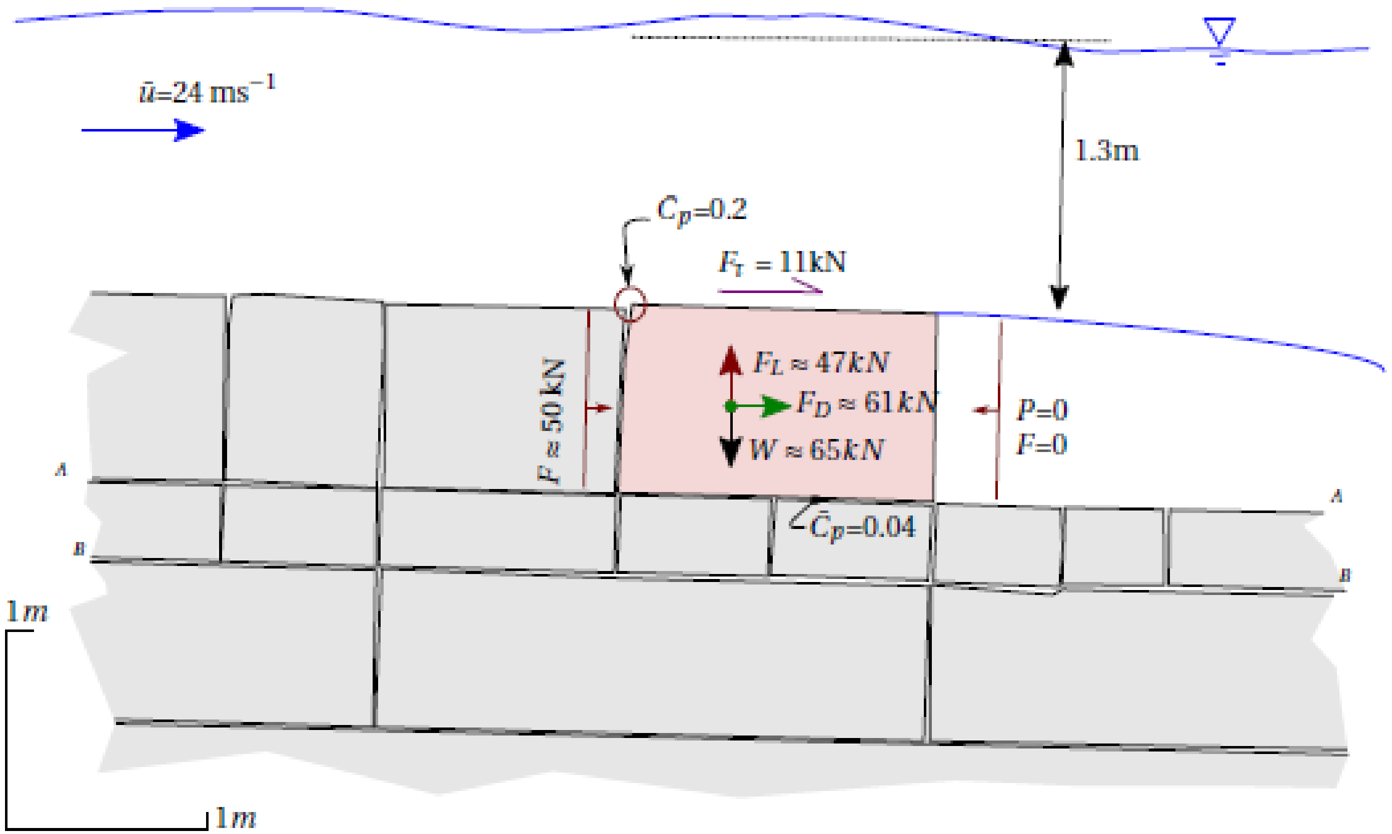


$P = \rho g(1.3 + 0.0 \times 29)$
$F \approx 25$ kN
F_τ=11 kN
$F \approx 50$ kN
$F_L \approx 47$kN
$F_D \approx 11$kN
$W \approx 65$kN
1.2m
$F_{RL} = 11\tan\phi$
$F \approx 50$ kN
2m
$P = \rho g(2.5 + 0.04 \times 29)$
$F \approx 72$ kN

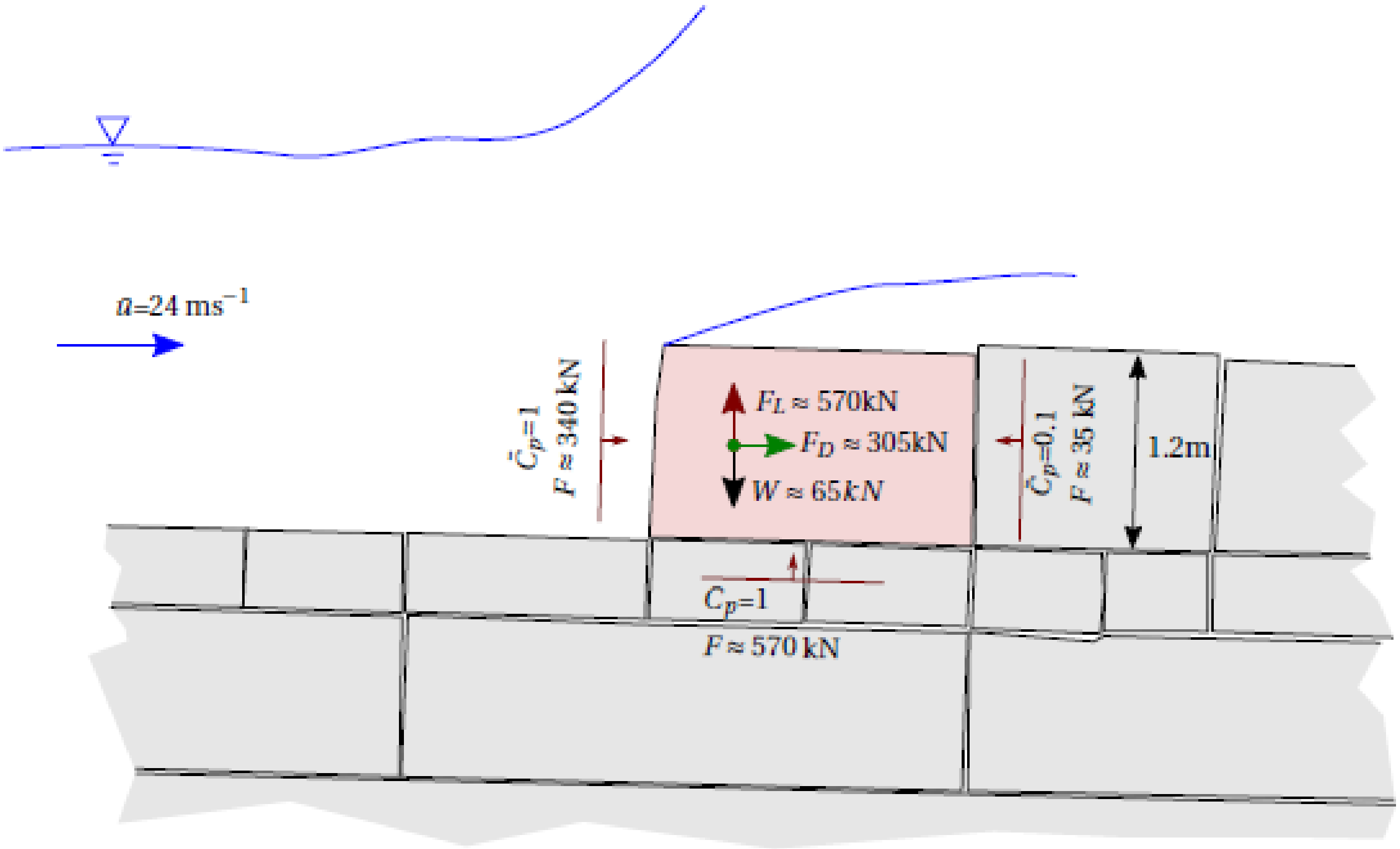
Fluctuating removal of a block





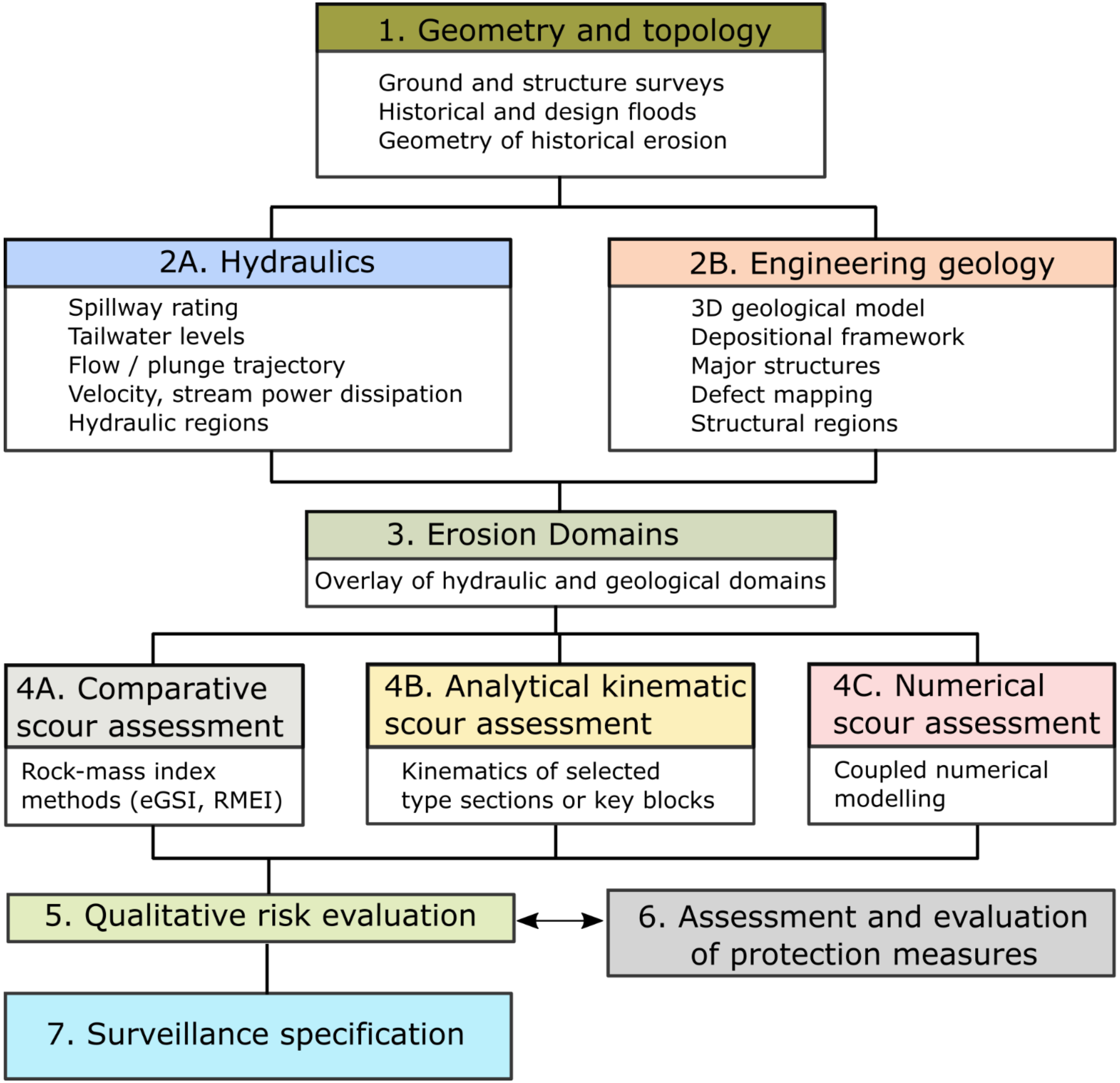


$\bar{u}$=24 ms^{-1}
1.3m
$\bar{C}_p$=0.2
F_T = 11kN
$F_L \approx 47kN$
$F_D \approx 61kN$
$W \approx 65kN$
$F \approx 50$ kN
P=0
F=0
$\bar{C}_p$=0.04
A
B
1m
1m

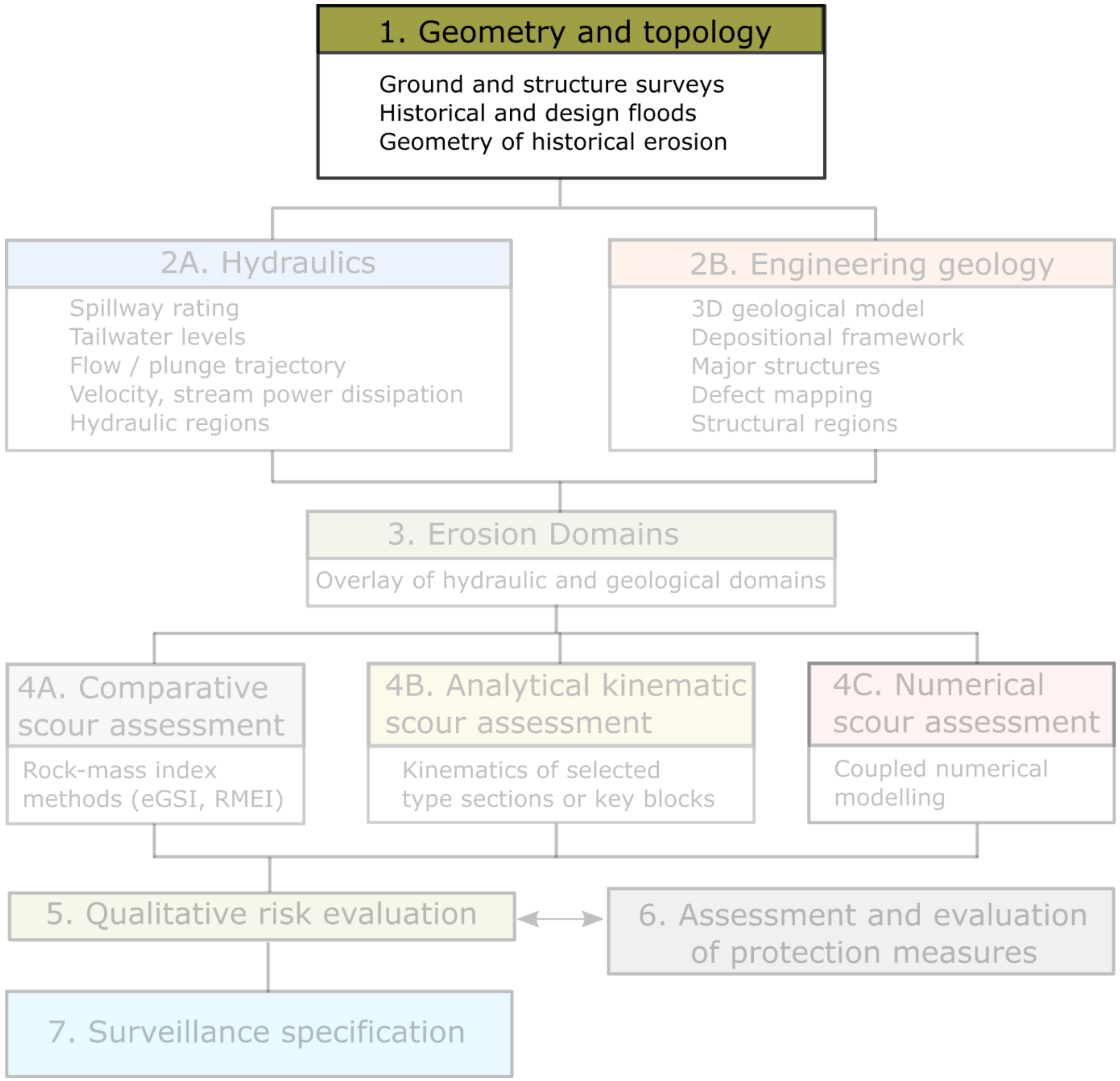

$\bar{u}$=24 ms^{-1}
$F_L \approx$ 570kN
$F_D \approx$ 305kN
$W \approx 65kN$
$\hat{C}_p$=1
$F \approx$ 340 kN
$\hat{C}_p$=0.1
$F \approx$ 35 kN
1.2m
C_p=1
$F \approx$ 570 kN

State of the art:
Assessment of spillway erosion

State of the art

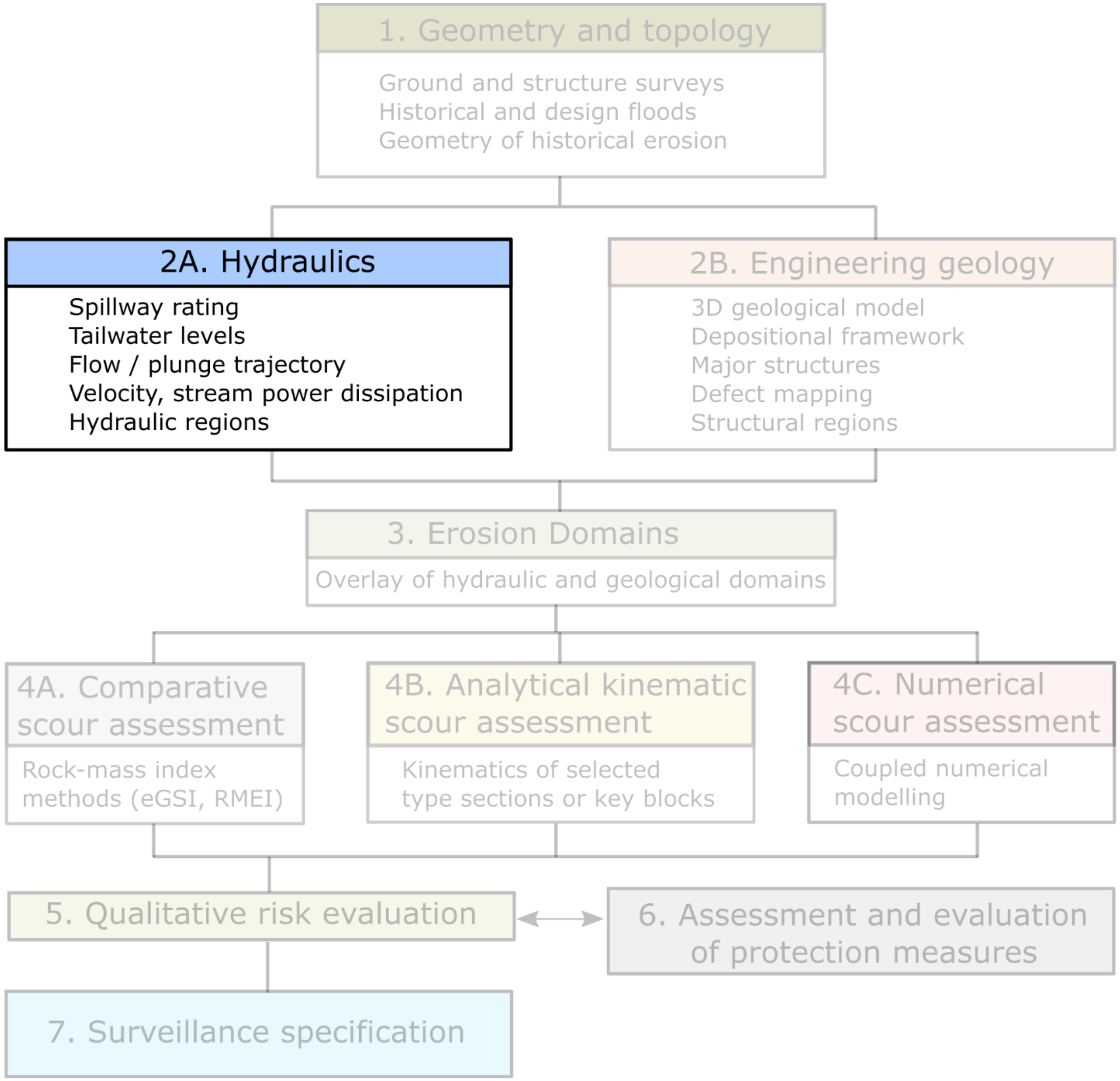


1. Geometry and topology

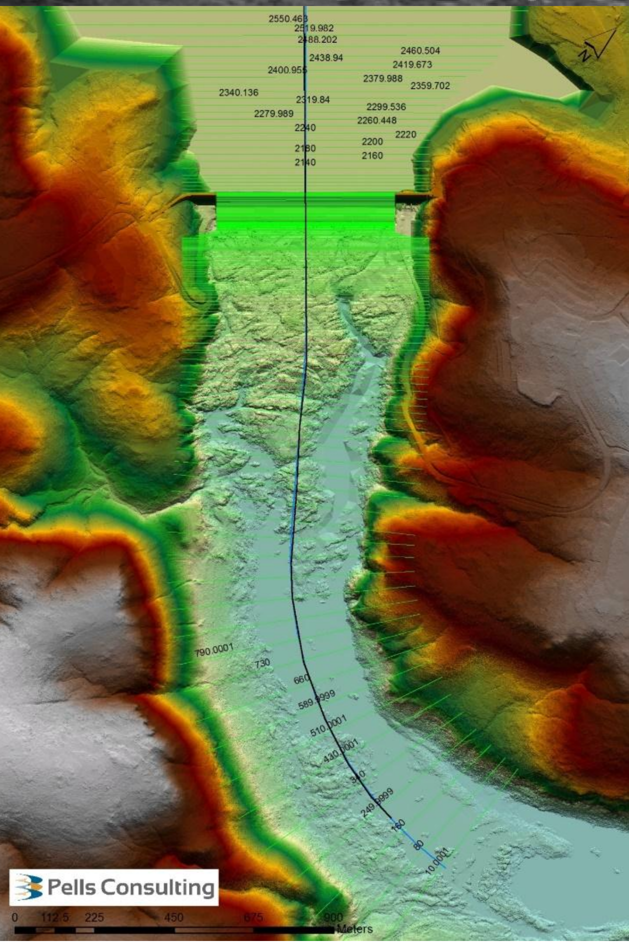


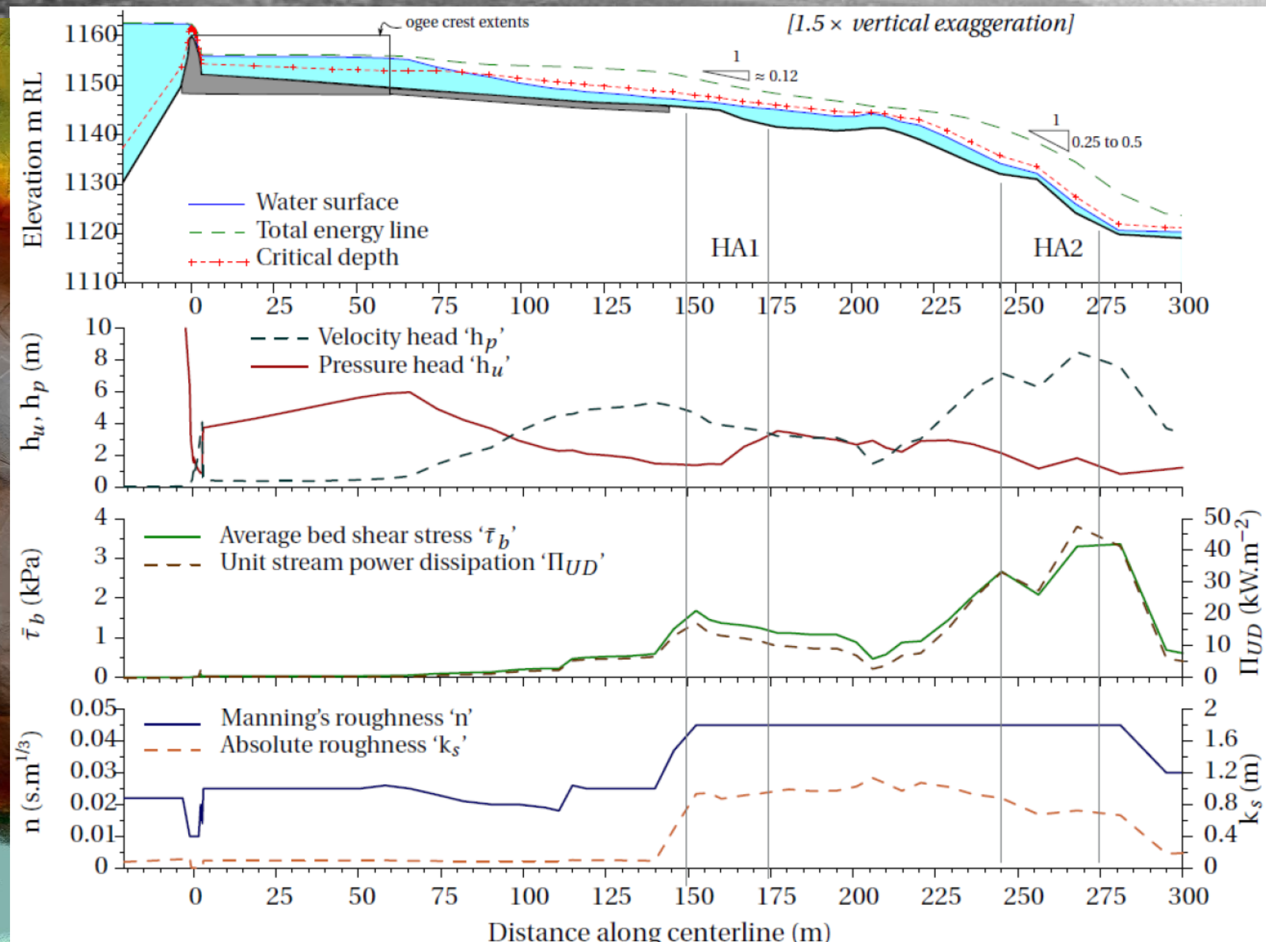
1. Geometry and topology

2A. Hydraulics

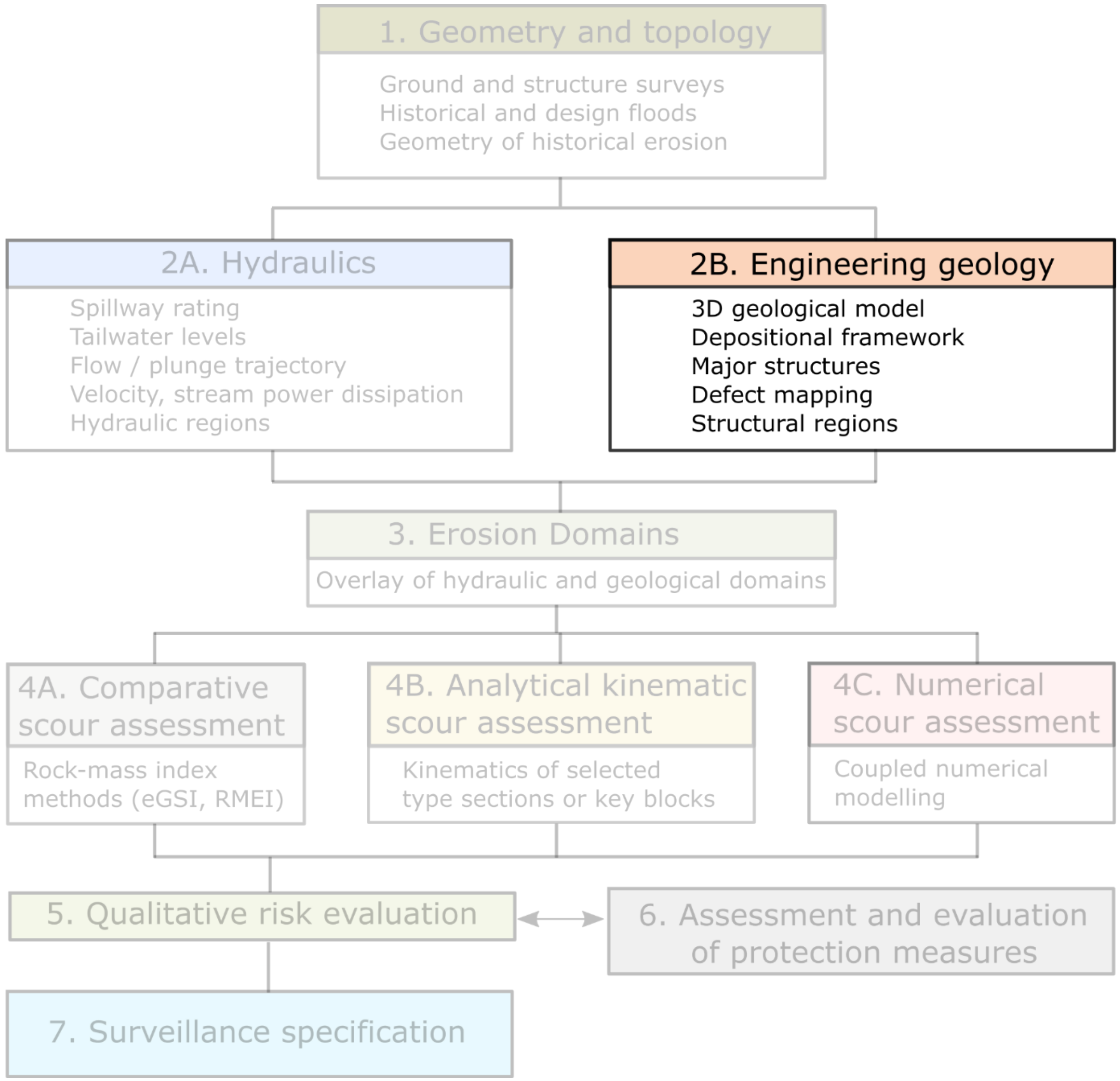


2A. Hydraulics

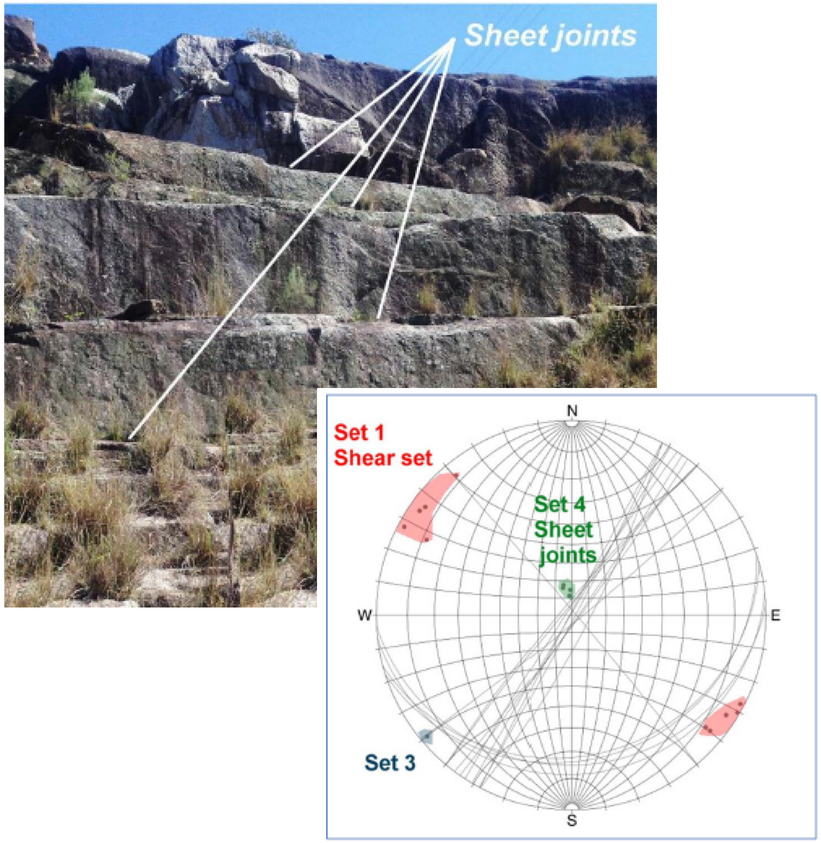


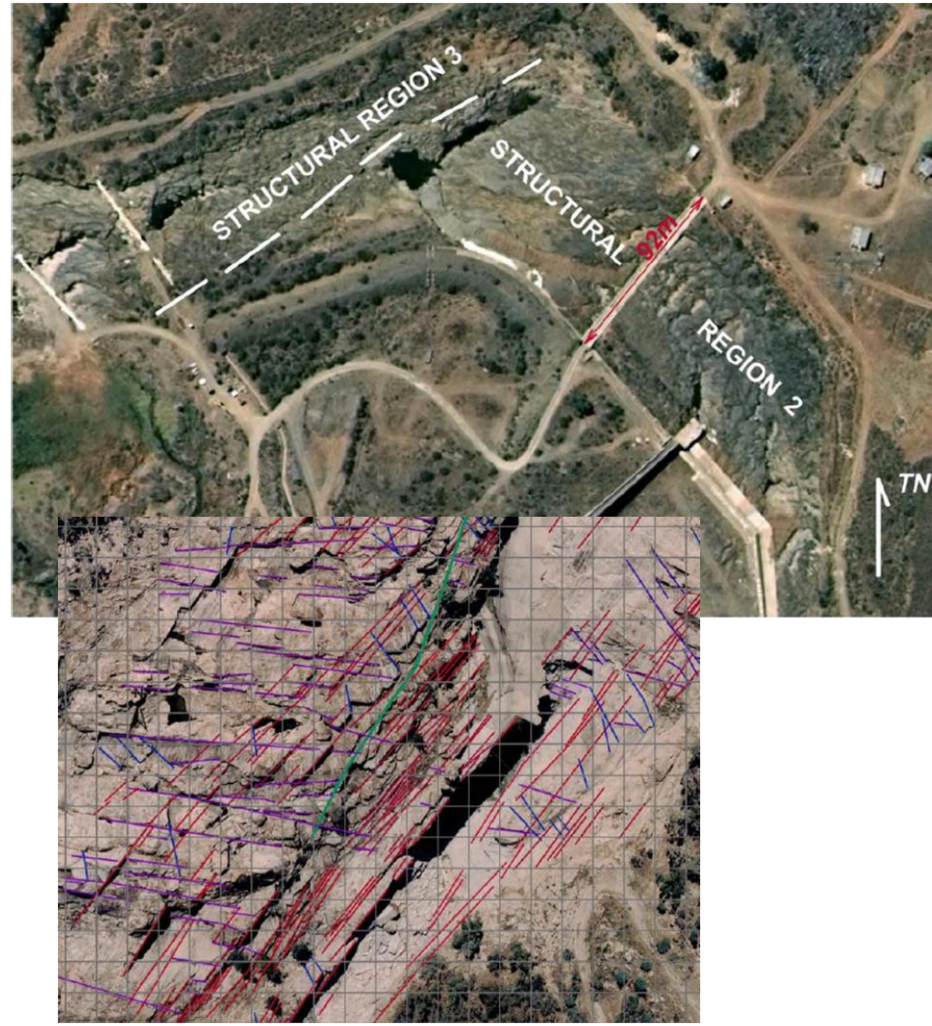


2B. Engineering geology

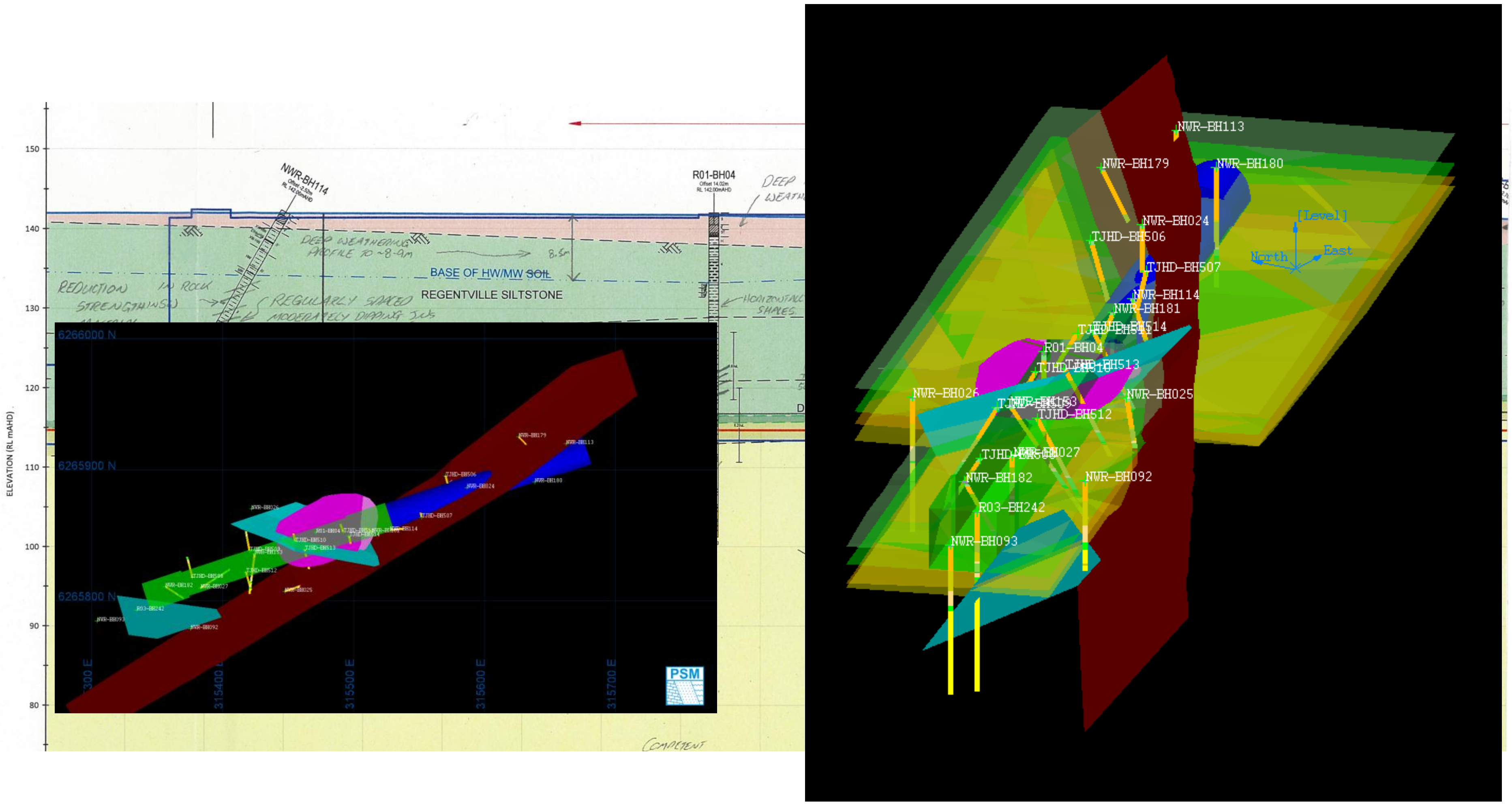


2B. Engineering geology

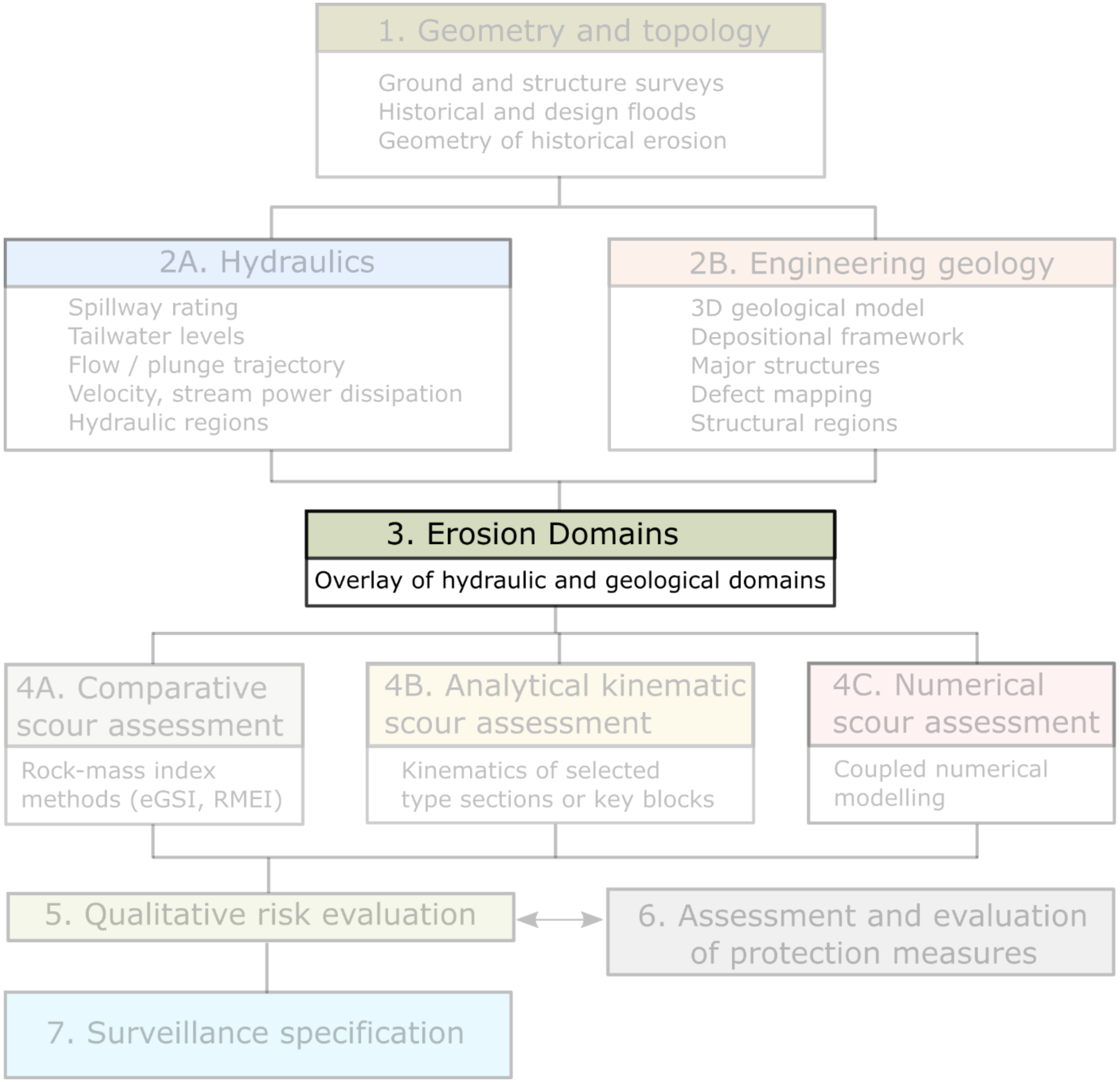




2B. Engineering geology

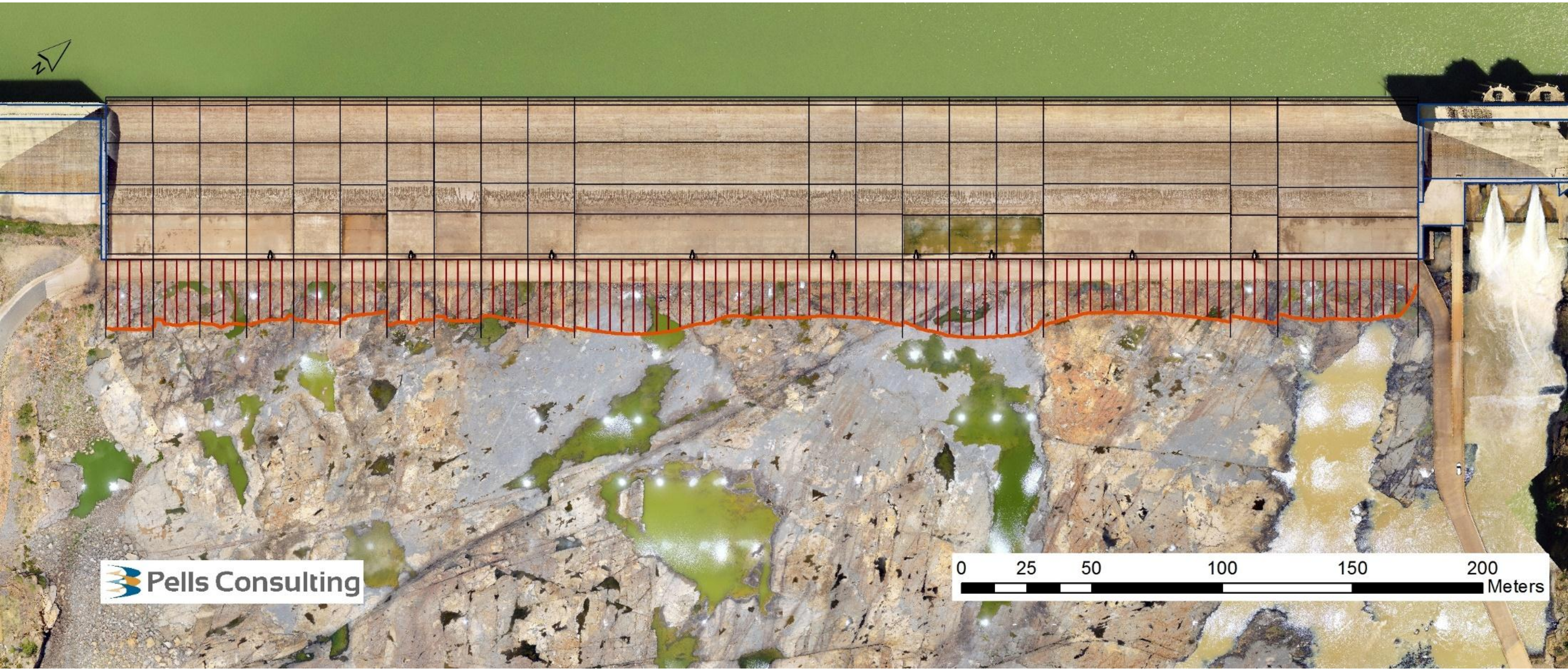


3. Erosion domains

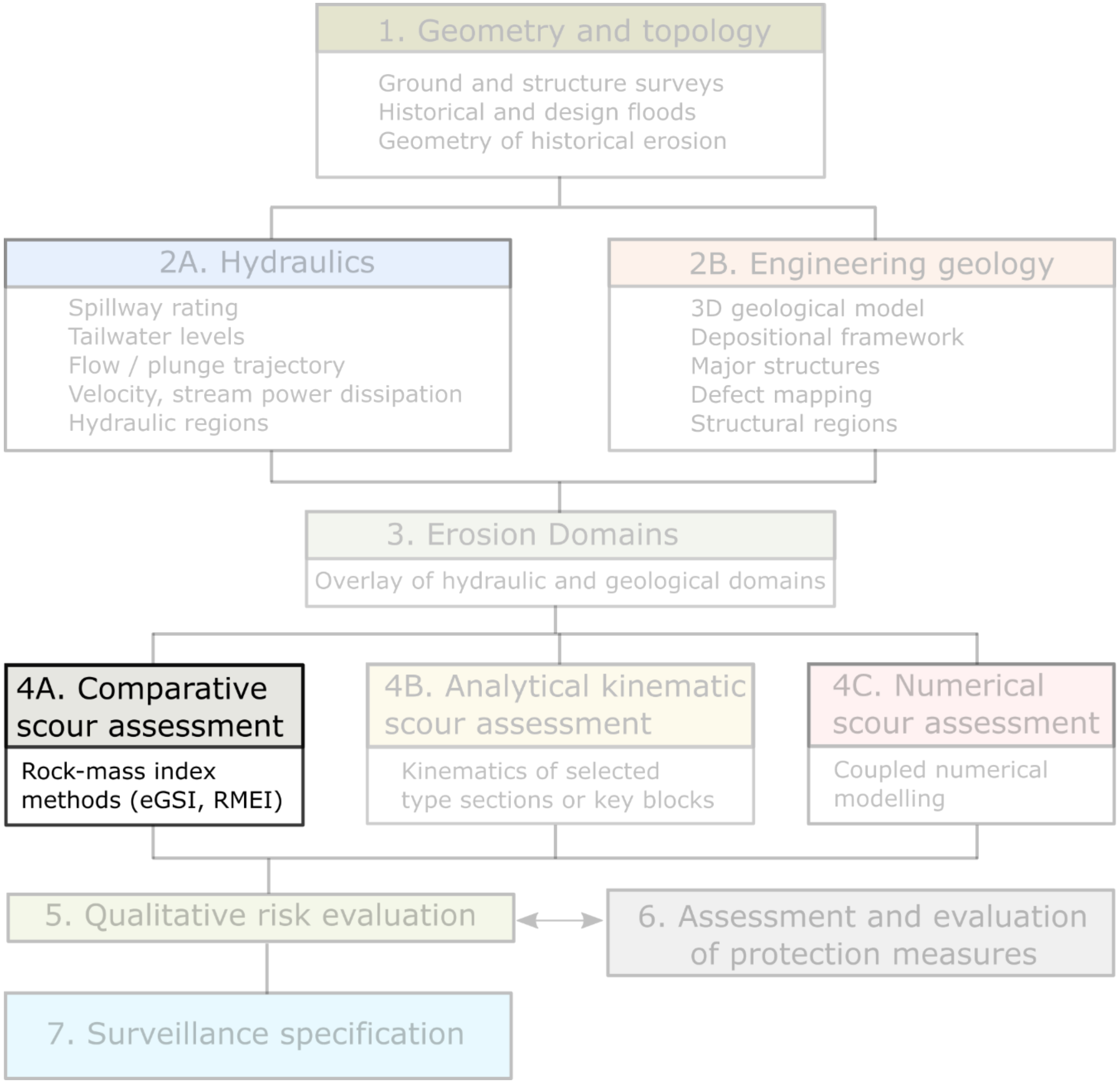


3. Erosion domains

3. Erosion domains

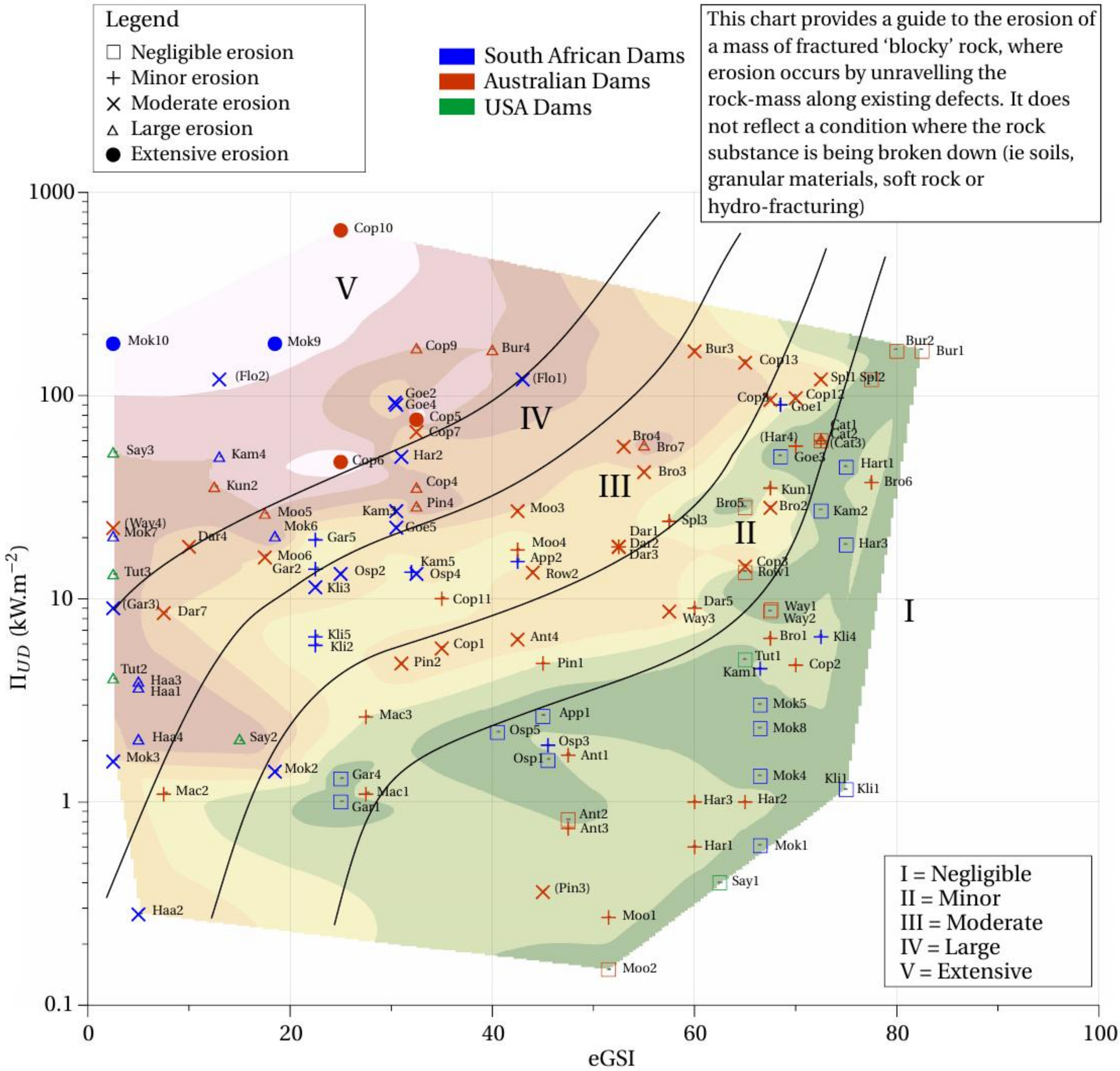


4A. Comparative scour assessment

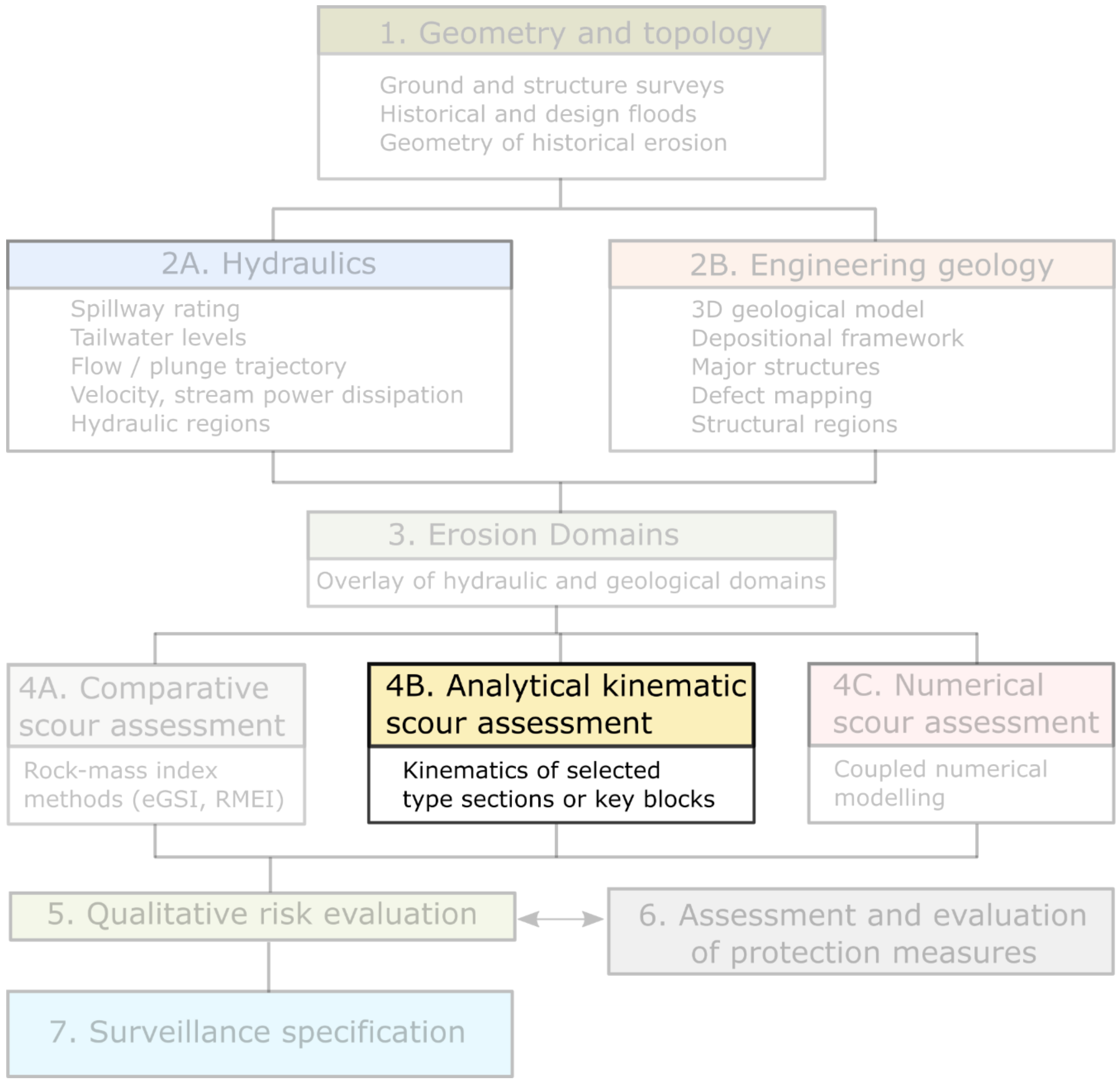


The 'eGSI' method …

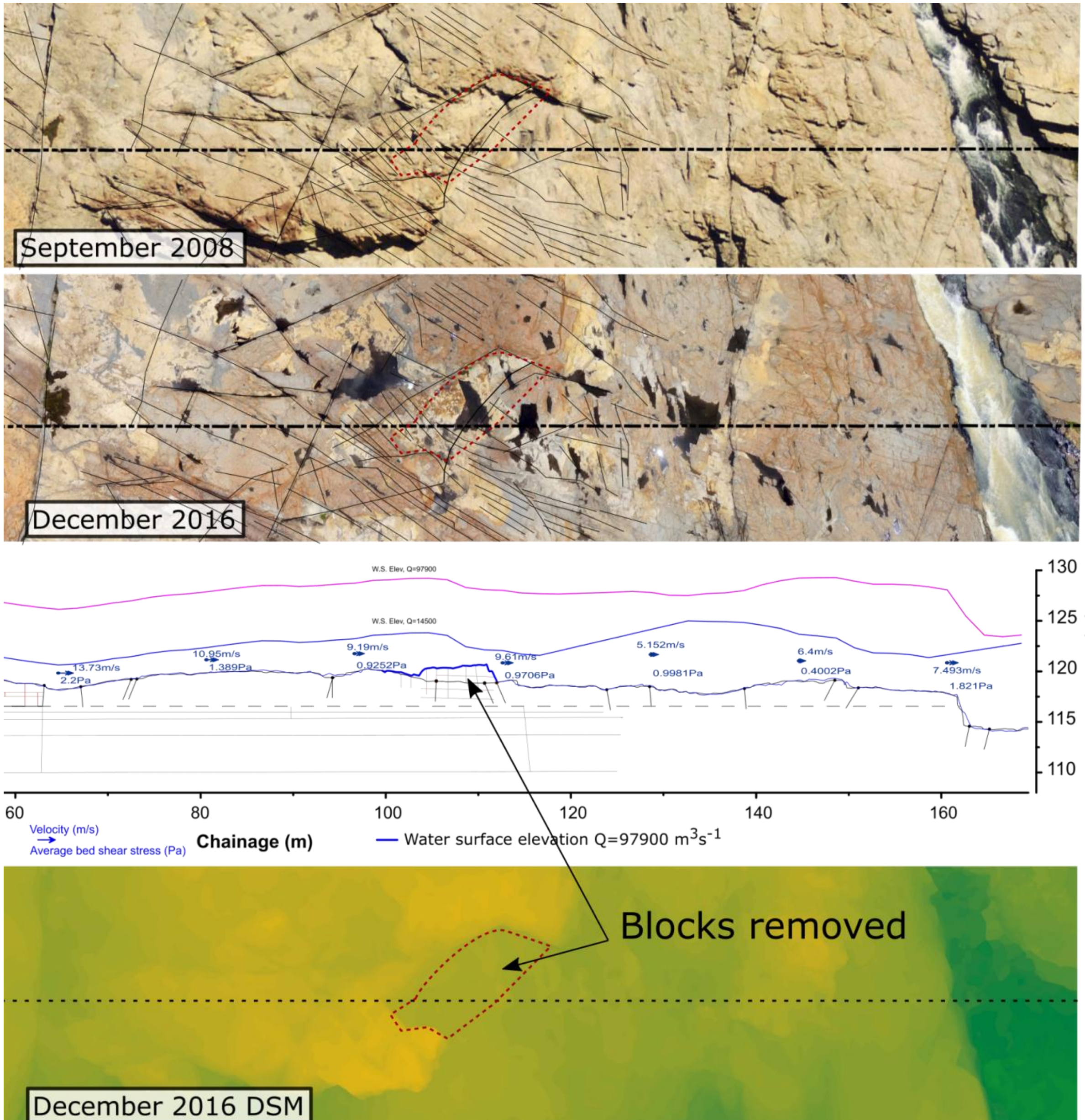
- Simpler
- Larger data set for rock
- Can trace case studies
- Gradation, not a 'threshold'
- GSI is current and credible
- No RQD
- No Mass Strength
- Appropriate inference of accuracy
- Reliable even when used by non-geologists

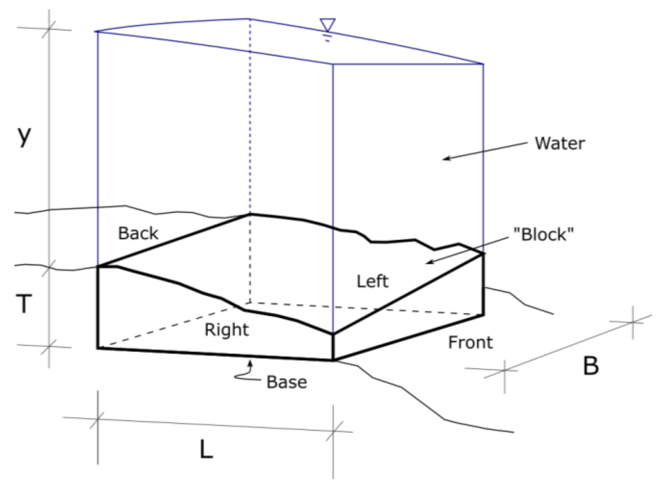


4B. Kinematic scour assessment

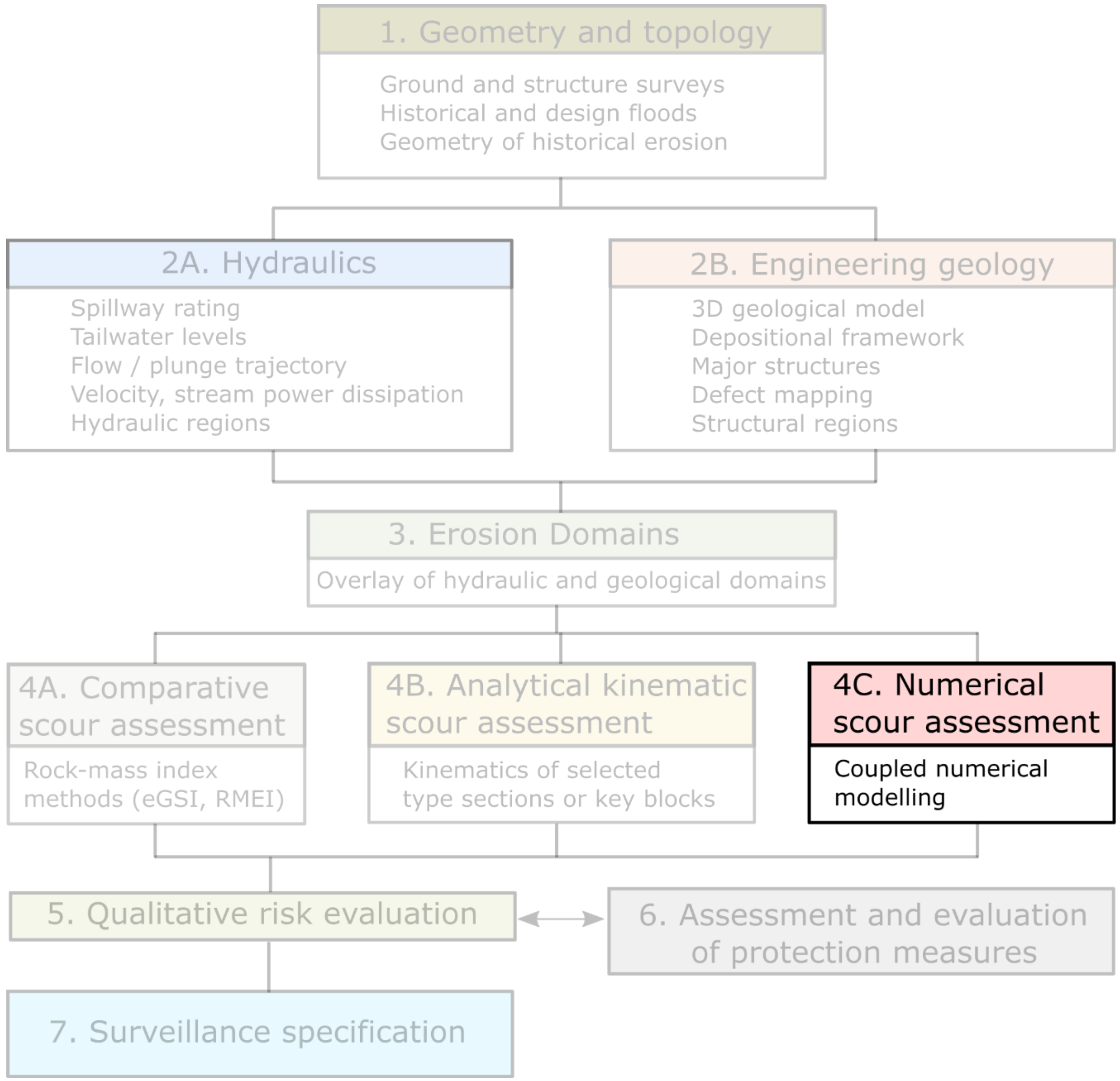


4B. Kinematic scour assessment

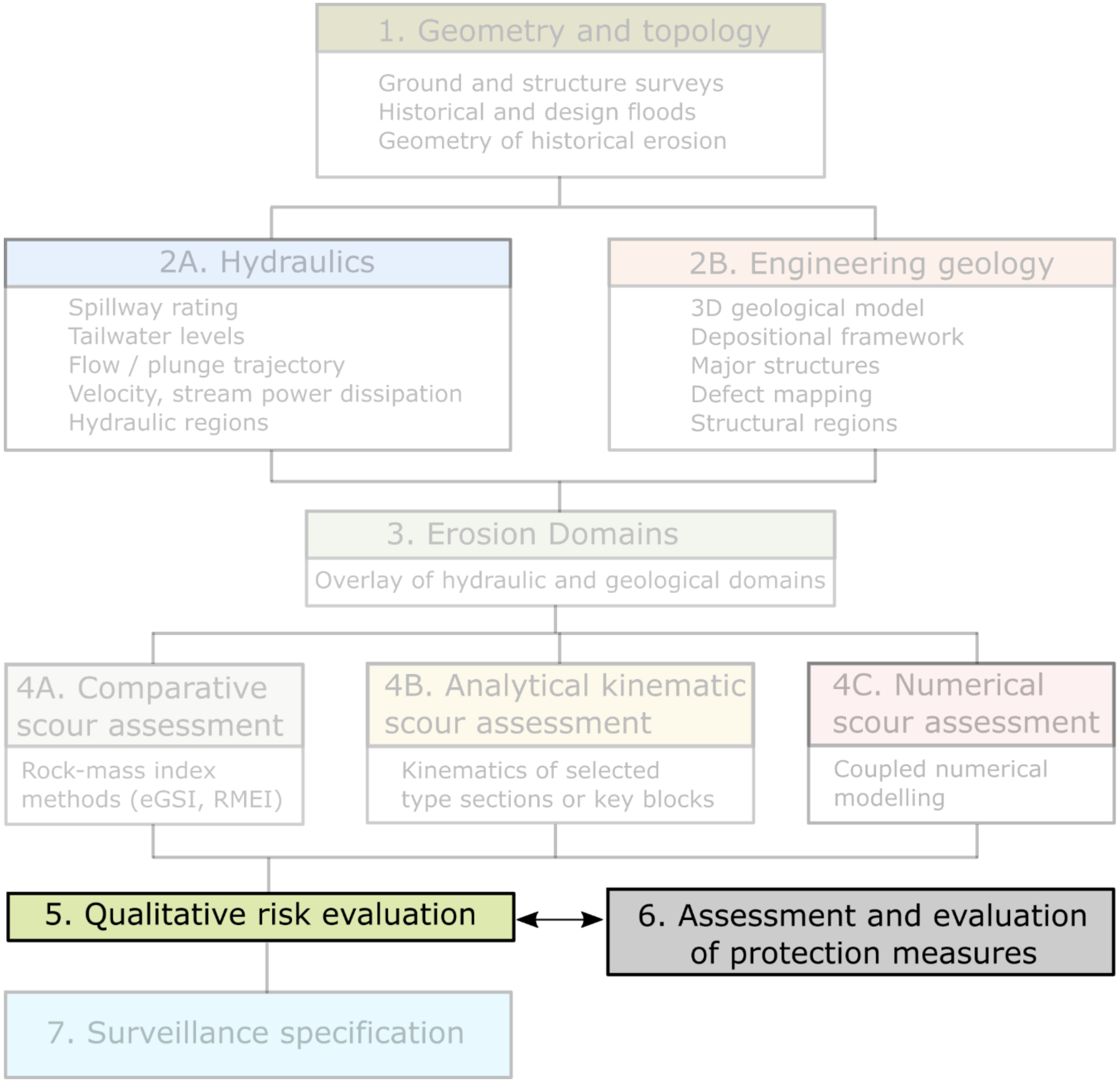




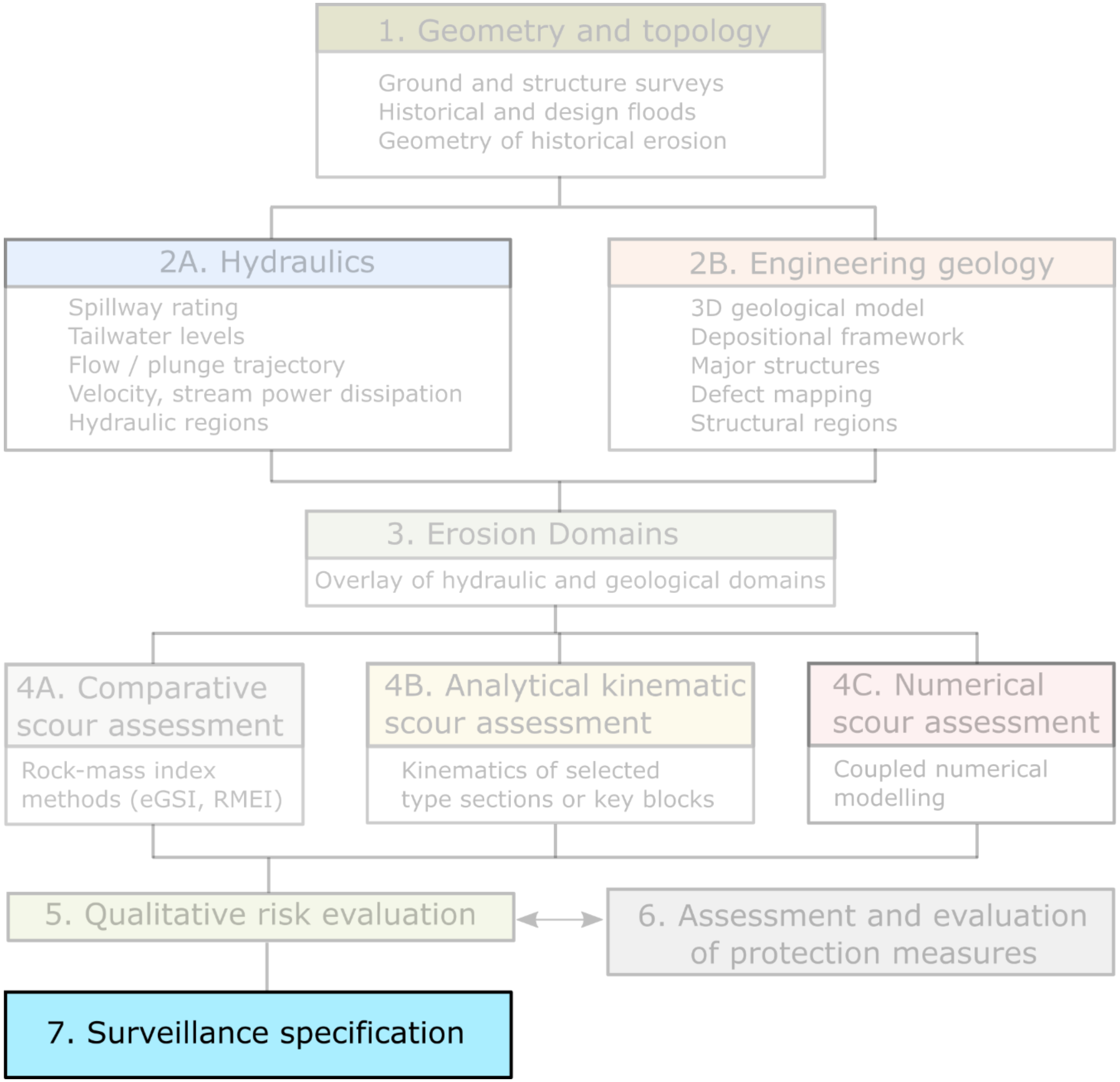
4C. Numerical scour assessment



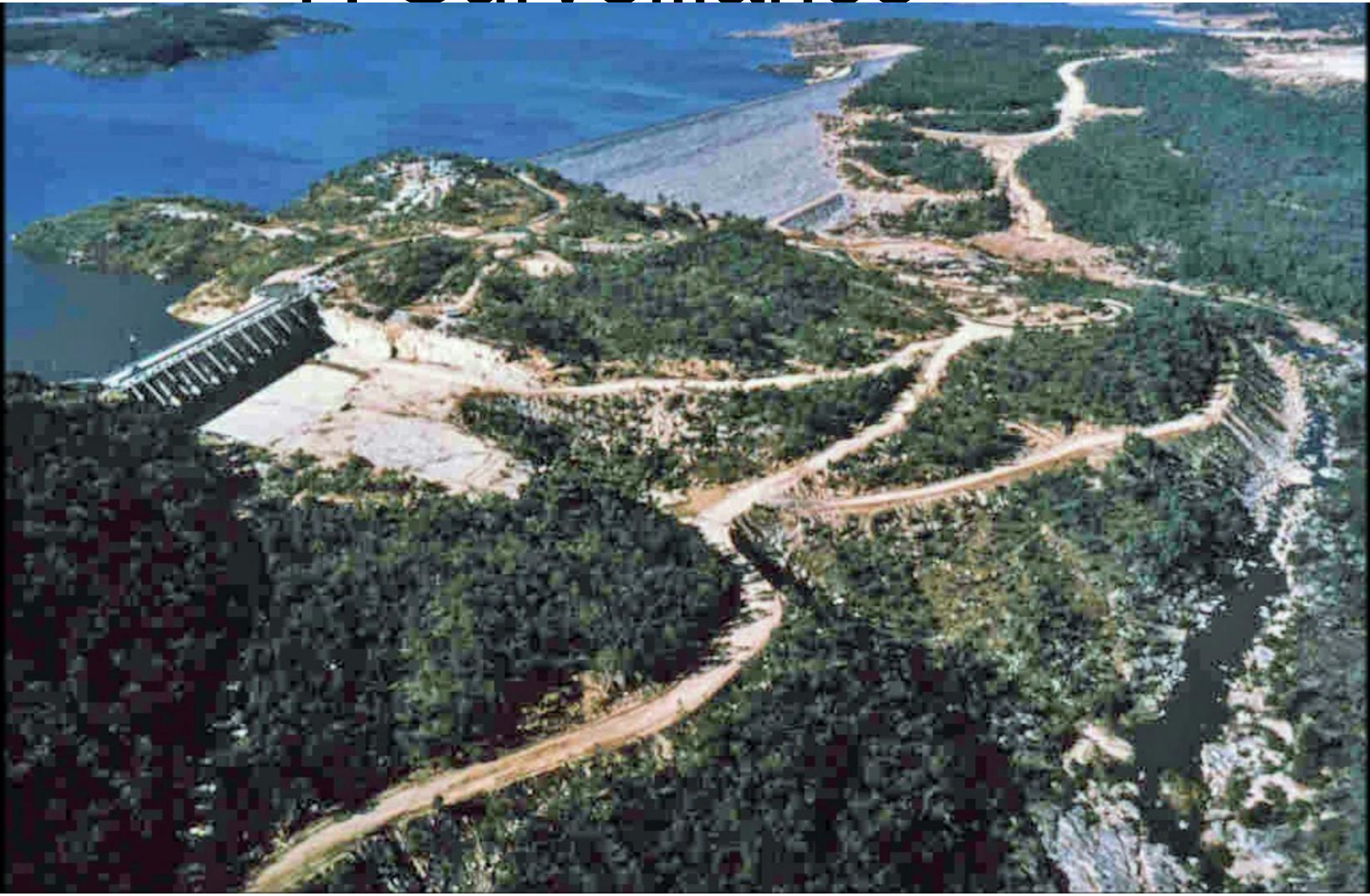
5 & 6. Risk and solutions

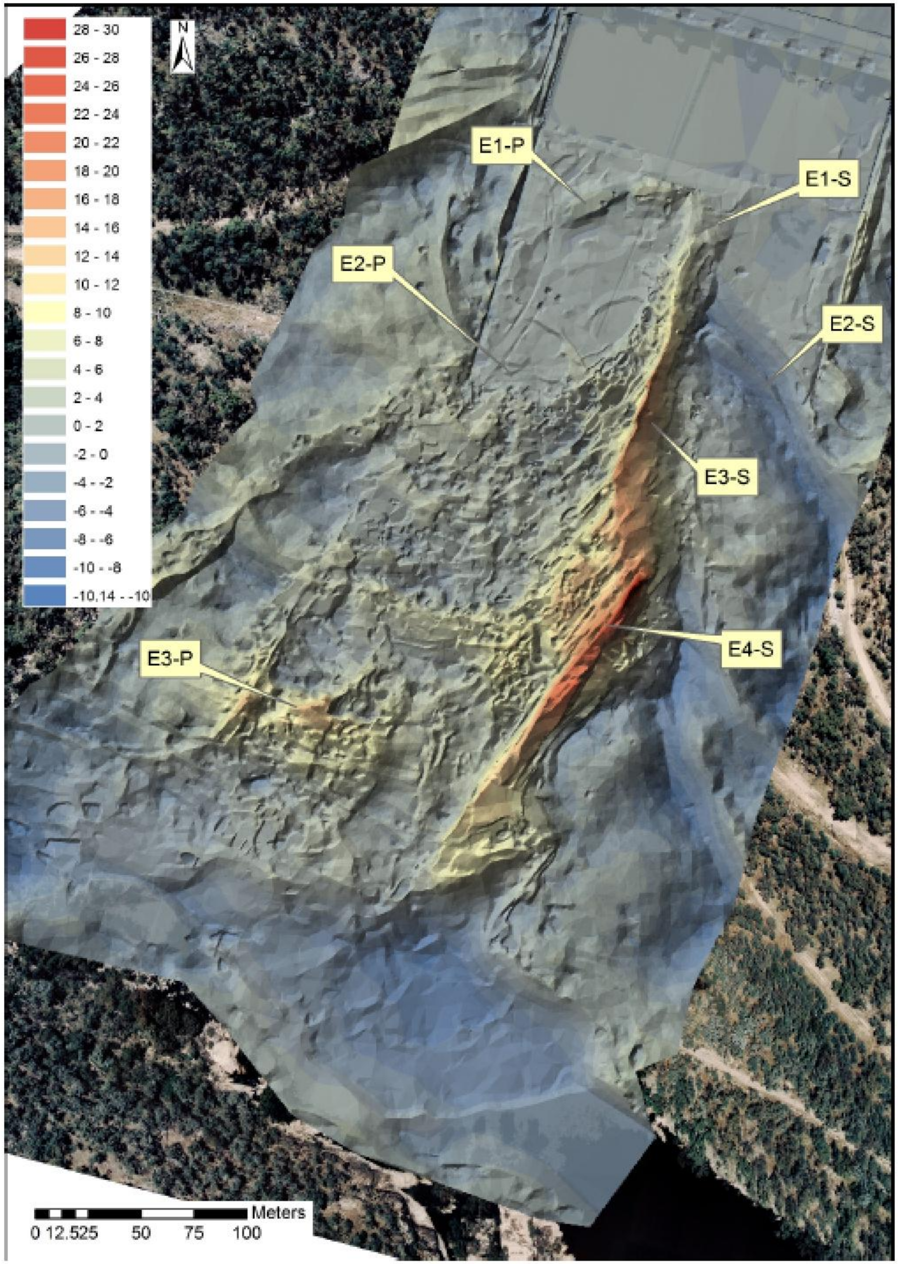


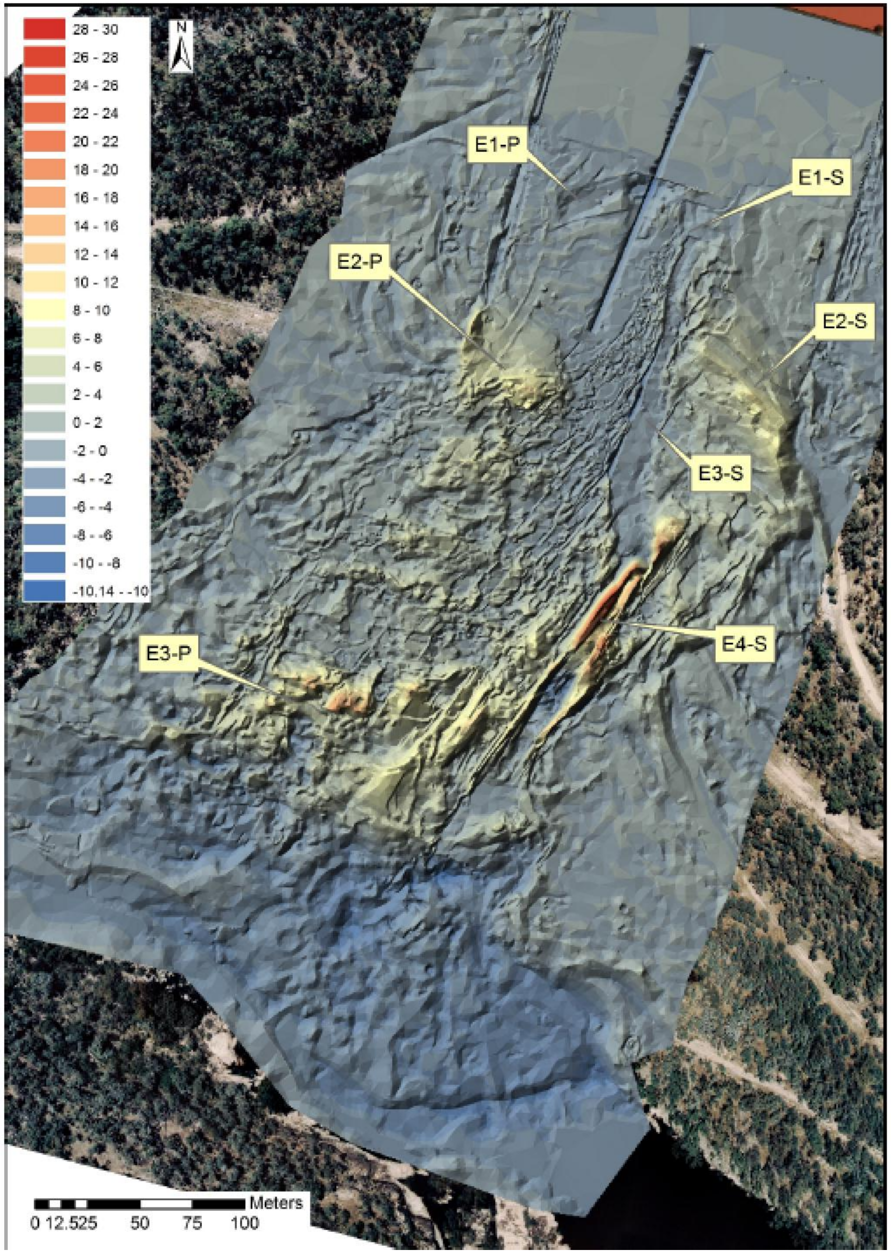
7. Surveillance

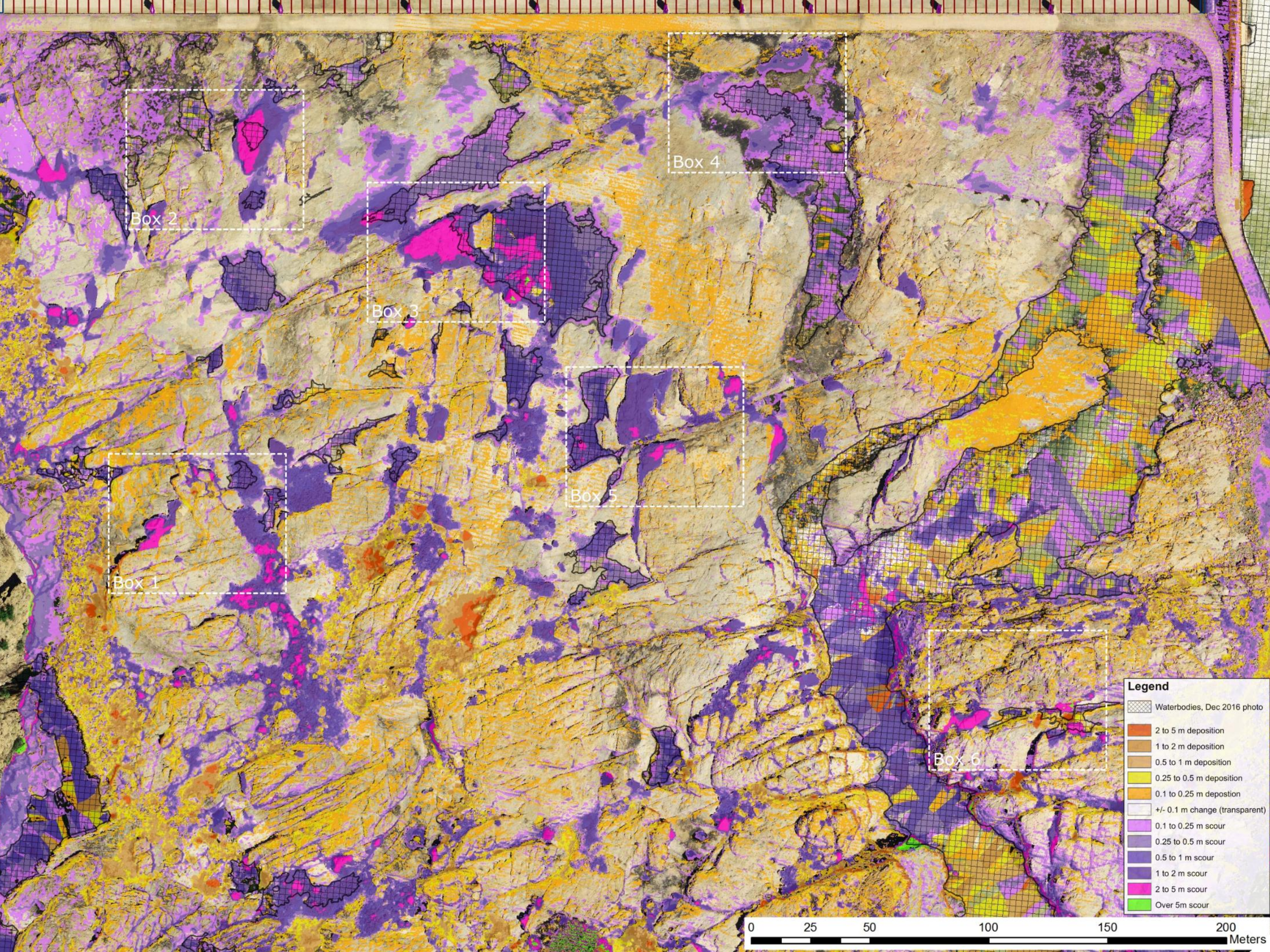


7. Surveillance



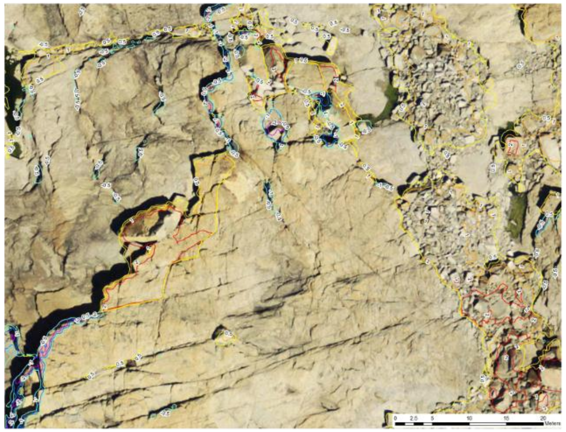

28 - 30
26 - 28
24 - 26
22 - 24
20 - 22
18 - 20
16 - 18
14 - 16
12 - 14
10 - 12
8 - 10
6 - 8
4 - 6
2 - 4
0 - 2
-2 - 0
-4 - -2
-6 - -4
-8 - -6
-10 - -8
-10.14 - -10
N
E1-P
E1-S
E2-P
E2-S
E3-S
E4-S
E3-P
Meters
0 12.525 50 75 100

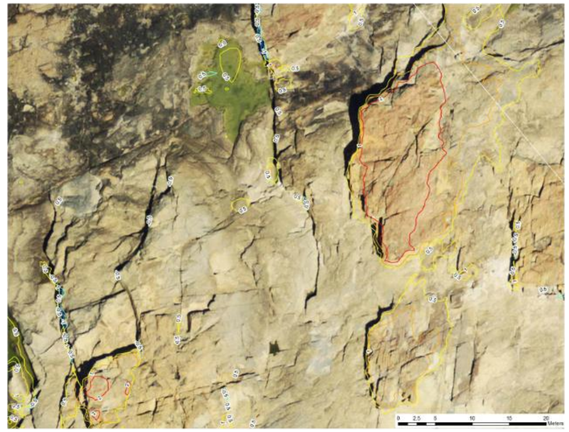

28 - 30
26 - 28
24 - 26
22 - 24
20 - 22
18 - 20
16 - 18
14 - 16
12 - 14
10 - 12
8 - 10
6 - 8
4 - 6
2 - 4
0 - 2
-2 - 0
-4 - -2
-6 - -4
-8 - -6
-10 - -8
-10.14 - -10
N
E1-P
E1-S
E2-P
E2-S
E3-S
E4-S
E3-P
Meters
0 12.525 50 75 100

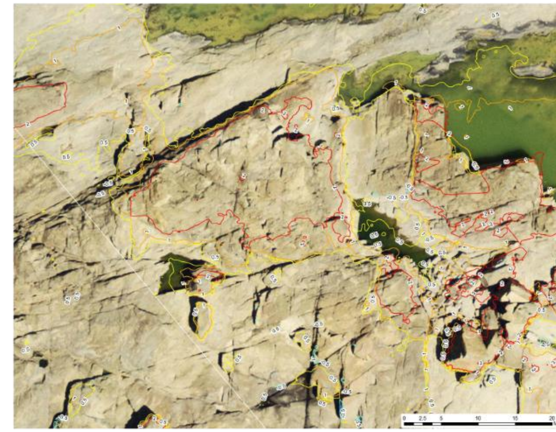


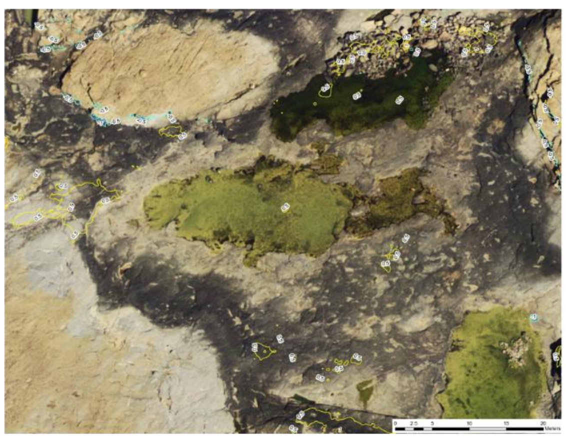
Box 2
Box 4
Box 3
Box 5
Box 1
Box 6
Legend
Waterbodies, Dec 2016 photo
2 to 5 m deposition
1 to 2 m deposition
0.5 to 1 m deposition
0.25 to 0.5 m deposition
0.1 to 0.25 m deposition
+/- 0.1 m change (transparent)
0.1 to 0.25 m scour
0.25 to 0.5 m scour
0.5 to 1 m scour
1 to 2 m scour
2 to 5 m scour
Over 5m scour
0 25 50 100 150 200
Meters

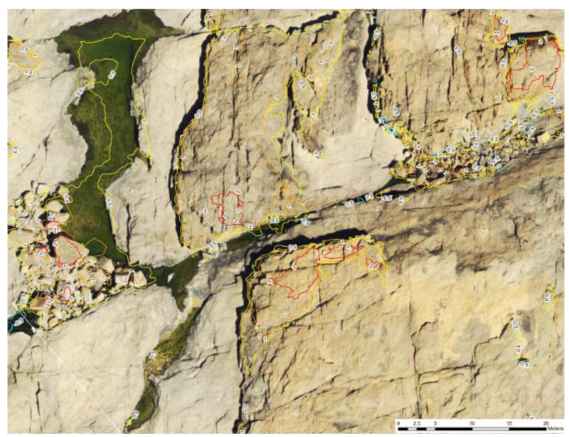
7. Surveillance

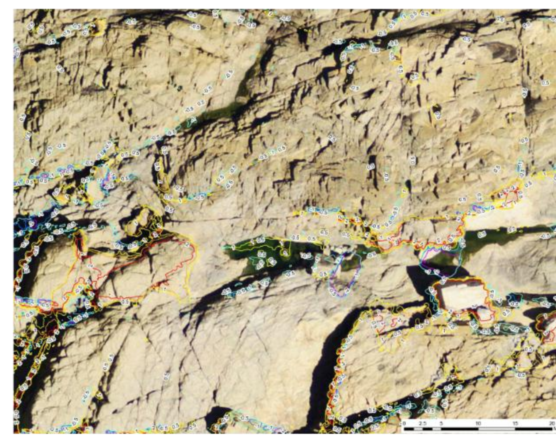

Box 1 2008


Box 2 2008


Box 3 2008


Box 4 2008

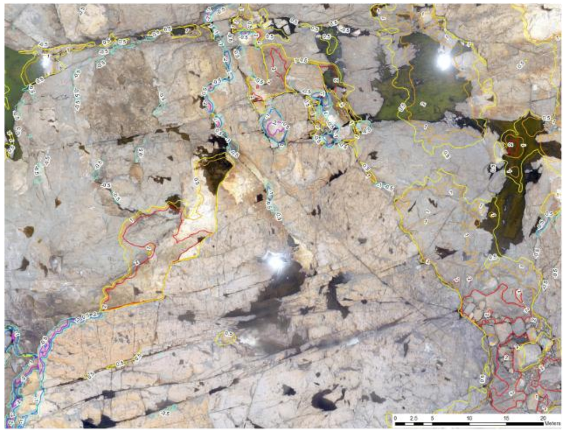

Box 5 2008


Box 6 2008

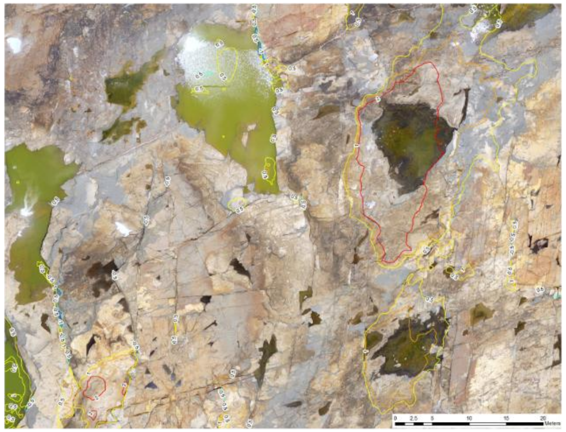
Contours (Dec 2016 minus Sept 2008)

- 2m accretion
- 1m accretion
- 0.5m accretion
- 0.5m erosion
- 1m erosion
- 2m erosion

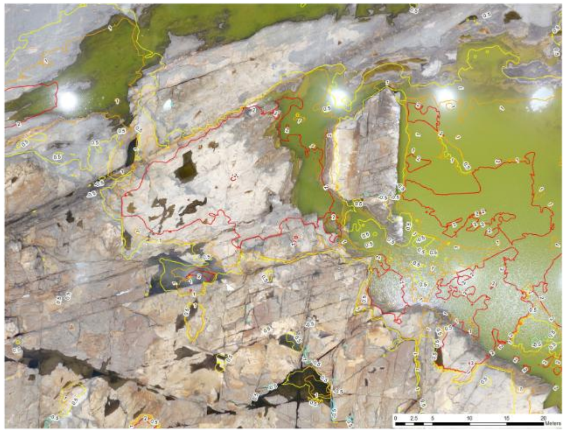
7. Surveillance



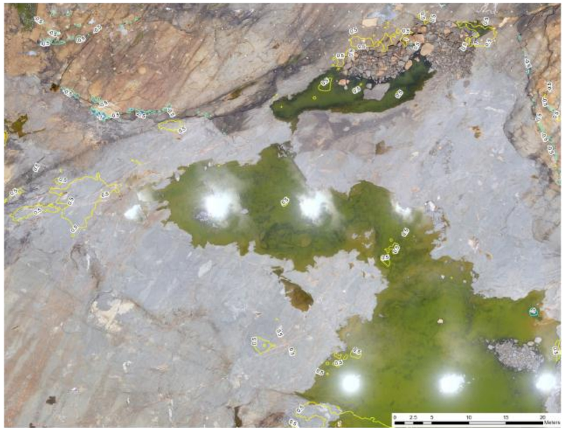
Box 1 2016



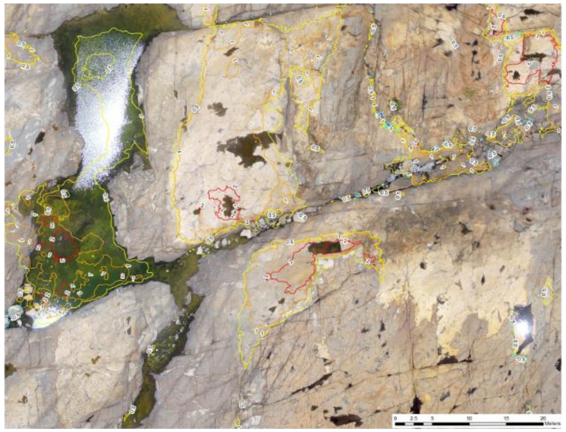
Box 2 2016



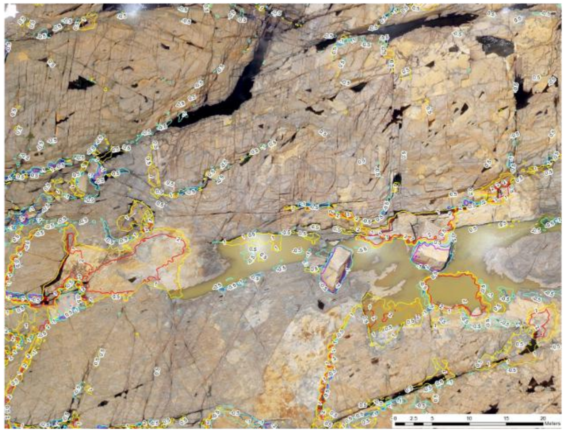
Box 3 2016



Box 4 2016



Box 5 2016



Box 6 2016

Contours (Dec 2016 minus Sept 2008)

- 2m accretion
- 1m accretion
- 0.5m accretion
- 0.5m erosion
- 1m erosion
- 2m erosion

Further research

Further research

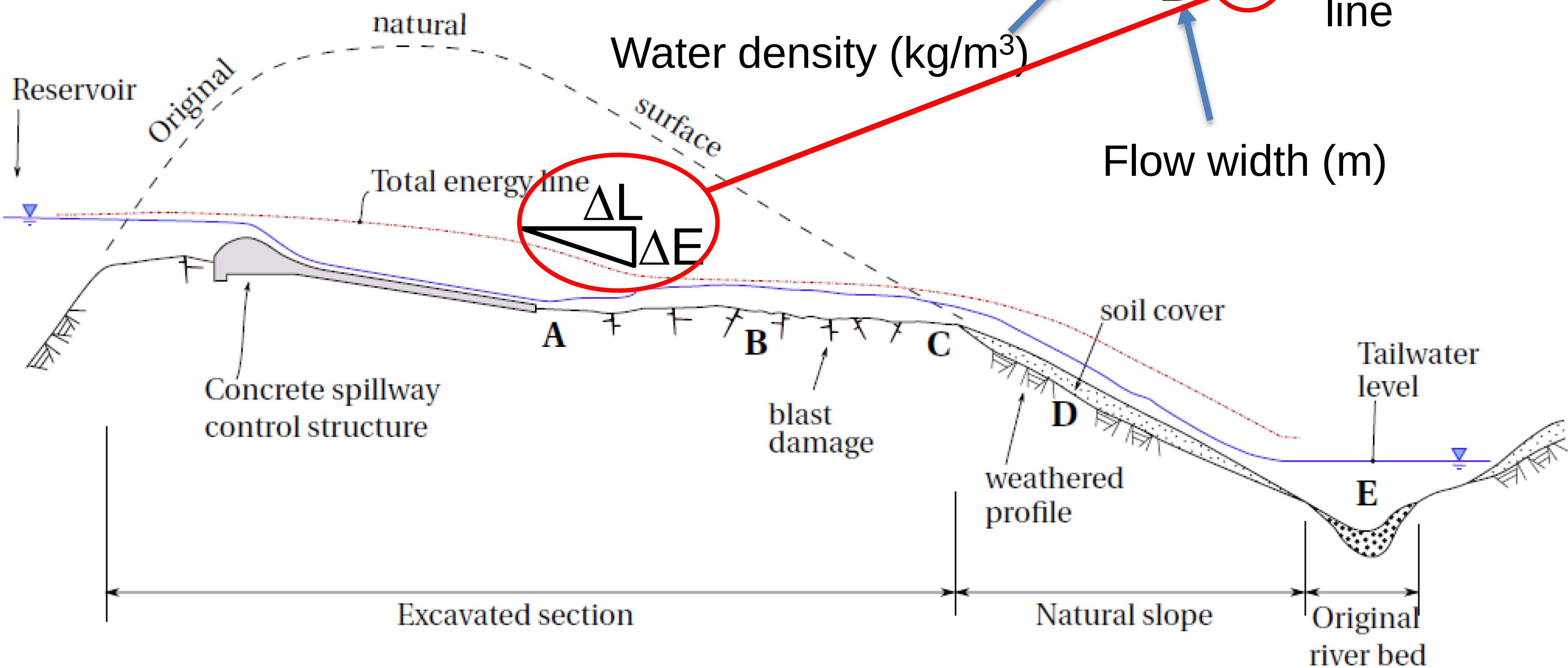
1. UAV surveys
2. Additional laboratory testing
3. Stream power dissipation
4. Coupled numerical modelling of erosion

Further research

Stream power dissipation:

$$\Pi_{UD} = \rho g \frac{Q}{B} s_f$$

- Dissipation of hydraulic power per unit area (Watts/m²) → Π_{UD}
- Gravity (m/s²) → g
- Discharge (m³/s) → Q
- Slope of the total energy line → s_f
- Water density (kg/m³) → ρ
- Flow width (m) → B

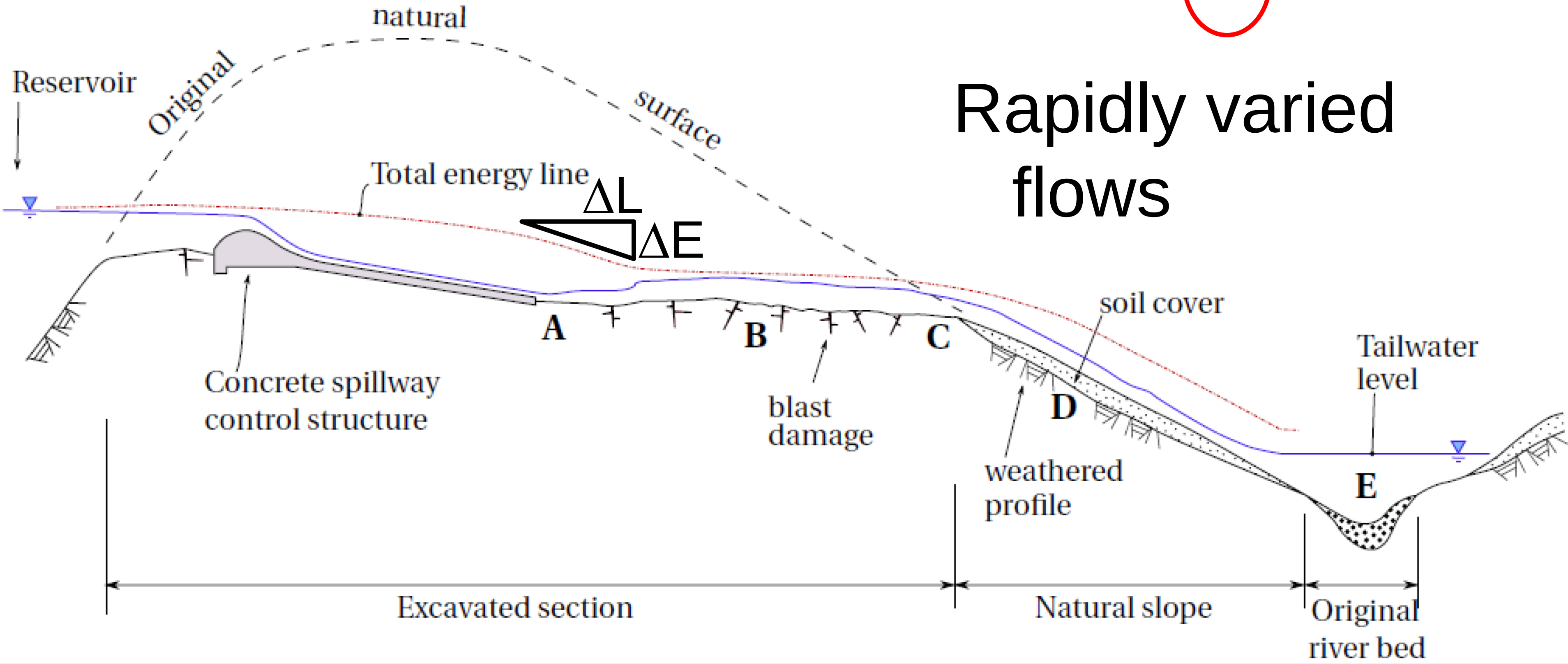


Further research

Stream power dissipation:

$$\Pi_{UD} = \rho g q \frac{\Delta E}{\Delta L}$$

Rapidly varied flows

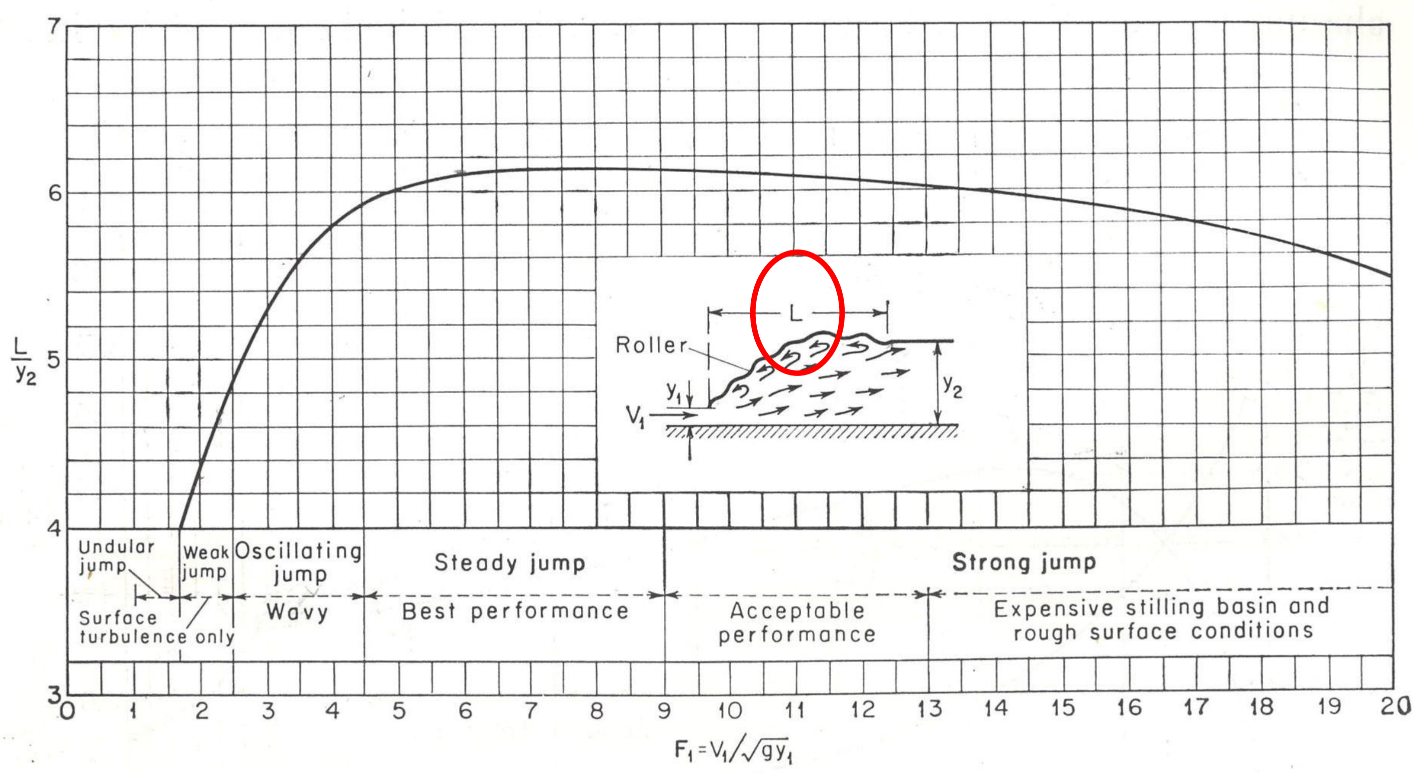


Further research

Stream power dissipation:

Hydraulic jumps

$$\Pi_{UD} = \rho g q \frac{\Delta E}{\Delta L}$$

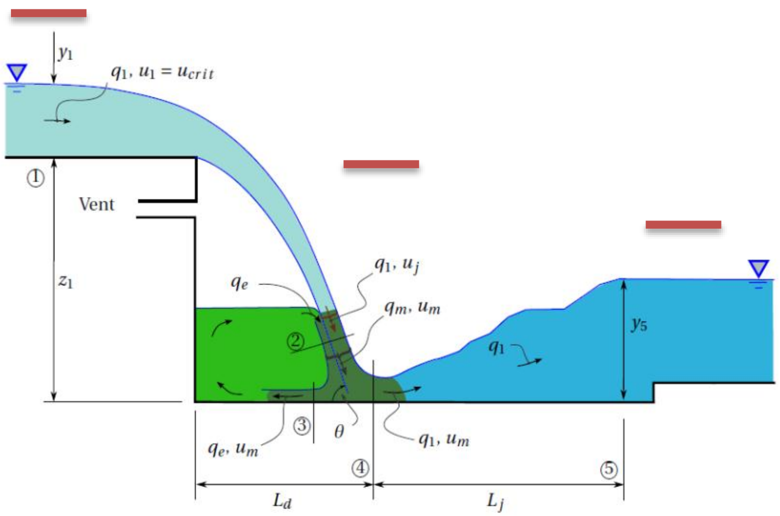


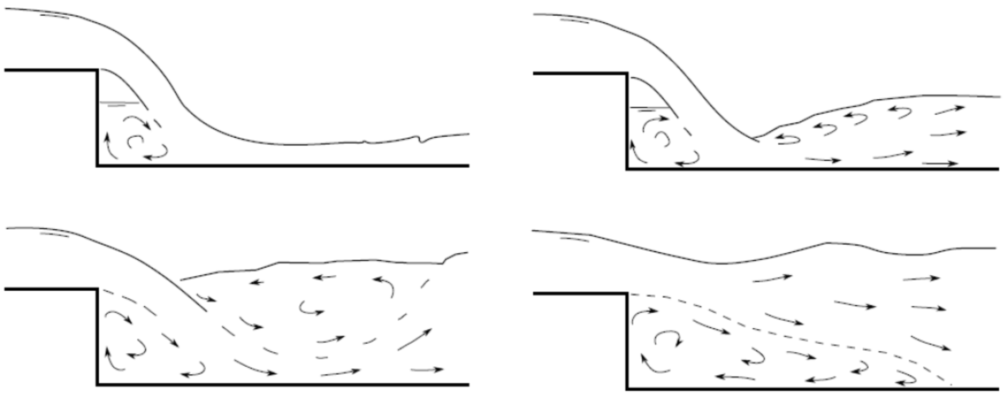
Further research

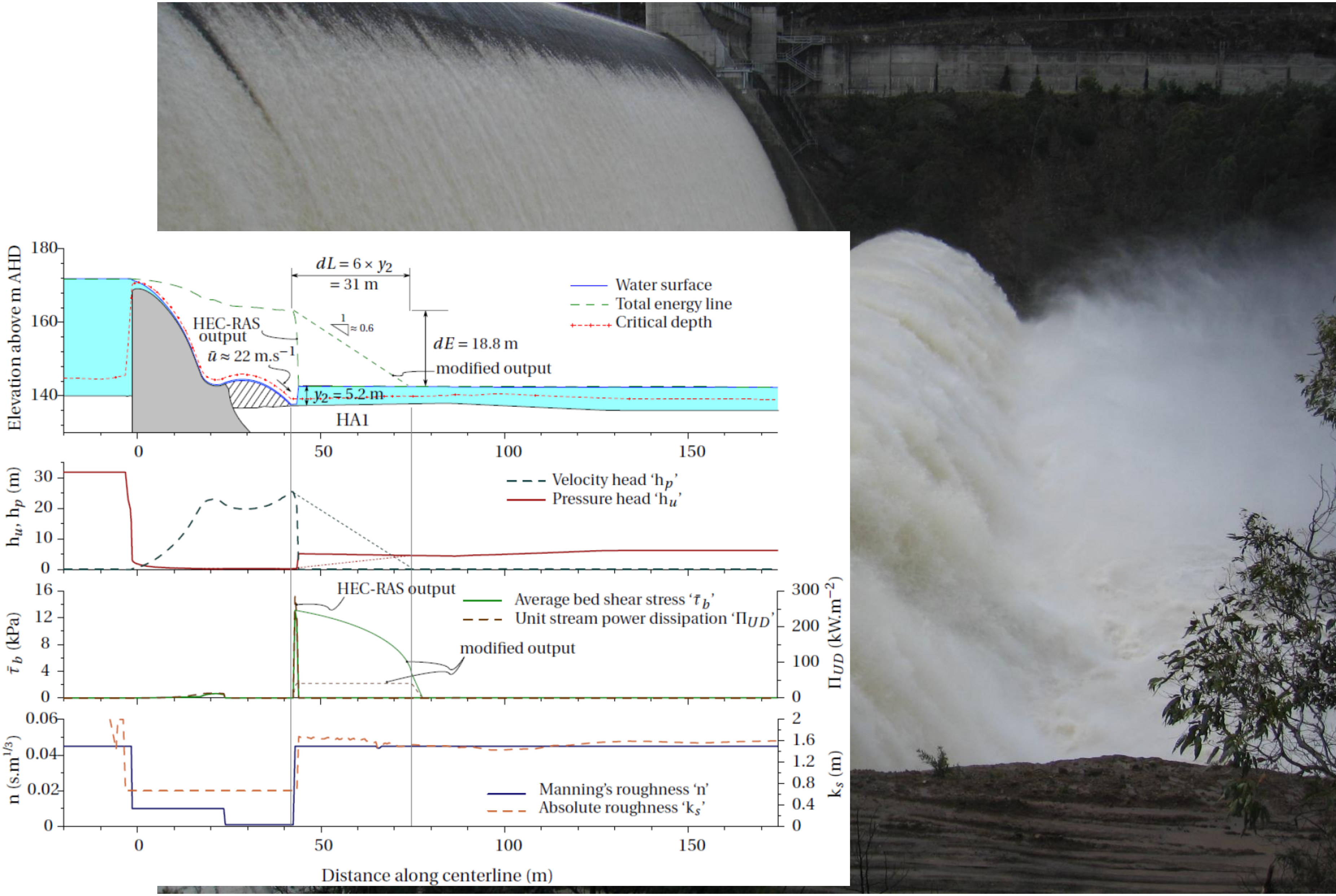
Stream power dissipation:

Drop structures

$$\Pi_{UD} = \rho g q \frac{\Delta E}{\Delta L}$$







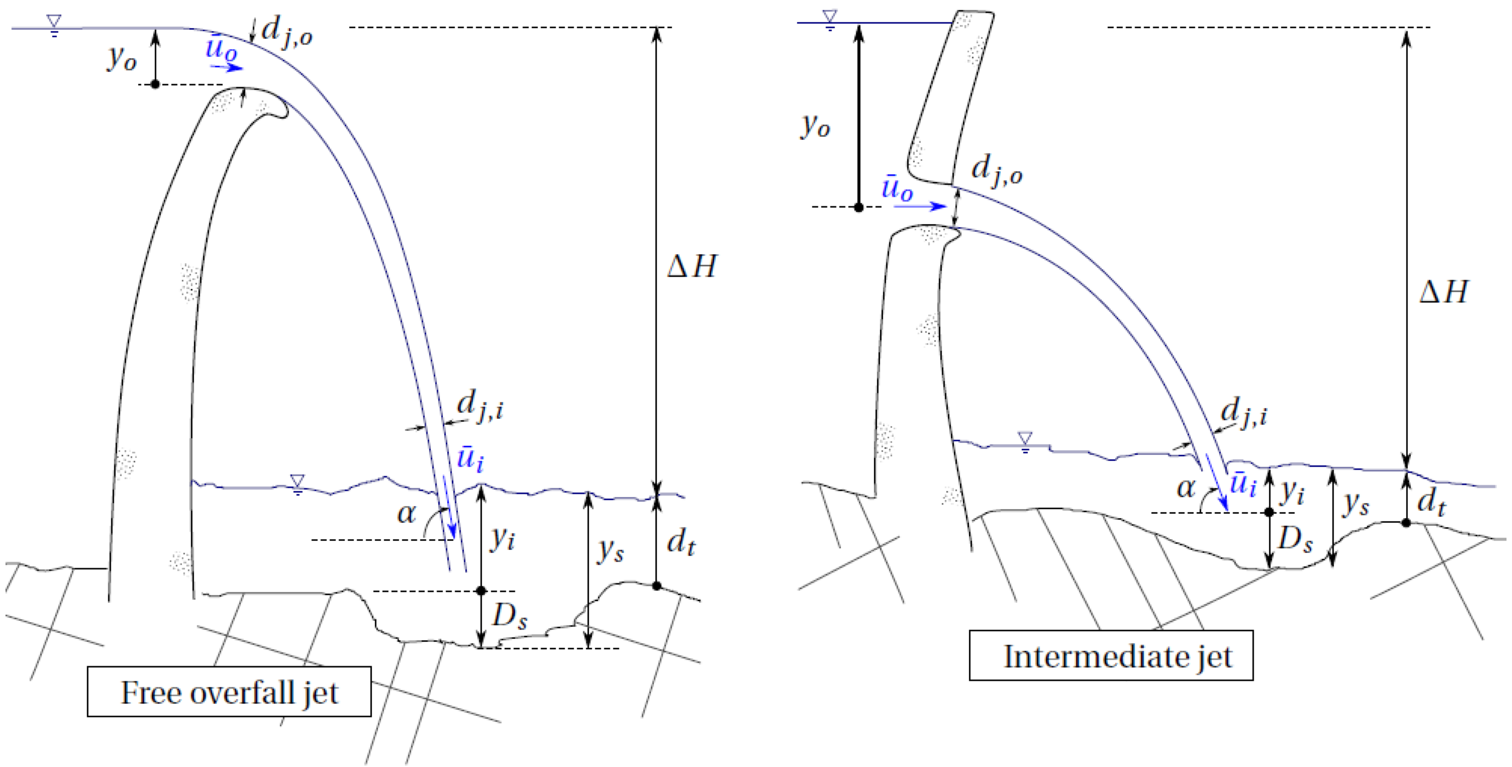
Elevation above m AHD
dL = 6 × y2
= 31 m
Water surface
Total energy line
Critical depth
HEC-RAS
output
ū ≈ 22 m.s−1
dE = 18.8 m
modified output
y2 = 5.2 m
HA1
hu, hp (m)
Velocity head 'hp'
Pressure head 'hu'
τ̄b (kPa)
HEC-RAS output
Average bed shear stress 'τ̄b'
Unit stream power dissipation 'ΠUD'
modified output
ΠUD (kW.m−2)
n (s.m1/3)
Manning's roughness 'n'
Absolute roughness 'ks'
ks (m)
Distance along centerline (m)

Further research

Stream power dissipation:

Plunging flows

$$\Pi_{UD} = \rho g q \frac{\Delta E}{\Delta L}$$

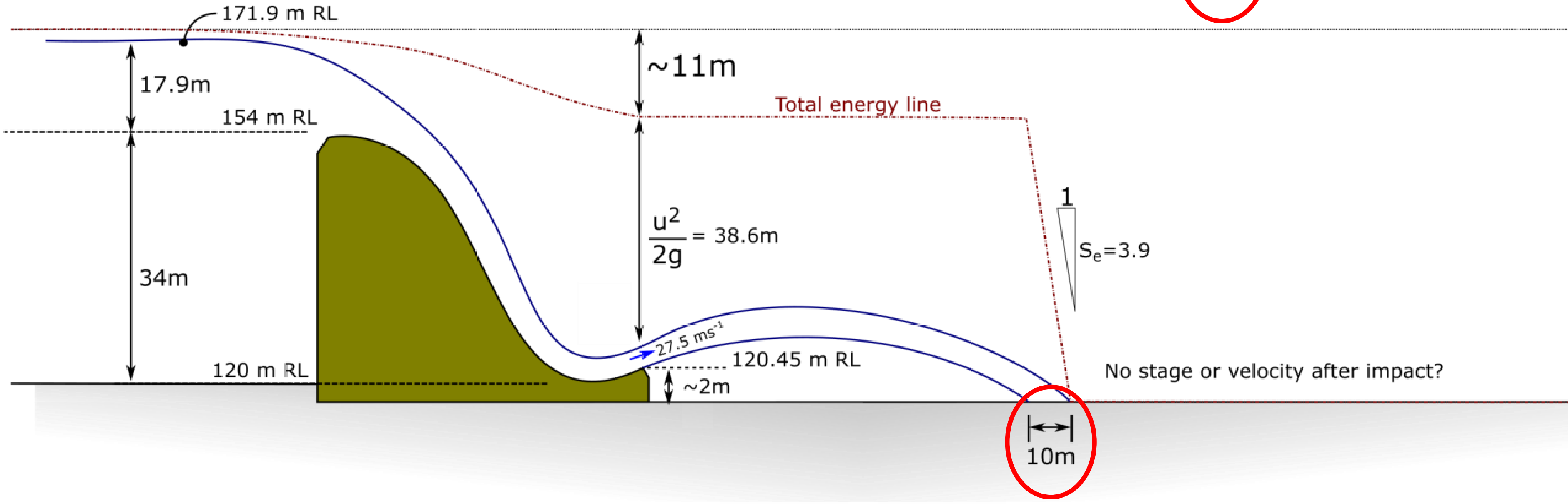


Further research

Stream power dissipation:

Plunging flows

$$\Pi_{UD} = \rho g q \frac{\Delta E}{\Delta L}$$

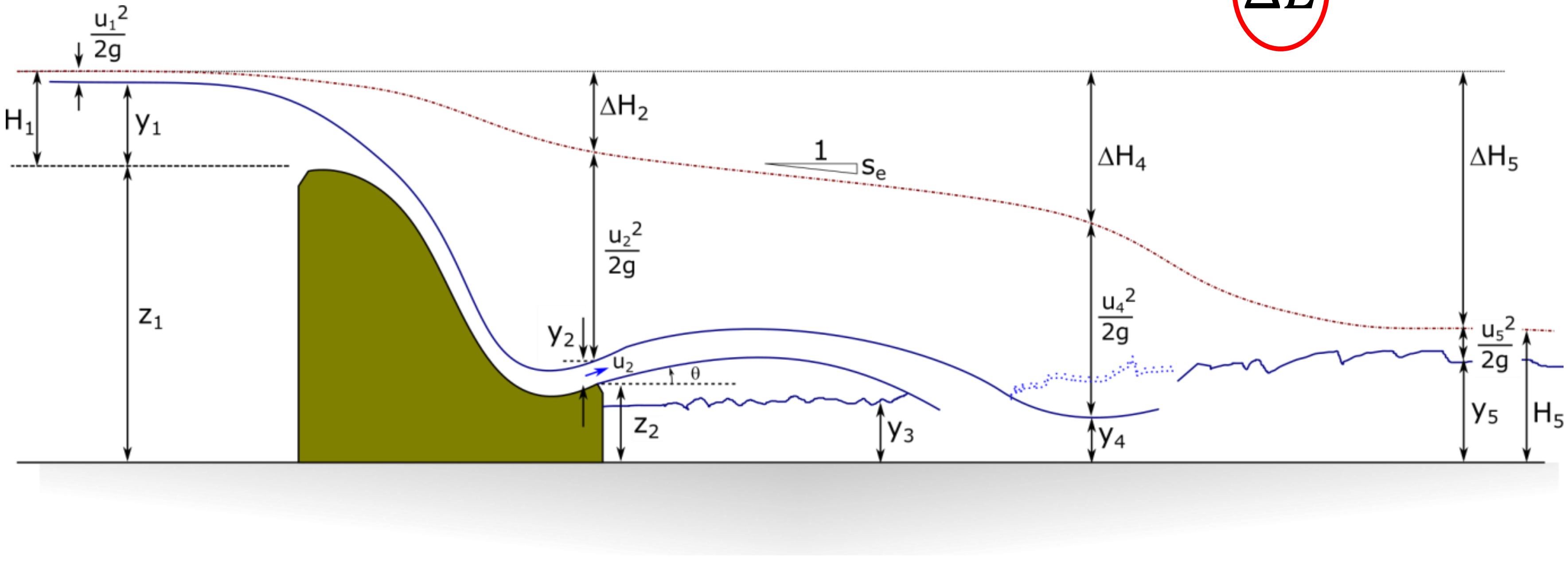


Further research

Stream power dissipation:

Plunging flows

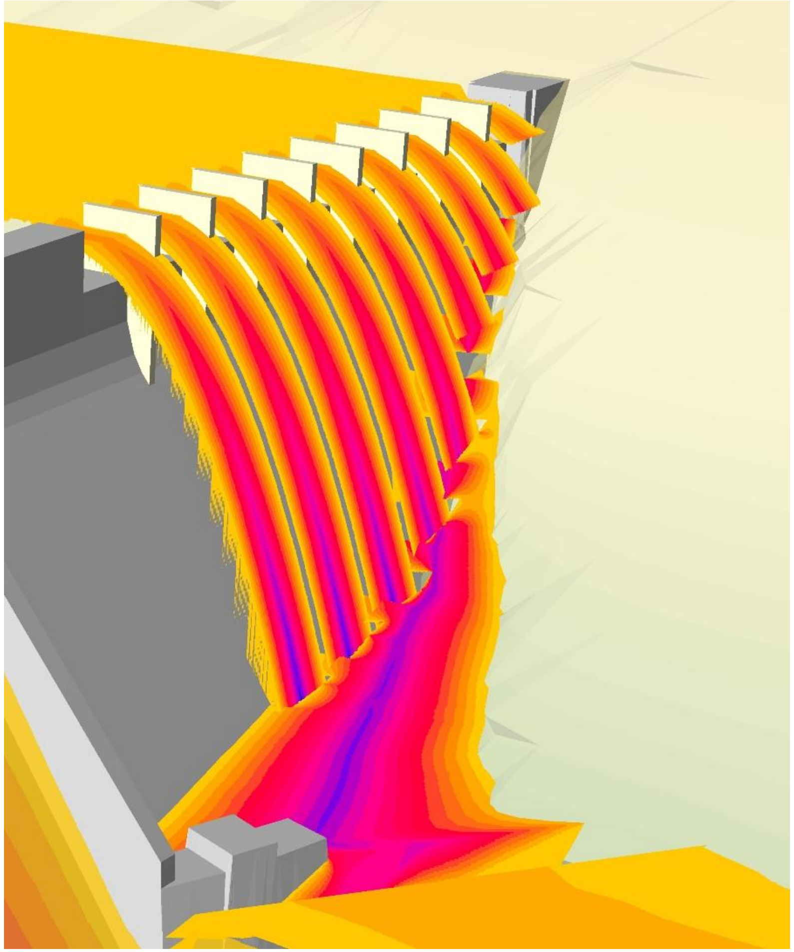
$$\Pi_{UD} = \rho g q \frac{\Delta E}{\Delta L}$$



Further research

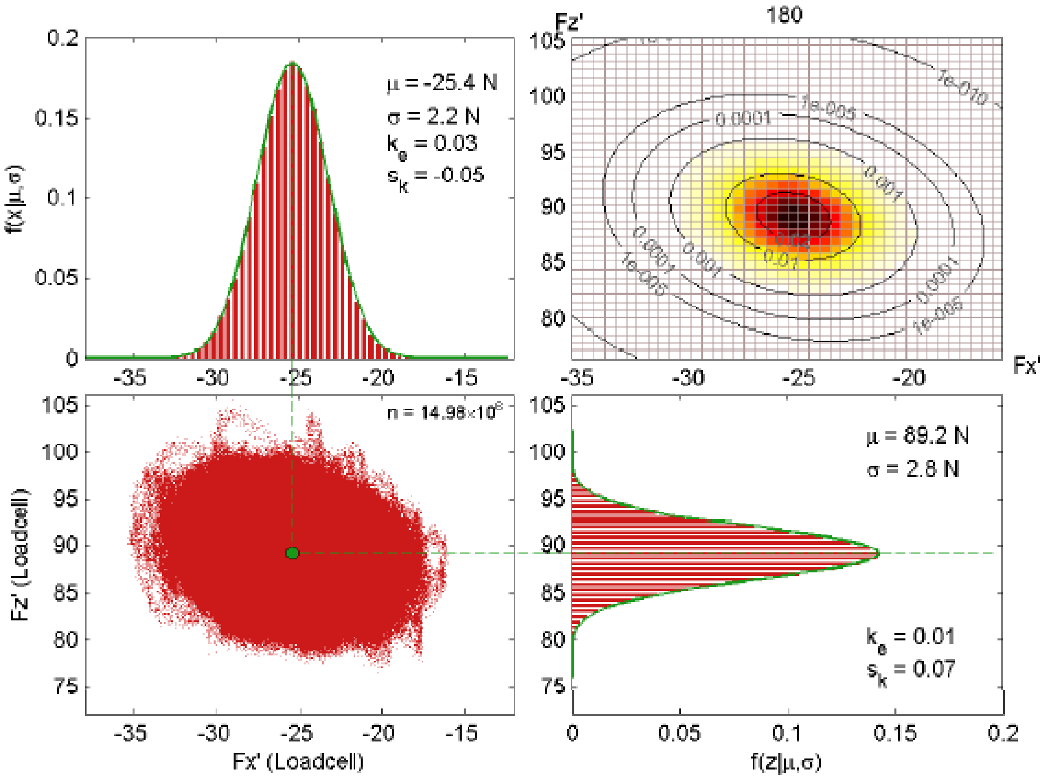
Stream power dissipation:

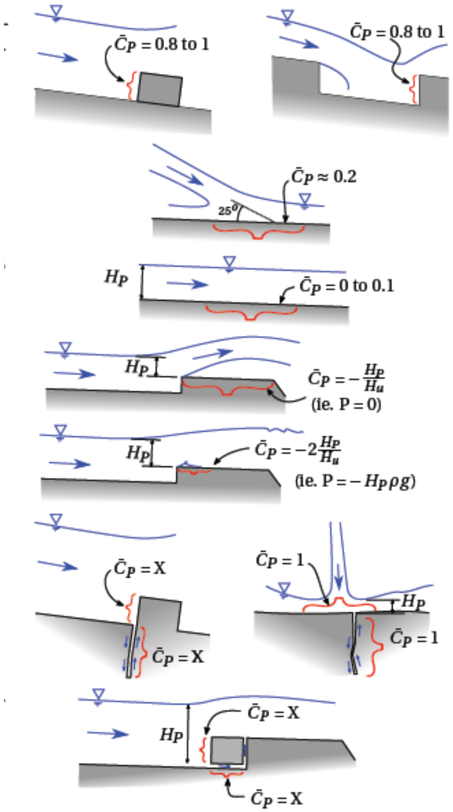
Plunging flows

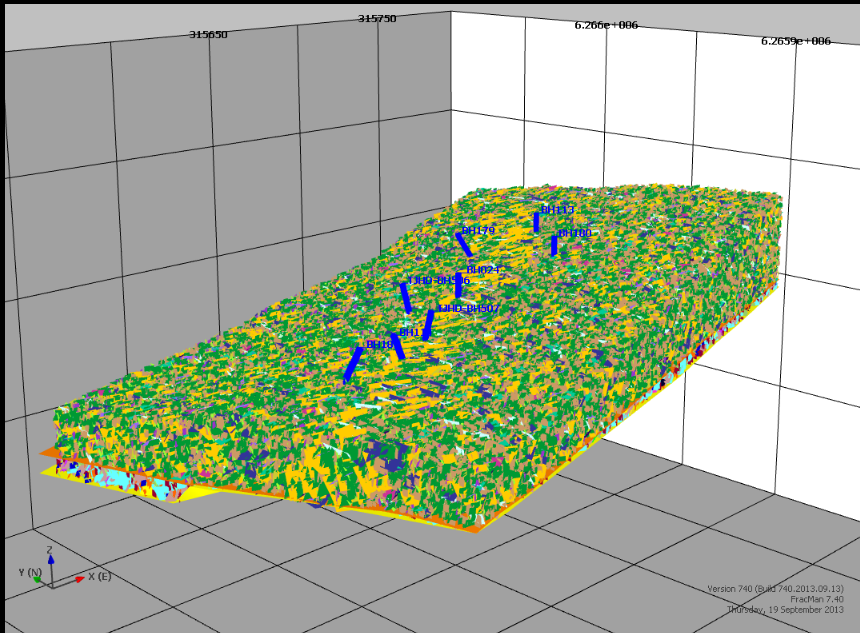


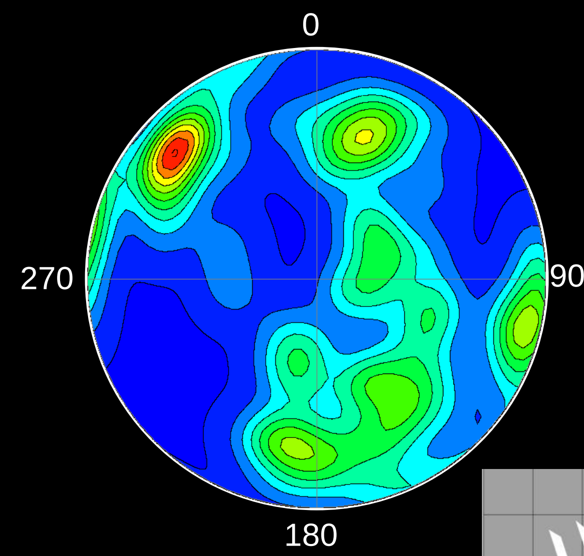
Further research

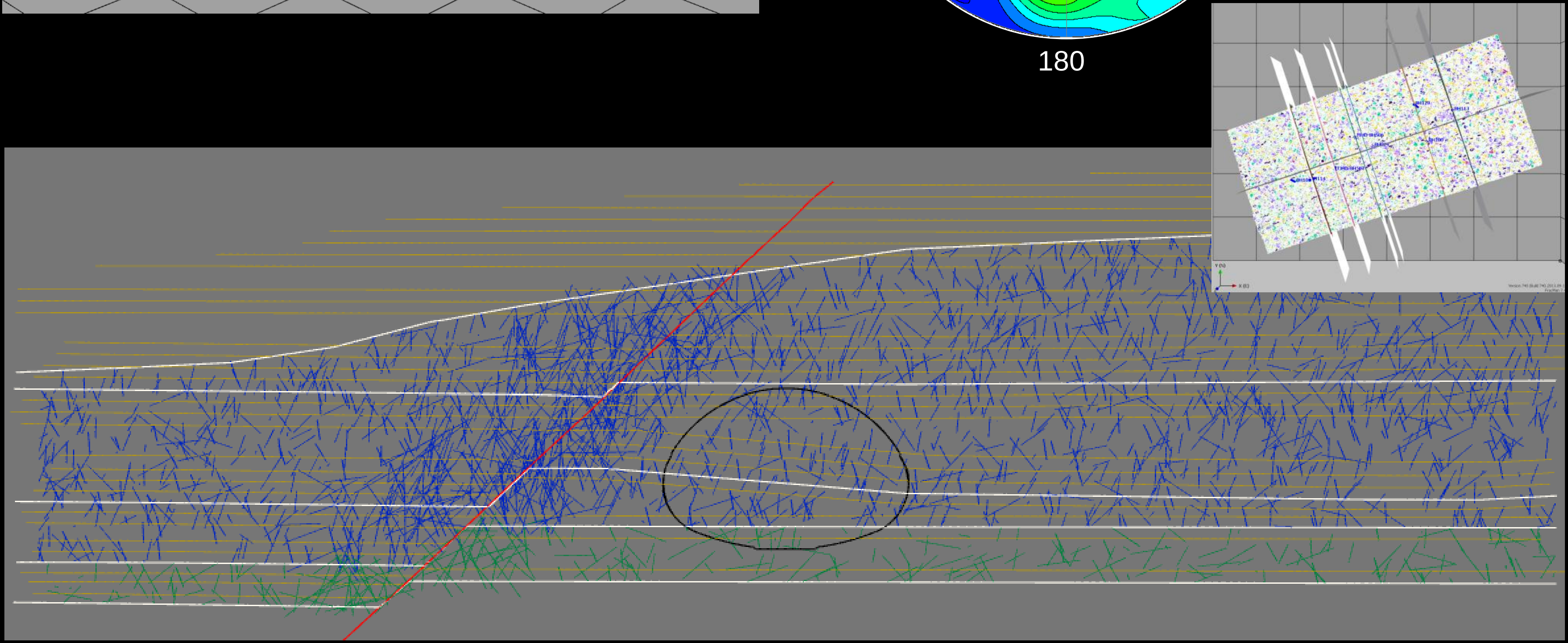
Coupled numerical modelling



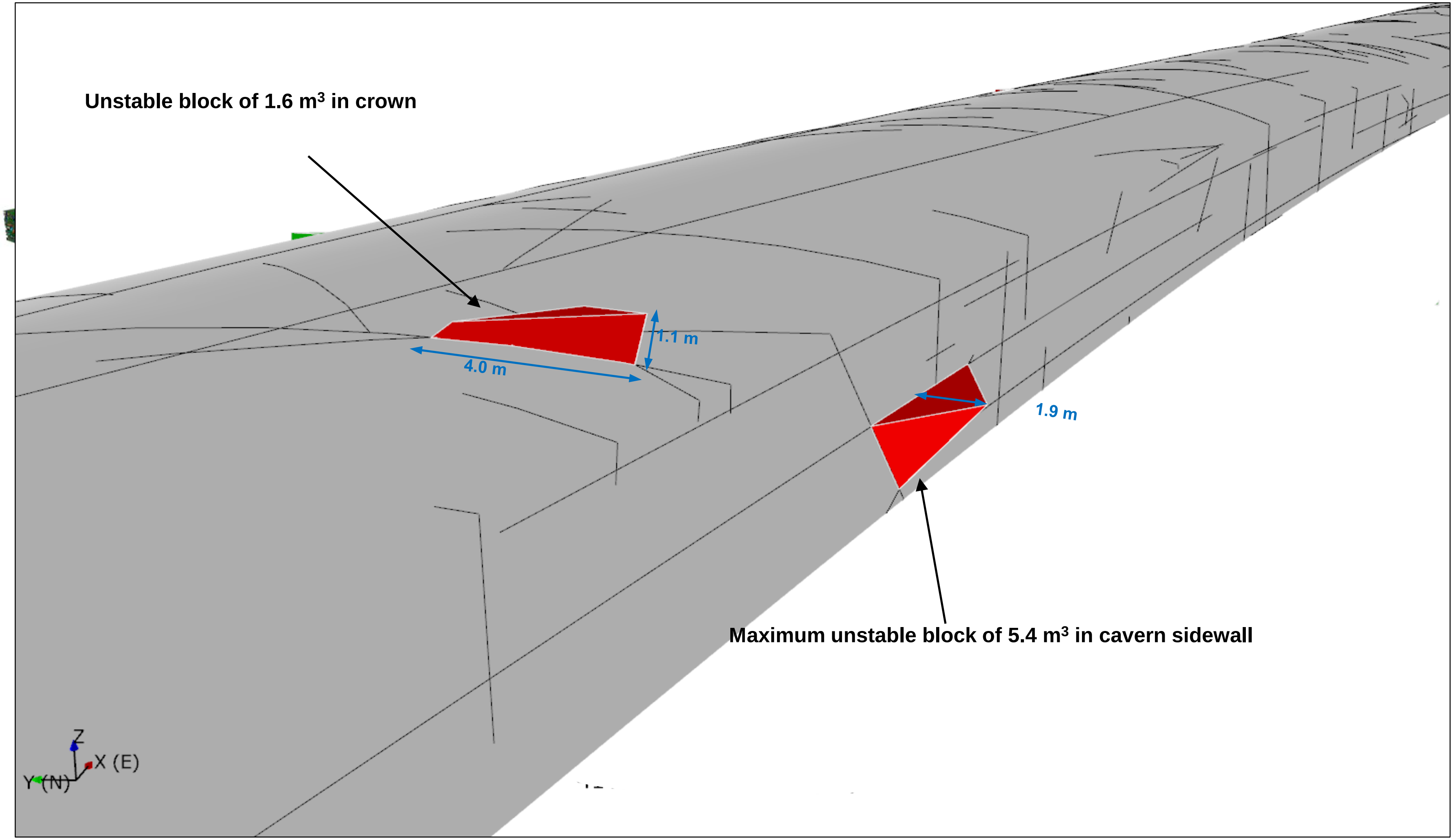


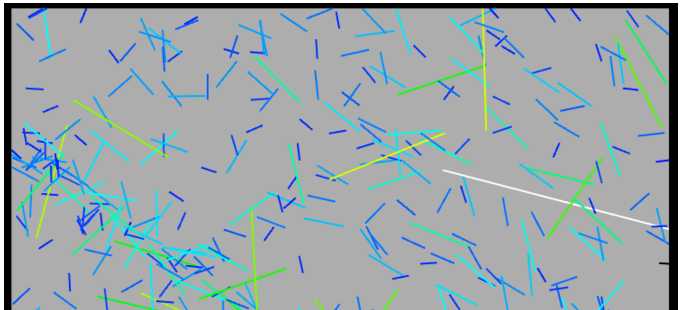

315650
315750
6.266e+006
6.2659e+006
BH113
BH179
BH180
BH024
TJHD-BH507
Z
Y (N)
X (E)
Version 740 (Build 740.2013.09.13)
FracMan 7.40
Thursday, 19 September 2013

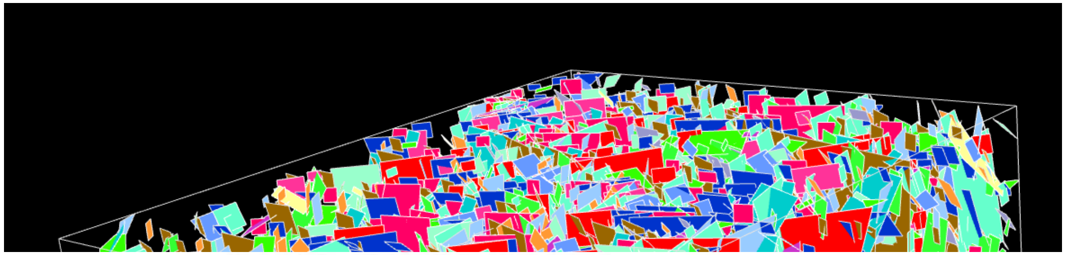

0
90
180
270

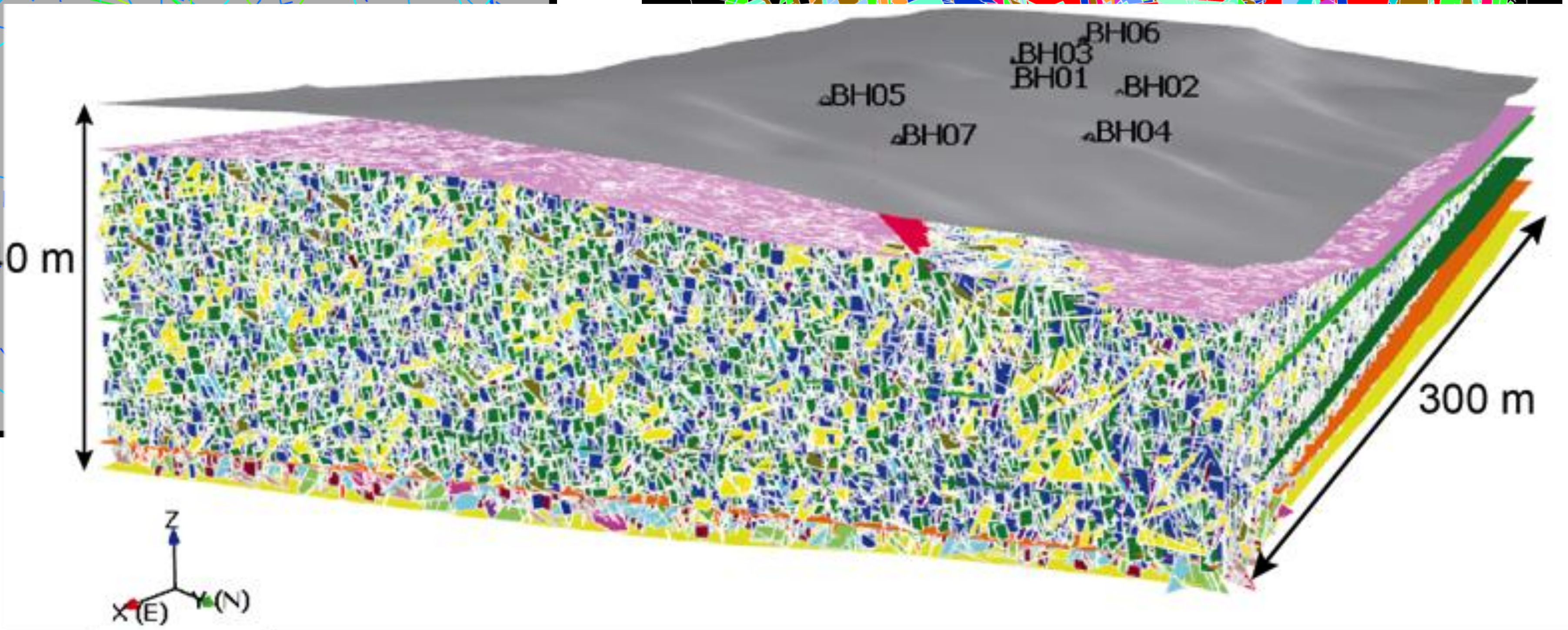


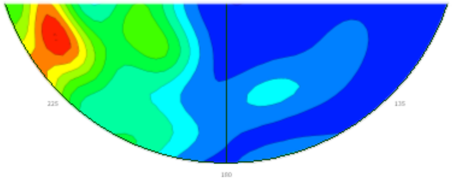
Rock Wedge Analysis



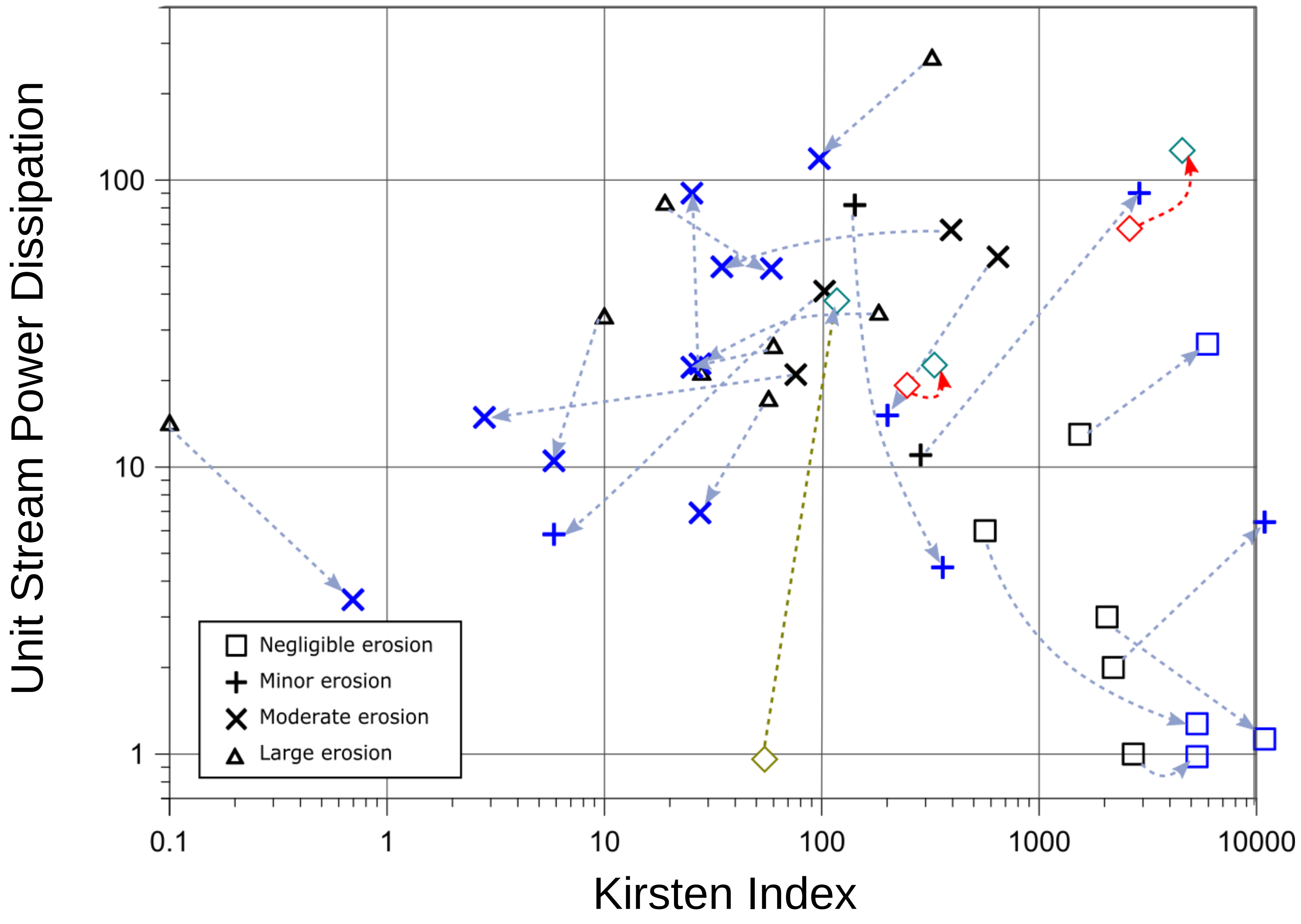





BH06
BH03
BH01
BH02
BH05
BH07
BH04
40 m
300 m
Z
X (E)
Y (N)



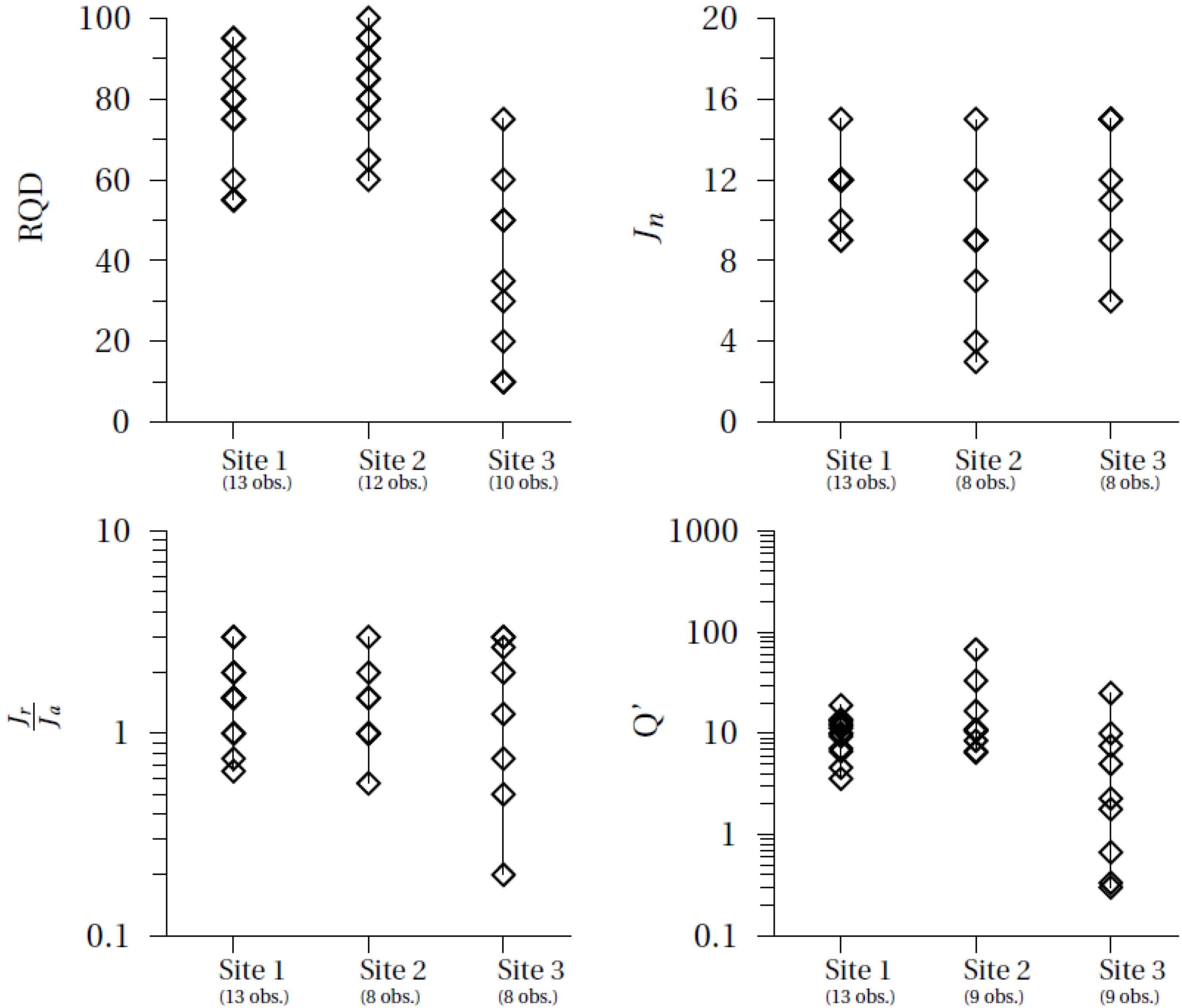
Questions?


Unit Stream Power Dissipation
100
10
1
0.1
1
10
100
1000
10000
Kirsten Index
Negligible erosion
Minor erosion
Moderate erosion
Large erosion

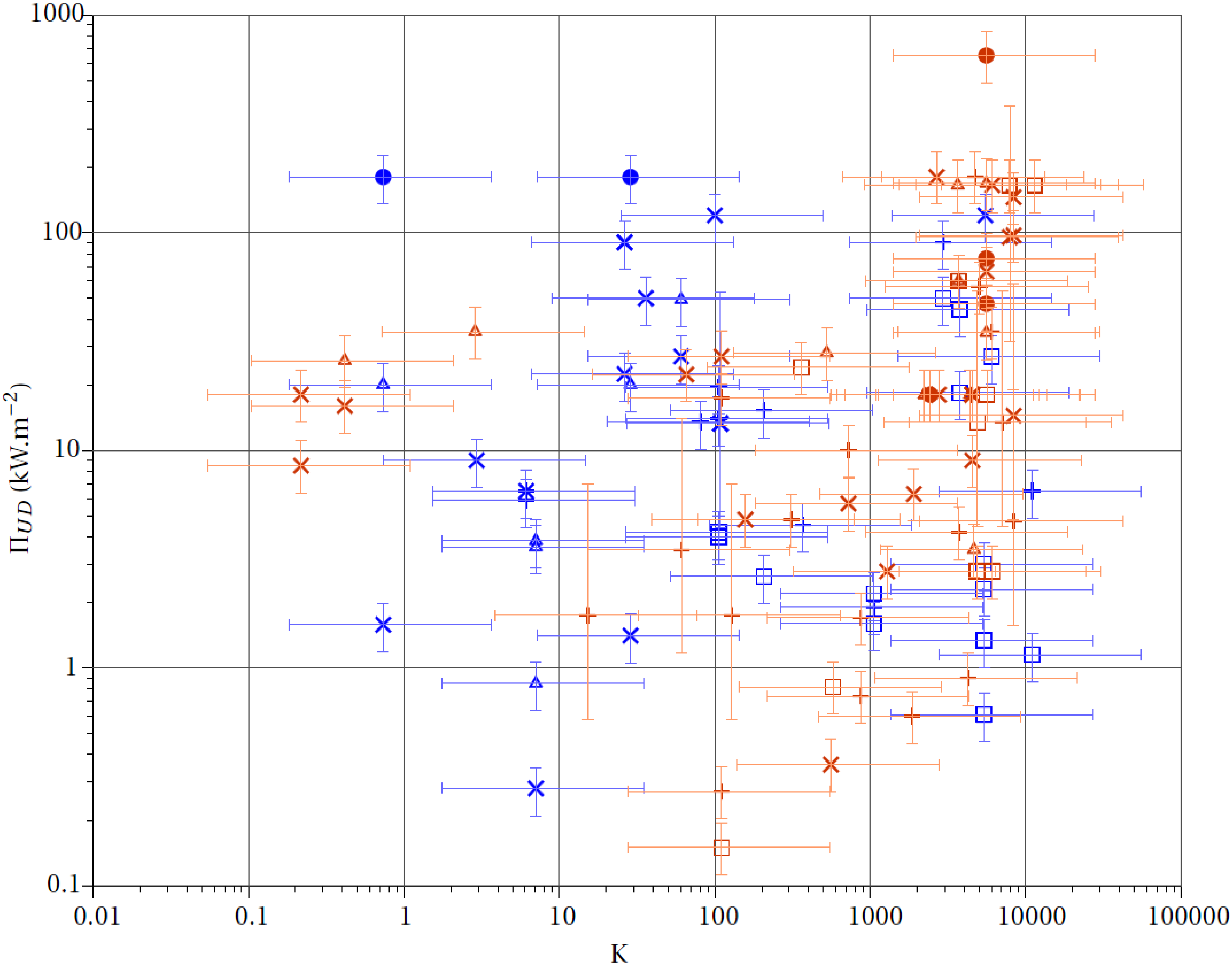
Subjectivity in interpretation of Rock Mass Indices ...

A 'blind test'

Golder Associates –	1 person
University of NSW -	1
Douglas Partners -	2
AECOM -	1
URS -	1
Pells Consulting -	2
PSM	5

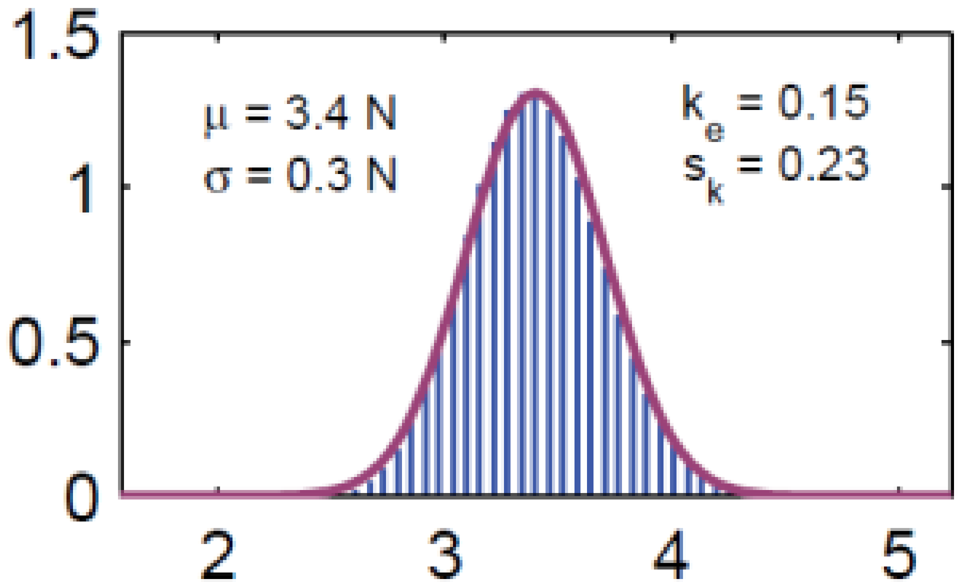


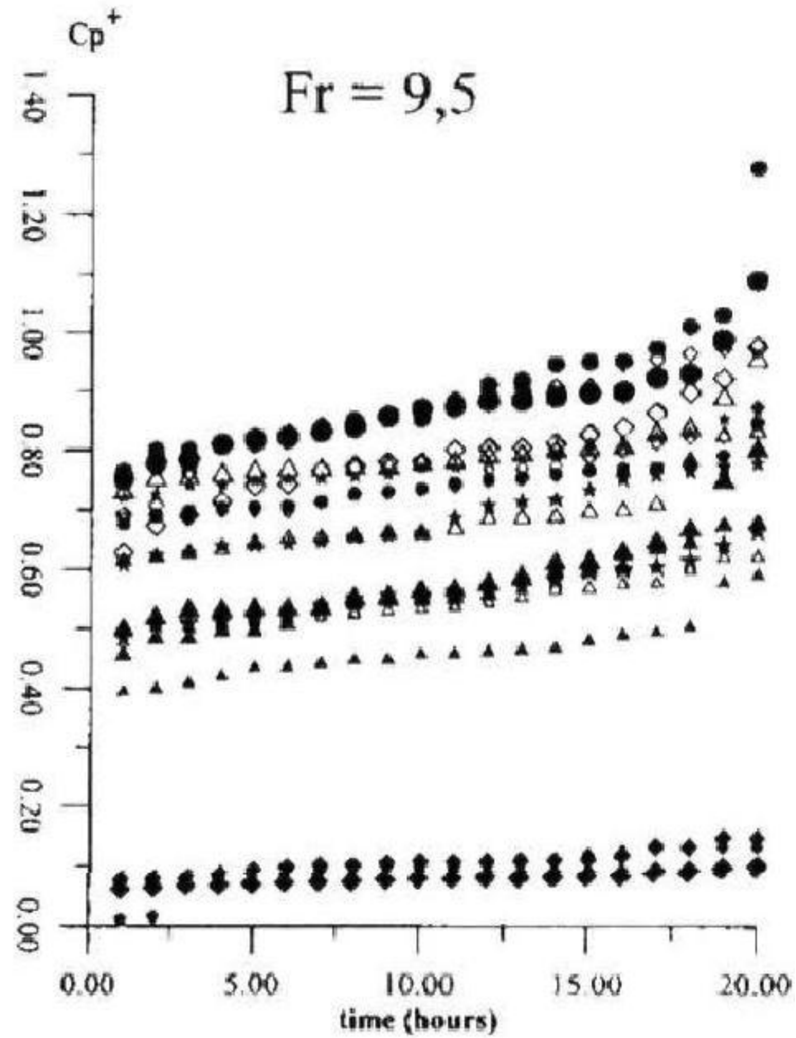
RQD
100
80
60
40
20
0
Site 1 (13 obs.)
Site 2 (12 obs.)
Site 3 (10 obs.)
J_n
20
16
12
8
4
0
Site 1 (13 obs.)
Site 2 (8 obs.)
Site 3 (8 obs.)
$\frac{J_r}{J_a}$
10
1
0.1
Site 1 (13 obs.)
Site 2 (8 obs.)
Site 3 (8 obs.)
Q'
1000
100
10
1
0.1
Site 1 (13 obs.)
Site 2 (9 obs.)
Site 3 (9 obs.)



1000
100
10
1
0.1
Π_{UD} (kW.m^{-2})
0.01
0.1
1
10
100
1000
10000
100000
K

Peak pressure?





Armenio et al. (2000))

Peak pressure?

eg:

$$C_{p,max}$$

Probability of a certain pressure …

eg:

$$P(p = x) = \frac{1}{\sqrt{2\pi}\sigma_p} e^{-(x-\bar{P})^2/(2\sigma_p{}^2)}$$

$$(\bar{C}_p,\ C_{p,\sigma})$$

Considering statistics allows to assess time of erosion