

ANCOLD MASTERCLASS
Darling Harbour, Sydney, 26 October 2022

EROSION OF UNLINED SPILLWAYS

Where is it all at?

Steven Pells

1.0 INTRODUCTION

1.1 Case examples

Googong Dam, Australia



After construction



1.0 INTRODUCTION

1.1 Case examples

Googong Dam, Australia



Spillway after initial operation.



1.0 INTRODUCTION

1.1 Case examples

Googong Dam, Australia

remediation



1.0 INTRODUCTION

1.1 Case examples

Googong Dam, Australia

... more remediation



1.0 INTRODUCTION

1.1 Case examples

Copeton Dam, Australia

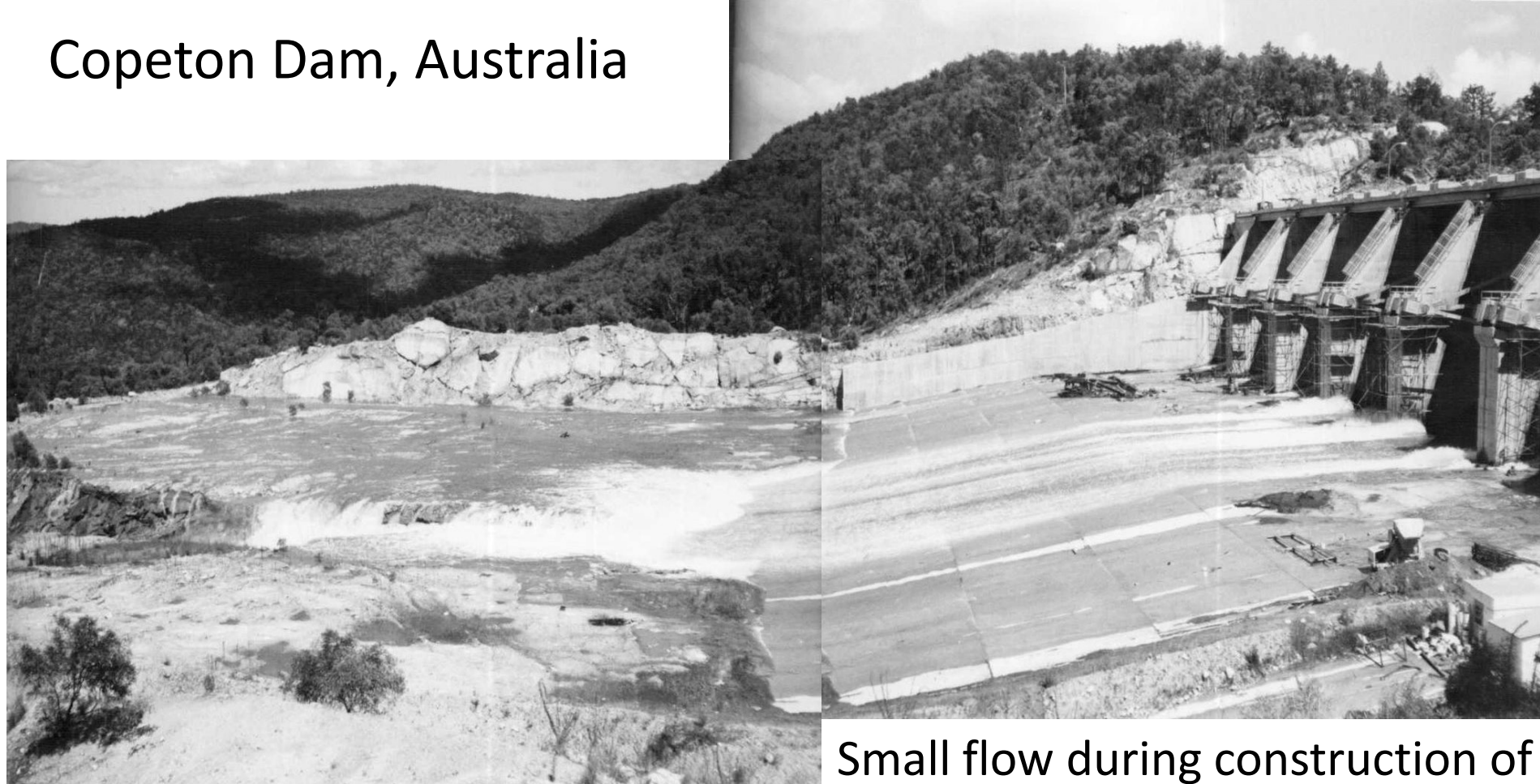
After construction



1.0 INTRODUCTION

1.1 Case examples

Copeton Dam, Australia



Small flow during construction of gates $\sim 200\text{m}^3/\text{s}$
(Design flood $\sim 15000\text{ m}^3/\text{s}$)



1.0 INTRODUCTION

1.1 Case examples

Copeton Dam
Australia



1.0 INTRODUCTION

1.1 Case examples



1.0 INTRODUCTION

1.1 Case examples

Regional NSW



1.0 INTRODUCTION

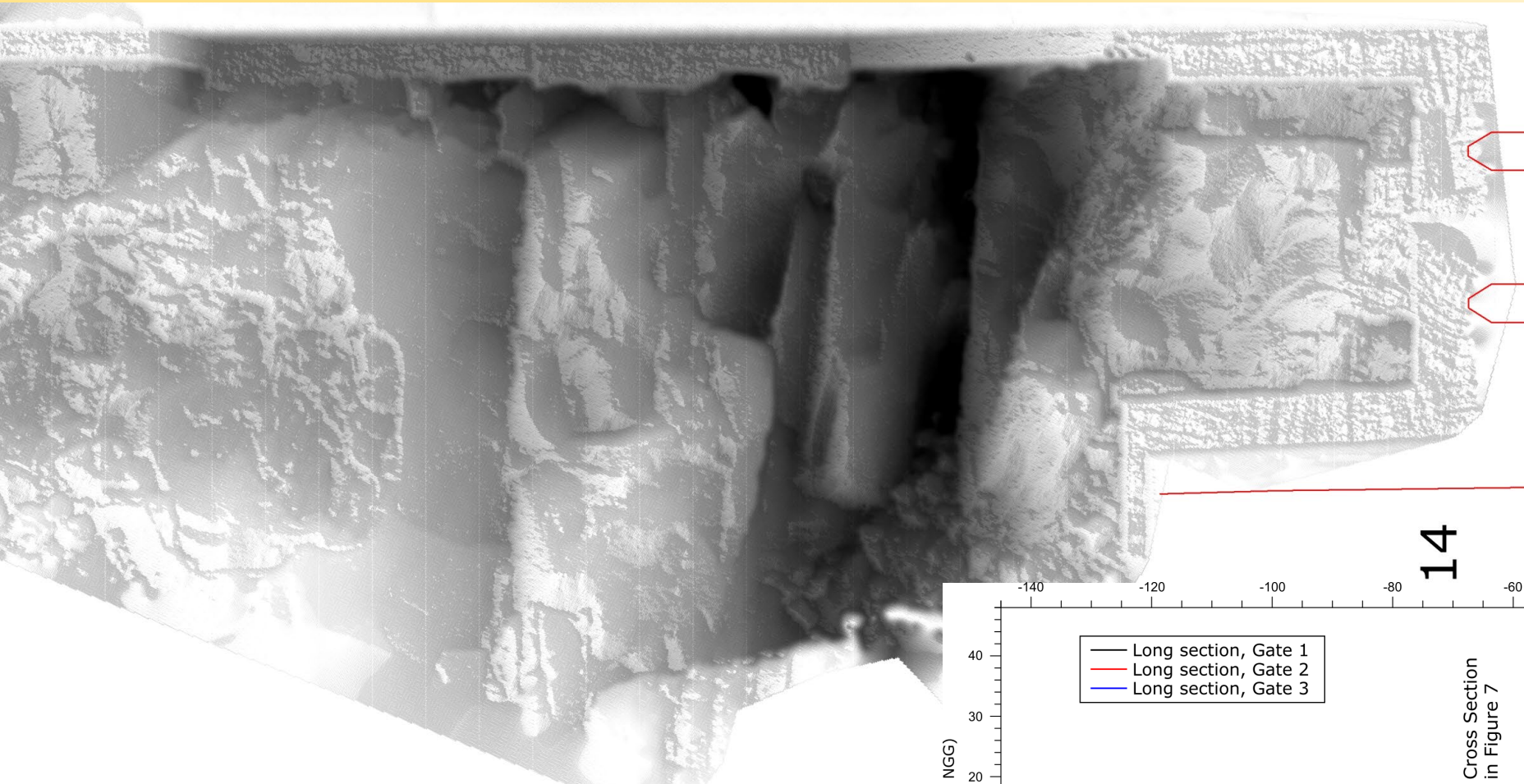
1.1 Case examples

Petit-Saut Dam, French Guiana

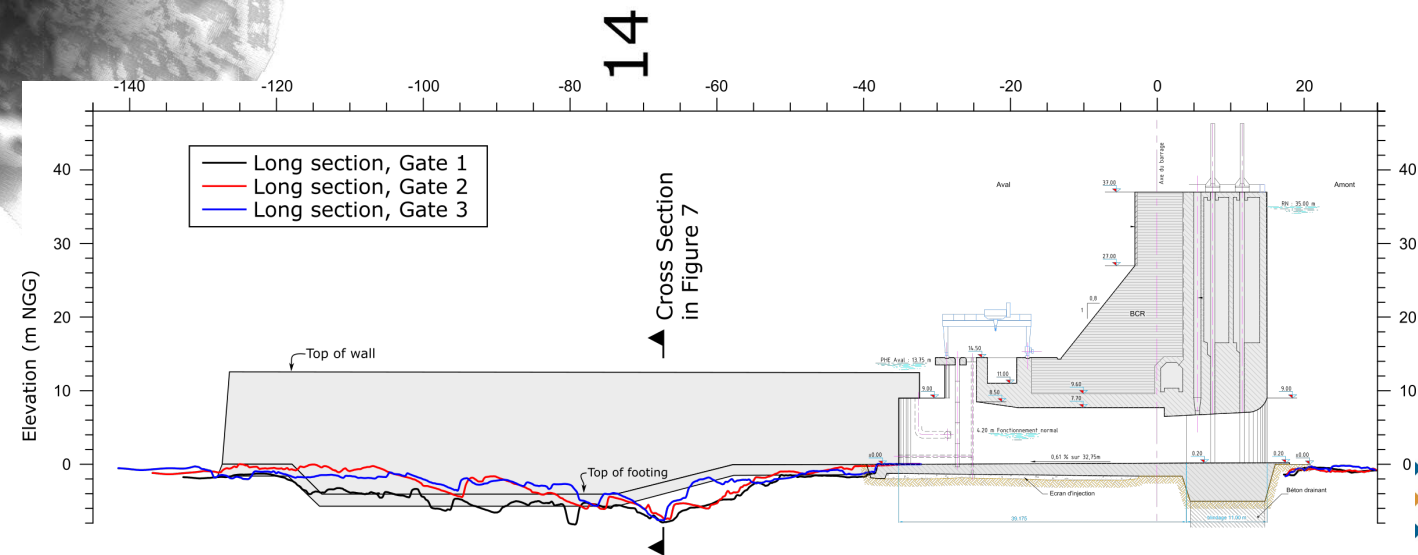


1.0 INTRODUCTION

1.1 Case examples



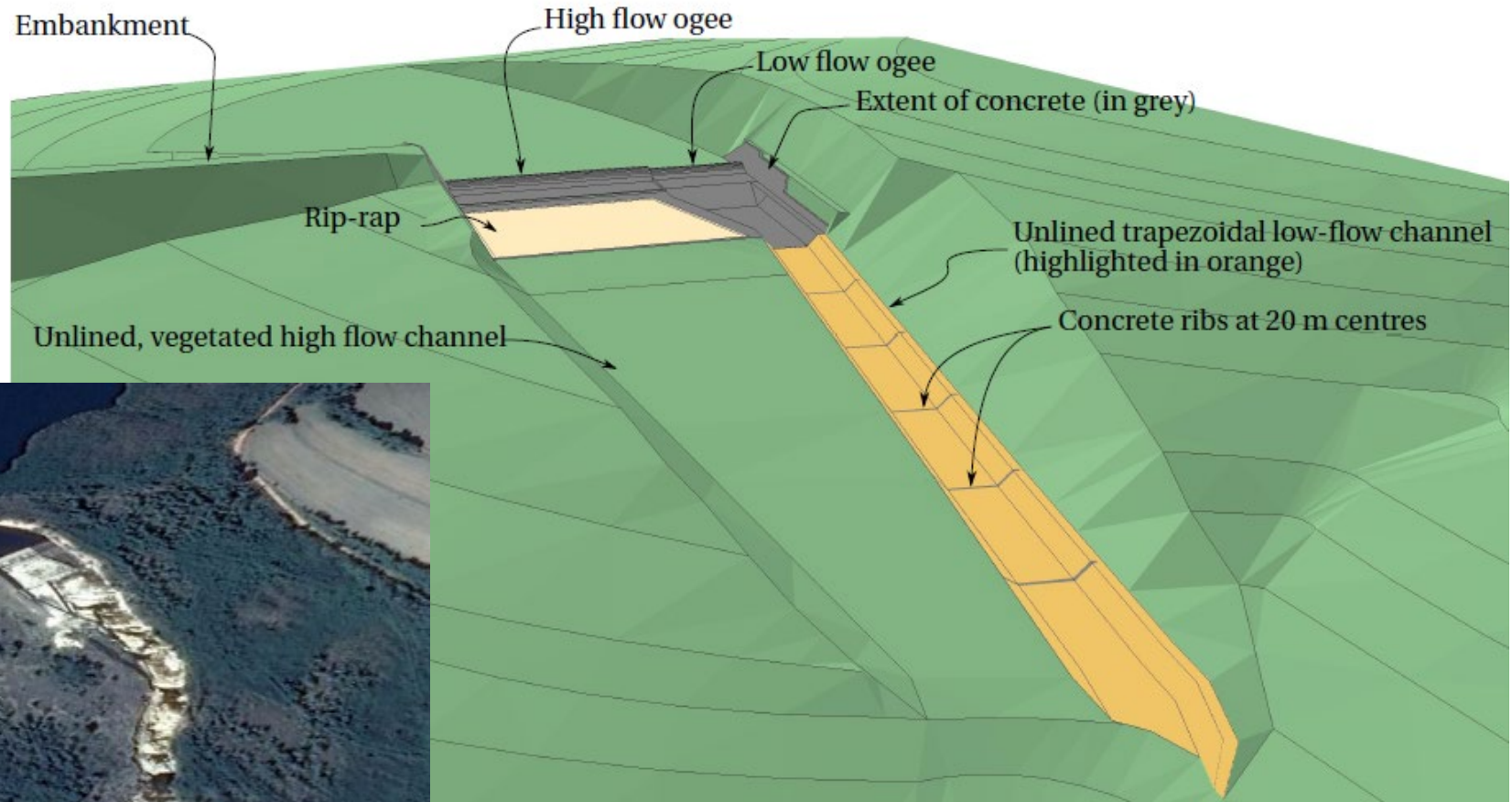
Petit-Saut Dam,
French Guiana



1.0 INTRODUCTION

1.1 Case examples

Haarlem Dam, South Africa



1.0 INTRODUCTION

1.1 Case examples

Haarlem Dam, South Africa



1.0 INTRODUCTION

1.1 Case examples

Haarlem Dam,
South Africa



1.0 INTRODUCTION

1.1 Case examples

Haarlem Dam,
South Africa



1.0 INTRODUCTION

1.1 Case examples

Paradise Dam



1.0 INTRODUCTION

1.2 The problem

1. We don't like this happening
2. Ageing infrastructure which is experiencing floods
3. Revision (usually upwards!) of design floods in Australia



1.0 INTRODUCTION

1.2 The problem

3. Revision (usually upwards!) of design floods in Australia

Example: Somerset Dam

Original design discharge: $4700 \text{ m}^3/\text{s}$

Specific discharge of $45 \text{ m}^3/\text{s}/\text{m}$ through the stilling basin

Current design discharge: $9600 \text{ m}^3/\text{s}$

Specific discharge of $125 \text{ m}^3/\text{s}/\text{m}$ through the stilling basin

Nearly tripled! What will happen to the unlined section?



1.0 INTRODUCTION

1.3 The industry-linkage study

Around 2012, an industry linkage grant awarded to research improved methods of assessing spillway erosion



Australian Government
Australian Research Council



Public
Works



ELFORSK



URS



This present masterclass provides an overview of the findings of the study (PhD) and industry experience in the years subsequent



1.0 INTRODUCTION

1.4 Some notes on rock

Rock-mechanics fundamental:

A material comprising *substance* and *defects*

- ✗ Its not like sediment transport
- ✗ Its not like rip-rap or rockfill
- ✗ Its not about abrading of the rock substance
- ✗ Its not about hydro-fracturing
- ✗ Its not about cavitation

✓ It is about the mechanical unravelling of a mass of interlocking irregular blocks by both static and chaotic hydraulic forces



2.0 LABORATORY TESTING OF HYDRAULICS

2.1 The test setup



2.0 LABORATORY TESTING OF HYDRAULICS

2.1 The test setup

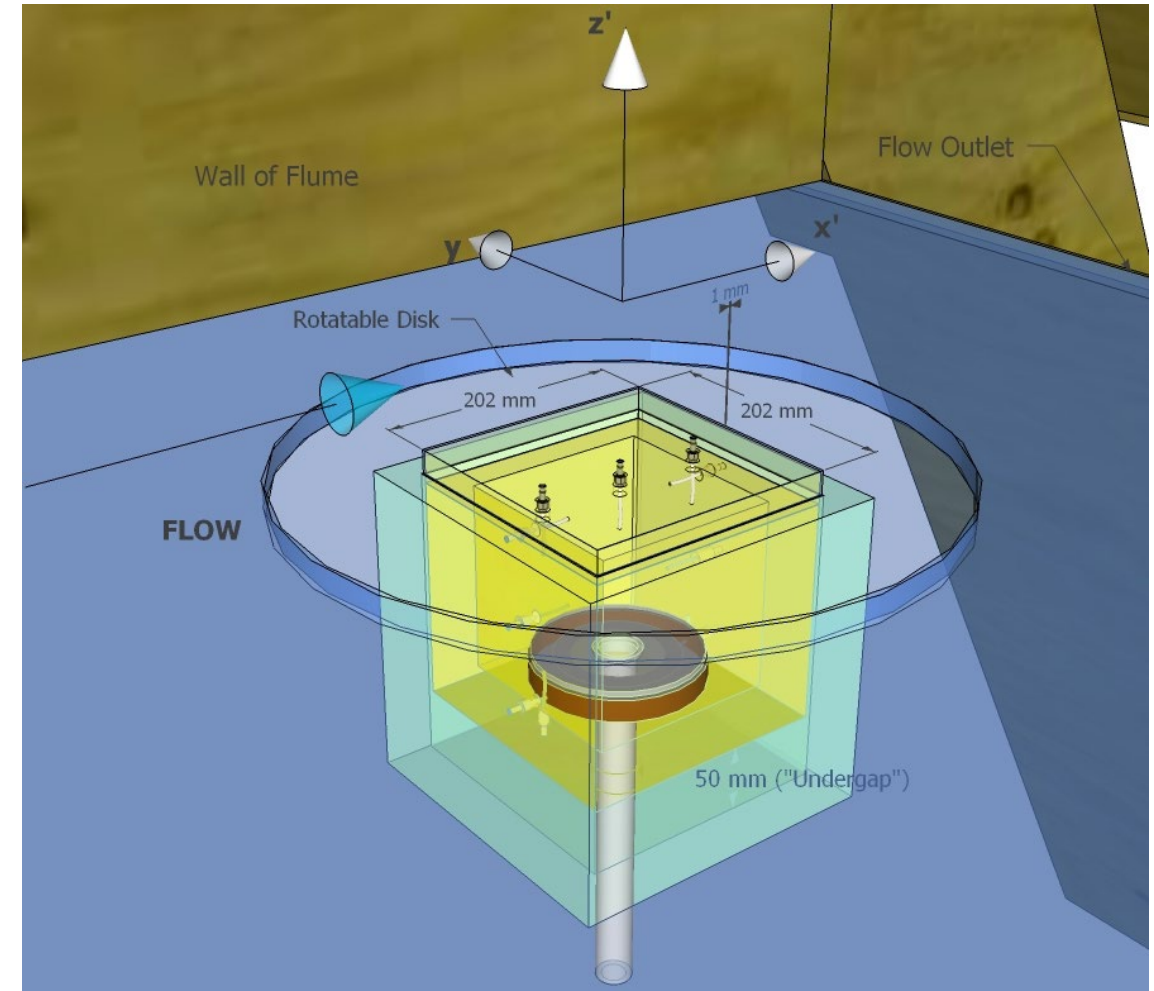
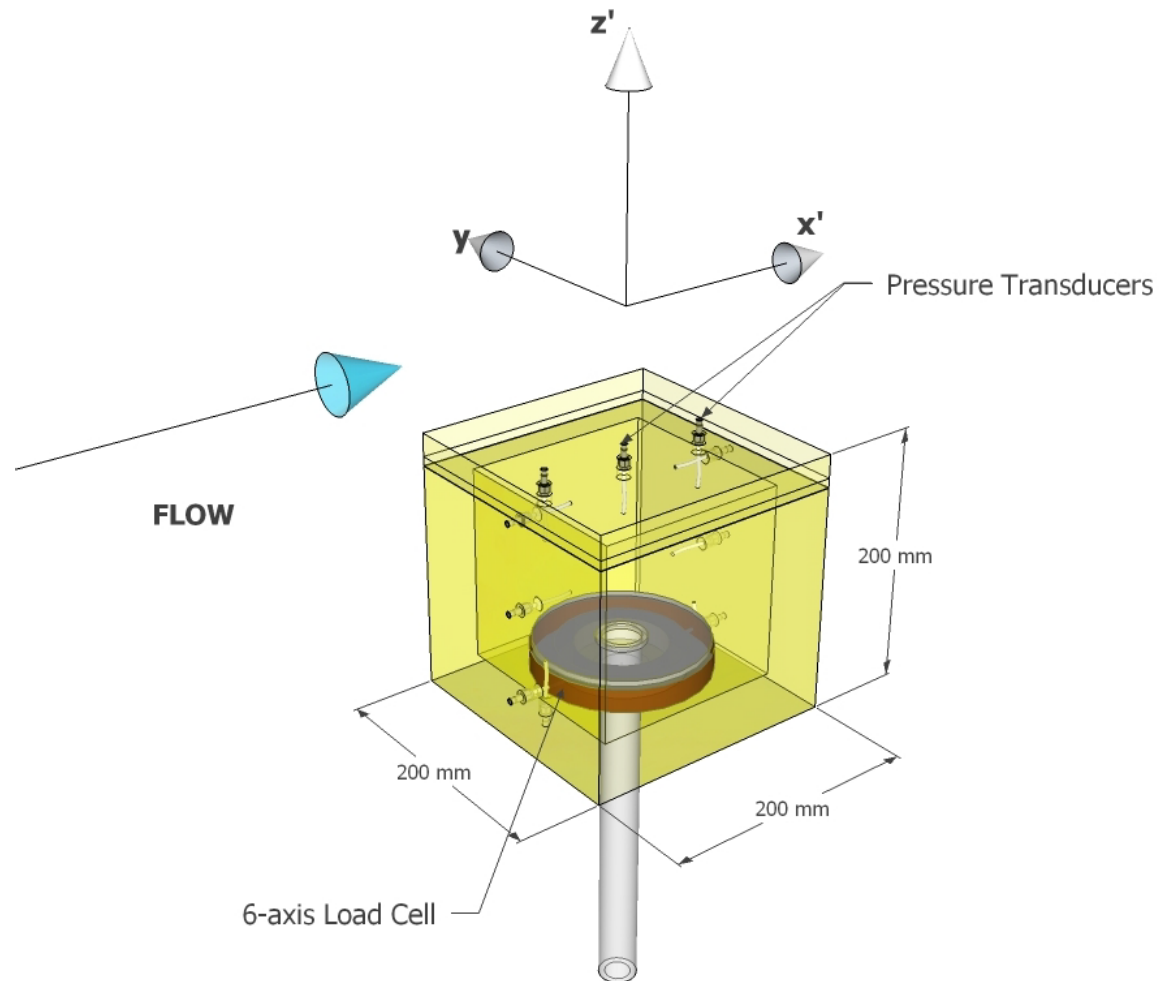
The flume



2.0 LABORATORY TESTING OF HYDRAULICS

2.1 The test setup

The “block”



2.0 LABORATORY TESTING OF HYDRAULICS

2.1 The test setup

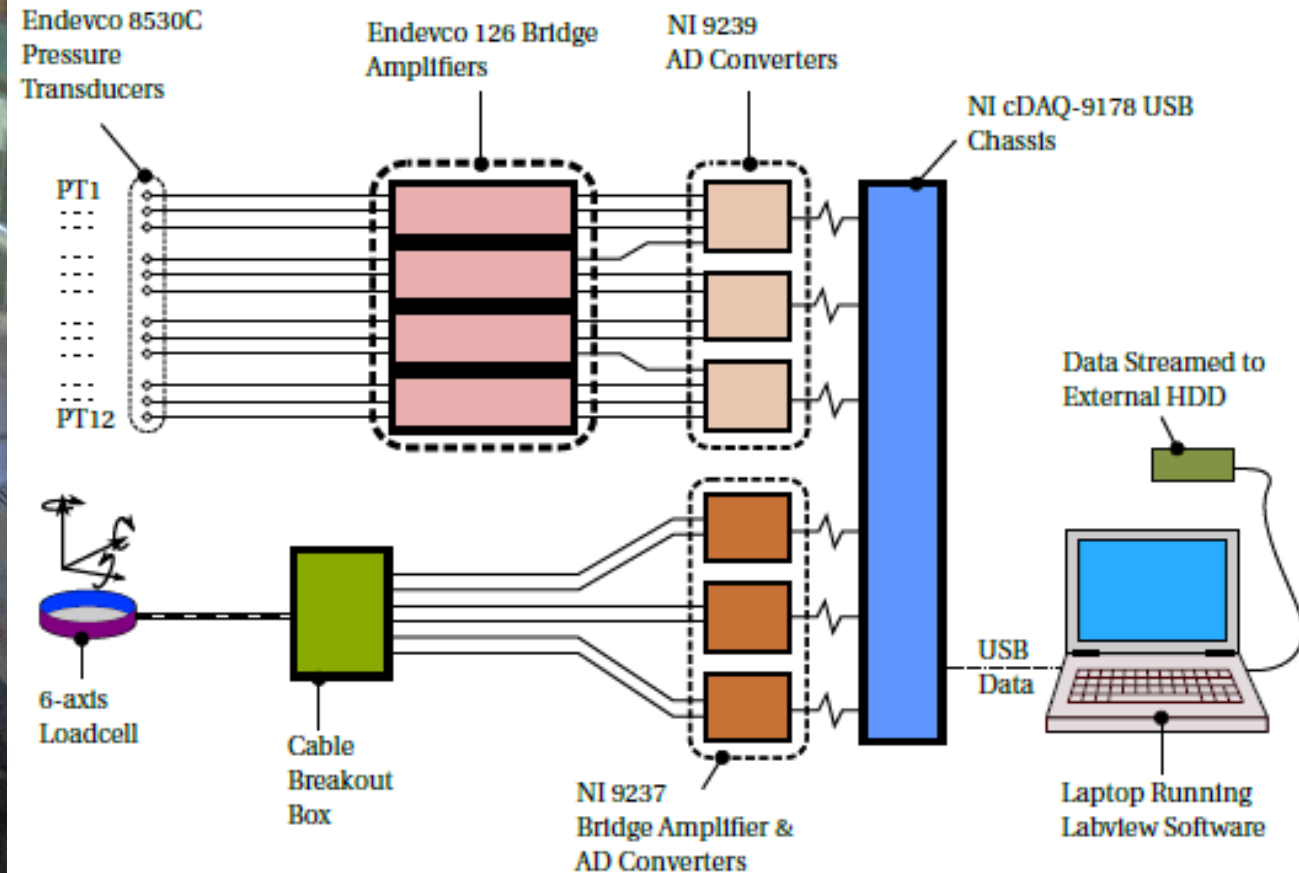
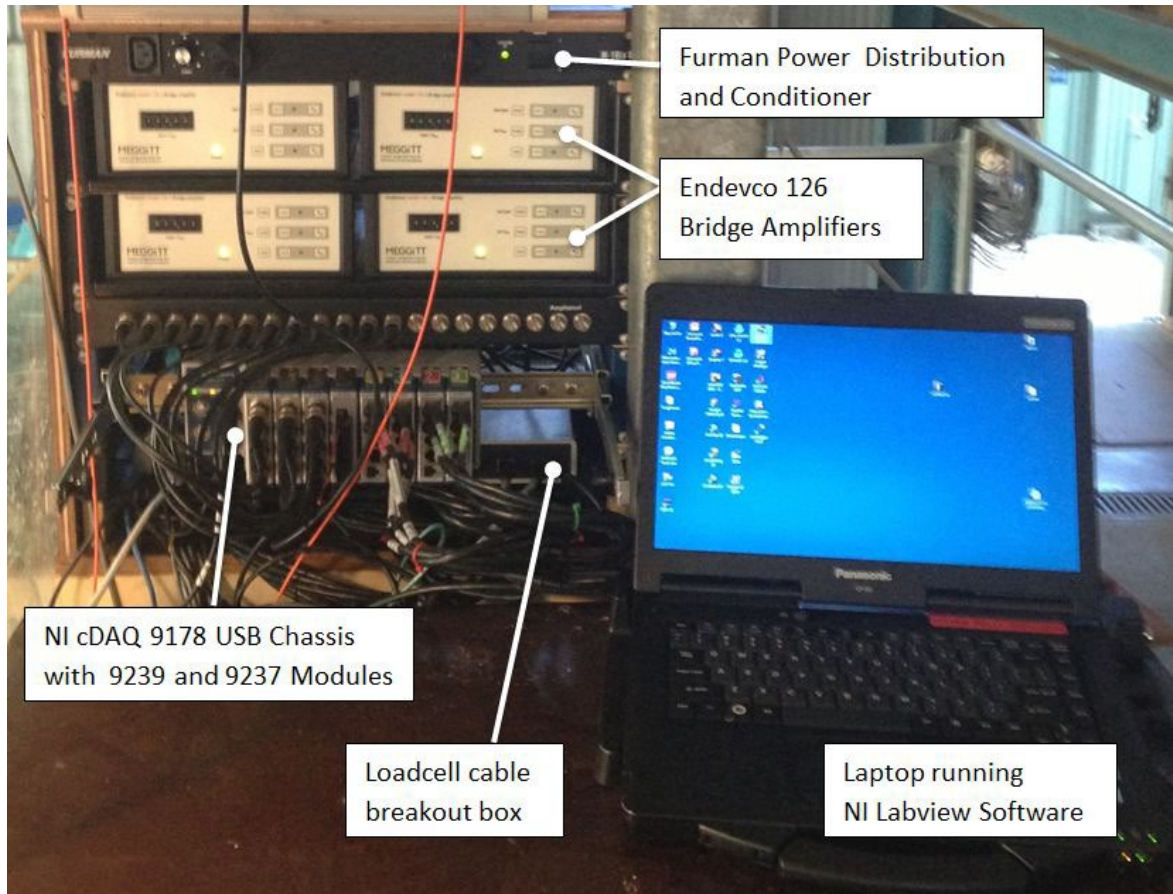
Instruments – pressure transducers and 6-axis load cell



2.0 LABORATORY TESTING OF HYDRAULICS

2.1 The test setup

Data acquisition – 25 kHz sample rate



2.0 LABORATORY TESTING OF HYDRAULICS

2.2 Tests

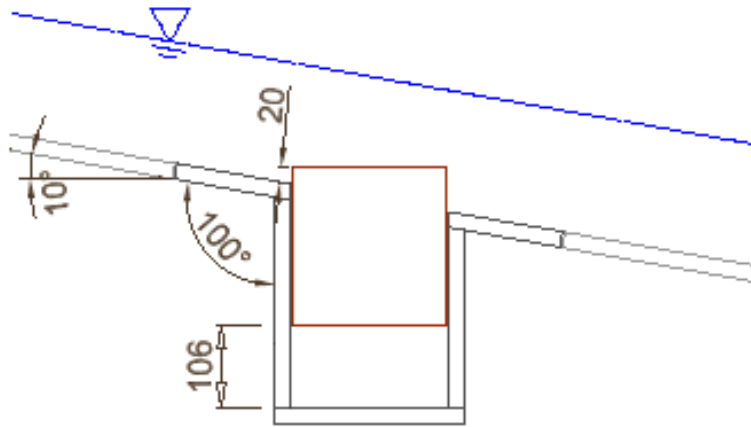
Varied protrusion



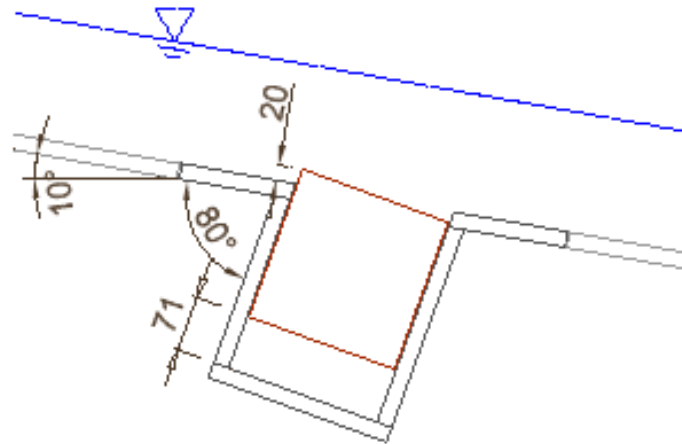
2.0 LABORATORY TESTING OF HYDRAULICS

2.2 Tests

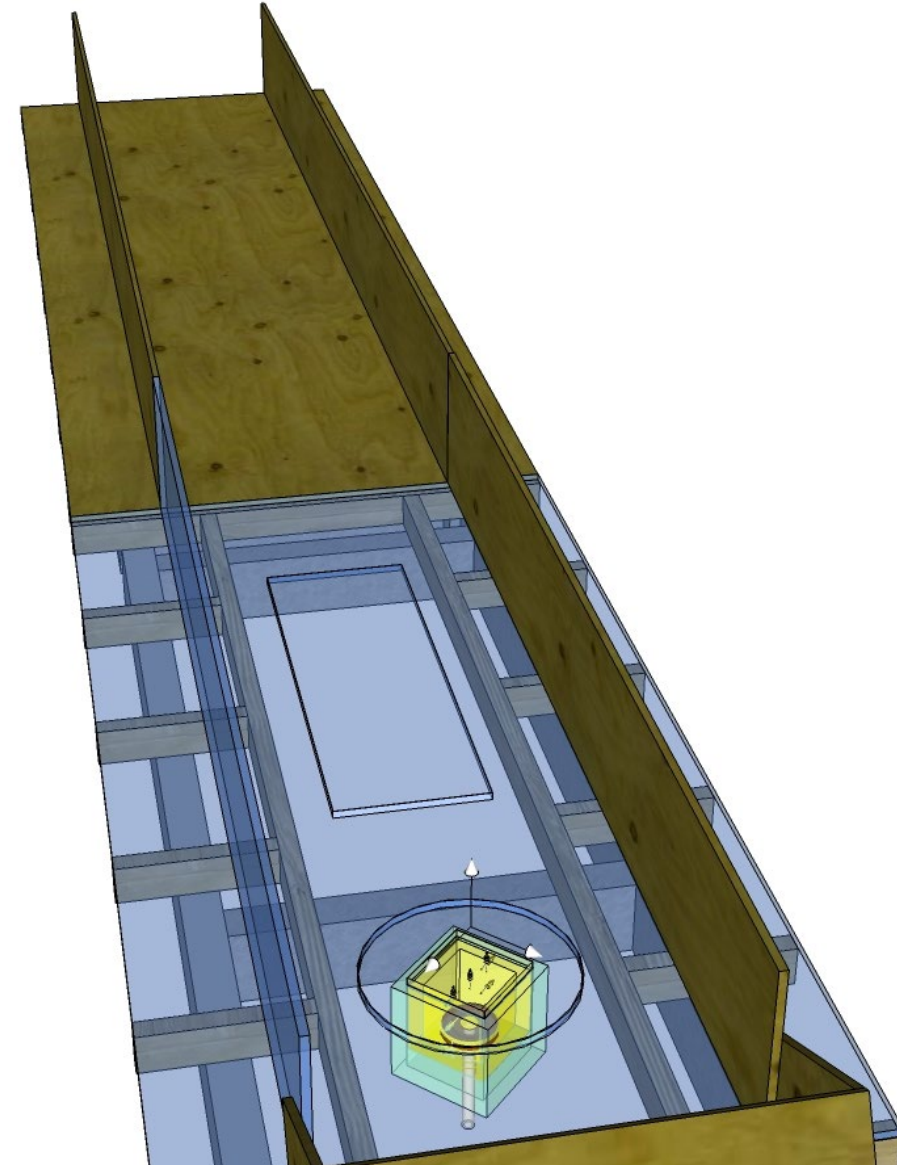
Varied orientation



Test V1 at 10 degrees slope



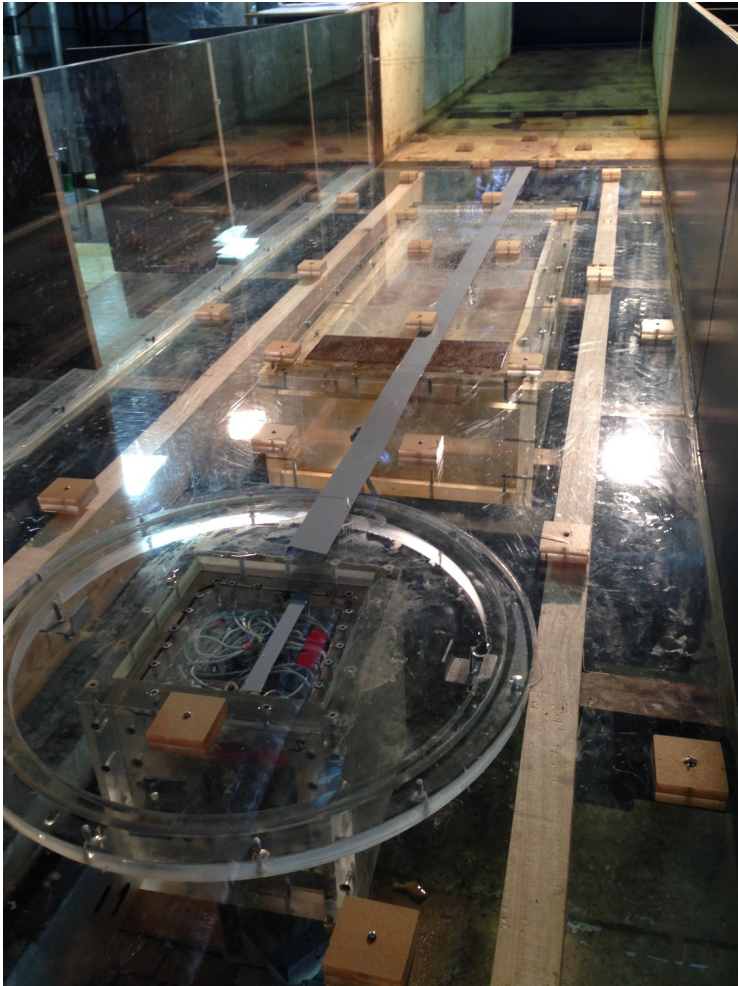
Test V2 at 10 degrees slope



2.0 LABORATORY TESTING OF HYDRAULICS

2.2 Tests

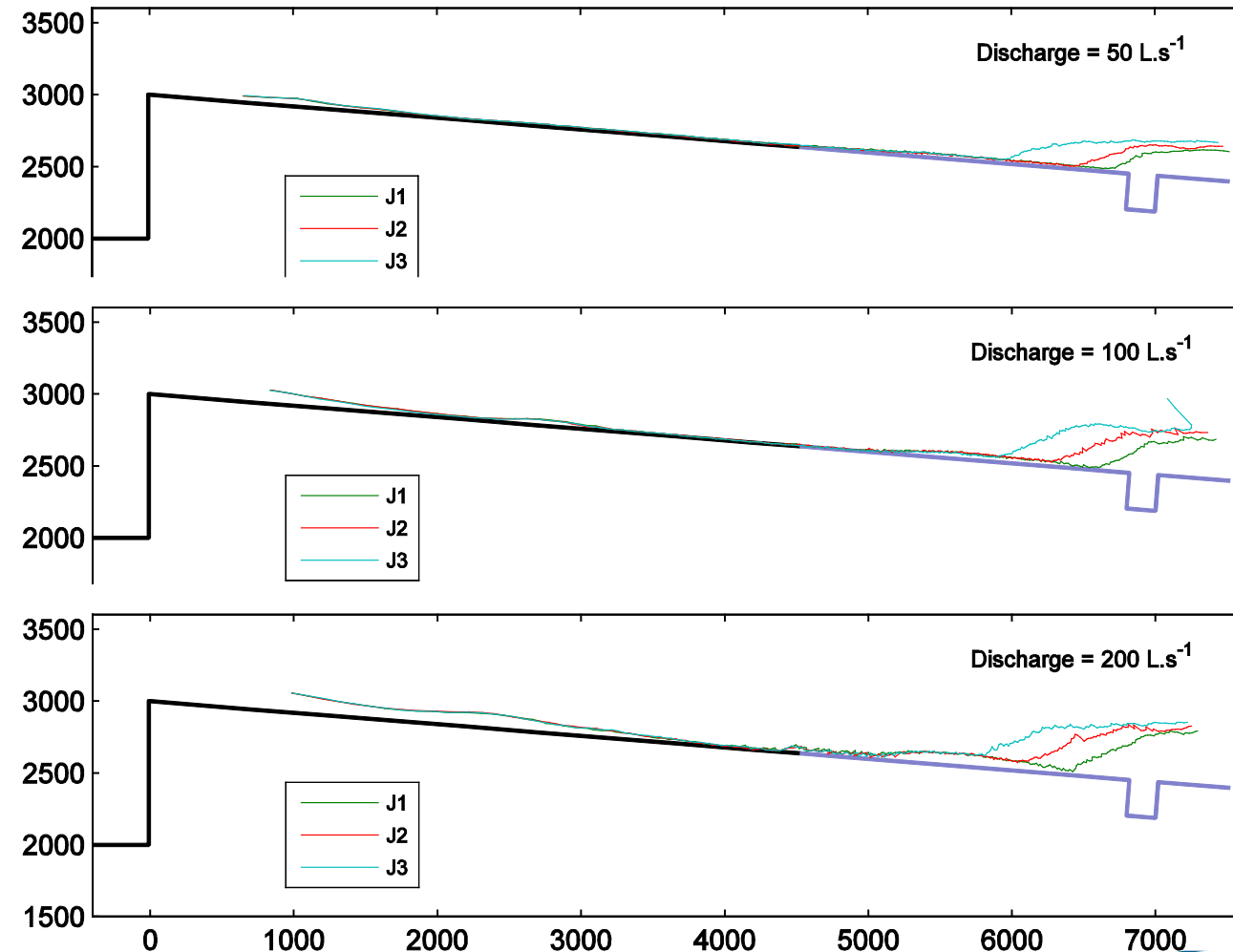
Varied roughness



2.0 LABORATORY TESTING OF HYDRAULICS

2.2 Tests

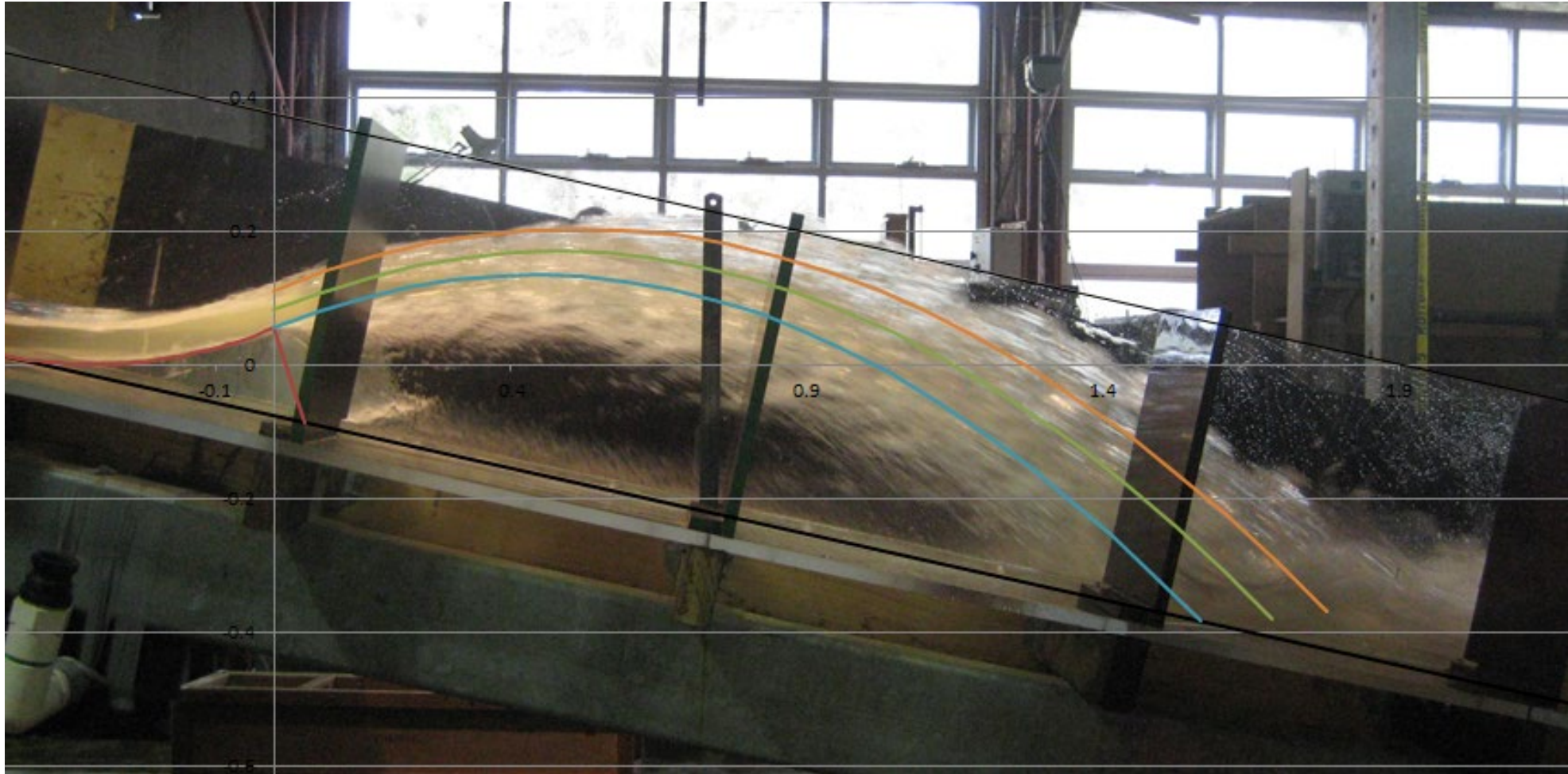
Tests with hydraulic jumps



2.0 LABORATORY TESTING OF HYDRAULICS

2.2 Tests

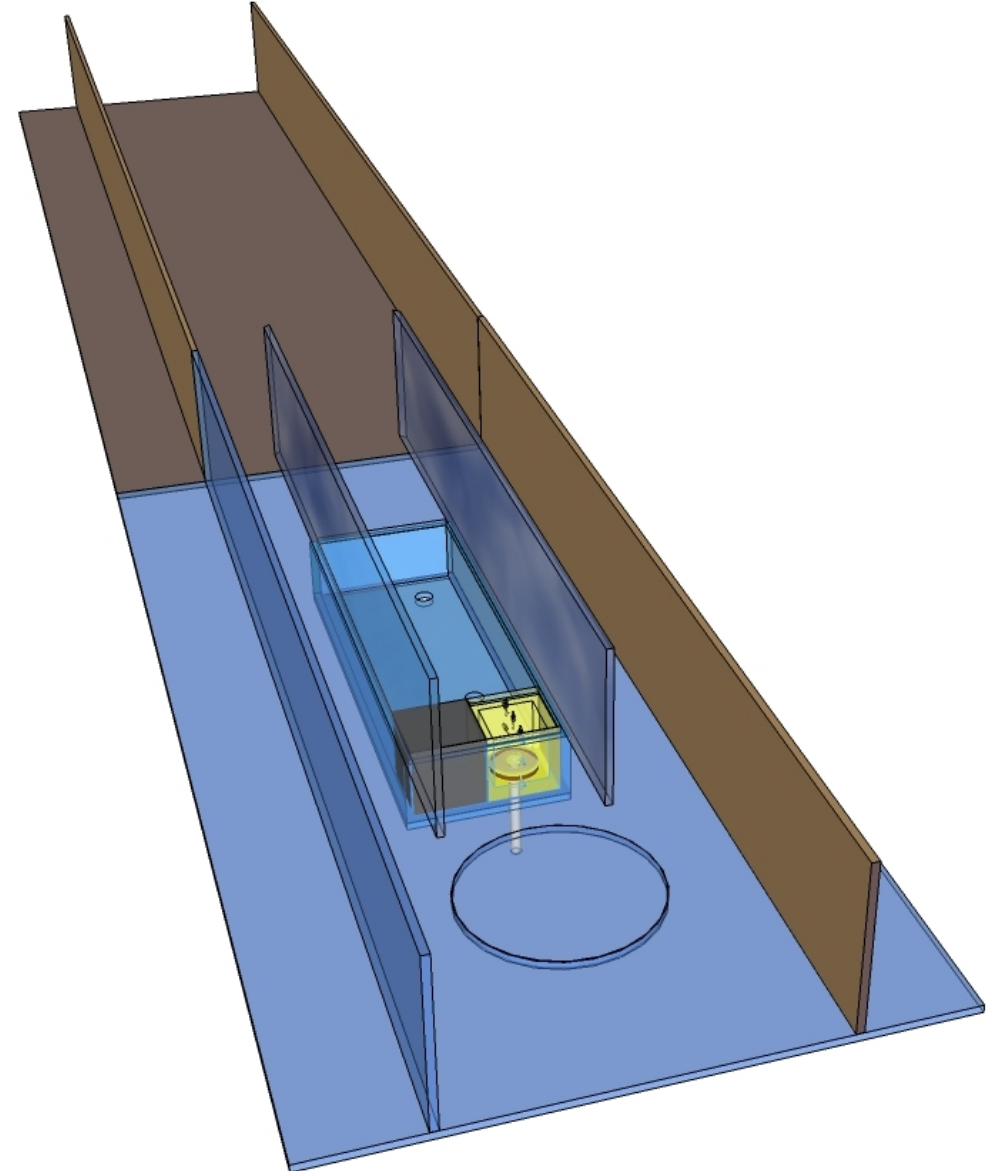
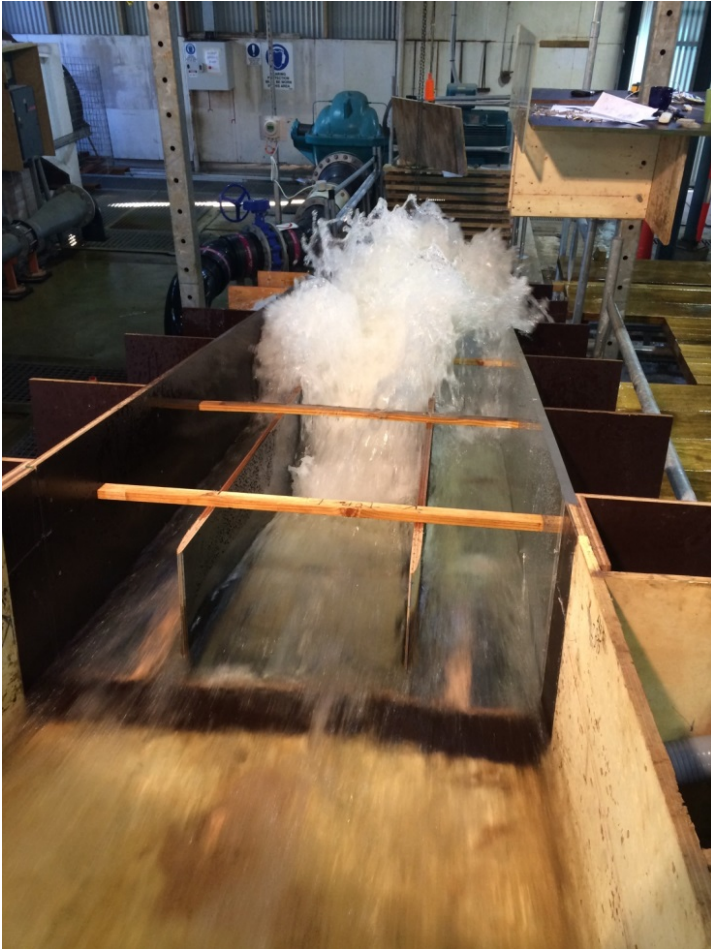
Tests with plunging flows



2.0 LABORATORY TESTING OF HYDRAULICS

2.2 Tests

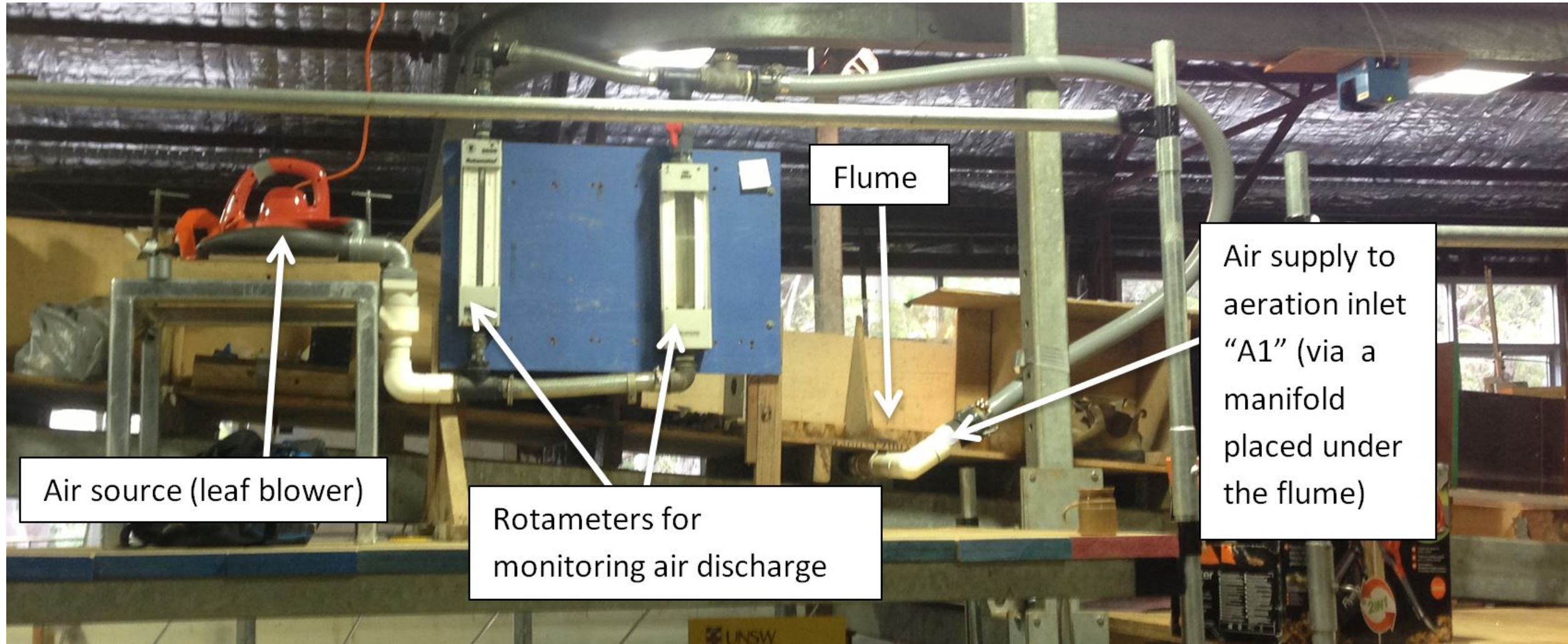
Headcutting and scour holes



2.0 LABORATORY TESTING OF HYDRAULICS

2.2 Tests

Aeration



2.0 LABORATORY TESTING OF HYDRAULICS

2.2 Tests

Aeration



2.0 LABORATORY TESTING OF HYDRAULICS

2.2 Tests

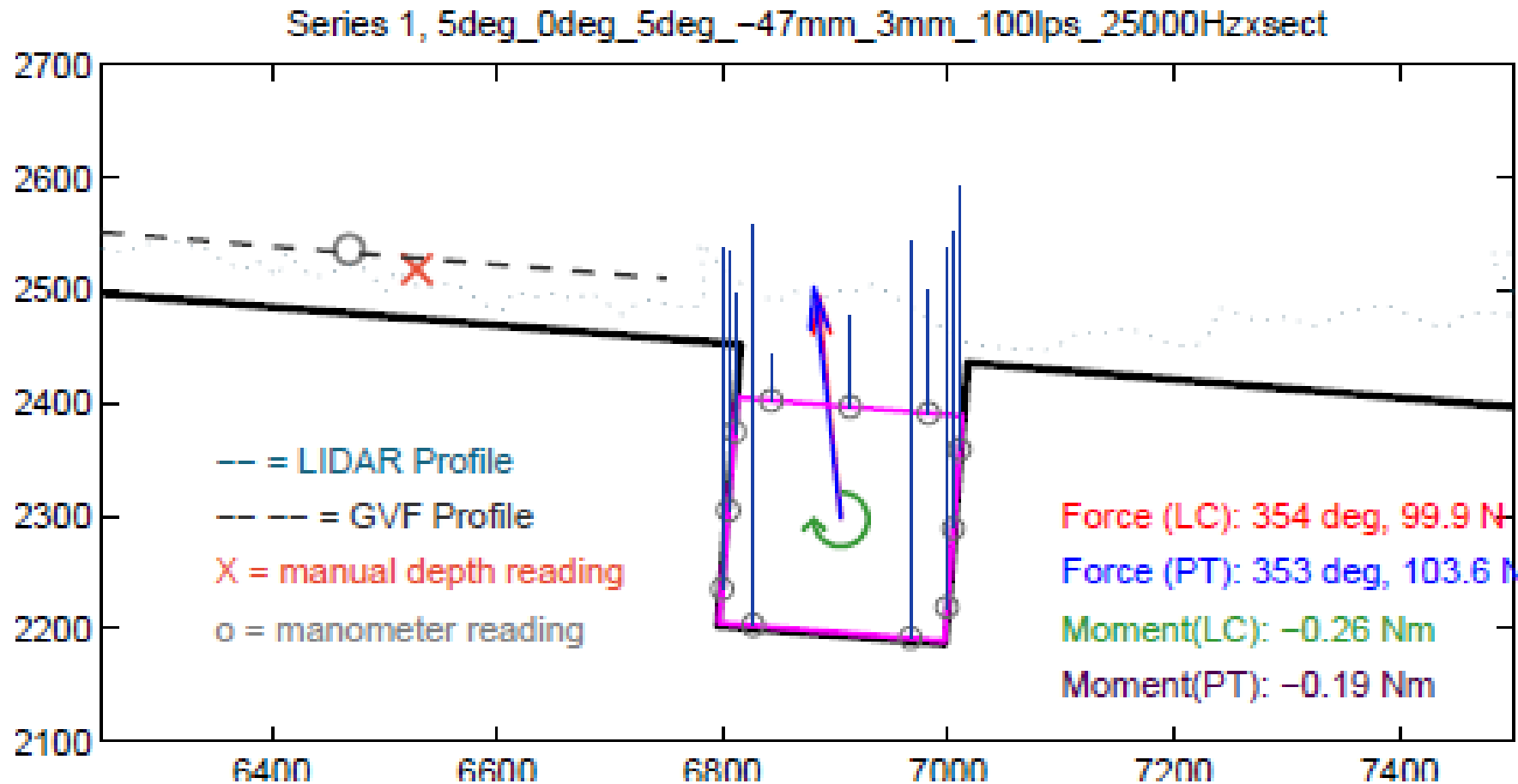
Aeration

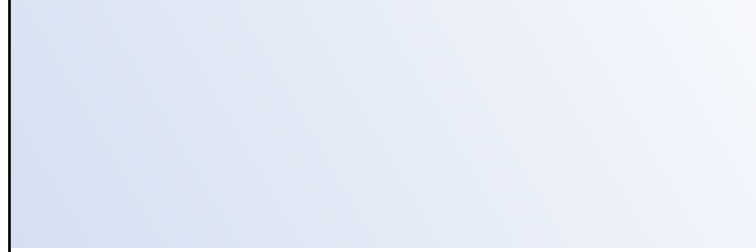


2.0 LABORATORY TESTING OF HYDRAULICS

2.3 Results

Statics

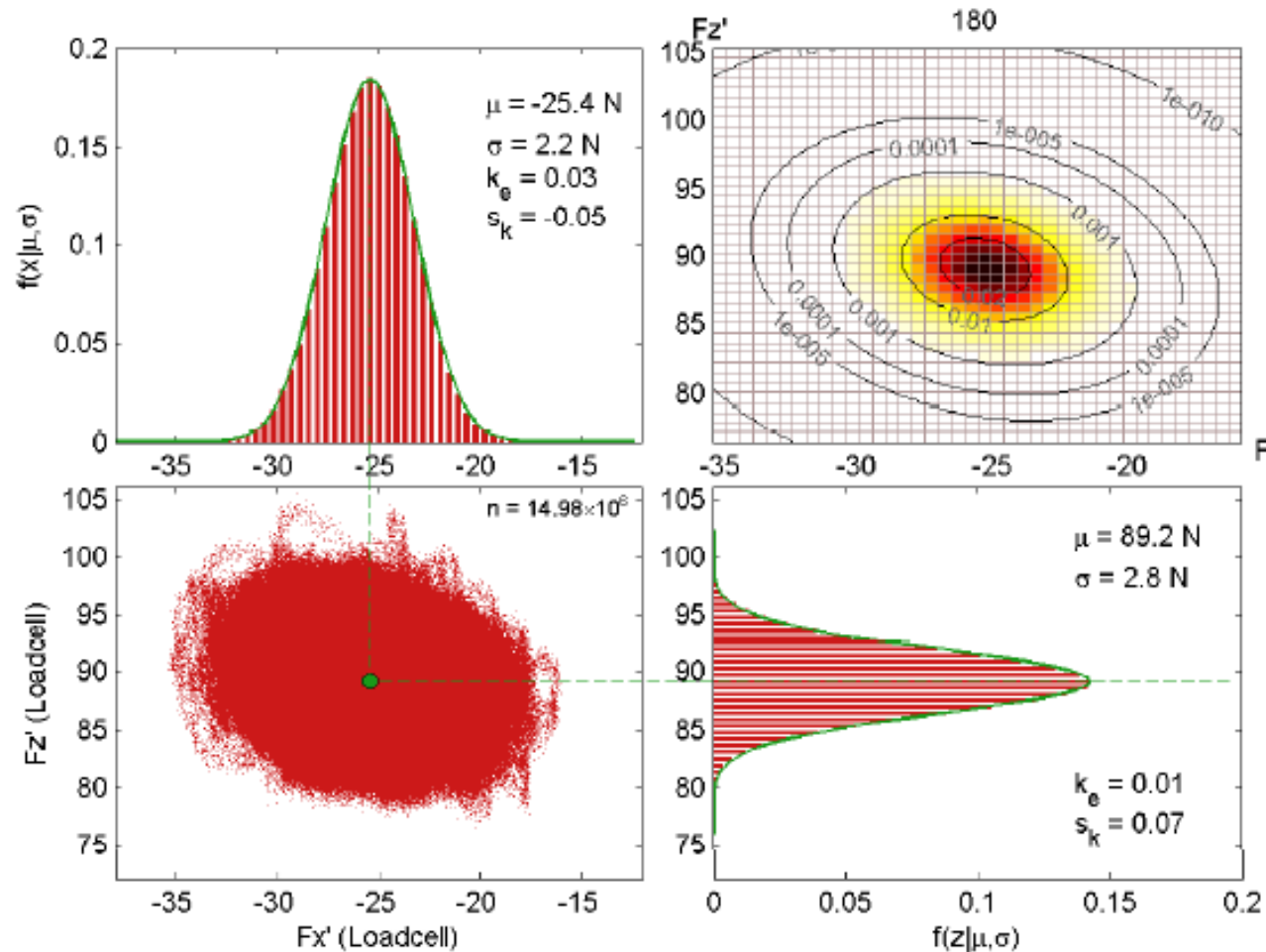




2.0 LABORATORY TESTING OF HYDRAULICS

2.3 Results

Dynamics



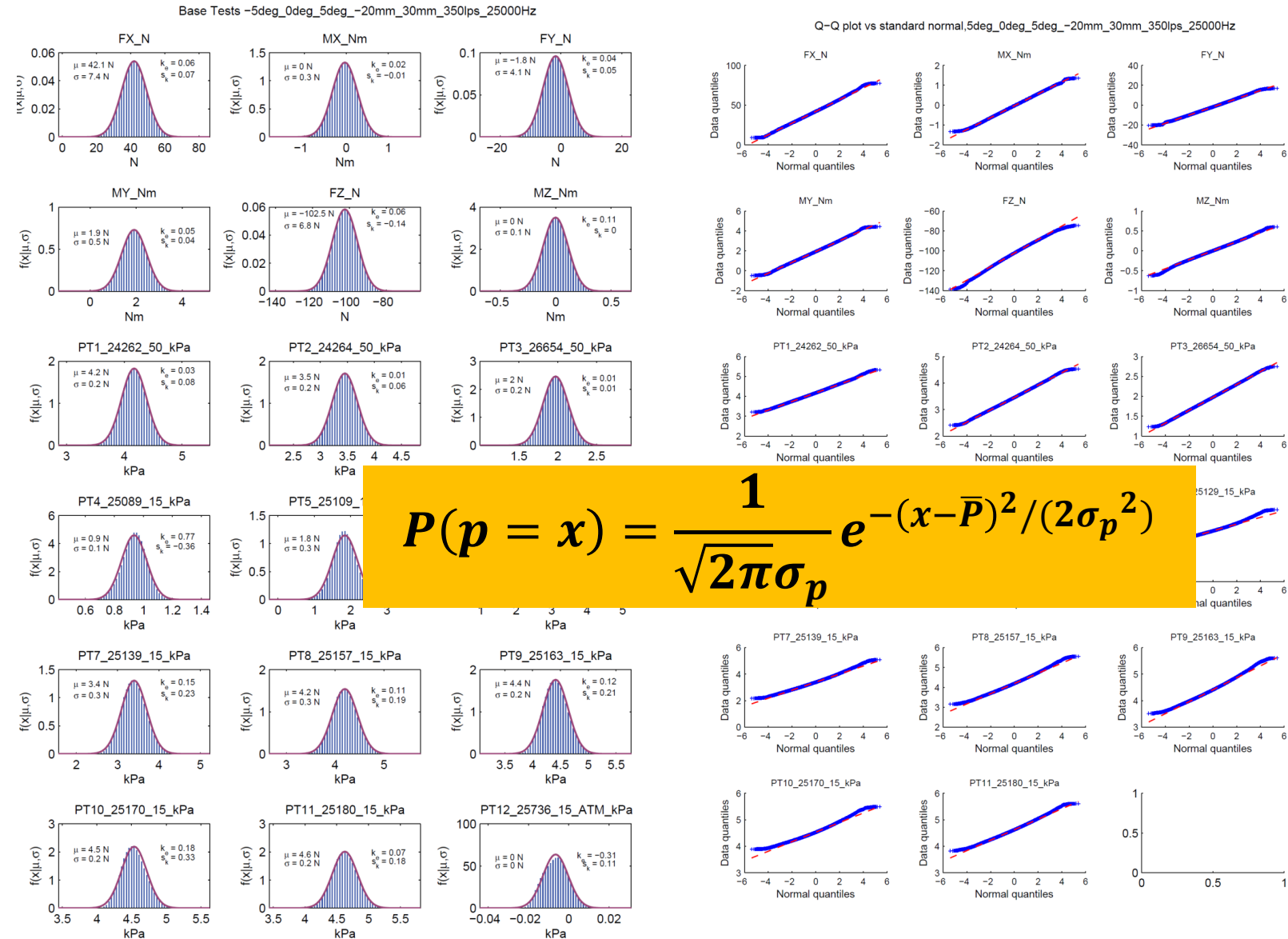
2.0 LABORATORY TESTING OF HYDRAULICS

2.3 Results

Fluctuations

“Peak”

Pressure ?



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.1 What are analytical solutions?

A bunch of equations

Usually solvable by hand or at least excel

... and a bunch of simplifications

Example – the ‘infinite slope’ solution

Used in geotechnical engineering

Another example: the classical “heat equation”

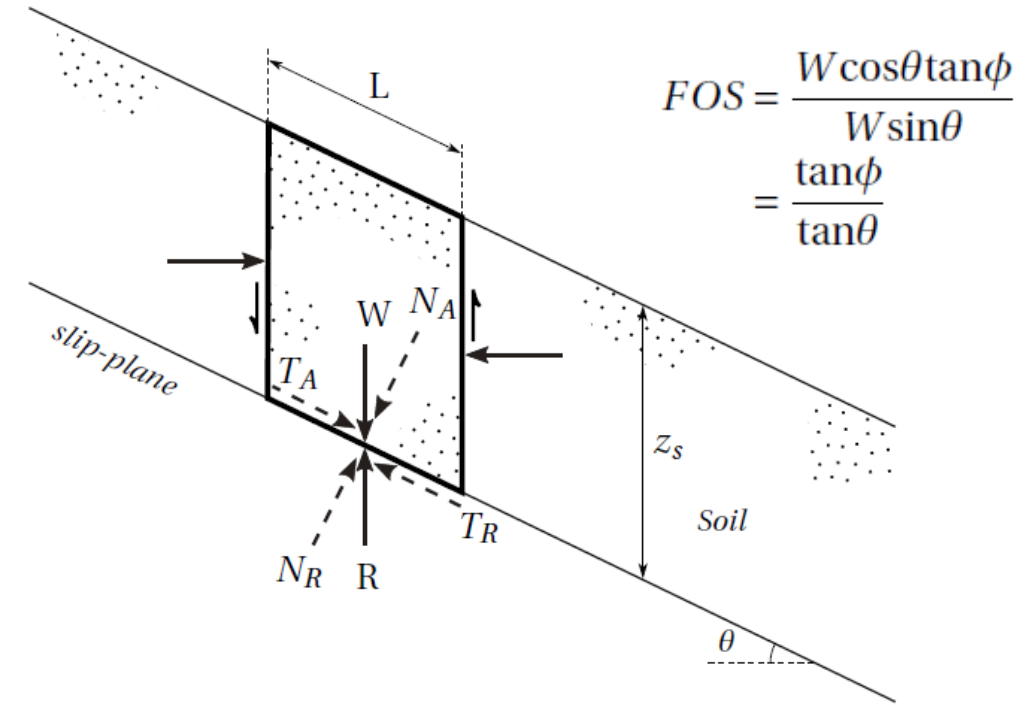


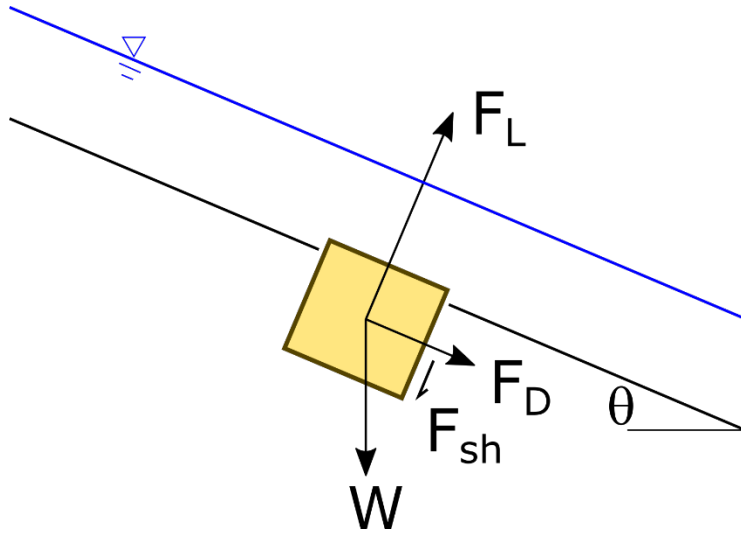
Figure 7.8 The ‘infinite slope’

$$\nabla^2 T = \frac{c_p \rho}{k} \frac{\partial T}{\partial t}$$



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.2 A simple freebody



Consider the case of lifting of the block.

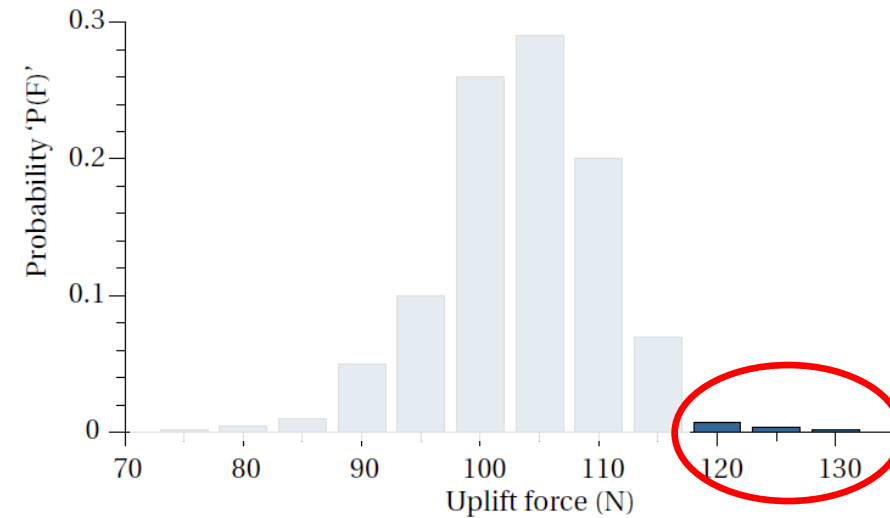
For the purpose of illustration, assume:

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:

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

$$F_L > 115 \text{ N}$$



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.2 A simple freebody

$$F = ma$$

$$a_{\text{rock}} = \frac{F_{\text{net}}}{m_{\text{rock}}} = \frac{F}{V_s \cdot \rho_s}$$

$$s_{\text{rock}} = \int \int_0^t a_{\text{rock}} dt = \frac{1}{V_s \cdot \rho_s} \int \int_0^t F_{\text{net}} dt$$

Displacement

Time

$$s_{\text{rock}} = \frac{F_{\text{net}}}{V_s \cdot \rho_s} \frac{t^2}{2}$$

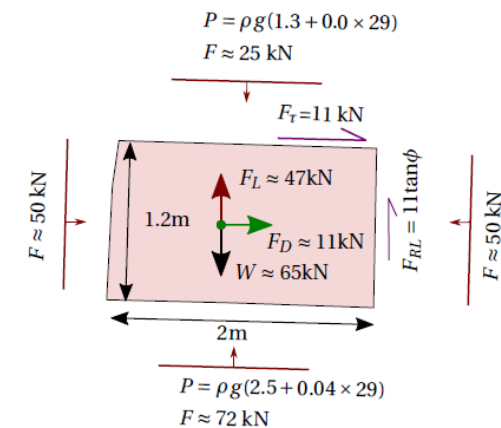
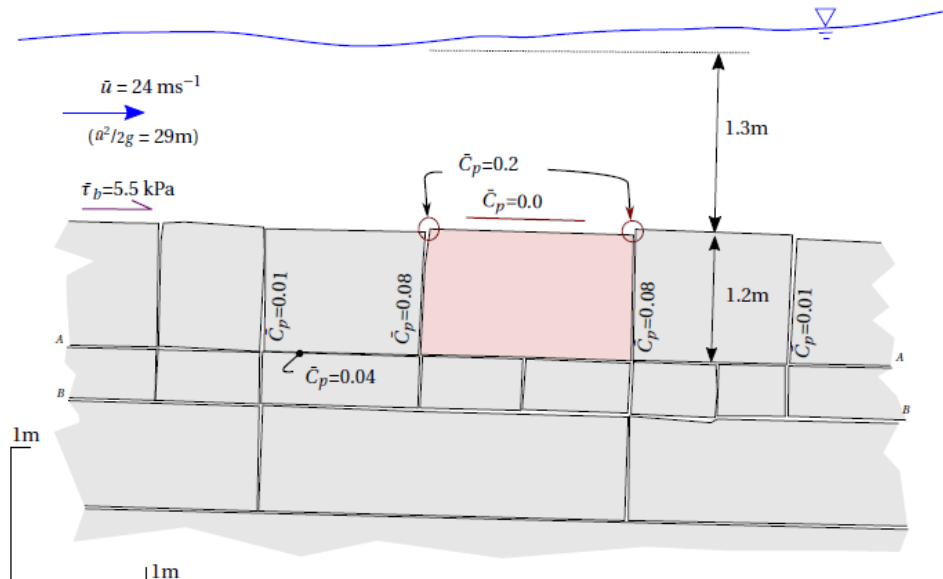
Lift Force	P(F)	Force Duration	Net	Restraining force		F_{net}	Displacement	
			applied	$F_D \tan \phi$			Case 1	Case 2
			force $F_L - W$	available	applied		up/down	up only
(N)		(secs)	(N)	(N)	(N)	(N)	(mm)	(mm)
75	0.002	$= 0.002 \times 60 = 0.12$	-23.1	17.3	-17.3	-5.8	-4.2	0.0
80	0.005	$= 0.005 \times 60 = 0.3$	-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 after 60 seconds



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

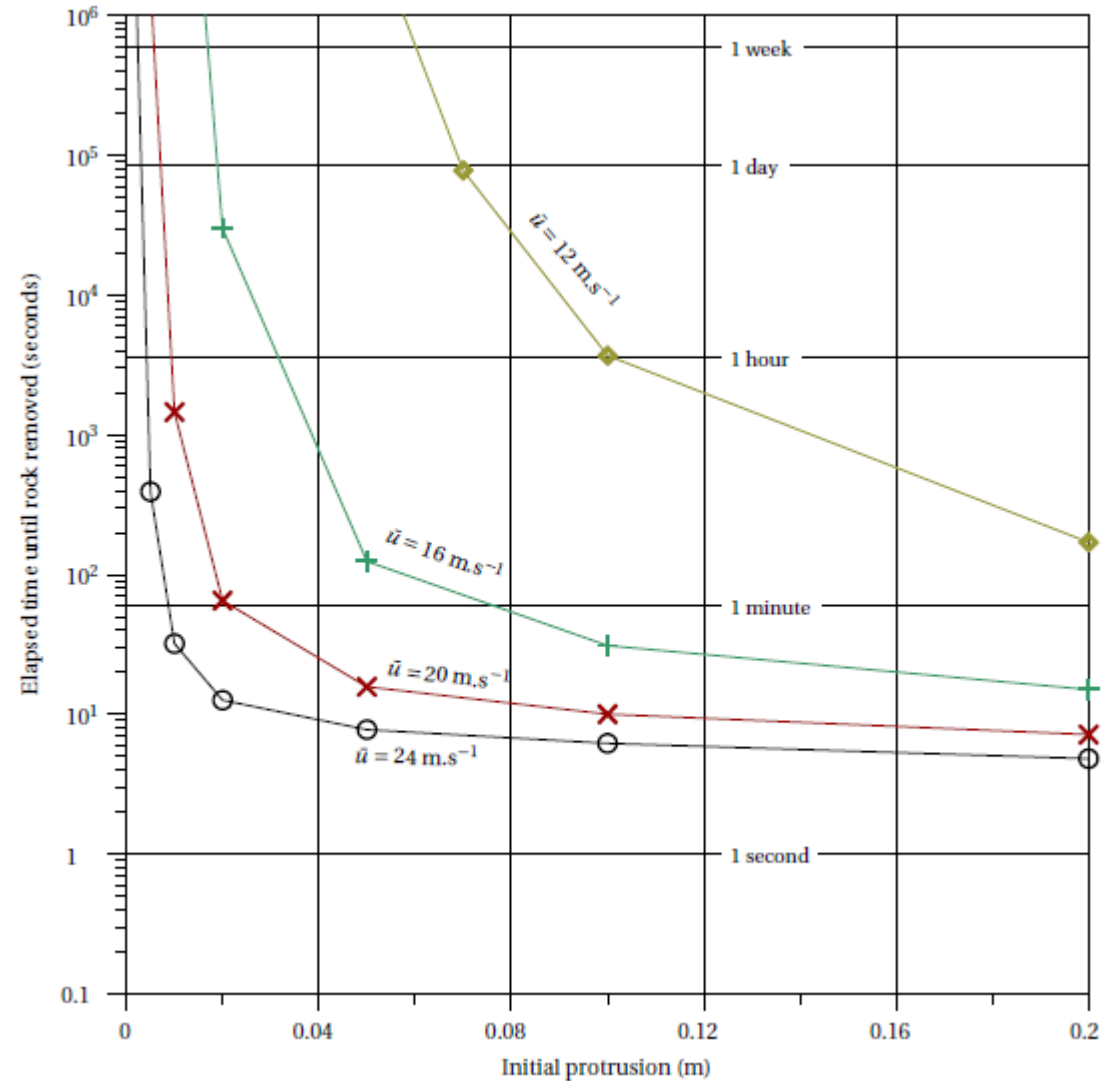
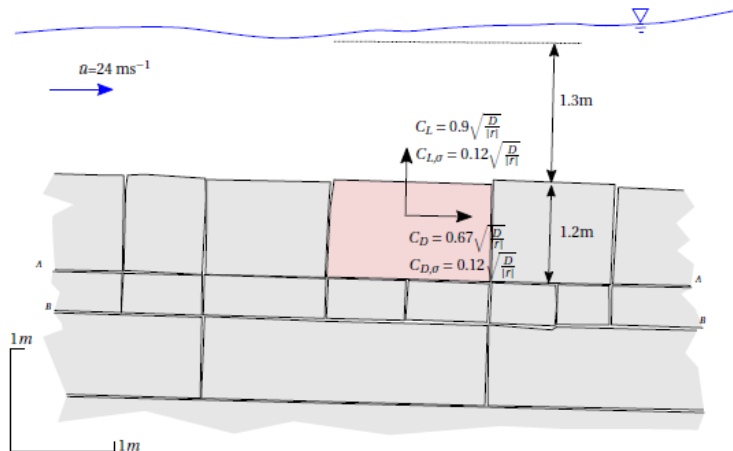
3.2 A simple freebody



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.2 A simple freebody

Fluctuating removal of a block



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.3 The list of assumptions

Assumptions about geometry and geotechnics of our rock

Block size

Block shape

Block mass

Block strength

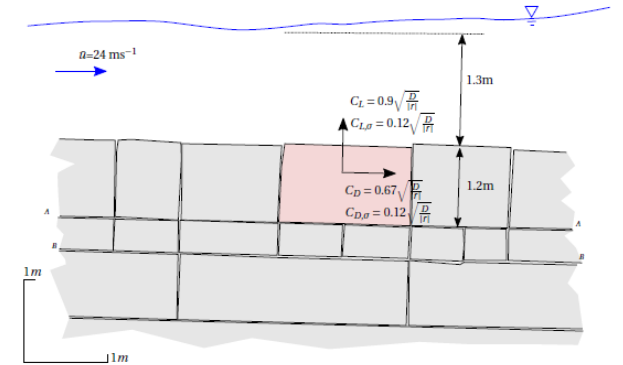
Defect orientation

Defect aperture

Defect persistence

Defect strength

Block sheltering or penetration



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.3 The list of assumptions

Assumptions about hydraulics

our (steady) flow condition is representative of a whole hydrograph

surface pressure

velocity field

directionality

Fluctuations

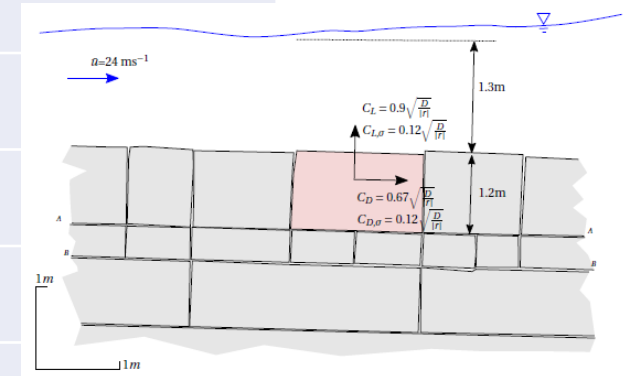
Stagnation pressure

How much pressure penetrates into defects (proportional to aperture cubed?)

Time lag between upstream and downstream defects

Seepage pressures in rock mass

All these hydraulic conditions stay the same as it moves



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.3 The list of assumptions

Assumptions about mechanics

Our block is the key block

That our block only moves in isolation - all other blocks stay still

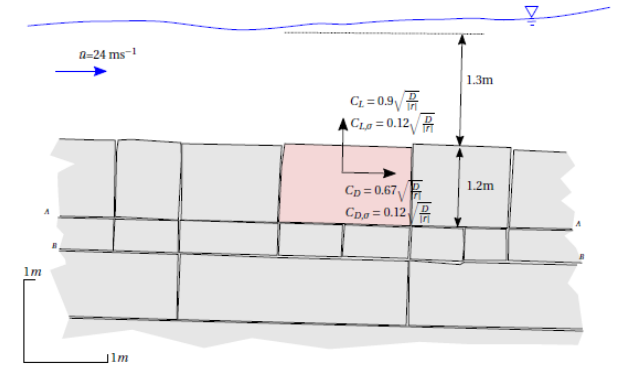
It only moves upwards

It does not rotate

Defect shear / interlocking is constant

It does not fracture more

Once it pokes its head up enough, it disappears



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.3 The list of assumptions

Assumptions about the rock mass

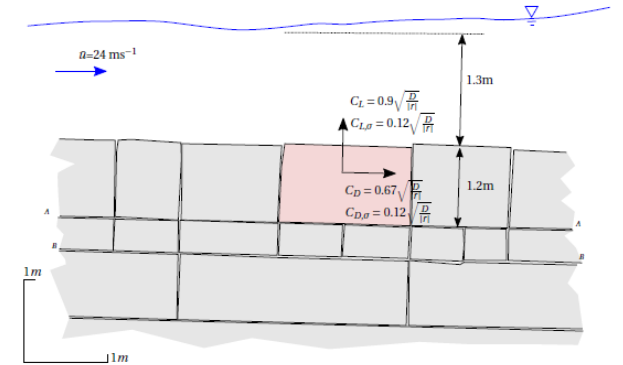
The whole mass can be represented by one size / shape of rock and defect

The process our rock is repeated to all other rocks (even although the geometry is significantly changed once the first is removed)

Only one rock moves at a time - We don't have a mass of rocks moving simultaneously

Rocks don't accumulate

What if a different block moved first? - completely different answer?



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.4 The problem of rock masses



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.5 The Kurt Douglas moment



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.5 The Kurt Douglas moment



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.6 Give us pressures!

Dimensionless coefficients derived from lab measurements.

Mean of the Kinetic Pressure

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

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

Pressure head, assuming a hydrostatic profile

Inferred velocity head at transducer

Mean velocity head of the flow

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

Re-arrange to give design equation



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.6 Give us pressures!

Dimensionless coefficients derived from lab measurements.

Fluctuations of the Kinetic 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

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

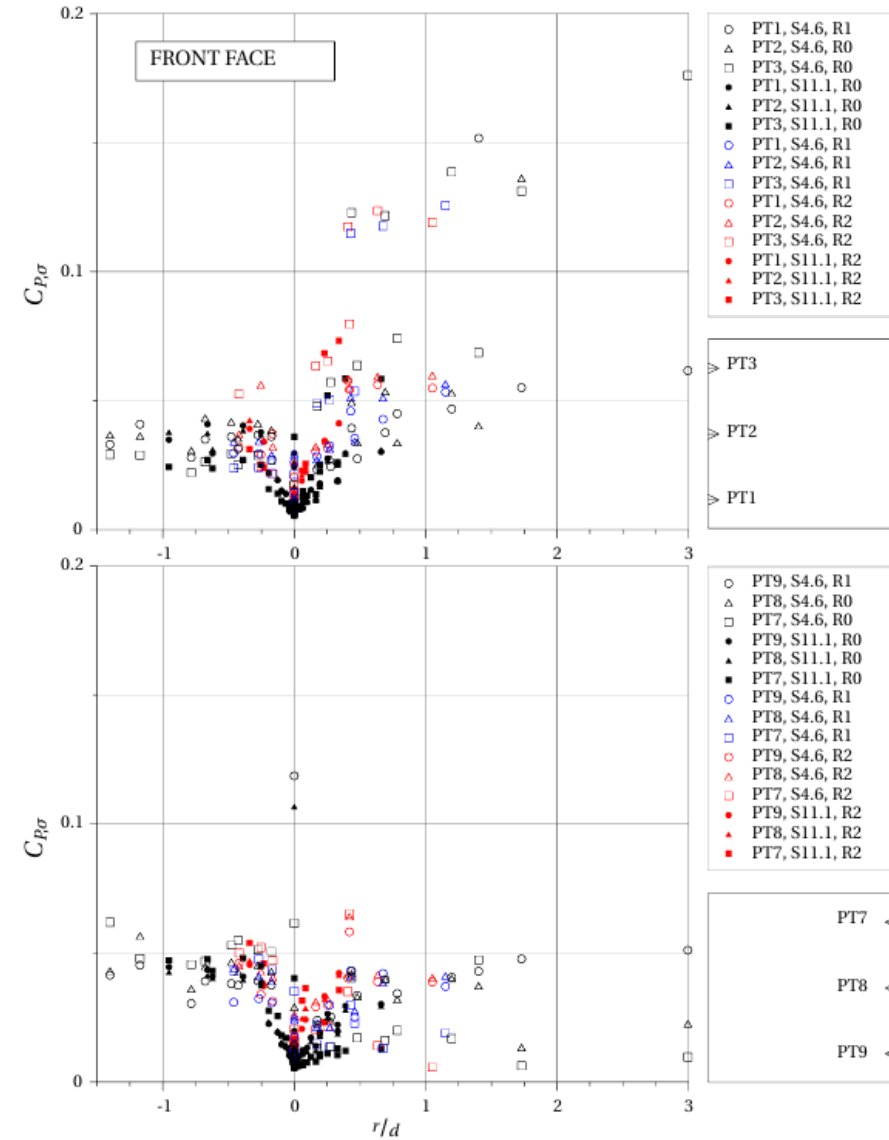
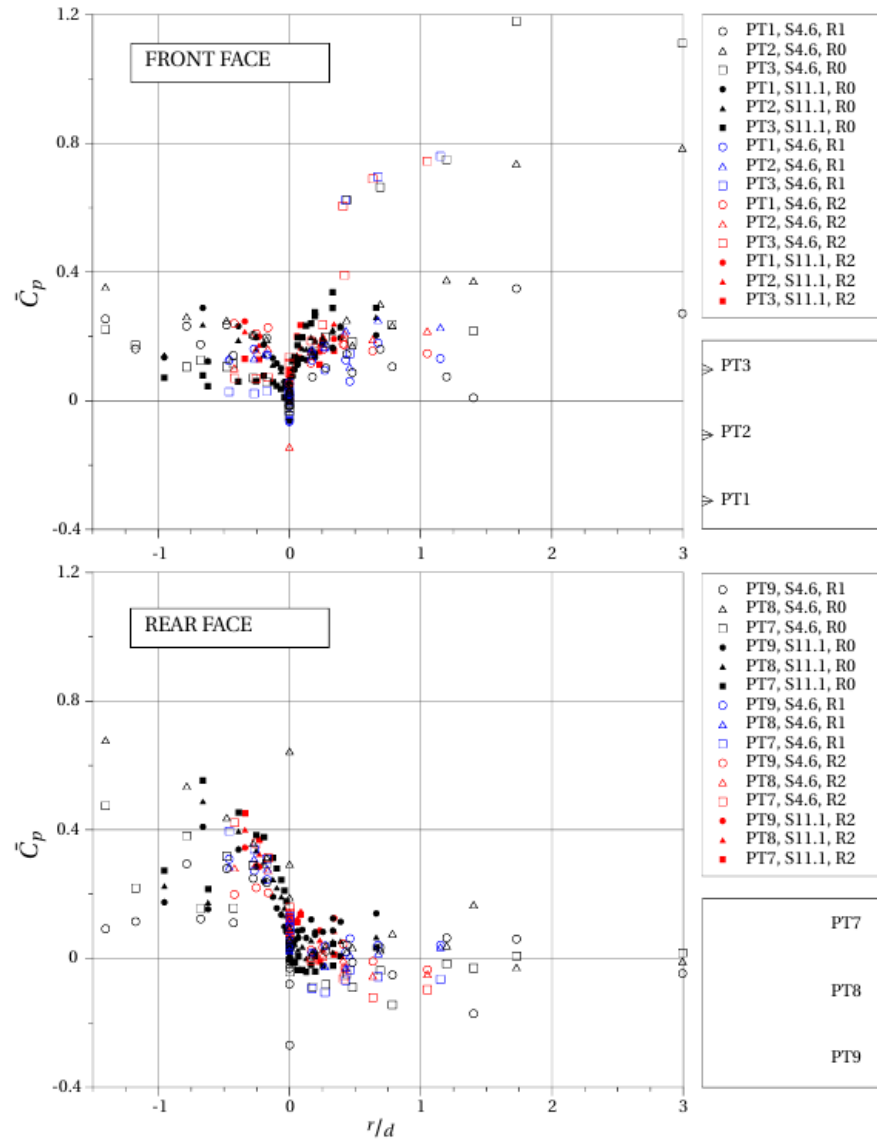
Re-arrange to give design equation



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.6 Give us pressures!

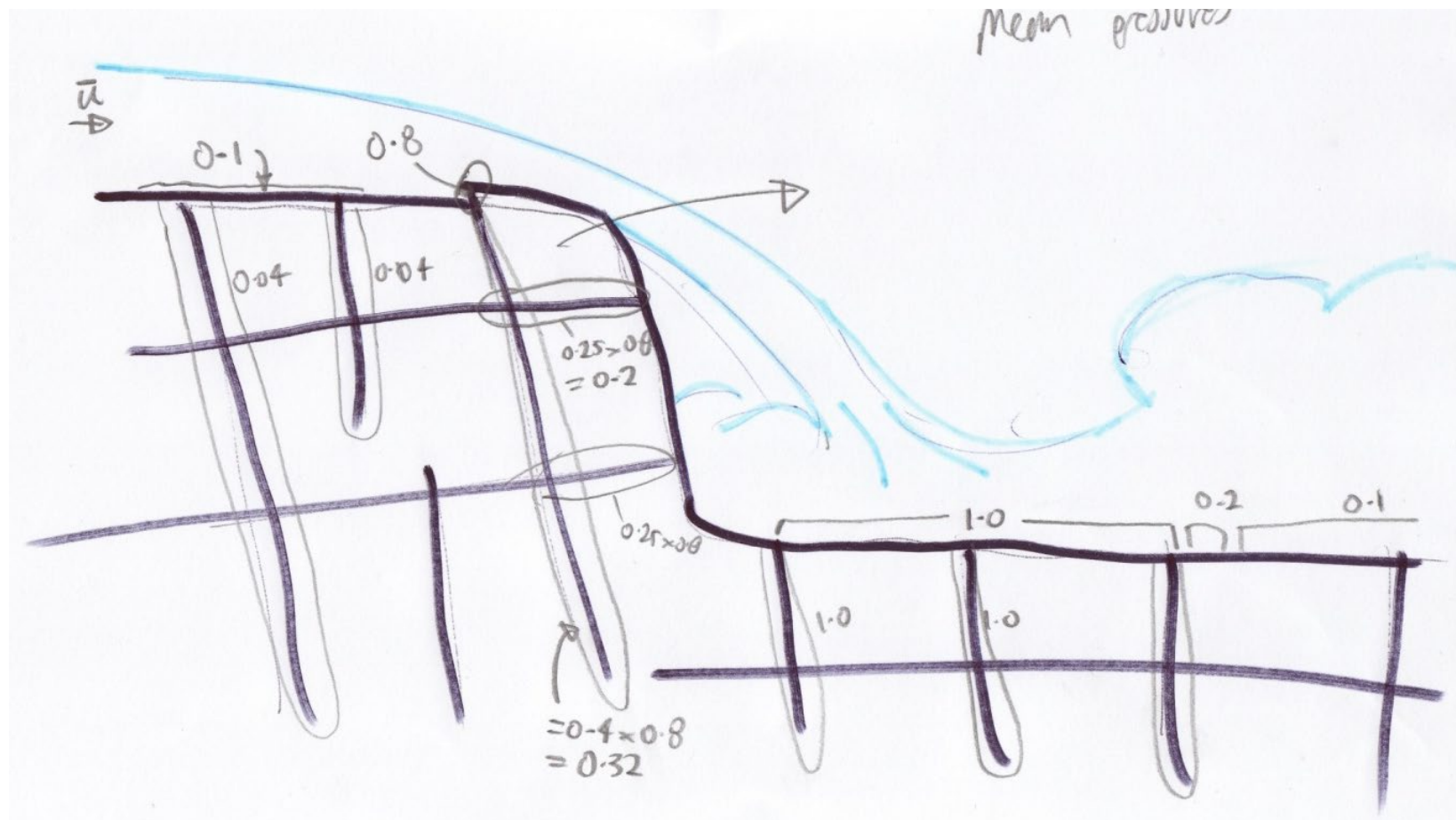
Test data



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.6 Give us pressures!

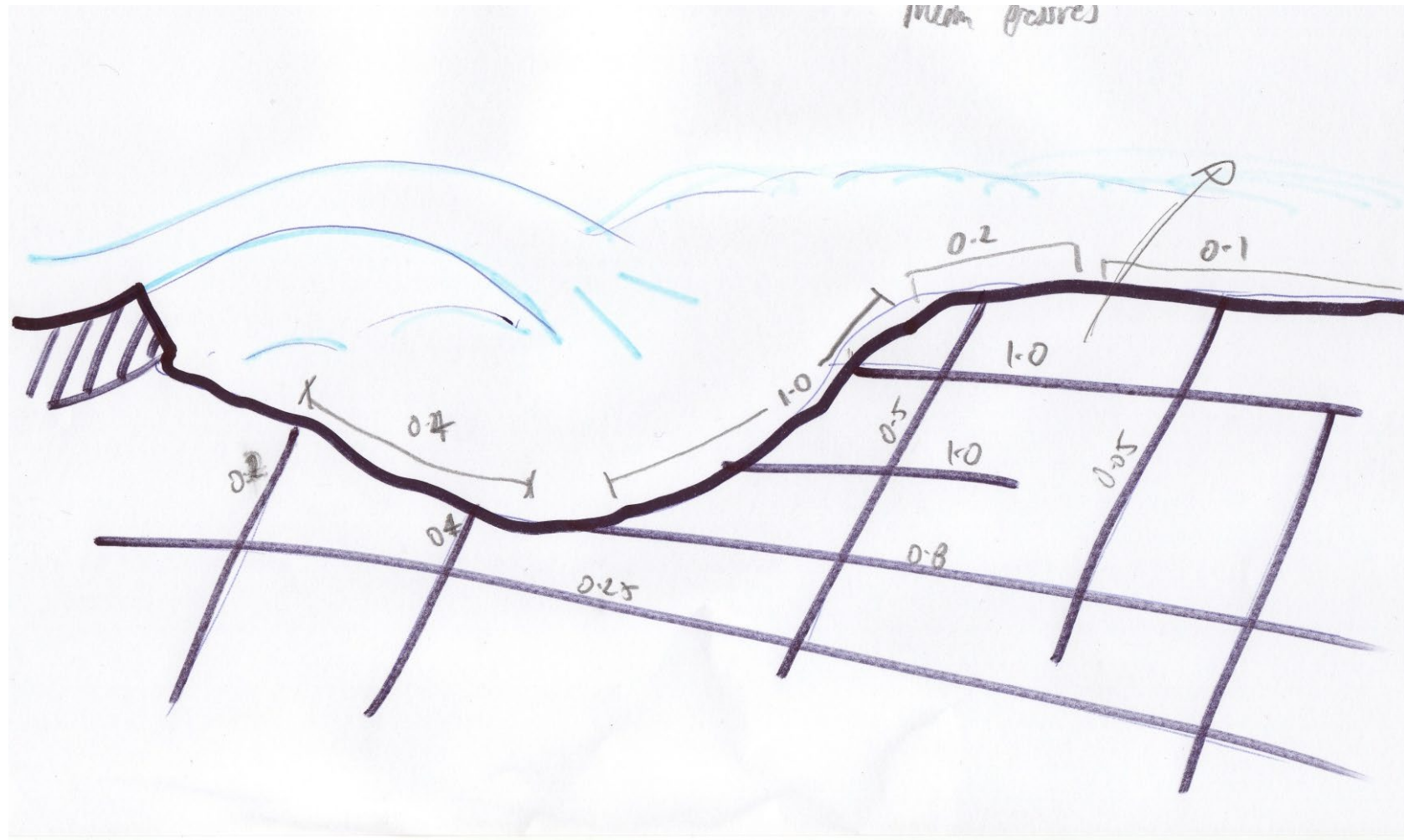
Eg headcutting ...



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.6 Give us pressures!

Eg Wivenhoe style ...

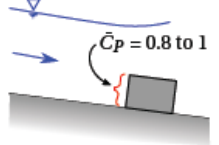
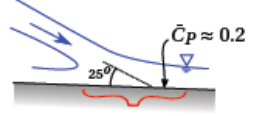
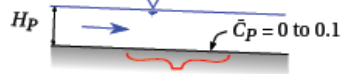
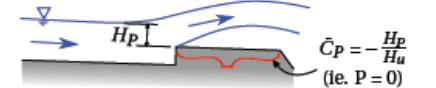
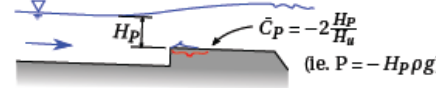
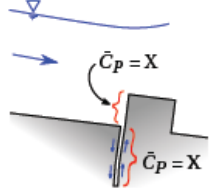
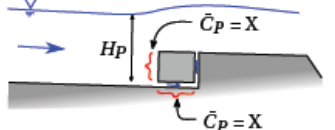


3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.6 Give us pressures!

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 impingement.	Figure 6.35 (PT3); Figure 6.37 (PT1, PT2, PT3 for scour hole cases)	
		$\bar{C}_p = 0.2$ for surfaces 25° 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, throughflowing, defects with dip parallel to impinging flow adopt the surface $\bar{C}_p$ value.	Figure 6.38 (PT10, PT11 for scour hole cases)	



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.6 Give us pressures!

Design coefficients

Daylighting, thoughflowing, defects with dip perpendicular to impinging flow adopt $0.4 \times$ surface $\bar{C}_p$ value.

Buried (ie - non-daylighting) defects adopt $0.75 \times$ average of connected defect $\bar{C}_p$ values.

Figure 6.35 (PT1, PT2 for $0 < r/d < 1.5$; PT8, PT9 for $-1 < r/d < 0$)

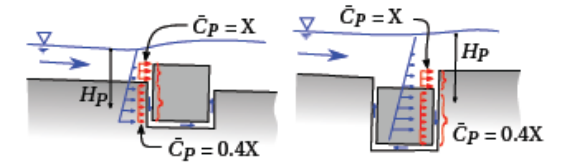
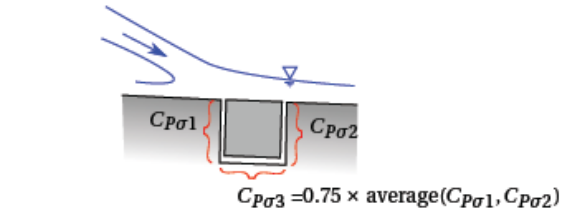


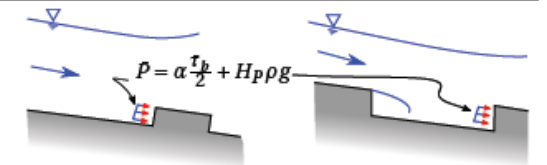
Figure 6.37 (PT7, PT8, PT9 for scour hole cases), Figure 6.26 (F_{σ} increase as two joints exposed due to rotation), Figure 6.36 (PT10 and PT11)



$$\bar{P} \text{ (kPa)} = \alpha \frac{\tau_b}{2} + H_p \rho g$$

for surfaces protruding perpendicular to bed-parallel flow (preferable for small protrusions).

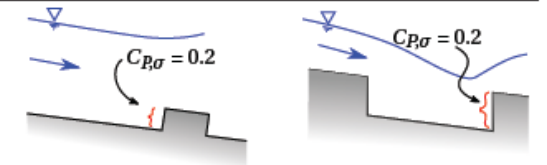
α from Equation A.1.69. See Section 6.4.5



$$\sigma_p \text{ (kPa)} = C_{p\sigma} \rho \frac{\bar{u}^2}{2}$$

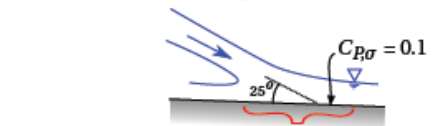
$C_{p\sigma} = 0.2$ for surfaces protruding perpendicular to bed-parallel flow or jet impingement.^{#1.}

Figure 6.41 (PT3); Figure 6.43 (PT1, PT2, PT3)



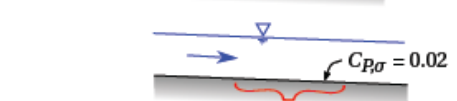
$C_{p\sigma} = 0.1$ for surfaces 25° to flow direction or jet impingement.^{#1.}

Figure 6.44 (PT4, PT5, PT6)



$C_{p\sigma} = 0.02$ for surfaces parallel (stream-lined) to flow, no detachment.^{#1.}

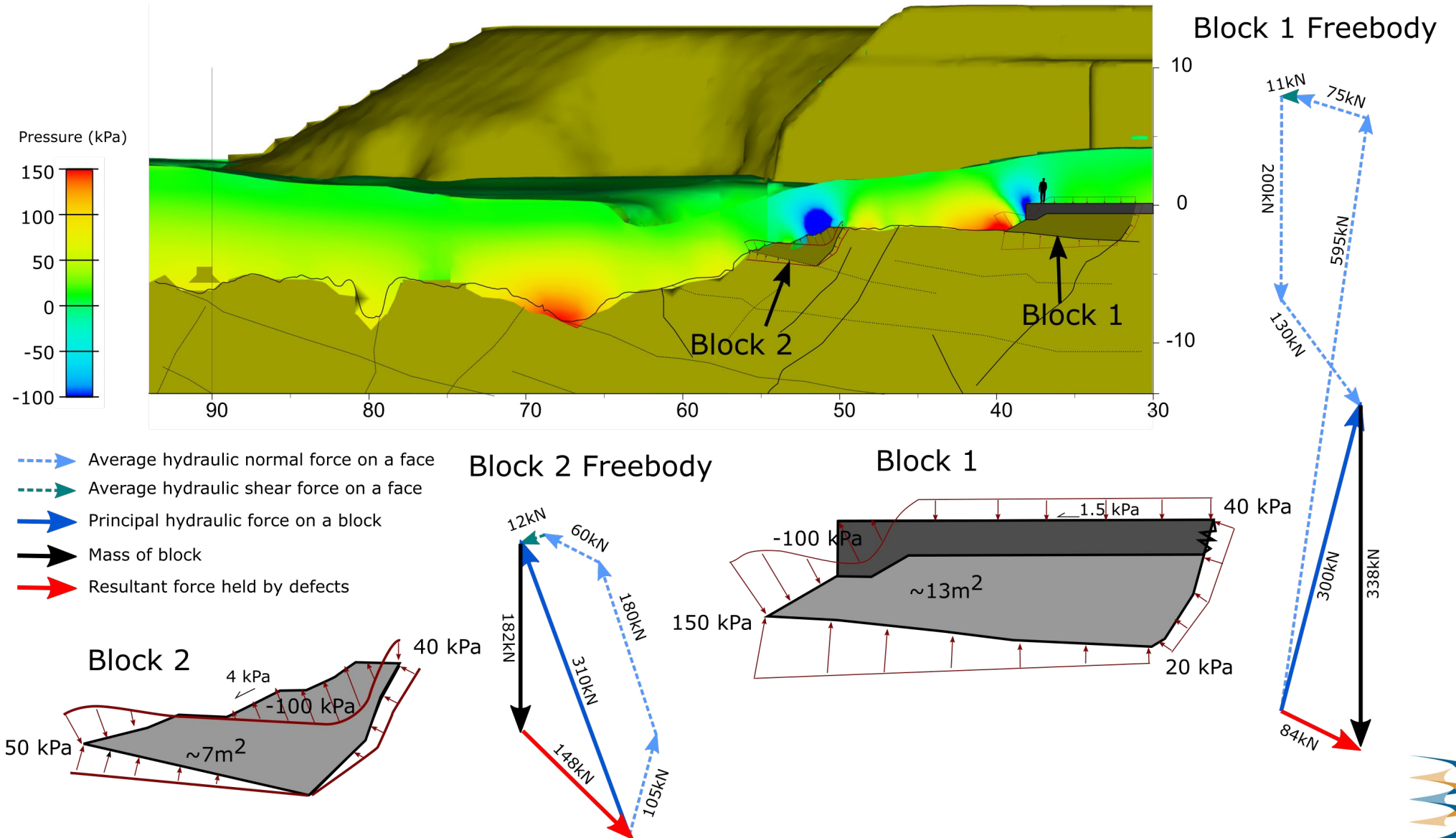
Figure 6.42 (PT4, PT5, PT6 for $r/d=0$)



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.6 Give us pressures!

An example

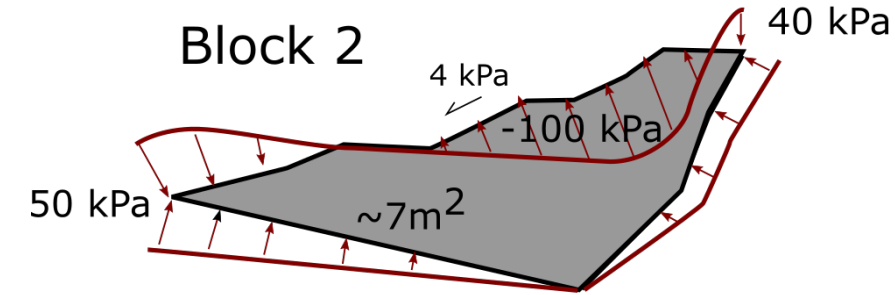


3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.6 Give us pressures!

An example

These pressures are based on 'interpreted' C_p values and conceptualised {guessed} penetration



It is possible to calculate pressures in defects, but would require assuming defect shape, persistence and aperture, and ... the existence of the block is interpreted anyway. Calculations create an aura of accuracy, on what basis?



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.7 Salutory warnings from groundwater

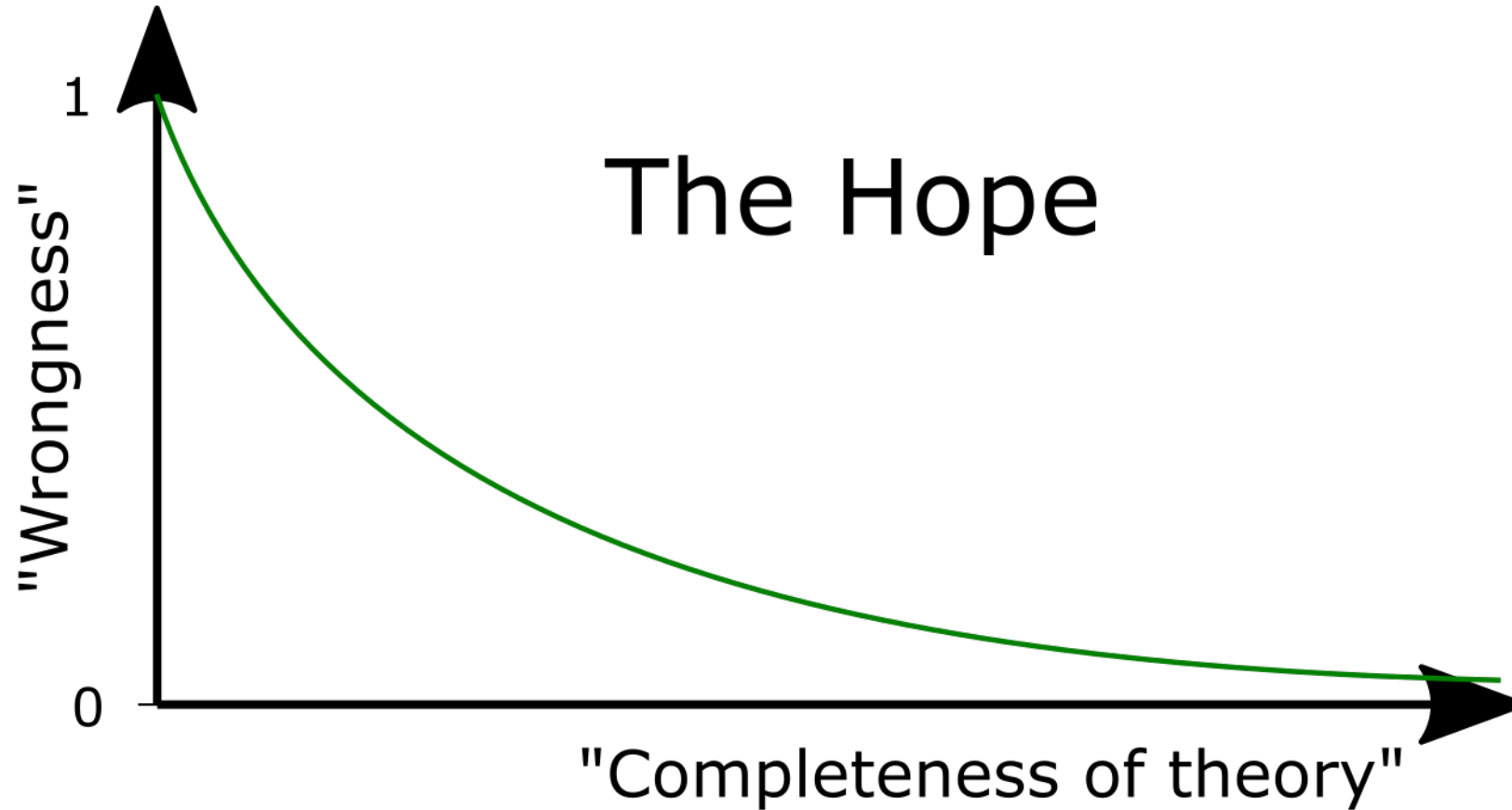
Due to their simplified physical assumptions and geometry, analytical solutions normally do not directly solve 'real-world' problems. Nevertheless, they serve a number of important purposes. First, they are useful as instructional tools ... elegant analytical solutions are most useful in presenting fundamental insights. [Secondly], despite their simplifying assumptions, analytical solutions can be used as a tool for first-cut engineering analysis in a feasibility study. More sophisticated models normally require ... information that is either not available or not known to the required resolution at the time of initial investigation. A sophisticated model without the support of reliable input data does not provide more accurate results.

Cheng and Ouazar, in Bear et al 1999



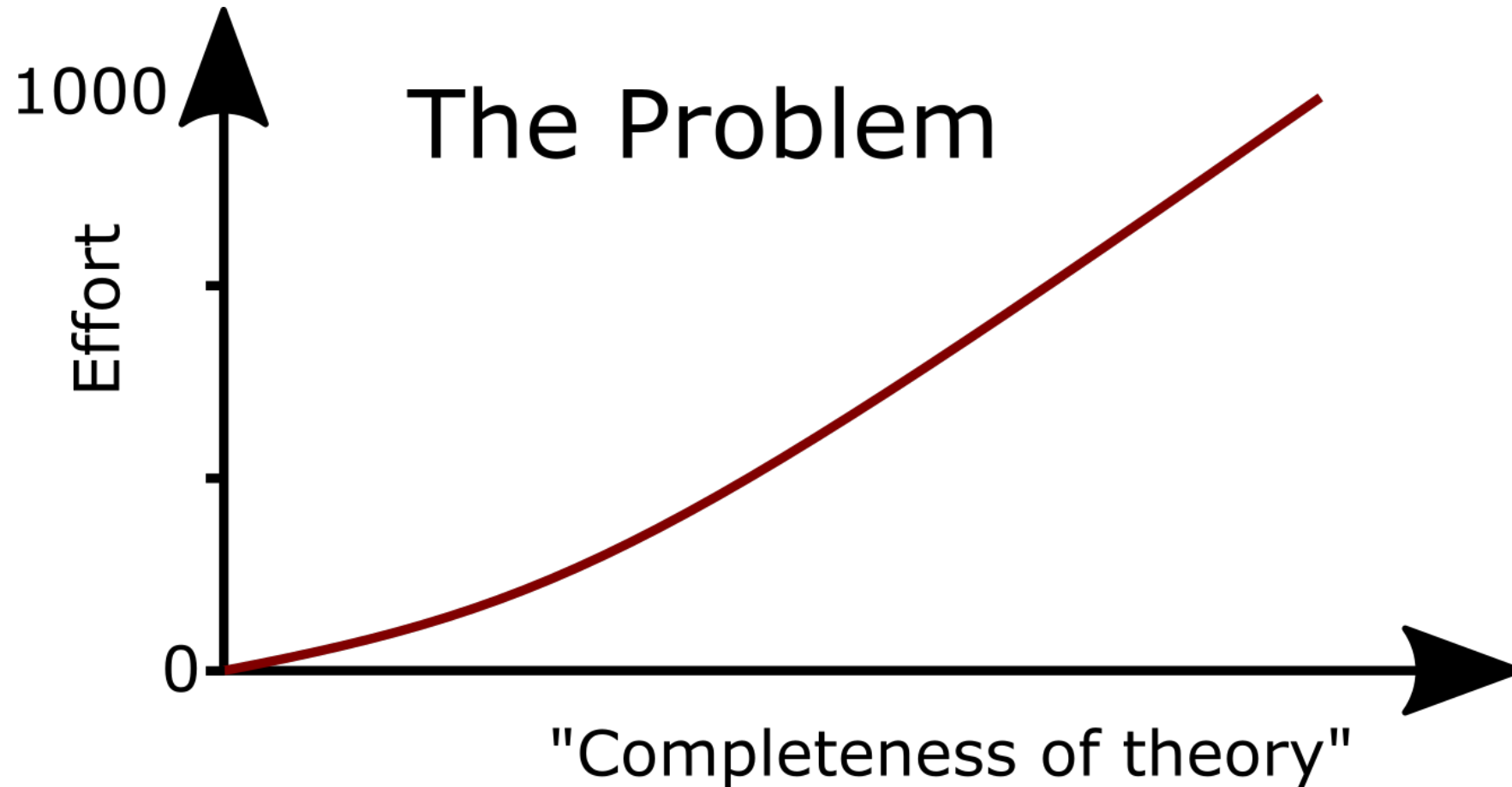
3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.8 All models are wrong



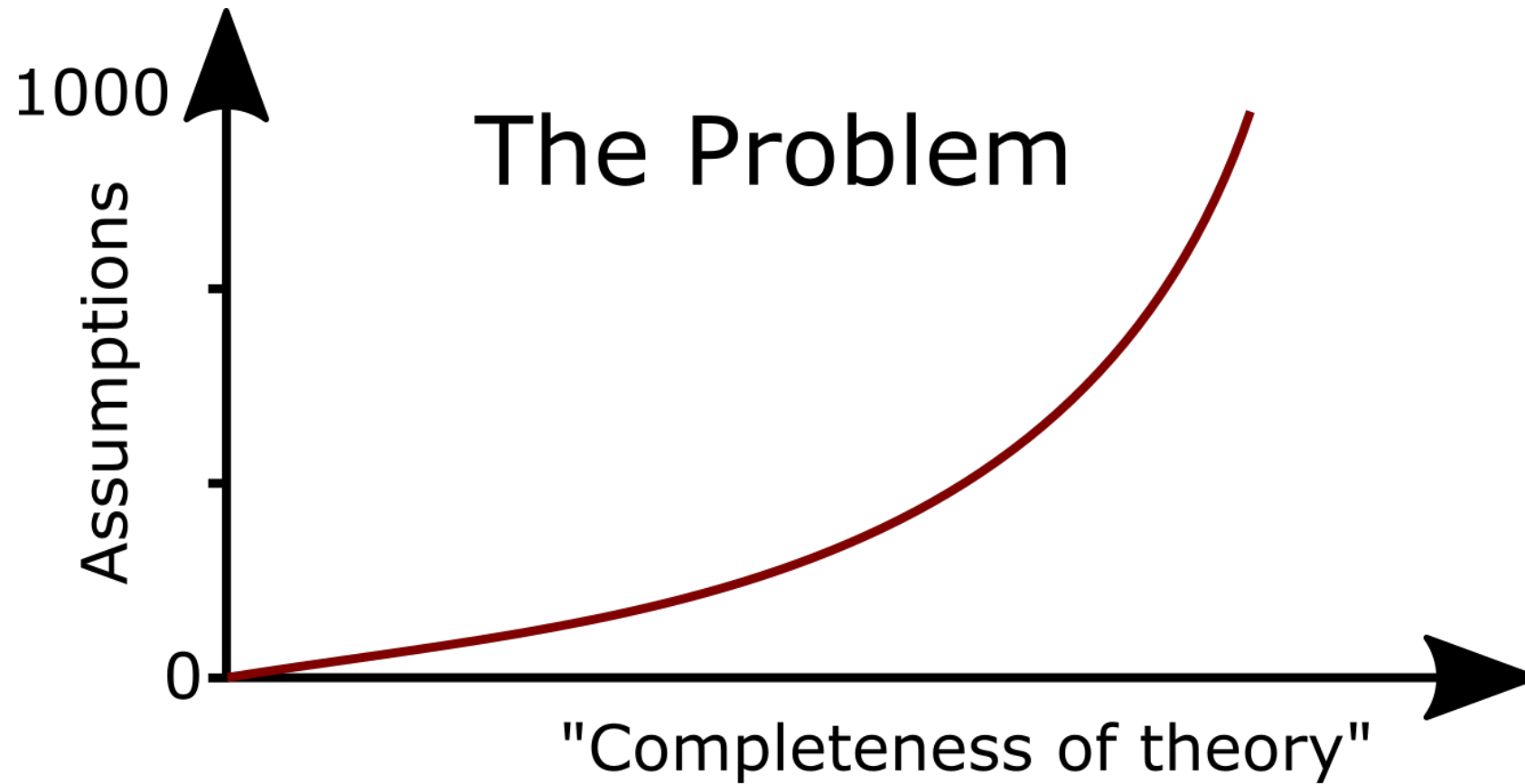
3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.8 All models are wrong



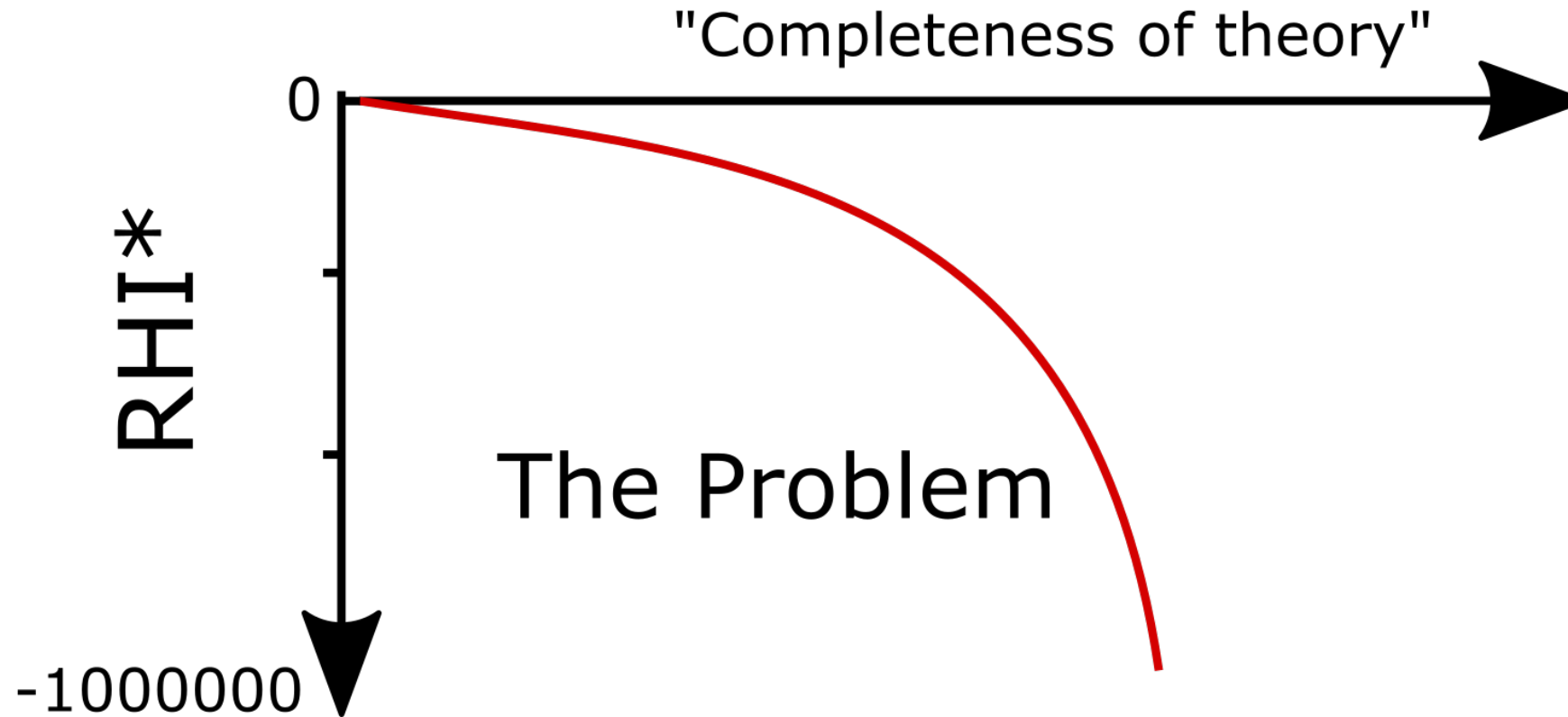
3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.8 All models are wrong



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.8 All models are wrong

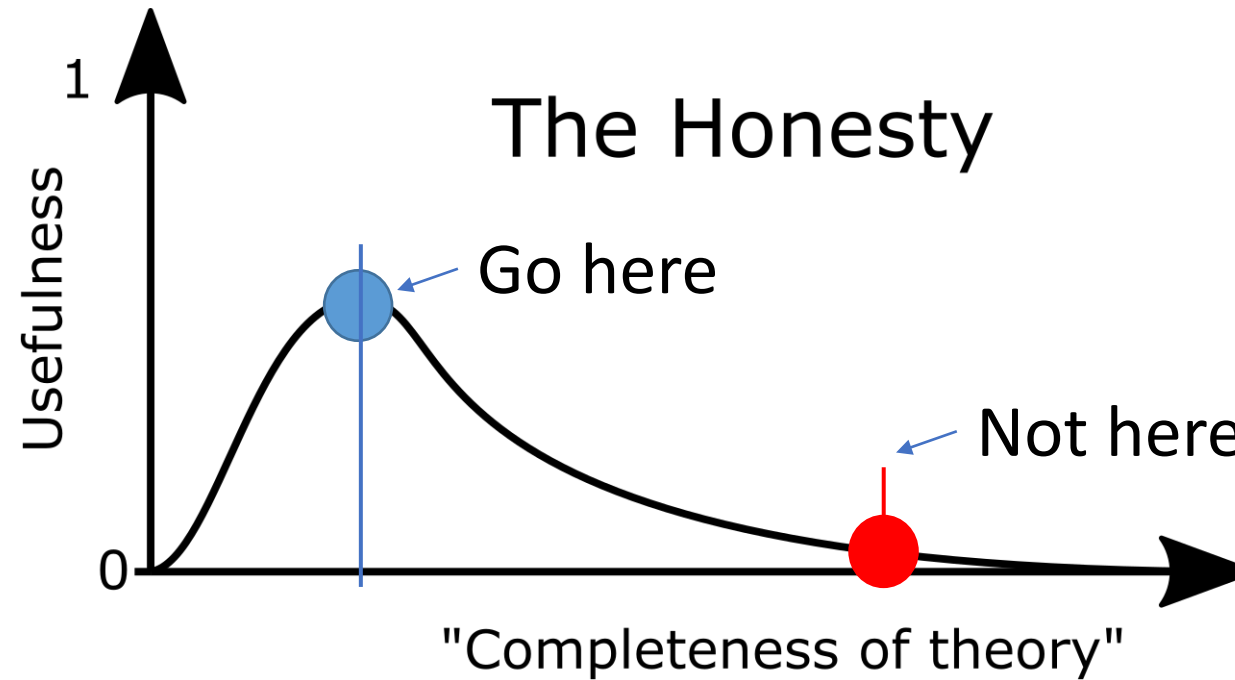


* RABBIT-HOLE INDEX



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.8 All models are wrong



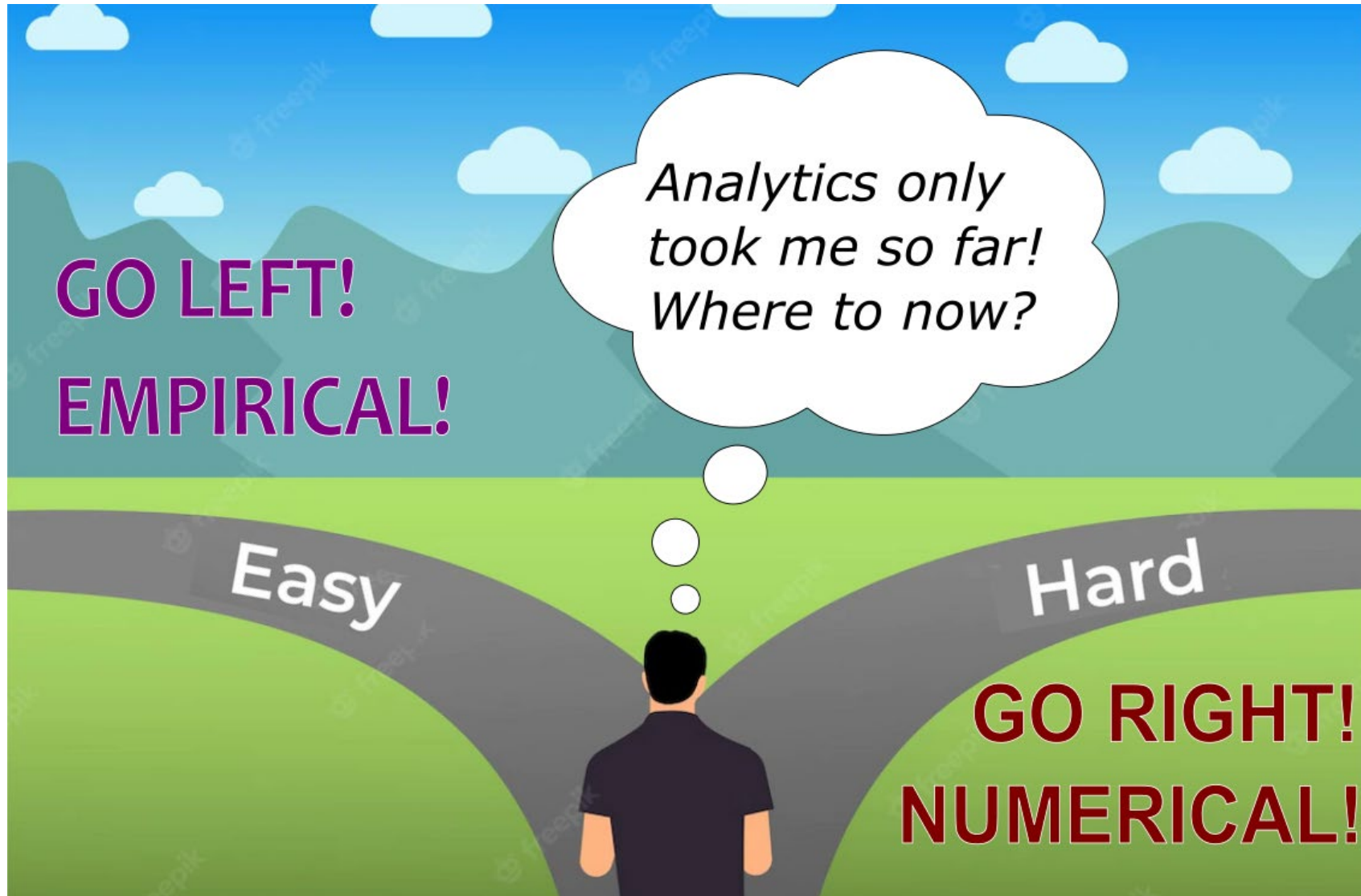
"all models are wrong, some of them are useful".

(George Box ??, 1976)



3.0 KINEMATICS AND ANALYTICAL SOLUTIONS

3.9 Where do we go?

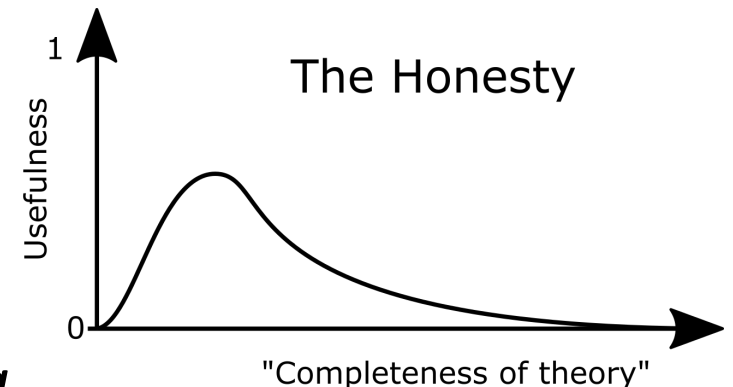


4.0 GO LEFT! – COMPARATIVE TECHNIQUES

4.1 Rock mass indices

- Early 1970's rock mechanics was still emerging as a new discipline
- Many leading academics were from mechanical engineering
 - Used to concrete, steel etc – materials with known engineering properties
 - Rock masses are comparatively random structures – problematic to their thinking
- Bieniawski in 1973 from CSIR in South Africa, presented RMR system
 - Numbers assigned to describe qualities of rock substance and defects
 - A final number assessed with mathematical operations
- Barton in 1974 released the Q system
- Numerous “rock mass index” systems now exist
 - Usually derivatives of the Q and RMR systems

“A compromise between a complete theory and ignoring rock mass properties entirely” Hudson and Harrison 2005



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.1 Rock mass indices

Example – the Q system

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

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	5
F. Three joint sets	6
G. Three joint sets plus random	7
H. Four or more joint sets, randomly jointed, "sugar cube"	8
J. Crushed rock, earthlike	9

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) 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

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°)
F. Softening or low friction clay inite, gypsum or other mineral fillings (Continuous, < 5 mm in thickness)	4.0	(8°—16°)
H. Medium or low over-consolidation, softening, clay mineral fillings. (Continuous, < 5 mm in thickness)	6.0	(16°—24°)
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, 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, 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 $(\phi)_r$ are intended as an approximate guide to the mineralogical properties of the alteration products, if present

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



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.2 Birth of the ‘comparative’ method

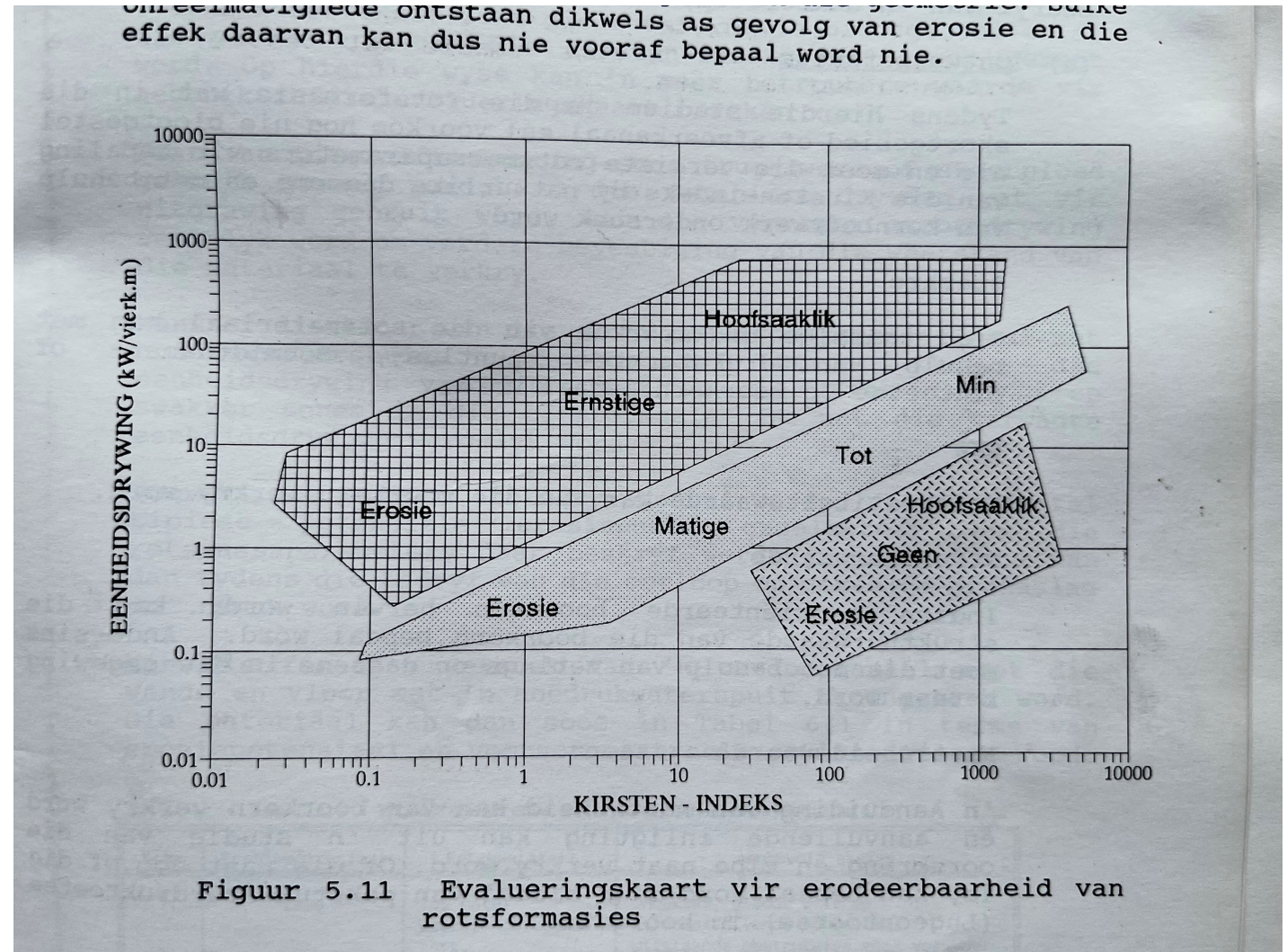
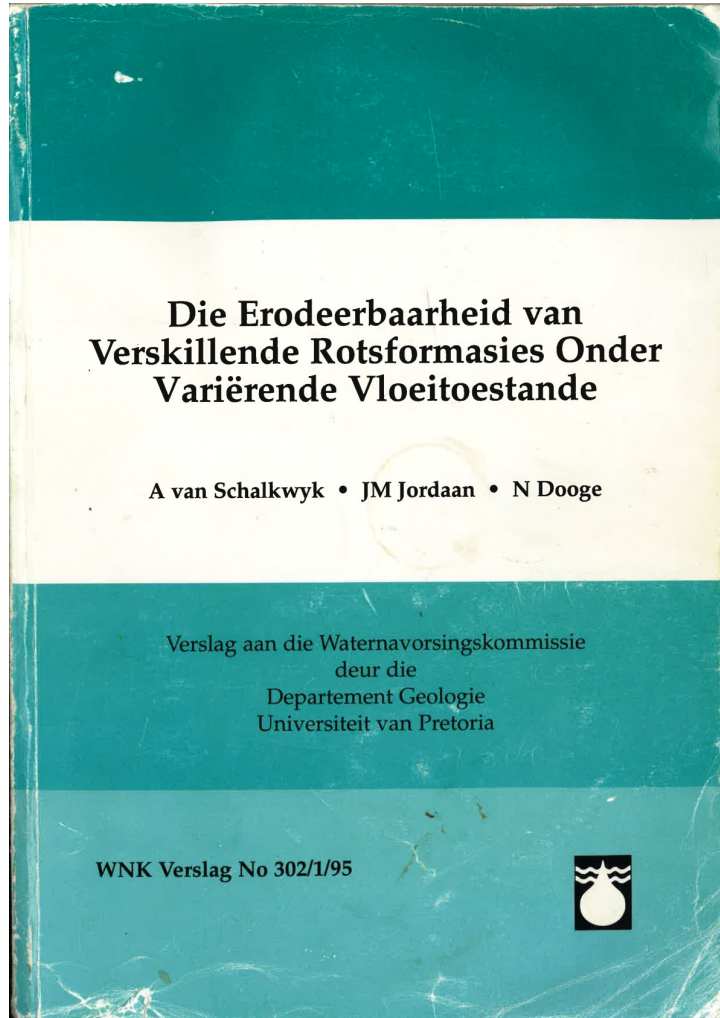
- One such derivative system was an index of “excavatability” by Hendrik Kirsten in South Africa (1982) (based on the Q-system)
- At a conference in mid-80’s Hendrik attended a talk on rock mass erosion. At that time he stood up and suggested that maybe erosion of rock by water is similar to excavation of rock by a ‘ripper’
- He later discussed this with his then colleague at SRK in Johannesburg - George Annandale – who suggested that the index of stream power as used in fluvial geomorphology may be a useful index of erosion power
- Armed with these two ‘indexes’, they set out to co-publish a paper on the matter – started collecting data
- Professor Monty van Schalkwyk in University of Pretoria started collecting data from case studies of spillway erosion around South Africa



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.2 Birth of the 'comparative' method

Van Schalkwyk, 1994



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.2 Birth of the ‘comparative’ method

Annandale, 1995

Erodibility
Erodabilité

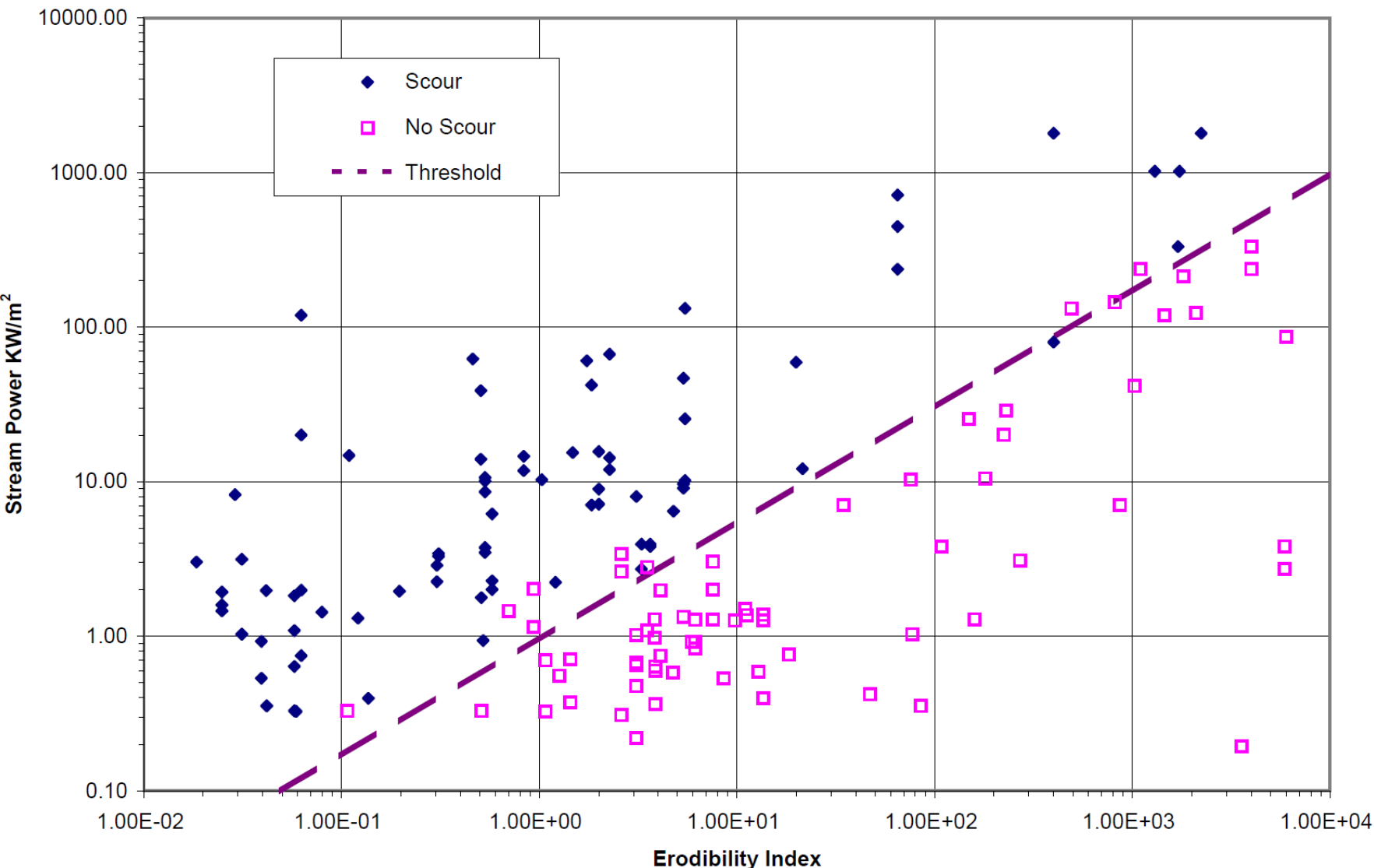


G. W. ANNANDALE
Engineering & Hydrosystems Inc.
8122 SouthPark Lane, Suite 208
Littleton,, Colorado 80120
(303) 683-5191
e-mail: george.annandale@enghydro.com

ABSTRACT
Hydraulic erodibility of natural and engineered earth materials, including both soil and rock, can be evaluated in terms of a rational correlation between rate of energy dissipation of flowing water and an erodibility classification of the materials. Earth materials ranging on a continuum from cohesionless granular soil through massive hard rock can be characterized in terms of an erodibility index, K . The parameters of the index include key material and mass properties that can be measured in the field and at low cost. These properties include earth mass strength, block/particle size, discontinuity/inter-particle bond shear strength, shape of material units and their orientation relative to the flow. The relative magnitude of erosive power of flowing water is represented by its rate of energy dissipation for a variety of flow conditions, including head cuts, hydraulic jumps, grade changes, and open channel flow. A log-log plot of experienced rate of energy dissipation versus the erodibility index of the studied materials demonstrates a correlation from which the critical threshold to initiate erosion of a material can be predicted for any given set of hydraulic conditions. The method is based on an analysis of 137 field observations of spillway performance collected by the U.S. Department of Agriculture, observations at Bartlett Dam, Salt River Project, Arizona, at four South African dams, and published data pertaining to initiation of sediment motion.

RÉSUMÉ
L'érodabilité sur le plan hydraulique de matériaux de terrain naturels ou remaniés, comprenant à la fois de la terre et des roches, peut être évaluée en terme de corrélation entre le taux de dissipation d'énergie de l'eau qui percole et une classification des matériaux selon leur érodabilité. Ces matériaux à base de terre, formant un continuum allant du sol constitué de granulats sans cohésion jusqu'au rocher massif peuvent être caractérisés par un indice d'érodabilité K . Les paramètres de cet indice comprennent des propriétés caractéristiques de la nature du matériau et de sa masse qui peuvent être mesurées in situ pour un coût minime. Ces propriétés comprennent la résistance interne du matériau, la taille des éléments granulaires, la résistance au cisaillement inter-particules, la forme des granulats et leur orientation relativement à l'écoulement. L'intensité relative du pouvoir érosif de l'eau en mouvement est représentée par son gradient de perte de charge pour une variété de conditions d'écoulement, comprenant des coupures de l'écoulement, des ressauts hydrauliques, des changements de régime et des écoulements à surface libre. Une représentation graphique log-log des mesures de perte de charge en fonction de l'indice d'érodabilité des matériaux étudiés montre une corrélation à partir de laquelle le seuil critique de début d'érosion d'un matériau peut être prédit pour tout ensemble donné de conditions hydrauliques. La méthode est basée sur l'analyse de 137 observations de terrain sur le fonctionnement d'un évacuateur de crues faites par le Département de l'Agriculture des USA au barrage de Bartlett sur le projet de la Salt River en Arizona, à quatre barrages en Afrique du Sud et à des données de la littérature concernant le début d'érosion.

Introduction
This paper presents a rational method for determining the erodibility of earth materials. The term earth material is considered to embrace the entire spectrum of soil and rock materials, ranging continuously from



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.2 Birth of the ‘comparative’ method

Kirsten, 2000

ERODIBILITY CRITERION FOR AUXILIARY SPILLWAYS OF DAMS

Hendrik A. D. Kirsten¹, John S. Moore², Louis H. Kirsten³ and Darrel M. Temple⁴

ABSTRACT

The ability to reliably design auxiliary spillways has become a pressing requirement because of the very large number of dams involved. An empirical classification index representing the erosional resistance of the overall range of particulate, jointed, and intact earth materials is presented and correlated for a number of practical cases from Arkansas and Kansas in the United States of America and from South Africa with the specific stream power of flows observed to be associated with various degrees of erosion. The United States Department of Agriculture data base and the format in which the data were prepared for the purposes herein, are described in detail. The modes of erosion that occur in spillways are defined. Guidelines are provided for evaluating the failure status of an erosion damaged spillway that enables determination of whether the incident specific stream power exceeded, equalled, or fell below the erosional resistance of various sections of the ground profile affected. The correlation function between specific stream power and erodibility index provides the required design criterion.

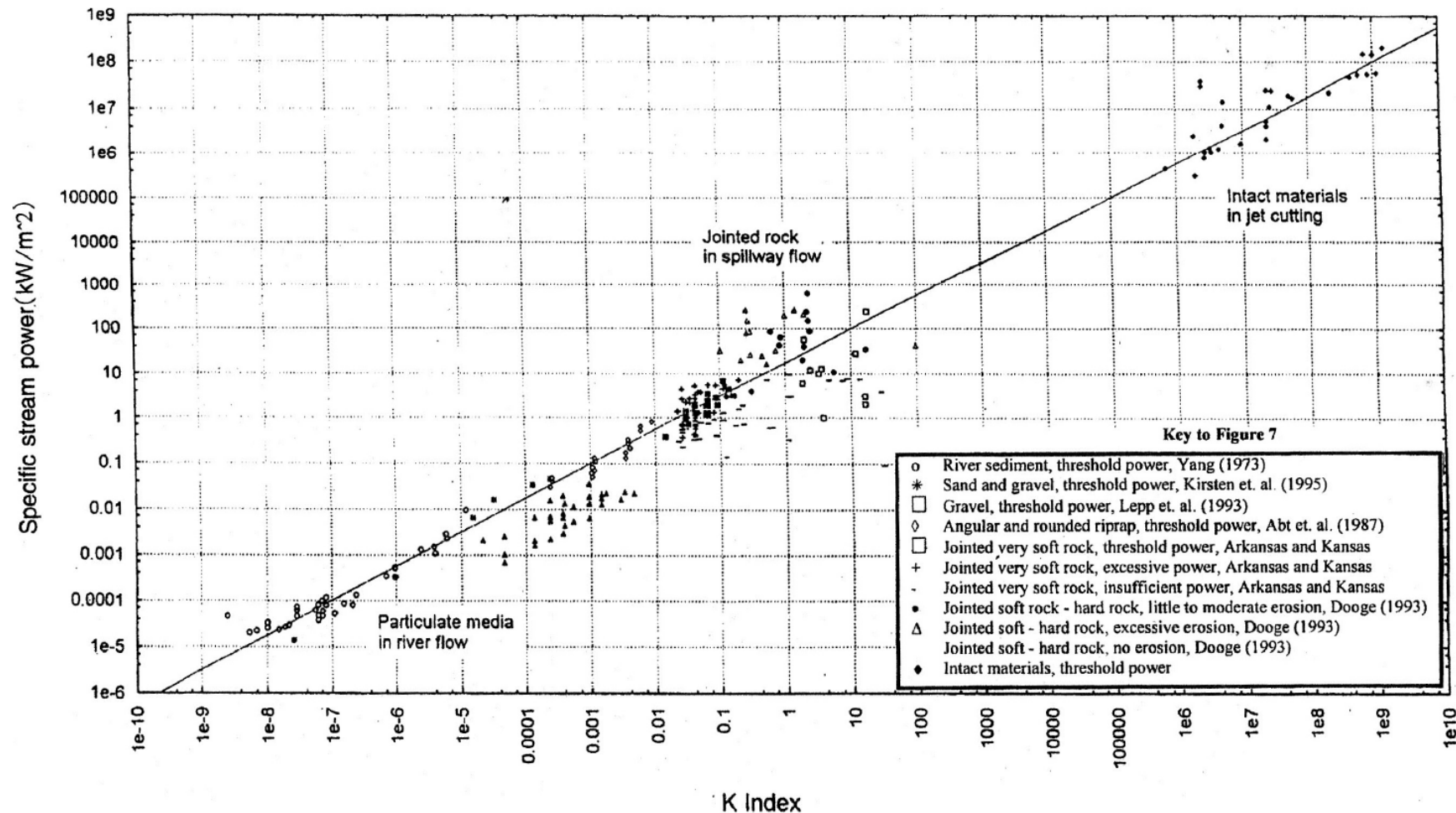
Key Words: Auxiliary spillway, Erosional resistance, Erodibility index, Stream power

1 INTRODUCTION

Dams have been designed traditionally not to be overtopped during probable maximum flood events. According to Powledge et. al. (1989), many tens of thousands of dams have, however, become potentially subject to overtopping as a result of improvements in the quality of flood data and in the methods for determining probable maximum floods for which it is not possible nor economically feasible to consider modifications to prevent overtopping. Some dams have moreover been observed to have withstood moderate overtopping. Efforts have as a result been concentrated in recent years on the accurate determination of the erodibility of natural ground in auxiliary spillways as a first step in the provision of low cost modifications to the many dams threatened by overtopping.

The Agricultural Research Service (ARS) and Soil Conservation Service (SCS), now known as Natural Resources Conservation Service (NRCS), U.S. Department of Agriculture (USDA), has accordingly collected a substantial body of data on erosion performance of earth spillways since 1983, Temple et. al. (1993). The data cover a range of materials from soils through rocks of varying lithology, structure, and strength. The spillways represent a variety of widths, lengths, and gradients, in each of which the successive reaches comprised engineered and natural surfaces. The engineered surfaces were either bare of vegetation or were covered with cultivated sod. The natural surfaces generally contained brush and grassland vegetation. The erosion performance of the spillways could be divided into three classes, viz., situations in which the flows exceeded, matched, or fell below the erosional resistance of the material. The data represent dams in 11 states and were collected for the general purpose of evaluating the effectiveness of current design criteria and for recommending improvements in this regard. A specific objective was to determine the advance rate of headcutting in earth spillways.

Moore et. al. (1994) demonstrated in an initial evaluation of the data that it was feasible to develop a criterion for the onset of erosion in terms of stream power and the classification index for ripability developed by Kirsten (1982). The data for Arkansas and Kansas have since been evaluated in more definitive detail. A general classification system for hydraulic erosion has in addition been developed by Kirsten et. al. (1995).



¹ Steffen, Robertson, and Kirsten, Inc.; Box 55291, Northlands 2116, S. Africa

² Natural Resources Conservation Service, USDA, Box 2890, Washington, DC 20013

³ Civil & Structural Engineering Dept., Iscor Mining, Pretoria, S. Africa

⁴ Agricultural Research Service, USDA, 1301 N. Western St., Stillwater, OK 74075

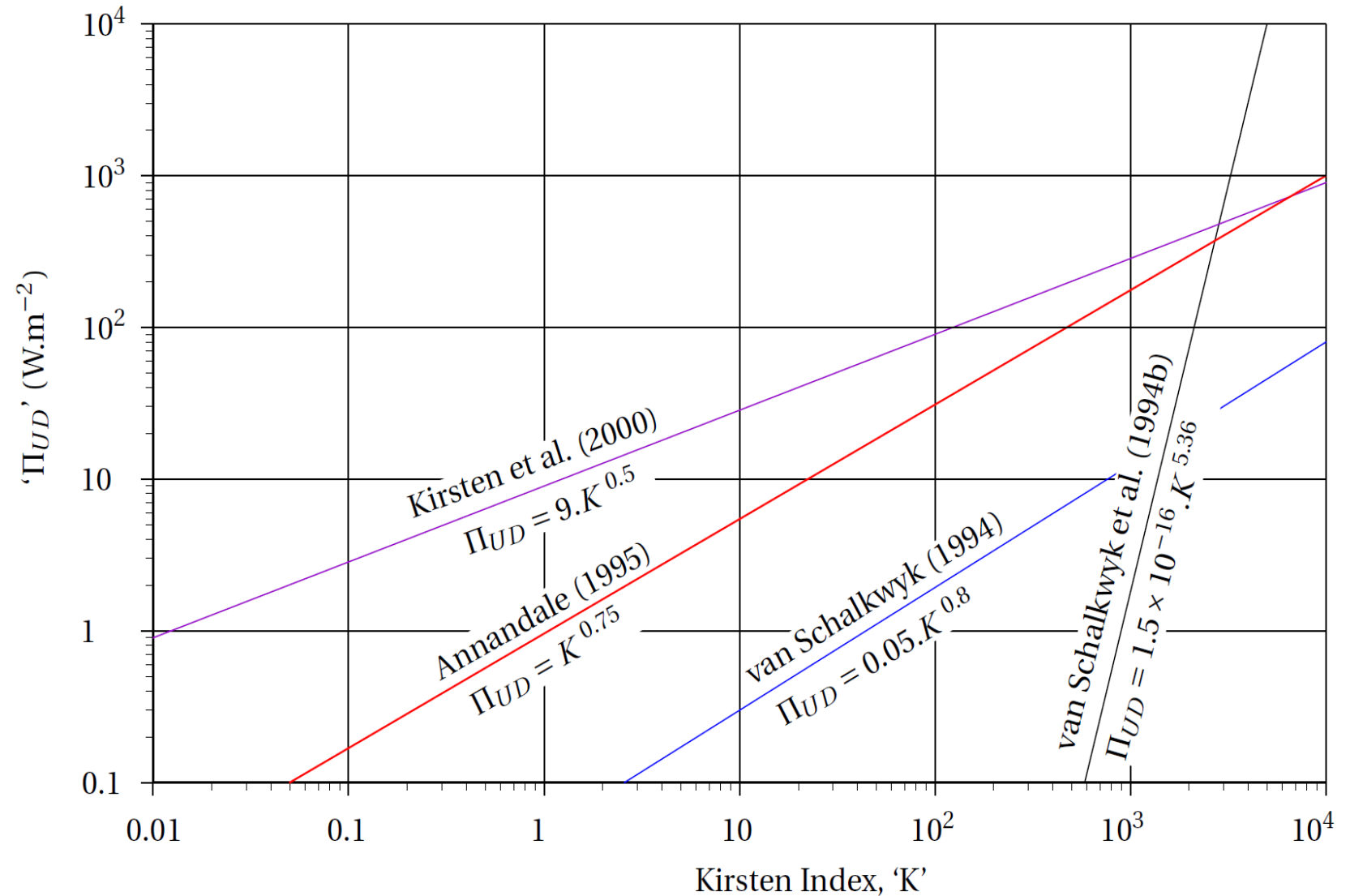
Note: The manuscript of this paper was received in March 1999, Discussion open until March 2001.



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.2 Birth of the ‘comparative’ method

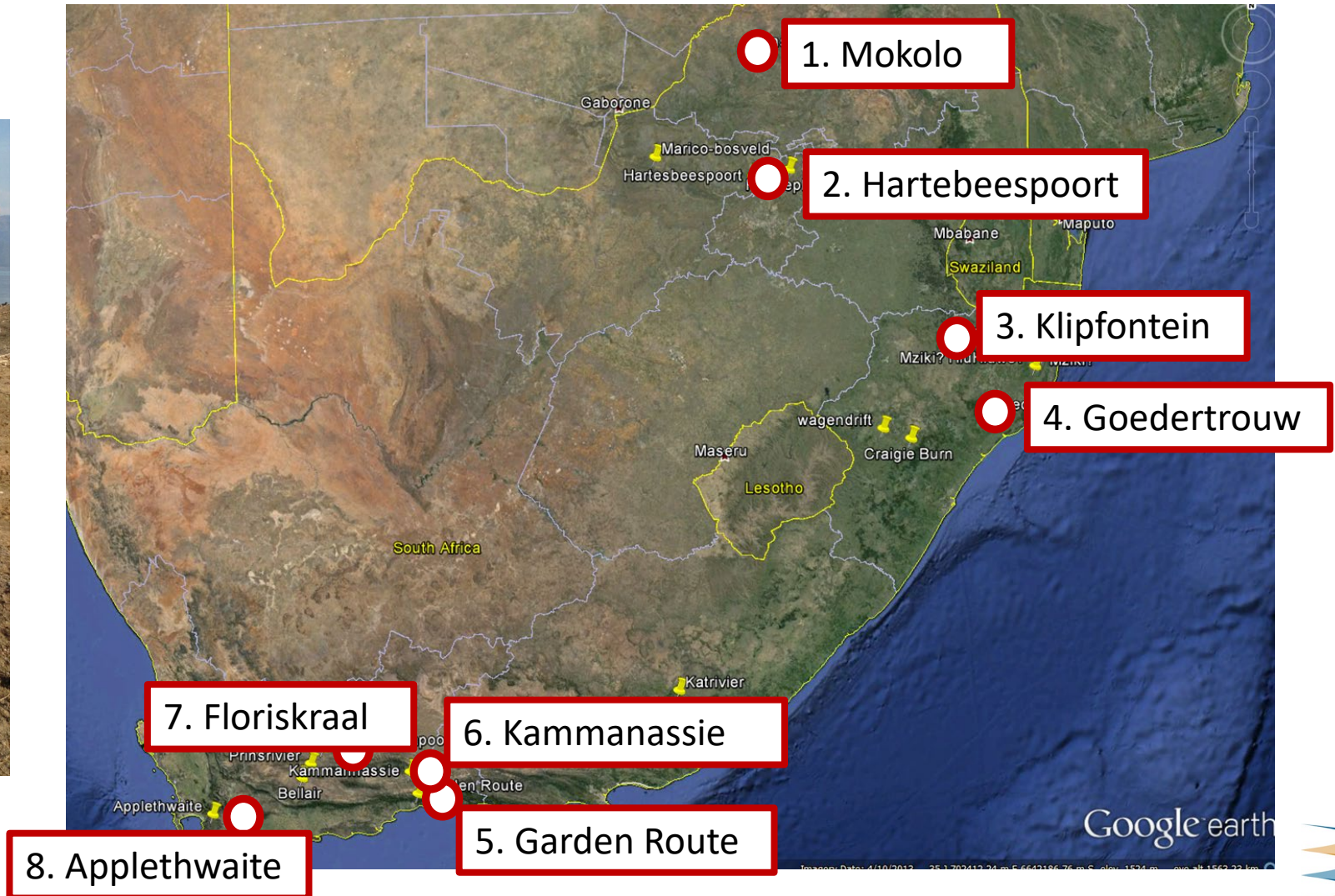
Which to use?



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.3 Review of “Kirsten Index Methods”

Went to South Africa ...



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.3 Review of “Kirsten Index Methods”

At each site

1. Documented amount of erosion

It is subjective – very little ground survey data

Max Depth <i>m</i>	General extent <i>m³ per 100 m²</i>	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



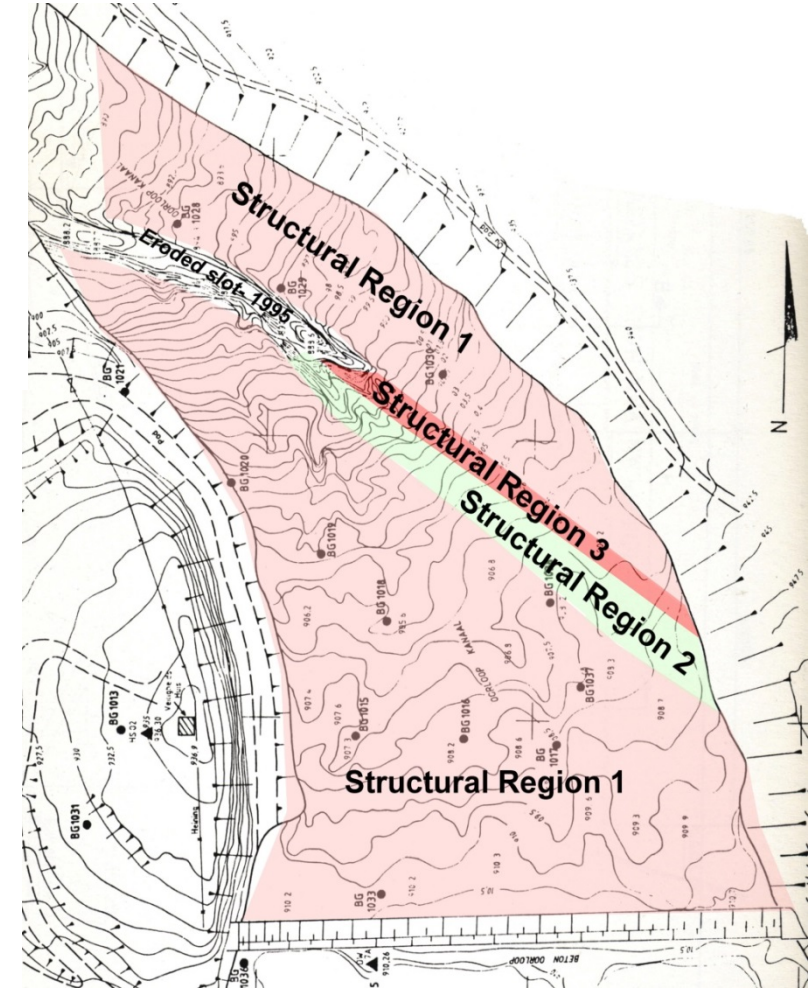
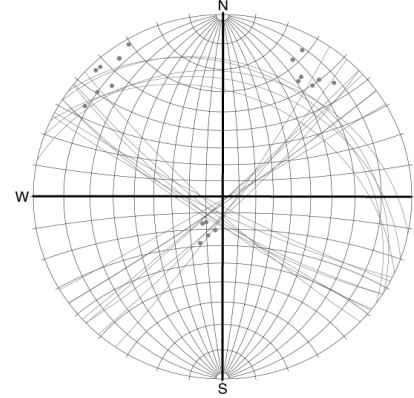
4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.3 Review of “Kirsten Index Methods”

At each site

2. Geological interpretation

- Interpreted geological ‘domains’
- Interpret the properties of rock that was eroded
- Interpret what the mechanism was
- Rock mass indices:
 - Kirsten
 - Q system
 - RMR
 - GSI

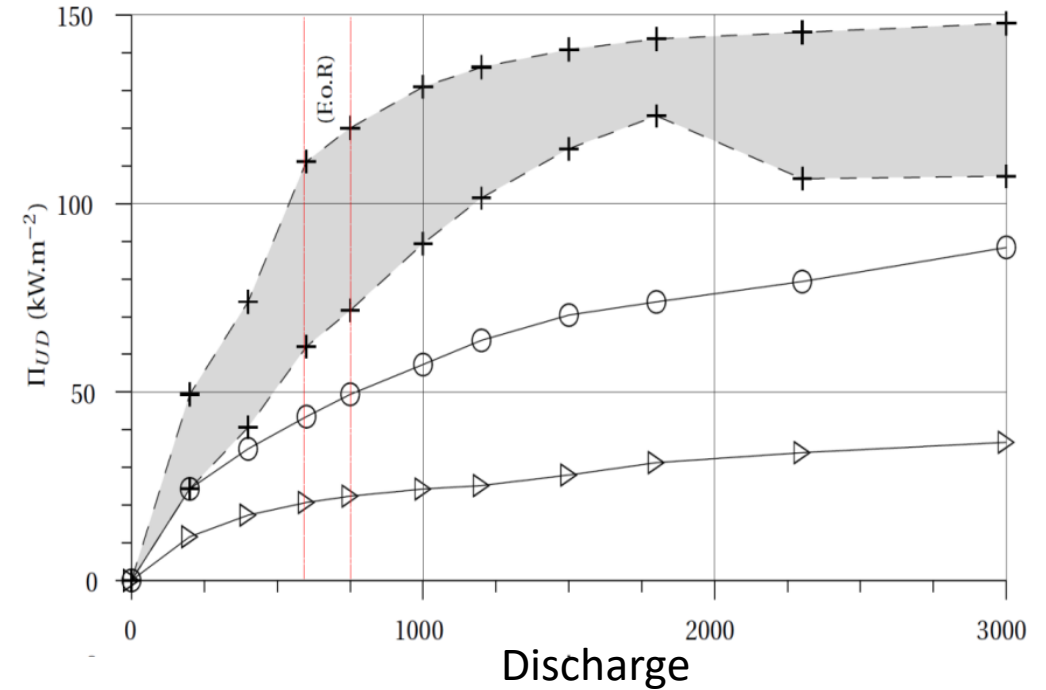
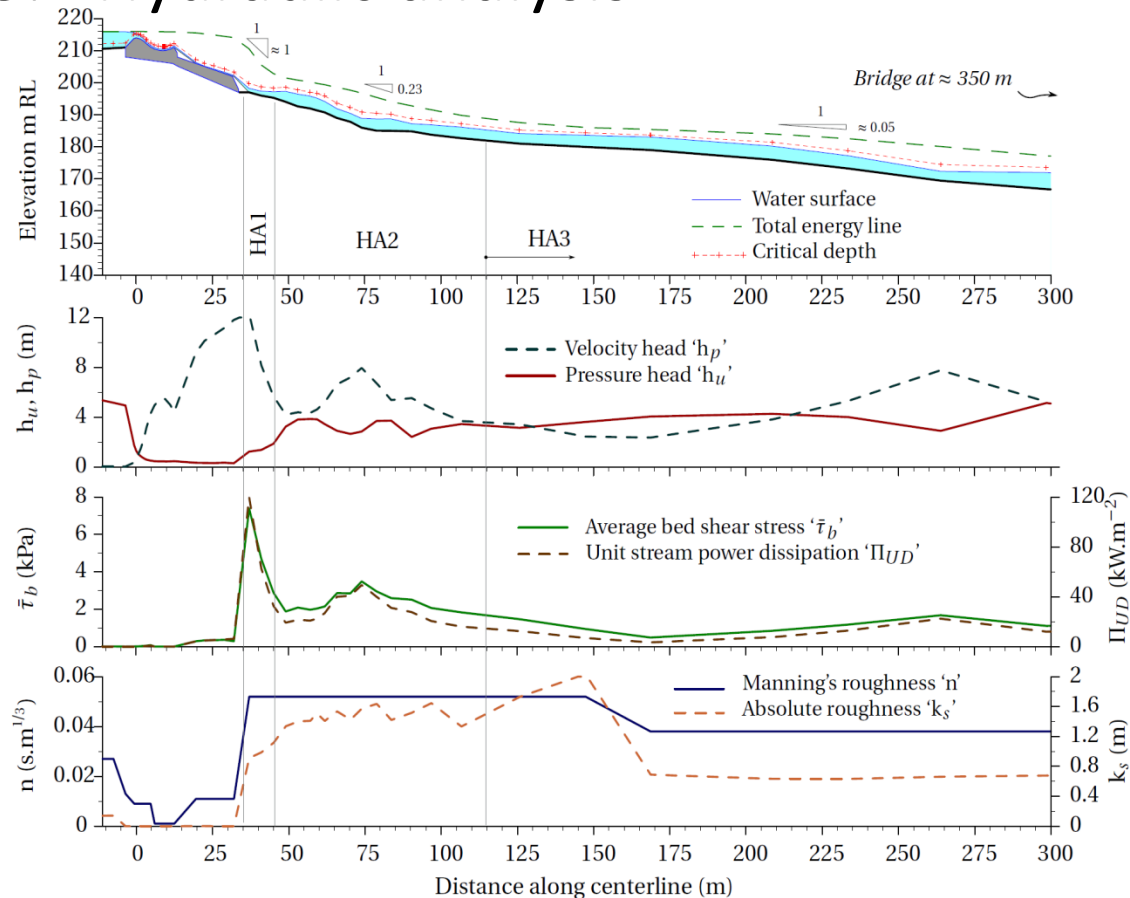


4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.3 Review of “Kirsten Index Methods”

At each site

3. Hydraulic analysis*



*discussed later



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.3 Review of “Kirsten Index Methods”

Repeated the process for further dams in Australia and USA

Australia (19)

South Africa (11)

USA (2)

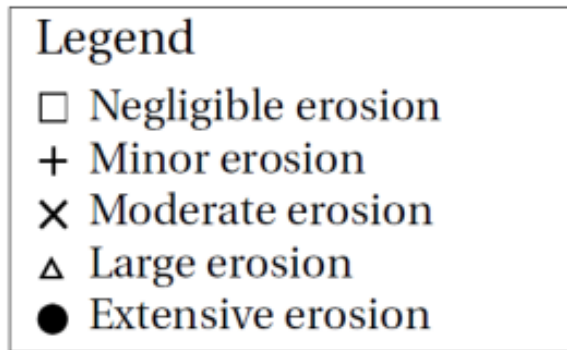
~120 datapoints of erosion in fractured rock environments (vs. ~20 in Annandale)

Country	Dam Name	Inspection		Reporting		Exam. areas
		Date	Personnel ¹	Hydraulics	Geology ²	
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	13-May-14	SEP; PJNP	-	Ref. 2	-
	Raubenheimer					
	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

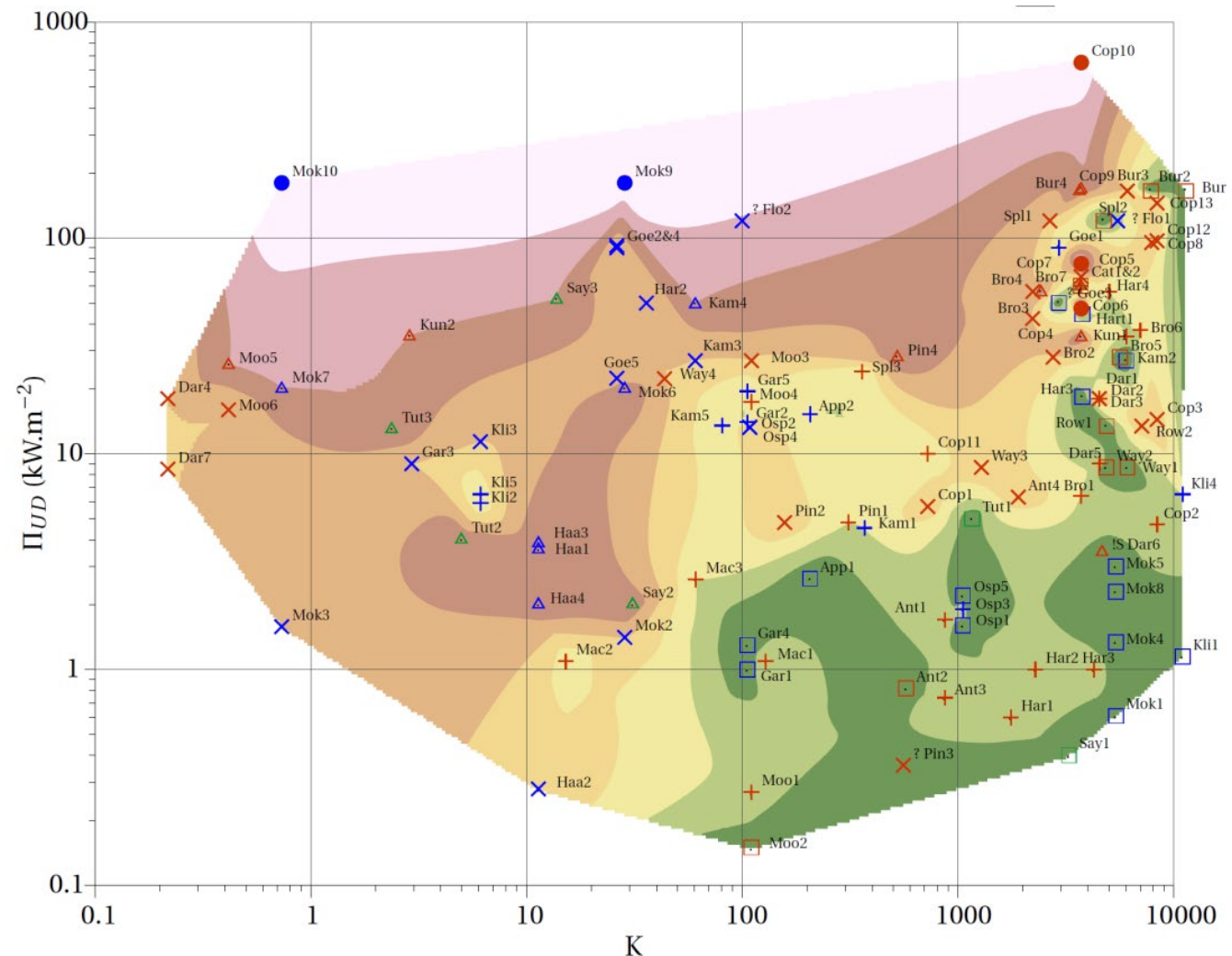
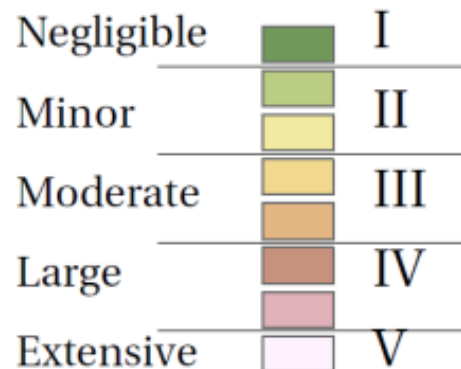
4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.3 Review of “Kirsten Index Methods”

The result



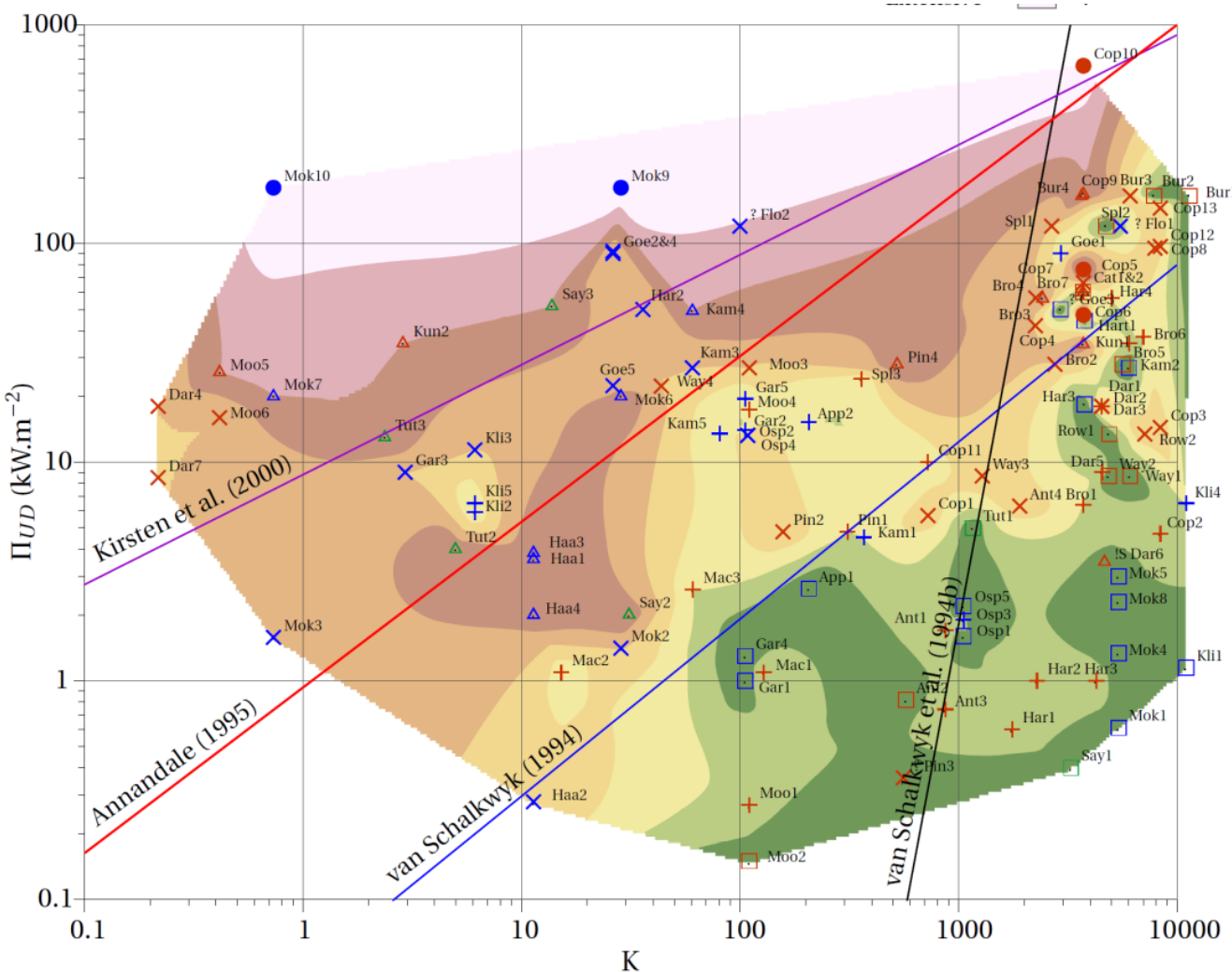
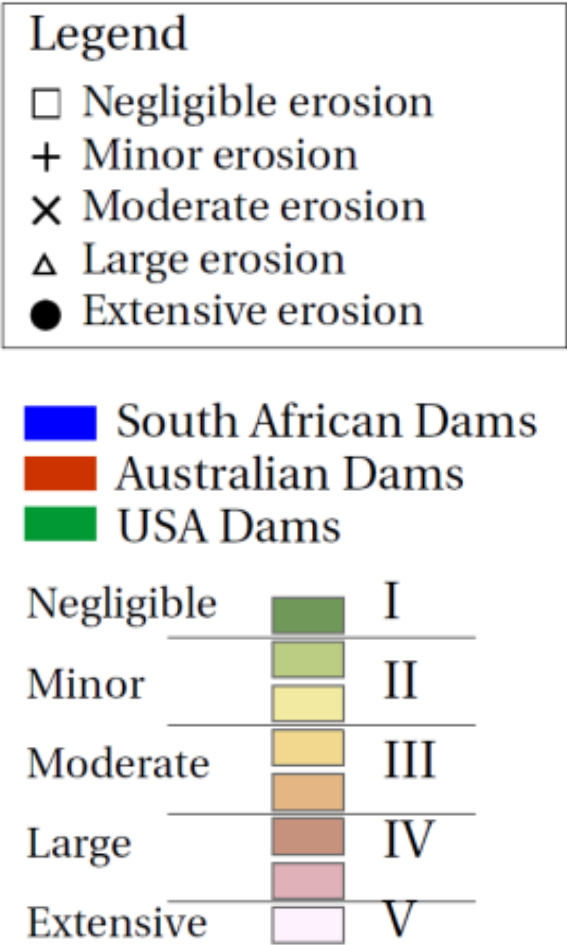
■ South African Dams
■ Australian Dams
■ USA Dams



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.3 Review of “Kirsten Index Methods”

The result



4.0 GO LEFT – COMPARATIVE TECHNIQUES

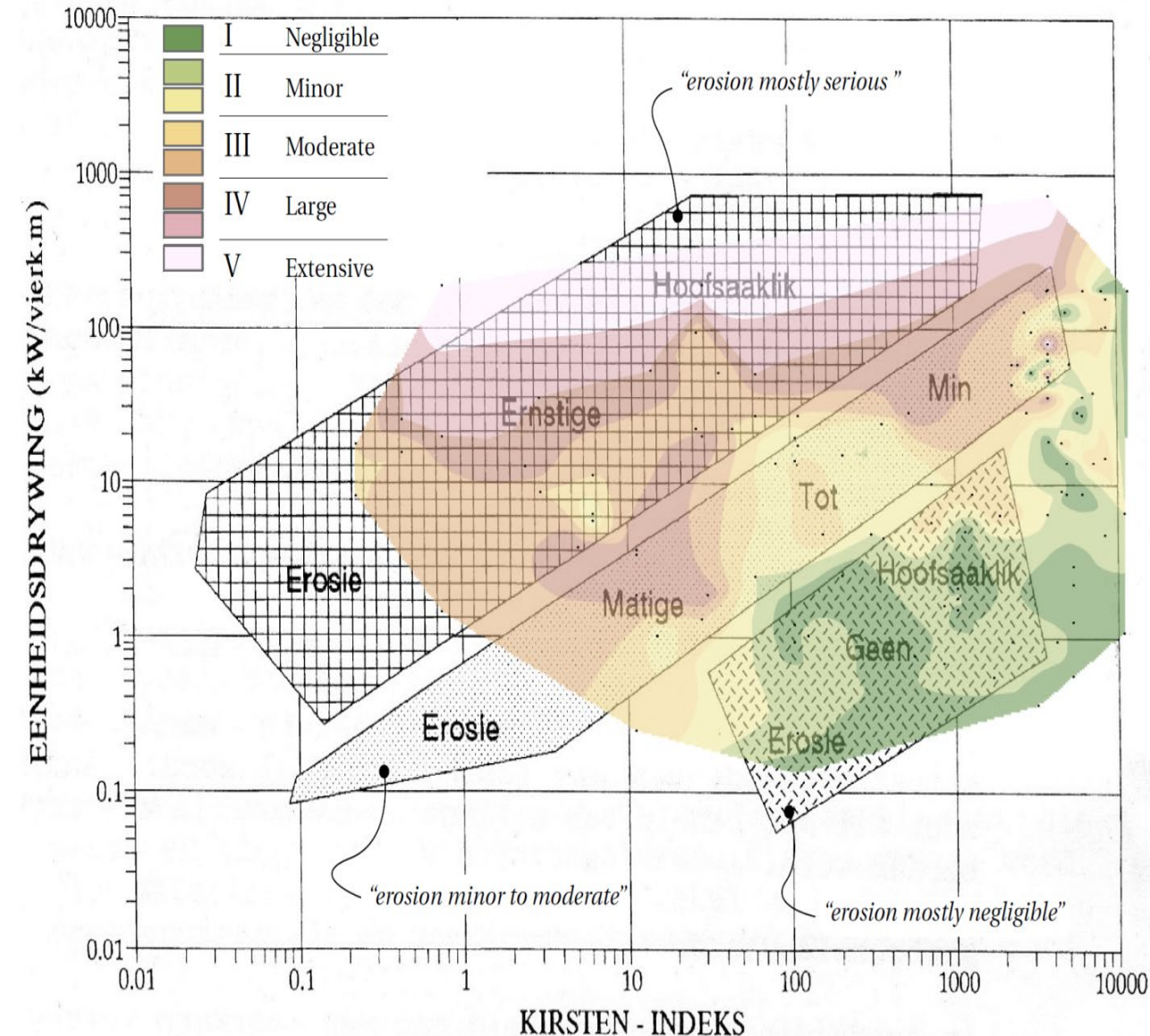
4.3 Review of “Kirsten Index Methods”

The result

Kind of agreed with
van Schalkwyk

“it must be pointed out that the evaluation chart was based on the observed behaviour of soil and rock formations at a number of dams in the USA and South Africa and it should be realised that the chart may not in all cases be able to accurately predict the behaviour of different material types under various flow conditions.” (van Schalkwyk, 1994, pg699)

“this method ... may not be representative of all geometrical, geomechanical and hydraulic situations ... it may be used as a first indication of erosion potential for rock in unlined spillways.” (van Schalkwyk et al., 1994b, pg 566)



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.4 eGSI method

eGSI

We wanted to use a currently accepted rock mass index – GSI one example
And had found in case studies that orientation matters

$$RMR = \sum (\text{classification parameters}) + \text{discontinuity orientation adjustment} \quad (3.3.4)$$

$$GSI = RMR'_{76} = F_1 + F_2 + F_3 + F_4 + 10 \quad (3.3.5)$$

where: F_1 to F_4 are 'classification parameters' from Bieniawski (1976)

So if we provide a new discontinuity orientation adjustment, tailored for erosion, we have an Erosion-GSI, ie eGSI



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.4 eGSI method

eGSI

$$eGSI = GSI_{\text{Chart}} + E_{\text{DOA}}$$

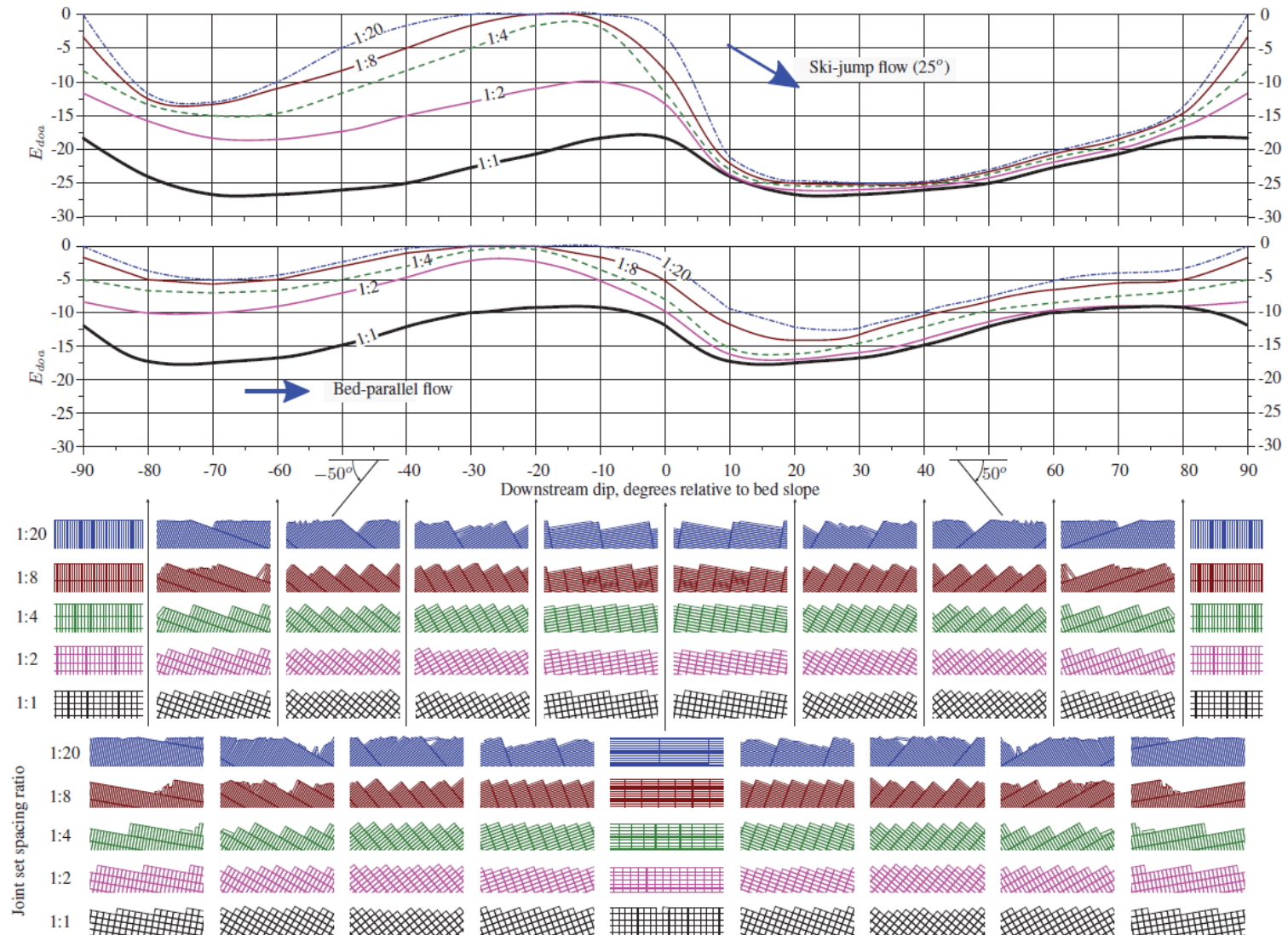


Figure 3.20 Discontinuity orientation adjustment for erosion (E_{DOA}) for horizontal beds and various approach flows

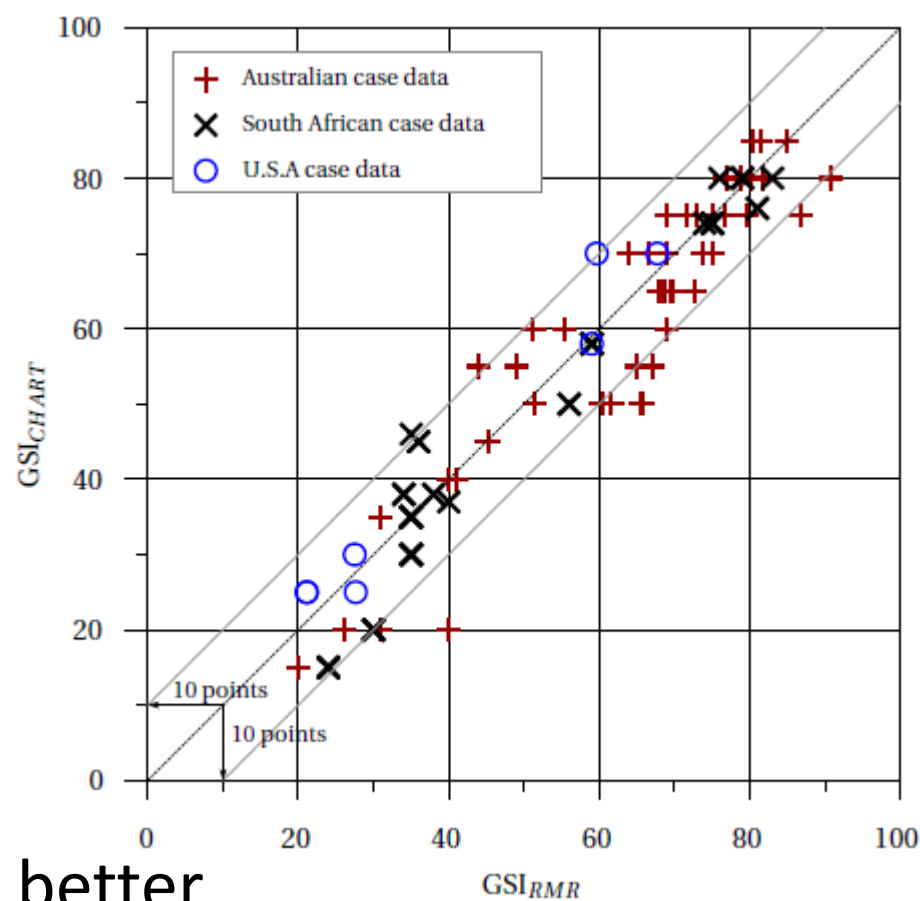


4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.4 eGSI method

GSI

Chart method



- No worse, possibly better
 - (especially in the hands of hydraulic people!)
- Easier
- Appropriate inference of accuracy

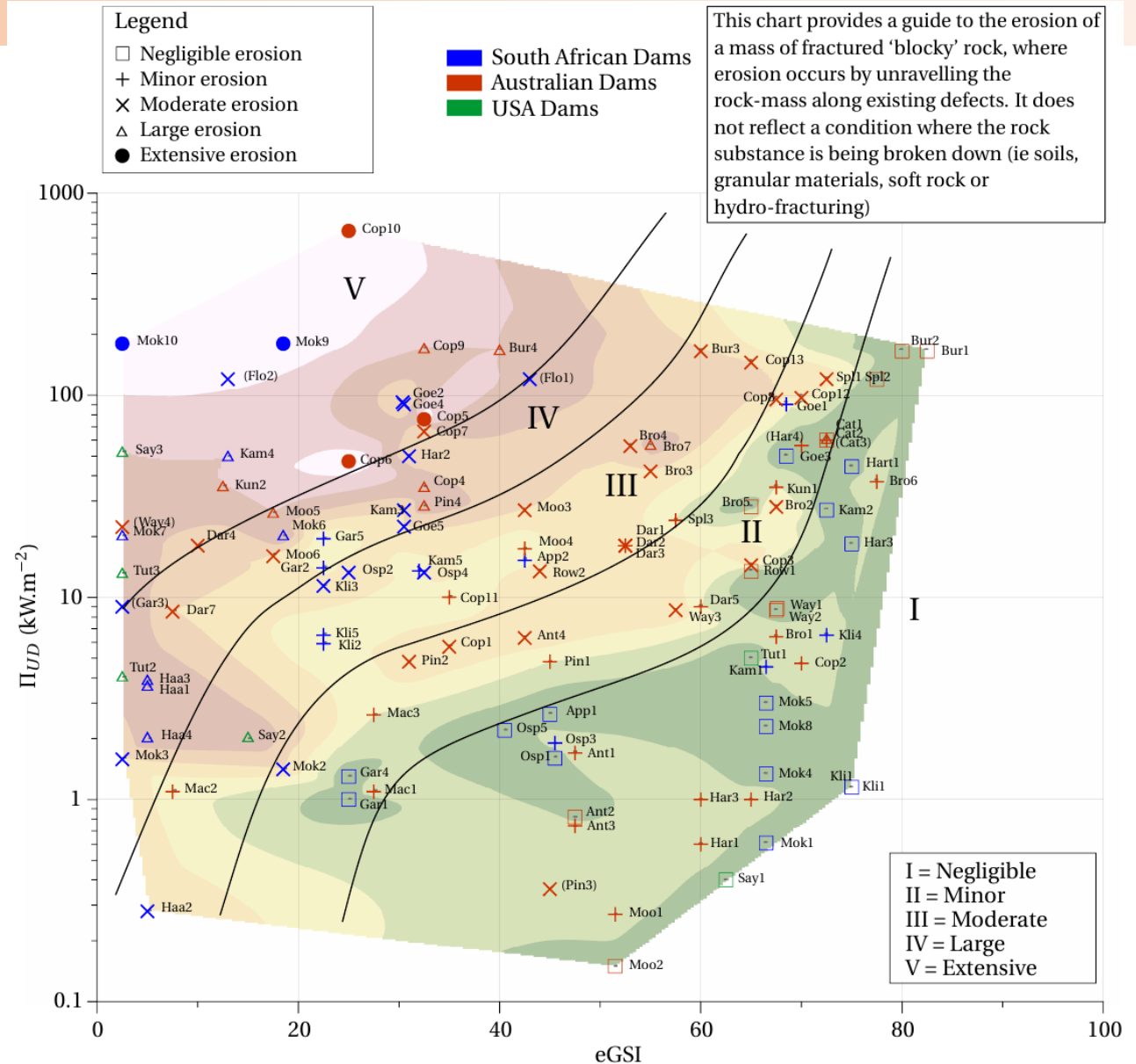
GEOLOGICAL STRENGTH INDEX FOR JOINTED ROCKS (Hoek and Marinos, 2000) From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the 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 if 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
STRUCTURE		DECREASING SURFACE QUALITY →				
	INTACT OR MASSIVE - intact rock specimens or massive in situ rock with few widely spaced discontinuities	90			N/A	N/A
	BLOCKY - well interlocked undisturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets	80	70			
	VERY BLOCKY- interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets		60			
	BLOCKY/DISTURBED/SEAMY - folded with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity			50		
	DISINTEGRATED - poorly interlocked, heavily broken rock mass with mixture of angular and rounded rock pieces			40		
	LAMINATED/SHEARED - Lack of blockiness due to close spacing of weak schistosity or shear planes				30	
					20	
						10
		N/A	N/A			

4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.4 eGSI method

eGSI

- 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



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.5 RMEI Method

Mechanism

Rock mass indices
arguably don't
address the
mechanism of
erosion well



Figure 3.36 Dartmouth dam - persistent planar beds parallel to flow direction



Figure 3.43 Moochalabra dam - sliding of jointed rock

4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.5 RMEI Method

Mechanism

Fell and Douglas developed a

ROCK MASS
ERODIBILITY INDEX
(RMEI)

Based on a “toolbox” type system

The intent is to prompt thinking about mechanism of erosion

Note – typo in my PhD. Use the publication (in list at end of this presentation)

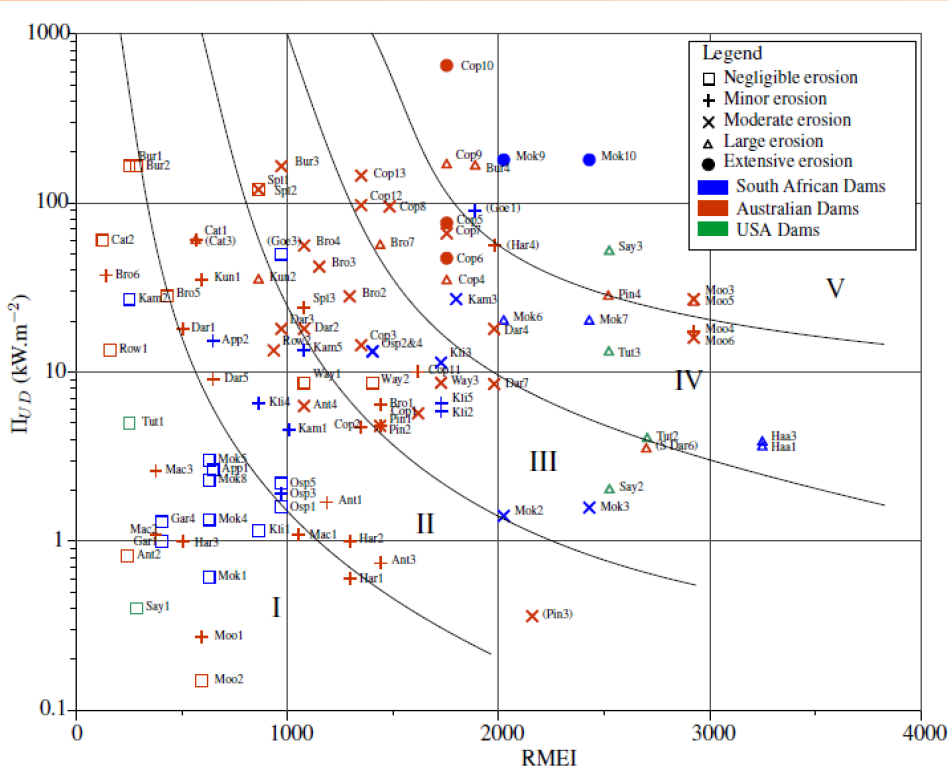


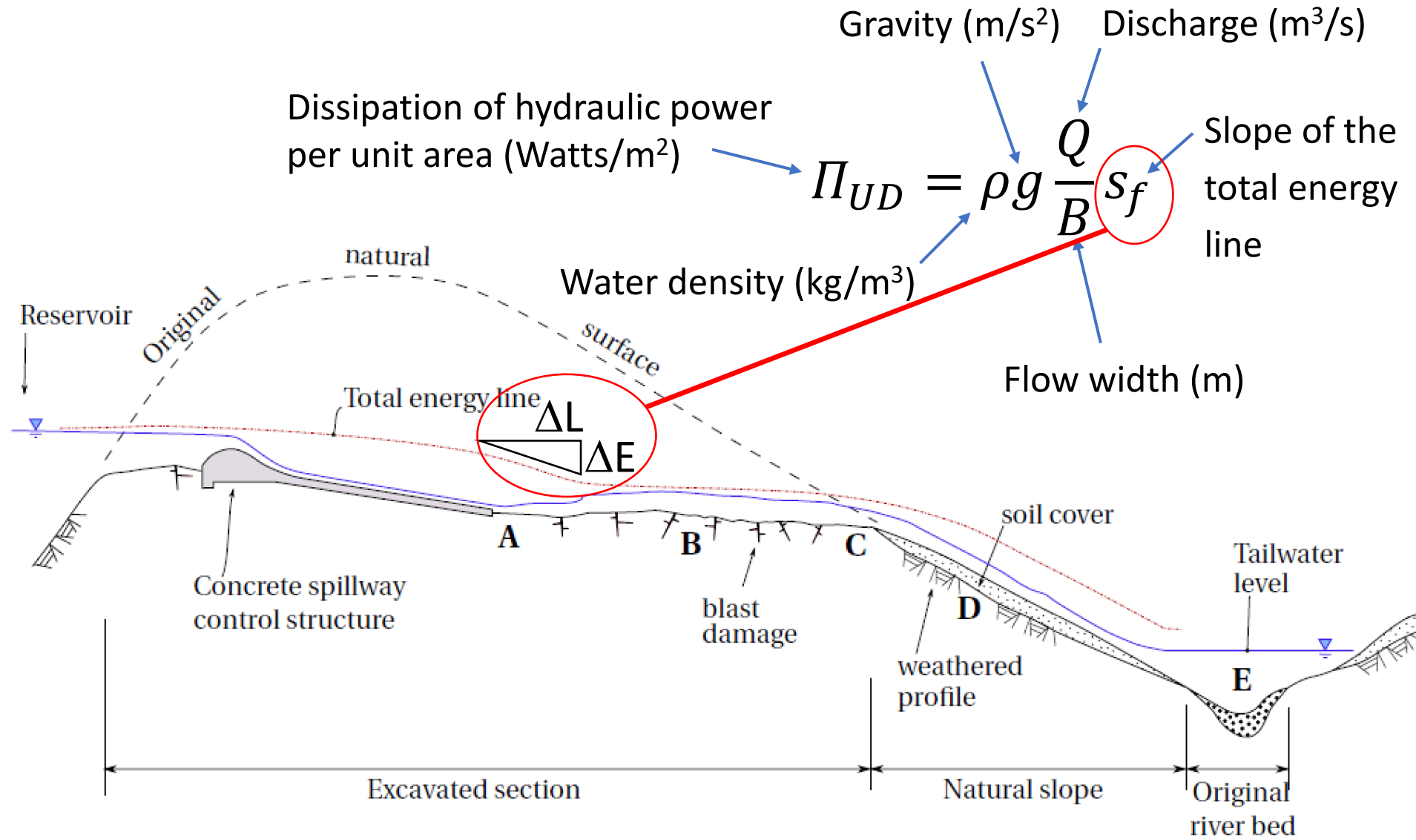
Table 3.3 Estimation of Rock Mass Erosion Index (RMEI)

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;	Rock with three or more defects, with: basal defect sub-parallel to spillway floor, Joint 2 protruding from surface, or;	Rock with three or more defects, with: persistent basal defect dip 10 to 30 degrees upstream relative to the spillway floor, or;	Rock with three or more defects, with: persistent basal defect dip ≤ 10 degrees upstream relative to the spillway floor, or;	Persistent basal defect sub-parallel to the spillway floor, day lighting upstream or downstream, or;
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	Aperture < 1mm	Aperture 1-2mm	Aperture 2 to 5mm	Aperture > 5mm
P4: Spacing of basal defect ⁴	1	UCS > 50MPa	UCS 20MPa to 50 MPa	UCS 5MPa to 20MPa	UCS 1MPa to 5MPa	UCS < 1MPa, or Soft gouge > 5mm thick
		>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.

4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.6 Notes on calculation of “stream power”



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.6 Notes on calculation of “stream power”

- Stream power – should technically be called “unit stream power dissipation”
 - It is the rate of dissipation – not the total power
- All published comparative methods used 1D hydraulics
 - It is therefore averaged over space and depth and time – a very coarse measure
- Step-by-step guidance set out in ICSE 2020 paper:

Guidance on the calculation of stream power dissipation for rock scour assessments

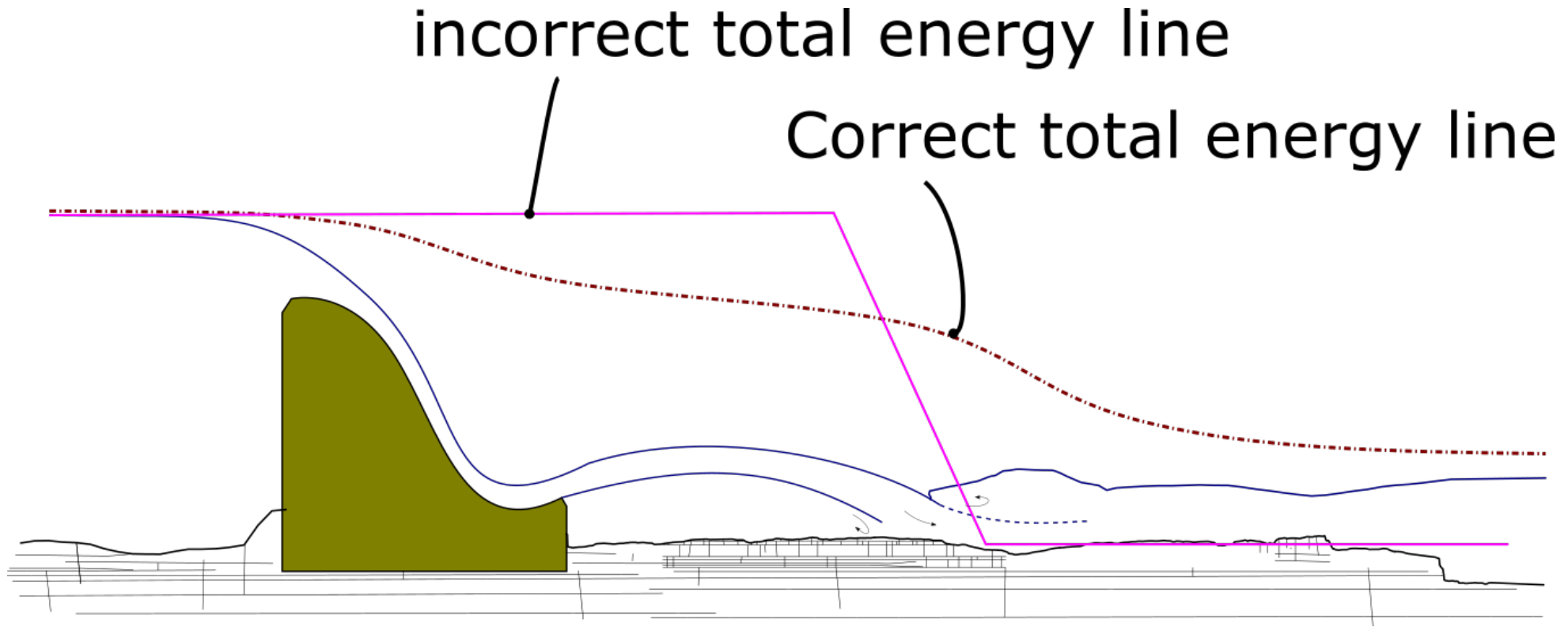
Steven E Pells¹, William L Peirson², Fanar Al-Qassab¹



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.6 Notes on calculation of “stream power”

Be sure to plot energy line from reservoir to tailwater – it ensures against spot-errors

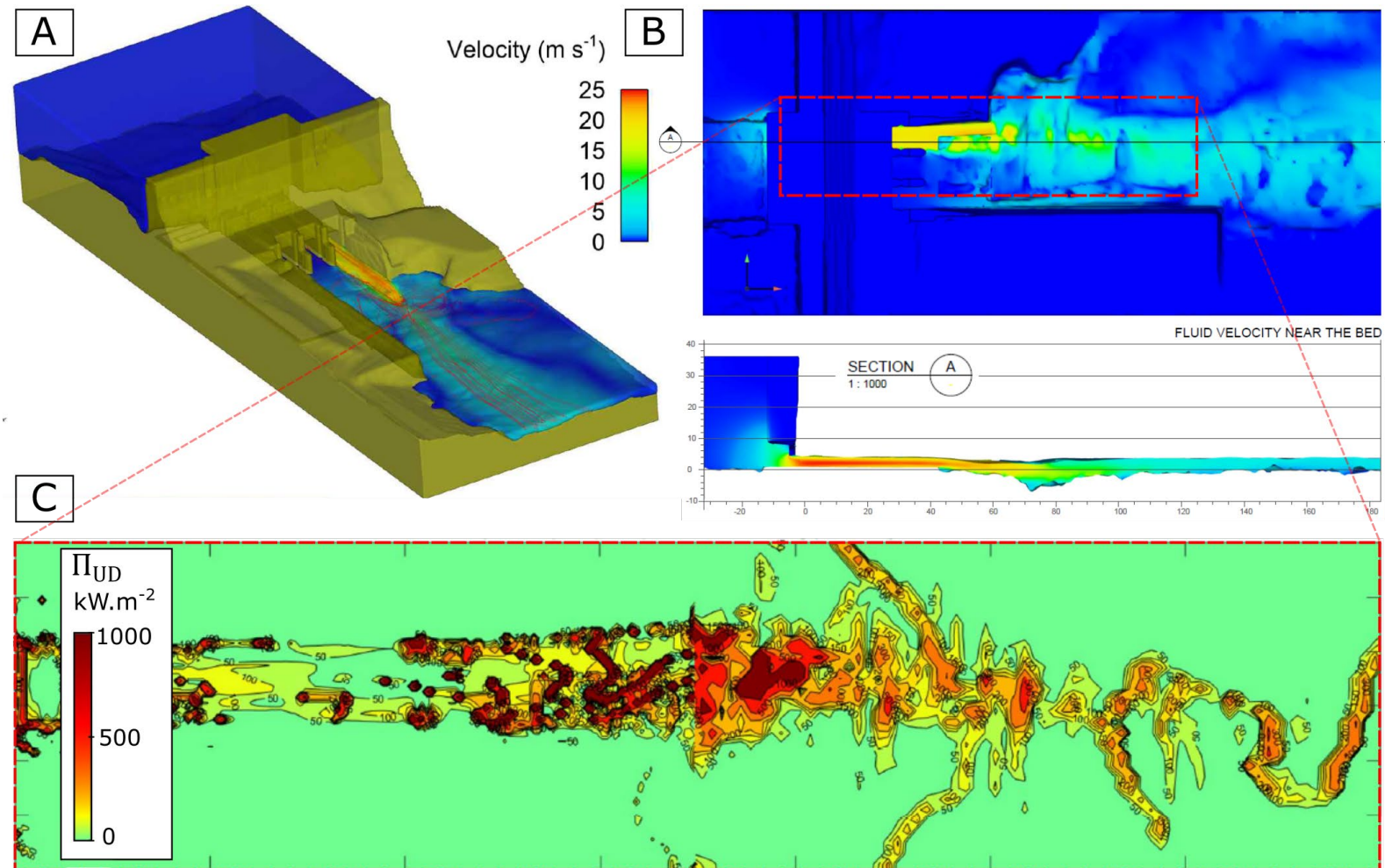


4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.6 Notes on calculation of “stream power”

Use of CFD models

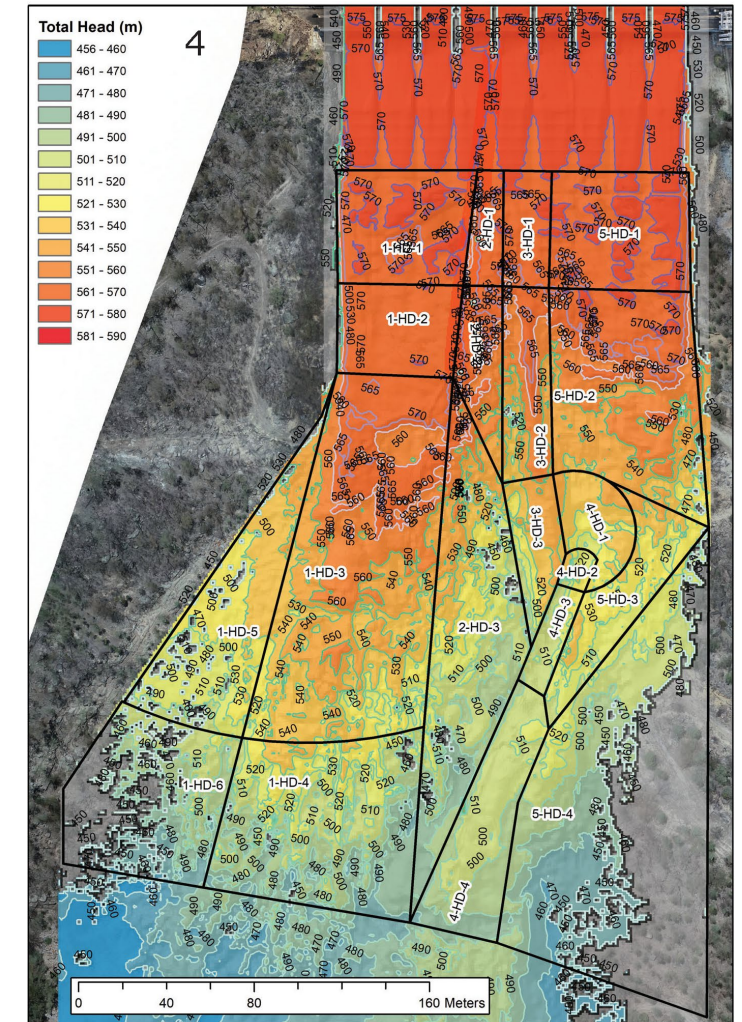
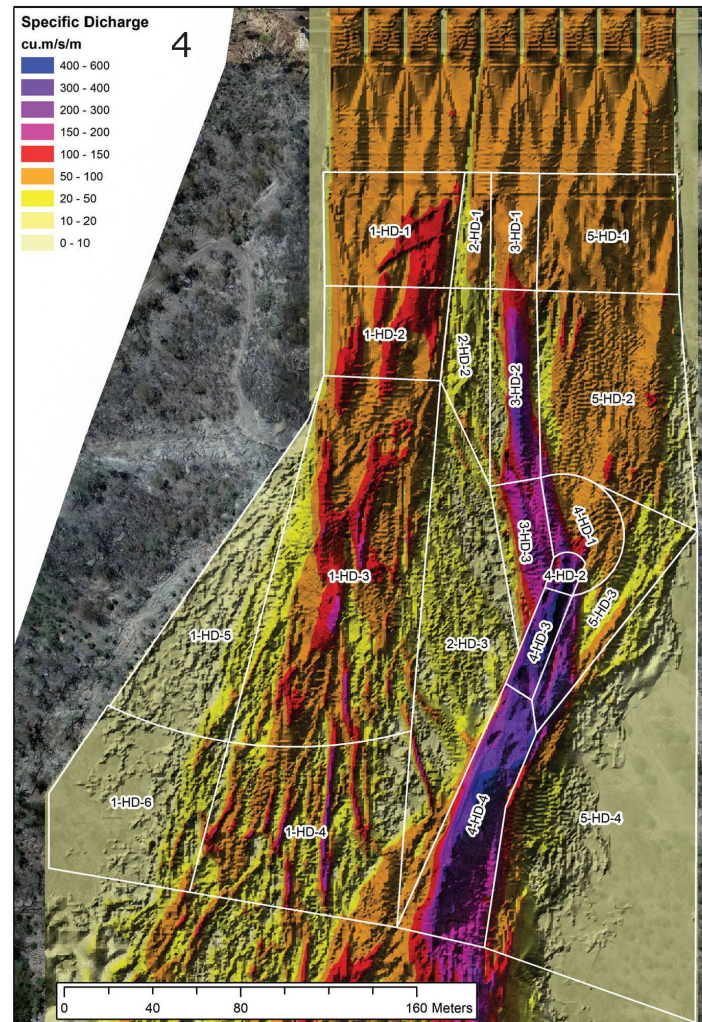
1. Required in cases where rapidly-varied flow and geometry doesn't conform to the idealised geometry of an analytical solution
2. Can calculate at the cell level, but we don't have the field dataset - hot spots infer erosion in places that a corresponding 1D study would show no such risk



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.6 Notes on calculation of “stream power”

A possible method from CFD



4.0 GO LEFT – COMPARATIVE TECHNIQUES

4.7 Note why its called “comparative”

I have called it “comparative”:

All it is doing is allowing you to compare a site in question against a bunch of case studies, where a rock mass index compares rock structure, and stream power dissipation compares hydraulic conditions



5.0 GO RIGHT! – NUMERICAL METHODS

5.1 Example



5.0 GO RIGHT – NUMERICAL METHODS

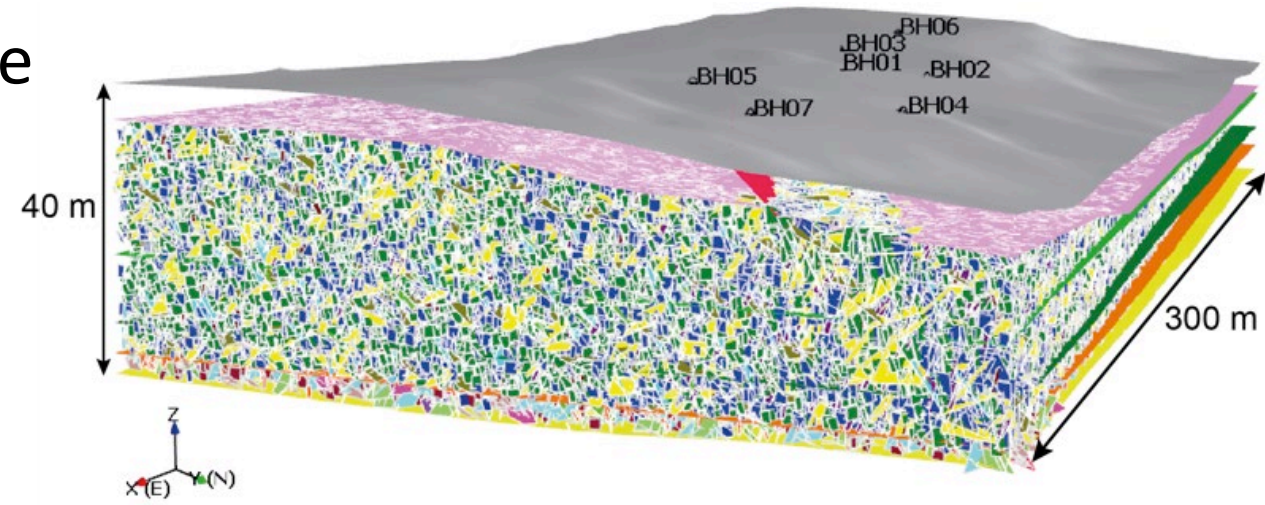
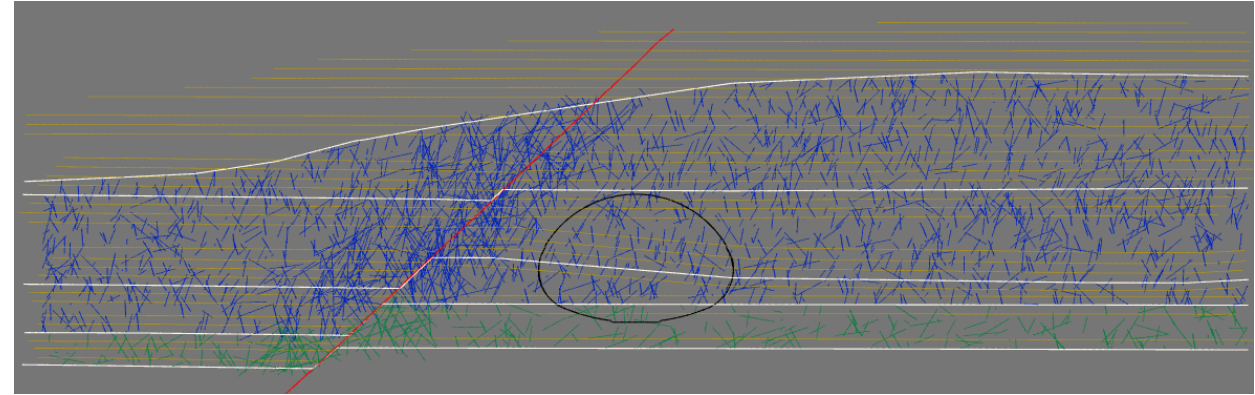
5.2 The ultimate goal

Coupled (hydrodynamic and rock-mechanics) modelling

- Hydrodynamics – CFD
- Rock mechanics – discrete element – Multiphysics

In principle, it's a good idea

- For modelling the rock mass, could use Discrete Fracture Network (DFN) model
- And import into Multiphysics model (eg Abaqus, or 3DEC etc)
- And unravel using pressures from a CFD model



5.0 GO RIGHT – NUMERICAL METHODS

5.2 The ultimate goal

Coupled (hydrodynamic and rock-mechanics) modelling

- Hydrodynamics – CFD
- Rock mechanics – discrete element –
Multiphysics

In practice, it's unlikely to be achievable

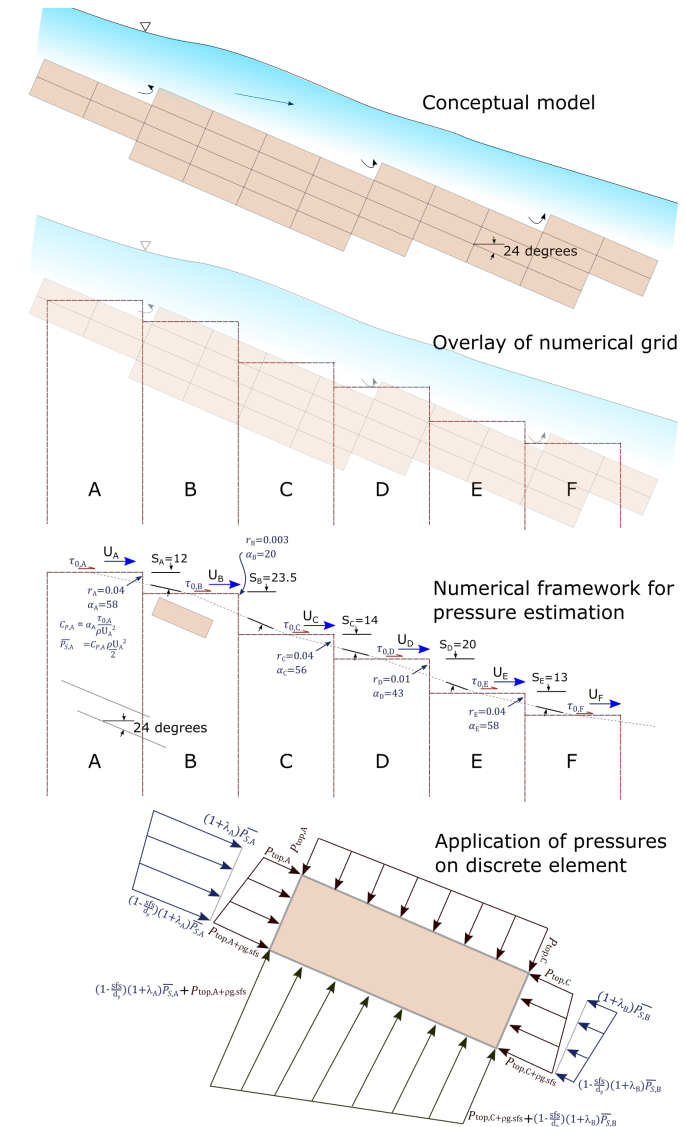
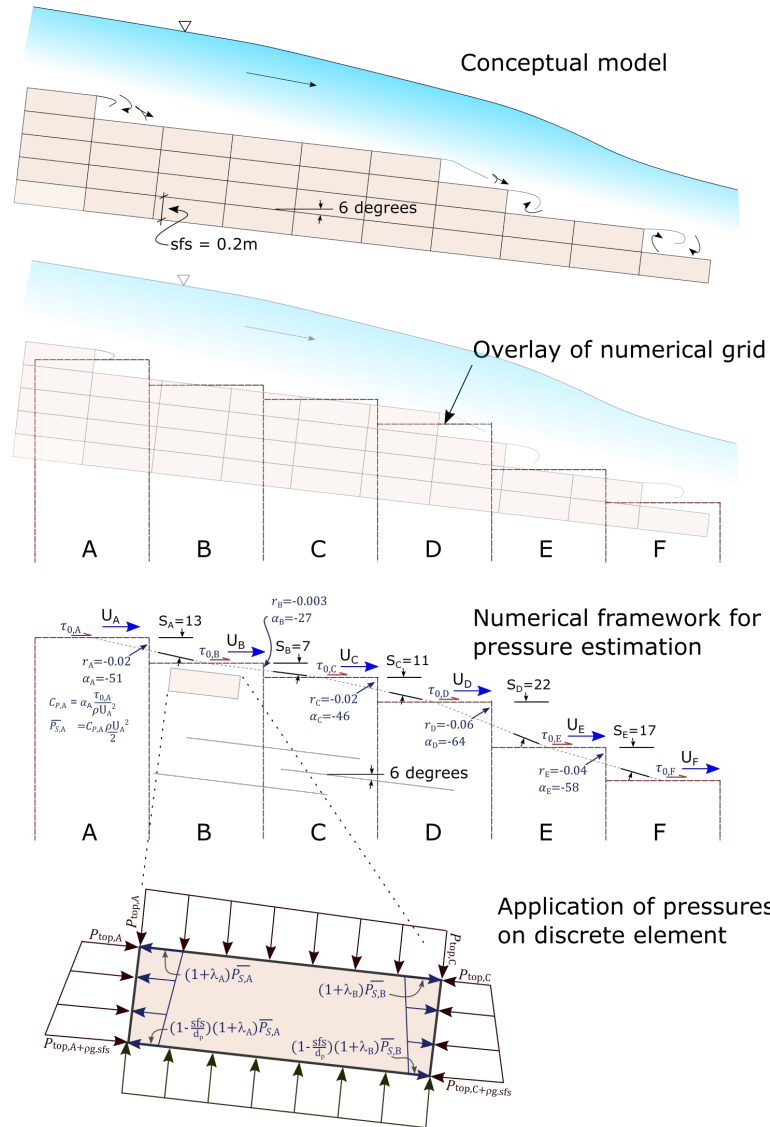
- Multiphysics of a DFN at spillway scale already demanding, without water
- To directly model stagnation pressures into defects, require grid less than defect aperture – this is incredibly fine!
- Needs to track movement of units, and constantly update hydraulics to fit

Maybe one day



5.0 GO RIGHT – NUMERICAL METHODS

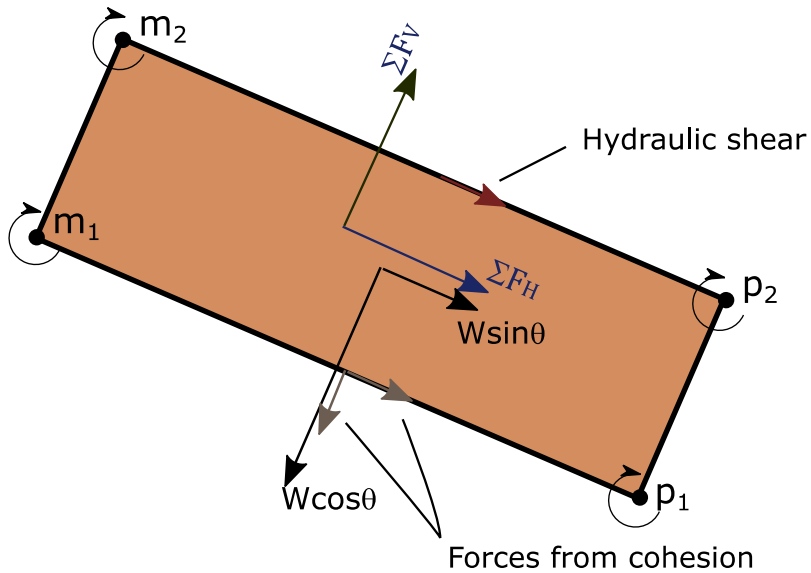
5.3 Analytical methods inside a numerical grid



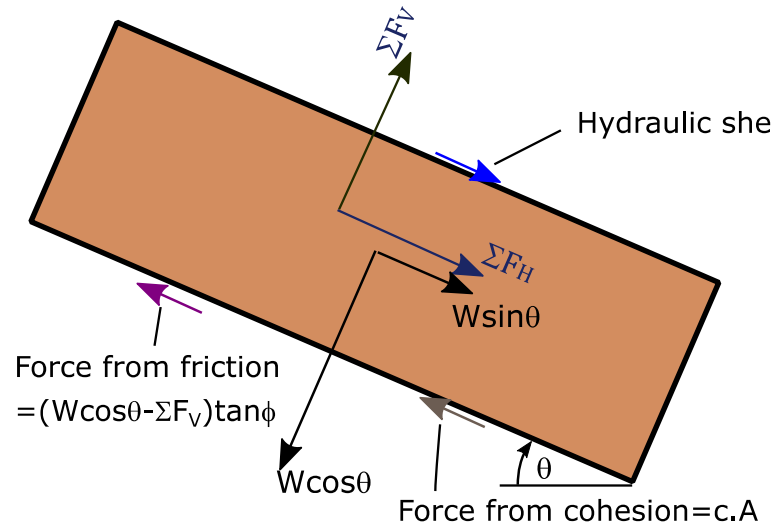
5.0 GO RIGHT – NUMERICAL METHODS

5.3 Analytical methods inside a numerical grid

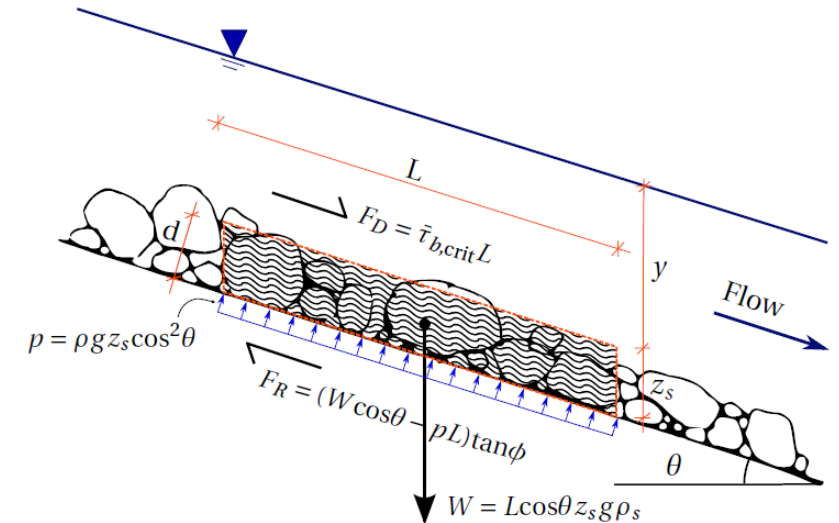
SLIDING



ROLLING



... and if it collects in a pile .. SLUMPING



5.0 GO RIGHT – NUMERICAL METHODS

5.3 Analytical methods inside a numerical grid

HOW TO INCLUDE TIME

For each mechanism, movement was simulated to occur at each timestep on the model from acceleration of blocks under the net action of forces on a block. i.e. from Newton's Second Law of Motion:

$$F = ma$$

With rearrangement, the acceleration of a rock element can be estimated as:

$$a_{\text{rock}} = \frac{F_{\text{NET}} \cdot g}{W}$$

In a numerical model that incorporates time 't' as a sequence of n timesteps each of duration dt, the rock element velocity V_{rock} can be assessed as:

$$V_{\text{rock}, t=dt} = a_{\text{rock}} dt$$

$$V_{\text{rock}, t=n \cdot dt} = V_{\text{rock}, t=(n-1)dt} + \frac{F_{\text{NET}, t=n \cdot dt} \cdot g}{W} dt$$

The movement of rock (per unit width) can be expressed as a discharge q_{rock} :

$$q_{\text{rock}, x} = V_{\text{rock}} dz \quad (\text{where } dz \text{ is a change in elevation}).$$

For the numerical scheme representing the slope with a structure of cells, then the net rock discharge at each cell can be considered as:

$$q_{\text{rock}, \text{NET}} = q_{\text{rock}, \text{IN}} - q_{\text{rock}, \text{OUT}}$$

Erosion or accretion at a particular element location can then be represented as a change dz in surface elevation

$$dz = \frac{q_{\text{rock}, \text{NET}} dt}{A} \quad (A \text{ is the surface area of the numerical cell})$$

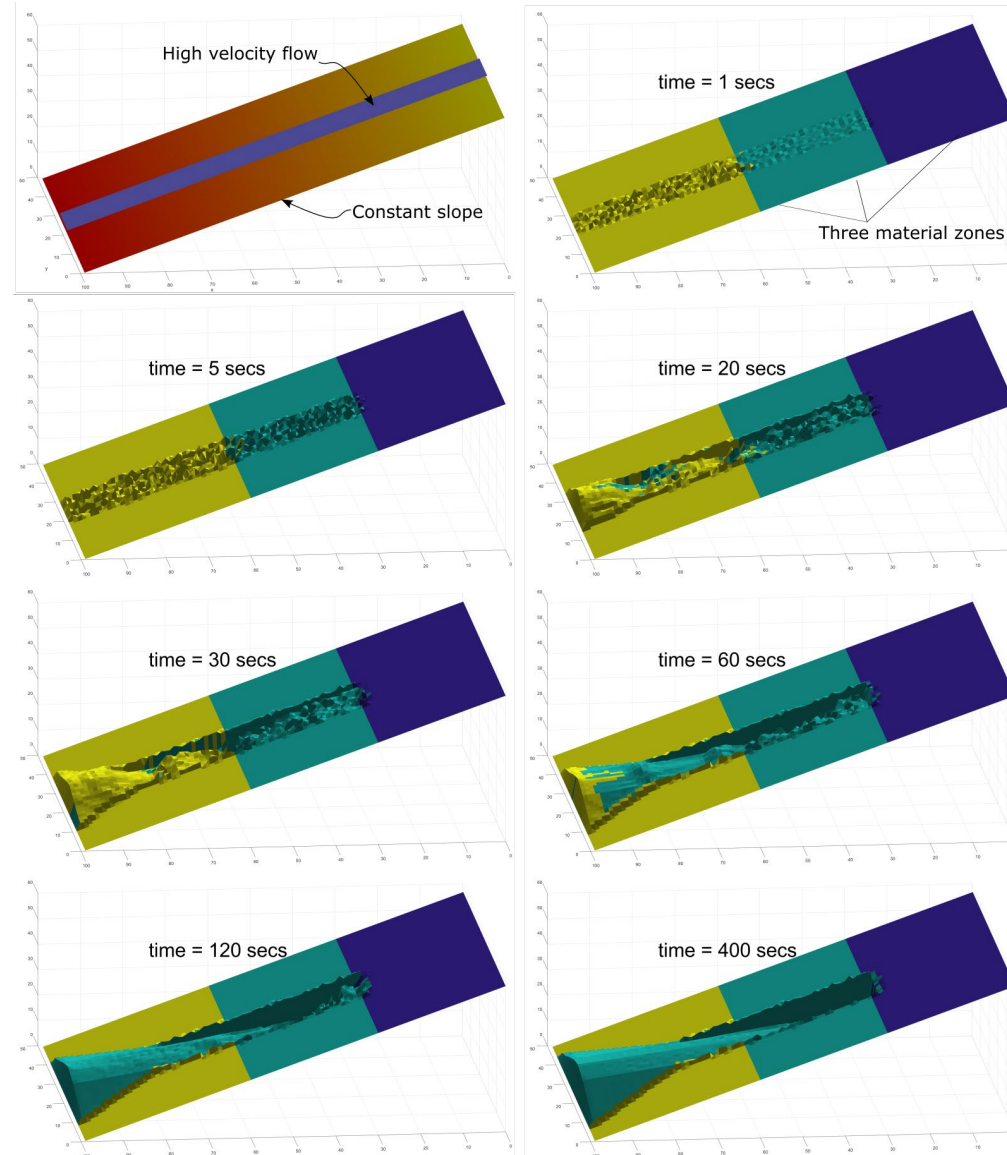
In this way, a numerical model was established which tracks the accretion / erosion over a slope which is discretised as a series of cells. These equations were extended to 2D by considering movements in x and y direction independently.



5.0 GO RIGHT – NUMERICAL METHODS

5.3 Analytical methods inside a numerical grid

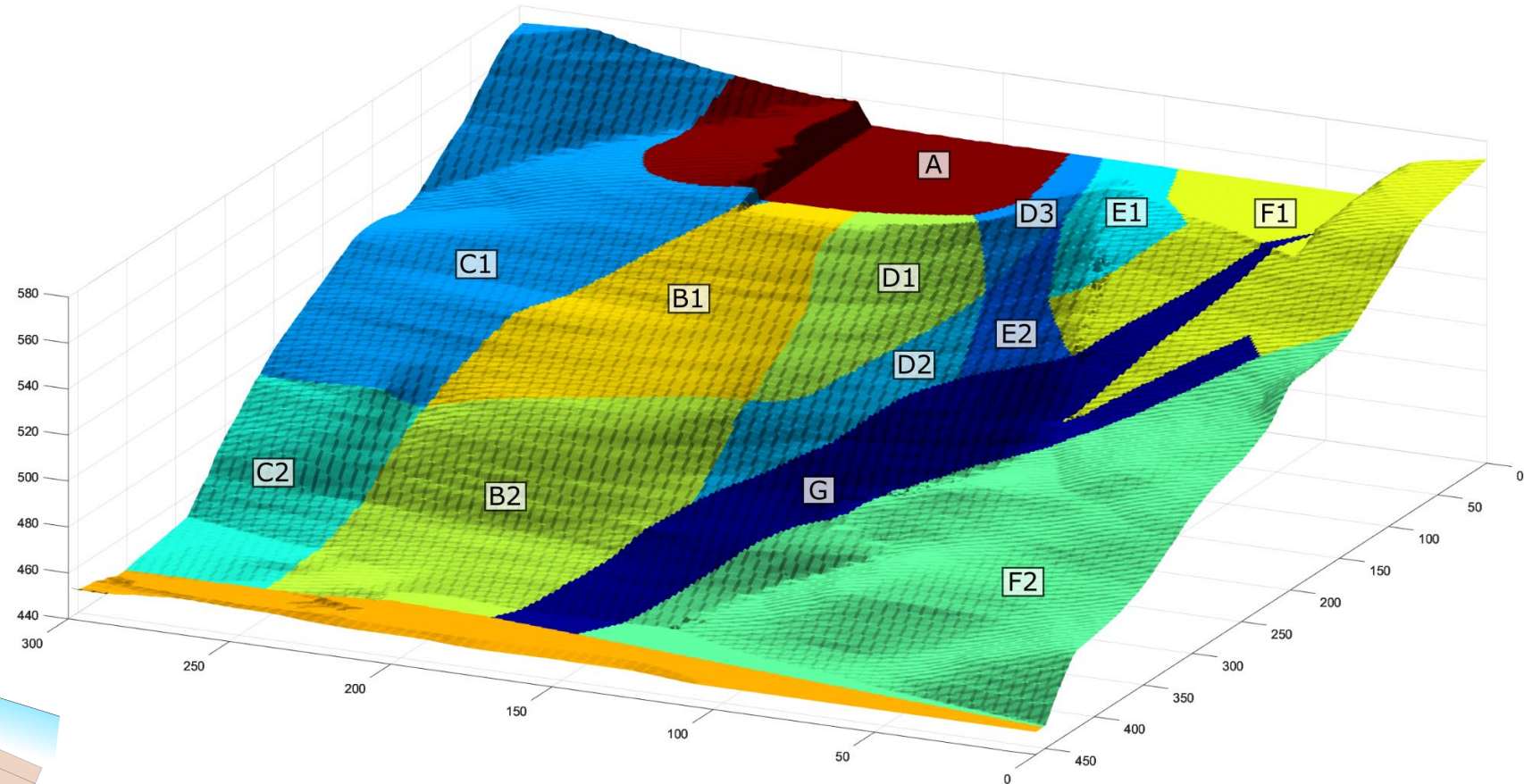
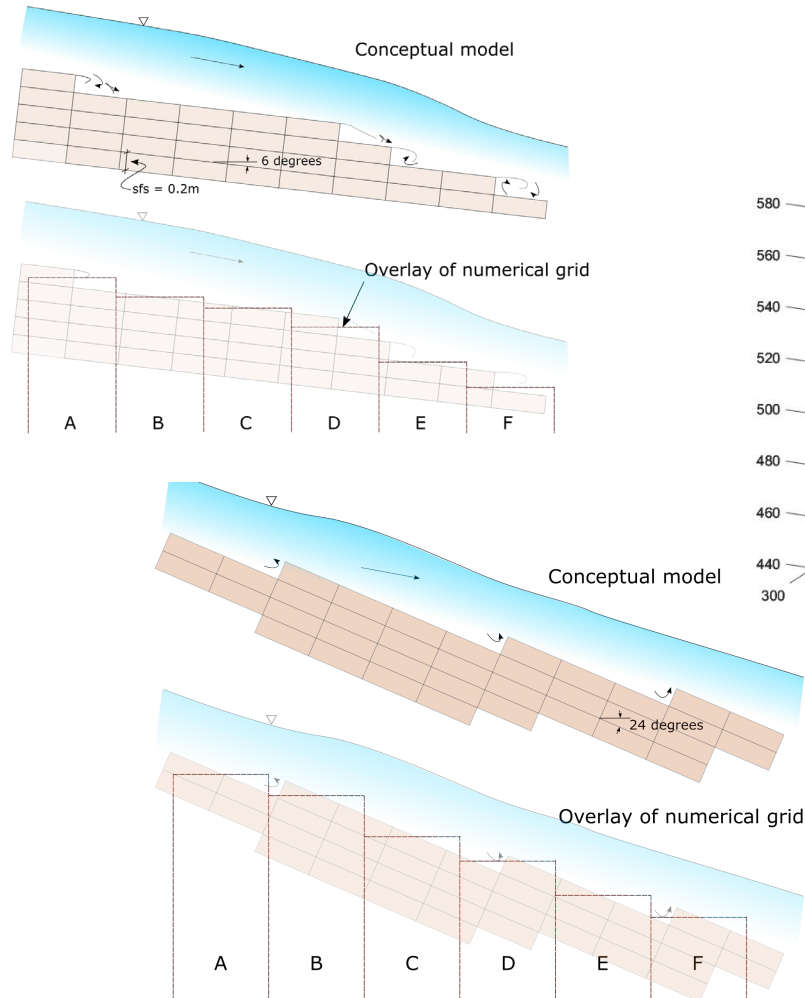
PILOT MODEL



5.0 GO RIGHT – NUMERICAL METHODS

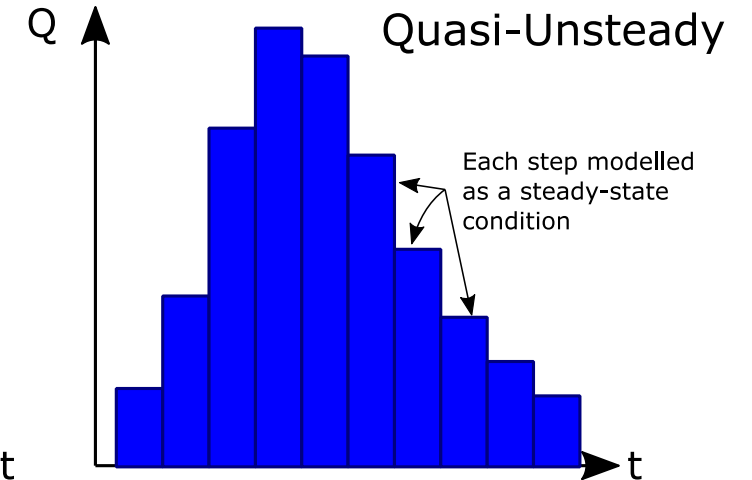
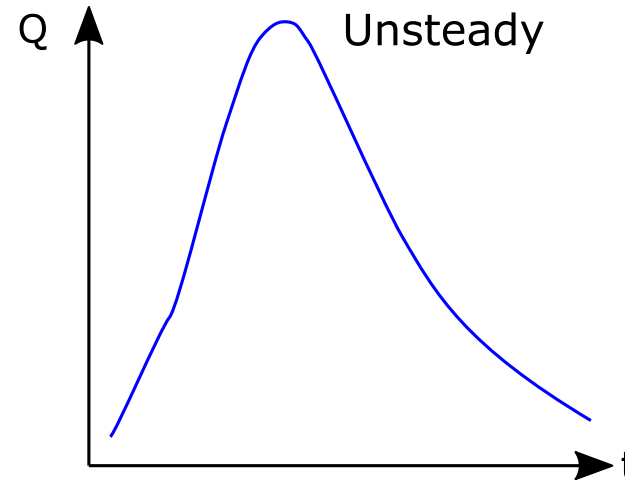
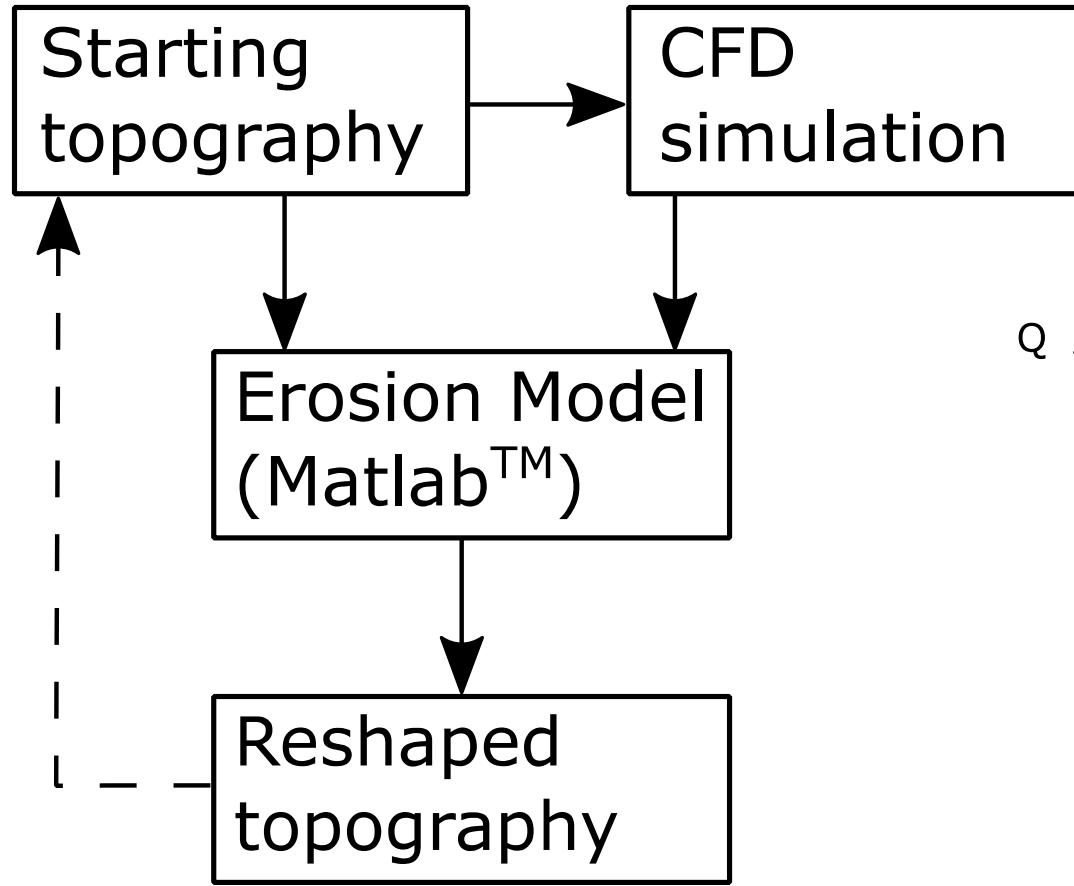
5.3 Analytical methods inside a numerical grid

SPILLWAY MODEL



5.0 GO RIGHT – NUMERICAL METHODS

5.3 Analytical methods inside a numerical grid



5.0 GO RIGHT – NUMERICAL METHODS

5.3 Analytical methods inside a numerical grid

Copeton
1976 event



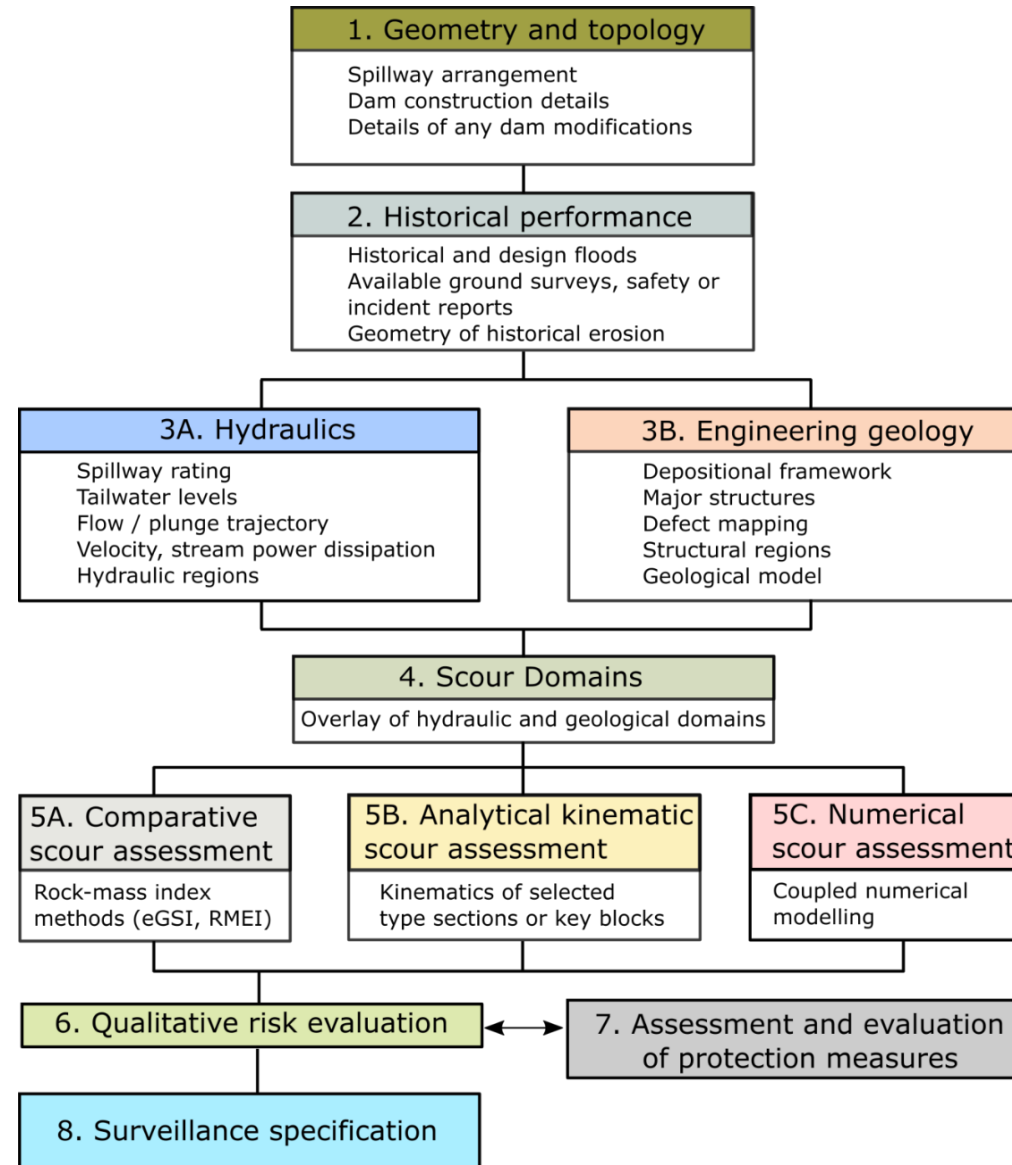
5.0 GO RIGHT – NUMERICAL METHODS

5.3 Analytical methods inside a numerical grid

Copeton
1:1000yr
event



6.0 HYDRO-GEOTECHNICAL SCOUR ASSESSMENT



Some useful references

eGSI - easier reference than wading through PhD

- Pells, Steven E., Kurt Douglas, Philip J. N. Pells, Robin Fell, and William L. Peirson. “Rock Mass Erodibility.” *Journal of Hydraulic Engineering* 143, no. 5 (May 2017): 06016031. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001243](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001243).

RMEI – to avoid typo’s in PhD, use

- Douglas, Kurt, Steven Pells, Robin Fell, and William Peirson. “The Influence of Geological Conditions on Erosion of Unlined Spillways in Rock.” *Quarterly Journal of Engineering Geology and Hydrogeology* 51, no. 2 (May 2018): 219–28. <https://doi.org/10.1144/qjegh2017-087>.

Hydro-geotechnical scour assessment – how its done

- Steven E Pells, Fanar Al-Qassab, Felicia Weir, Anaïs Faivre, Thierry Leturcq, Benoit Blancher “Hydro-geotechnical rock scour assessment at Petit-Saut Dam » to be published 4th International Seminar on Dam Protections against Overtopping Madrid (Spain). November 30th – December 2nd, 2022
- Pells, S and Douglas, K 2019 Guidelines for assessment of scour in unlined spillways. Africa 2019, conference for the International journal on hydropower and dams, 2-4 April 2019, Windhoek, Namibia

Example of analytical analysis of selected key blocks

- M. George C. Christiansen A. Rickel B. Israel G. Annandale “Erodibility evaluation of an unlined rock spillway: comparison between the erodibility index method and a new method based on block theory” » to be published 4th International Seminar on Dam Protections against Overtopping Madrid (Spain). November 30th – December 2nd, 2022

How to calculate stream power dissipation

- Steven E. Pells, William L. Peirson, Fanar Al-Qassab 2021 “Guidance on the calculation of stream power dissipation for rock scour assessments” Proceedings of the 10th International Conference on Scour and Erosion (ICSE-10)

e: steven@pellsconsulting.com.au

w: www.pellsconsulting.com.au

