The Cost of Uncertainty in Geotechnical Design and Implementation

Michael Dunn

WAGCG / EAGCG
Adelaide
7-8 Nov 2013

Agenda

Geotechnical design & implementation processes

Uncertainty in:

- geotechnical design
- implementation

Uncertainty and cost – examples:

- design
- implementation

Dealing with uncertainty

Conclusions

Geotechnical design process

There are many published design flow charts, guidelines etc.

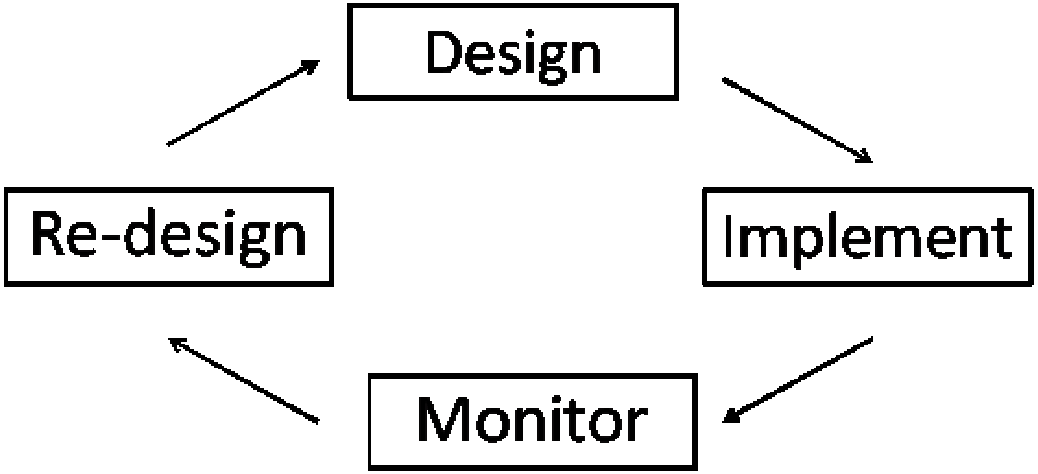
- Read and Stacey
- Hoek, Kaiser and Bawden
- Cable bolt design process (Hutchinson & Diederichs)
- Terzaghi's Observational Approach
- etc.

Design should follow a methodical and rigorous approach that is defensible and meets serviceability requirements i.e. safety and purpose are achieved

Geotechnical design process

A simplified version of Terzaghi’s Observational Approach is generally applied in mining

The complete observational approach is a bit more involved



Geotechnical design process

Peck (1969)	Bieniawski (1991)	Stacey (2004, 2009)
Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.	Clarity of design objectives and functional requirements;	Statement of the problem (performance objectives)
		Functional requirements and constraints (design variables and design issues)
Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.	Minimum uncertainty of geological conditions;	Minimization of uncertainty (collection of information e.g. site characterization, rock properties, groundwater, in situ stresses)
Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.	Simplicity of design components	Concept formulation (geotechnical model)
Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.	State-of-the art practice	Analysis of solution components (analytical, numerical, empirical, observational methods)
Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.		Synthesis and specifications for alternative solutions (shapes, sizes, locations, orientations of excavations)
Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.	Optimisation	Evaluation (performance assessment)
Measurement of quantities to be observed and evaluation of actual conditions.		Optimization (performance assessment)
Modification of design to suit actual conditions.	Constructability	Recommendation
		Implementation (efficient excavation and monitoring)

Geotechnical sign process

All three authors state the need to minimise uncertainty

Peck (1969)

“Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role”.

Bieniawski (1991)

“Minimum uncertainty of geological conditions”

Stacey (2004)

“Minimization of uncertainty (collection of information e.g. site characterization, rock properties, groundwater, in situ stresses)”

Uncertainty - What is it?

The term “uncertainty” is loosely applied in geotechnical engineering.

- Baecher & Christain (2003) distinguish between uncertainty related to natural variations in time and space (randomness) and uncertainty related to lack of understanding or knowledge.

- These are referred to as aleatory and epistemic uncertainly respectively by Kiuregihain & Ditevsen (2009).

- Hadjigeorgiou & Harrison (2011) argue that uncertainty and sources of error are two different components of engineering analysis design
    - They are linked – errors result in uncertainty and uncertainty can result in errors
    - Understanding of both is important in geotechnical engineering

Uncertainty - What is it?

Brown (2007) concluded that there are two general types of uncertainty

- what we know we don’t know, or parameter uncertainty; and
- what we don’t know we don’t know, or conceptual uncertainty.

McMahon (1985) outlined six types of uncertainty encountered in geotechnical engineering.

- The first three types of uncertainty are due to geological or natural constraints
- The others are due to social or human nature.

Uncertainty - What is it?

McMahon’s (1985) – 6 Types of Uncertainty

Type	Description	Examples
1	Risk of encountering an unknown geological condition	Unknown structures or weak zones Unexpected presence of water
2	Risk of using the wrong geotechnical criteria	Incorrect failure mechanism identified Inappropriate numerical modelling applied
3	Risk of bias and / or variation in design parameter being greater than estimated	Material properties variability underestimated Poor understanding of joint spacing and length
4	Human error	Poor quality data collected Poor sampling practices
5	Design changes	Poor planning requiring redesign Design changes made in the field without consultation
6	Over Conservatism	Assuming full excavation width wedges Applying discounting factors at all stages of the design

Uncertainty - What is it?

- Natural uncertainty - properties vary
- Spatial uncertainty – properties vary in space
- Temporal uncertainty – properties vary over time
- Errors result in uncertainty
- Uncertainty results in errors
- Things we don't know – lack of knowledge or data

Uncertainty isn't confined to the design process - there are considerable uncertainties in the implementation phase

Uncertainty and Cost

Uncertainty will invariably result in increased cost or a missed opportunity. The main issues are:

- **Design**
  - Poor understanding of geotech environment – lack of data
  - Over-conservatism in design
  - Design methodology (e.g. empirical)
  - Rogue feature or events
- **Implementation**
  - Design specifications / requirements not effectively communicated
  - Design specifications and requirements not understood
  - Poor QA /QC

Uncertainty and Cost

Geotech environment – lack of data

- Poor understanding of geology
- Poor understanding of major structures and fabric
- Poor understanding of rock mass and properties
- Poor understanding of hydrogeology
- Poor understanding of stress regime and seismological setting

If the confidence of the geotechnical model and it various components doesn’t match that required for design you will over under-design or over-design – THIS WILL COST $$$$$

Uncertainty and Cost

Over conservatism in design

- Higher acceptance criteria applied (FOS & POF)
- Using unrealistically low input values (materials, support etc.)
- Assuming maximum block size is the valid design block
  - full drive size blocks
  - unrealistic wedges on walls (assumptions on joint length)
- Ubiquitous maximum blocks (don’t consider relative probability)
- Blanket approach e.g. cablebolts in all intersections
- Inappropriate design methods / models

Uncertainty and Cost

Rogue events

There is always the possibility of unforseen events or features

- Unknown structures behind the slope
- Unexpected hydrogeological conditions
- Surface water (high rainfall events)
- Unknown weak zones
- Response to seismicity

Uncertainty and Cost

Implementation

- Is the design implemented as intended?
  - Bench faces cut flatter or steeper than design
  - Surface water drainage not put in place
  - Shotcrete applied at thicknesses > design
  - Bolts not grouted
  - Bolt spacing varies
- Do people respond to observed changes in conditions?
- Is data collected and models / and designs updated?
- Is the monitoring effectively implemented?
- Does the planned optimisation occur (e.g. backfill binder %)?
- QA/QC - Are you getting what you paid for?

Uncertainty and Cost

What is the cost of a failure due to uncertainty:

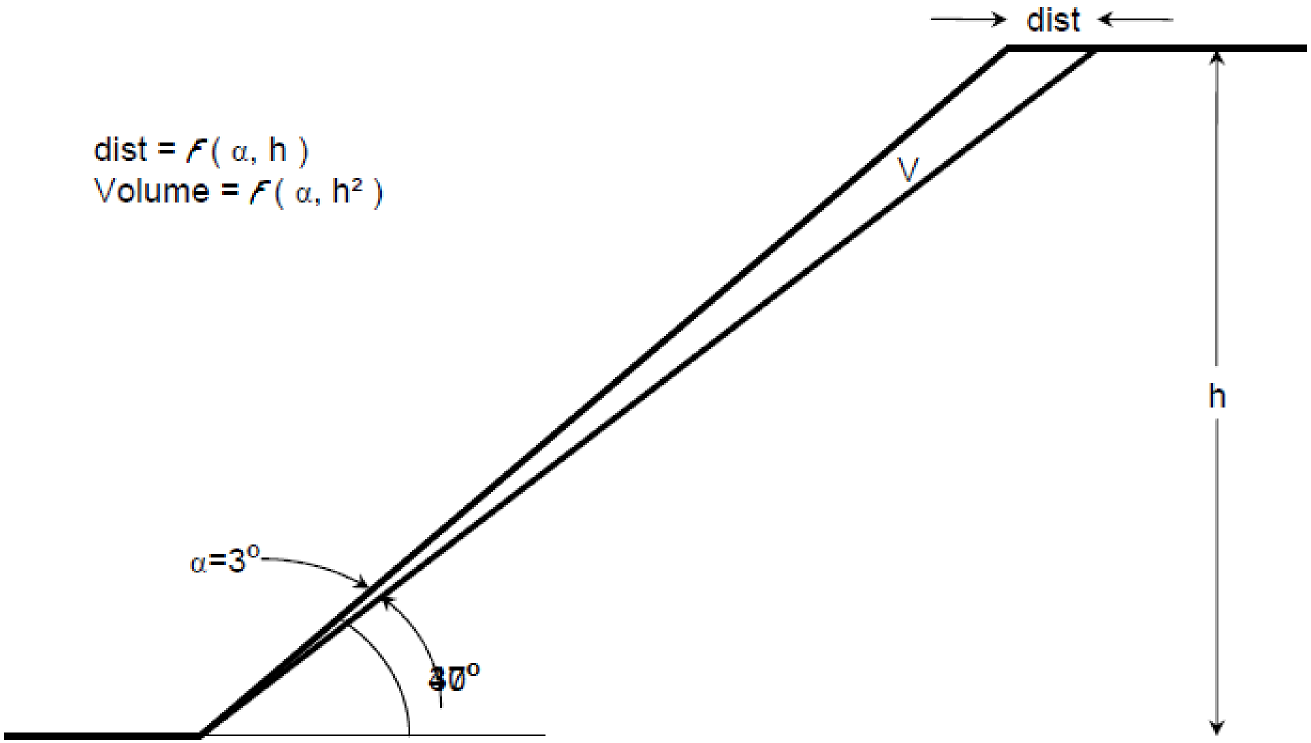
- Harm to people
- Lost or delayed production
- Damage or loss of equipment
- Remediation

Companies and insurers calculate these cost but they are not accessible – they can be significant

Over-conservatism

What is the cost of a conservatively designed slope?

- Additional stripping
- Ore not mined



$\text{dist} = f(\alpha, h)$
$\text{Volume} = f(\alpha, h^2)$

Height m	Dist m	Volume m³ /m
100	13.5	676
300	40.6	6,088
500	67.6	16,911
700	94.7	33,146
900	121.8	54,793

(Gill, 2009)

Cost of geotech model uncertainty

- 1.5 Mt failure part of a larger 8Mt instability
- Lost pit production ~1year
- Remediation costs

Back analyses (Yang et al, 2011)

- Properties of weak layer overestimated
- Position of weak layer shallower than expected

Uncertainty in implementation

- 10 Mt waste dump failure
- Covered a highway (460m)
- Significant remediation costs
- Contributing factors
  - Low strength material in lower lifts
  - Increase PWP due to consolidation
  - Material weaker than initially thought

(Sheets & Bates, 2008)

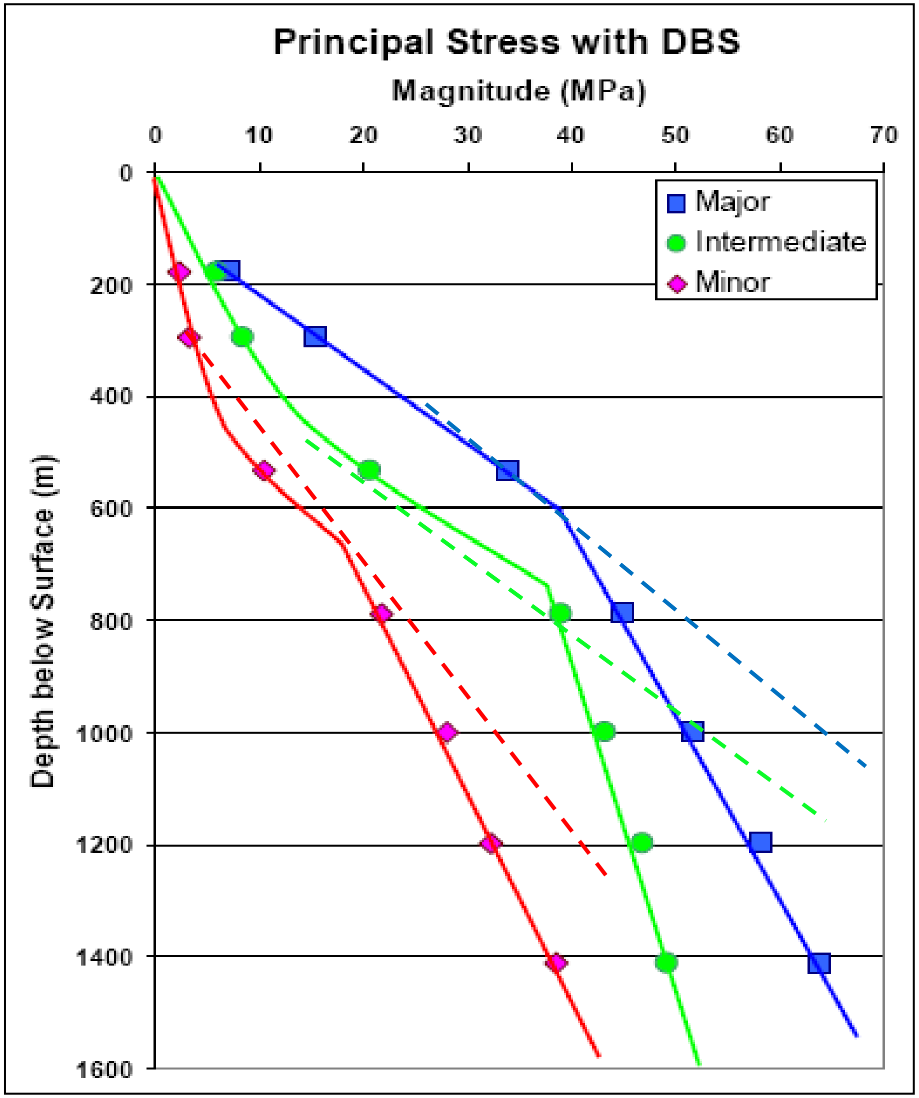
Uncertainty due to extrapolation of data

Initially the deepening project used extrapolated stress conditions

Subsequent measurements confirmed that this was too conservative

Be careful about assumptions and extrapolating data

You could provide over conservative guidance which impacts heavily on project economics



Unexpected response

Main haulage was heavily supported – bolts, mesh, shotcrete & cables

~90m of haulage was closed in response to a M~2.3 seismic event

Unexpected response

Return airway is 20m away and parallel to the haulage

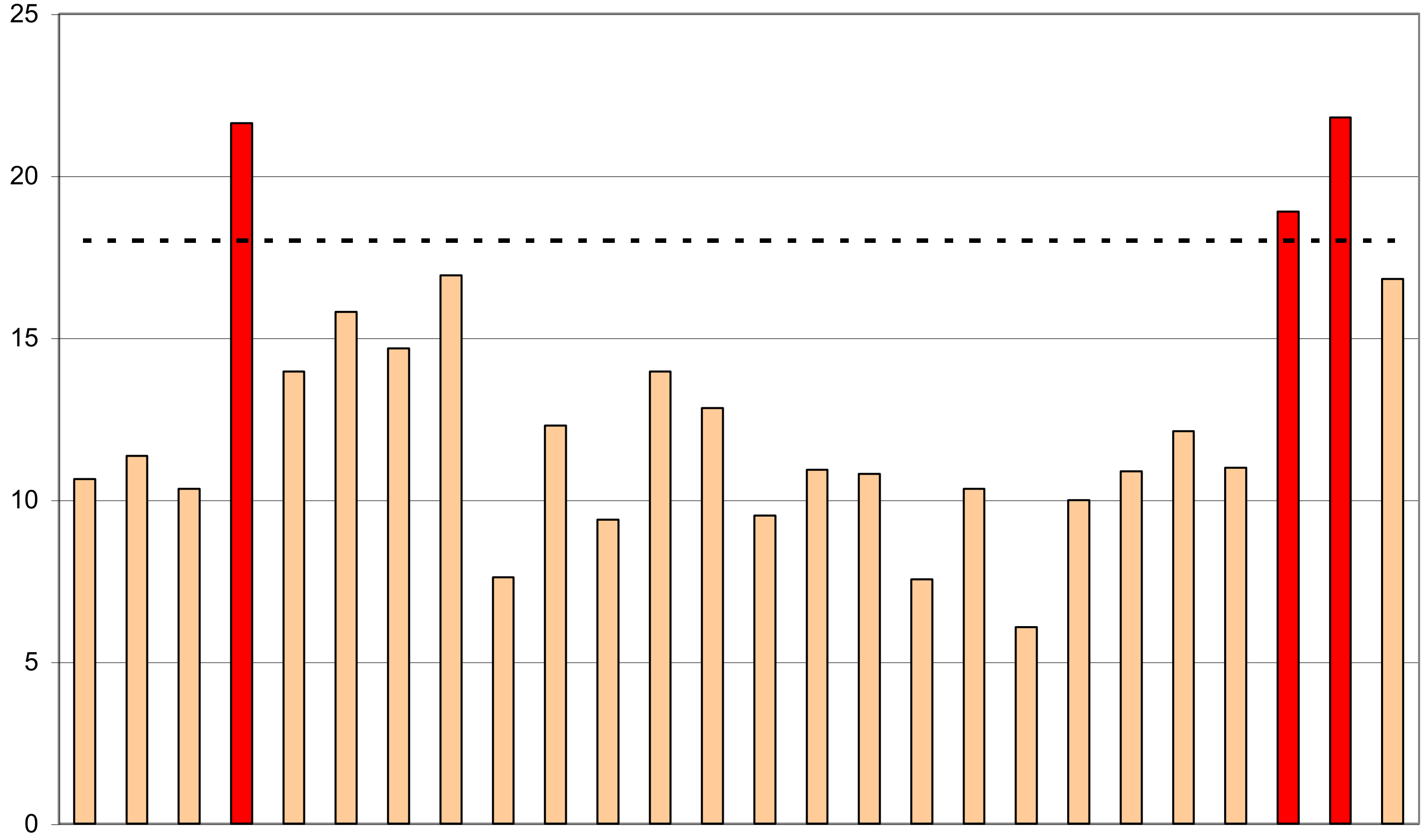
Lightly supported with pattern bolts

Minor shakedown damage in response to the M~2.3 seismic event

Uncertainty in Implementation

Shotcrete quality control – are you getting what you paid for?

28 day UCS (MPa) of cored samples from various underground sites



Dealing with Design Uncertainty

The first step to dealing with design uncertainty is recognising that it exists and understand what type of uncertainty you're dealing with

The second is recognising that it may not be possible to eliminate all uncertainty and that contingency plans are required

Thirdly, uncertainty is a cost ($$$$$)

Once there is recognition of these facts, a design process that attempts to reduce uncertainty to reasonable limits can be defined

Dealing with Design Uncertainty

Data collection to minimise design uncertainty

- Critical step in the minimisation of uncertainty
- Includes field collection and lab testing programmes
- Programmes are often limited by the resources – motivate for additional resources or focus on critical aspects
- Sometimes you have to proceed with limited data
    - document assumptions and limitations
    - develop contingencies.

Hadjigoergiou (2012) provides a good overview of shortcomings in data collection and how data can be more effectively used in solving geotechnical problems.

Dealing with Design Uncertainty

Minimise input data uncertainty by:

- Understand what data is needed – programme goals;
- Data density & distribution;
- Good data collection procedures & adequately trained staff;
- Implement quality control procedures;
- Implement sound sampling procedures;
- Use accepted testing procedures & certified laboratories;
- Use statistical methods to define minimum number of samples;
- Develop statistical descriptions & distributions for all parameters;
- Ensure that data is stored databases;
- Use visualization tools (3D) - understand spatial distribution.

Dealing with Design Uncertainty

Minimising uncertainty in analysis and design

- Use a well thought out design process that takes into account uncertainty
- Use the appropriate tools – matched to inputs and problem
- Design methods
  - Empirical
  - Analytical
  - Numerical
- Deterministic or probabilistic
- Design acceptance criteria

Dealing with Design Uncertainty

Tunnel support design

Probabilistic methods (JBlock) used to define design block sizes

- Discontinuity orientations
- Spacing
- Length

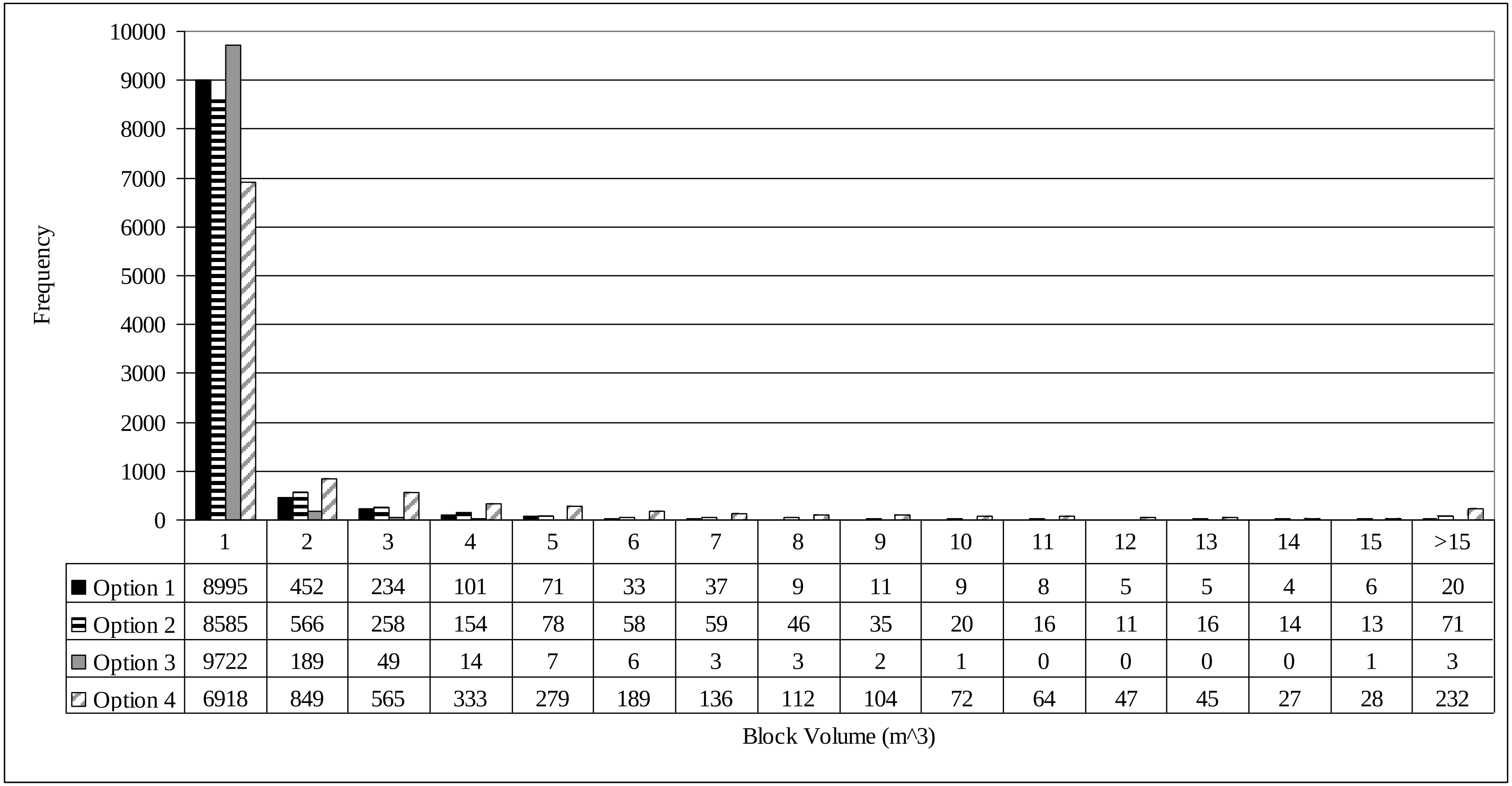
Used this to scale wedges in UnWedge (hybrid approach)

Used a 95% cumulative criterion to design - conservative but significantly less conservative than worst case or full excavation span block

Can determine probability of occurrence for different block sizes – move towards a risk based design

Dealing with Design Uncertainty

- Discontinuity data used to generate 10000 removable blocks
- Parameters varied to assess sensitivity
- Block size distribution correlates with observed conditions

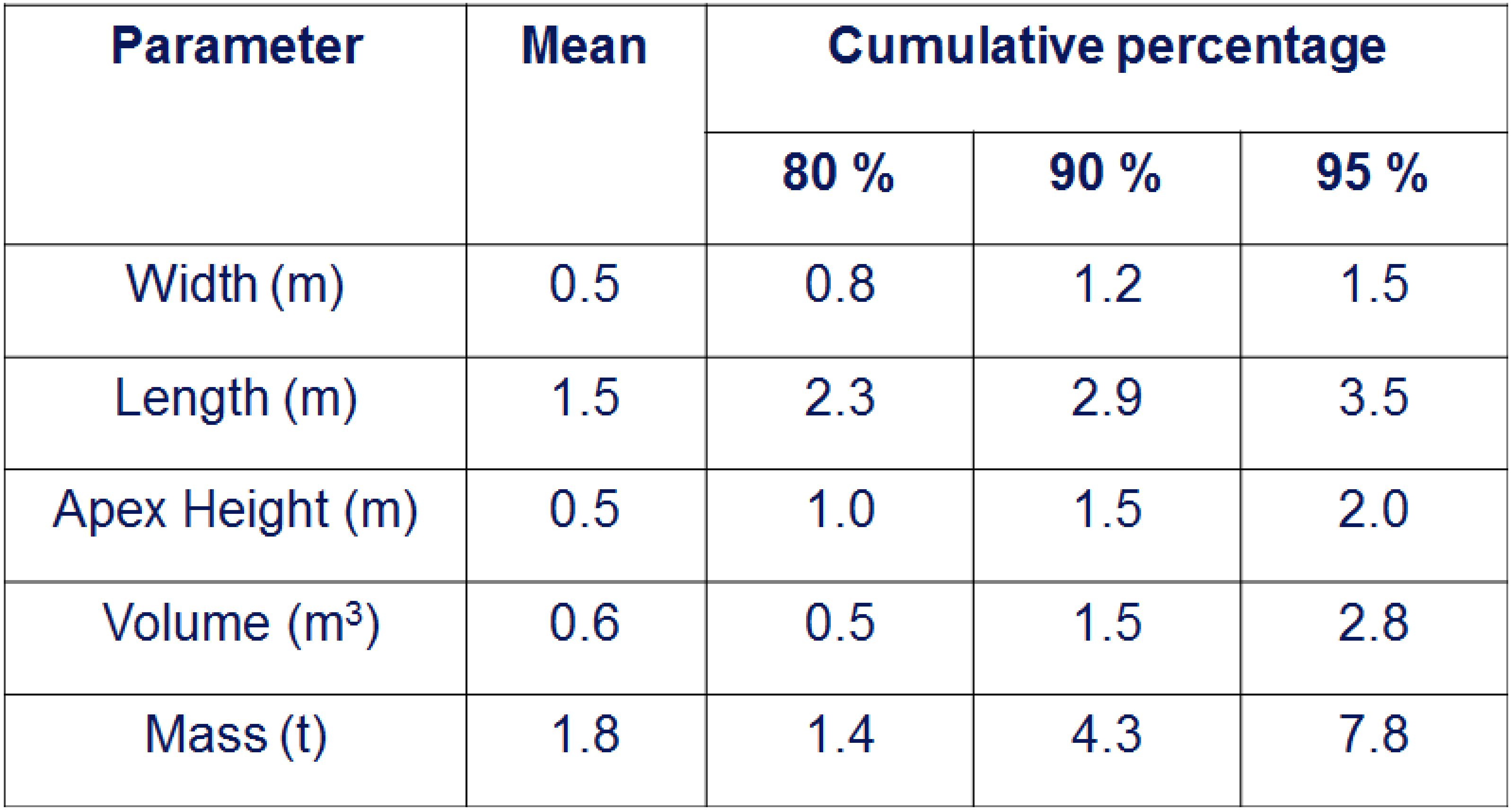


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	>15
■ Option 1	8995	452	234	101	71	33	37	9	11	9	8	5	5	4	6	20
▤ Option 2	8585	566	258	154	78	58	59	46	35	20	16	11	16	14	13	71
▩ Option 3	9722	189	49	14	7	6	3	3	2	1	0	0	0	0	1	3
▨ Option 4	6918	849	565	333	279	189	136	112	104	72	64	47	45	27	28	232

Block Volume (m^3)

Dealing with Design Uncertainty

Can generate block statistics



Parameter	Mean	Cumulative percentage		
		80 %	90 %	95 %
Width (m)	0.5	0.8	1.2	1.5
Length (m)	1.5	2.3	2.9	3.5
Apex Height (m)	0.5	1.0	1.5	2.0
Volume (m^3)	0.6	0.5	1.5	2.8
Mass (t)	1.8	1.4	4.3	7.8

Dealing with Implementation Uncertainty

Communicating the design

- Design confidence level
- Design specification
  - Unit specifications
  - Ground support standard
- Design applicability and trigger levels for design changes
- Quality assurance and monitoring
  - Must be clearly defined to relevant parties
  - Include in contract documents

Dealing with Implementation Uncertainty

- Training
  - Supervisors and operators
  - Need to understand support systems and why they are used
  - Be able to recognize when something has changed
- SOP and installation procedures
- Supervision and quality control systems
- Change management procedures
- Target action response plans and contingencies
- Performance monitoring

Conclusions

Uncertainty is a reality in both the design and implementation.

Uncertainty is a cost

Dealing with uncertainty:

- recognise that it exists;
- recognising that it may not be possible to eliminate all uncertainty - contingency plans are required;
- important to recognize types of uncertainty.

Once there is recognition of the above, design and implementation processes that attempt to reduce uncertainty to reasonable limits can be developed.

Conclusions

Design input uncertainty can be minimised by implementing quality data capture and testing programmes.

You need to understand variability - descriptive statistics and distributions.

A variety of tools exist that can be applied in design to reduce uncertainty.

Geotechs should not lose sight of the implementation phase, which has its own associated uncertainties.

Cost- benefit analyses – why should you reduce uncertainty

It is not acceptable to overlook uncertainty – it will cost you!

References

Baecher, G.B. and Christian, J.T. (2003) Reliability and Statistics in Geotechnical Engineering, Wiley, 618 p.

Bieniawski, Z.T. (1992) Principles of engineering design for rock mechanics, in Proceedings 33rd US Symposium on Rock Mechanics, J.R. Tillerson and W.R. Wawersik (eds) 3-5 June 1992, Santa Fe, USA, Balkema, Rotterdam, pp. 1031–1040.

Brown, E.T. (2007) Block Caving Geomechanics, Second edition, JKMRC, Brisbane, 696 p.

Hadjigeorgiou, J. and Harrison, J.P. (2011) Uncertainty and Sources of Error in Rock Engineering, in Proceedings 12th ISRM International Congress on Rock Mechanics, Harmonising Rock Engineering and the Environment, Q. Qian and X. Zhou X. (eds), 18-21 October 2011, Beijing, China, CRC Press, Leiden, pp. 2063–2067.

Hadjigeorgiou, J. (2012) Where do the data come from? In Proceedings Sixth International Seminar on Deep and High Stress Mining.Y. Potvin (ed), 28-30 March 2012, Perth, Australia, Australian Centre for Geomechanics, Perth, pp. 259- 277.

Kiureghian, A.D. and Ditlevsen, O. (2009) Aleatory or epistemic? Does it matter? Structural Safety, 31, pp. 105–112.

McMahon, B.K. (1985) Geotechnical design in the face of uncertainty. Austalian Geomechanics Society E.H. Davis Memorial Lecture.

Peck, R.B. (1969) Advantages and Limitations of the Observational Method in Applied Soil Mechanics. Ninth Rankine Lecture. Geotechnique 19, No. 2, pp. 171–187.

Stacey, T.R. (2004) The link between the design process in rock engineering and the code of practice to combat rock fall and rockburst accidents, The Journal of The South African Institute of Mining and Metallurgy, pp. 29–34.

Stacey, T.R. (2009) Design—a strategic issue, The Southern African Institute of Mining and Metallurgy, Vol. 109, pp. 157–162.