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Investigation & Remediation of Existing Landslides

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Introduction

- This presentation is an introduction to landslide investigation, mechanisms and remediation.
- Understanding the mechanism of a landslide is essential for rational design of stabilisation works.
- The investigation and remediation of the Motu St Landslide is a good example of the process.
- A video giving a general overview of landslides and their mechanisms is found at: https://slideplayer.com/slide/3815341/

Geotechnical Environment of Slopes

Determining landslide mechanisms depends on understanding the geological and hydrological environment of the surrounding area i.e. THE GEOTECHNICAL ENVIRONMENT, comprising:

- Geological History

The sequence of events and processes which produced the soil, rocks and the geological structures within them.

- Groundwater Flow Systems

General nature of groundwater in the vicinity of the slope, and important local variations in permeability and flow conditions.

- Stress History

The past and present stresses acting on the soil and rock, including the magnitudes and signs of the stress changes.

- Weathering Processes and Products

The depth and nature of the weathering profile (see example on right of a landslide in China in highly weathered volcanic Tuff similar to Motu St).

- Seismicity

The present seismicity of the area.

- Climate Effects

Climate and surface hydrologic effects including rainfall, flood levels, depth of frost action etc.

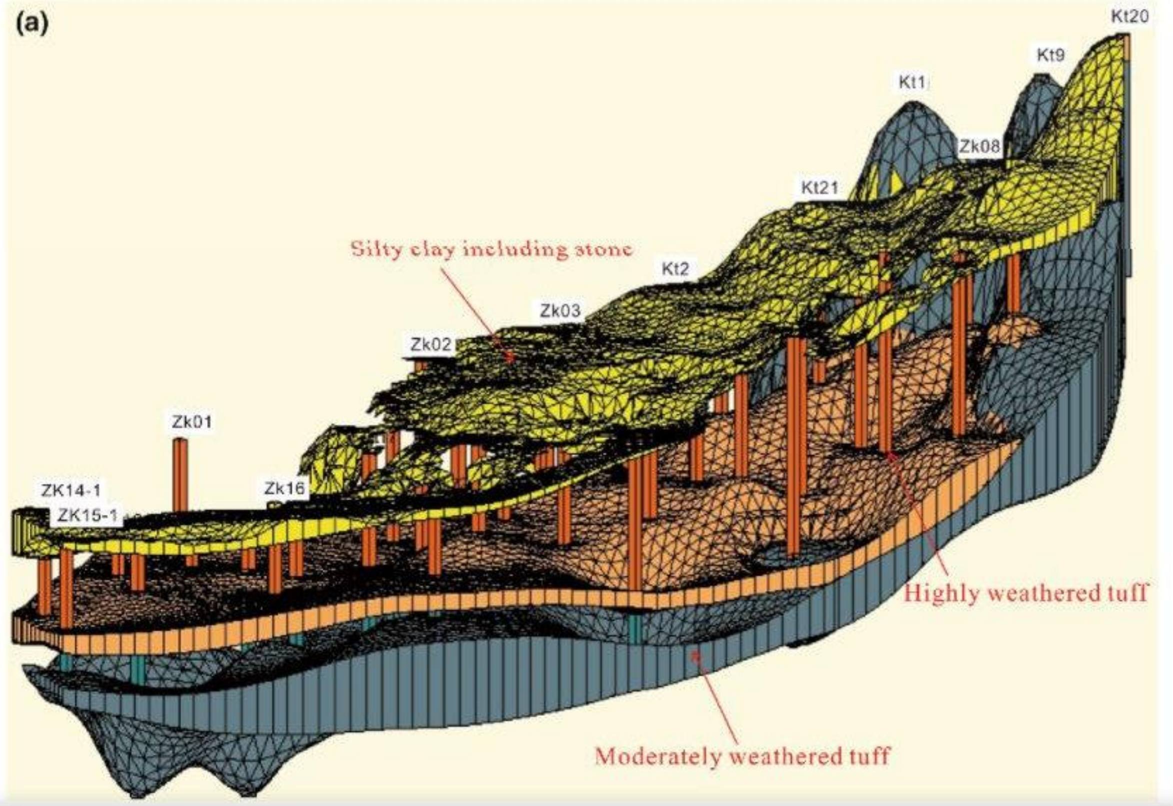


Fig. 7 3-D geological model and cross section (3–3') of the slope

Published in Environmental Earth Sciences 2019
Mechanism analysis of a landslide in highly weathered volcanic rocks of Niushoushan Hill in Nanjing
Xiaoying Yan, B. Xu, L. Zhang, Weiqi Wang, Chang-hong Yan

Otago Landslide Geotech Environments

Otago has geotechnical slope environments that have produced some of the most well known and expensive landslides problems in NZ history.

Coastal Otago

- Weak Tertiary/ Cretaceous mudstones, combined with high rainfall, loss of original native vegetation, and land disturbance by excavations etc have resulted in many landslide problems.
- The most well known is the Abbotsford Slide, where a large residential area suddenly moved rapidly downslope after an initial period of slow creep. Intensive Geotech investigations found the failure surface was a thin, very weak clay horizon.(see photo on right)
- Moeraki, Seacliff & Kilmog are other areas where such instability has caused problems with infrastructure and residential development.
- Heavy weathering of Dunedin Volcanics to weak clayey silt soils, in a high rainfall environment has caused many problems with residential developments and infrastructure around Dunedin. eg Motu Street Slide.

Central Otago

- Schist bedrock with foliation defects, and steep topography due to uplift, glacial and river erosion has produced large slowly creeping debris landslides.
- Such landslides around the reservoir of the Clyde Dam were stabilised before reservoir filling at a (1990) cost of $400 million.
- Similar landslides in the Queenstown –Lakes region cause ongoing problems with infrastructure and residential development,

Landslide recognition by remote sensing

- The first step in landslide investigation is the examination of aerial imaging of the site area. This allows the identification of geomorphic features such as scarps that define the slide perimeter, often hard to detect in the field. These features should be marked up for field examination (see example of stereo pairs of the Frankton landslide with marked up scarp.

- Black and white aerial photography of the Otago region dates from the 1940s.and are available on the Retrolens Website: http://retrolens.nz/map/ More recent ORC colour photo runs are also available at the site.

- Older aerials often show features that are not visible on more recent runs, due to building construction and other forms of land development (at Motu St 1940s housing unfortunately obscures the oldest photos).

- The 3D capacity of Google Earth is now widely used for landslide investigations, but it often does not show up geomorphic features that are visible on aerials.

Stereo pairs of Frankton slide Queenstown

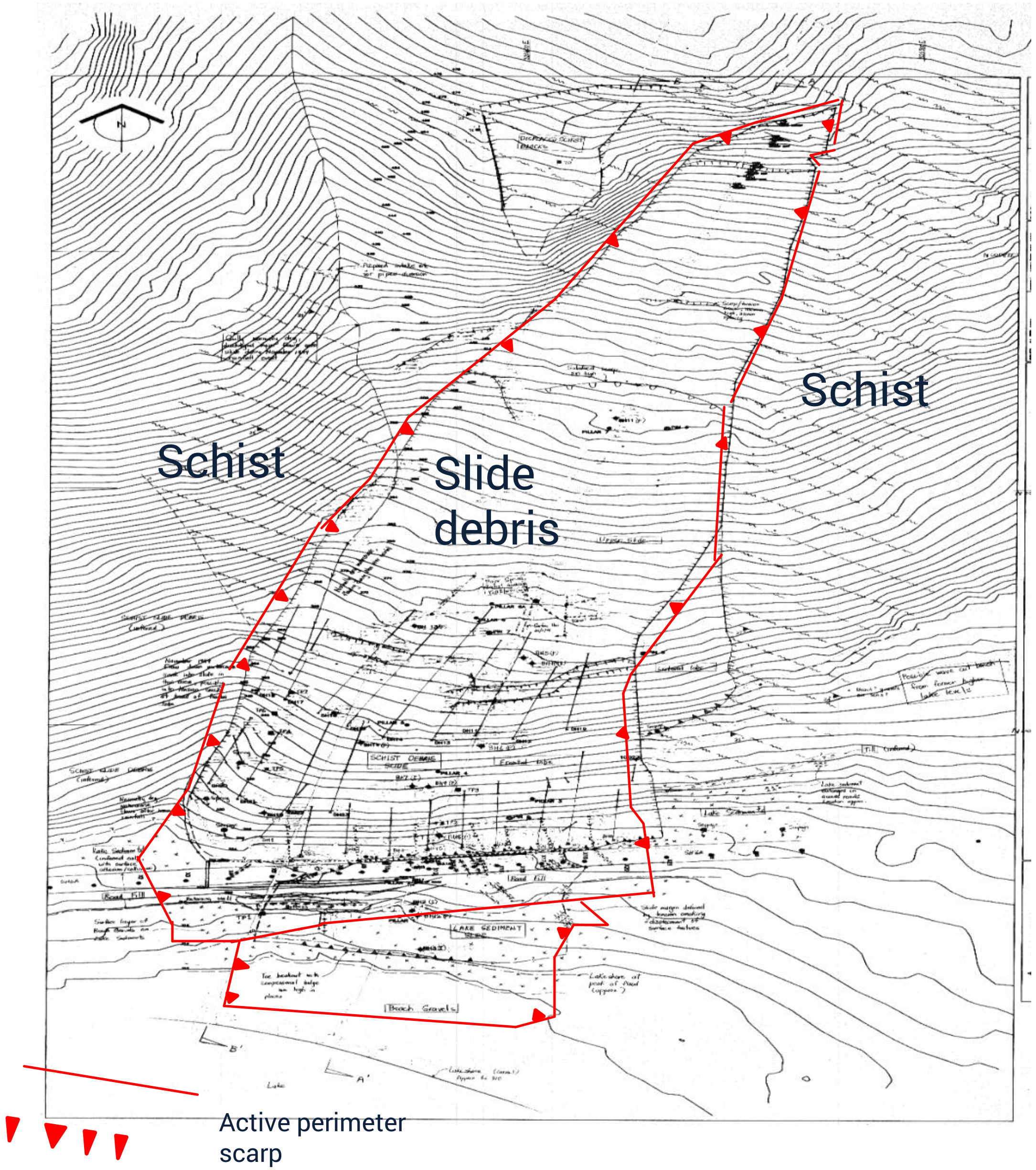
Engineering Geological Mapping

- Before field mapping commences, all existing information on the geotechnical environment of the site should be examined. This includes GNS and other geological maps (eg Benson's map of Dunedin), ORC and QLDC landslide hazard maps and geotechnical reports from adjacent sites.

- The engineering map should show the basic site geology (rock types, bedding attitudes etc), plus relevant slide geomorphic features such as active / inactive scarps, hummocky topography etc. (see map of a schist debris landslide at Queenstown on right). Springs and seepages indicative of the groundwater regime should also be recorded.

- A paper by Dearman & Fookes , Engineering Geological mapping for Civil Engineering Practice in the UK describes the general principles and Fig 7 shows appropriate symbols for a landslide area map.

- It is important that mapping extends well beyond the obvious landslide area to give a broader picture of the geotechnical environment of the slide. Landslides often prove to be much larger than originally realised.



Engineering geological map of Frankton Slide Queenstown

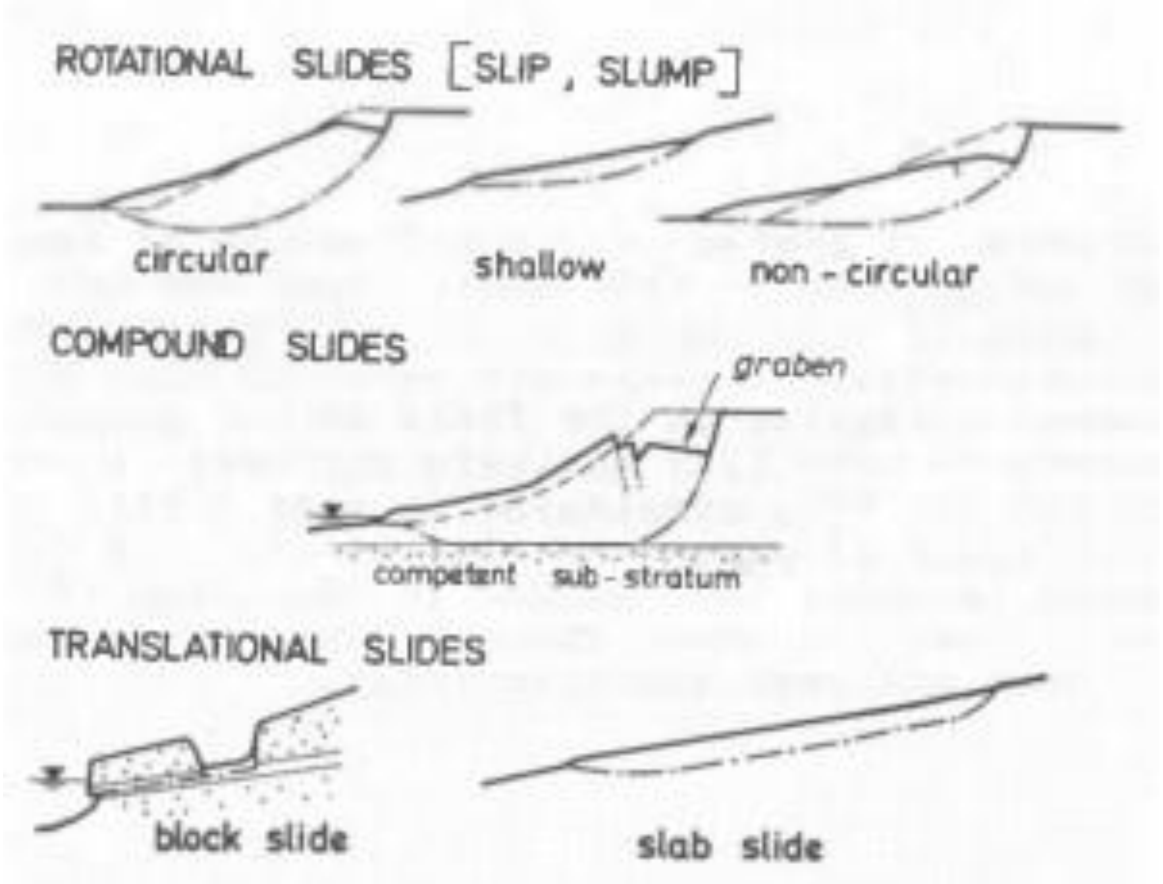
Landslide Kinematics

- Rotational landslides have spoon –shaped arcuate failure surface (see opposite figure and paper by Skempton and Hutchinson, 1969).

- Translational landslides with planar surfaces typically occur where there is a weak failure layer following bedding or foliation. They typically show grabens marked by reverse scarps.

- Compound (Rotational/ Translational) landslides combine the characteristics of both. They typically show evidence of internal deformation in the form of cracking/ scarps. The Motu St slide is this type.

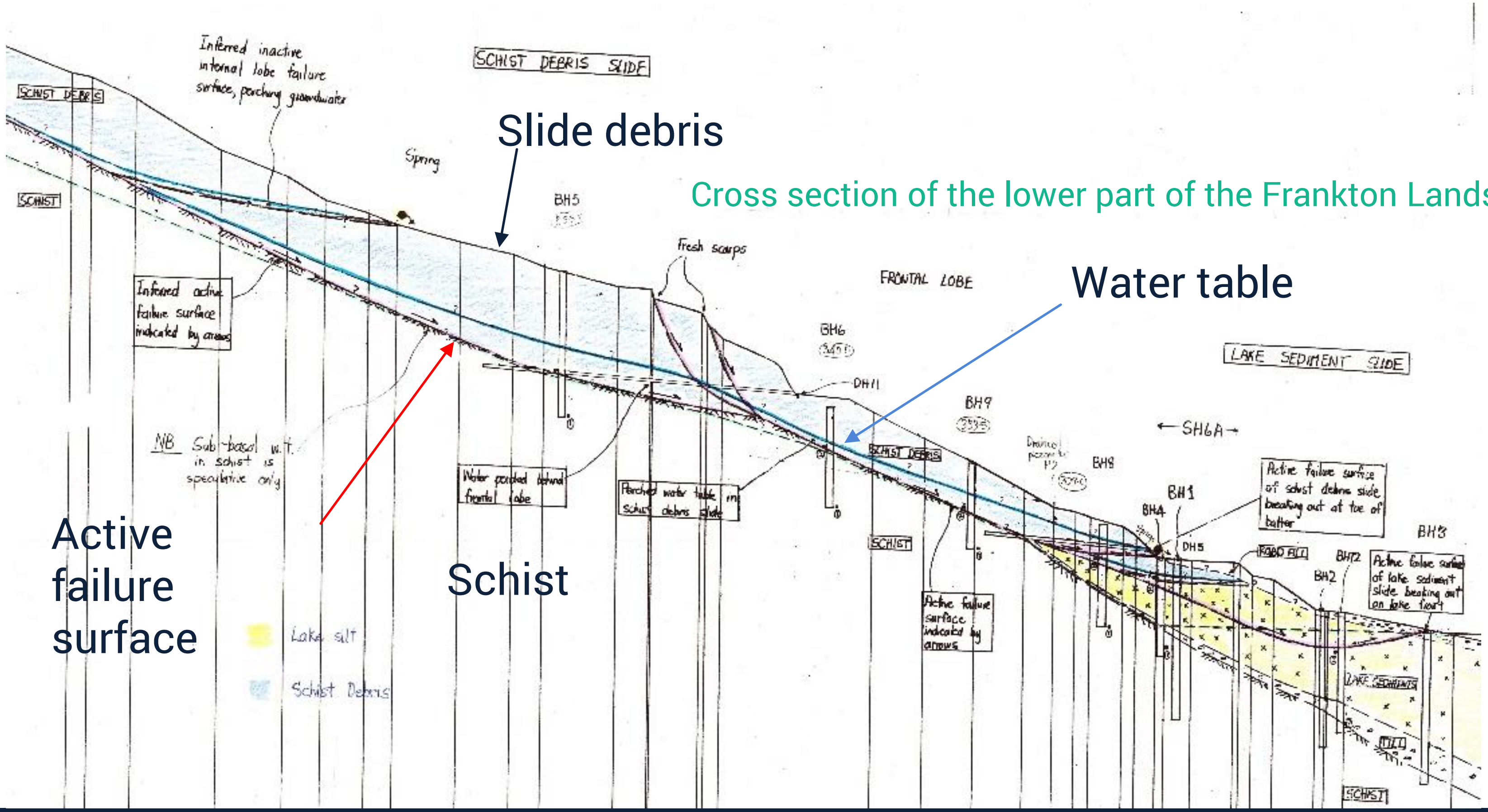
- The Skempton & Hutchinson (1969) paper illustrates other kinematic mechanisms such as multiple retrogressive sliding.



Rotational, translational and compound slide failure mechanisms

Geological Models & Cross-sections

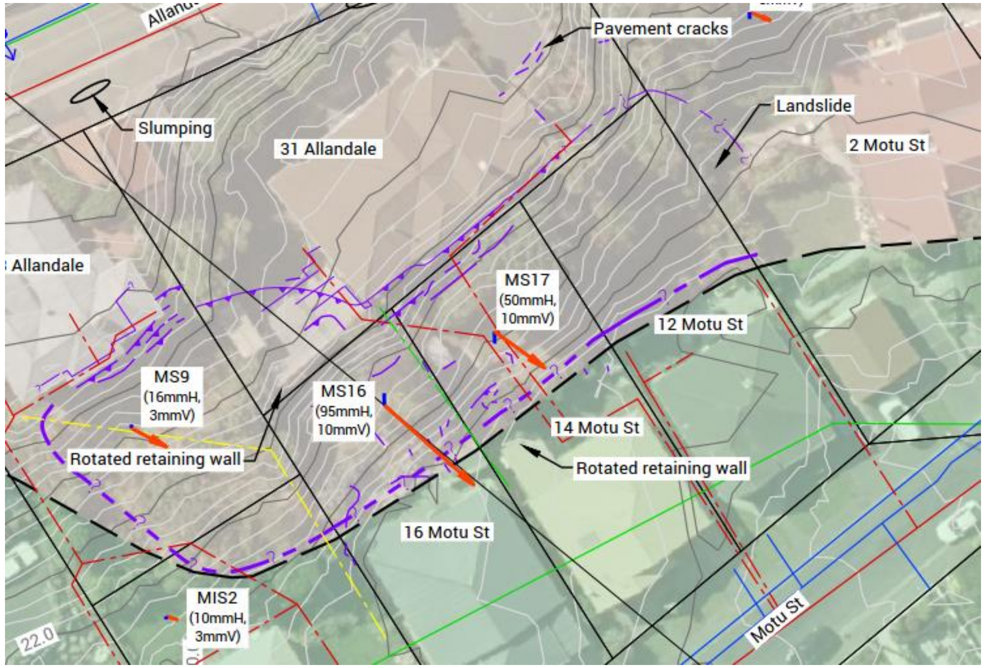
- Determination of the 3D geology of landslide requires subsurface data from drilling , test pits penetrometer testing etc in addition to surface mapping.
- The geological model is typically presented as cross-sections, parallel to the downslope movement direction of the slide.
- The sections show investigation drilling data, the geological units, the inferred failure surface, and groundwater tables (see below).

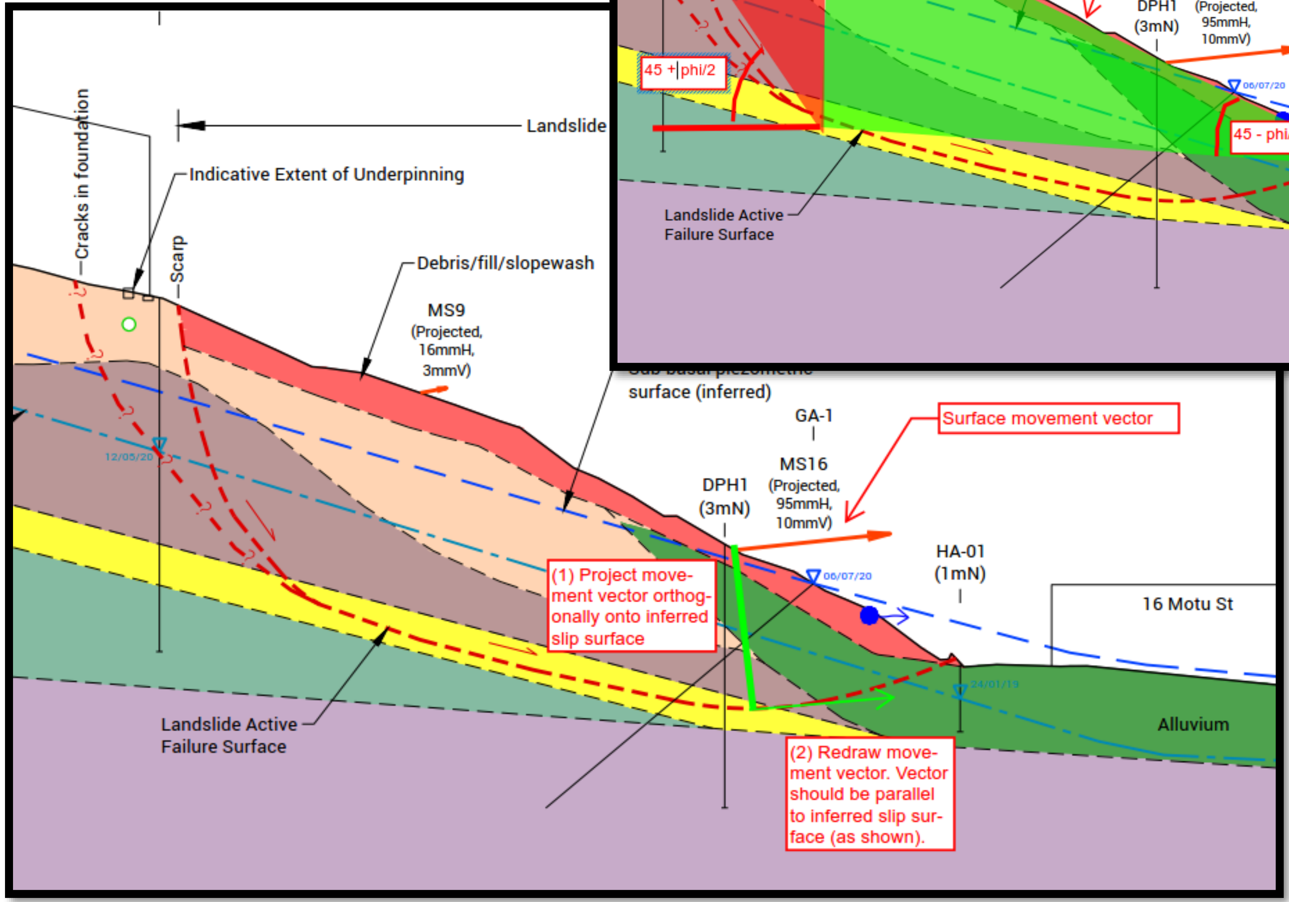


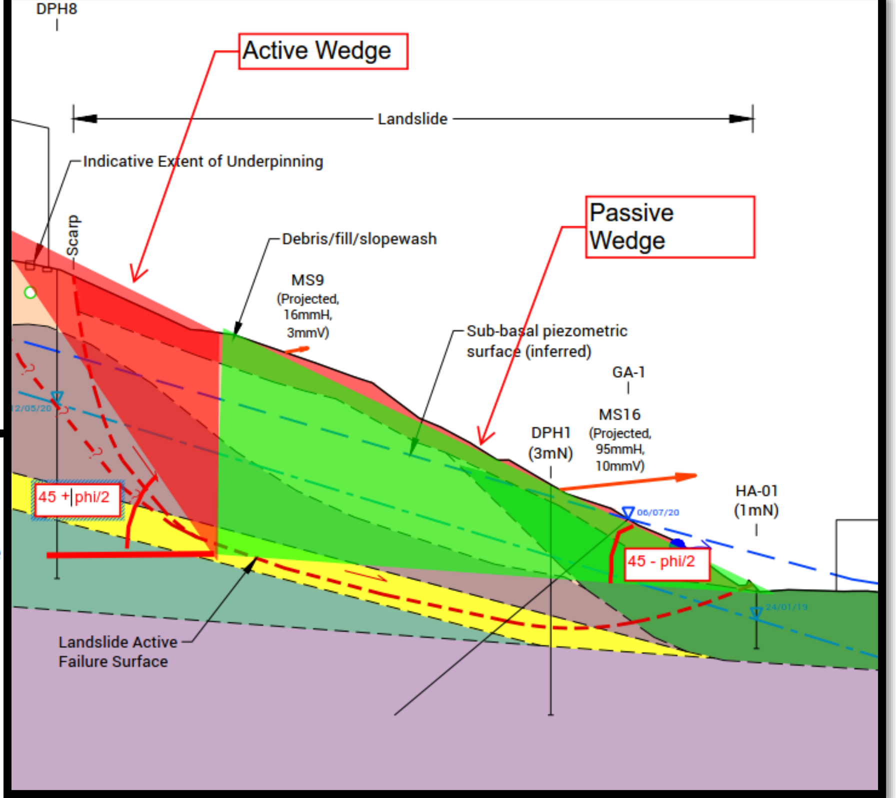
Cross section of the lower part of the Frankton Landslide, Queenstown

Inferring Failure Surfaces

- Use surface deformation observations (cracks/movements in structures for example) and surface monitoring data (survey)
- Passive/Active wedge theory for estimating the location of the inferred slip surface at the head and toe of the slide







Groundwater & Slide Movement

- Groundwater is critical in the stability of slides, as the porewater pressure on the failure surface reduces effective normal stress, mobilised shear strength and hence slide stability.
- The governing porewater pressure can come from above the failure surface within the slide, or from the formation below.
- Investigations need to establish the groundwater regime of the landslide. This is done by mapping of surface seepages, drilling and piezometer installation to establish the porewater pressures acting on failure surfaces.
- A sub-basal groundwater system confined beneath a low permeability basal failure surface is a common regime. This is present at Motu St and controls the stability of the landslide. Rainfall infiltration upslope of the slide can rapidly increase pore water pressures and reduce the shear strength of the slide mass
- "Perched" groundwater above the slide surface is another common situation, and also occurs at Motu St.
- Typical groundwater systems found in landslides in the Cromwell gorge are shown opposite.
- Changes in groundwater conditions in cut clay slopes and their effect on stability is discussed by Skempton (1964)

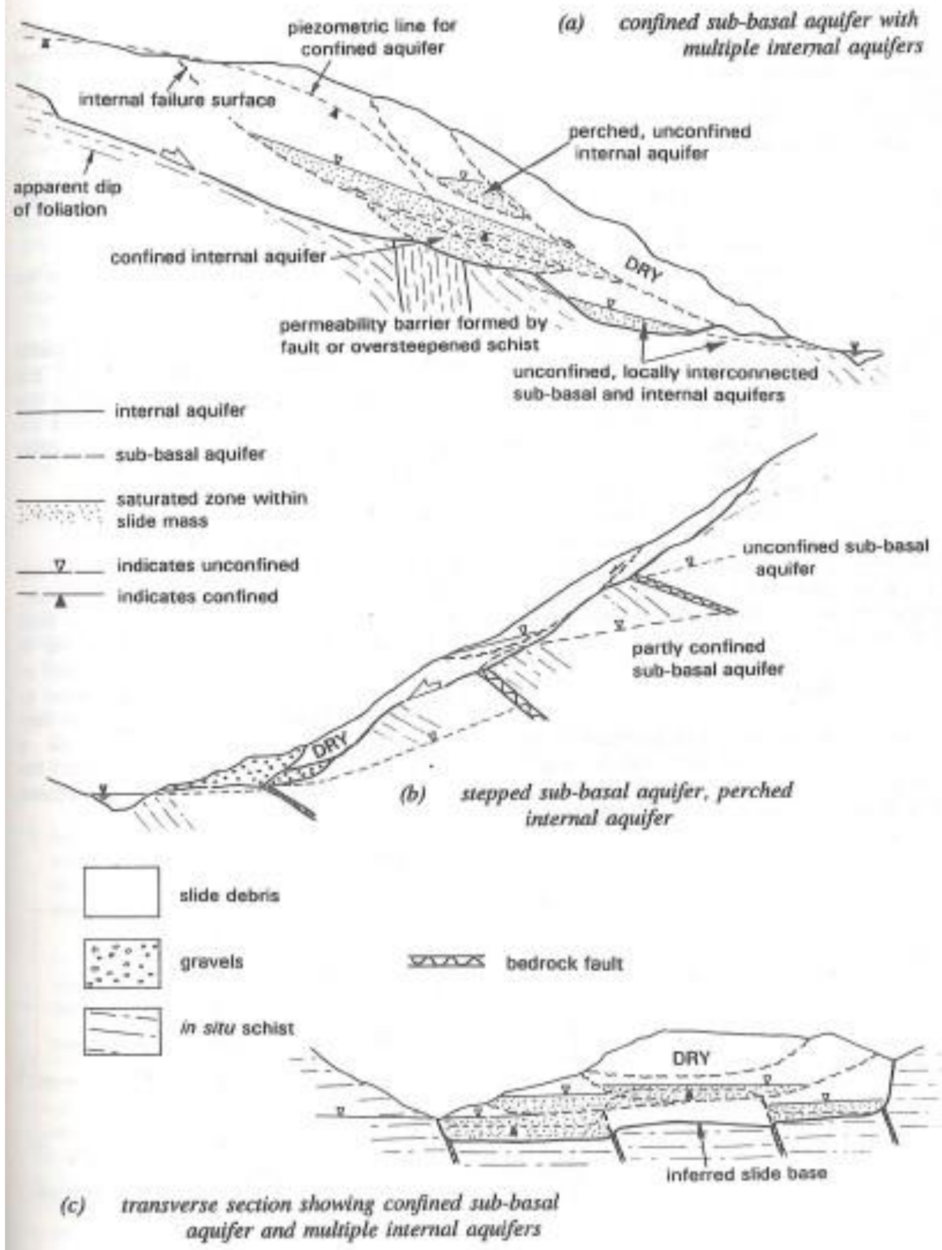


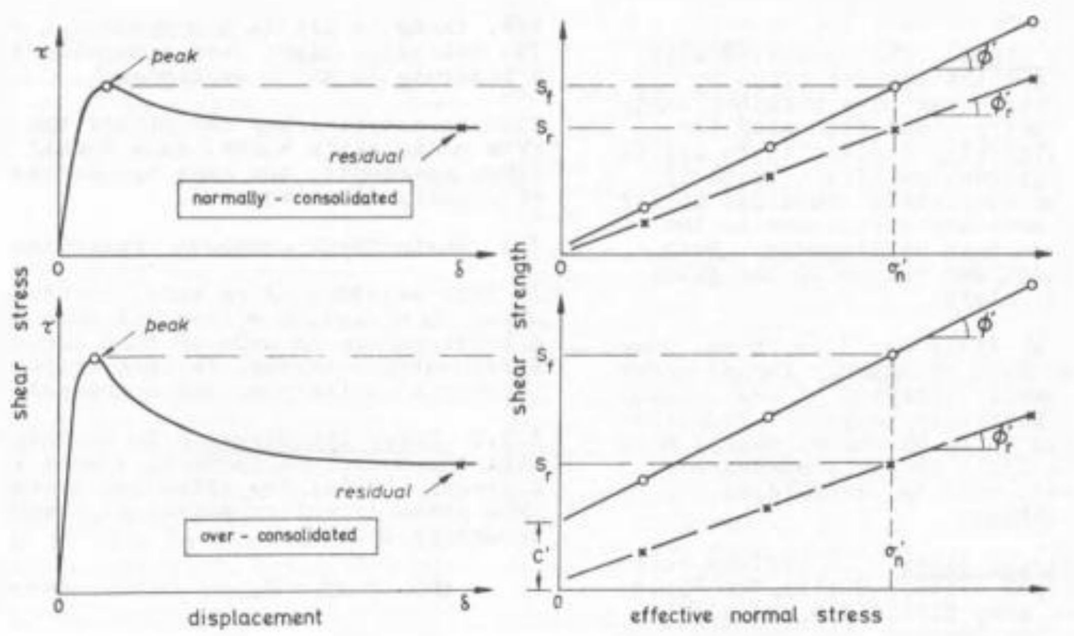
Figure 2. Examples of groundwater systems in Cromwell Gorge landslides.

Peak and Residual Shear Strength

- Determination of the nature of the failure surface material at the base of the slide and its strength properties is important to understanding the landslide mechanism.

- The paper by Skempton and Hutchinson section 3.2.3 explains the difference between the Peak Strength of a soil and the typically lower Residual Strength once it has been sheared by landslide movement. This is treated in more detail in a paper by Skempton (1985)

- The Residual Strength of fine grained failure surface materials can be conveniently determined by ring shear testing.

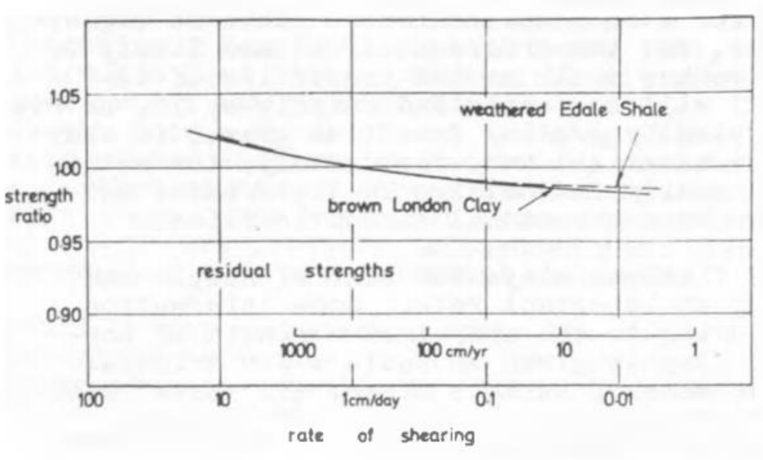


Simplified shear strength properties of clay
(after Skempton 1964)

- For active landslides with significant movements recorded at head scarp locations, it can be presumed that the soils are at residual strengths and that the reduction from peak to residual strength has already occurred. This is why first time landslides are particularly dangerous and prone to catastrophic failure. Existing landslides with pre-sheared surfaces that haven't already catastrophically failed are less likely to do so if the appropriate measures are taken.

Rate of Shearing vs Shear Strength

- Applicable to mainly cohesive soils (there are little to no shearing rate effects with granular materials, man made or virgin)
- Most clays exhibit a positive rate effect (ie. increasing shear strength with increasing displacement rate). Soils/gouge that exhibit the opposite (negative shear rate) are concerning, and at much higher risk for catastrophic landsliding. This mechanism is inferred to have occurred at the infamous Vaiont Slide in Italy
- This relationship is critical when assessing the **mobility** of the landslide is the relationship between the residual shear strength of the soils and the rate of shearing



Example of a soil with a positive rate effect (Skempton and Hutchinson, 1969)

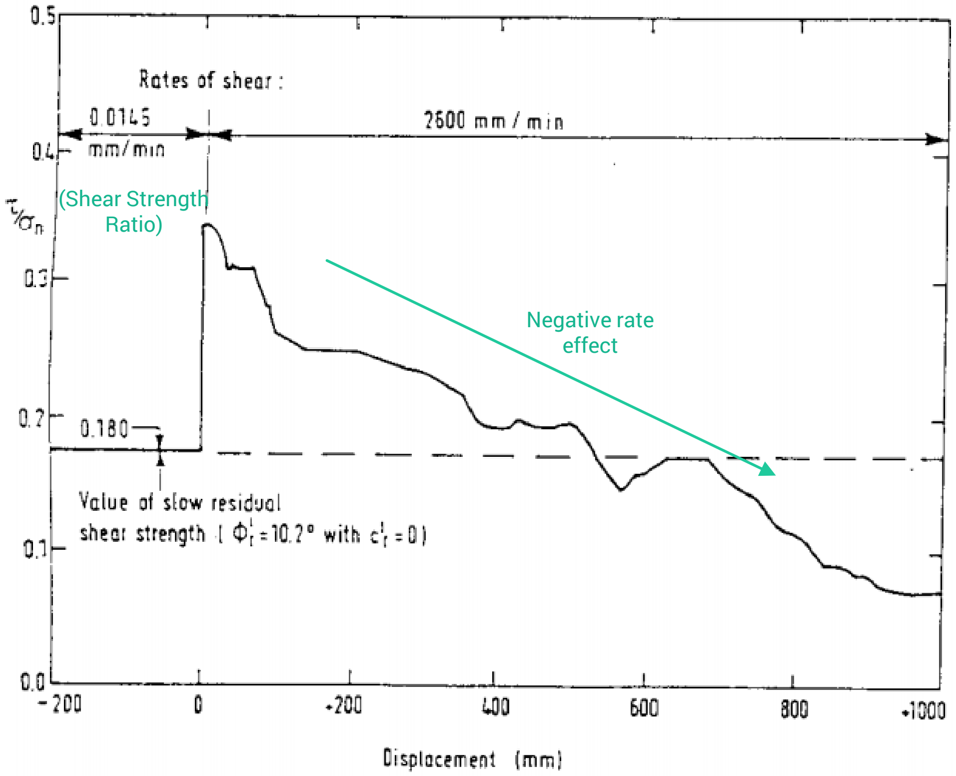


FIG. 15 — *Results* of slow and fast ring shear tests at σ_n = 980 kPa on Sample 3 of gouge from the Vaiont slip surface. The fast stage was carried out at 2600 mm/min after the slow residual strength of the sample had been established. After Tika - Tassilikos & Hutchinson (in preparation).

Ref: (Hutchinson, 1994)

Landslide Mobility

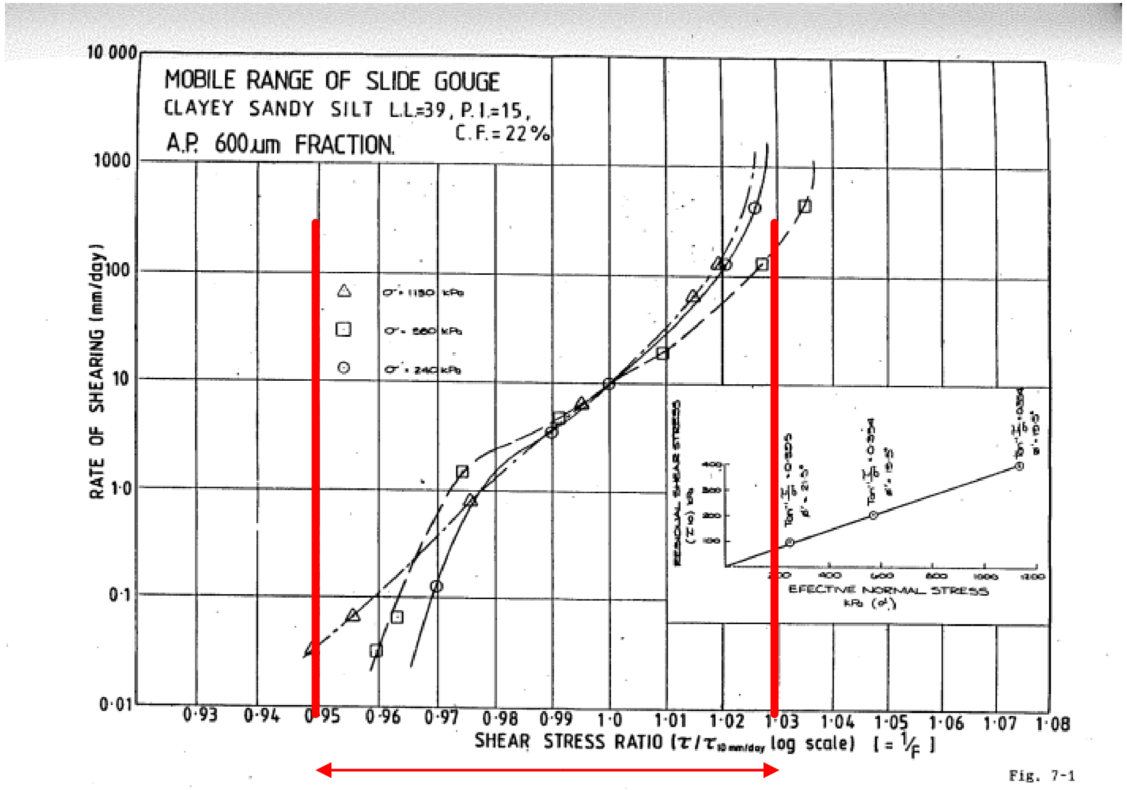
- Assessment of landslide mobility involves

  (i) Use of precedent, using field indications of the past and present behavior of large active and dormant slides in the immediate locality

  (ii) Interpretation of the surface and sub-surface deformation surveys of movement rates, taking measured hydrological factors into account

  (iii) Examination of documented case histories of slides in similar materials

  (iv) Laboratory testing using conditions corresponding to hose existing in the field, together with conventional limit equilibrium methods to assess influence of proposed works



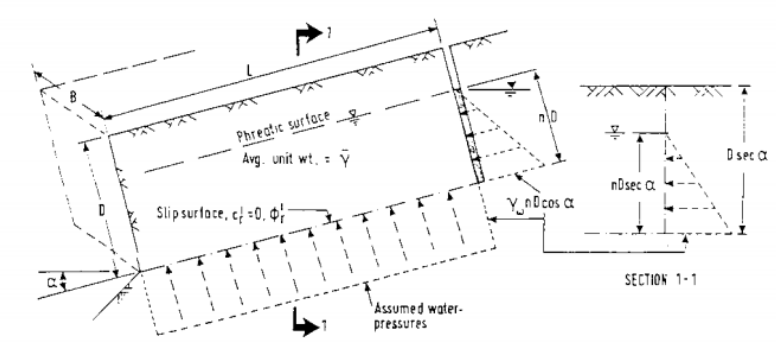
Ref: Thesis on Reservoir Slope Stability (Salt, 1991)

Mobile Range: 8% Increase in factor of Safety before rapid failure (ie. A very small increase of shear will induce disproportionally large increases in slide velocity)

In other words, if landslide with the above material is initially stationary and a destabilizing force is slowly introduced (groundwater rising), then the factor of safety can be decreased by up to 6-8% without likelihood of rapid failure

Slope Stability Analysis

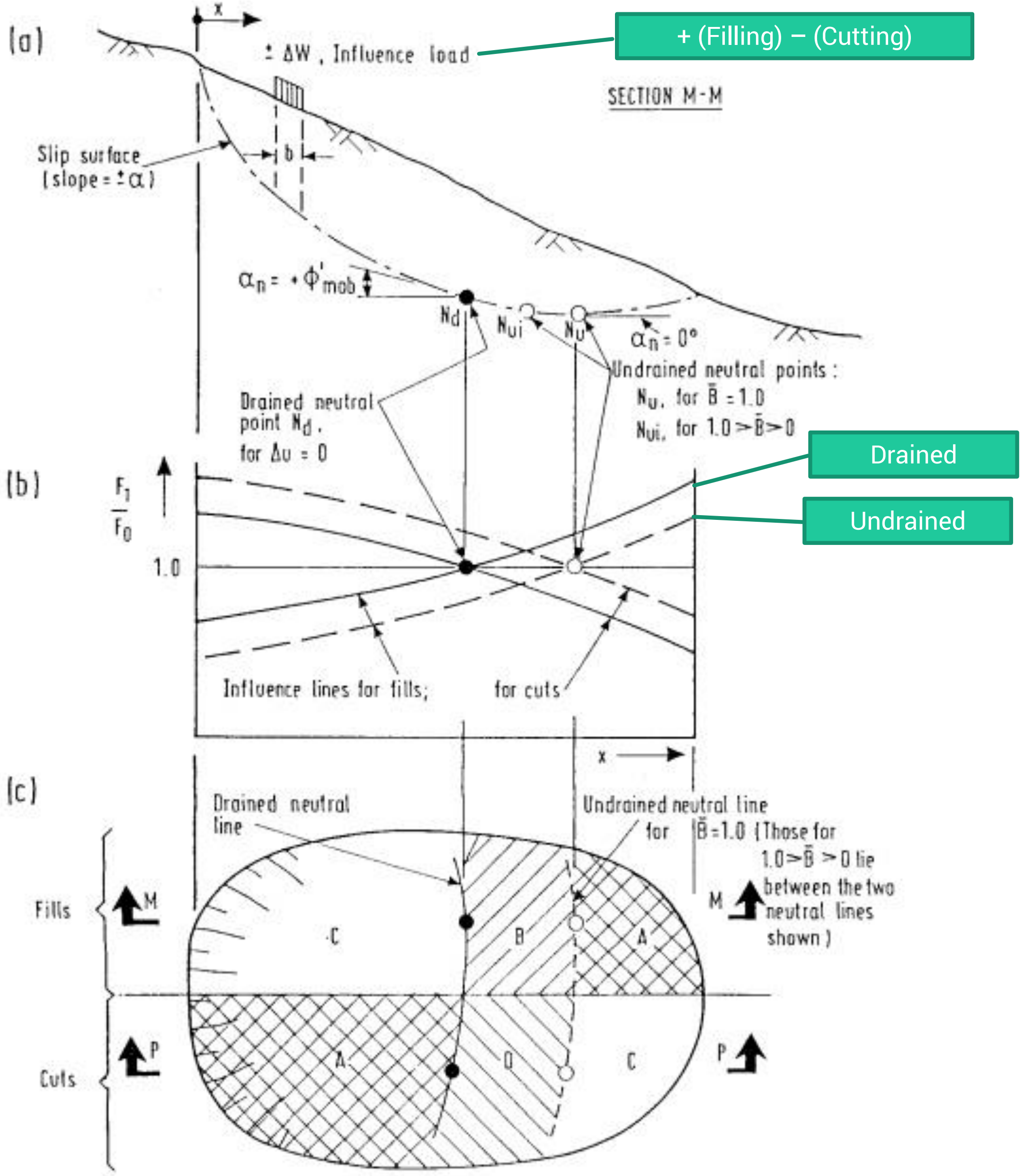
- Consider the “influence line approach” to understand the stabilizing and destabilizing effects of cutting and filling, drainage and anchors (Hutchinson, 1994) Influence lines for filling and cutting in drained and undrained conditions shown to the right.
- **Three Dimensional Stability (F3)**
  Most slope stability analyses are undertaken on a 2D basis. 2D is typically more conservative (ie. neglects lateral restraint). Difference between Factors of safety depend on B (width) with respect to D (depth). As B/D increases (ie. the wider the landslide) the influence of lateral restraint becomes less.



TAB. 2 — Values of the ratio B/D below which the value of F_3/F_2 exceeds 1.10.

— Valore del rapporto B/D al di sotto del quale il valore di F_3/F_2 supera 1.10.

K	α = 10°		α = 30°	
	dry	fully wet	dry	fully wet
1,0	10,3	10,6	13,3	16,3
2,0	20,6	21,2	26,7	32,5



Acceptable Factors of Safety for Existing Slopes

(From G.C.O. 1984)

Table 5.4 - Recommended Factors of Safety for the Analysis of Existing Slopes and for Remedial and Preventive Works to Slopes for a Ten-year Return Period Rainfall

Risk to Life	Recommended Factor of Safety Against Loss of Life for a Ten-year Return Period Rainfall		
	Negligible	Low	High
	> 1.0	1.1	1.2

Note : (1) These factors of safety are minimum values to be used only where rigorous geological and geotechnical studies have been carried out, where the slope has been standing for a considerable time, and where the loading conditions, the groundwater regime and the basic form of the modified slope remain substantially the same as those of the existing slope.

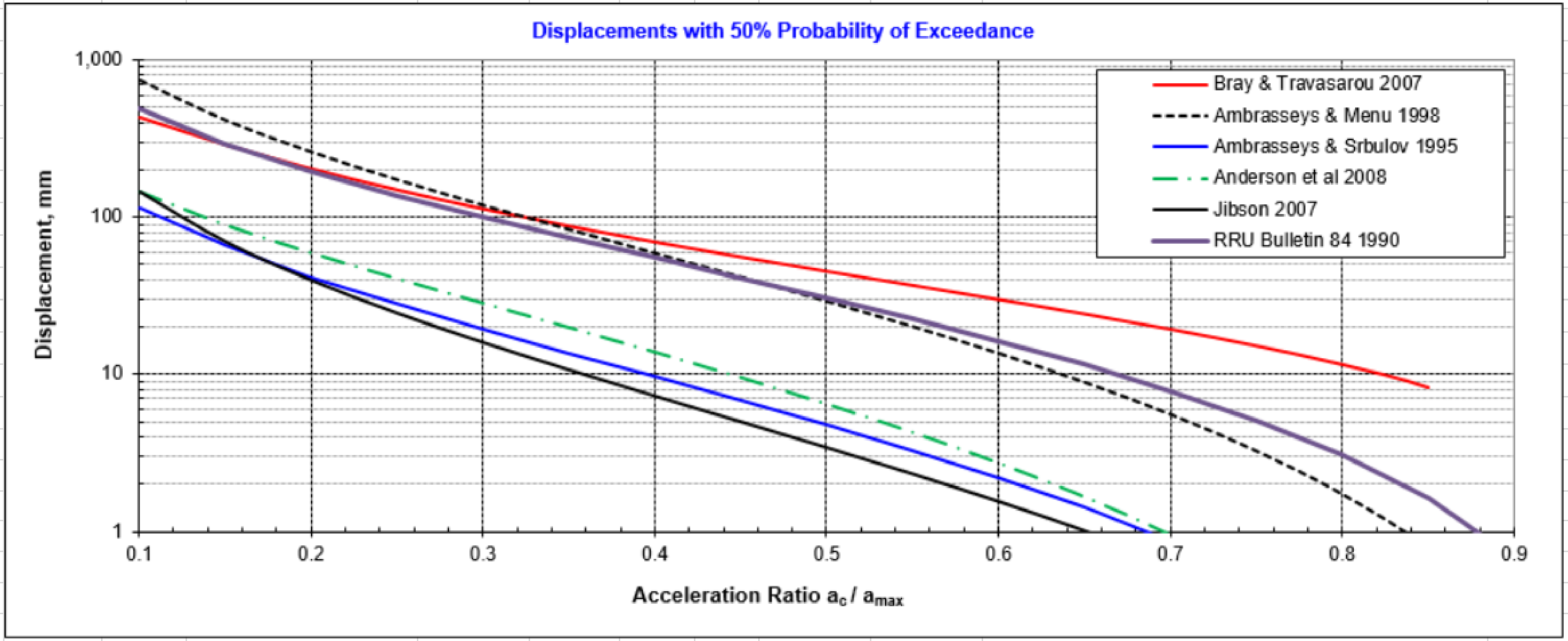
(2) Should the back-analysis approach be adopted for the design of remedial or preventive works, it may be assumed that the existing slope had a minimum factor of safety of 1.0 for the worst known loading and groundwater conditions.

(3) For a failed or distressed slope, the causes of the failure or distress must be specifically identified and taken into account in the design of the remedial works.

- Reference to left from Geotechnical Manual for Slopes, Geotechnical Control Office, Hong Kong (G.C.O, 1984)
- These factors of safety are not to be utilized in the construction of new slopes, they are solely applicable to **a 10 year return period rainfall load case, existing slopes where the slope has been standing for considerable time, and where the loading conditions, groundwater regime and basic form of the modified slope remain substantially the same as those of the existing slope**

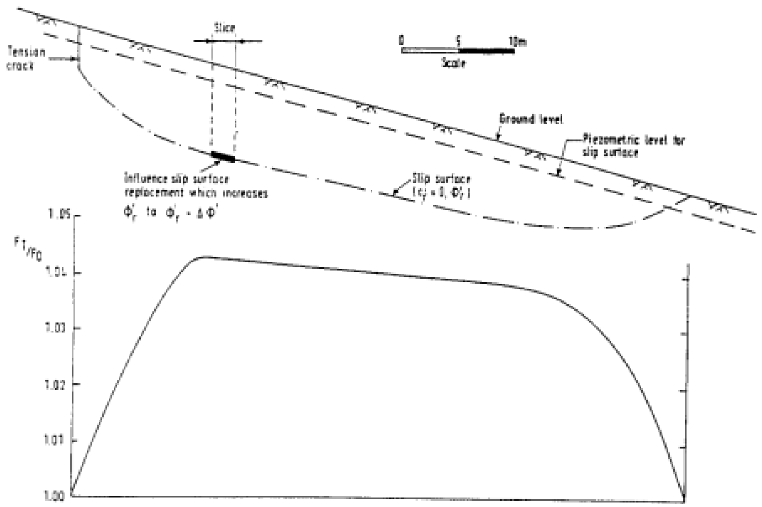
Seismic Displacement Estimates

- Seismic displacements can be estimated as a function of critical acceleration, a_c, (seismic acceleration when FoS of slope is 1.0) divided by max acceleration, a_{max}, for design earthquake event
- There are several methods for predicting displacements, mainly using newmark block type analyses. A comparison of methods are shown below:

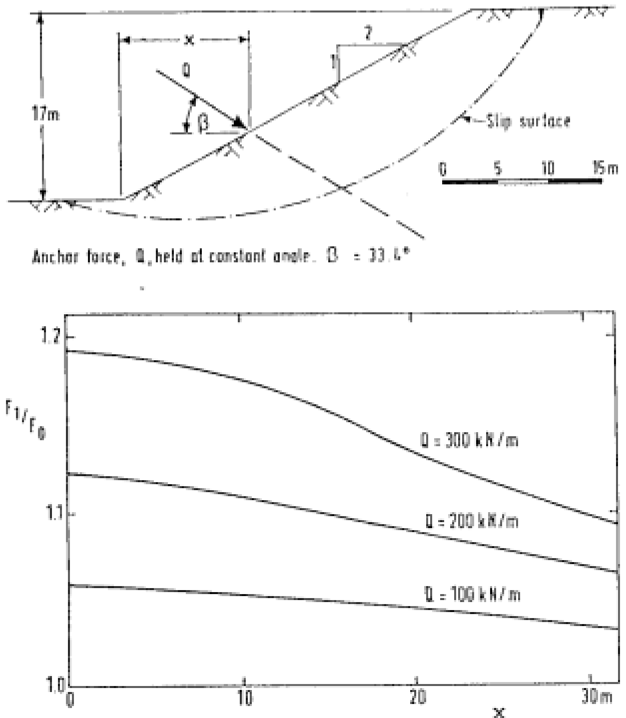


Remediation Measures

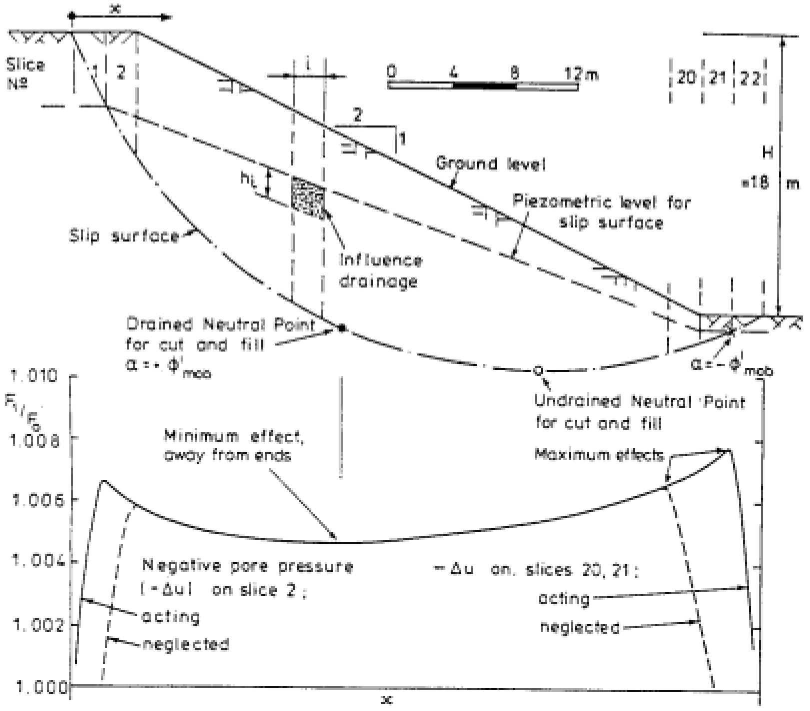
- Remediation measures should be determined once the landslide mechanism for movements has been established (In the case of Motu St, groundwater)
- Drainage
- Slip surface replacement (typically counterfort drains)
- Anchors



Slip surface replacement effect (countefort drains), shallow, non-circular landslide, c'=0, φ = 20°, γ = 20 kN/m3



Anchorage effects, β = 33.4 deg, c' = 9.8kPa, γ = 19.73 kN/m3



Drainage effects, influence lines for circular rotational slide (c' = 10 kPa, phi' = 30deg, γ = 20 kN/m3)

Investigating Landslides Conclusions

- Conduct a full appraisal of a landslide including:
  (a) Review of history of movements
  (b) Landslide recognition by remote sensing
  (c) Engineering geological mapping
  (d) Kinematics (identifying surface movement vectors and the associated underlying movements)
  (e) Subsurface investigations including piezometer installation
- Build a geological model → transferring to a geotechnical model with strength parameters
- Consider complexities of underlying groundwater
- Consider peak vs residual shear strength, drained vs undrained loading and the effect of shearing rate on shear strength (mobile range)
- Slope stability analyses (consider the influence and sensitivity of different remedial elements or construction activities such as cutting, filling, draining, slip surface replacement (counterfort drains) and anchoring)
- Slope stability load cases, consider different load combinations. Target FoS is proportional to the probability of each case occurring.
- Landslide mobility depends on the % increase in FoS with increasing shearing rate. If destabilising forces are small enough (<%mobile range), then rapid movements are unlikely to occur. To prevent movements, FoS must be increased by at least the mobile range.
- Remediation measures shall be chosen with due consideration for the load mechanism for failure. Take care in choosing the appropriate means to remediate. Reducing overall slope angle with cutting (a common technique), where the landslide mechanism for movement is associated with groundwater can actually destabilise the slope.

Links and References for Further Information

Slide 2 https://slideplayer.com/slide/3815341/

Slide 4 http://retrolens.nz/map/

Slide 6 https://www.issmge.org/uploads/publications/1/38/1969_04_0005.pdf

Slide 9 https://www.icevirtuallibrary.com/doi/10.1680/geot.1964.14.2.77

Slide 10 https://ir.canterbury.ac.nz/bitstream/handle/10092/100154/Smith_1991_thesis.pdf?sequence=1&isAllowed=y
https://www.scribd.com/document/186385575/1985-Residual-Strength-of-Clays-in-Landslides-Skempton-GE350101

Slide 12 http://151.100.51.154/Volumi/VOL%2030/GR_30_1_13_%20Hutchinson.pdf