# DISTINGUISHED LECTURE

# THE EVALUATION OF SLOPE STABILITY: A FURTHER 25-YEAR PERSEPECTIVE


by
Norbert R. Morgenstern
Distinguished University Professor (Emeritus)
Department of Civil and Environmental Engineering
University of Alberta
Edmonton, Canada


to
Hong Kong Institution of Engineers

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# INTRODUCTION

"… a Further 25-Year Perspective"

- Analysis and Design
- Mobility and Risk
- Professional Practice

# ANALYSIS AND DESIGN

"… one can imagine a time when simulation is so firmly embedded within the observational method that it becomes recognized as an essential tool in assisting the practicing engineer to evaluate correctly all of the information available to him. This places a greater burden on the engineer to recognize and understand in an ongoing manner the limitations of advanced analysis."

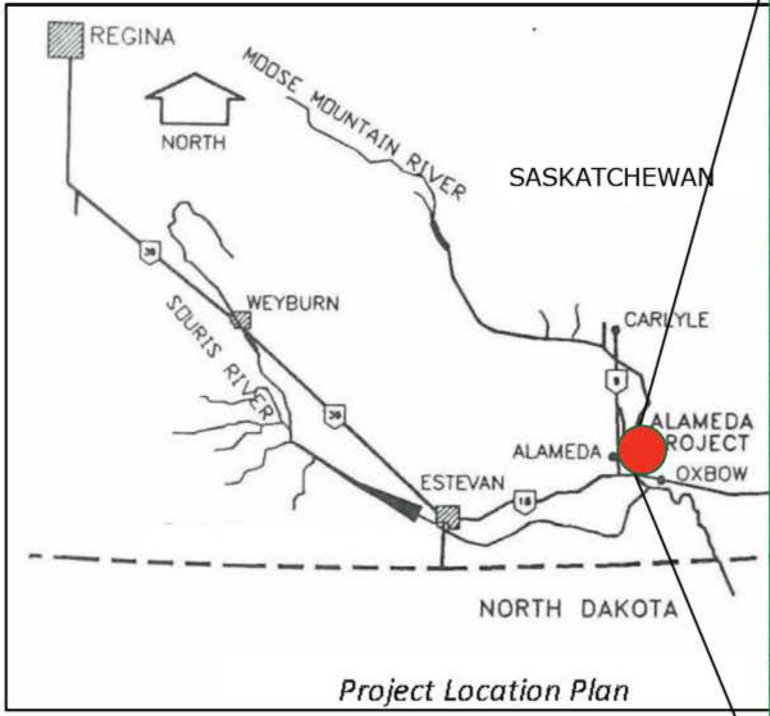
Morgenstern, N.R., 1992. The evaluation of slope stability – a 25-year perspective. Proceedings of the Conference on Stability and Performance of Slopes and Embankments – II. ASCE, Vol. 1, p. 1-26. Berkeley, CA.

# ANALYSIS AND DESIGN

"The most important development in LEA in recent years have related to three-dimensional methods of analysis."

Morgenstern, N.R., 1995. The role of analysis in the evaluation of slope testing. Proceedings of the 6th International Symposium on Landslides, Vol. 3, p. 1615-1630. Christchurch: Balkema.

# CASE STUDY – ALAMEDA DAM





Quinn, J., Chin, B., Pernito, M. and Scammell, J. (2014). Geotechnical Assessment of Alameda Dam. Proceedings, Canadian Dam Association Conference, Banff, Alberta, October 4-9, 2014

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# ISSUE OF CONCERN

- Excessive runoff in the spring of 2011:
  - Reservoir surcharged ~5 to 6 m above FSL (to near MAFL) to reduce d/s flood flows;
  - Increased rates of shear displacements in the clay shale foundation
- Interim stability analyses (Sept 2011):
  - Minimum factor of safety near 1.0

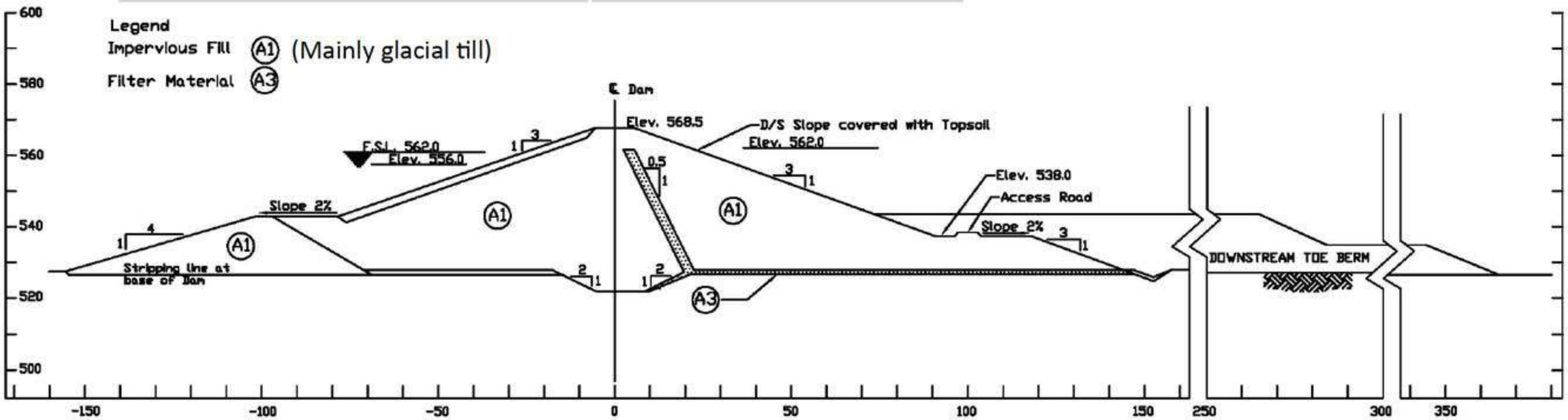
- Recommendations were:
  - Lower reservoir (to FSL or lower) ASAP
  - Carry out site investigations ASAP
  - Conduct detailed assessment ASAP

Click for June 2011 photo

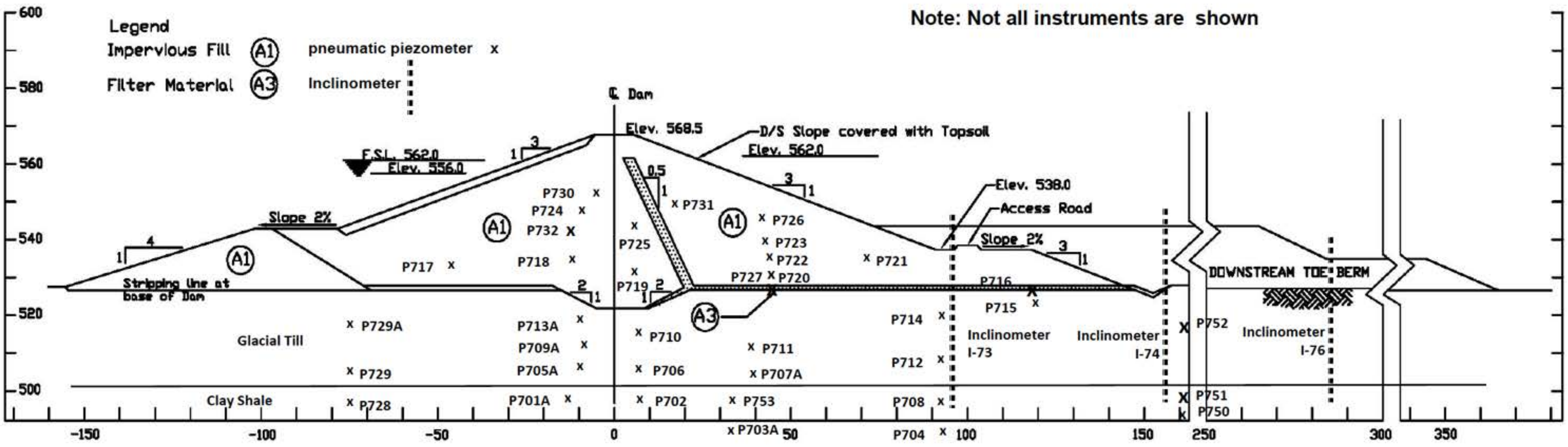
# ALAMEDA DAM – MAIN FEATURES

| Component | Data |
|---|---|
| Full Supply Level (FSL) | 562.0 m |
| Maximum Allowable Flood Level (MASL) | 567.0 m |
| Top of Dam Elevation | 568.5 m |
| Crest Length of Dam Crest | 1250 m |
| Dam Slopes | 3H:1V U/S and D/S with berms (overall D/S ~ 8.5H:1V) |
| Crest Width | 11 m |
| Maximum Dam Height | 42 m |

2010 DSR classified the dam as Extreme Consequence (2007 CDA Guidelines)



# INSTRUMENTATION LOCATION – TYPICAL SECTION



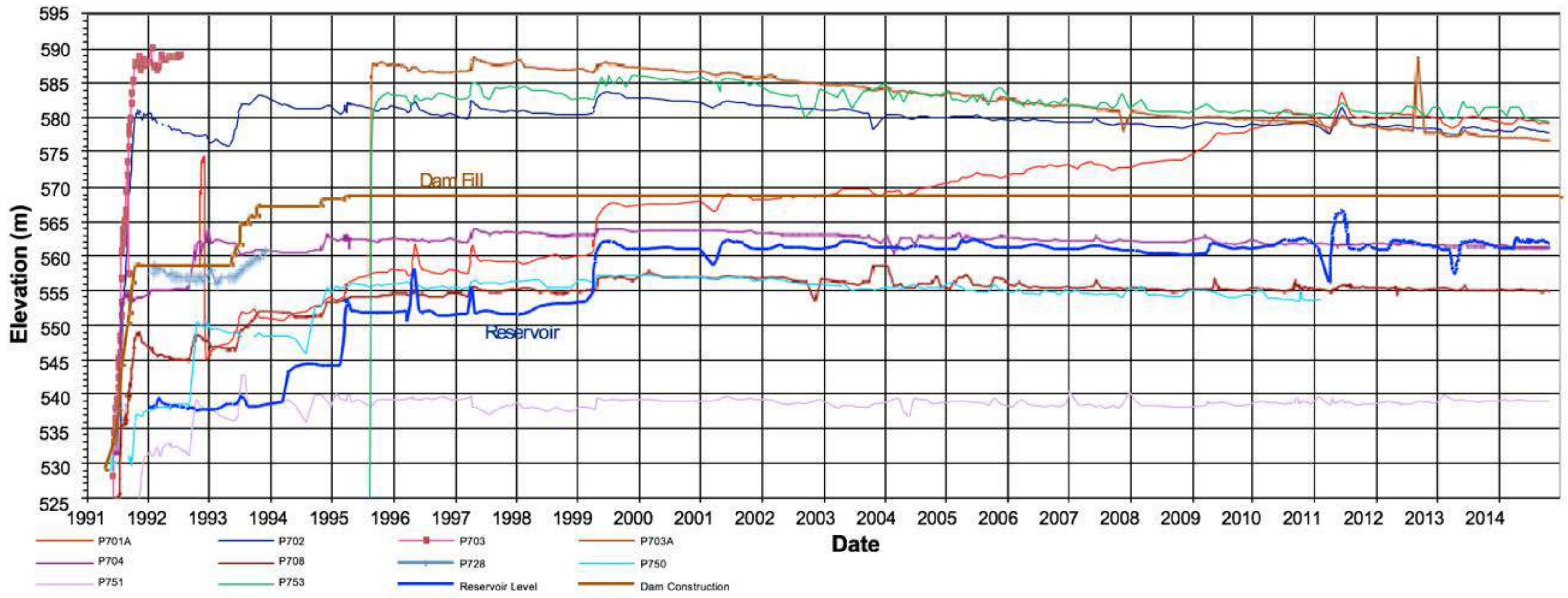
# OVERVIEW OF HISTORICAL PERFORMANCE OF DAM

- Excellent account is provided by Mittal and Rahman (2000)[1]. Overview summary:
  - Mid-1991 to 1995 construction period
  - Unanticipated large shear displacements in clay shale (max. 400 mm @ end of construction) and higher-than-expected excess pore pressures in glacial till ($\overline{B}$ of 0.7 to 0.85) and clay shale ($\overline{B}$ of 0.9 to 1.0)
  - Stopped construction for 18 months:
    - Dam section was re-designed → upstream and downstream buttress added
    - Remainder of dam (El. 558 to 568.5 m) was completed in a number of carefully controlled and closely monitored stages
- Reservoir filled to FSL in 1999.

[1]Mittal and Rahman (2000). Stability of Alameda Dam During Construction. Proceedings, Canadian Dam Association Conference, Regina, Saskatchewan.

# CLAYSHALE PORE PRESSURES

- High excess pore pressures during construction
- Very slow post-construction dissipation; still high pore pressures today
- Responds to total stress change from reservoir – response attenuates rapidly in downstream direction

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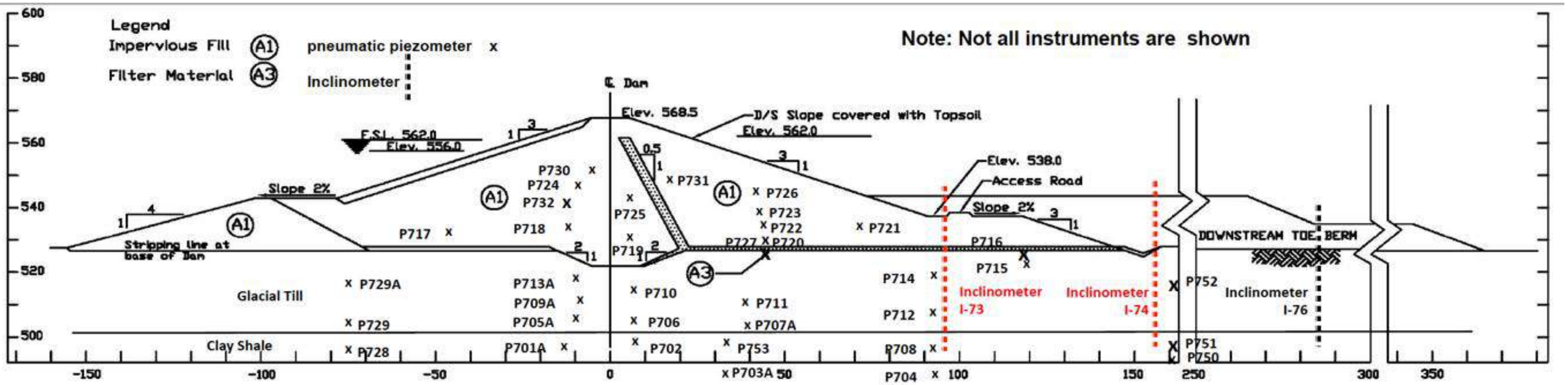
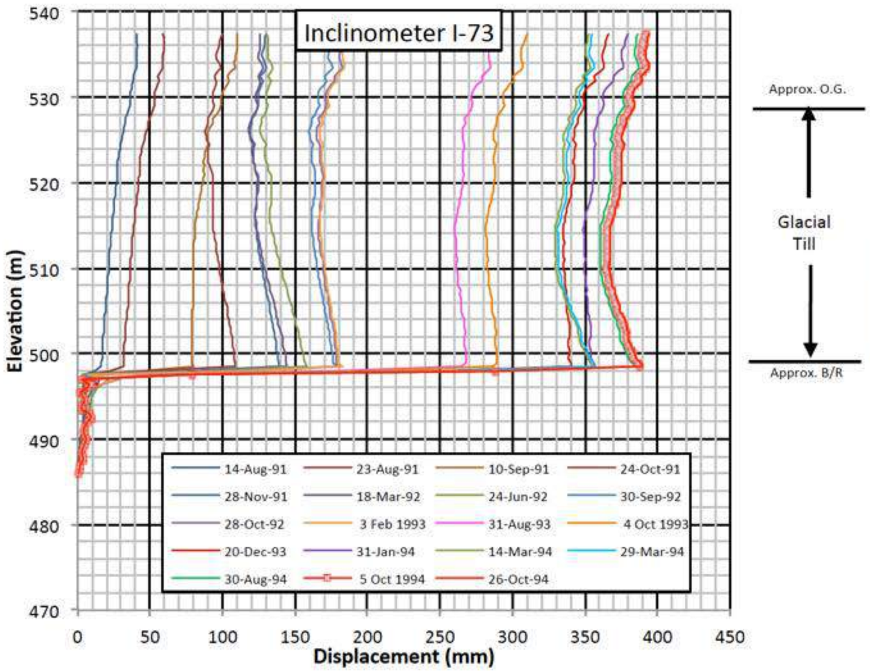
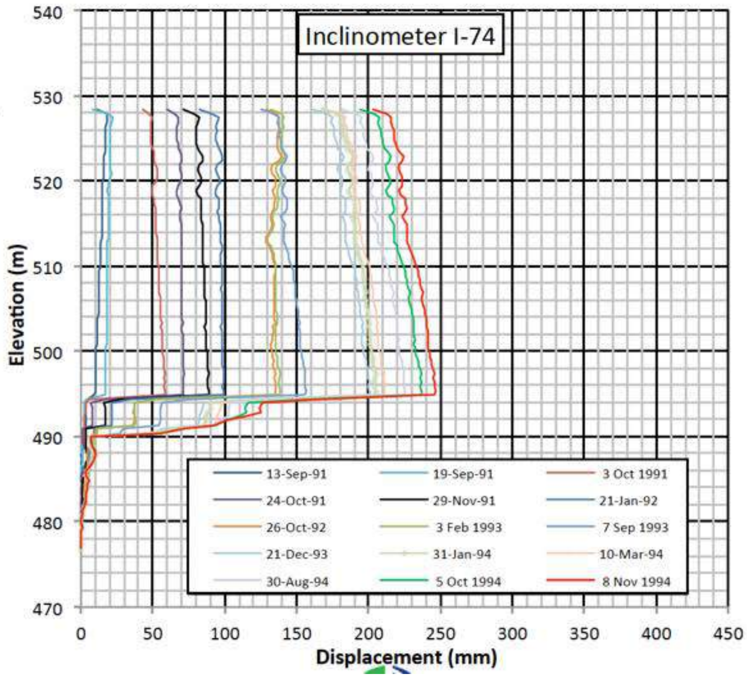
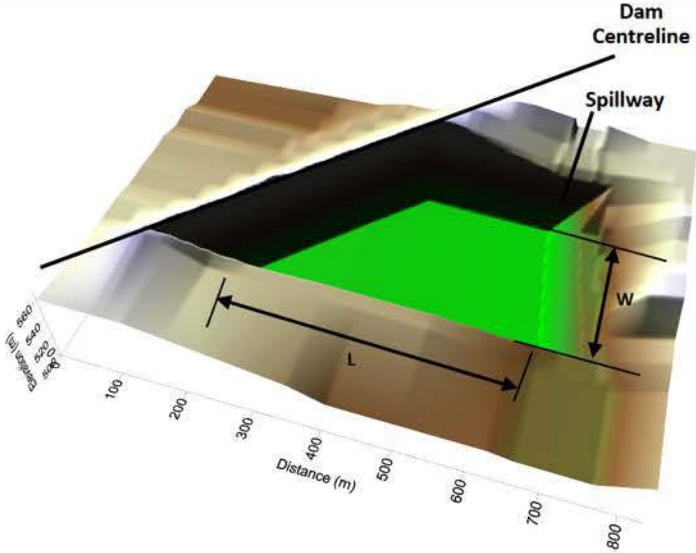
# FOUNDATION MOVEMENT

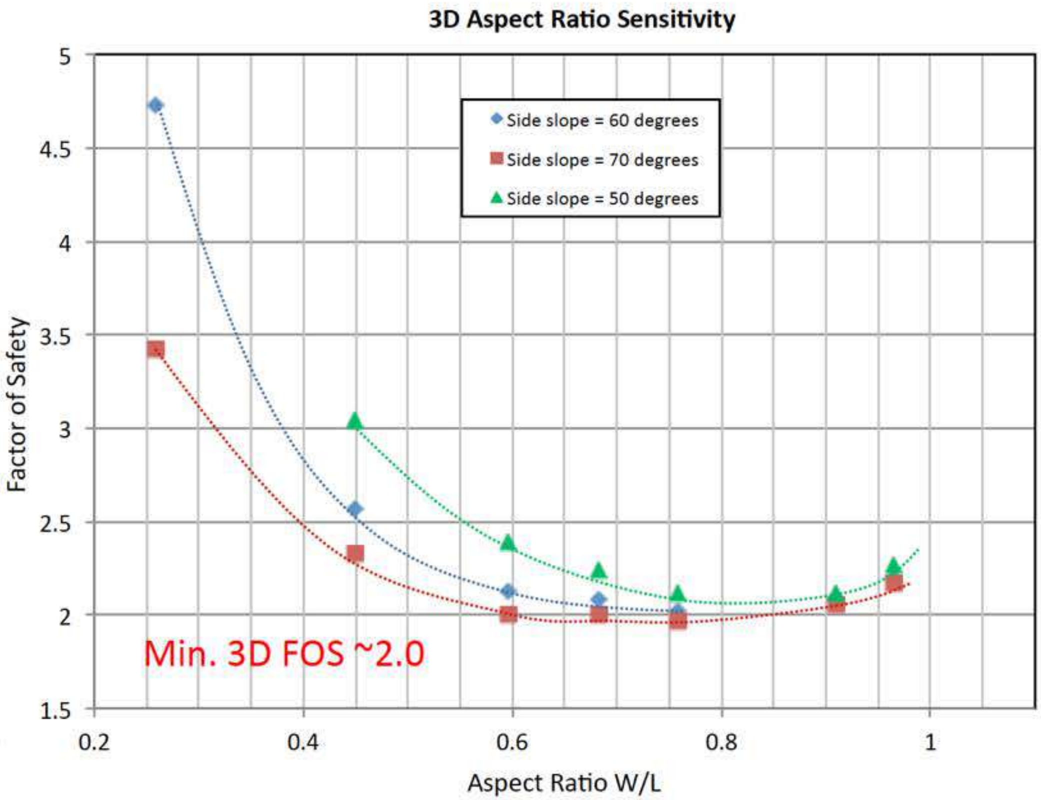


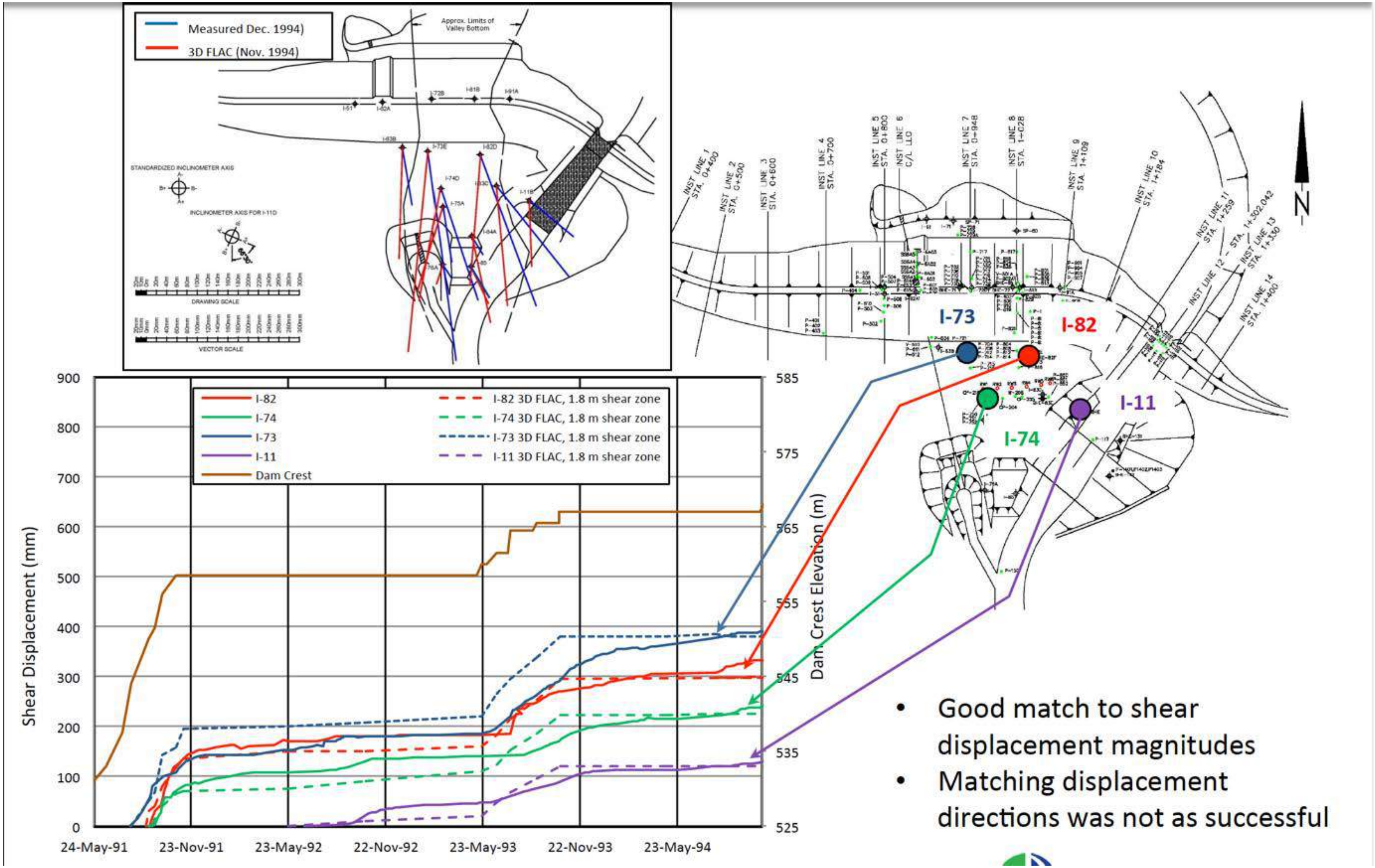



# 3D LIMIT EQUILIBRIUM STABILITY ANALYSES



# 3D FLAC – SHEAR DISPLACEMENT

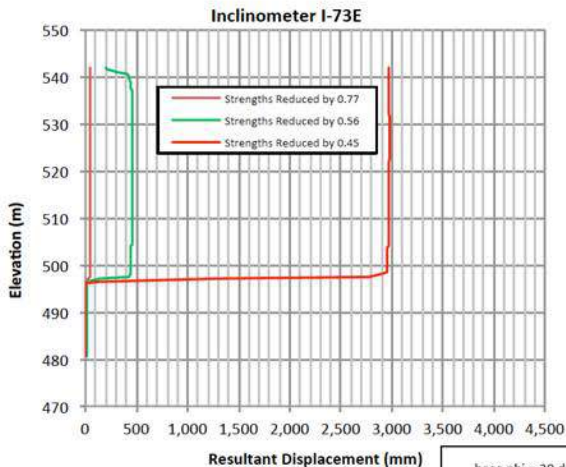


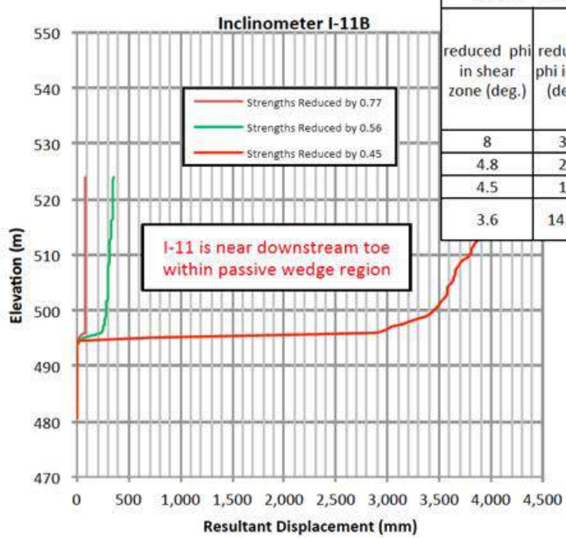

- Good match to shear displacement magnitudes
- Matching displacement directions was not as successful

# 3D MODEL – FAILURE ASSESSMENT

- Having 'matched' the model response to the inclinometer data, it was used to generate failure scenarios for comparison with the monitoring results:
  - 'Conventional strength reduction'
    - Strength of all materials progressively reduced until failure (defined by model non-convergence) occurs
    - Consistent with conventional definition of limit equilibrium FOS
  - 'Till strength reduction only'
    - Strength of till reduced until failure occurs

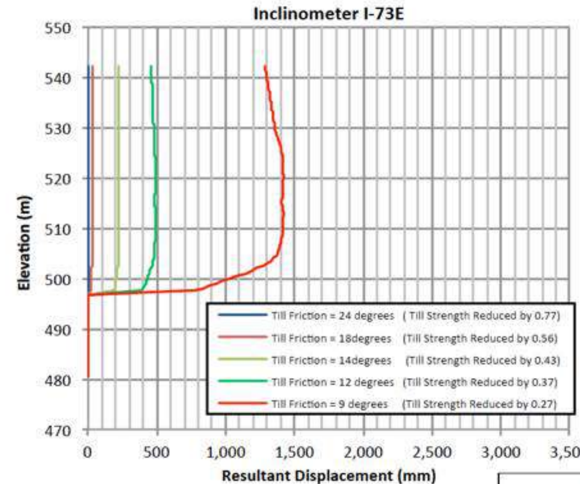
# THEORETICAL DISPLACEMENTS VERSUS STRENGTH REDUCTION

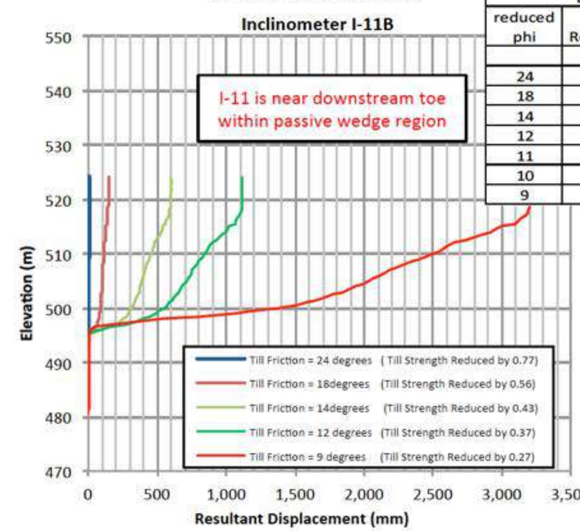



| base phi = 30 deg. (till); 8 deg. (Shear Zone) | | | |
|---|---|---|---|
| reduced phi in shear zone (deg.) | reduced phi in Till (deg.) | Strength Reduction | $FOS_{(3D)}$ (Conv.) |
| 8 | 30 | 1.0 | 2.24 |
| 4.8 | 24 | 0.771 | 1.73 |
| 4.5 | 18 | 0.562 | 1.26 |
| 3.6 | 14.44 | 0.45 | 1.00 |

Conventional Strength Reduction




| base phi = 30 deg | | |
|---|---|---|
| reduced phi | Strength Reduction (Till) | FOS (Till) |
| 24 | 0.771 | 2.81 |
| 18 | 0.562 | 2.05 |
| 14 | 0.432 | 1.57 |
| 12 | 0.368 | 1.34 |
| 11 | 0.337 | 1.23 |
| 10 | 0.305 | 1.11 |
| 9 | 0.274 | 1.00 |

"Till Only" Strength Reduction

# Looking to the Future:

## Precautionary Based Design

(Factors of Safety, monitoring, observational method)

## Performance Based Design

(Reserve resistance(s), monitoring, observational method, integrates real-time response modelling)

# A Challenge for Regulation

Current Alberta Dam Safety Guidelines (draft) are based on the following:

- NO specification of minimum factors of safety
- Existing industry guidelines are referenced, but selection of factors of safety must consider influencing factors such as:
    - Consequence of failure
    - Uncertainty in material properties and subsurface conditions
    - Variable construction and operating conditions
    - Comprehensive site investigations and geotechnical monitoring
    - Soil response (contractive/dilative) and its variation with confining stress and shear stress level, including potential for brittle failure
    - Time-dependent, deformation dependent and stress-path dependent processes that may affect the critical material properties
    - Strain-incompatibility of different materials
    - Seismic loading as appropriate
    - Implementation of an effective risk management system (e.g., observational method)

**Is this the way forward to maximize trust and public safety?**

# 3. MOBILITY AND RISK

"… It appears that from an engineering point of view, the motions of mobile flows and the design of protective structures should proceed using principles of fluid mechanics rather than the more common considerations of shearing resistance in soil and rocks. However, a considerable effort is needed to systematically classify soil and rock flows and to understand the processes whereby they become fluidized."

Morgenstern, N.R., 1978. Mobile soil and rock flows. Geotechnical Engineering, Vol. 9, p. 123-141.

Cases:

- Sau Mau Ping, Hong Kong
- Port Alice Debris Flow, Canada
- Grota Fundo Slide, Brazil
- The Barrier, Rubble Creek Flow, Canada

# Contributions of Professor Oldrich Hungr

Hungr, O., 1981. Dynamics of rock avalanches and other types of slope movements. Ph.D. Thesis, University of Alberta.

Hungr, O., 2016. A review of landslide hazard and risk assessment methodology. Conference on Landslides and Engineered Slopes. Vol. 1, p. 3-26. (Heim Lecture)

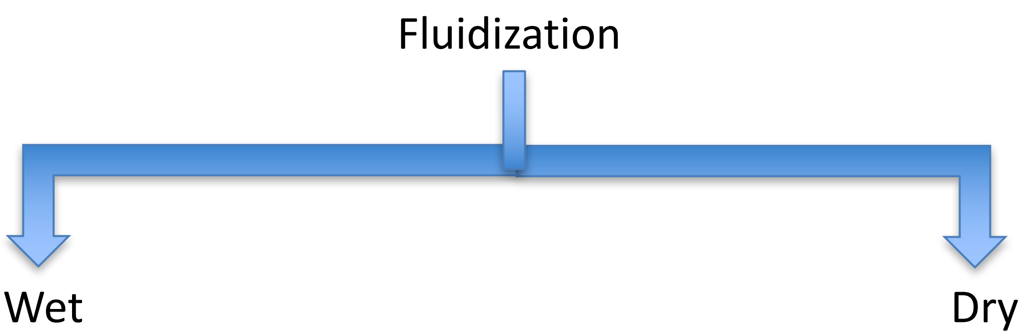
**Evolution of runout analyses:**

Hungr, O., Morgenstern, N., and Wong, H.N., 2007. Review of benchmarking exercises on landslide debris runout and mobility modelling. In Proceedings of the 2007 International Forum on Landslide Disaster Management, edited by Ho and Li, Hong Kong Geotechnical Engineering Office, p. 755-812.

McDougall, S., 2017. Landslide runout analysis – current practice and challenges. Canadian Geotechnical Journal, Vol. 54, p. 605-620.

In practice, relatively simple rheology is commonly assumed in back analysis and as noted by Hungr (2016):

"… the rheology specified in all these models is not a true material characteristic, but a representation of the bulk flow resistance as evidenced by the behaviour of full-scale case histories. Thus, the rheological parameters cannot be independently measured, but must be determined by calibration."




Wet:

- collapse liquefaction
- sliding surface liquefaction

Dry:

- vibrational/acoustic fluidization
- dynamic mode fragmentation

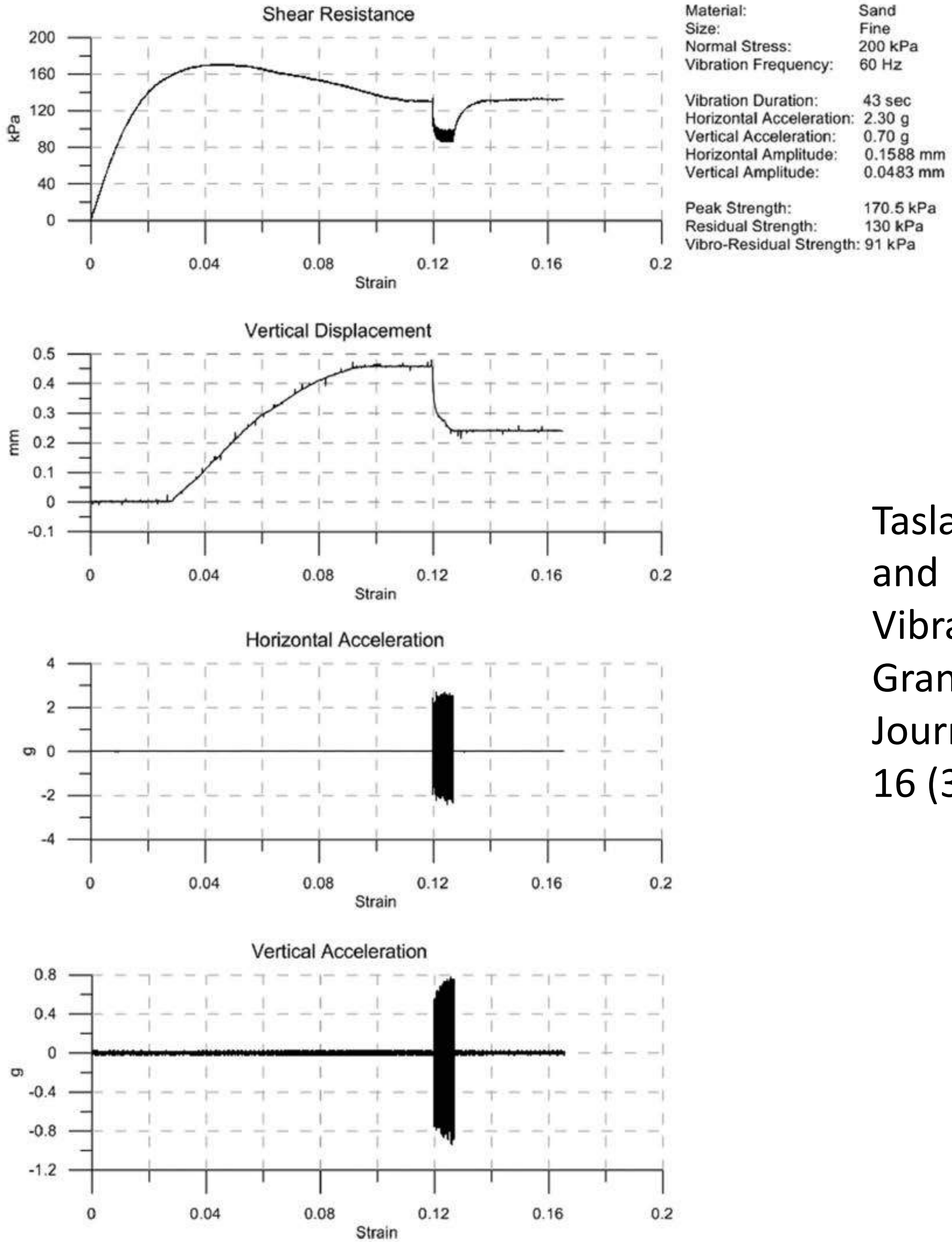



**Fig. 5.** Results of a fine sand sample tested at $\sigma = 200$ kPa, $\omega = 60$ Hz, and $\Gamma_h = 2.3$

Taslagyan, K.A., Chan, D.H., and Morgenstern, N.R. 2016. Vibrational Fluidization of Granular Media. International Journal of Geomechanics, Vol. 16 (3), pp. 04015080-1 – 22.

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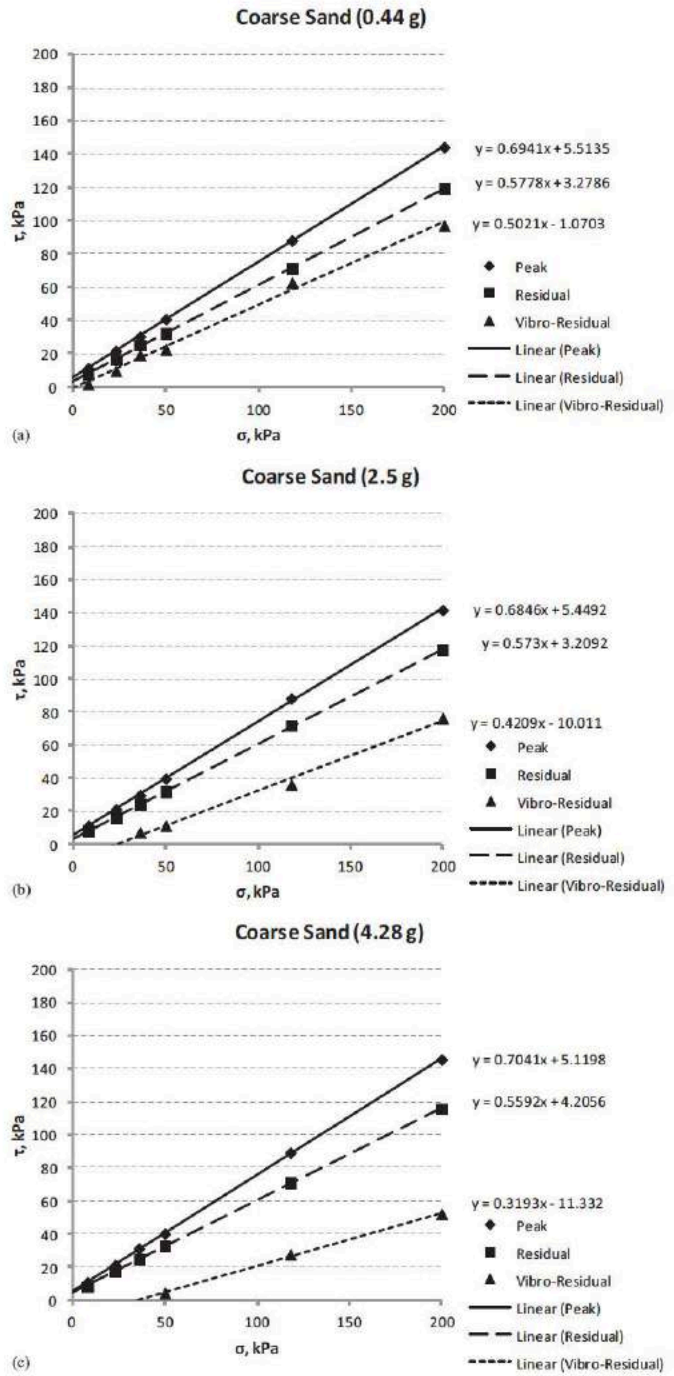



**Fig. 8.** Shear strength diagrams of coarse sand tested at (a) $\Gamma = 0.42$; (b) $\Gamma = 2.42$; and (c) $\Gamma = 4.28$

This appears to be the phenomenon of vibrational/acoustic fluidization postulated by Melosh (1979) and suggests that the rheology of a flowing granular mass is much influenced by the vibrational interaction along its flowpath.

See: Melosh, H.D. 1979. Acoustic fluidization – A new geologic process. Journal of Geophysical Research, Vol. 84, p. 7513-7520.

# Landslide Risk and Public Policy

Quantitative Risk Analysis (QRA) applied to landslides are well-understood in the Hong Kong community which was the first government to formally adopt tolerable landslide risk criteria in practice. This was a watershed in the application of QRA to landslide hazards in practice. The history of this seminal development has been written by Malone (2005).

Malone, A.W. 2005. The story of quantified risk and its place in slope safety policy in Hong Kong. See Chapter 22 in Landslide Hazard and Risk, ed. Glade, T., Anderson, M.G., and Crozier, M.J. John Wiley & Sons Ltd., p. 643-674.

# Landslide Risk and Public Policy

A recent review of practice in various parts of the world related to landslide risk management found wide differences between the current scientific understanding of risk acceptance and actual application in practical circumstances. This is particularly marked in the absence of public jurisdictions to follow Hong Kong's lead. Example of legally binding regulations in public policy were found only in Canada. This review was undertaken by Hungr et al. (2016).

Hungr, O., Clague, J., Morgenstern, N.R., VanDine, D., and Stadel, D., 2016. A review of landslide risk acceptability practices in various countries. Landslides and Engineered Slopes: Experience, Theory and Practice, International Conference ed. by Aversa et al., Associazione Geotecnica Italiana, p. 1121-1128.

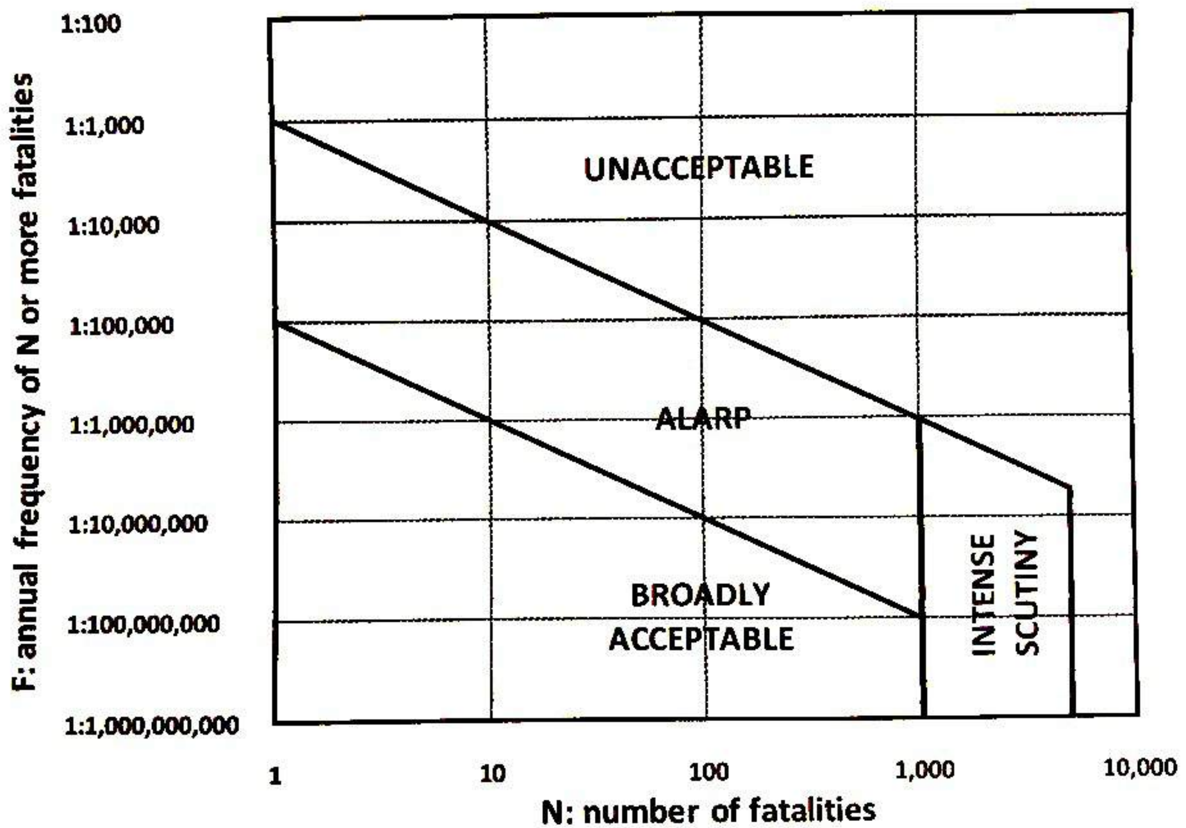
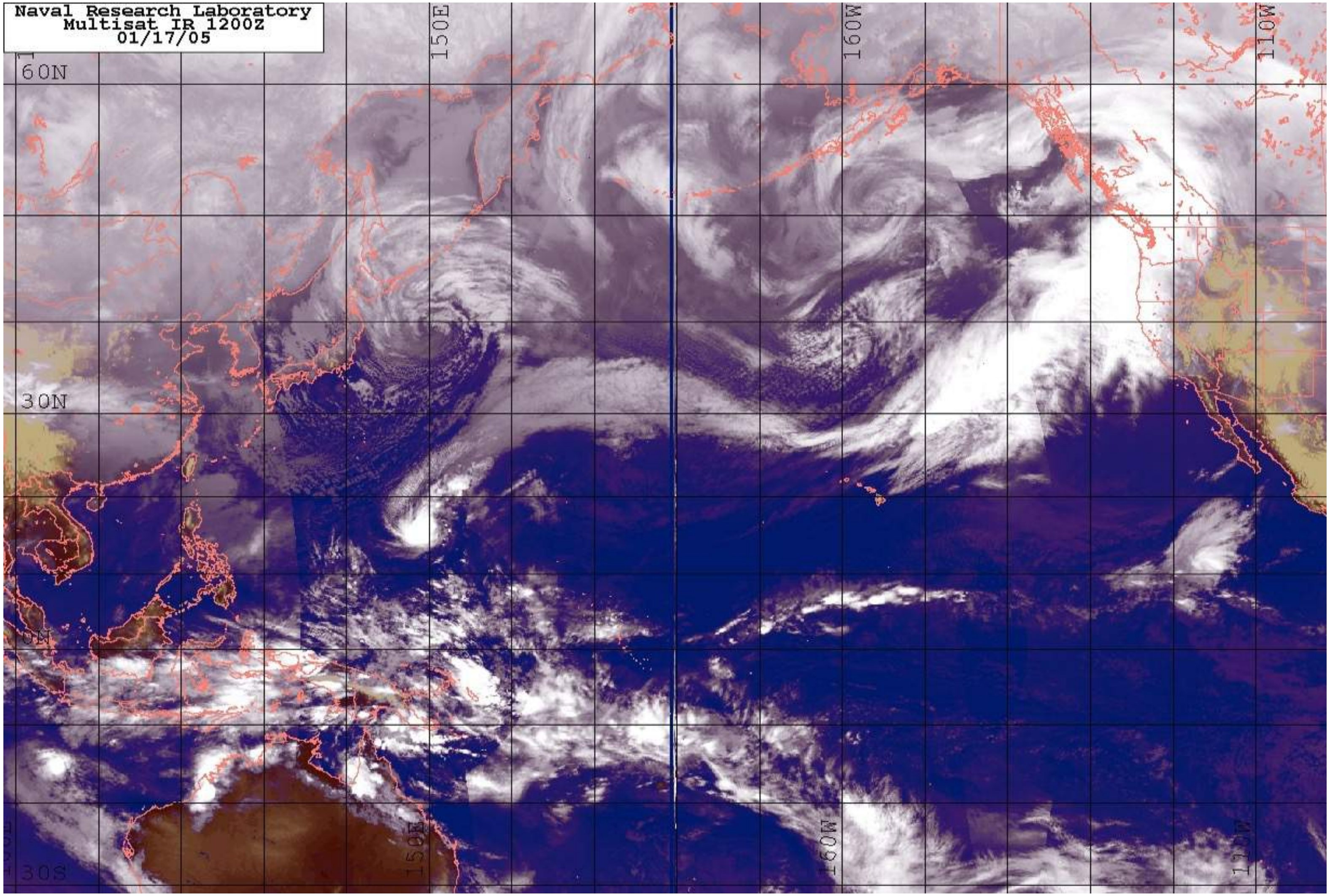


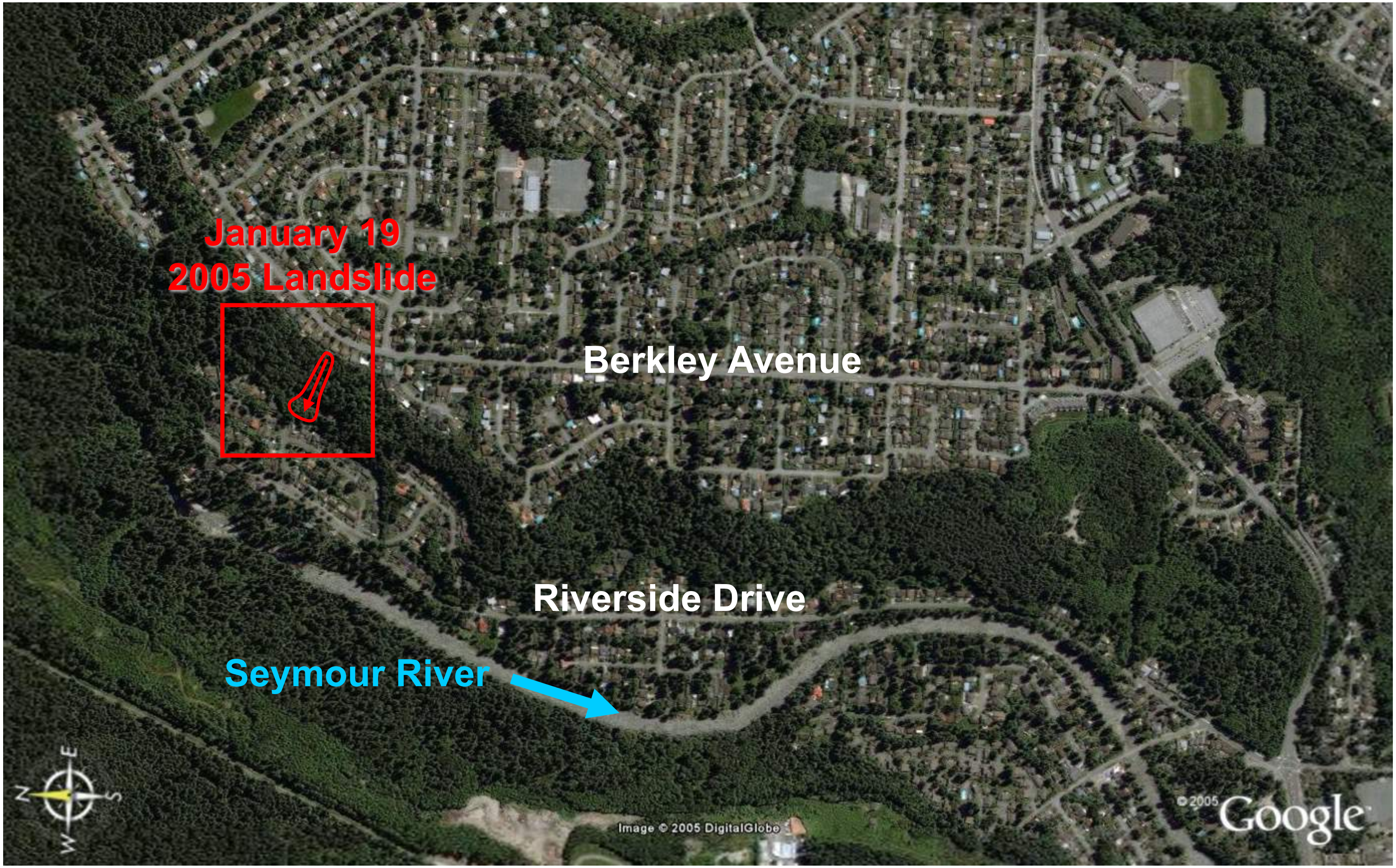

Figure 3. Societal risk tolerance criteria for landslides in Hong Kong (GEO 1998).

# ~ January 15, 2005




> 200 mm of rain, Intensities ~ 10 mm/hr

# Berkley Escarpment, District of North Vancouver

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## January 19, 2005 Landslide

- Occurred early in the morning
- Storm rainfall ~ 175 mm
- Initial failure width = 20 m (enlarged to 26 m)
- Initial volume = 800 $m^3$
- Final volume = 3,500 $m^3$
- Runout length = 160 m
- Runout angle = 21° (significant damage to 23°)

- Classified as an Extremely Rapid Earth Flow, with velocity and runout the result of static liquefaction… "Flow Slide"

# Flow Slide - Consequences

**Top Stories**

Wed. Jan. 19 2005 11:30 PM ET

**This North Vancouver home's pool hovers on the edge of a cliff which has been drastically eroded by the heavy rains.**

## Woman killed in massive North Van mudslide

*CTV.ca News Staff*

One woman is dead while her husband recovers in hospital after a sudden and deadly mudslide in North Vancouver early Wednesday.

The woman was a resident in one of the two homes smashed by the rain-fed mudslide at the foot of Mount Seymour.

Her body was found by rescue workers as they searched through the debris Wednesday afternoon.

Earlier, neighbours spotted Michael Kuttner -- the woman's husband -- lying face down in the wreckage and managed to free him within minutes.

"And then my husband right away start digging in there because he hears some person, help, help and that is Michael our neighbour," said area resident Lynn Hart.

Kuttner was sent to hospital where he remains in critical condition.

The 13-year-old daughter of that couple has been accounted for. She's attending boarding school out of the country.

Fearing more landslides, about 80 homes in the area have been evacuated until experts declare that it's safe to return.

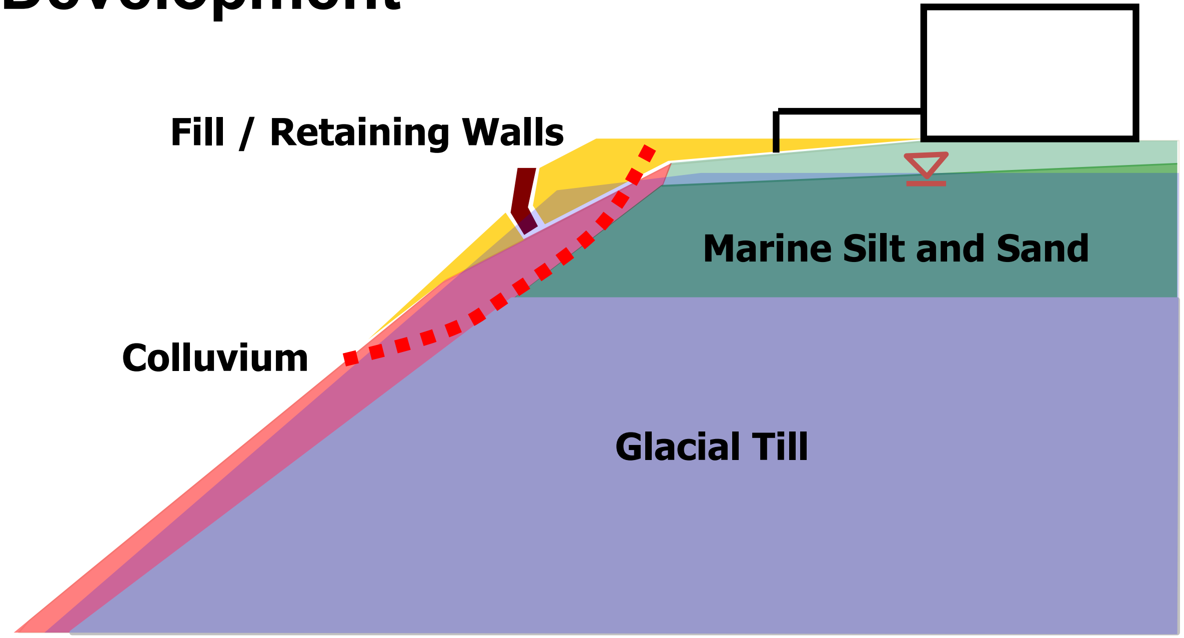
## Geological Setting

# Glacial Advance and Retreat

# Marine Inundation

# Uplift and Down-cutting of Seymour River

# Residential Development



## Landslide Risk Estimation

- Risk = $P_{Slide}$ x N (fatalities per year)

- Consequence = expected number of fatalities
  - N = $P_{S:H}$ x $P_{T:S}$ x V x E

$P_{S:H}$: Based on position of homes and runout behaviour of previous slides

$P_{T:S}$: 12 to 16 hrs per day

V: 0.29, based on consequences of previous slides

E: 4 people per home

# History of Sliding

CBC News

NEWS
Indepth »
Viewpoint »
BUSINESS
SPORTS
ARTS & ENTERTAINMENT
WEATHER
HEALTH & SCIENCE
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## 1980 report warned of mudslide risk

*Last Updated Fri, 21 Jan 2005 21:55:11 EST*
CBC News

VANCOUVER - A report written after a 1979 mudslide in North Vancouver warned about the danger of more slides in the area, specifically mentioning the backyard that killed a woman as it collapsed onto the slope below this week.

- RELATED: 1980 consulting report on landslide area

The consulting engineer's report was commissioned after a mudslide destroyed Jane and David Cowan's house on a cliff in the Berkeley-Riverside neighbourhood more than 25 years ago.

*The Cowan's house after the 1979 mudslide in a North Vancouver*

This week's slide killed Eliza Kuttner and seriously injured her husband Michael.

The District of North Vancouver commissioned Klohn Leonoff to prepare the 1980 report, which recommended remedial work to shore up the hillside at places like 2175 Berkeley St.

**There are 6 known Landslides:**

- **1 Slide in 1972 (no damage)**
- **3 Slides in 1979**
  - **1 home destroyed, 1 damaged**
- **1 Slide in 1999 (no damage)**

**Challenge: Preserve Corporate Memory**

# Landslide Likelihood Estimates

## Subdivided crest into 75 Increments

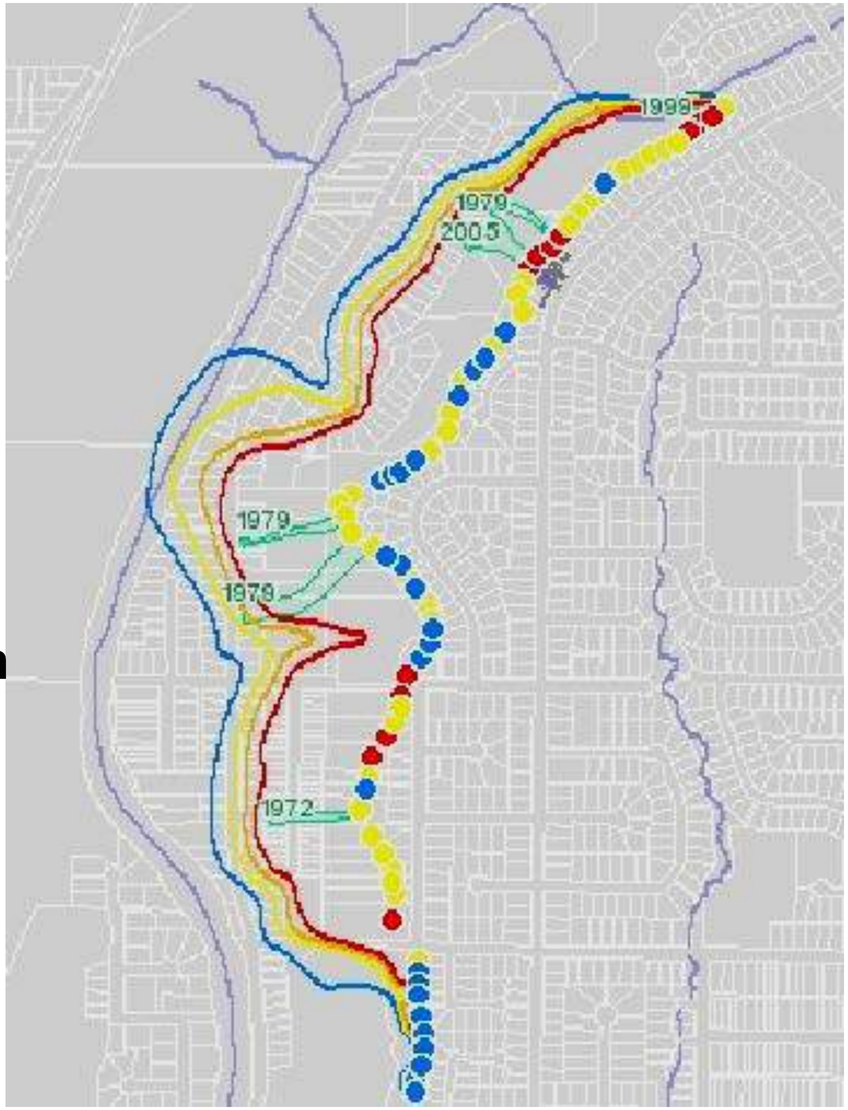
## Rank based on:

- thickness of fill
- drainage conditions
- slope angle
- evidence of past movement


- (red) > 2 times Average
- (yellow) ~ Average
- (blue) < ½ Average

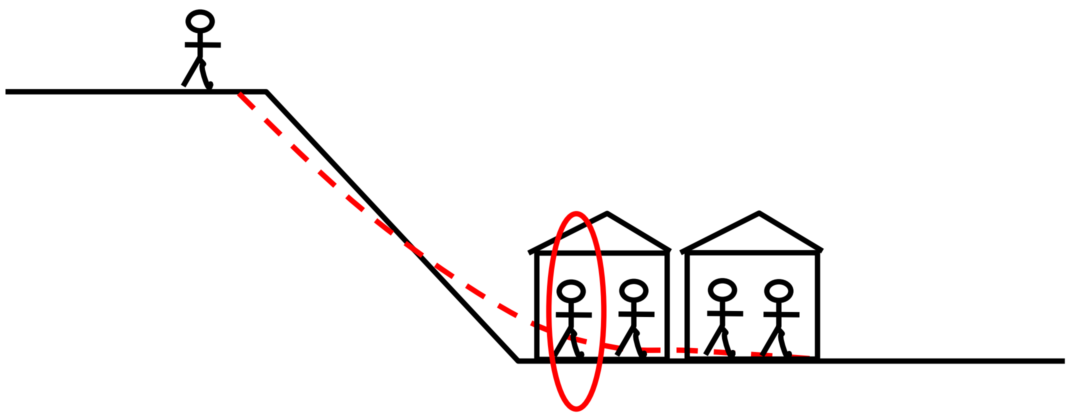
# Landslide Runout

- >25° **Moderate to high likelihood of damage to homes**
- >23° **Low to moderate likelihood of damage to homes**
- >21° **Damage possible; mostly sedimentation and flooding**
- >19° **Minor flooding**



## Individual Risk

# Risk faced by a single individual exposed to one or more landslide hazards



**Interim Criteria:**

- Existing slopes: $10^{-4}$ per year (1:10,000)
- New development: $10^{-5}$ per year (1:100,000)

# Individual Risk Estimates for Berkley Escarpment

**Risk > $10^{-4}$ per year**

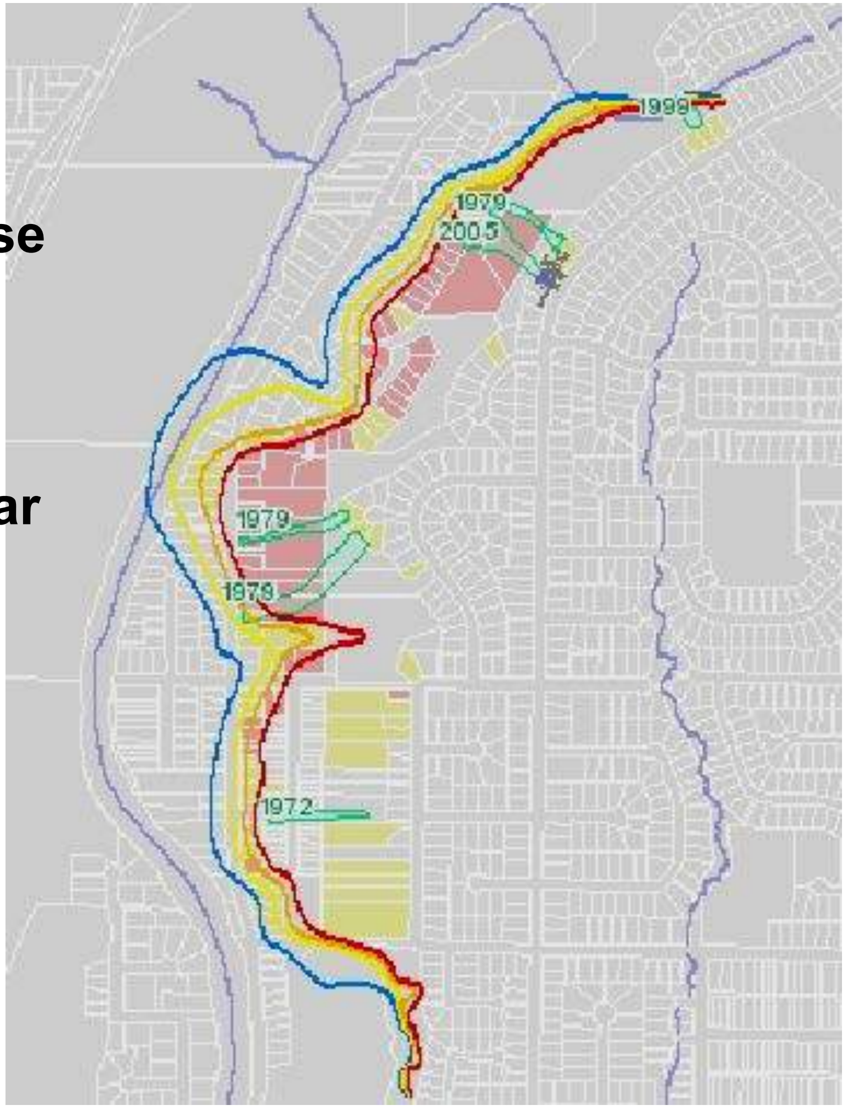
- **51 properties at base**
- **1 property at crest**

**Risk = $10^{-4}$ to $10^{-5}$ per year**

- **additional 56 properties**

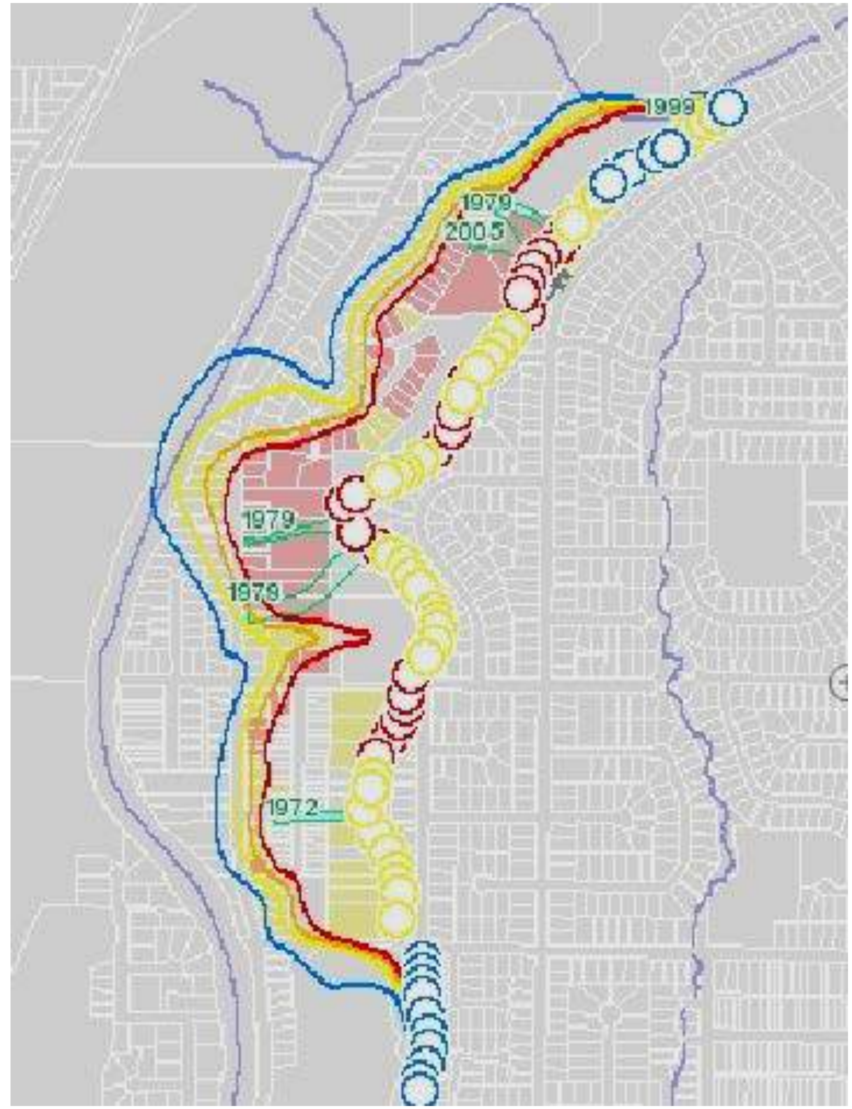
**Risk < $10^{-5}$ per year**

- **rest of escarpment**



# Societal Risk Estimates for Berkley Escarpment

## Assigned to the 75 source areas along escarpment crest




**Unacceptable Risk**
- 22 source areas

**ALARP Zone**
- 37 source areas

**Broadly Acceptable**
- 16 source areas

**(Interim Criteria)**

# Tolerable Risk and Public Policy

Stakeholders, jurisdictions and decision-makers ultimately have to select, ideally by means of an appropriate public process, the appropriate risk evaluation parameters (hazard probability, landslide volume and/or peak discharge) for a particular situation or jurisdiction. This selection has to balance the risks from landsides with societal values. Societal value includes such things as public safety, affordable residential land, and return on investment.

# Risk Communication

Tappenden, K.M., 2014. The district of North Vancouver's landslide management strategy: role of public involvement for determining tolerable risk and increasing community resilience. Natural Hazards, Vol. 72, p. 481-501.

A community task force approach was evaluated in terms of four criteria for successful public involvement:

1. Representative participation
2. Early involvement
3. Information availability
4. Impact on policy

The DNV has received international recognition for their Natural Hazard Management Program, of which the Landslide Management Strategy forms an important part. In 2011, the DNV received the United Nations Sasakawa Award for Disaster Risk Reduction, and in 2012, when the United Nations published the handbook "How to Make Cities More Resilient", the DNV was recognized as an example of innovation and community engagement.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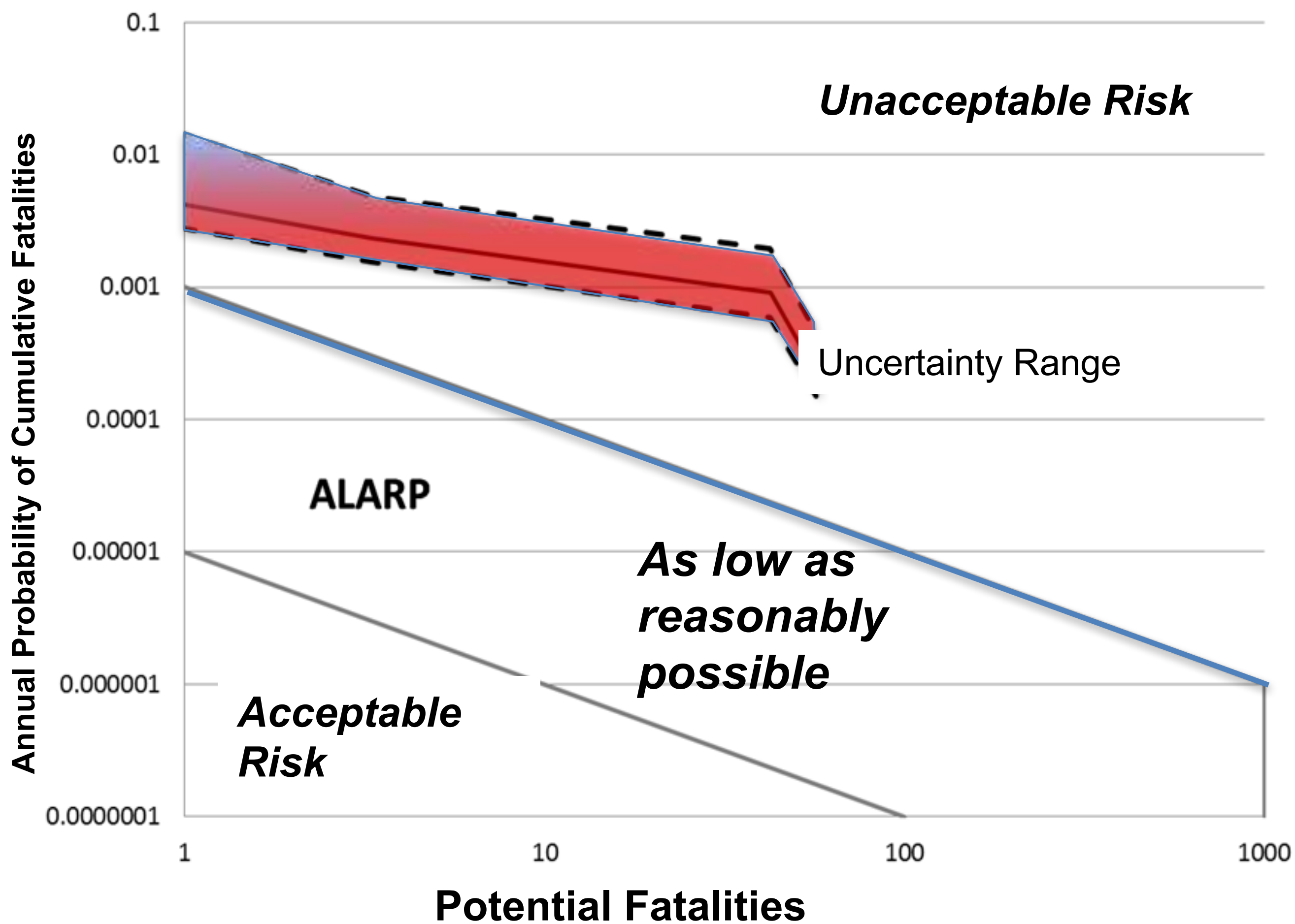
# Risk Assessment

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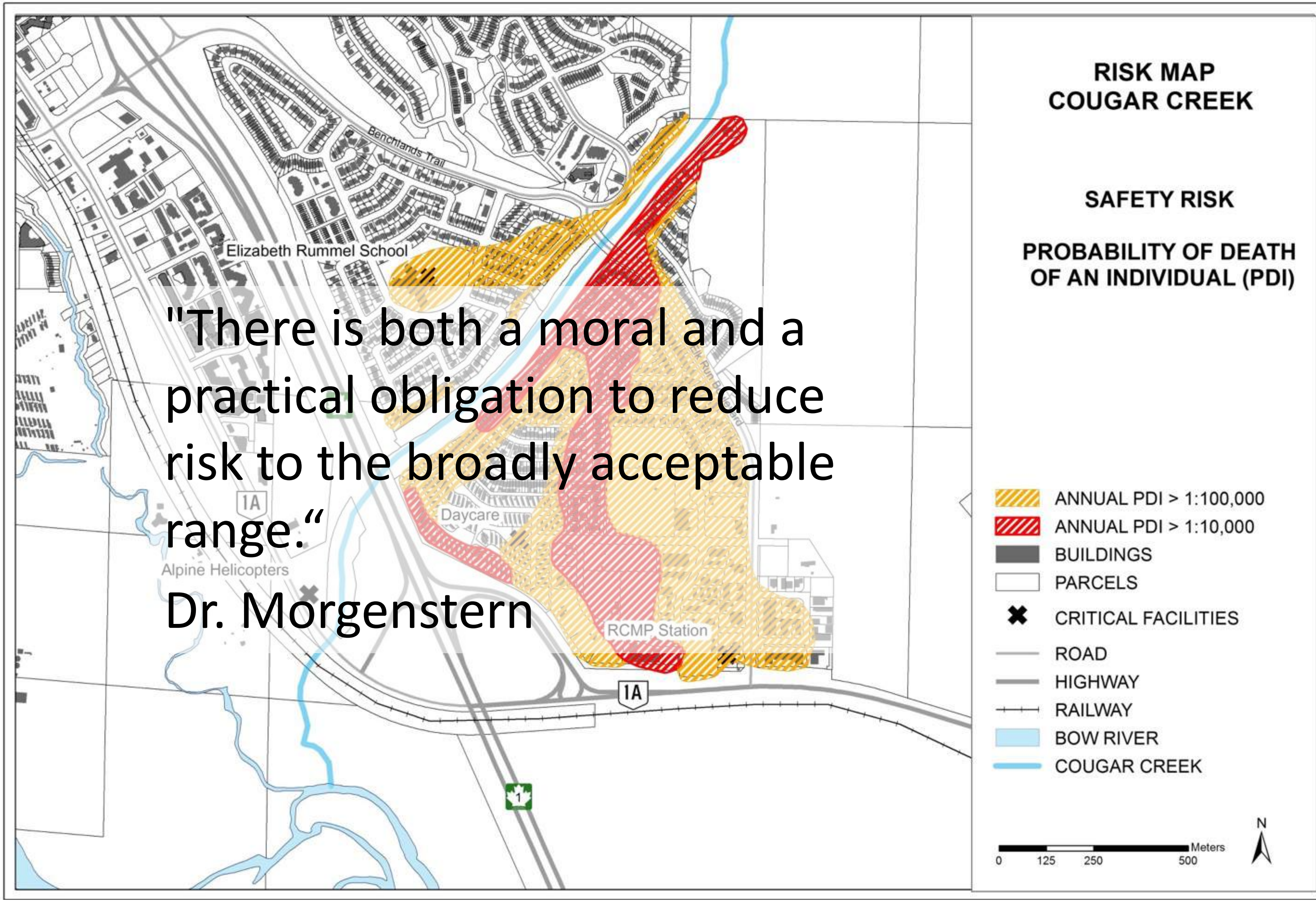


"There is both a moral and a practical obligation to reduce risk to the broadly acceptable range."

Dr. Morgenstern

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# Test Trenching

Deciphering the “deep past”



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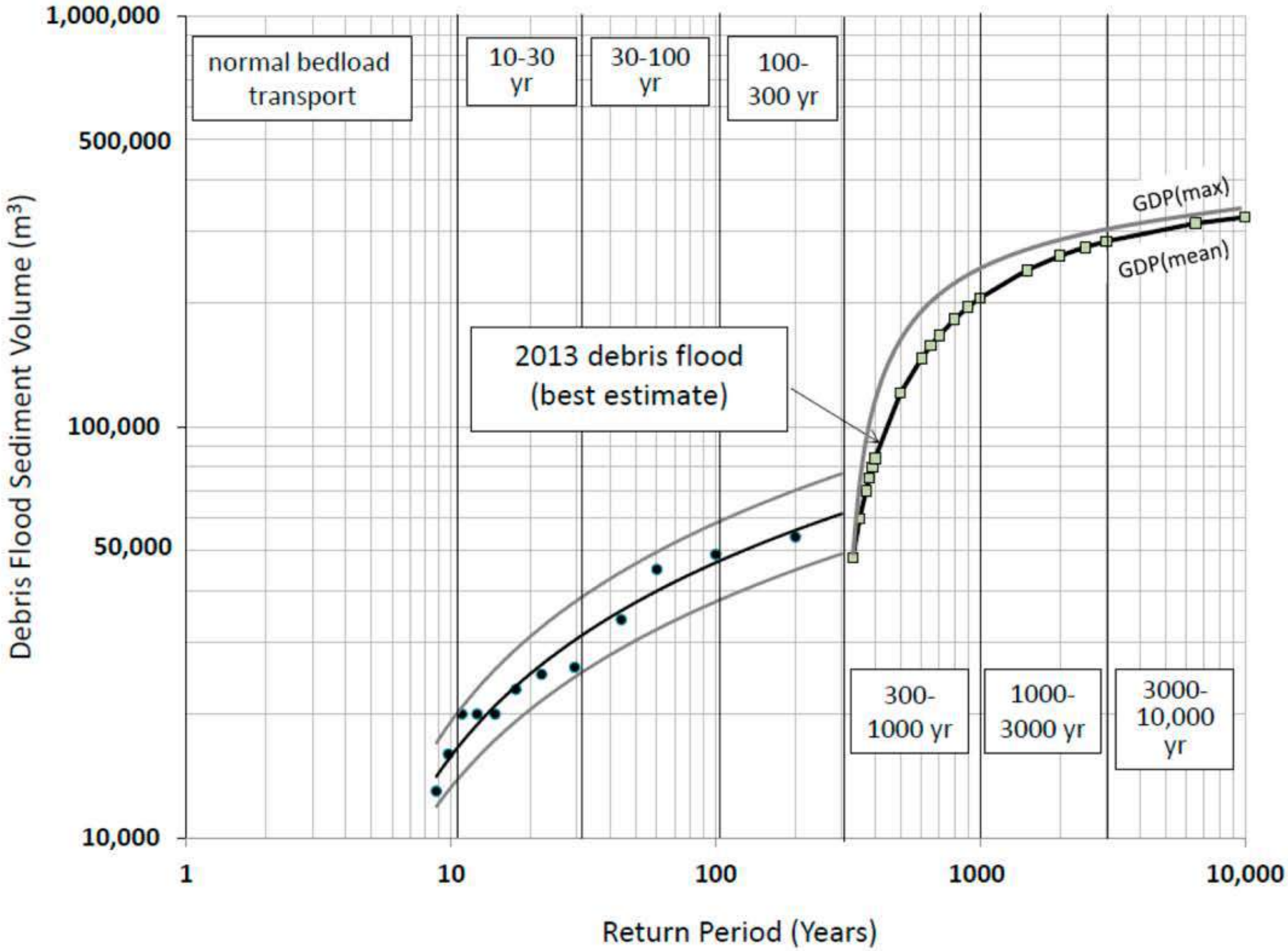



**Figure 9.** The Cumulative Frequency-Magnitude Analysis (MCF) method was applied to the "small" debris flood datasets while the presumed landslide dam outbreak floods where analysed with the Generalized Pareto Distribution (GDP).

# Methodology

- Frequency of Magnitude Relationship
  - Return period, sediment volume, peak discharge, process
- Debris flood modeling (various scenarios)
  - Extent, flow depth, impact intensity ($I_d$ = depth x velocity$^2$)
- Risk assessment
  - Spatial analysis of vulnerability, loss of life, building damage, (hazard probability, spatial and temporal probability)
- Mitigation options

Jakob, M., Stein, D., and Ulmi, M., 2011. Vulnerability of buildings to debris flow impact, *Natural Hazards*, Vol. 60, p. 241-261.

# Debris Flood Retention Structure

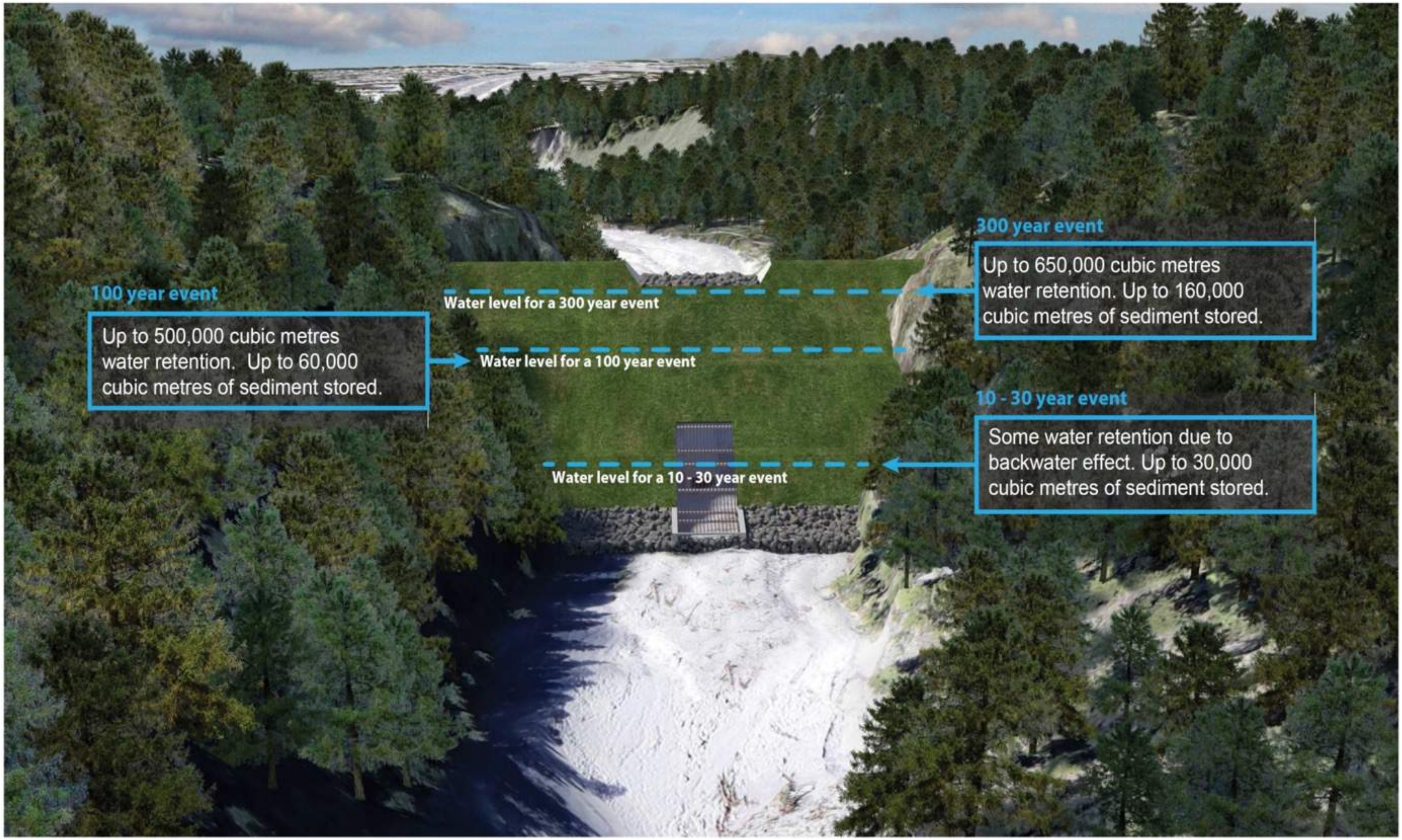
**Design Basis:**

- Based on European design
- Earth and rock filled embankment dam
- No water retention during regular operation (dry dam) – water flows freely through an outlet
- The outlet is protected by a rake that prevents blockage by woody debris and large boulders

**Structure size:**

- 29.85 m tall (existing creek bed to crest of structure)
- 40 m wide at creek level – 100m at crest level
- 150 m long (creek axis)
- Sized to retain a 300 year flood event, including the 2013 event

# Debris Flood Retention Structure



# Public Policy

Town of CANMORE

## Steep Creek Hazard and Risk Policy

**DATE APPROVED:** September 20, 2016

**COUNCIL RESOLUTION:** 239-2016

1. **POLICY STATEMENT**
The Town's objective is to avoid and reduce intolerable risk associated with steep creek hazards. This policy identifies the lands within the town that are impacted, or are potentially affected by, steep creek hazards. Where development exists or may be allowed in hazard areas, this policy outlines the process to be followed to ensure appropriate safety and sustainability of the development.

2. **PURPOSE**
The Municipal Development Plan establishes Canmore's approach to managing steep creek hazards and the integration of risk into the land use and development decision-making process. The purpose of this policy is to explain in better detail how risk is measured and what criteria is used, the Town's approach to managing those risks and to define zones for different levels of intensity impacted by steep creeks.

# Sample Entries for a Maturity Matrix for Assessing Community Engagement

| Elements | Level I | Level II | Level III |
|---|---|---|---|
| Dam or levee safety reviews | No activity | Standards-based only | Introduction of additional review criteria (e.g., failure mode analysis) |
| *Other programs related to conventional dam/levee safety activities* | *Each tool is defined at different levels to show progression from minimum activity (Level I) through best industry practice to full community member and stakeholder engagement and collaboration (Level V)* | | |
| Emergency action plans | No activity | EAPs developed internally by owner | EAPs developed with input from emergency management agency |
| *Specific tools related to emergency planning response, including development of community preparedness measures, warning and evacuation procedures, and recovery plans* | *Each tool is defined at different levels showing progression from minimum activity (Level I) through best industry practice to community member and full stakeholder engagement and collaboration (Level V)* | | |
| Floodplain management | No floodplain management plans | Floodplain management plans in place | Floodplain management plans accommodate shadow floodplain associated with catastrophic dam or levee failure |
| *Specific tools such as those related to land-use planning and floodplain management, including initiatives for financial incentives and zoning reform* | *Each tool is defined at different levels showing progression from minimum activity (Level I) through best industry practice to community member and full stakeholder engagement and collaboration (Level V)* | | |

National Research Council, 2012. Dam and Levee Safety and Community Resilience: A Vision for Future Practice

# Sample Entries for a Maturity Matrix for Assessing Community Engagement (continued)

| Level IV | Level V | Examples of Possible Outcomes |
|---|---|---|
| Application of quantitative risk assessment by using criteria developed by owner or regulator with input from community members and stakeholders | Application of quantitative risk assessment by using criteria that reflect the community's societal values | Community is fully apprised of current level of risk |
| EAPs developed with input from community members and stakeholders and emergency management agency and shared with selected community representatives | Community collaboration with owners or operators to develop integrated EAPs that reflect community values | Community collaboration results in EAPs that minimize consequences of defined emergencies by incorporating community values and the potential for community resilience |
| Floodplain management plans integrated into community comprehensive or general plans | Floodplain management plans fully integrated into dam and levee owners' planning processes | Full participation by both community and dam and levee owners in floodplain management facilitates adoption of complementary resilience-enhancing measures |

National Research Council, 2012. Dam and Levee Safety and Community Resilience: A Vision for Future Practice

# Professional Practice

"The assurance of geotechnical performance would be enhanced if geotechnical engineering shifted from the promise of certainty to the analysis of uncertainty."

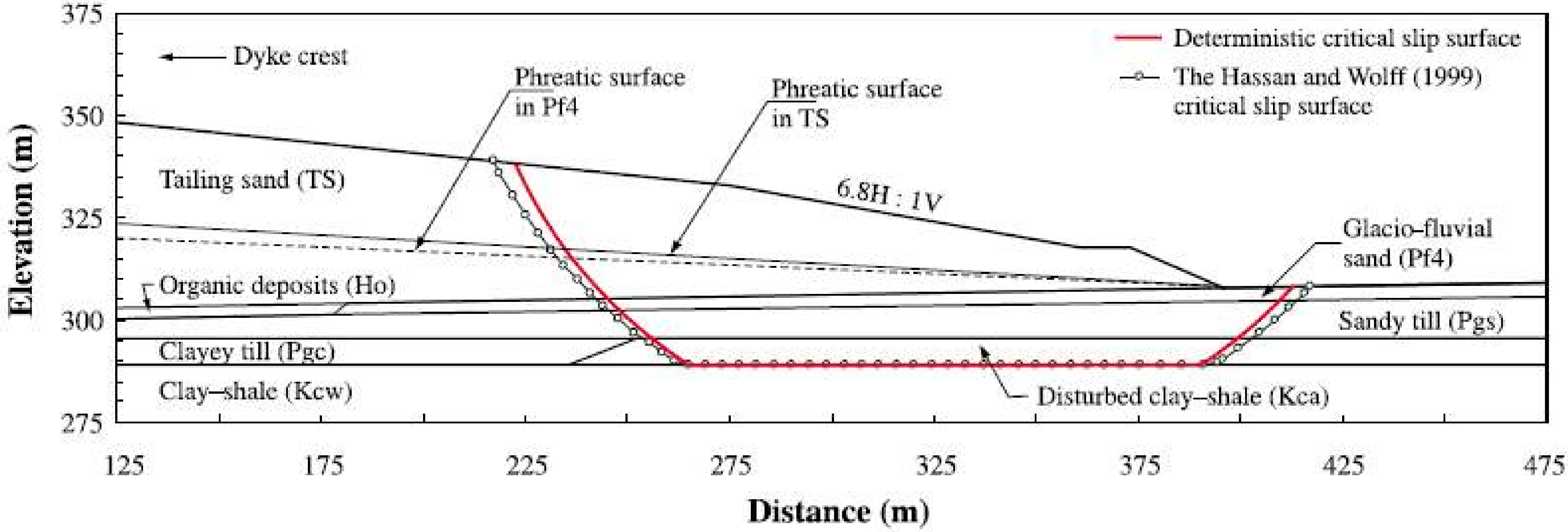
Morgenstern, N.R., 2000. Performance in Geotechnical Practice, Inaugural Lumb Lecture, *Transactions*, Hong Kong Institute of Engineers, Vol. 7, pp. 1-15.

1) **Parameter Uncertainty**

2) **Model Uncertainty**

3) **Human Uncertainty**

# Dyke Profile and Stratigraphy at section 53+00E – cell 23: Syncrude Tailings Dam




El-Ramly, H., 2001. Probabilistic Analyses of Landslide Hazards and Risks: Bridging Theory and Practice. Ph.D. Thesis, University of Alberta, 430 p.

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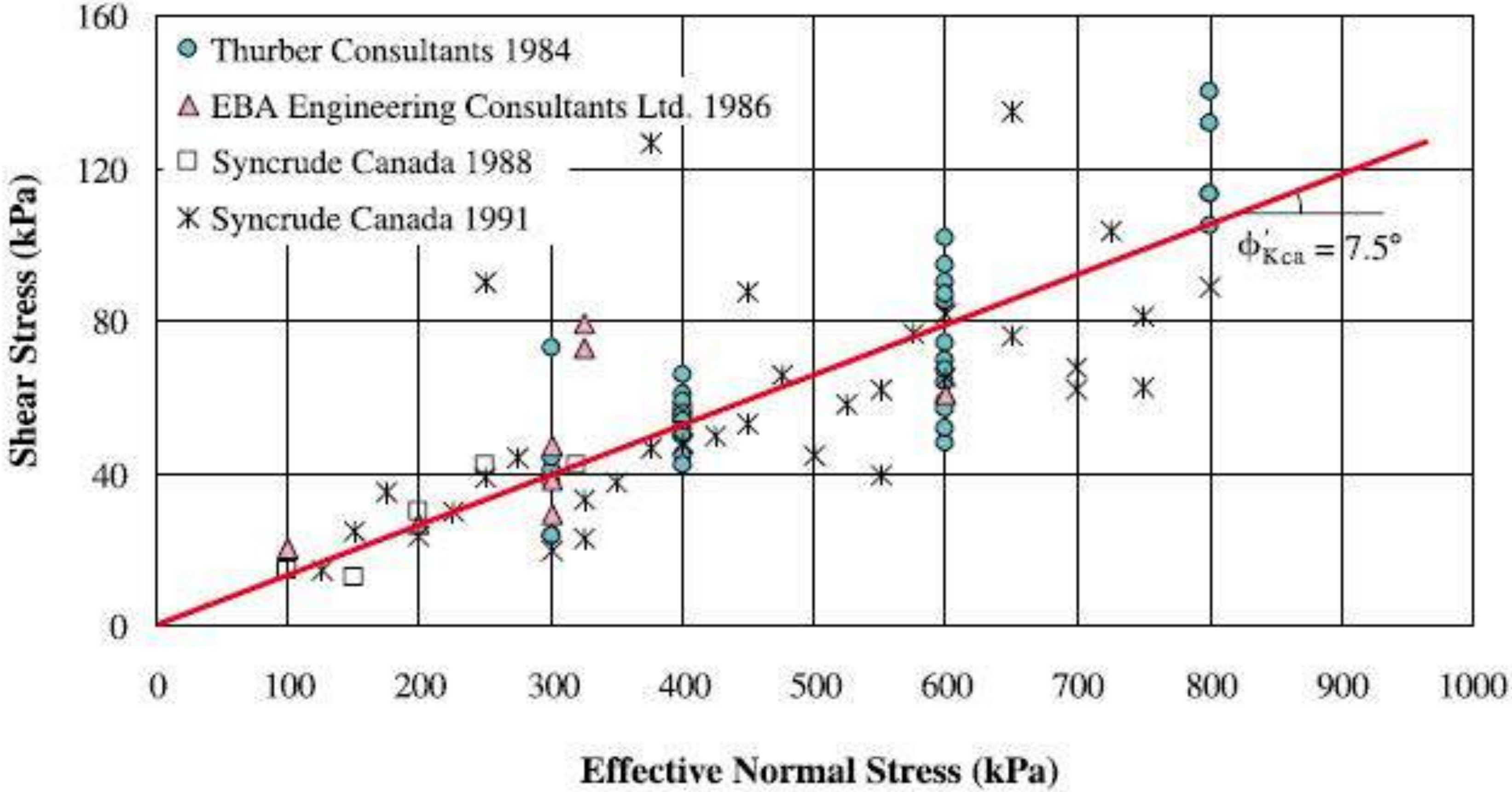
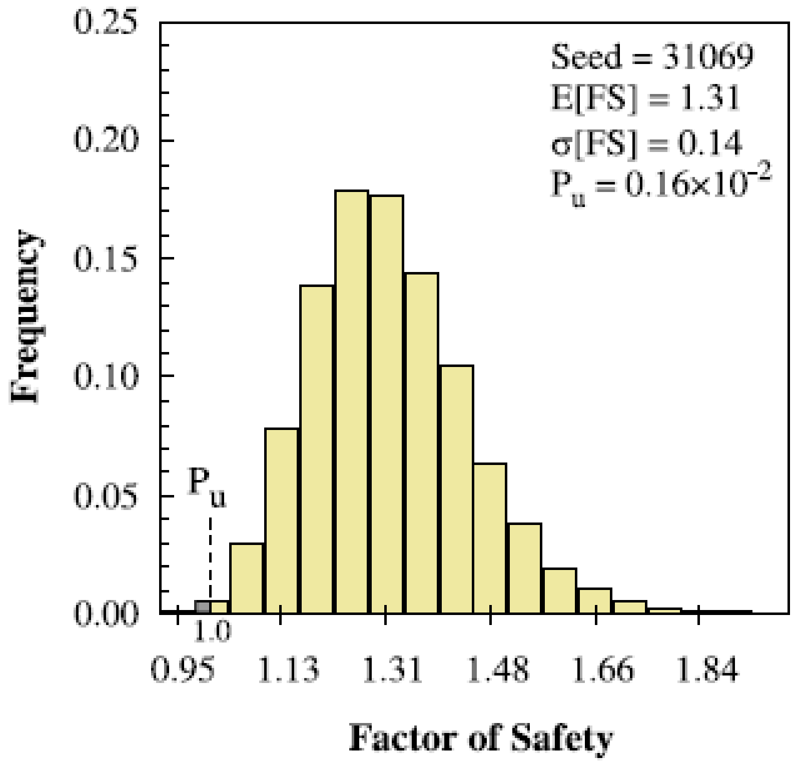
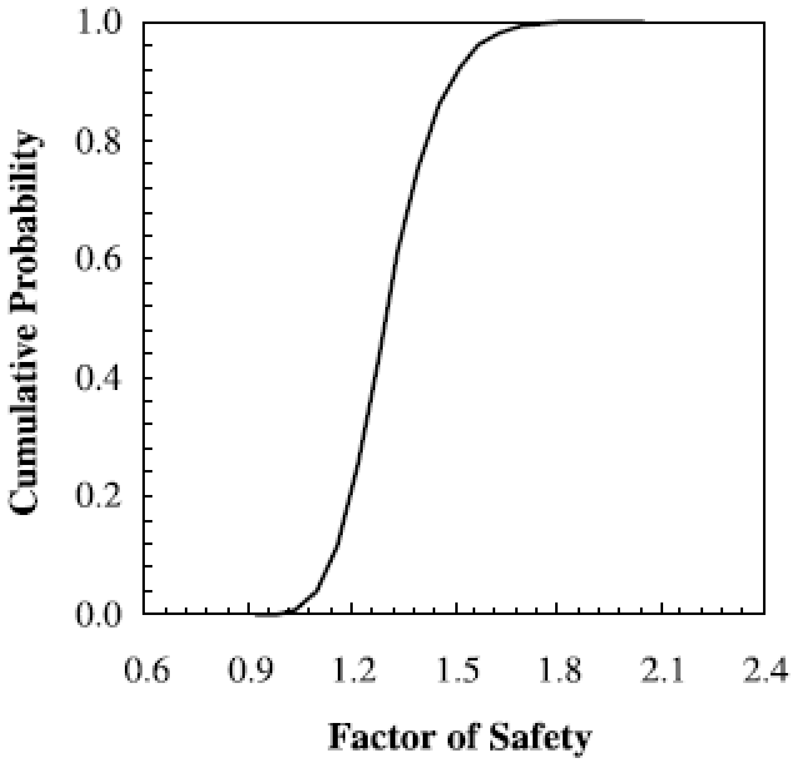
# Shear Box Testing Results of the Residual Strength of the Kca Clay-Shale



# Histogram and Probability Distribution Function of the Factor of Safety – Number of Simulation Iterations Equals 34,000

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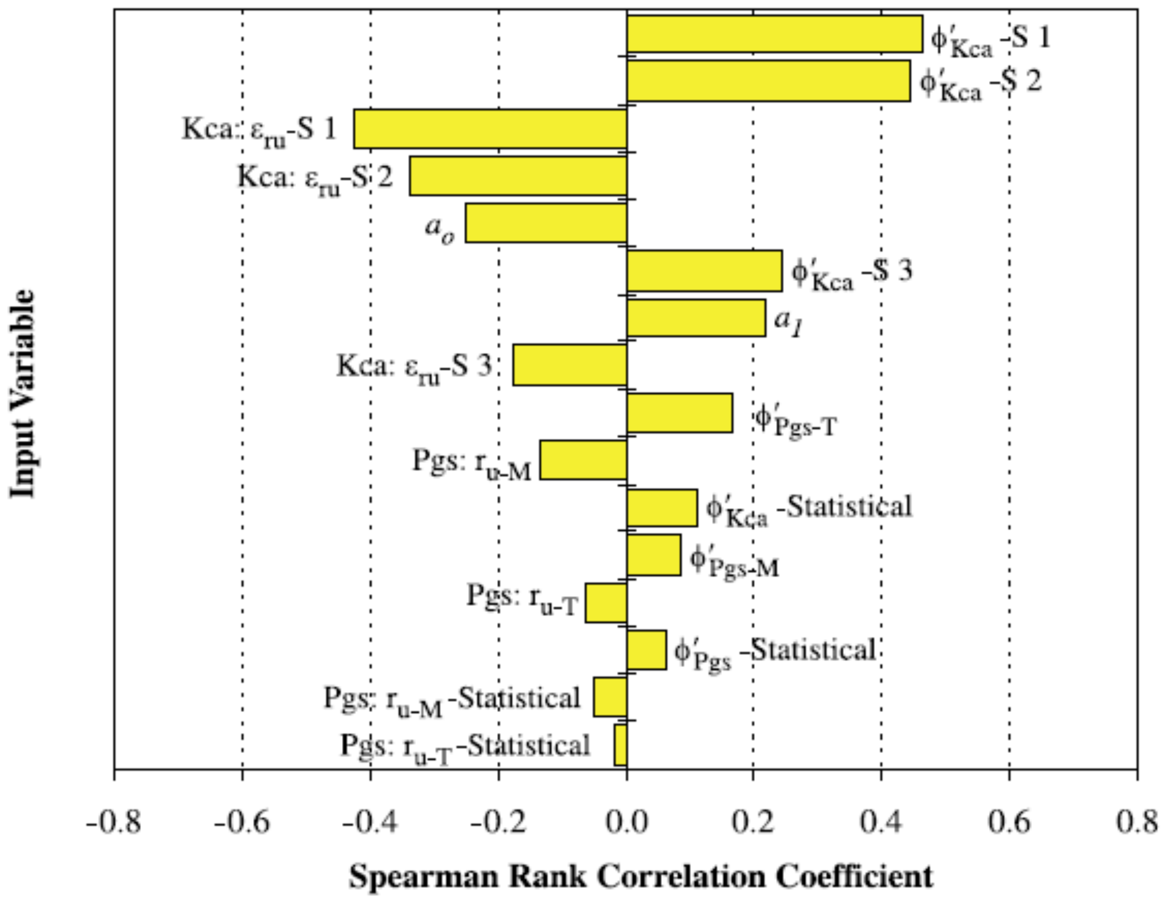
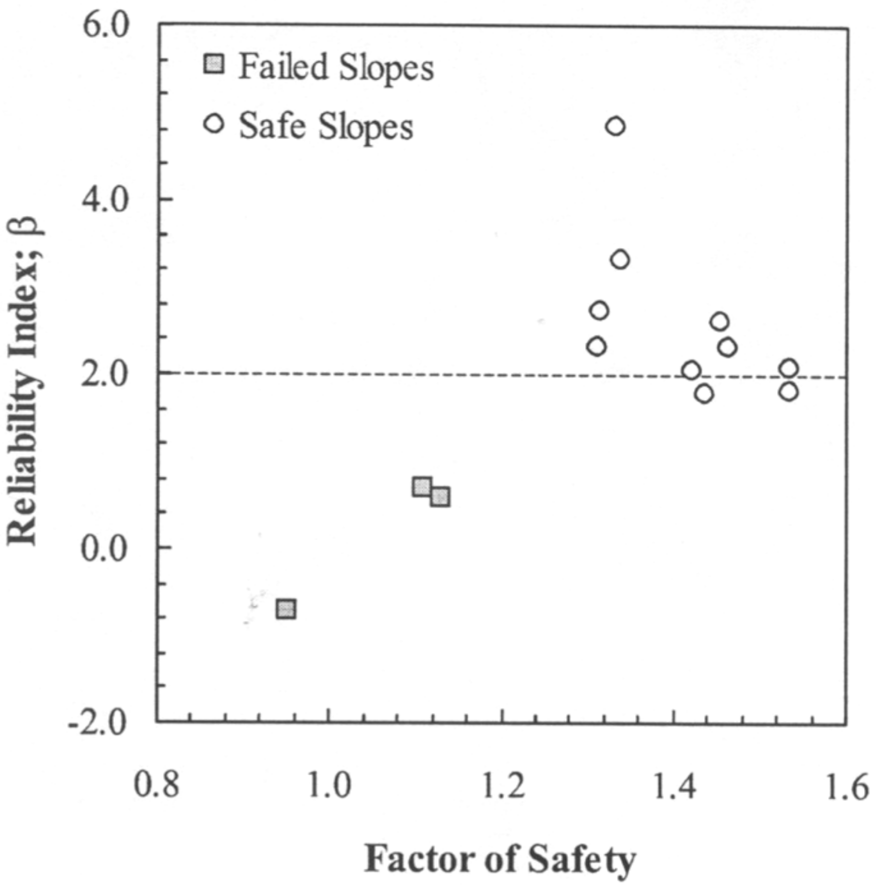
# Spearman Rank Correlation Coefficients Between Input Variables and the Factor of Safety



# Reliability Index versus Factor of Safety – Proposed Methodology



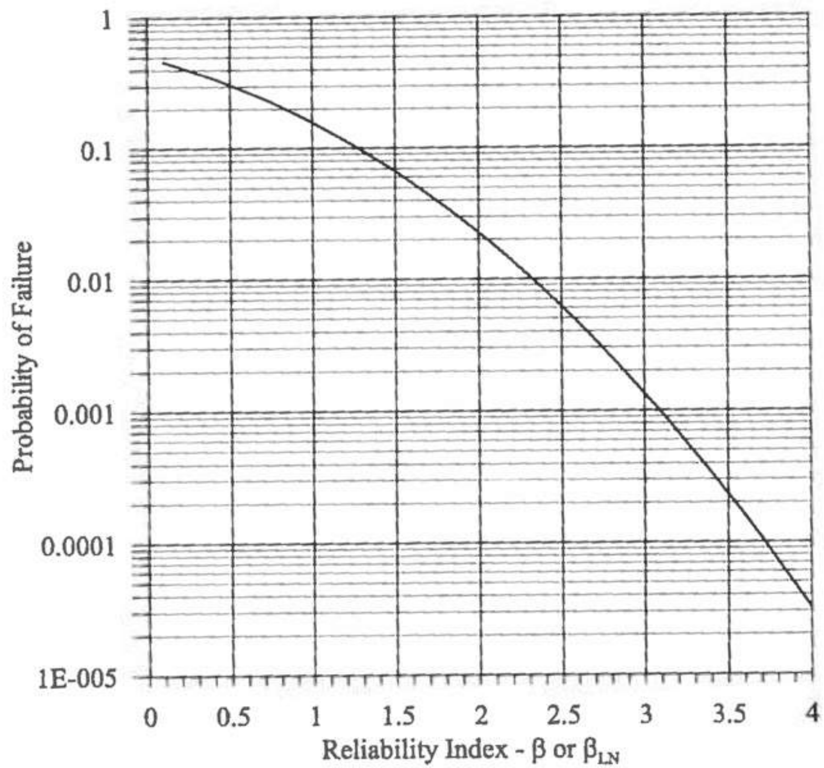




**Figure 13.5** Variation of $P_f$ with $\beta$.

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# Mount Polley Tailings Facility

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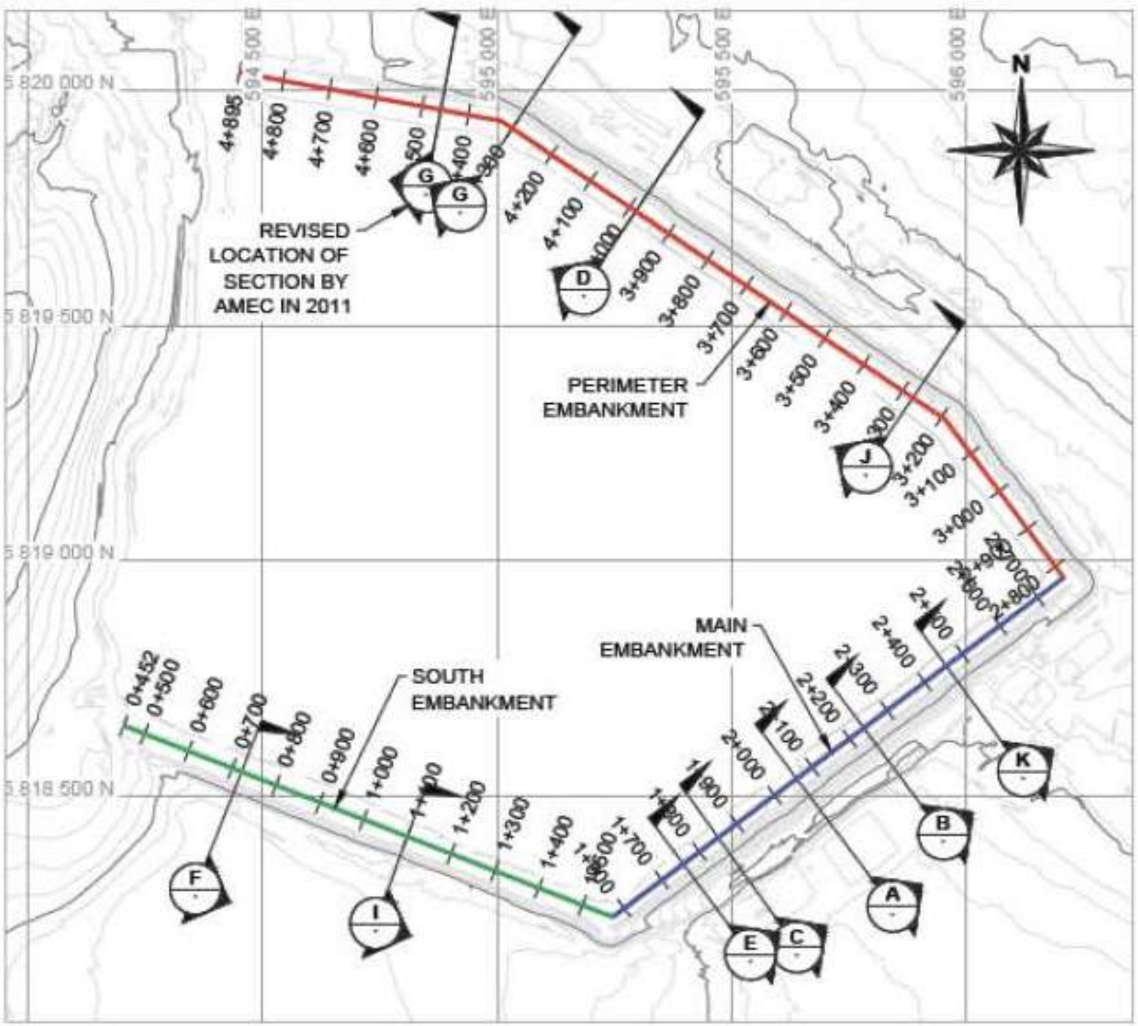
# Mount Polley Tailings Facility

FIGURE 3.1.1: TAILINGS STORAGE FACILITY PLAN

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# Mount Polley Tailings Facility

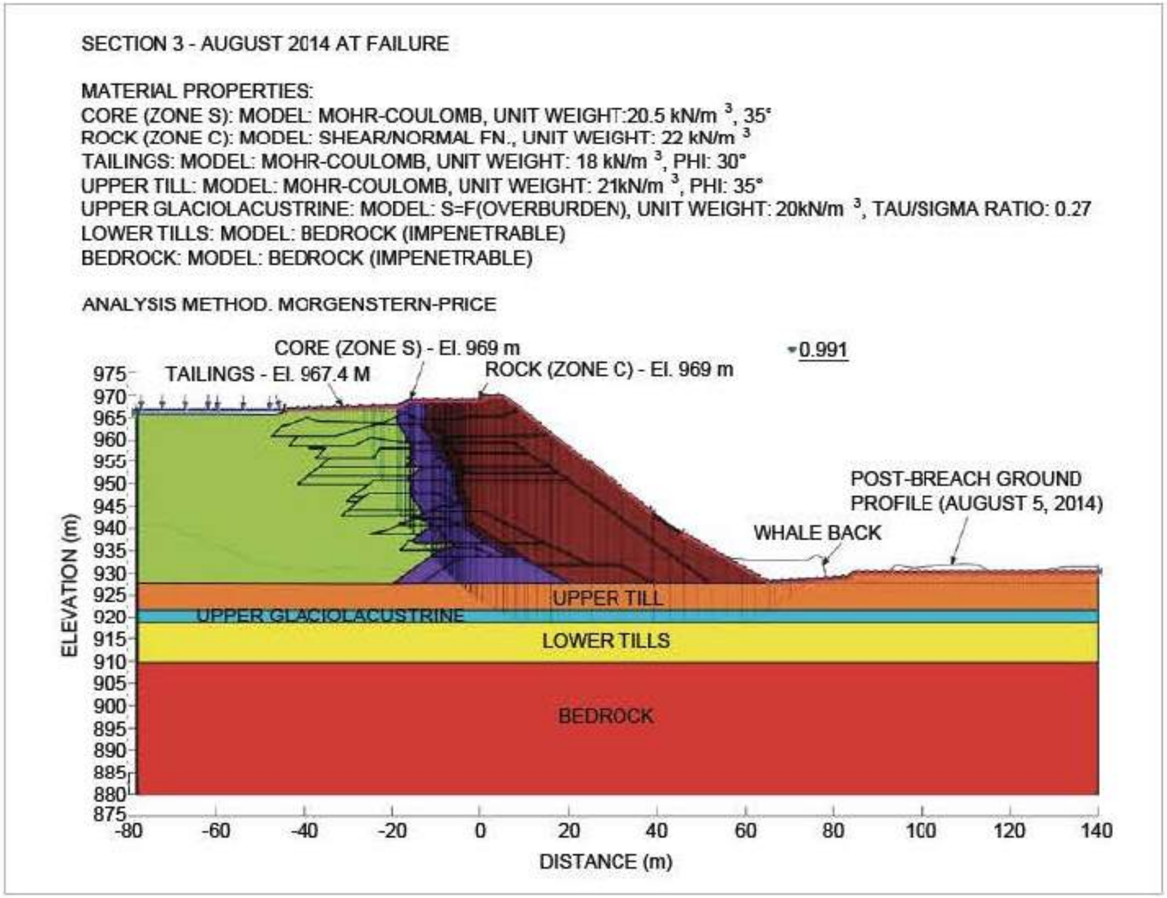
FIGURE 5.1.1: VIEW LOOKING UPSTREAM THROUGH THE BREACH (ARROW SHOWS DIRECTION OF OUTFLOW)

# Mount Polley Tailings Facility

FIGURE 5.1.5: APPARENT BEDDING ROTATION ON LEFT ABUTMENT OF BREACH (SEPT. 4, 2014 PHOTO)

# Mount Polley Tailings Facility

FIGURE 6.2.1: DETAILED SECTION USED FOR LIMIT EQUILIBRIUM ANALYSIS (HIGH WATER TABLE, UNDRAINED STRENGTH RATIO 0.27)



# Root Cause

- The root cause of the breach was the undrained failure of the Upper GLU under the imposed load of the Perimeter Embankment on August 4, 2014.
- The design did not take into account the complexity of the sub-glacial and pre-glacial geological environment associated with the Perimeter Embankment foundation.
- The omissions associated with site characterization may be likened to creating a loaded gun.
- If constructing unknowingly on the Upper GLU constituted loading the gun, building with a 1.3H:1V angle of repose slope over this stratum pulled the trigger.

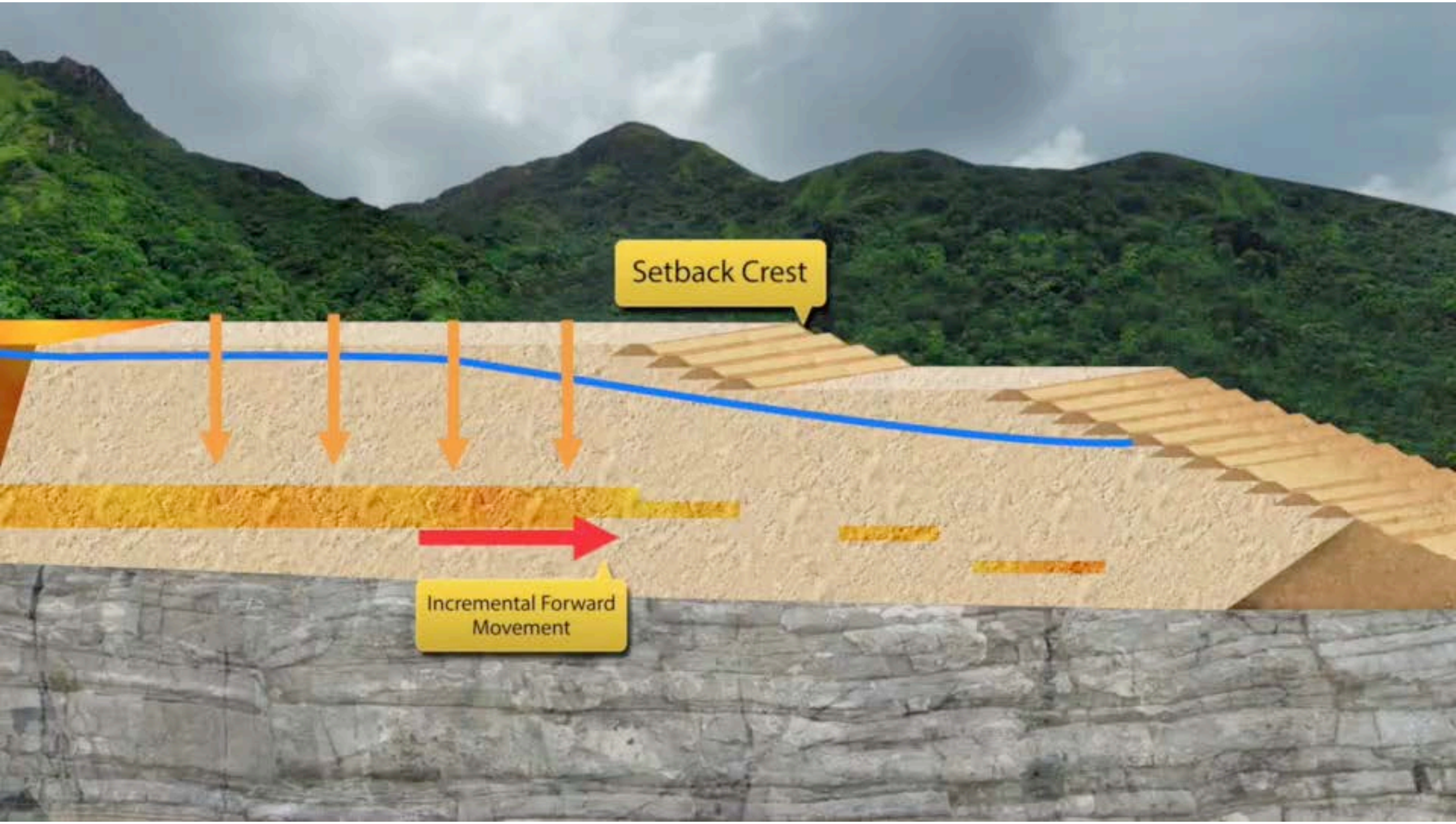
Mount Polley Independent Expert Investigation and Review Report
<https://www.mountpolleyreviewpanel.ca>

# Fundao Dam


Image source: http://blogs.agu.org/landslideblog/2015/11/10/fundao-dam/

# Fundao Dam

Image source: http://blogs.agu.org/landslideblog/2015/11/10/fundao-dam/


Setback Crest
Incremental Forward Movement


12 : 16

# Root Cause

"… the failure of the Fundão Tailings Dam by liquefaction flowsliding was the consequence of a chain of events and conditions. A change in design brought about an increase in saturation which introduced the potential for liquefaction. As a result of various developments, soft slimes encroached into unintended areas on the left abutment of the dam and the embankment alignment was set back from its originally-planned location. As a result of this setback, slimes existed beneath the embankment and were subjected to the loading its raising imposed. This initiated a mechanism of extrusion of the slimes and pulling apart of the sands as the embankment height increased. With only a small additional increment of loading produced by the earthquakes, the triggering of liquefaction was accelerated and the flowslide initiated."

Morgenstern, N.R., Vick, G.S., Viotti, C., Watt, B., 2016. Report on the Immediate Causes of the Failure of the Fundão Dam. <http://fundaoinvestigation.com>

# Concluding Remarks

This lecture has drawn on my experience in recent years to highlight evolving trends in geotechnical practice that provide examples of challenges and positive direction for our way forward. This includes:

i) Analysis and Design – the increased adoption of Performance-Based Design as more powerful and automated instrumentation is coupled with increasingly powerful numerical simulation to integrate all potential failure modes of important geotechnical structures in an increasingly realistic manner.

ii) Mobility and Risk – the increased adoption of QRA methodologies to strengthen risk-informed decision making both in private organizations and in public policy, at least for communities of sufficient technological maturity.

iii) Professional Practice – the increased penetration of probabilistic-based design for slopes and dams, at least in parallel with more traditional procedures.

# Concluding Remarks

However, this lecture does not end on a positive note as it draws attention to the inadequacies in practice of dealing with model and human uncertainty. Gaps in knowledge and incorrect interpretation of failure mechanisms with dire consequences are too frequent, and public trust in the geotechnical community will remain weakened until these conditions are not only remedied, but also are seen to have been remedied.

The success here in Hong Kong in moving toward zero risk related to landslide hazards provides an example to our communities of what can be achieved and, hopefully, emulated in the future.

# Acknowledgement

In the preparation of this presentation, I have benefitted from shared experiences not only with my colleagues and numerous past graduate students at the University of Alberta, but also with collaborative engagements with both owners and consultants involved in many challenging assignments. They are too numerous to identify singly, and I hope that this broad note of appreciation will suffice.