

SLOPE STABILITY GEOTECHNICAL GUIDANCE SERIES

UNIT 2 LANDSLIDE RECOGNITION, IDENTIFICATION AND FIELD INVESTIGATIONS

AN INDUSTRY REFERENCE DOCUMENT COMPILED AND PUBLISHED
BY THE NEW ZEALAND GEOTECHNICAL SOCIETY (NZGS)

FEBRUARY 2025



ACKNOWLEDGEMENTS

AUTHORSHIP GROUP

- Eleni Gkeli – Stantec, NZGS (Unit lead)
- Nick Peters – Tonkin & Taylor
- Tom Revell – KiwiRail
- Christoph Kraus – Beca, NZGS

STEERING COMMITTEE

- Richard Justice – ENGEO, NZGS (Project Lead)
- Phil Robins – Beca, NZGS Chair
- Eleni Gkeli – Stantec, NZGS Immediate Past Chair
- Ross Roberts, Auckland Council, NZGS
- John Scott, Auckland Council
- Kiran Saligame, MBIE
- David Stewart, WSP

PEER REVIEW

- Ann Williams – Beca
- Don Macfarlane

COVER Aerial Image of Broken River
Landslide near Cass, Inland Canterbury.

DISCLAIMER

This document is published by the New Zealand Geotechnical Society (NZGS), a non-profit organisation, and is designed only for use by NZGS members and agents of consenting authorities who are appropriately qualified and experienced in the geotechnical field of slope stability in New Zealand. It must not be used by non-qualified and / or inexperienced persons as a substitute for professional advice.

This document was developed by NZGS with assistance and funding from various parties (the parties). To the maximum extent permitted by law, NZGS and the parties accept no liability, whether under the law of negligence or otherwise, for any inaccuracy, error, or omission in this document, or for any loss resulting from any use of this document.

The information provided in this document is general guidance only and has not been released under Section 175 of the Building Act. It is not mandatory to use the guidance in this document, but if used:

- The guidance does not relieve any person or consenting authority of the obligation to conduct their own professional enquiries, research or assessments, and to exercise their own independent judgement, according to the circumstances of the particular case;
- Consenting authorities are not bound to accept the guidance as demonstrating compliance with any relevant Acts, Codes or Standards.

The information provided in this document does not replace or alter the laws of New Zealand or alter any regulations, official guidelines or other requirements.

NZGS may modify or update this guidance at any time.

By continuing to use the document, a user confirms that they agree to these terms.



New Zealand Geotechnical Society (NZGS)
PO Box 12 241
Wellington 6013

© COPYRIGHT

The copyright owner authorises reproduction of this work, in whole or in part, so long as no charge is made for the supply of copies, and the integrity and attribution of the contributors and publishers of the document is not interfered with in any way.

DOCUMENT STATUS

Issue Date: February 2025
Issue Status: Draft



CONTENTS

PART 1 INTRODUCTION AND PURPOSE	5	PART 3 STAGE 2 INVESTIGATIONS	
1 INTRODUCTION	6	- SURFACE AND SUBSURFACE INVESTIGATIONS, INSTRUMENTATION AND MONITORING	40
1.1 Background	6	4 SURFACE INVESTIGATION METHODS	41
1.2 Purpose and context of This guidance document	8	4.1 Engineering Geological Mapping	41
1.3 Audience	9	4.2 Mapping of discontinuities along rock slopes	47
1.4 Interface with other guidance documents	9	4.3 Ground Surveys	47
1.5 Objective of landslide investigations	10	5 SURFACE INVESTIGATIONS	51
		5.1 Purpose of Subsurface Investigation of landslides	51
PART 2 STAGE 1 INVESTIGATIONS	11	5.2 Planning Investigations	51
- LANDSLIDE RECOGNITION AND IDENTIFICATION METHODS		5.3 investigation methods	57
2 LANDSLIDE IDENTIFICATION AND RECOGNITION	12	5.4 in situ testing	65
2.1 Landslide Types	12	6 FIELD INSTRUMENTATION FOR LANDSLIDE MONITORING	75
2.2 Recognising landslide types	12	6.1 Planning a landslide monitoring system	75
2.3 rock slopes	16	6.2 Monitoring methods considerationS	76
2.4 Recognition of Potential Landslides	17	6.3 Specifications for monitoring	78
2.5 Importance of surface cracking	17	6.4 Instrumentation Selection	78
3 PRIMARY METHODS FOR LANDSLIDE IDENTIFICATION	26	6.5 data analysis	81
3.1 Published Information	26	6.6 Duration of monitoring	84
3.2 Review of Aerial Imagery and Elevation Data	29	7 REFERENCES	84
3.3 Initial Site Walkover (site reconnaissance)	36	APPENDIX A MAPPING SYMBOLS	87

PART 1

INTRODUCTION AND PURPOSE



PART 1: INTRODUCTION AND PURPOSE

1 INTRODUCTION

Any new development on or adjacent to slopes must take into consideration the potential for past, existing, and future landslides. Recognition and identification of landslide type is the first stage of any landslide investigation. Once this step has been completed, then the most appropriate surface and subsurface investigation techniques can be applied.

Unit 1, Part 2 describes the different landslide types that result from variations in underlying geology, topography, climate, vegetation cover, surface water, and groundwater conditions. Unit 1, Parts 3 and 4 cover the Recognition and Identification and Landslide Investigation Methods respectively.

Unit 2, *Landslide Recognition, Identification and Field Investigations* expands on what has been provided in Unit 1, Parts 3 and 4. Its purpose is to discuss in more detail the techniques and methods to identify the type of landslide that may be present and the different field investigation techniques that are available. It firstly identifies the basic geological and geomorphological features used to recognise landslides as well as specific landforms that enable differentiation between various types of landslide activity. It then presents an overview of the commonly available resources, techniques, and methods that should be considered to aid in the recognition, identification and investigation of landslides.

It is also the intent of Unit 2 to provide a summary of advantages and disadvantages of the different techniques and to aid interpretation and understanding. Unit 2 provides information to support the other Units in this series, like the slope stability analysis of soil and rock slopes discussed in Unit 3.

Some sections of Unit 1 have been repeated in Unit 2 to ensure that Unit 2 can be read as a standalone and independent document.

1.1 BACKGROUND

Geoprosessionals (the collective term for Engineering Geologists, Geotechnical Engineers and Hydrogeologists) are often involved with site assessments for future developments, new infrastructure, management or upgrades of existing infrastructure, landslide remediations, and other projects. If these activities are to interact with a slope,

consideration must be given to the potential risk posed by past, current, and future landslides.

The recognition and identification part of this guidance includes a series of techniques (i.e. desktop assessment and initial site walkover) that can be applied in any landslide assessment, regardless of size. These are the good practice techniques that form **Stage 1** of any landslide investigation, which help to develop the Conceptual Engineering Geological Model. These Stage 1 techniques also provide the basis for planning surface and subsurface investigations and locating appropriate instrumentation.

The surface and subsurface investigation part of the guidance covers engineering geological mapping, as well as subsurface investigations and common monitoring techniques that enable the geoprofessional to obtain sufficient understanding of the landslide and to reduce remaining uncertainties. These investigations and monitoring techniques can also be used to define the landslide mechanism such that consequences, likelihood and risks can be adequately assessed along with appropriate mitigation options.

This is **Stage 2** of the investigations and contributes to the development of the Observational Engineering Geological Model. The EGM knowledge framework supports “the interpretation and assessment of the engineering geological conditions and allows the interaction of these conditions with the proposed project to be evaluated, so that appropriate engineering decisions can be made throughout the life cycle of the project from inception to decommissioning” (IAEG C25; Baynes and Parry, 2024).

Ideally the geoprofessional should have an understanding of the landslide mechanisms typical in the project area and from Stage 1 investigations, before undertaking surface and subsurface investigations. This is where local knowledge is important: having experience of landslide types through knowledge of local geology. Also, it is very important for the geoprofessional to recognise landslide types from the geomorphology they have observed during their desktop assessment and initial site walkover in Stage 1. This ensures the most appropriate surface and subsurface investigation methods are applied.

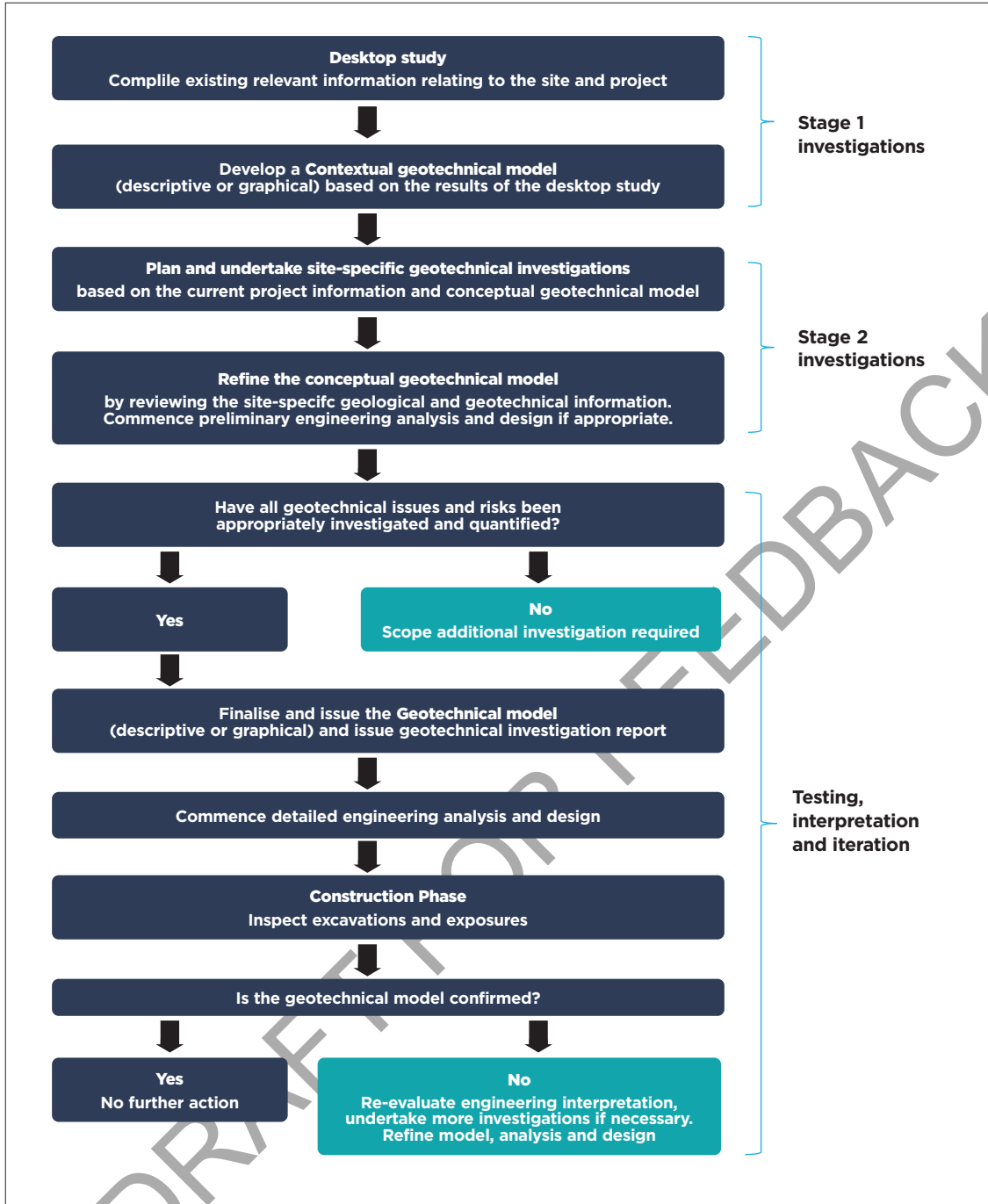


FIGURE 1: The geotechnical investigation process (from NZGS & MBIE MBIE 2021).

Following Stage 1 of the investigation (including desktop assessment and initial site walkover), Stage 2 techniques need to be considered and will depend upon the size, complexity and (un)certainty of the landslide. Stage 1 and Stage 2 techniques are described in the following sections.

Module 2 of the Earthquake geotechnical practice series (NZGS and MBIE, 2021) provides a simplified

flowchart of the typical stages of the geotechnical site investigation process for large and complex projects, which is reproduced in Figure 1. Unit 2 is structured to guide landslide identification and investigations through a similar process and following the concept of a gradually built and updated Engineering Geological Model (EGM) through an iterative manner of investigations and interpretation (see Figure 2; refer also Section 1.5).

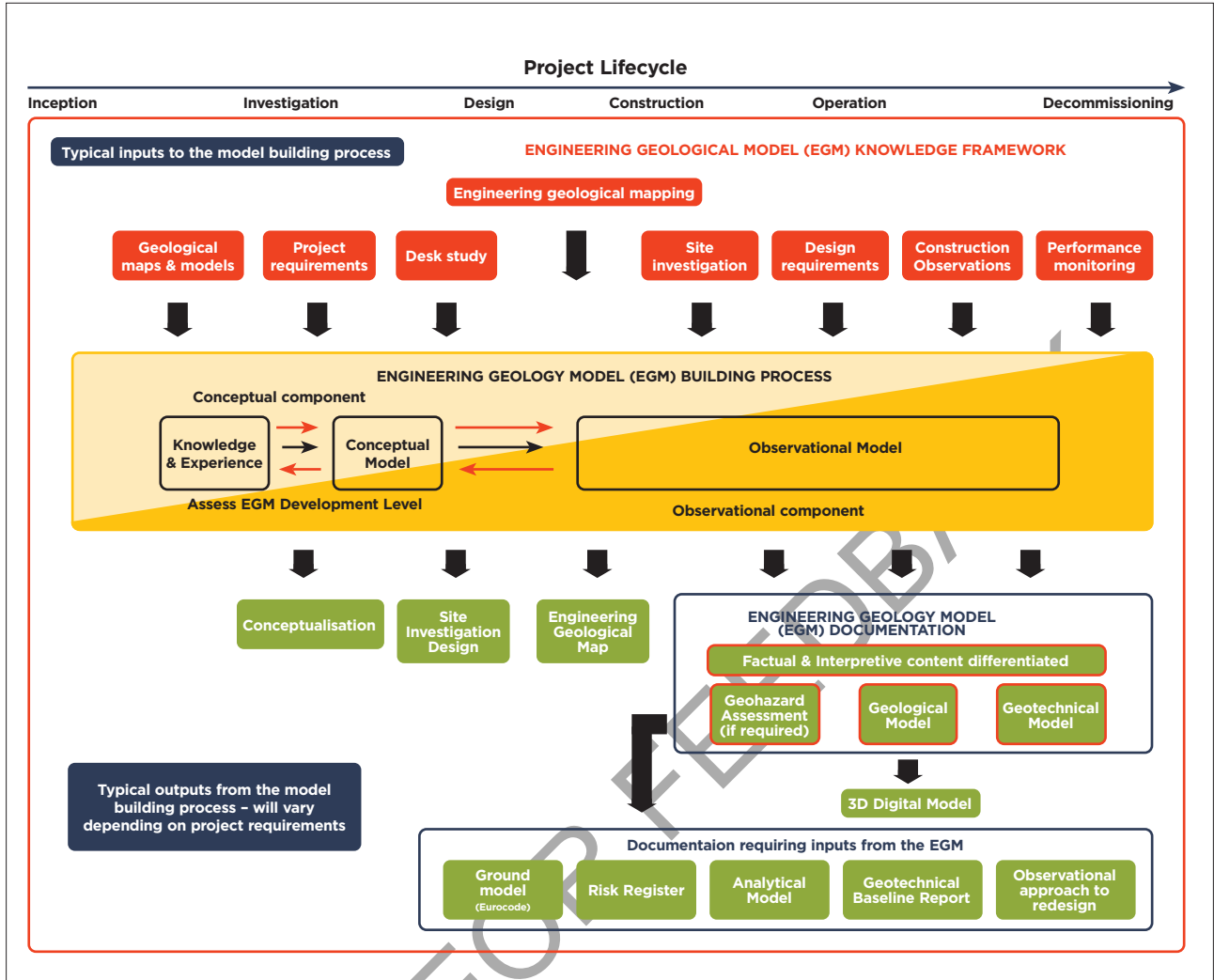


FIGURE 2: Schematic visualisation of the EGM development through the project lifecycle (IAEG Commission C25; Baynes and Parry, 2024)

1.2 PURPOSE AND CONTEXT OF THIS GUIDANCE DOCUMENT

This Slope Stability Guideline summarises current good practice in geotechnical engineering with a focus on New Zealand conditions, regulatory framework, and established methodologies when undertaking investigations to recognise, identify and monitor landslides. The purpose is to provide technical and practical guidance to geoprofessionals (engineers, engineering geologists, hydrogeologists) and other

professionals involved in assessing and managing the stability of slopes in a New Zealand context. The guidance document helps to ensure that slope stability assessments are performed in a competent manner, using established good practices and current technical knowledge. Almost all the content of Unit 2 is derived from existing literature, and sources are referred to as appropriate so that users can refer to the original publications. The structure of Unit 2 is presented in Table 1:

TABLE 1: Structure of Unit 2

PART 1: Introduction and Purpose	
Section 1	Background, purpose, overview of content covered and interaction with other guidance documents.
PART 2: Stage 1 Investigations - Landslide Recognition and Identification Methods	
Section 2	Landslide types and recognition, rock slopes, recognition of potential future landslides, and importance of surface cracking.
Section 3	Primary methods for landslide identification and recognition: review of published information, aerial imagery, elevation, remote sensing, site walkovers
PART 3: Stage 2 Investigations - Surface and Subsurface Investigations, Instrumentation and Monitoring	
Section 4	Surface investigation methods: engineering geological mapping, ground surveys.
Section 5	Subsurface Investigations: Purpose, scoping, planning, methods of subsurface investigations, <i>in situ</i> testing.
Section 6	Field instrumentation for landslide monitoring

Unit 2 forms part of the NZGS Slope Stability Guidelines Units. It includes cross references to the other Units of the series, where complementary or related information is included. The other documents of the series are listed below:

Unit 1 – General Guidance: provides a general overview of the problem.

Unit 3 - Slope Stability Analysis: focuses on methods of slope stability analysis and target performance of slopes.

Unit 4 – Slope Instability Mitigation: focuses on design of engineering measures and solutions to mitigate slope instability and landslides.

Unit 5 – Rockfall Assessment and Analysis: complements the existing guidance on rockfall analysis and design of mitigation measures.

Unit 6 - Debris Flow Assessment, Analysis, and Mitigation: focuses on debris flows specifically.

Unit 7 – Special Cases and Materials: focuses on specific regions and geological formations encountered in New Zealand.

These guidelines are not intended to be a book of prescriptive rules—users are assumed to be qualified, practicing geotechnical professionals with sufficient experience and knowledge to apply professional judgement in interpreting and applying the recommendations that they contain.

1.3 AUDIENCE

This Slope Stability Guidance document is primarily aimed at:

Engineering Geologists: Professionals who specialise in the application of geological principles and knowledge to assess and manage geological and geotechnical risks in engineering and infrastructure projects, as well as aspects of land-use planning, identifying and mitigating geological hazards.

Hydrogeologists: Professionals who specialise in understanding the interaction of groundwater with soil and rock (the geology).

Geotechnical Engineers: Professionals whose primary focus is on understanding the behaviour of soil, rock, and groundwater and using this knowledge to provide engineering solutions that ensure the safe and stable design, construction, and maintenance of infrastructure.

The collective term used throughout the guidance for the above three groups is 'Geoprofessional'. There is a large overlap between engineering geology, hydrogeology and geotechnical engineering. In simple terms, engineering geologists and hydrogeologists identify and define a problem, then geotechnical engineers design the solution. In reality, all three disciplines must work together to fully identify, assess and analyse the ground conditions so that suitable mitigations can be implemented and maintained.

Other professionals who may benefit from the Slope Stability Guidance include:

Civil Engineers: Engineers involved in the design and construction of structures, roads, bridges, and other infrastructure projects that may impact slopes.

Environmental Engineers: Engineers who work on environmental issues and challenges, including those related to slope stability and erosion control.

Land-use Planners: Professionals involved in land-use planning policy and consenting, including for the management of slopes and the potential risks they pose to human life and property.

Regulators: Government agencies and other organisations responsible for enforcing regulations and standards related to slope stability and soil erosion.

The guidance document provides technical and practical information for these groups to assist them in making informed decisions regarding the stability and safety of slopes

1.4 INTERFACE WITH OTHER GUIDANCE DOCUMENTS

This guidance document can be read alongside other guidance documents and Acts.

Good Practice Guidance Documents

1. IAEG Commission 25 – Guidelines for the Development and Application of Engineering Geological Models on Projects (Baynes & Parry, 2024)
2. IAEG Commission 37 (in prep) – Landslide Nomenclature
3. AGS 2007 Guidelines for Landslide Risk Management, which comprise:
 - a. AGS (2007a). Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning
 - b. AGS (2007b). Commentary on Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning
 - c. AGS (2007c). Practice Note Guidelines for Landslide Risk Management 2007
 - d. AGS (2007d). Commentary on Practice Note Guidelines for Landslide Risk Management 2007
 - e. AGS (2007e). The Australian GeoGuides for Slope Management and Maintenance

Landslide Planning Guidance

The Landslide Planning Guidance – Reducing Landslide Risk through Land-Use Planning, (De Vilder et al, 2024), sets out how landslide risk can be reduced through consistent land-use planning practices and approaches. Its primary focus is for planning, policy and building compliance staff to help make informed decisions on how the land’s suitability for development can be determined and measures to mitigate, reduce or avoid the effects of identified landslides. It is also for Geoprofessionals to align

their assessments in the practices and approaches included in the guidance.

Acts

- 1. Building Act 2004** (in particular Sections 72, 124).
- 2. Resource Management Act (RMA)** (in particular Section 6(h) and 106).
- 3. Natural Hazards Insurance Act 2023 (and the Earthquake Commission Act (1993))**. This has a specific focus in regard to determining the extent and repair of natural hazard damage to both insured land and buildings. While it does not provide minimum acceptable standards for slope stability assessment, many practitioners undertake assessments under the provisions of this Act over their professional careers and should be aware of its specific requirements for landslide (‘landslip’) assessment. The EQC Act was replaced with the Natural Hazards Insurance Act on 1 July 2024.

1.5 OBJECTIVE OF LANDSLIDE INVESTIGATIONS

A basic principle used throughout this guidance is the concept of continually building the Engineering Geological Model (EGM), highlighting areas of uncertainty and using techniques to build upon the information gained, as set out in IAEG Commission 25.

A well-developed EGM helps to reduce and manage geotechnical risk, allows determination of whether landslide mitigation is required and informs the engineering design. The EGM allows assessment of risk, constructability of mitigation solutions and consideration of safety during the project lifecycle. Detailed objectives of investigations for landslides and slopes are shown in Table 2.

TABLE 2: Objectives of site investigations for landslides and slopes

Key objective	Sub-objectives
Development of Engineering Geological Model (EGM)	<ul style="list-style-type: none"> • Identify geological environment and landforms anticipated. • Identify potential landslide mechanisms in this geological environment. • Identify engineering geological units. • Interpret spatial distribution of the geological units within the slope. • Identify groundwater levels, range and recharge and discharge sources.
Landslide identification and characterisation	<ul style="list-style-type: none"> • Define the extents of the landslide. • Define the depth and shape of the failure surface and landslide mass. • Identify the engineering geological units that form both the stable and the unstable mass. • Investigate the critical units or discontinuities in the soil or rock formation that formed or could form instabilities.
Groundwater conditions	<ul style="list-style-type: none"> • Measure and monitor groundwater levels within the slope. • Identify the type of groundwater table in the slope (permanent, seasonal, perched, artesian etc.). • Measure seasonal fluctuations. • Record flow rates of recharge and discharge sources. • Identify groundwater pressures within the slope and acting on the landslide.
Geotechnical model and slope stability analysis¹	<ul style="list-style-type: none"> • Define geotechnical units and parameters, including dynamic (seismic) parameters. • Identify type, orientation, location and continuity of discontinuities within or between the rock formation/s that could cause instability, and their parameters.
Risk assessment, remaining uncertainties and future project stages²	<ul style="list-style-type: none"> • Inform project risk register. • Define residual uncertainties and risks in the geological and geotechnical models. • Inform the landslide risk assessment and management • Identify monitoring regime if applicable. • Define additional investigations required in future design stages. • Set out confirmations required during construction.

¹ Development of the geotechnical model and slope stability analysis are not covered in Unit 2. Refer to Unit 3 of the Slope Stability Guidelines for these topics.

² Risk assessments and geotechnical designs are not covered in Unit 2. For risk assessment of slopes refer to AGS Landslide Risk Assessment Guidelines and for slope analysis and design refer to Unit 3 of the Slope Stability Guidelines series.

PART 2

STAGE 1 INVESTIGATIONS - LANDSLIDE RECOGNITION AND IDENTIFICATION METHODS

The background features abstract geometric shapes. A large yellow parallelogram is positioned in the lower-left quadrant. To its right, a series of parallel yellow lines form a trapezoidal shape. In the bottom-right corner, there are several parallel blue lines forming a smaller trapezoidal shape. The overall design is modern and technical.

PART 2: STAGE 1 INVESTIGATIONS

- LANDSLIDE RECOGNITION AND IDENTIFICATION METHODS

2 LANDSLIDE IDENTIFICATION AND RECOGNITION

Any landslide investigation begins with recognising where and when landslides occur in the local environment, and understanding the key contributing factors within that environment, which may be any, several or all of the following:

1. **Topography:** typically (but not necessarily), steeper slopes are more prone to landslides.
2. **Geology:** specific rock and soil types or combinations are more susceptible to failure and will generally have a common failure mechanism, (e.g., rotational, translational, toppling etc.).
3. **Water:** rainfall (short term high intensity, long duration and / or long term above average rainfall), stormwater runoff, or elevated groundwater levels can saturate slopes, reducing stability.
4. **Vegetation:** The presence or absence of vegetation can affect slope stability. This can be a positive effect of mature vegetation reducing erosion and potentially lowering groundwater level in a slope, or a negative effect by roots jacking apart fractures in a rock mass. When vegetation is eventually undermined it will take with it a portion of the slope which may result in further movement.
5. **Human activities:** Construction, cuts or fills into or adjacent to slopes, mining, deforestation, changes in land use and drainage can alter the landscape and without proper mitigation can increase the landslide risk.

2.1 LANDSLIDE TYPES

Table 3 illustrates the Landslide Classification system recommended for use in New Zealand. In Table 3 a clear distinction is drawn between the different types of movement (slides, falls, spreads etc.) that may occur in rock, debris and earth slopes.

2.2 RECOGNISING LANDSLIDE TYPES

This section describes the surface features that are commonly associated with the different types of landslide movement. Identifying the type of landslide that may be present at the project site is essential so that:

- Future patterns and velocity (speed) of movement can be predicted.
- An assessment can be made as to whether the landslide is part of a much larger landslide or whether the observed landslide may further develop beyond its existing extent and movement.
- Effective mitigation or remediation measures can be determined, within project constraints.

Table 3.1 of Unit 1 of the guidelines (NZGS, 2024) provides guidance on the features that aid in the recognition of different landslide types, and Section 2.2 of Unit 1 provides an outline of the different landslide types (including photographs). Key points are briefly outlined again in the following sections.

Existing landslides are most commonly recognised from geomorphic expression and observable ground damage. Some of the same features may also be indications of the development of potential future landslides. It is important that geoprofessionals can distinguish between these.

Figure 3 and Table 4 illustrate and list some typical landslide features and criteria for recognising them in the field. For further information on how to record these and other key features in the field, refer to Section 4 of this Unit.

TABLE 3: Landslide Classification System (Hungr et al, 2014). The words in italics are placeholders. (use one only).

Type of Movement	Rock	Soil
Fall	1. <i>Rock / ice</i> fall*	2. <i>Boulder / debris / silt</i> fall*
Topple	3. Rock block topple*	5. <i>Gravel / sand / silt</i> topple*
	4. Rock flexural topple	
Slide	6. Rock rotational slide	11. <i>Clay / silt</i> rotational slide
	7. Rock planar slide*	12. <i>Clay / silt</i> planar slide
	8. Rock wedge slide*	13. <i>Gravel / sand / debris</i> slide*
	9. Rock compound slide	14. <i>Clay / silt</i> compound slide
Spread	15. Rock slope spread	16. <i>Sand / silt</i> liquefaction spread*
		17. Sensitive clay spread*
Flow	18. Rock avalanche*	19. <i>Sand / silt / debris</i> dry flow
		20. <i>Sand / silt / clay</i> flowslide*
		21. Sensitive clay flowslide*
		22. Debris flow*
		23. Mud flow*
		24. Debris flood
		25. Debris avalanche*
		26. Earthflow
27. Peat flow		
Slope deformation	28. Mountain slope deformation	30. Soil slope deformation
	29. Rock slope deformation	31. Soil creep
		32. Solifluction

For formal definitions of the landslide types, see text of the paper.

*Movement types that usually reach extremely rapid velocities as defined by Cruden and Varnes (1996). The other landslide types are most often (but not always) extremely slow to very rapid.

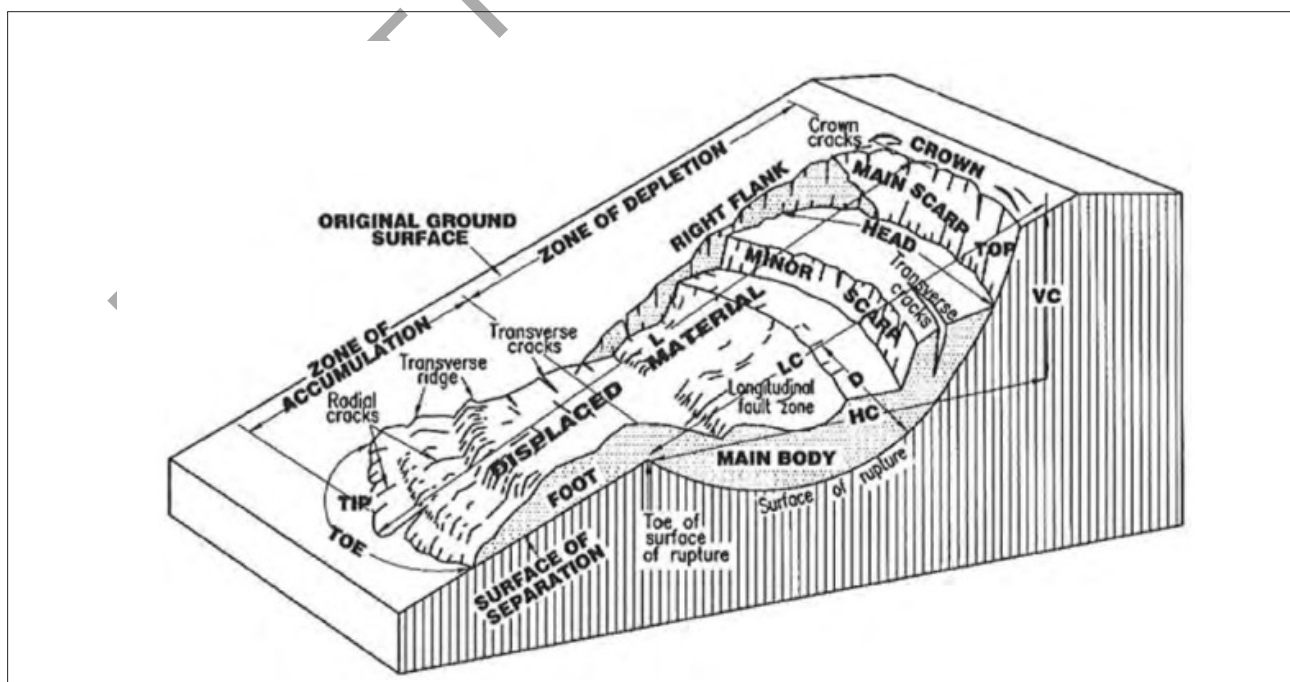


FIGURE 3: Idealised Landslide Components (Varnes, 1978). Definitions of the various components are given in Cruden and Varnes (1996)

TABLE 4: Typical landslide features and criteria for field recognition (de Vilder and Massey, 2024)

Landslide Features	Description of Features
Active Landslides (and recently active or dormant landslides)	
Landslide scar	Includes the source area and debris trail.
Source area	The area at the head of the landslide (zone of depletion) where the landslide mass (debris) is derived from.
Landslide debris	Material (rock, soil, vegetation) displaced from the source area and transported downslope by gravity.
Main scarp	The main scarp is the steep slope in undisturbed ground at the head of the slide (head scarp) – the visible part of the failure surface. Minor (secondary) scarps may be present within the displaced material of the landslide mass.
Tension cracks	Often located upslope of the landslide main scarp and tend to be aligned in an arc; can be continuous or discontinuous but are essentially linear. These indicate horizontal (pull-apart) movement but may also show vertical and shear movement.
Hummocky ground	Ground surface irregular, often formed of low-amplitude hummocks, resulting from differential (compressional and shear) deformations within the displaced material – a feature of many landslides (active and inactive).
Ponds (un-drained)	Ponds formed in depressions, which are often un-drained, are present within the displaced material of many landslides, especially at the slide head; they may be filled by seepage from springs or by rainfall.
Springs, seepages	Give rise to areas of swampy or boggy ground; seepage water may accumulate in ponds.
Trees with curved trunks or that are leaning backwards	Wind, snow loading, steep topography and ground movement can all give rise to non-vertical tree trunks, so care is required in their interpretation and additional supporting evidence of landslide movement is required.
Disruption of natural drainage	May be seen directly or inferred from seepages. Also, where landslide debris may have totally / partially blocked a drainage line or where the drainage line has been forced to alter its course.
Cracking to structures and paved surfaces and dislocation of drainage structures	These can also be related to local settlement of fill and foundations so additional supporting evidence is required, e.g. presence of source areas / landslide debris, tension cracks, trees leaning backwards.
Relict Landslides (inactive old landslides with little potential for reactivation)	
Relict landslides typically have eroded, rounded, and subdued features, with no sharp features or bare scarps visible. The main scarp is generally eroded and well-vegetated. The displaced landslide mass often has ponds and hummocky and irregular ground. Generally, no cracks or indications of movement are visible. Trees and established vegetation show no evidence of tilting, non-vertical trunks or disturbance.	
Typical Erosion Features and Geomorphic Landforms	
Erosional river terraces. River / stream banks and bed, and water-eroded rills and gullies formed on slopes and other geomorphic surfaces by rapid runoff during rainstorms. Steep cliffs along streams, rivers, glaciers and the shores of lakes and coastal areas are also erosion features formed by progressive erosional under cutting and collapses of these over-steepened slopes.	

2.2.1 Slides

As described in Unit 1, slides are mass movements occurring on a surface of rupture or a distinct zone of intense shear strain (the basal shear surface) that separates the sliding mass from the more stable underlying material. In some cases, there will be clear side shears also. The shape of the rupture surface allows slides to be categorised into:

- Rotational slides that occur along a curved or spoon-shaped surface. Back-tilting may occur near the scarp of the landslide and there is often a toe of displaced material.

- Translational slides, in which the sliding mass moves along a relatively planar surface with little to no rotation or backward tilting. A block slide is a translational slide in which the moving mass consists of a single block, or a group of semi-intact or closely related blocks, moving downslope as a relatively coherent mass.

In slide-type landslides the head area is commonly extensively cracked with a steep, bare headscarp that is concave towards the slide and the evacuated area is defined by well-developed flank scarps (side shears) decreasing in height toward the foot. Striae,

if present on the flank scarps typically have a strong vertical component near the head and strong horizontal component near the foot. The slide debris may be higher than the original ground surface in the accumulation zone between foot and toe. En-echelon cracks outline the slide mass in the early stages of its development.

Soil slides: The slide mass includes remnants of the original land surface and is flatter than the original slope or even tilted upslope creating depressions at the foot of headscarp and / or internal scarps in which ponds may form. The slide mass is characterised by transverse cracks, minor scarps, grabens, and displaced blocks. Trees, if present, may lean uphill.

Rockslides: Sliding failures in rock occur when the controlling geological structure (bedding, foliation, shear or joint) is adversely oriented to the slope. The debris material is blockier than in soil slides and does not deform plastically. The slope behind the head scarp is likely to show loose rock as well as defect-controlled cracking between blocks.

2.2.2 Flows

Flows typically comprise a gravity driven, fluidised mass movement that involves significant internal distortion of the displaced material. Flows are typically elongate (their length is much greater than width) and may be either confined in a steep stream channel, or unconfined on an open slope.

Flow type landslides commonly display a head area that is concave towards the slide with little or no upslope cracking. In gully flow types, the scarp may be nearly circular, with the slide debris issuing through a narrow orifice before flowing down the stream to spread out in a lobate form when the velocity reduces.

Debris flows comprise a very rapid to extremely rapid surging flow of saturated debris. Debris flows are commonly caused by intense surface-water flow resulting from heavy rainfall, leading to the erosion and mobilisation of loose soil or rock in gullies on steep slopes. The debris generally extends out onto the valley floor to form an alluvial fan. Refer Unit 6 of the Slope Stability Guidance Series for more detail.

Earthflows constitute flow-like movement of 'earth'. This type of landslide usually moves on moderate slopes, under saturated conditions.

Rock avalanche (dry material) are a rapid, massive, flow-like motion of fragmented rock from a large rock slide or rock fall (Hungr et al, 2014). They typically display an irregular surface of jumbled rock fragments sloping down from the source region and generally extending far out onto the valley floor.

In contrast, **debris avalanches** comprise very rapid to extremely rapid flow of partially or fully saturated debris on a steep slope, without confinement (Hungr et al, 2014).

2.2.3 Falls

Falls consist of rapid movement of material that becomes detached from steep slopes or cliffs. Separation occurs along discontinuities such as fractures, joints, and bedding planes, while the movement occurs by free-fall, bouncing, and rolling.

Falls are usually of a small volume (a few individual blocks) that travel only a short distance below their source. Fallen material forms a heap of rock or soil next to the headscarp.

Rockfalls: The landslide body forms an irregular surface of jumbled rock, sloping away from the scarp. If the rockfall is large, the debris may contain depressions, and the toe area will likely be an irregular pile of debris or talus. Depending on slope height, angle and surface characteristics, individual rock blocks may bounce or roll for a considerable distance downslope, particularly when earthquake-induced.

Soil falls: Detachment of soil fragments or blocks of cohesive (cemented or unsaturated) soil. Fallen material forms a heap adjacent to scarp with an irregular surface.

2.2.4 Topples

Topple failures involve the forward rotation and movement of a mass of rock, earth or debris out of a slope. This kind of slope failure generally occurs around an axis (or point) at or near the base of the block of rock.

A topple often results in the formation of a debris wedge or debris cone at the base of the slope. New talus cones are unvegetated; old talus cones can have weeds and even trees growing on them.

Rock slopes: Toppling failures can occur in both natural and cut slopes in rock with regularly spaced fractures or bedding planes that strike parallel or subparallel to the slope, and dip steeply into the face. Toppling may be either **flexural**, where the rock mass deforms in a plastic fashion by bending and forward rotation on closely spaced defects, or **block**, where the stability of thicker, rigid rock blocks is governed by defect orientations (see Figure 2.5 in Unit 1 and Figure 14 in Unit 3). Rock topples tend to leave unstable overhanging bluffs above the fallen rock blocks and may demonstrate a sawtooth shaped slope behind the head of the slope.

Soil slopes: Toppling failure can be recognised in a number of soil types along near-vertical slopes, for example along riverbanks, in weakly cemented soils, and in loess.

2.2.5 Spreads

This form of landslide is characterised by lateral extension and accompanied by shear or tensile fractures and usually occurs on very gentle slopes.

In soils, failure may be caused by liquefaction of susceptible soils, usually triggered by a strong ground motion from high magnitude earthquake events (lateral spread), as occurred in several areas of Christchurch following the 2010 - 2011 Canterbury Earthquake Sequence.

When coherent material overlies liquefiable material, the upper unit may undergo fracturing and extension and may then subside, translate, rotate, disintegrate, or flow.

2.2.6 Creep

Creep is an imperceptibly slow, downward movement of soil or rock. Movement is caused by shear stresses sufficient to produce permanent deformation, but too small to produce shear failure.

As described in Unit 1, the two main types of creep failure are:

- **Shallow (soil) creep** that is evidenced by terracettes roughly along the contour on the ground surface. It commonly affects only the top 0.5 m of the soil profile (Selby 1993). The creep rate is commonly a few centimetres / year but can develop into shallow failures (earth flows) as a result of extreme rainfall.

- **Deep-seated gravitational slope deformation (DSGSD)** is creep of rock masses, typically controlled along bedding, foliation, or low angle shear zones. Movement rates can be imperceptible without monitoring.

As Deep-seated gravitational slope deformations (DSGSD's) may displace rock volumes of up to hundreds of millions of cubic metres, with thicknesses of up to a few hundred metres, and can have major engineering implications. Well documented examples are found in the Cromwell Gorge upstream from the Clyde Dam.

DSGSD typically display persistent linear morpho-structural features (trenches, scarps and counter scarps, double ridges, elongated depressions) in their upper-slope sectors, indicating a predominantly extensional regime. Compressional features (toe bulging, variably fractured rock masses) and minor secondary landslides are often associated with the lower slope sectors of DSGSDs.

2.3 ROCK SLOPES

Figure 4 illustrates the most common types of rock slope failures. The features of these failures can also be described using some of the descriptive terms (such as head scarp, displaced material, toe) applied to soil slope failures, although the nature of these features is likely to be somewhat different in rock slopes. Further information regarding rock slope failures can also be found in Unit 3 (NZGS, in prep.).

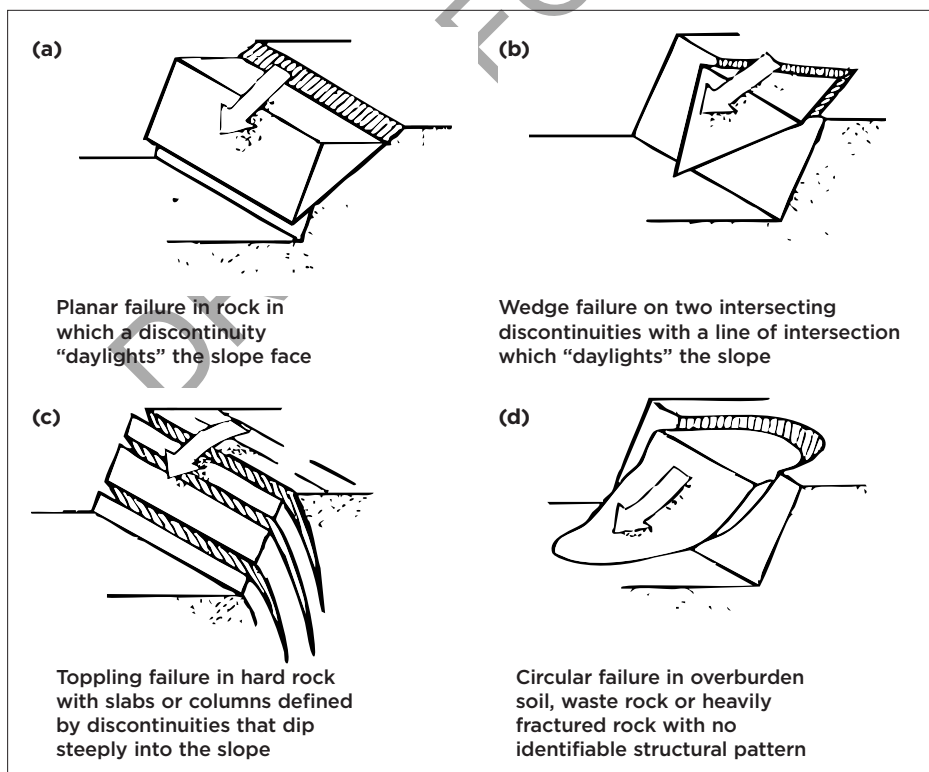


Figure 4: Common types of rock slope failure (Hoek & Bray 1977)

2.4 RECOGNITION OF POTENTIAL LANDSLIDES

Recognising the potential for future instability in construction and development works is discussed in Part 3 of Unit 1. The potential for future instability in natural and modified slopes must also be considered as part of an investigation programme. In addition, the run out and potential impacts of any neighbouring landslides should be considered. The importance of recognising the potential for landslides is further discussed in Section 3.1 of this Unit.

Table 5 below summarises the evidence to identify potential landslides. This includes geomorphic features and the characteristics of the surrounding area. The potential trigger events must also be considered. Some areas may also have readily available landslide susceptibility maps and landslide inventories (e.g. by a local authority).

Geological structures and rock weathering may play a key role in the potential for landslide initiation and further development. Steep slope angles, rugged

topography and erosion at the toe of the slope all contribute to the potential for the formation of a new ('first time') landslide.

2.5 IMPORTANCE OF SURFACE CRACKING

Surface cracking is one of the most important pieces of evidence for recognising and classifying landslides in the field and can also be one of the first signs indicating where ground movement may occur (i.e. prior to slope failure). Figure 5 shows an example where surface cracks which were mapped prior to failure subsequently formed the lateral scarp of the landslide.

Surface cracking can provide important indicators of the style, extent, and direction of movement of the landslide. It is therefore important to develop accurate and detailed maps of surface cracking to help determine patterns and causes of movement, as well as landslide type, extent, and overall movement direction. The patterns of cracking may indicate multiple orientations of movement (e.g. localised movement, versus overall global landslide movement).

TABLE 5: Considerations for identifying potential future landslides

Characteristic	Soil slopes	Rock slopes
Past history	The area has a past history of landslides.	The area has a past history of rock falls or rockslides.
Topography (slope angle and aspect)	Slopes steeper than about 20° ³ and slopes facing the predominant weather direction may be more susceptible to instability depending on underlying geology.	Slopes steeper than about 35° ⁴ may be more susceptible depending on underlying geological structures. Slopes steeper than 60° are very likely susceptible to future instability.
Weathering	Area is weathered to residual soils or completely weathered rock.	Surfaces of joints or bedding weakness are highly weathered, commonly this can occur with a red-brown to yellow-brown staining.
Ground cracking or depressions	Depressions or cracking parallel to slope, arcuate cracks on slope.	Depressions or cracks aligned with defect sets; open apertures between rock blocks.
Surface features (vegetation, anthropogenic structures, etc.)	Deformation of structures, such as changes in cant of roads, or bowing of vegetation across the slope.	Root penetration visible through joints and defects within rockmass, deformation of surface structures.
Groundwater	Springs or seeps from slope or at toe.	Visible, flowing water along joints, shears or bedding fractures; springs or seeps.
Trigger	Rainfall, earthquakes, coastal / fluvial influences, compounding conditions.	erosion, wildfires, volcanism, anthropogenic
Modified hillslopes	Past modification of hillslopes, especially non-engineered fill slopes constructed pre-1960 lacked the same level of engineering input and testing available today.	Cut slopes constructed pre-1960 that lacked the same level of engineering geological assessment available today.

³ In particular geological settings, notably where low angle bedding planes occur within saturated mudstone or clays, movement can occur along sub-horizontal planes with slope angles < 10°.

⁴ In highly weathered rock slopes, where the predominant failure mechanism is a rock mass failure, the typical slope angle for landslide development may be close to that of soil.



FIGURE 5: Surface cracking mapped prior to failure (left), and the lateral scarp of the landslide at the same location of the mapped cracks following failure (right).

When mapping surface cracks it is important to record the orientation (compass bearing), length, aperture, and vertical offset (height or depth) of the cracks, as well as any notes which aid in the interpretation of the cracking. Where slickensides are observed (Figure 6), the compass bearing of these should be recorded as they indicate direction of movement. In addition to plotting the surface cracking on a map, creating sketches of the observed cracking patterns can also be useful for interpreting and communicating the data.

It is also useful to install labelled markers (e.g. survey pins, survey stakes, or dumpy pegs) either side of prominent surface cracks to enable consistent and

relatively precise manual measurements to monitor the development of cracks. Spray paint may be used to mark surface cracks for ease of mapping (Figure 7) and to allow for comparisons between site visits to see if new tension cracks have formed. For further information on monitoring of surface cracks refer to Section 6 of this Unit.

The sketches in Figures 3 and 8 show the common locations of surface cracking on landslides, and Table 6 provides a summary of common surface cracking observed in landslides. Table 3-1 of Unit 1 of the guidelines (NZGS, 2024) provides further comment on surface cracking for different landslide types.



FIGURE 6. Slickensides indicating direction of movement.



FIGURE 7. Marked up patterns of surface cracking and subsidence. Mapping the pattern of surface cracking and subsidence has clearly delineated the possible extent and head of potential future slope movement. Note: the road was closed at the time of the inspection.

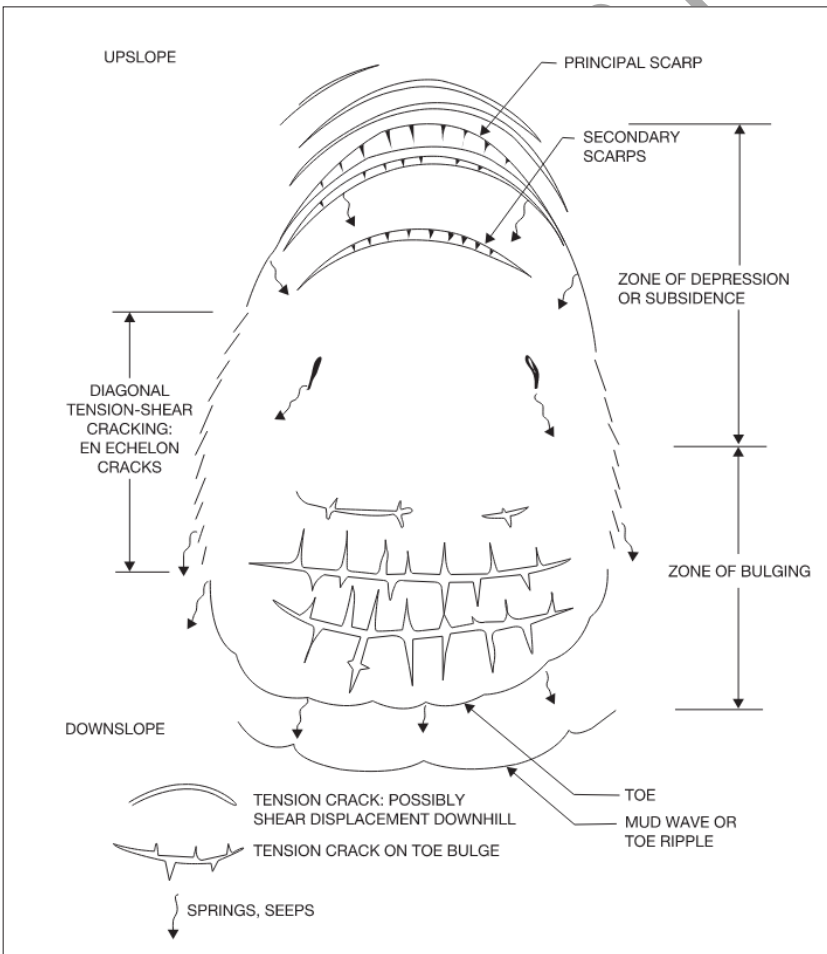


FIGURE 8. Sketch showing common locations of surfaces cracking on landslides (Griffiths, 2005)

TABLE 4. Common surface cracking resulting from slope movement


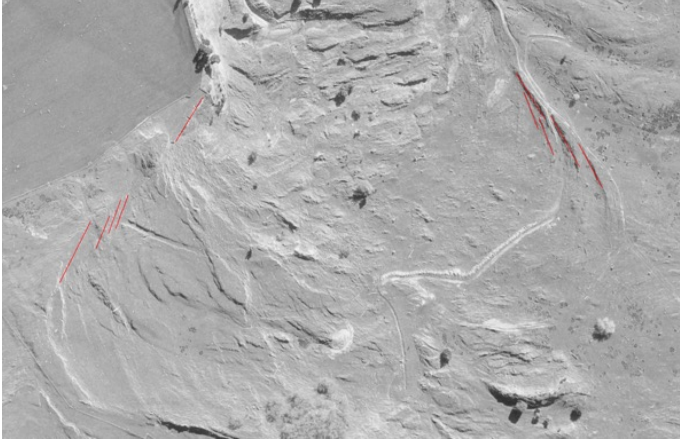
Feature	Description	Photo
<p>Tension cracks at or near the headscarp</p>	<p>Prior to landslide failure, tension cracks commonly develop at or near the location of the future landslide head scarp, and some tension cracks may develop into the headscarp (or secondary scarps) of the landslide.</p> <p>Commonly, surface cracks near the head of the landslide are oriented perpendicular to the landslide movement, therefore provide useful insight into landslide movement direction.</p> <p>In soil slides these cracks tend to be concave toward the slide, while in rock slides cracks tend to follow fracture patterns in the original rock. In block slides, crown cracks tend to follow the contour of slopes (Rib & Liang, 1978).</p> <p>Tension cracks behind the headscarp (referred to as 'crown cracks' in some literature) can indicate potential retrogression of the landslide upslope.</p>	 <p>Aerial photograph showing tension cracks near the headscarp.</p>
<p>En-echelon zones of tension cracks</p>	<p>Surface cracking along the sides of the landslide may initially appear as en-echelon zones of tension cracks, but these can develop into linear strike-slip fault like features as landslide movement progresses.</p> <p>These cracks generally delineate the flanks of a landslide, separating the moving landslide mass from the adjacent slope.</p>	 <p>En-echelon tension cracks, indicated by the red lines (source: RetroLens).</p>

TABLE 4. Common surface cracking resulting from slope movement (continued).





Feature	Description	Photo
Transverse tension cracks	<p>Transverse tension cracks may be observed in the body of the landslide, as well as the lower parts of the landslide. These cracks are often oriented normal with respect to landslide movement.</p> <p>In some landslides paired transverse tension cracks may define horst and graben features. Where graben features have formed, both sets of cracks will be vertically offset but one set of cracks will be facing downhill, while the other is facing uphill. A simple rule of thumb is that the distance between the downhill and uphill facing tension cracks, which define the width of the graben, provides an approximate indication of the landslide depth.</p>	<div style="display: flex; flex-direction: column; align-items: center;">    </div> <p style="text-align: right; margin-right: 50px;">ABOVE Aerial photographs showing transverse cracking.</p> <p style="text-align: right;">LEFT Historic aerial photograph showing evidence of relict transverse cracking from previous landslide movement (source: RetroLens)</p>
Radial cracks	<p>Near the toe of the landslide, radial cracks, approximately parallel to landslide movement, may be observed.</p>	<div style="display: flex; align-items: center;">  <div style="margin-left: 20px;"> <p>LEFT Aerial photograph showing radial cracking near the toe of the landslide. Photo by D. Townsend, courtesy of GNS Science.</p> </div> </div>

TABLE 4. Common surface cracking resulting from slope movement (continued).

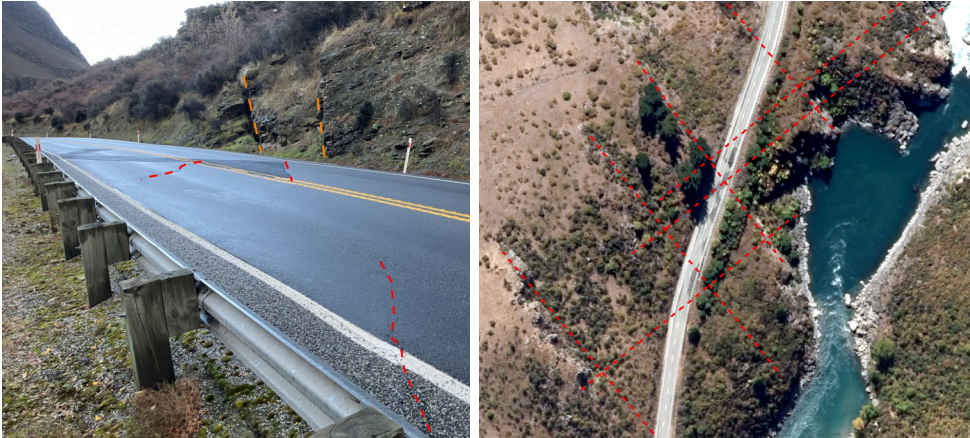

Feature	Description	Photo
Structurally controlled cracking along discontinuities (defects)	<p>Surface cracking can form along existing structurally controlled discontinuities (defects) in the rock mass, such as joints, bedding, foliation, and faults.</p> <p>Where this is the case, these can provide release surfaces for the landslide.</p>	 <p>Left: Cracking (as shown by the red dashed lines) along existing defect sets in the rock (as shown by orange dashed lines in the outcrop). The defects intersect with another defect set (as indicated by recent asphalt patching) to form a wedge failure. Right: Aerial view of the same site, with red lines showing approximate locations of the structurally controlled defects. Note the asphalt patches in the road lining up with defect orientations.</p>  <p>Surface cracking in the road aligning with near vertical defect in the road cutting.</p>

TABLE 4. Common surface cracking resulting from slope movement (continued).

Feature	Description	Photo
Cracking behind retaining structures	<p>Surface cracks or subsidence may be observed behind existing retaining structures. These could indicate slope movement due to distress or onset of failure of the retaining structure, and / or movement of the retaining structure due to global to landslide movement.</p>	 <p>Examples of cracking observed in the road behind retaining walls.</p>
'Stretching' around rigid bodies	<p>In some landslides 'stretching' of the ground surface can be observed surrounding a rigid body in the landslide, which can result in cracking or voids forming. Where observed this can be indicative of deep-seated slope movement (Ritchie, 1958; Rib & Liang, 1978).</p>	 <p>Stretching of the ground surface around a historic dewatering well. Landslide movement is to the left.</p>

2.5.1 Non-landslide related surface cracking

When mapping surface cracking it is important to distinguish landslide induced cracks from other cracks which are not related to landslide movement. Some examples of non-landslide related cracking are shown in Table 7. If there is any uncertainty regarding

whether cracks are landslide induced or not, it is recommended to map the cracks and note the uncertainty surrounding the origin of the cracking as well as any supporting information regarding the potential origin of the surface cracking.

TABLE 7: Examples of non-landslide related cracking


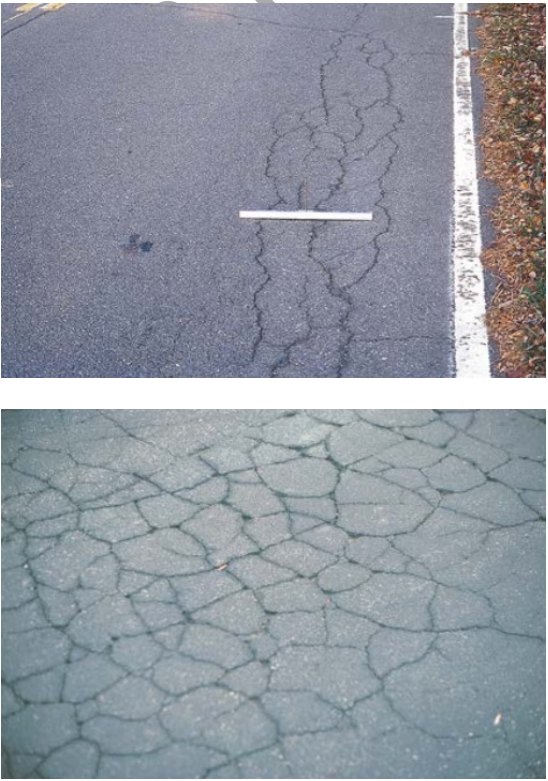
Feature	Description	Photo
Desiccation cracking	<p>Desiccation cracks can result from the drying out of surficial soils. These cracks are a drying-induced natural phenomenon which typically results in an interlocking pattern of cracks.</p>	 <p>Desiccation cracking in clay soils (Wei et al., 2020)</p>
Asphalt fatigue cracking	<p>Fatigue cracking can occur in pavements subjected to repeated traffic loadings and can appear as longitudinal cracks in the wheel path, or a series of interconnected cracks. The interconnected cracks can result in broken up irregular shaped pieces, which is referred to as alligator cracking.</p>	 <p>Fatigue cracking in asphalt (FHWA, 2014)</p> <p>Alligator fatigue cracking in asphalt (FHWA, 2014)</p>

TABLE 7: Examples of non-landslide related cracking (continued)

Feature	Description	Photo
Block cracking in asphalt	<p>Thermally induced block shaped cracks can form in asphalt.</p>	 <p>Block cracking in asphalt (FHWA, 2014)</p>
Agricultural drainage	<p>In order to drain fields with high groundwater, farmers sometimes install a series of subsoil drainage channels using a blade or plough (sometimes referred to as 'mole drains').</p> <p>These can appear similar to tension cracks. However, they can be identified by their linear and consistent nature, including even spacing between drainage lines (often 1-2 m).</p>	 <p>Mole drain installation (MSU, 2023)</p> <p>Mole drains, spaced about 1 m apart.</p>
Animal tracks	<p>When viewed on aerial or satellite photographs, or from afar on-site, well-worn animal tracks can at times be mistaken for surface cracking or shallow soil movement. Site inspections should confirm whether these features are indeed surface cracking, terracettes indicative of shallow soil creep movement, or simply well-worn animal tracks. Note that where terracettes are present, animals often take advantage of them, thereby creating animal tracks.</p>	 <p>3D model showing multiple animal tracks on the side of a slope.</p>

3 PRIMARY METHODS FOR LANDSLIDE IDENTIFICATION

The three primary techniques that form the starting point for investigation of actual or potential landslides are, in order:

1. Reviewing published information (including geological maps and sections).
2. Reviewing available aerial imagery and elevation data and determining whether additional aerial imagery or data collection is required.
3. Undertaking a site walkover and capture any additional aerial imagery required.

Techniques and methods used in the subsequent steps of investigating landslides, for example mapping, subsurface investigations, instrumentation and testing are discussed in later sections of this unit.

3.1 PUBLISHED INFORMATION

The desktop study and review of published information is an important first step in determining the likely presence of landslides within a region or site. It enables the geoprofessional to begin assessing the impact that landslide(s) may have on the project, and the degree to which each of the influencing factors outlined in the previous section may have contributed to the conditions which have allowed the landslide(s) to form.

This section outlines the common sources of information that could be considered and reviewed during the desktop study.

GEOLOGICAL SETTING – KNOW YOUR AREA

Geology significantly influences the types of landslides that may occur. Being knowledgeable about the local geology and resulting formations is essential for understanding the potential landslide types that could affect a specific location.

It is important that during the desktop study the wider potential for landslides to occur is considered alongside the site-specific assessment. In some situations, no landslides may be identified within a specific site, however, when examining the surrounding area other landslides may be identified in locations with similar characteristics to the project site. This may indicate that there is potential for a similar landslide to occur at the project site. In this scenario, a focus could be to determine why the slope within the project site has not failed, when compared to similar slopes within the wider area. In addition, the site may show no signs of local landslides but may sit within a much larger landslide feature, within immediate proximity of a landslide, or in the potential run out area of a landslide.

3.1.1 Key Sources of Information

There are a variety of sources that contain records of landslides and other information that can assist in determining the likelihood of landslide activity associated with the site. The common sources of information in New Zealand are presented in Table 8. Following a review of these sources and collation of relevant data to the specific project site, the EGM can further be developed to identify the key behaviours relating to landslide activity, as well as areas of uncertainty that require further assessment and investigation.

3.1.2 Limitations of Published Information

The use of published information for landslide recognition does have limitations. These include:

1. Available data may lack the level of detail required, may omit recent events and may not capture localised or small-scale occurrences.
2. Across the data sources there is a significant amount of variability in data quality that can affect the reliability of the information.
3. Published sources may not cover all relevant factors, like site specific topographic intricacies or human activities that may impact landslide activity.

To mitigate against these limitations, integrating diverse data sources, reviewing available aerial imagery and elevation data, as well as obtaining field observations is essential for a comprehensive and accurate landslide recognition approach. In some instances where data is conflicting, precedence shall be given to the most reputable and site-specific information, alongside careful judgement.

TABLE 8: Common sources of information relating to landslide investigations.

Source	Use	Access
Topographic Maps (NZ Topo Map)	<ul style="list-style-type: none"> - Topographic Maps are provided at a 1:250,000 and 1:50,000 scale for New Zealand, and in some areas including Auckland, a 1:25,000 series are available and can be obtained online through TopoMap or LINZ. - Topographic maps are useful for an initial assessment of high-level landforms and major lineaments. 	https://www.topomap.co.nz/
Geological Maps	<ul style="list-style-type: none"> - GNS provide 1:250,000 geological maps for New Zealand, and in some areas 1:50,000, which can be obtained online through GNS. Some other historic maps at other scales are also available through GNS. - Provide an overview of the geological setting, and mapped geological features (faults, folds, horizons, etc.). - Some large Quaternary landslides are mapped, however these are generally limited to landslides > 1.5 km in size. - If more information or detail is required, a view of the scanned maps which were used to create the geological maps, can be accessed using the link provided. 	https://data.gns.cri.nz/geology/ https://data.gns.cri.nz/metadata
New Zealand Geotechnical Database (NZGD)	<ul style="list-style-type: none"> - Database of existing ground investigation data which can be extracted and used to confirm local ground conditions and in some cases groundwater depths. 	https://www.nzgd.org.nz/ARCGISMapView/mapviewer.aspx
New Zealand Landslide Database	<ul style="list-style-type: none"> - Provides an overview of mapped landslides across New Zealand. - This database is still in development and may not hold all landslide information. - It is encouraged that any new landslides identified are loaded into this database for future use. 	https://landslides.nz/nz-landslides-database/
New Zealand Landslide Dam Database (NZLDD)	<ul style="list-style-type: none"> - Database of the mapped landslide dams across New Zealand 	https://slidenz.net/data-tools/
GNS Science Landslide Database	<ul style="list-style-type: none"> - Provides an overview of landslides which have been mapped by GNS Science across New Zealand 	https://data.gns.cri.nz/landslides/wms.html
Endeavour Landslide Programs (GNS)	<ul style="list-style-type: none"> - Several GNS led Endeavour programs, such as Earthquake-Induced Landscape Dynamics (ELID), the Hōretireti Whenua Sliding Lands program, and Landslide Watch Aotearoa, already have or will have, data, databases, models, and reports publicly available over the next few years. 	https://www.gns.cri.nz/research-projects/eild-earthquake-induced-landslide-dynamics/ https://www.gns.cri.nz/research-projects/sliding-lands/
New Zealand Active Fault Database	<ul style="list-style-type: none"> - Provides the mapped location of surface traces of onshore active faults at a scale of 1:250,000. This provides a high-level overview of fault locations, but in many cases is not suitable for a site-specific study. At this time of writing, GNS is working on a High-Resolution model at a scale of 1:10,000. This is currently available for select areas and provides an improved level of resolution and accuracy. - This information can be used to determine potential seismic triggers or correlations with previous events when reviewed against geomorphological mapping and historical imagery. 	https://www.gns.cri.nz/data-and-resources/new-zealand-active-faults-database/
Natural Hazards Portal (NHC)	<ul style="list-style-type: none"> - Provides a simplified overview of specific property information relating to natural hazards including landslides. - Provides access to EQC / NHC Claims Information for specific properties which can indicate if property (or surrounding properties) has been damaged due to previous landslides. 	https://www.naturalhazardsportal.govt.nz/s/
Published Reports	<ul style="list-style-type: none"> - Following larger landslide events, specific reports are occasionally generated (for example following cyclone Gabrielle 2023 for West Auckland, the Paekakariki Storm in 2003 or Whanganui Region in 2015). 	Various
Published research articles	<ul style="list-style-type: none"> - A search should be completed to see if any research articles have been published on the area of study, or the wider area of interest. These may provide insights about past events in the project area, the local and wider geology, geomorphology and groundwater conditions. 	Google and Google Scholar provide a starting point

TABLE 8: Common sources of information relating to landslide investigations (continued).

Source	Use	Access
University theses	- University research theses can also contain useful information pertaining to specific landslides or areas of study.	Various; may be identifiable using Google Scholar
Regional District Plans	- Larger landslides or areas of mass movement are sometimes included within District Plans, this can be used alongside other sources to identify either proximity to a known landslide, or alternatively similar conditions (topography, geology etc.) where landslides have occurred within the area. - It should be noted that if no landslide is marked on the district plan, that does not mean there is no landslide present.	Various
Local Council Databases	- Some local and regional councils may have their own hazard data layers, susceptibility maps, and landslide inventories accessed via their respective GIS viewer. Examples include CanterburyMaps or GWRC Wellington Region Earthquake Induced Slope Failure maps. - Some local councils also have records of historic (or recent) cut and fill slopes, or earthworks consents, which may be useful to identify significantly modified areas. - Councils may also commission landslide investigation or specific mapping studies relating to land movements, such as Christchurch City Councils 2013 Port Hills Mass Movement Area Assessments and Auckland Council Southern Landslide Zone.	Various (readily accessed by typing the Council name and 'GIS maps' into the search engine of your browser)
National Library & Papers Past	- The National Library contains multiple collections of digitised photographs, newspapers, books, magazines, and journals. - Papers Past is a database of the National Library containing digitised New Zealand newspapers, magazines and journals. - Can be used to search for historic landslide events to provide insight into magnitude and frequency of events.	https://natlib.govt.nz/ https://paperspast.natlib.govt.nz/
Archives NZ	- Archives NZ hold government records dating back to about 1840, including reports, official records, and photographs. Archives NZ hold many old DSIR and Ministry of Works reports and drawings. - Can be used to search for reports, investigations, designs, and events which may provide insight into historic landslides and historic works in the area of interest.	https://www.archives.govt.nz/
NIWA Historic Weather Events Catalogue	- Provides an overview of severe weather events recorded, and in some cases, records weather triggered landslides	https://hwe.niwa.co.nz/
Accident Registers (TAIC / CAS)	- If the site is adjacent or near road or rail, a review of the available accident registers can sometimes provide insight into landslide activity when resulting in a recorded accident.	https://www.taic.org.nz/inquiries https://spatial.nzta.govt.nz/portal/apps/webappviewer/index.html?id=5e2fde731ebe42f69d5d989d02ab1b41
GNS Shop	- Can purchase maps, publications, reports, and data sets held by GNS Science - Includes legacy publications and data sets from the DSIR, New Zealand Geological Survey, and Geophysics Division.	https://shop.gns.cri.nz/
Hazardous Activities Industrial List (HAIL)	- Used to determine if the landslide material may include or affect areas of contaminated land - this should always be checked before going to site to be more aware of the site hazards. - HAIL databases are held regionally and accessed via various council portals.	Various
Google StreetView and Argonaut Roadrunner	- If the project site is located along a road, reviewing current and historic StreetView and / or Argonaut Roadrunner images may provide information about the site development, past construction activities, and historic landslide activity.	https://www.google.co.nz/maps/ https://roadrunner.argonautltd.co.nz/
Before U Dig	- Similar to the above, it is vital that any mapped services are assessed, especially if any of these services may have been damaged as a result of any landslide movement.	https://www.beforeudig.co.nz/nz/home
Client information	- The client and / or landowner may have relevant data which is not publicly available. All available geotechnical data (and other relevant data) should be requested from the client. - Land Information Memorandums (LIM) and Building Consents may also reference landslide hazards specific to the property, these may be held by the property owner and / or local councils.	Client specific

3.2 REVIEW OF AERIAL IMAGERY AND ELEVATION DATA

The purpose of reviewing the available aerial imagery and elevation data is to further develop the conceptual engineering geological model by better understanding the observable landforms and changes to the site over time.

3.2.1 Key Sources of Aerial Imagery and Elevation Data

Aerial imagery and elevation data can come in many formats. Table 9 provides an overview of common sources of existing imagery and data that may be used.

3.2.2 Limitations of Publicly Available Imagery and Elevation Data

Publicly available aerial imagery and elevation data may have limited resolution for the particular project site, and although are collected relatively regularly, the imagery and data for the specific site and landslide behaviour may be insufficient.

These images and data offer valuable information for developing the initial conceptual engineering geological model and collecting site specific aerial imagery and elevation data is typically only necessary for more detailed site-specific assessments.

3.2.3 Site Specific Aerial Imagery and Elevation Data

The requirement for obtaining new site-specific aerial imagery and elevation data will likely be determined by the level of detail needed for the specific landslide assessment and based on the available aerial imagery.

The advancement in Unmanned Aerial Vehicle (UAV or drone) capability in recent years means

that these devices are now an essential tool for the geoprofessional, providing a means for the efficient capture of high-resolution aerial imagery and elevation data on-site. Partnered with developments in photogrammetry, the process of developing 3D Digital Terrain Models (DTMs) gives geoprofessionals much more data on which to base an interpretation of landforms and identify landslides and potential landslides. However, knowing what landforms to recognise and how these can be confirmed in the field remains an essential skill.

DRONE RULES

Currently UAV and drone operation is managed by the Civil Aviation Authority (CAA). Any person operating a UAV/drone must comply with all CAA regulations. In addition, there may be further regulation by the local council, infrastructure operators, and landowners.

It is the UAV operator’s responsibility to know and comply with all regulations.

3.2.4 Aerial Imagery Interpretation

Examples of common geomorphic features that can be identified in available aerial imagery and that may indicate landslide activity are shown in Table 10.

In addition to the assessment of landforms, aerial imagery can also assist in reviewing changes in land use, such as recent developments, construction or modification of infrastructure, incremental urbanisation, or vegetation coverage, all of which can impact the potential for landslides to occur.



FIGURE 9: (left) Aerial imagery available from Toitu Te Whenua Land Information New Zealand, compared to Google Earth (right), showing the difference in quality and resolution between sources.

TABLE 9: Common sources of aerial imagery and elevation data

Source	Use	Access
Google Earth	<ul style="list-style-type: none"> - Serves as a valuable tool for initial landslide identification within a designated area. - Provides good access to previous satellite imagery within recent (10-15 year) timeframes. - However, quality of photographs often fails to capture subtle details and important features crucial for precise analysis. - Factors like vegetation cover or small-scale changes in topography might not be adequately identifiable. - Therefore, while Google Earth imagery provides a useful starting point, it should be supplemented with higher-resolution data where possible. 	https://earth.google.com/web/
RetroLens (or similar)	<ul style="list-style-type: none"> - Valuable to review changes over time, considering some areas have imagery from as early as the 1930s. - These photos can provide a useful tool for assessing how landforms have changed over time, and to capture changes in land-use over time (e.g. progression and timing of developments, infrastructure, and pastoral). - Historical imagery was taken as overlapping images (stereo pairs) which can be viewed in 3D using a stereoscope or used to create anaglyphs (see below). - Resolution of imagery is limited and may miss subtle details and important features. Photos are not orthorectified, and not georeferenced (beyond the referencing for use in the search tool). 	https://retrolens.co.nz/
Land Information New Zealand (LINZ) Aerial Imagery	<ul style="list-style-type: none"> - Land Information New Zealand (LINZ) database contains most aerial imagery collected across New Zealand. Aerial imagery is frequently divided into rural and urban datasets, where urban datasets have a higher resolution (typically 0.05 - 0.10 m) compared to rural datasets (typically 0.2 - 0.5 m), but rural datasets have a generally wider geographical coverage. Photos in the LINZ database generally date back to the early to mid-2000s at the earliest. - Photos from LINZ database can be downloaded as orthorectified and georeferenced files, meaning the images can be readily imported into GIS and other software. They can often provide good resolution compared to google earth imagery to enable a more detailed review of landforms and features, an example is shown in Figure 9. 	https://data.linz.govt.nz/
Land Information New Zealand (LINZ) LiDAR / DEM	<ul style="list-style-type: none"> - Land Information New Zealand (LINZ) is currently capturing LiDAR for large parts of the country, and producing both raw data sets, and a 1m Digital Elevation Model (DEM). - This information can be useful to review landforms, especially in areas of heavy vegetation which may obscure subtle landforms. - The resolution is still rather coarse for a site-specific assessment but can form the basis of an assessment as well as a baseline for future monitoring. - The data can be imported into GIS and other software. - DEM's can be converted into hillshade models which allow the user to easily identify critical landforms on varying scales, which may otherwise be missed using just aerial photographs. 	https://linz.maps.arcgis.com/apps/MapSeries/index.html?appid=2552c3a5cee24f7b87806b085c3fee8a

TABLE 9: Common sources of aerial imagery and elevation data (continued)

Source	Use	Access
Regional (rural or urban) aerial imagery	- Councils may have their own aerial imagery databases within various GIS portals (e.g. CanterburyMaps). Some council GIS portals also provide ortho-rectified and georeferenced historical aerial imagery (aerial images sourced from RetroLens which are not ortho-rectified and not georeferenced).	Local Council GIS pages
Nearmap	- Nearmap is a paid service that captures and uploads aerial imagery across various locations in New Zealand multiple times per year. This is a paid service (cf. LINZ and Google Earth).	https://www.nearmap.com/nz
Stereopair Anaglyphs	- Using available stereopair imagery from various sources such as Retrolens, Council or historic Ministry of Works (MoW) held aerial imagery (currently held by WSP), can be turned into red / blue anaglyphs for 3D interpretation. - This use of stereopair anaglyphs can assist in viewing the terrain in 3D to identify large scale features (e.g. lineaments) and critical landforms, such as bulging or hummocky ground which would otherwise be missed in conventional methods (Buxton, 2021)	Various
LandSAT Imagery	- Provides moderate spatial-resolution (30 m) imagery that provides large areas of repeated data coverage at a scale to view overall landforms and land-uses, but not at a scale of individual landslide features - This imagery can be well integrated with GIS to monitor recent change over time of larger landform features, but is limited in the overall resolution	Various (e.g. https://earthexplorer.usgs.gov/)
National Library	- The National Library hosts a vast collection including the Whites Aviation Ltd photographs taken between 1907 and 1988. They give extensive coverage of NZ from the air and from the ground. The collection has about 80,000 images in total.	https://natlib.govt.nz/items?i[collection_any_id]=482467&i[-category]=Groups
Aerial Surveys	- Aerial Surveys, one of the suppliers of aerial imagery and LiDAR, have a library of imagery and elevation data that they have collected to date. The images and data can be requested through Aerial Surveys.	https://www.aerialsurveys.co.nz/services-1
OpenTopography	- Provides links to free publicly available topography data which can be imported into GIS and other software.	https://portal.opentopography.org/dataCatalog
Topographical Maps	- Provides contour data and an overview of landforms viewed at both 1:250,000 and 1:50,000. - In a few cases landslides and scarps are mapped, however in most cases landslides are not captured. - Large landslides can sometimes be identified by their anomalous topographic signature	https://www.topomap.co.nz/
SAR Imagery	- Open-source SAR satellite data for InSAR processing can be downloaded from the Alaskan Satellite Facility.	https://asf.alaska.edu/

TABLE 10: Common geomorphic features observed on aerial imagery that may indicate landslide activity






Feature	Description	Example Aerial Image
Bowl-shaped breaks of slope	<ul style="list-style-type: none"> - Circular indentations generally developing around natural flow paths - May have multiple steps within the break of slopes - Rounded and predominantly found in softer materials such as soils or completely weathered rock. 	
Scallop shaped escarpments	<ul style="list-style-type: none"> - Often made more obvious by downslope debris trails, indicated by lack of or younger vegetation growth. - Clear definition in change of slope around main scarp. - Cracking may be present around main scarp - Can be found anywhere on slope, generally closer to ridge lines or if mid-slope will occur within drainage flow paths. - Indicative of earth material (weathered rockmass or soil). 	
Depositional fans	<ul style="list-style-type: none"> - Occur at the base of the slope, generally where a river meets a body of water or where a stream debouches onto flatter ground such as a river terrace. - Can provide insights into debris flow potential, based on quantity of material, grading, and distance from expected source. - Vegetation coverage and variation can indicate frequency of events. 	
Steep slopes	<ul style="list-style-type: none"> - Generally easier to identify in DEM or LiDAR data and can easily be cross-checked with topographic maps. - Identified in aerial imagery by limited vegetation and outcropping of underlying geology. - Generally found in the upper reaches and higher (relative) elevations. - Localised steep slopes may be harder to identify in aerial imagery. 	

TABLE 10: Common geomorphic features observed on aerial imagery that may indicate landslide activity (Continued)

Feature	Description	Example Aerial Image
Cracking	<ul style="list-style-type: none"> - Depending on the scale and age of cracking may be hard to identify in aerial imagery. - Misinterpretation often associated with animal tracks associated with grazing. - Cracking may form part of other geomorphic features. - Often only visible where vegetation cover is low and cracking is relatively recent at the time the imagery is captured. - Requires verification during site walkover. 	
Hummocky ground	<ul style="list-style-type: none"> - Indicated by uneven or irregular surface. - Deformations may be erratic and uncoordinated - Can be a feature of active or inactive landslides - Can be blocked by dense vegetation 	
Natural ponding	<ul style="list-style-type: none"> - Most obviously identified by ponding water. - Generally forming in depressions within the slope. - In some cases may provide indication of the level of groundwater level, discharge or slope saturation. 	
Landslide Debris	<ul style="list-style-type: none"> - Generally observed adjacent to larger landslides. - In coastal or river environments may indicate relatively recent activity. - Can be verified on-site as well as by review of DEM / LiDAR data. - Deposited as a mass of rock, soil and or vegetation. - Indicated by a displacement of material from a source area. - Larger deposits can result in disruption (damming) or alteration (deviations) of natural drainage pathways. 	

3.2.5 Elevation Data Interpretation

At some sites, there will be a suitable resolution of digital elevation data available, but in some cases the complexity and size of the project necessitates the capture of digital elevation data. Digital elevation data can be captured using a range of methodologies, including LiDAR (often completed using either a fixed wing aircraft, helicopter or in specific cases UAVs), laser scanning or photogrammetry. The method chosen is dependent on project requirements; more detail is provided in Section 4.3 of this document.

3.2.6 InSAR

3.2.6.1 Principles

Spaceborne Interferometric Synthetic Aperture Radar (InSAR) is an active remote sensing imaging system that monitors surface deformation on a cm to mm scale accuracy (Hu et al. 2014). By comparing the phase component of repeated SAR acquisitions over the same area, at different times (Figure 10), maps of range changes between the ground and the satellite at spatial resolutions of metres to 10’s of metres can be assessed (Simons and Rosen 2007). For landslide monitoring, this data provides a great way of understanding spatial extents and rates of movement.

3.2.6.2 Advantages and Applications

Spaceborne SAR imaging systems offers advantages which can be used to compliment traditional *in situ* based ground measurements, such as:

1. It is designed to be able to detect slow continuous surface displacement with up to millimetre precision on a regional scale.
2. It is most effective in detecting slow landslide processes moving at slow to very slow (< 1.5 m/year to 15 mm/year) to extremely slow (< 15 mm/year) velocities (as defined by Hungr et al. 2014).
3. It can survey remote sites and wide areas affected by landslides without putting people or equipment at risk and provide preliminary results to help target specific areas for further investigation.
4. It can provide a time series analysis of ground displacement. It can detect signs of slow deformation prior to failure, making it useful for predicting landslide events.

Figure 11 displays an example of an InSAR data set focusing on the Tahunanui Slump in Nelson, using Sentinel-1 data. This urban landslide is ideal for InSAR due to its slow movement and numerous coherent targets, such as buildings. Its westward slope

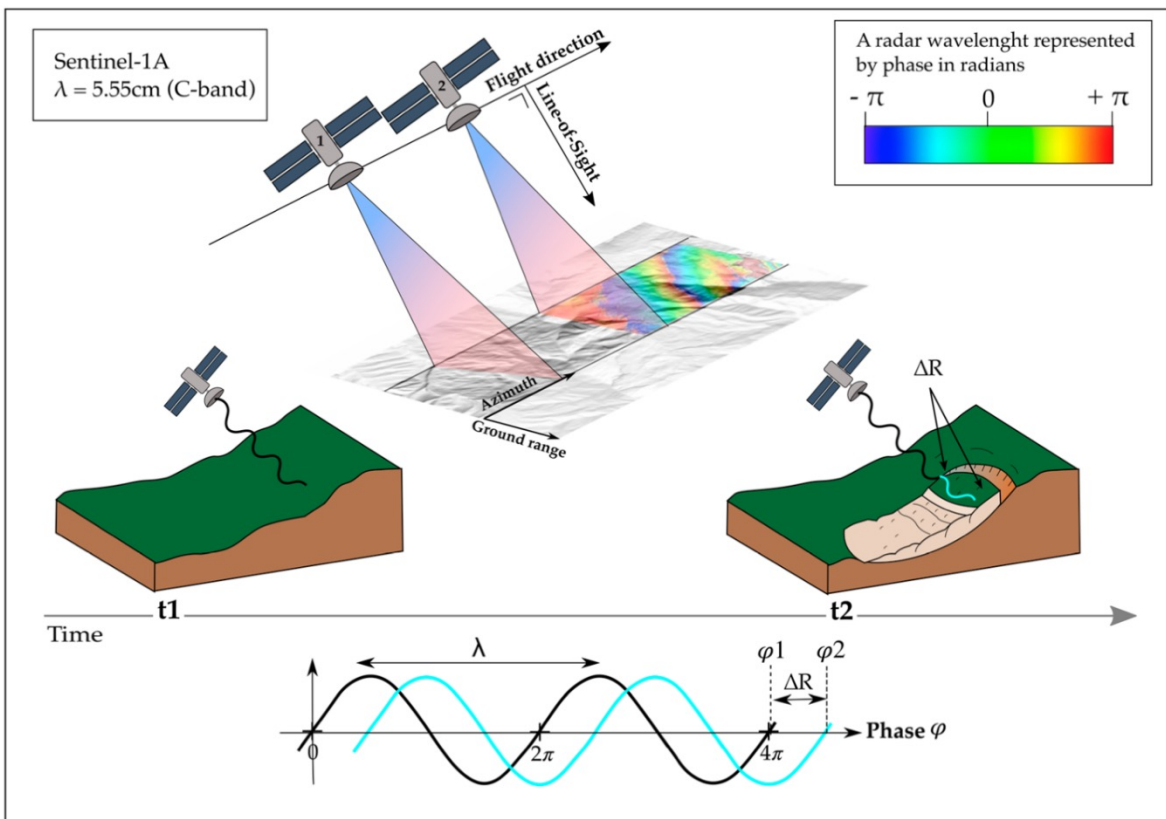


Figure 10: Principles of InSAR used for landslide mapping using the D-InSAR method showing the repeat pass method (t_1 and t_2) of the satellite over the same area before and after a landslide activation (from Piroton et al. 2020).

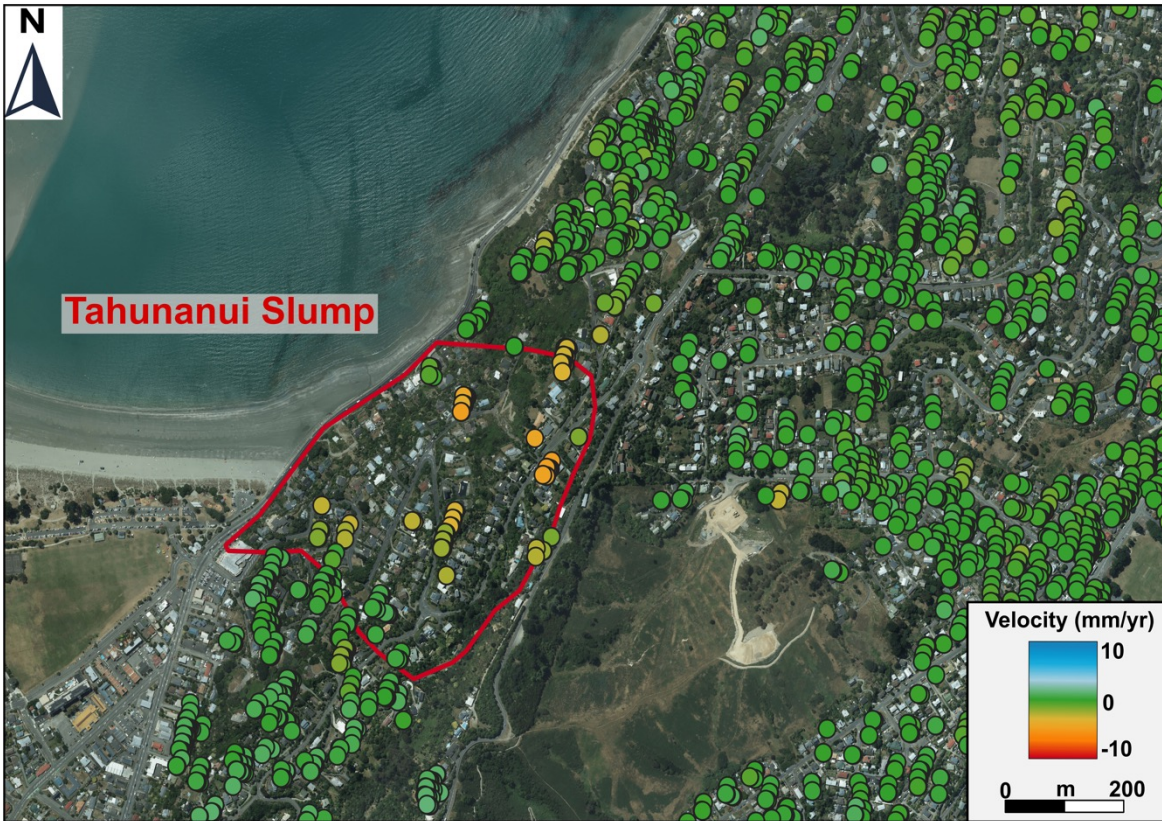


FIGURE 11: Outline of the Tahunanui Slump in Nelson with InSAR data showing the average velocity of each point (mm/yr). The data contains Sentinel-1 images from 2014-2024. Negative values (orange red) indicate movement away from the sensor (downslope) and positive values represent movement towards the sensor (blue). Figure courtesy Tonkin + Taylor.

displacement aligns well with the line-of-sight of the sensor. Most SAR sensors, with their right-looking sensors and near-polar orbits, offer two distinct viewing geometries, ascending and descending (Moreira et al. 2013; Qin et al. 2020). Ascending orbits are suited for eastward movements, whereas descending orbits, which are ideal for the Tahunanui Slump, favour westward movements. The Taihape landslide, documented by Haghshenas Haghghi and Motagh (2016), is another example of using InSAR to observe slow-moving landslides in New Zealand.

3.2.6.3 Limitations

Although InSAR can be an effective tool for landslide detection and analysis, it also presents some limitations which can lead to the under-estimation of the actual number of active or dormant landslides in an area (e.g., Bayer et al. 2018). These include:

1. InSAR measures displacement in the direction of the line of sight (LOS), which means there is a low sensitivity to any movements that are perpendicular to the satellite line of sight (Colesanti & Wasowski 2006). In the case of most operational satellites, this means that landslides with a strong north-south direction of movement will be challenging to detect.
2. Rapid movement such as earthflows and small-scale landslides can be challenging to detect depending

on the satellite’s spatial and temporal resolution (Rosi et al. 2017).

3. A low density of coherent targets will be acquired over tree covered or bush clad areas, especially with shorter wavelength SAR systems.
4. As with most remote sensing datasets, the spatial resolution of the SAR satellite will limit the size of a landslide that can be detected. For Sentinel-1, the pixel size is approximately 5 m in E-W and 20 m in N-S, and if a landslide occupies a small number of pixels, it can be indistinguishable from localised background noise (Xu et al., 2021), (Wasowski and Bovenga, 2014).
5. InSAR only records a 1D displacement in the satellites’ line of sight (LOS) and is only a relative measure of the ground displacement.
6. While noise contained within the measured interferometric phase (e.g. atmospheric, topographic, and other noise components), is mostly removed during the processing of the interferograms, the processing method, filtering and other parameters will impact the LOS displacement results.
7. Computation of InSAR time series is time-consuming, requires large amounts of data storage and data procurement can be costly. Processing and interpreting the data require specialised expertise and software.

3.2.7 Aerial Imagery and Elevation

Data Reporting

The interpreted features and information need to be clearly reported and referenced so that the findings can be clearly communicated to, and understood by, other geoprofessionals, engineers, clients, and stakeholders. Commonly an assessment of aerial imagery and elevation data is summarised on an annotated image and included in the corresponding memorandum or report.

3.3 INITIAL SITE WALKOVER (SITE RECONNAISSANCE)

An essential part of any landslide investigation is the initial site walkover. The intent of the initial site walkover is to gain an appreciation of the following:

- **Scale** – often being present on-site gives a better spatial appreciation for the landslide and landforms.
- **Context** – checking the spatial context of the different features and landforms to one another, and nearby assets (property, infrastructure, services, etc.).
- **Water** – the presence of water can often be overlooked during the desktop study. This may be due to the seasonal or climatic variability when information is captured. During the site walkover, locations and volumes of water discharge if this is occurring can be recorded. It is also important to record the current and antecedent weather conditions when on-site, as this may impact the presence of water observed (i.e. ponding, ephemeral streams, erosion etc.).
- **Change** – a key aspect of ground-truthing will be confirming if the geomorphological features identified in desktop assessment are still present, and importantly recording any changes observed. This will provide valuable information, especially if the latest aerial imagery available is not recent.
- **Engage** – one of the most overlooked parts of a field inspection is engaging with the local landowners and / or stakeholders. They will likely be able to provide some key insights into areas of movement, where water flows in heavy rain, and historical events.

Landslide initial walkovers may be undertaken for different reasons. They may be because landslides have affected a commercial, industrial or property development and they are assessed for insurance, safety, or long-term stability purposes. Initial site walkovers may also be required for assessing the impact of landslides on future development (i.e. at site feasibility or resource consent stage). In other cases, they may be required to assess landslide impact on residential and private properties, in particular for insurance claims under the Natural Hazards Insurance Act or Earthquake Commission Act.

THE IMPORTANCE OF COMMUNICATIONS

A landslide can wreak havoc on property, health, and finances, evoking a spectrum of emotions in affected individuals. Property owners may grapple with anger, fear, or frustration. Geoprofessionals tasked with assessing landslide risks must balance empathy with safety concerns while gathering crucial information. Empathy involves understanding the homeowner's perspective and demonstrating respect for their unique situation. While geoprofessionals should listen attentively, they cannot address all homeowner concerns and may need to refer landowners to appropriate agencies, such as Civil Defence, NHC and their insurers for assistance.

Providing resources like contact information for relevant agencies can aid homeowners in navigating the situation.

If at any point the geoprofessional is concerned about their own safety, they should leave site and arrange for further support.

3.3.1 Preparing for the Site Walkover

Before undertaking an initial site walkover, there are a number of preparations that will make the limited time available on-site as productive as possible. Some of the common tasks in preparing for a site assessment include completing a desktop study (see Section 3.1 to 3.2 of this Unit), making sure the required tools and equipment are available, land access is arranged, and that the weather is appropriate for the required site work. For more information about each of these items refer to Section 4 of this Unit.

Some key questions to consider when preparing to go to site include (Griffiths, 2005):

1. What is the distribution of existing landslides at the site?
2. Is the area prone to landslides, what are the likely controls for landslide formation in the area, and where are landslides likely to occur?
3. What is the potential for first time failures or reactivation of existing landslides?
4. What are the likely consequences or impact of landslides?
5. If there are existing landslides at the site, what is the cause, and are they likely to reactivate?
6. What are the groundwater conditions?

Being properly prepared for site and reviewing what could be encountered will also better highlight any hazards that need to be captured and managed in the health and safety documentation for the site, which is discussed in the following section.

HEALTH AND SAFETY AROUND LANDSLIDES

The following section outlines general guidance only and this document nor any associated party does not take any responsibility for the reader to comply with the Health and Safety Work Act 2015 (or later revision at the time of use).

All works associated with landslide assessments must comply with the Health and Safety Work Act 2015 (or later revision at the time of use). This is most relevant during the site walkover phase where there are generally more hazards present that require active management and mitigation.

A geoprofessionals input to the health and safety documentation prior to any site walkovers will often be captured in the form of a Safe Work Methodology Statement (SWMS) or Job Specific Assessment (JSA), essentially a document capturing the site-specific hazards and control measures required to ensure the risk is managed adequately. In the case of site walkovers for landslides some areas for consideration include:

- **GEOTECHNICAL HAZARDS** – in several cases the landslide area to be inspected will pose a hazard, this may be in the form of continued landslide movement, rockfall, and / or unstable ground.
- **STEEP TERRAIN** – as landslides are more common in steeper terrain, access and inspecting landslides may include traversing steep, uneven ground with the risk of falls. If a slope is steep enough that a fall would result in continued uncontrolled movement, it is likely that roped access or other fall prevention measures is required.
- **TRAVEL** – in most cases travelling to and from site will present hazards generally associated with driving, stopping and working on or adjacent to a highway. This is more significant for remote areas where distances and times may be greater. Remoteness of the site may also be a hazard.
- **BURIED SERVICES** – being aware of any buried services, or processes to deal with unexpected or discovered services should be considered.
- **CONTAMINATION** – this can be in the form of being within a HAIL site, or near geological material that can pose a risk to health, such as Uranium.
- **CULTURALLY SENSITIVE AREAS** – Consideration should be given to the wider cultural landscape a landslide site has occurred. There may be culturally sensitive areas within a landslide site, which may include valuable material entrained within a landslide. Contacting local Iwi should be considered when addressing landslide remediation or clearance.

3.3.2 Field Interpretation

During the initial site walkover stage of a landslide assessment, there are three categories to consider: *features, characteristics, and elements at risk (i.e. roads, property, etc.)*. The features are what can be observed on-site, and the characteristics are used to interpret the behaviour of the landslide.

Further to the outline provided at the start of Section 2, interpreting the following features on-site can provide valuable insights into the landslide's behaviour and type.

- **Geomorphology** – landforms can provide the first tell-tale signs to indicate the scale, speed and direction of landsliding. Landforms include overall slope geometry, cracking patterns, and the development of bulging or hummocky ground. The geomorphological features can be used to identify the likely type of landslide movement.
- **Geology** – understanding the underlying geology, including geological units, structures, and bedding orientations, is critical to understanding the landslide.
- **Vegetation** – vegetation can be used to interpret landslides in multiple ways. In areas of dense vegetation, historic landslides can often be identified by areas of younger vegetation compared to the surrounding slope; this may allow estimation of the return period of a landslide event. In addition, older vegetation such as trees can be used to identify slower creeping landslides, observed by bowed trunks; the severity of the 'bowing' can provide an insight into the speed and direction of the landslide. Vegetation changes are also a good indicator of changes in soil moisture content and saturated soils. Patches of bright green grass compared to surrounding browner grass can also indicate water seepage or saturated ground.
- **Human Activities** – a human-made structure may be present within or adjacent to the landslide area. This may vary from a simple farm fence through to a building or linear structure, such as a road or kerb. Deformation of these structures can often provide insight into landslide movement.

For more information about what information and features to record on site, refer to Section 4 of this Unit.

Understanding the characteristics of the features associated with a landslide include:

- **Velocity** – the velocity of a landslide will vary depending on a number of different factors and may vary over time, ranging from a slow creeping landslide moving mm/year to rapid rockfalls travelling at m/s. Landslide velocity classes are provided in Figure 2.13 of Unit 1.
- **Scale** – the landslide may occur over a localised area or cover a much wider area; there may be different scales of landslide within a single site, with small debris flows occurring within a larger rotational / translational slide.
- **Direction** – not always as simple as “downhill”; understanding the direction the landslide is travelling is key to understanding the risk to any associated assets. Geomorphology and subsurface geology can complicate this when flows or falls are directed away or sliding occurs along a dipping bed or plane resulting in oblique movement.

Collation of the information gathered on the site walkover supports development of the conceptual

engineering geological model further and communication of landslide risk. There are several ways in which site walkovers can be reported, however site mapping is generally considered the best form as it allows features to be spatially represented and forces the geoprofessional to consider the inter-relatability of their observations in the field. An example from an initial site map, produced during the site walkover is shown in Figure 12.

3.3.3 Common Misinterpretations on site

Landslides can be very complex, and it is possible that at some point misinterpretation of the data or site mapping observations will occur in the assessment. Some common features that could arise in misinterpretations are listed in Table 11.

In most situations, it is the ground truthing stage of this initial site walkover where misinterpretations from the data and imagery reviews become apparent, which is why the walkover is so critical in developing the engineering geological model. Even so, misinterpretations and / or uncertainty may carry through, so it is crucial that the model and failure mechanism of the landslide are continually challenged, considered and validated as discussed further in the following sections of this document.

TABLE 11: Common misinterpretations on-site.

Feature	Misinterpretation and cause
Non-critical cracking / cracking unrelated to landslide movement	Not all cracking is landslide related. Crack patterns that are not related to landslide movement, can for example include desiccation cracking or localised settlement. Occasionally animal tracks can appear as cracking during aerial imagery review. For more information see Section 2.5.1 of this Unit.
Seepage/springs and unrelated ponding	Water seepage may be the result of broken services. This may still be important to understand but may change the interpretation around natural drainage pathways and groundwater depth. Ponding of water, either within ephemeral or low gradient drainage, may also be due to poorly performing stormwater drains or small-scale agricultural dams.
Retaining wall bulge	Possibly localised due to poor or no drainage behind the structure, especially older retaining walls, which may be unrelated to landslide movement.
Extents	Often the vertical and lateral influence of a landslide will be different than initially assessed; be open to adjusting the landslide footprint
Rates of movement	Determining the rate of movement is very challenging and in different landslides may vary based on several factors. Past performance is not always an indicator for future behaviour

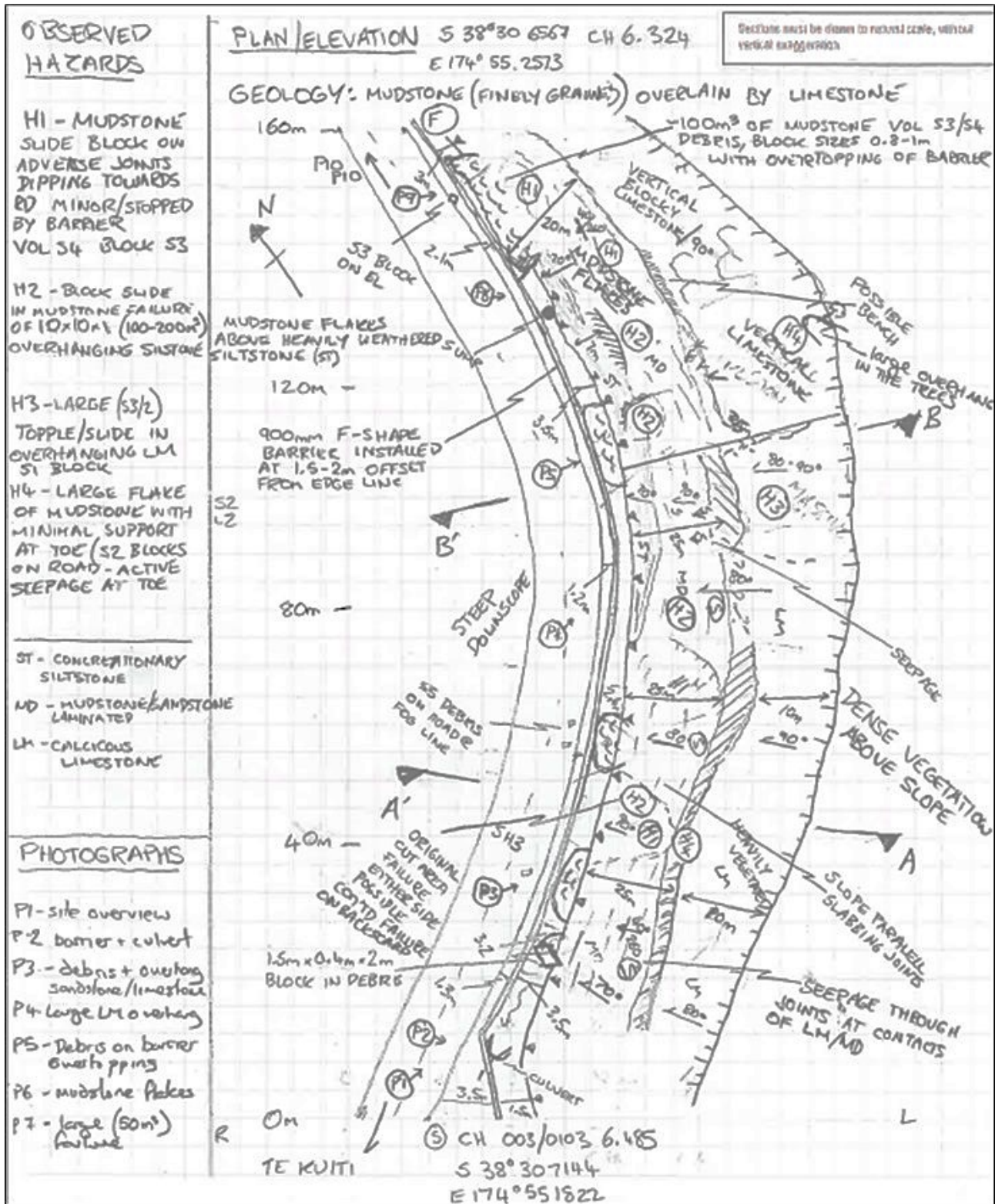


FIGURE 12: Initial site map produced during the site walkover.

PART 3

STAGE 2 INVESTIGATIONS - SURFACE AND SUBSURFACE INVESTIGATIONS, INSTRUMENTATION AND MONITORING



PART 3: STAGE 2 INVESTIGATIONS - SURFACE AND SUBSURFACE INVESTIGATIONS, INSTRUMENTATION AND MONITORING

The primary methods described in the previous sections of this Unit are referred to as **Stage 1** investigations. Stage 1 investigations form the basis for

- Scoping and planning surface and subsurface investigations and slope monitoring schemes to support the engineering analysis and design that follow.
- Generating the conceptual engineering geological model of the site, as defined by the IAEG Commission 25.

The surface and subsurface investigations and slope monitoring schemes form the **Stage 2** investigations, which help develop the conceptual engineering geological model to an observational one and are discussed in the following sections.

4 SURFACE INVESTIGATION METHODS

Topography can provide indications of potential, and / or existing instability. Accurately evaluating the surface characteristics of a landslide helps to a large degree understand the likely subsurface characteristics. As noted in Unit 1, this is typically done by using a combination of aerial photographs and satellite imagery followed by a ground survey, and drone survey (if appropriate).

4.1 ENGINEERING GEOLOGICAL MAPPING

This section outlines the preparations required to complete engineering geological and geomorphological mapping, the information and features which should be recorded and mapped, the level of detail and accuracy to consider when producing maps, and how to illustrate maps. For the purposes of this document, the IAEG Commission C25 definition for engineering geological mapping is used (see text box below). Suggested mapping symbols are provided in Appendix A.

Engineering geological mapping forms a critical part of identifying and assessing landslides. The IAEG C25 guidelines (Baynes & Parry, 2024) describe engineering geological mapping as “the preparation of a map depicting the distribution and surface boundaries of engineering geological units, geological structures, geomorphology and hydrogeological conditions that are of significance to the project, using appropriate symbology and carried out at a scale and level of detail determined by the purpose of the mapping.”

4.1.1 Purpose(s)

The primary purpose of the data collected during the mapping is to assist development of the engineering geological model. It may also be used, if required, to determine the locations of targeted ground investigations (where each location has a clear purpose) and to support the development of hydrogeological and other geotechnical models and engineering designs. In some cases, the map may also be required to support consent application requirements.

4.1.2 Preparation

Prior to going to site, a desktop study comprising a review of published information, aerial photographs and available elevation data (as is summarised in Section 3 of this Unit) should have been completed. In certain situations (e.g. emergency call outs) it may not always be possible to complete a full desktop study, however a basic review of the published geology, aerial photographs, and elevation data should always be completed prior to starting the mapping.

When preparing to go to site, having the right equipment available is critical. Collecting and recording the mapped information can be completed in a number of ways, but generally the following equipment is considered to be required for all mapping: (i) GPS, (ii) geological compass (with the correction for the local magnetic declination applied, or remember to apply the correction to the measurements when back in the office), (iii) tape measure, (iv) geological hammer, (v) camera, (vi) hand lens, (vi) a putty knife for cleaning outcrops, (viii) a suitable basemap for recording the data, and (ix) a notebook.

Additional tools to collect the data frequently include: (i) UAVs to take up to date aerial photographs and collect up to date elevation data, (ii) laser range finders for distance and angle measurements, (iii) tablets for recording the data electronically, as well as (iv) spray paint, survey pins, and survey stakes (or dumpy pegs) to install manual monitoring markers across surface cracks.

4.1.3 Information and features to record

An overview of what information to map and record is provided in Table 12. If there are additional features that are important to the site, but not listed in the table below, these should be recorded. GPS locations should be recorded for all relevant data points, and for linear features multiple GPS points along the feature may be required. During the mapping the geoprofessional should record any elements that have been affected by slope movement or are at risk of being affected by slope movement.

When mapping features associated with slope movement, it is important to distinguish whether they are associated with active or ongoing movement or result from historic movement. Features resultant from recent or ongoing movement are generally sharp and unvegetated. Conversely, features derived from historic movements, with little to no ongoing movement, will generally become increasingly rounded and more vegetated with time. For example, the presence or absence of vegetation can provide evidence as to whether a tension crack has formed recently or historically (a fresh face without any vegetation would be expected for a recently formed tension crack).

In addition to the features noted in Table 12, aerial photographs and up to date topographic data should be collected using a UAV if possible and must be appropriate to the scale of the project. The aerial photographs and topographic data can then be used to develop an up to date orthorectified photograph and digital elevation model of the site, both of which can support the development of the geological map (e.g. by providing an up-to-date aerial photograph as the basemap for the final publication). For further detail see Section 4.3.

MAPPING EXTENTS

The mapping should extend beyond the site itself so that an overall understanding of the wider geological and geomorphological setting can be attained. It is important to recognise if the project site or landslide is in fact located within a much larger landslide (a small failure in an embankment or along a slope could be a precursor to larger scale landslide movement).

4.1.4 Level of detail to consider, accuracy of information and scale

- **Level of detail:** The map should provide the necessary level of detail to document the geology and geomorphology of the site or landslide, develop the engineering geological model, and, if required, to determine the locations of targeted ground

investigations. It is highly recommended to collect as much data in the field as possible. At times, detailed field maps may need to be simplified for clarity for the final publication or for use in consent applications.

- **Evolution of the map:** As the project progresses and more data is gathered, the map should continually be updated to record the new information and data, and to reflect the increased understanding of the site. As such, the level of detail of the map may increase over the project lifecycle.
- **Accuracy and precision:** The accuracy and precision of field measurements (e.g. locations of recorded features, orientations, distance / height measurements, etc.) is critical as these measurements form a key input to the engineering geological model, and may influence fundamental assumptions, as well as future analyses and design as the project progresses.
- **Scale:** The map should be completed at a scale appropriate for its end use. It is important to consider the scale that the map is being completed to, and the scale that any external inputs included on the map have been mapped at. Compatibility of scale is important, and if features from existing maps are being added to the project map, the geoprofessional needs to be cautious of the scale that these features have been mapped at and the associated limitations of using that data at different scales. For example, if geological units from a 1:250,000 scale geological map are added onto a 1:5,000 map for the project, this could lead to significantly inaccurate maps. The scale of any external inputs to the map, as well as any limitations, should be clearly documented.

4.1.5 How to illustrate the map

The engineering geological map should be shown on a suitable base map consisting of topographic contours, a hill shade digital elevation model, or an aerial photograph. The base map should include clearly annotated features (e.g. roads, power lines) which allow the reader to locate the site. An inset map showing the location of the site within the wider region may also be used. If using an aerial photograph as a basemap, the most recent photograph should be used, and the opacity of the photograph should be reduced to allow the mapped features to stand out.

As part of these guidelines, we propose that the mapping symbols attached in Appendix A are adopted for future projects in New Zealand to provide consistent maps which can be easily interpreted. Some of the map symbols shown in Appendix A are the same as those provided in the AGS (2007c) guidelines and the NSW RMS (2014) guidelines (which have been adopted by the NZ Transport Agency Waka Kotahi) to allow for consistency across commonly used guidelines in New Zealand.

PART 3 STAGE 2 INVESTIGATIONS

In addition to the appropriate mapping symbology, every map should, as a minimum, contain the following items:

- Legend, listing all symbols used on the map
- Title
- North arrow
- Scale (bar or clearly annotated for the page size)
- Source and date of the background image or topographic data

Examples of engineering geological maps are provided in Figures 13 to 15. The maps should be accompanied by cross-sections at representative locations, and a report which clearly communicates the interpretations made during the mapping.

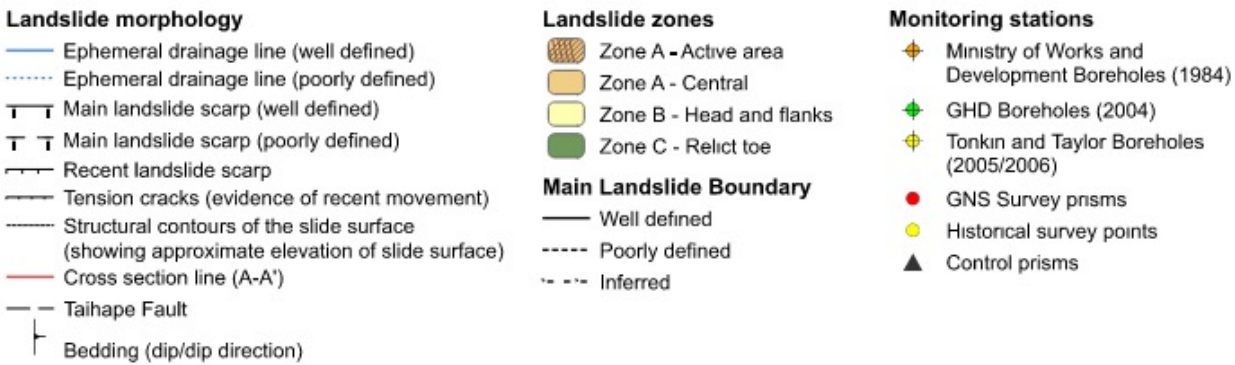
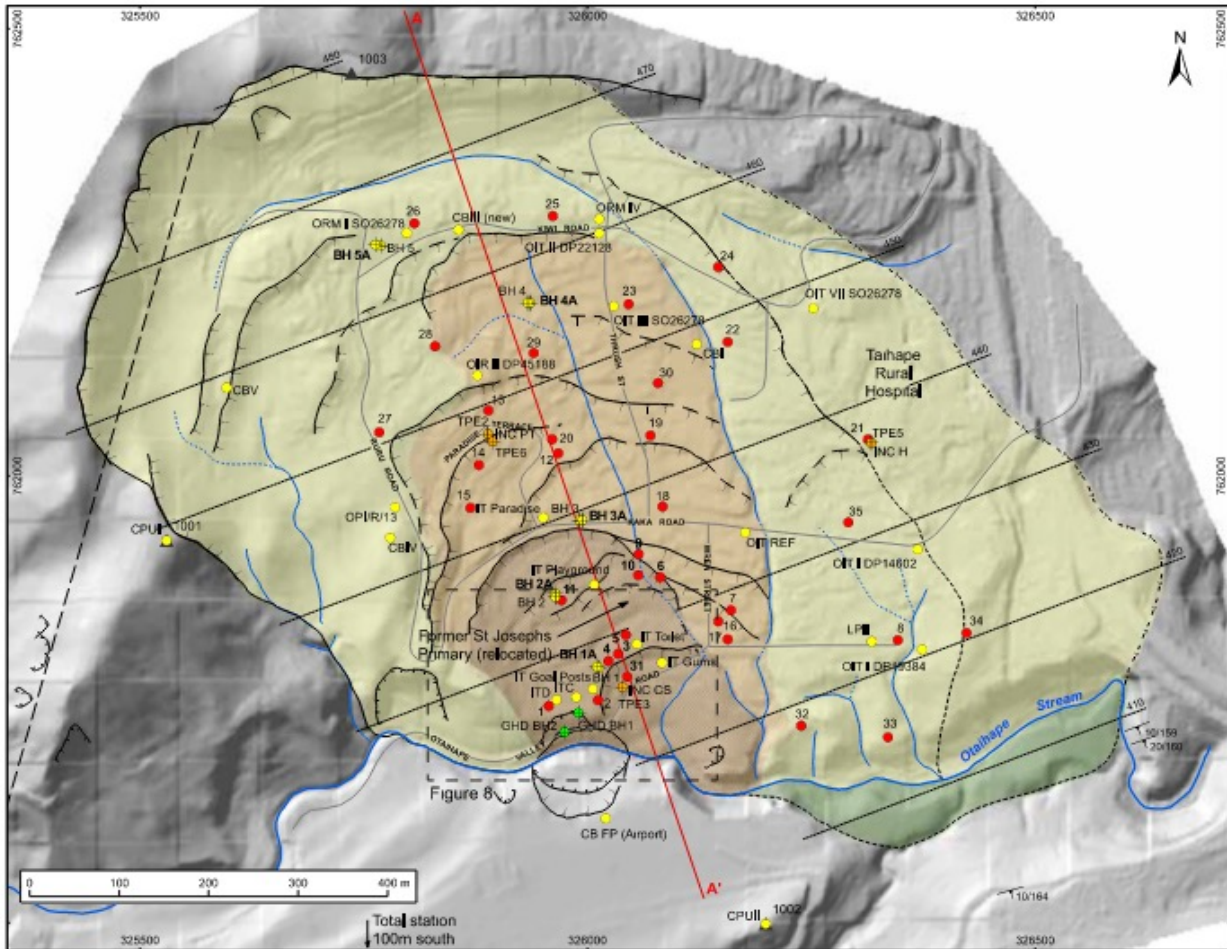


FIGURE 13: Engineering geological map of the Taihape Landslide, using a hillshade digital elevation model (generated from photogrammetry) as the background (Massey et al., 2016).

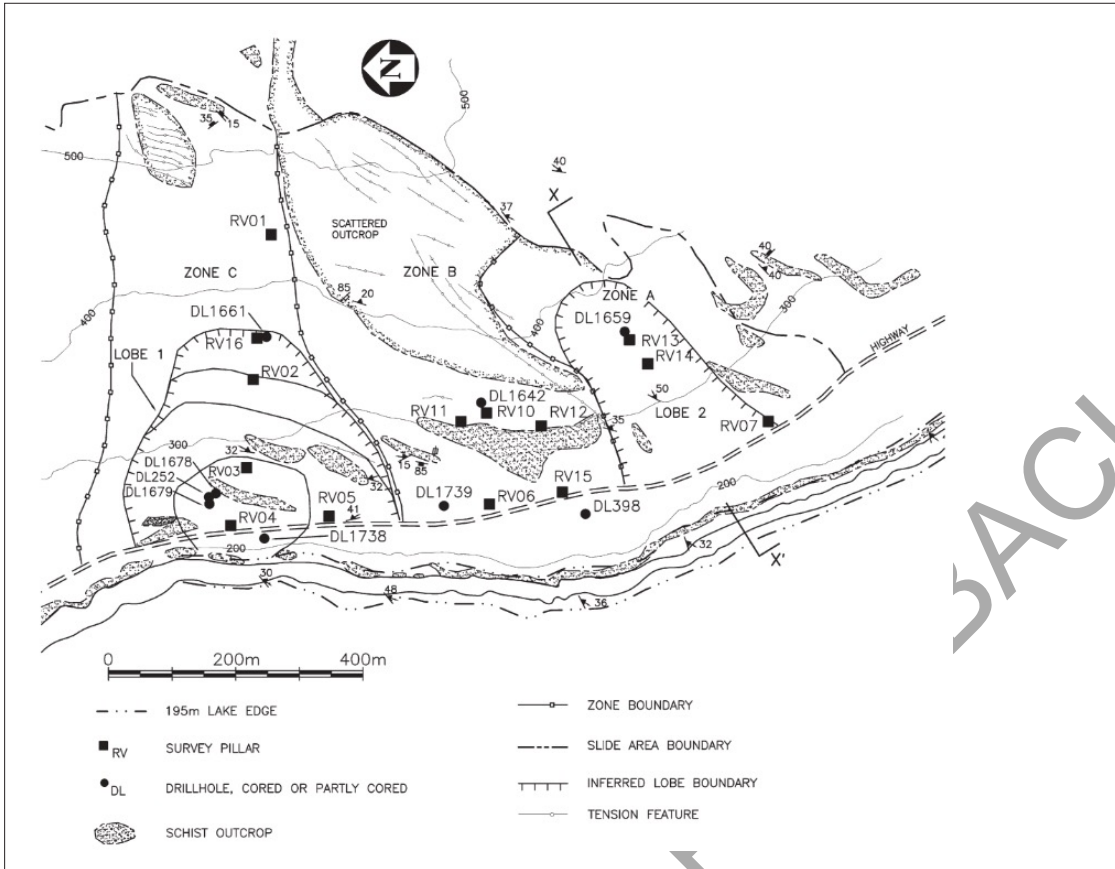


FIGURE 14: Geology and geomorphology of the downstream segment of the Ripponvale Landslide, using topographic contours as the basemap (Macfarlane, 2009).

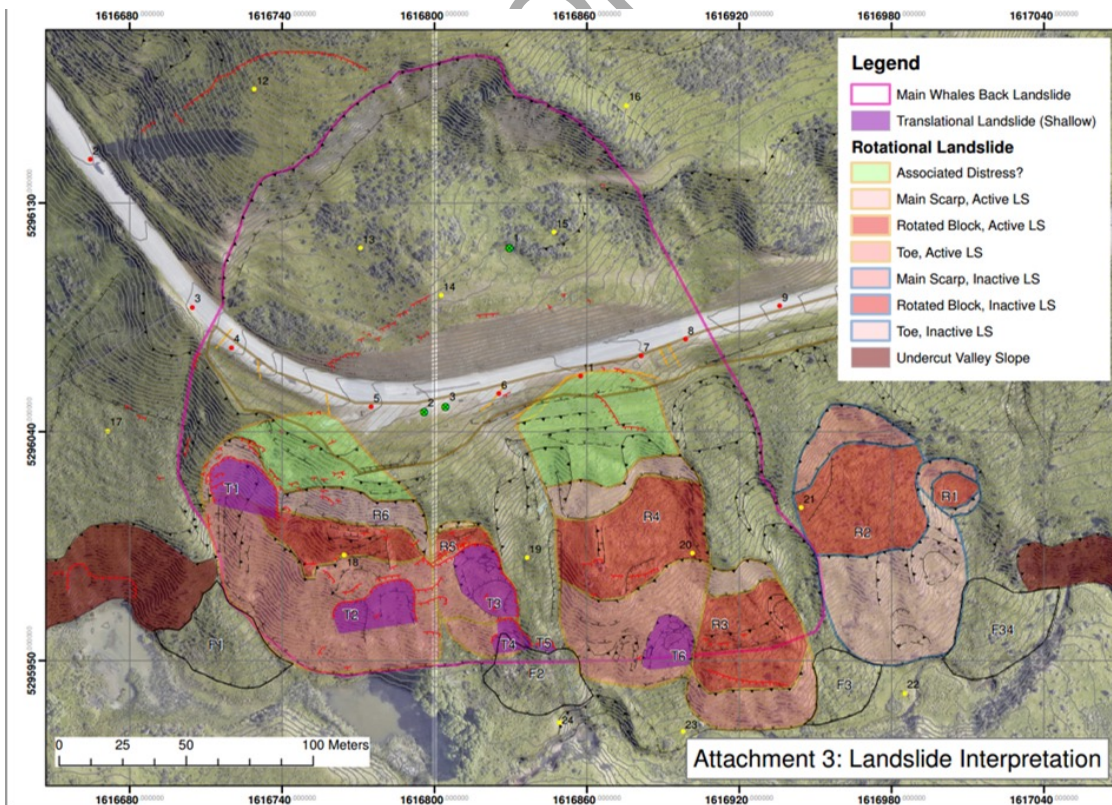


FIGURE 15: Engineering geological map of the Whales Back Landslide using an aerial photograph as the background (map courtesy of Steve Parry).

TABLE 12: Features to record for recognising landslides in the landscape and developing engineering geological map.

Type	Feature	What to record
Slope and landslide morphology	Areas of subsidence / settlement	Record any areas where subsidence has occurred. Map the shape, orientation, and vertical offset resultant from the subsidence. If known, note the cause of the subsidence.
	Alluvial fans	If present, map the location and extents of alluvial fans.
	Back-tilted slope faces	Record the location, length of slope, and compass bearing of back-tilted slopes faces or cracks. Also record the dip and dip direction of the face.
	Breaks in slope	Map any significant breaks in slope, including their dimensions and their general morphology, i.e. sharp or rounded, convex or concave.
	Bulging ground	Map any areas or sections of slopes where bulging ground is observed.
	Cracking	Map the length and compass bearing of the cracks and record their aperture and vertical offset (height or depth). Map any changes in orientation of the cracks. It is important to distinguish landslide induced cracks from other potential cracks not related to slope movement. Refer to the Surface Cracking section of this Unit for more information.
	Horst and graben	Map the location of horst and graben features. Record: - the strike (compass bearing), dip and dip direction of the cracks forming the horst and graben feature - the width and depth of the graben, as well as height and width of the horst.
	Hummocky terrain	Hummocky terrain is often associated with landslide movement. Map the area of hummocky terrain observed. Consider mapping the footprint and heights of individual hummocks if required.
	Landslide runoff extent	If mapping post-failure, map the extents of the landslide runoff.
	Modified (cut / fill) slopes	Map the locations of modified slopes. Measure dip angle and dip direction of the slope, as well as compass bearing of the slope.
	Ridges and gullies	Map the locations of ridges and gullies, including their length and compass bearing.
	Scarps	Map the location, length, and compass bearing of scarps. Record the vertical offset and depth (if it extends below ground), dip angle and dip direction of the scarp, and orientation of slickensides (if encountered). Log the exposed soil or rock in accordance with NZGS (2005) guidelines. Note if the scarp or landslide flank is structurally controlled.
	Slope shape (convex / concave) and angles	Record the shape of the slope (convex or concave), slope angles, and if there are any significant changes in slope angle or shape.
	Soil creep	Map areas of shallow soil creep.
Stepped morphology (benches and terraces)	Map the locations and size of benches / terraces, slope angles between benches / terraces, and compass orientation of the features. Record the likely origin of the stepped morphology (e.g. landslide movement, river terraces, etc.).	
Voids/sinkholes/tomos	Map the locations of voids / sinkholes / tomos, including their size, shape, depth.	
Geology	Soil and rock descriptions of outcrops	Where outcrops are observed, log the exposures in accordance with the NZGS (2005) guidelines, and map the geological unit. Note whether the outcrop is <i>in situ</i> or displaced (e.g. rafted block).
	Structural geology	Where exposed record strike and dip measurements of features such as bedding, defects / joints, foliation, and faults. Where slickensides are exposed measure the compass bearing of slickensides. Consider if the strike and dip measurements of bedding are in accordance with the regional strike and dip of bedding. If this is not the case, it can potentially indicate that the outcrop is not <i>in situ</i> and that past landslide movement has occurred.

TABLE 12: Features to record for recognising landslides in the landscape and developing engineering geological map (continued).

Type	Feature	What to record
Surface and groundwater	Sources of water (springs, seeps)	Map the locations and elevations of springs and seepages. Record the water flow rate from the spring and whether the spring is ephemeral or permanent. Note whether multiple springs / seepages are found along a similar elevation, or along a geological feature (e.g. bedding or faults).
	Ponds and stagnant water	Map areas where water is ponded, the extent of the ponded area, and the elevation. If possible, note whether the pond is due to natural processes unrelated to landslide movement, landslide movement, or anthropogenic activities.
	Streambeds, streams, and rivers	Map locations of streambeds, their channel width and record whether they have flowing water in them or not. If the streambed does not have surface water flowing, note whether the ground is dry or wet. If the stream / river has flowing water, record the approximate water levels and flow rates / velocities (if possible).
	Drainage pattern, including modifications	Map the overall drainage pattern through the site. It is important to record the source of the water. Record if the drainage pattern has been altered or disrupted, either by natural processes (e.g. faulting, landslide movement), or by anthropogenic activities (e.g. farm pond, drainage channels, culverts, etc.). Record the diameter, length, orientation, material, and condition of any culverts observed.
Vegetation	Leaning or rotated vegetation	Map vegetation that is leaning or rotated and note the direction of the lean or rotation. Note if tree trunks are curved near their base, which is indicative of past slope movement.
	Hydrophilic ('water-loving') vegetation and swampy ground	Map areas of swampy ground or areas that have hydrophilic vegetation (e.g. rushes), which could be indicative of shallow groundwater, springs, or stagnant / disrupted drainage.
	Disrupted or irregular vegetation patterns	Map any areas of disrupted or irregular vegetation patterns.
Structures and infrastructure	Retaining structures and their condition	Map all existing retaining structures, and record the type, dimensions (including retained height), and condition of the retaining structure (e.g. good working order, bulging, leaning, etc.).
	Surface structures and their condition	Record any relevant or significant structures, and their condition (are they showing signs of deformation or distress). Examples could include leaning power poles, cracks in building walls or foundations, displaced fences, structures showing signs of settlement, etc. Record all relevant measurements (e.g. the tilt angle and direction of a leaning power pole).
	Subsurface structures (including services) and their condition	Record the locations of subsurface structures, their dimensions and construction material (for pipes), and their approximate orientation (some this information may be obtained in the field, e.g. by lining up manholes, or from a Council GIS website during the desktop study - see Section 3 of this Unit). It is important to record if these structures cross the landslide, particularly if they pass below surface expressions of landslide movement (e.g. subsidence, cracking, scarps, etc.), as this could indicate that the subsurface structures have also been impacted by landslide movement. If subsurface structures are affected by landslide movements this could have implications for landslide stability (e.g. leaking water services) or public safety (e.g. gas pipes or powerlines). Record any signs indicating the condition of subsurface structures.
	Infrastructure	Map the surrounding infrastructure (e.g. roads, rail, footpaths, bridges), and record any signs of movement.
Land use	Current and historic land use	Map and record any evidence of current and historic land use which may be relevant (e.g. past quarrying / mining, gravel extraction along the river, evidence of sidcast fill placement during road construction, etc.).

4.2 MAPPING OF DISCONTINUITIES ALONG ROCK SLOPES

Where a project involves assessments of rock slope stability, the geoprofessional should, in addition to the items discussed in Section 4.1 and Table 12, map the rock slopes and discontinuities along these rock slopes in detail to help determine whether the slopes could be subject to kinematic instabilities. Discontinuities along a rock slope are commonly mapped using the following methods:

- **Scanline surveys:** This method involves laying a measuring tape along the outcrop and measuring and describing all discontinuities which cross the measuring tape using a geological compass.
- **3D point clouds:** This method involves capturing a 3D point cloud of the slope(s) being mapped using terrestrial or airborne remote sensing techniques (e.g. laser scanner, UAV photogrammetry, or a UAV mounted LiDAR unit). For reliable discontinuity mapping a high-resolution point cloud is required. Following the data collection and post-processing, discontinuities can then be mapped and measured using either manual, semi-automated or automated methods in computer programs.

Table 13 summarises the advantages and limitations of both methods.

TABLE 13: Advantages and limitations of mapping discontinuities along slopes using scanline surveys and 3D point clouds.

Method	Advantages	Limitations
Scanline survey	<ul style="list-style-type: none"> • Simple and inexpensive. Only a tape measure, compass and notebook are required. • No software required for picking defects. • Can be completed without a surveyor or survey equipment. 	<ul style="list-style-type: none"> • Restricted to areas of the slope which can safely be accessed on foot. • Potential for bias in discontinuity measurements and representation. May require adjustment for sampling biases. • Time consuming. • Manual digitisation of data required for inputting into software packages for further analyses and design. • Less safe for site personnel, as this method requires the geoprofessional to spend prolonged time at the toe of a slope. • Accuracy of the measurements is dependent on experience of the geoprofessional completing the measurements.
3D point cloud	<ul style="list-style-type: none"> • Reduced sampling bias. • Can capture significantly more data than scanline surveys, including sections of slopes which are inaccessible on foot. • Digital outputs which can easily be imported into other software packages for further analyses and design. • Safer for site personnel as this method does not require the geoprofessional to spend prolonged time at the toe of a slope. 	<ul style="list-style-type: none"> • Manual verification of some discontinuity measurements is highly recommended. • Data collection can be restricted by weather conditions. • Data generally needs to be post-processed by a surveyor, and a control survey (e.g. of ground control points) may be required. • Survey equipment can be expensive. • The survey may be restricted by access (e.g. some regions have restrictions on UAV use) • Vegetation cover or nearby buildings may obscure parts of the slope. • Detection of discontinuities can be limited by point cloud densities and corresponding minimum detectable volumes. These are dependent on the survey equipment and methodology. • Requires additional software packages for post-processing of the data and for picking / measuring the discontinuities.

References: Singh et al. (2023); Daghigh et al. (2022); Battulwar et al. (2021); Feng & Röshoff (2015); Wyllie & Mah (2004); ISRM (1978)

4.3 GROUND SURVEYS

Ground surveys are a critical part of investigating landslides, and may be required for:

- Providing up-to-date topographical data for the site, which can be used for mapping, development of the engineering geological model, analyses, and design.
- Accurate measurements of distances, heights and angles between points.
- Mapping the extent of the landslide(s), and accurately surveying the coordinates and elevation of important surface features (e.g. cracks, scarps, springs, etc.) and investigation locations.
- Monitoring of the landslide, including rates, patterns and directions of movement. This requires a 3D referencing system to establish ground control and a baseline survey against which future movements are compared. If it is known that ongoing monitoring will be required, the initial survey (if set up correctly) can serve as a baseline survey against which future monitoring can be compared. For more information regarding monitoring refer to Section 6 of this Unit.

There are various methods and techniques available for completing surveys, ranging in complexity, cost and accuracy. A summary of the commonly used methodologies, their advantages, limitations, and best uses is provided in Table 14. The table provides a guide to consider which survey methods may be required, but the geoprofessional should also seek advice from their survey team to confirm the correct methodology for their site and application.

TABLE 14: Summary of common survey methods, their advantages, limitations and best uses.

Method	Description	Relative accuracy	Absolute accuracy ¹	Advantages	Limitations	Best / Common Use
Pace / tape and compass / measuring wheel.	Manual measurements of distances using calibrated paces (i.e. calibrating paces of the person completing the survey against a known distance), or a tape measure, and a compass to determine direction.	Low to moderate	N/A	<ul style="list-style-type: none"> • Rapid production of an approximate map on-site. • Can be completed in any weather. • Can be completed by geoprofessional on-site. 	<ul style="list-style-type: none"> • Reliability can vary with experience and roughness of terrain. • Cannot be used to develop a topographic map of the site. • Cannot be used to determine the coordinates or elevation of locations / features in terms of a datum and projection. 	<ul style="list-style-type: none"> • Maps produced during initial site visits.
Laser distance measurement	Measurements with a handheld laser range finder to measure a distance and/or angle from the device.	Moderate	N/A	<ul style="list-style-type: none"> • Can measure the distance and angle to locations which are inaccessible on foot. • Can be completed in any weather. • Quick if only requiring a few measurement points. • Can be completed by the geoprofessional on-site. 	<ul style="list-style-type: none"> • Slow if needing a wide coverage of points. • Typically, cannot measure long distances (and devices for measuring long distances often cannot measure shorter distances). • Cannot be used to develop a topographic map of the site. • Cannot be used to determine the coordinates or elevation of locations / features in terms of a datum and projection. 	<ul style="list-style-type: none"> • Accurate distance and angle measurements when inspecting a slope or an inaccessible site.
Total station	Using a total station to measure specific points remotely and with high accuracy.	High	High	<ul style="list-style-type: none"> • Allows highly accurate and precise measurements of specific points (e.g. prisms, targets). • Fast if only a small number of accurate measurements is required. • Multiple connected setups will allow a high accuracy model to be developed. • Can be connected into the national geodetic database to get data in terms of a datum and projection. • If setup correctly (i.e. measurements locations at points of interest) can be used for monitoring going forward (see Table 25). • Can be used to complete a traditional topographic survey of a site. 	<ul style="list-style-type: none"> • Requires a surveyor on site to operate and process. • Only captures data for specific points, rather than data across the whole site (i.e. the surveyor has to pick up the correct points on-site). • All points captured need to be within line of sight. 	<ul style="list-style-type: none"> • High accuracy measurements of specific points on site. • To complete a traditional topographic survey of a site. • Ongoing monitoring of the slope or landslide.

TABLE 14: Summary of common survey methods, their advantages, limitations and best uses. (continued)

Method	Description	Relative accuracy	Absolute accuracy ¹	Advantages	Limitations	Best / Common Use
GNSS (Global Navigation Satellite Systems)	Various grades of Global Navigation Satellite systems devices, ranging from handheld to survey grade dual frequency receivers.	Low to high	Low to high	<ul style="list-style-type: none"> • Can be connected into the national geodetic database to get data in terms of a datum and projection. • Can measure specific points (that are accessible) quickly. • Can be used to complete a traditional topographic survey of an 'open sky' site. 	<ul style="list-style-type: none"> • Survey grade GPS requires either cell phone connection or a second base station setup to achieve high accuracy. • Requires the surveyor to physically access points needing to be measured. • High accuracy GNSS receivers require open sky to 'see' satellites. • Requires a surveyor on site to operate and process. 	<ul style="list-style-type: none"> • Can be used to complete a traditional topographic survey of an 'open sky' site. • Good for a small number of points over a number of sites.
Laser scan	Scanning instrument used to observe a full surface of data points. There is a range of different scanners available with different levels of accuracy.	Moderate to high depending on equipment used	Moderate	<ul style="list-style-type: none"> • Fast dense coverage of small to medium sized areas. • Scans of slopes can be used for defect mapping. • Can be connected into the national geodetic database to get data in terms of a datum and projection. • Allows repeatable scans of slopes which can be used for monitoring purposes. 	<ul style="list-style-type: none"> • Cannot penetrate vegetation. • Results in a lot of data, which can be time consuming to process. • Requires a surveyor on site to operate and process. 	<ul style="list-style-type: none"> • Scanning of slopes. • Scanning of small to medium sized areas. • Monitoring of slopes using repeat scans.
Unmanned Aerial Vehicles (UAV)	Use of a UAV to capture data via a sensor. This typically involves collecting aerial photographs along a preset flightpath which are then post-processed to create a 3D digital surface model and ortho-rectified aerial photographs. LiDAR units can also be used with UAVs to generate 3D digital elevation models.	Moderate to high	Low (no ground control, in built GPS only) to high (with ground control)	<ul style="list-style-type: none"> • Rapid coverage of large areas, that can use a pre-programmed flight path. • Data can be processed in a wide range of applications, to generate individual photos, ortho-rectified aerial photos of the site, point clouds and 3D digital elevation models. • If required the UAV can be flown by the geoprofessional on site, and a basic initial 3D surface model can be produced without ground control for preliminary work. However, caution is advised when producing 3D surface models without ground control as the absolute accuracy of such models is low (especially in terms of a vertical datum). As such, it is always recommended to install ground control points prior to the flight, so that the points can be measured by a surveyor at a later date, allowing the model to be re-processed to improve the absolute accuracy of the data. • Can be used to inspect areas which are otherwise not accessible. • Can be connected via ground control marks to in terms of a national geodetic database to get data in terms of a datum and projection. 	<ul style="list-style-type: none"> • All flights need to comply with Civil Aviation requirements. • Some geographic regions have restrictions on use (e.g. near airports), and there may be some landowner restrictions. • Weather (rain and wind) can prevent use. • Requires line of sight to UAV while flying • Generally, cannot penetrate vegetation (although some LiDAR units can find gaps depending on density of vegetation cover). 	<ul style="list-style-type: none"> • Rapid survey of large areas to develop elevation models. • Survey of areas inaccessible on foot. • Inspection of inaccessible areas. • Developing a 3D surface model and ortho-rectified photograph of the site.

TABLE 14: Summary of common survey methods, their advantages, limitations and best uses. (continued)

Method	Description	Relative accuracy	Absolute accuracy ¹	Advantages	Limitations	Best / Common Use
Fixed wing aircraft photogrammetry or LIDAR	Collection of aerial photographs and / or LiDAR data using fixed wing piloted aircraft. The data is then post-processed to create a 3D digital elevation model and / or ortho-rectified aerial photographs.	High	High	<ul style="list-style-type: none"> • Can cover very large areas more quickly and efficiently than UAVs or ground-based surveys. The area beyond which fixed wing aircraft are more efficient and cost effective than UAVs depends on the site conditions and UAV used. However, as a general guide, fixed wing aircraft should be considered for areas > 1 km². • Can produce high resolution and high accuracy ortho-rectified aerial photographs and 3D elevation models. • Can collect high resolution LiDAR data. • Can be connected via ground control marks to a national geodetic database to get data in terms of a datum and projection. 	<ul style="list-style-type: none"> • Expensive compared to other survey methods. • Weather (rain, cloud and wind) can prevent use. • Requires a specialist company to collect and process the data. 	<ul style="list-style-type: none"> • 3D elevation models and ortho-rectified aerial photographs for very large areas.

Notes:

¹ Absolute accuracy is in terms of a coordinate system and vertical datum.

DRAFT FOR FEEDBACK

5 SUBSURFACE INVESTIGATIONS

Although geological and geotechnical information can be obtained from surface investigations, subsurface investigations are also required to complete the observational engineering geological model (EGM). Subsurface investigations should follow an iterative process that is constantly adjusted as new information is obtained and hypotheses and mitigation strategies tested.

Subsurface investigations are also discussed in Part 4 of Unit 1, which focuses on investigations for possible or identified landslides. This section of Unit 2 provides additional guidance on investigations for:

- Stability assessments of existing slopes (where slope instability has not been conclusively identified); and
- The design of new cut slopes, for example along new transportation corridors or new land subdivisions.

5.1 PURPOSE OF SUBSURFACE INVESTIGATION OF LANDSLIDES

The primary purpose of geotechnical subsurface investigations is to provide adequate information to understand and manage the instability risk in a slope stability project.

Together with engineering geological mapping, subsurface investigations form critical building blocks for the development of the EGM, the investigation of slope instabilities, as well as the subsequent analyses and design of remedial measures (Lato et al., 2016).

Subsurface investigations aim to clarify the gaps and uncertainties in the conceptual EGM of the slope developed through Stage 1 investigations and develop it to an observational model. They also enable collection of the necessary information to generate the geotechnical models that are used for the design of a slope, the design of stabilisation measures or mitigation solutions for a landslide.

The formation and development of the EGM is an on-going process of knowledge accumulation that provides direction and control to the ground engineering. The development of this model is gradual and accumulative during multiple stages of site investigations throughout the project lifecycle, including the construction and operation stages.

For more information on the development framework of the EGM and how subsurface investigations fit in the process, refer to Figure 1-1 of the IAEG C25 Guidelines (Baynes and Parry, 2024). The same guideline provides the proposed levels of development of the EGM for different scales of project and geotechnical complexities (Tables 1-1 and 1-2 in the IAEG C25 Guidelines).

5.2 PLANNING INVESTIGATIONS

A well-designed subsurface investigation program is important to reduce the uncertainty regarding the ground conditions as far as practicable, but also to use the project resources efficiently.

The geoprofessional should have a good idea of the anticipated geology of a slope and the presence, possible extents, and the key features of a potential landslide, before designing the programme of subsurface investigations. To achieve that, the Stage 1 investigations and ideally the surface investigations described in the previous sections should precede the development of a subsurface investigation program.

5.2.1 Defining appropriate investigation scope

The investigation strategy requires decisions around the selection, scale, staging and sequence of the different investigation methods identified as necessary for the slope.

The most common factors that must be considered when deciding the strategy of geotechnical subsurface investigations for a landslide project are provided in Table 15.

More than one stage of subsurface investigations may be required for large scale projects that are developed in multiple stages of design and include extensive and / or high new slopes, large landslides and / or complex geological conditions. The stages of investigations should be adapted to the project design stage (i.e. feasibility, concept, developed or detailed design and construction).

A good example of staging geotechnical investigations, assessment and designs for slope stability projects is given in Figure 1 of the “Code of Practice for Land Development and Subdivision”, Chapter 2: Earthworks and Geotechnical (Auckland Council, 2022).

Access to hilly terrain, slopes and areas of instability can often be an onerous, unsafe, and costly activity. This may mean that only one stage of investigations is cost-efficient and feasible, even for large scale projects. In this case, the EGM developed from the Stage 1 investigations and engineering geological mapping, sometimes supplemented by shallow and geophysical investigations, is extremely important for planning a comprehensive one-stage subsurface investigation program.

5.2.1.1 Defining Appropriate Area and Location of Investigations

In all cases, the area covered, and the specific locations of subsurface investigations should be defined on the basis of the Stage 1 investigations and most importantly the geomorphological assessment and engineering geological mapping.

TABLE 15: Considerations in the selection of investigation scale and methods

Factor	Criteria
Project scale, complexity, and requirements	<ul style="list-style-type: none"> • Size, complexity, and value of the overall project. • Number, value of assets potentially affected and consequences of slope failure / landslide. • Anticipated design solution. • Seismic design requirements. • Project staging, budget, and timeline requirements.
Geological complexity and Geotechnical conditions	<ul style="list-style-type: none"> • Geological history of site. • Geological materials /units present. • Geological structure and sequence of geological units identified during Stage 1 and surface investigations. • Spatial variability of the geology along the slope. • Groundwater conditions. • Anticipated nature and strength of materials present. • Geotechnical parameters required for the design of the slope and / or landslide mitigation measures.
Landslide / slope features	<ul style="list-style-type: none"> • Length, height and angle of slope. • Size and area of the landslide. • Depth of failure surface. • Risk (anticipated likelihood and consequences of failure).
Site constraints and logistics	<ul style="list-style-type: none"> • Access, topography, slope angle. • Stability of site and associated safety issues. • Land ownership. • Presence of overhead and underground services.

Ground investigations should be undertaken in locations that (modified from Auckland Council, 2023):

1. Allow the best possible identification of the full range of conditions across the site
2. Manage the risks identified in the work completed to date (e.g. desktop study, preliminary site visit, or engineering geological mapping).
3. Test the preliminary ground model prepared in the previous stages so that this is robustly defined beyond the vertical and horizontal extents of the landslide area.
4. Provide design parameters at locations and depths appropriate for the assessment of the stability of the site, and the design of the remedial solution.

Depending on the project requirements, the EGM may be visualised in an engineering geological geotechnical elevation and / or one or more geological / geotechnical cross sections up to the development of a 3D digital geological model. For more detail on the visualisation of the EGM refer IAEG Commission 25 guidelines.

A key limitation in the subsurface investigations for characterisation of existing or new slopes and landslides is the tendency to limit the area to isolated parcels of land (i.e., within the client’s property lines). This limits the ability to unravel and explore the physical processes that likely shaped a hillside and all the factors at the higher parts of the hillslope that may influence the stability of an existing or new slope which is located within the client’s property. The geoprofessional should take this factor into account when defining the area and locations, assess the criticality of investigations beyond the project property lines and inform the Client in a timely manner to obtain access permissions.

5.2.1.1 Existing Slopes

For existing slopes, where the geology is exposed on the surface, information can be collected from engineering geological mapping. The slope may be able to be adequately characterised by a smaller area and number of subsurface investigations, if sufficient information can be collected from geological mapping to develop the geological model.

PART 3 STAGE 2 INVESTIGATIONS

A smaller area and number of investigations may be adequate for a relatively short length of slope and / or consistent geological conditions; in this case, one to two points of investigations, at a cross section, at the top and toe of the slope may be sufficient. A third point in the middle could be considered if access is feasible and is warranted by the geological conditions. The development of one cross section, usually at the highest or most critical in terms of stability part of the slope may be enough to characterise the geological and geotechnical conditions and support the stability analysis.

For long slopes, or if a great degree of geological variability has been identified during the engineering geological mapping, the proposed investigations

must extend along a wider area and aim to provide understanding of the spatial variability of the geology and its effects on stability conditions. The development of a slope elevation and more than one cross section may be required at areas of different or critical geological conditions for stability to enable a thorough stability analysis. In such cases the slope may need to be distinguished in domains, considering criteria such as geological conditions, height, slope angle, orientation, existing berms and other similar factors to enable a more efficient and comprehensive scheme of subsurface investigations.

Examples of the engineering geological cross-sections with identified instability and complex geology are shown in Figure 16 and Figure 17. In the case of

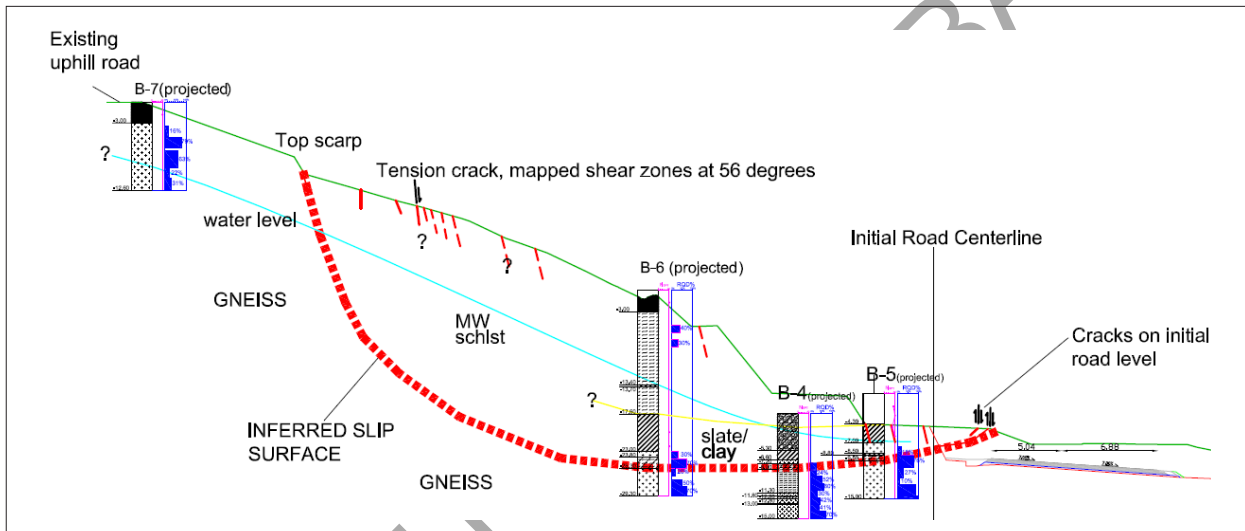


FIGURE 16: Example of the development of a geological model of an active landslide on an existing slope (Gkeli et al. 2015)

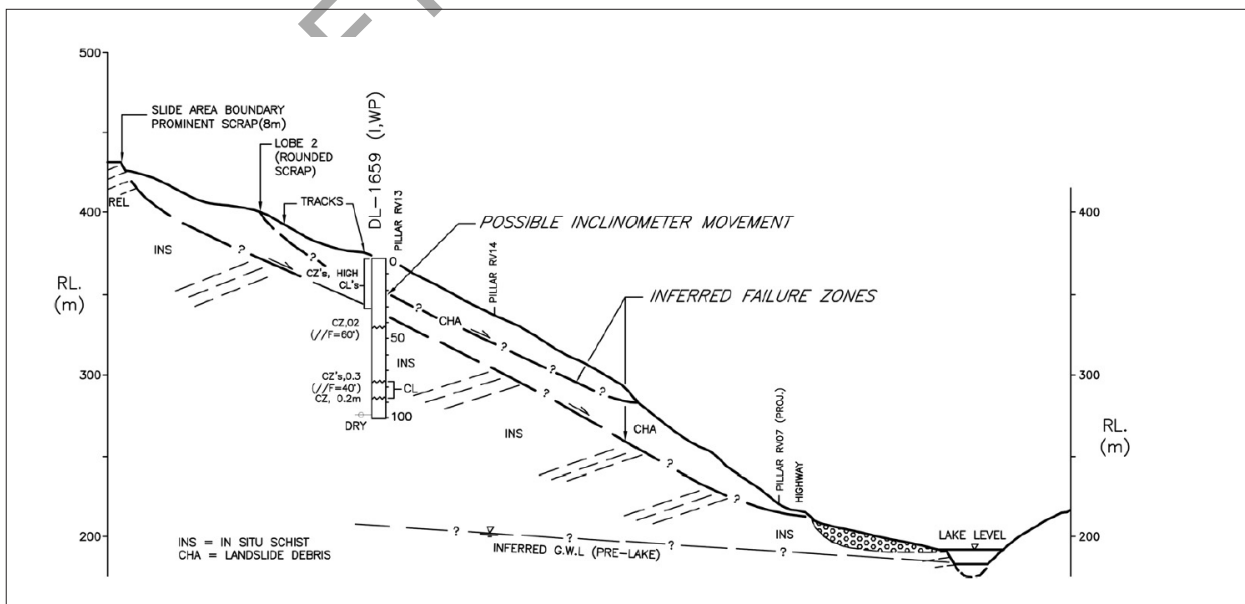


FIGURE 17: Cross-section through the Ripponvale Landslide (Macfarlane, 2009). The cross-section is drawn along X-X' in Figure 14.

Figure 16, multiple points of investigations were required to interpret the ground conditions and landslide area and depth. The landslide was inferred by connecting the surface expressions (cracking at the top and at the toe of the slope) identified from surface geological mapping and the soft clay layers found in the boreholes. The investigation locations shown in the figure were applicable for the conditions and geology of this particular slope. The number and locations of investigations must be considered on a case-by-case basis, see guidance in Table 16.

5.2.1.1.2 New Slopes

For new slopes in virgin ground, engineering geological mapping on the surface may be less representative of the actual ground conditions on the cut slopes, which may be much deeper than the original ground surface. In this case, the required subsurface investigations will be informed by parameters such as the height and length of the slope, the identified presence (or otherwise) of potential instability, the variability of geomorphology and geology defined by the Stage 1 investigations and engineering geological mapping.

Along transportation corridors or big land developments, the Stage 1 investigations must be supplemented by a study of existing slopes formed in similar geological materials in the area. The study of existing slopes will provide good understanding of stable and unstable slope angles, common mechanisms of failure and degree of variability of geological and geotechnical conditions possible for the materials expected on the slope.

The subsurface investigations for new slopes should include enough investigation points to provide cross sections to be used for modelling the slope for stability analysis. The investigations for slopes should target the following:

- the highest parts of new slopes.
- areas of identified or suspected instability.
- variability in geomorphological or geological conditions.

5.2.1.2 Defining Depth of Investigations

As discussed in Section 4.4.3.3, Part 4 of Unit 1, determining the required depth of subsurface investigations in advance can be difficult. The following factors influence the required depth of investigations:

- The height of slope (in cuts).
- The depth of the landslide. The depth of the intrusive investigations should exceed the depth of the basal failure surface and be well into the non-disturbed in situ material (see more in Section 5.3).
- The geological units present on the slope as understood in the conceptual EGM developed in Stage 1 investigations.

- The design objectives, e.g. design of a new slope, design of stabilisation measures of an existing slope, type of landslide mitigation measures.

To define the appropriate depths of investigation points it is useful to draw cross sections of the slope and the conceptual geological model. This will help to confirm that the locations and depths of the investigations are adequate for confirming the model and sufficient for the conceptual design of remedial works.

In most cases of slope stability assessments, deep investigations will be required for the full geological – geotechnical characterisation of a landslide or a slope. The primary limitations of shallow types of investigations are the depth and the geological materials they are suitable for.

Decisions to terminate the investigations earlier or extending to greater depths may be required during the execution of the investigations, depending on the actual ground conditions encountered. The geoprofessional should allow for contingencies in the investigation scope, programme, and budget, to enable the extension of the investigations to greater depths, if required.

A summary of the suggested area, number, locations, and depth of investigations for different cases of slope stability assessments is provided in Table 16.

5.2.2 SITE INVESTIGATION SPECIFICATION AND SCHEDULE OF QUANTITIES

All subsurface investigations should be undertaken for a clearly defined reason. Each slope stability assessment and design project should have a Site Investigation Specification, like any other project. The objectives of the ground investigation specification are listed below:

- Clearly identify the locations and reasons for the specific investigations.
- Clearly identify the methods and depths of the investigations.
- Specify the methods of in situ testing, frequency, locations and depths.
- Clearly define the standards and guidelines to be followed.
- Provide a Schedule of Quantities of the works.
- Assist in the procurement of the works.

The site investigation specifications should be part of the contractual documents. In New Zealand any subsurface investigations should be undertaken in accordance with the New Zealand Ground Investigation Specification (NZGS, 2017 or any future updated version). All investigation data which is not confidential should be uploaded to the New Zealand Geotechnical Database (NZGD), after relevant permission has been obtained from the project owner.

TABLE 16: Guidelines on area and locations of investigations for different cases of slope stability assessments

Slope Case	Slope geometry and geology	Information from engineering geological mapping	Recommended area and locations of investigations	Recommended depth
Landslide on existing slope	Refer to Sections 4.4.3.1 to 4.4.3.3 of Unit 1.			
Existing slope	Short length and / or uniform geology	Observational EGM can be defined by engineering geological mapping of materials and features exposed on the slope surface	<ul style="list-style-type: none"> One or two investigation points at a cross section to develop the model for stability analysis. Investigation point(s) target the highest part of slope or most critical geology / stability conditions, commonly at the top and toe of slope. A third point may be required in the middle or spatially along the slope to clarify uncertainties in the EGM. 	<ul style="list-style-type: none"> Shallow investigations may be appropriate when the geology is well understood (e.g. to investigate the depth and strength of colluvium over rock, or trenches on the slope to enable in depth geological mapping) When deep investigations are warranted, they should extend to sufficient depth to provide good understanding of the geology in conjunction with geological mapping. The full height of the slope may not need to be investigated.
Existing slope	Extensive length and / or erratic or complex geology	Observational EGM mostly defined by engineering geological mapping of materials and features exposed on the slope surface but: <ul style="list-style-type: none"> non-uniform geological conditions identified. Different mechanisms of failure identified. uncertainties of geological conditions in depth within the slope. 	<ul style="list-style-type: none"> Distinguish different slope domains based on different slope characteristics (height, geology, mechanisms of failure etc.) Development of multiple cross sections will be required, at least for each slope domain. Investigation locations as above for each domain. Additional investigations to address specific uncertainties identified during the investigation 	<ul style="list-style-type: none"> Shallow investigations may be appropriate when the geology is well understood (e.g. to investigate the depth and strength of colluvium over rock, or trenches on the slope to enable in depth geological mapping) When deep investigations are warranted, they should ideally extend at least 5 m below the lowest point of the slope.
New (engineered) slopes	Uniform geomorphology and geology - stable ground	Geological - geomorphological mapping at current ground surface.	<ul style="list-style-type: none"> Investigation points to target locations of high cuts (generally over 3 -4 m high for land developments and 10 m high for transportation corridors). One to two investigation points per cut at the highest part of the slope. 	<ul style="list-style-type: none"> Shallow investigations appropriate only for shallow cuts, or during Stage 1, or to supplement deep investigations. Depth of investigations should ideally extend at least 5 m below the lowest point of the new slope.
New (engineered) slopes	Non-uniform geomorphology and geology - identified instabilities	Geological - geomorphological mapping at current ground surface.	<ul style="list-style-type: none"> Distinguish project cut slopes in different domains of similar geomorphology - geology, stability conditions and heights of new cut slopes. One to three boreholes per cut to form a cross section for analysis. A larger area and more than three investigation points may be required for identified or suspected landslides and instability. 	<ul style="list-style-type: none"> Shallow investigations appropriate only for shallow cuts, or during Stage 1, or to supplement deep investigations. Depth of investigations should ideally extend at least 5 m below the lowest point of the new slope. see also Section 4.4.3.3 of Unit 1.

5.2.3 ROLES AND RESPONSIBILITIES DURING INVESTIGATIONS

Slope stability assessment is a specialised field and requires the involvement of specialised geoprofessionals from the initial stage of defining the problem to the advanced stages of scoping and executing to interpreting site investigations.

The primary disciplines to be involved in all stages of site investigations for slope stability assessments and design of new slopes are expected to be PEngGeol Engineering Geologists and CPEng Geotechnical Engineers (or international equivalent), specialised and experienced in landslides and slope stability assessments and analyses. The geoprofessionals should also have specialisation and local experience on the engineering behaviour and properties of the geological units expected to be forming the slopes, i.e. rocks and / or soils.

The Engineering Geologist should work closely with the Geotechnical Engineer throughout a slope stability project to develop the scope, execute and interpret the geotechnical investigations. Both should ensure from their different and overlapping perspectives that the slope instability problem has been adequately defined and investigated to give a strong basis for subsequent analysis and mitigation works.

The key roles of the geoprofessionals in the process of geotechnical investigations for slopes are summarised in Table 17. The table identifies in which activities the two key geotechnical disciplines should have primary or supporting roles, as well as provides guidance for the involvement of other supporting disciplines.

TABLE 17: The role of the geoprofessionals and other disciplines in site investigations for slopes.

Activity	Primary role	Supporting role	Input from other disciplines (for large and complex projects)
Scoping and executing primary and surface investigations	Engineering Geologist	Geotechnical Engineer Rock engineering specialist	Hydrogeologist Geomorphologist Engineering Designer
Development of Conceptual EGM	Engineering Geologist	Geotechnical Engineer	Hydrogeologist Geomorphologist Engineering Designer
Scoping and planning of subsurface investigations	Engineering Geologist and Geotechnical Engineer	Earthquake geotechnical engineering specialist Rock engineering specialist	Surveyor Project Manager Hydrogeologist Geophysicist Archaeologist Planner Environmental scientist Engineering Designer
Execution / Supervision of site investigations	Engineering Geologist	Geotechnical Engineer	Project Manager Surveyor
Interpretation of results and Development of observational EGM	Engineering Geologist	Geotechnical Engineer	Hydrogeologist Geophysicist
Development of geotechnical model and geotechnical parameters of materials	Geotechnical Engineer and Engineering Geologist	Earthquake geotechnical engineering specialist Rock engineering specialist	Hydrogeologists
Slope stability analysis – Slope design – stabilisation or mitigation measures design	Geotechnical Engineer and Engineering Geologist	Rock engineering specialist	Civil / Structural / Drainage designers
Construction input and supervision	Engineering Geologist and Geotechnical Engineer	Rock engineering specialist	Civil / Structural / Drainage designers

5.3 INVESTIGATION METHODS

Subsurface investigation techniques include intrusive and non-intrusive methods, where:

- **Intrusive methods** include hand augers, excavations (test pits), Cone Penetration Tests (CPTs), flat dilatometers (DMTs), and boreholes. Various in situ testing can be carried out in the intrusive investigations to supplement the subsurface information.
- **Non-intrusive investigations** include surface geophysical methods (e.g. seismic, electric resistivity, electromagnetic, gravity and ground penetrating radar) to derive information about the ground profile without any ground disturbance. These methods generally rely on being able to measure variations and contrasts of physical properties such as those provided by contacts between units, different soils and rock, water content, voids or faulting.

The following sections provide guidance on relevant intrusive and non-intrusive investigation methods, including their applications and limitations.

5.3.1 Selecting the Right Method

Types of subsurface investigation methods generally used for landslides are outlined in Table 18 (also refer to Section 4.4.5 of Unit 1).

The types of investigations for determining the dynamic parameters of materials to be used in seismic designs are discussed in the MBIE-NZGS Module 2 (2021) of the Earthquake geotechnical engineering practice series. These methods must be adjusted to be applicable for the investigation and design of landslides, per the guidance provided in Part 4 of Unit 1 and the present document.

TABLE 18: types of subsurface investigation methods

General category	Investigation	Common applications for slopes
Direct intrusive- Shallow	<ul style="list-style-type: none"> • Hand Augers • Scala Penetrometer Tests • Window samplers • Test pits • Trenches along or across existing slopes 	<ul style="list-style-type: none"> • Shallow slopes on soft stiff soils (3 - 4 m high) • Thin soil layer overlying rock • Shallow landslides (2-3 m deep) • Identifying soil strength for surficial and shallow soil layers
Direct intrusive- Deep	<ul style="list-style-type: none"> • Cored Boreholes (with in-situ testing) • Cone Penetrometer Tests (CPT) • Marchetti Dilatometer Tests (DMT) • Dynamic Probe heavy and super heavy (DPSH) • Pressuremeter Test (PMT) 	<ul style="list-style-type: none"> • Slopes >3 -4 m high • Deep landslides • Identify full slope height soil profile • Identify a wide range of soil and rock parameters • Design of deep stabilisation measures
Indirect intrusive - In-situ physical and geophysical testing in boreholes	<ul style="list-style-type: none"> • Standard Penetration tests • Shear vane tests • Groundwater testing and monitoring • Permeability tests • Mechanical Calliper • Seismic (downhole and cross hole) surveys • Optical and Acoustic viewers • Natural Gamma logging 	<ul style="list-style-type: none"> • Generally applicable as above for deep investigations.
Indirect - non intrusive Surface geophysical methods	<ul style="list-style-type: none"> • Ground Penetrating Radar • Multichannel analysis of surface waves (MASW) • Gravity methods • Seismic reflection • Seismic refraction • Seismic refraction tomography (SRT) • Electric Resistivity Tomography (ERT) • Airborne electromagnetic surveys 	<ul style="list-style-type: none"> • Generally applicable as above for deep investigations. • Some methodologies may have limitations on inclined ground – advice from a specialist geophysicist may be required during the scoping phase. • Some geophysical methods can provide dynamic parameters for seismic design.

It is important that the correct investigation methods are used depending on the requirements of the project. The common methods of investigations used in New Zealand most applicable for landslides are discussed in more detail in the following sections.

5.3.1.1 Shallow Investigations

All shallow techniques, from handheld to machine excavated, have limitations on the maximum depth they can reach, which is commonly up to 4 to 5 m. Furthermore, they will likely refuse on dense to very dense soil materials and rock formations, thus providing information for only a limited part of the slope. Shallow investigations are generally expected to:

- Be carried out during the initial investigations, to assist the development of the EGM and scoping of the deep subsurface investigations.
- Be supplementary to the deeper investigations and aim to provide more detailed information on the surficial and shallow layers.

Some cases where shallow investigations could be used for slope stability assessments, are indicated below:

- New slopes up to 3 – 4 m high, formed generally of soft to stiff soil materials.
- Existing slopes where the geology is well understood from engineering geological mapping on the slope surface.
- To enable discontinuity mapping on existing rock slopes (use of slope scrapes or shallow trenching).
- To investigate fault lines (trial pits and trenching).
- Shallow and surficial landslides (up to 1.5 – 2.0 m deep).

5.3.1.2 Deep investigations

Deeper investigations of landslides are often based on drilling, which allows data to be collected to depths of up to several hundred metres. However, borehole investigations are expensive and sample only a very small part of the landslide (i.e. they are a kind of point test). Consequently, important layers or features can remain undetected by drilling, and correlating between boreholes can lead to significant errors in the model in complex ground conditions. Further, inaccessible and steep terrains on landslides are often a significant problem for drilling rigs.

In contrast, geophysical methods are generally non-invasive and give highly resolved two-dimensional distributed data to significant depth. However, the

success of geophysical methods is mostly dependent on the presence of a significant and detectable contrast in the physical properties of different lithological units. Each technique has a different resolution and penetration depth that contribute to the final quality of a geometric model. Several preprocessing steps are needed to carefully check the data quality and, therefore, the resolution and penetration depth, before incorporation into a 3D model.

While geophysical methods can provide useful information on the layered structure of the slope and some mechanical parameters, intrusive methods (e.g. drilling) should always be used to link geophysical parameters and geological / geotechnical properties.

When geophysics are used in conjunction with intrusive methods, the geoprofessional should consider the benefits of carrying out the geophysics first, before scoping intrusive investigations in detail. Geophysics can provide better understanding of the geology of the slope and therefore enable scoping and locating intrusive investigations more efficiently.

5.3.2 EXCAVATION AND DRILLING

Table 19 provides details of the most commonly used intrusive investigation methods in New Zealand, including their applications, advantages and limitations.

It is important to note that all methods should be considered in terms of their applicability and limitations with respect to:

- the site (including access and topography);
- the slope or type of landslide being investigated;
- anticipated depth of investigations;
- expected ground conditions and the engineering geological model;
- the information required from the investigations;
- whether any disturbed or undisturbed samples are required to be collected;
- whether instrumentation needs to be installed at the investigation locations; and
- the expertise of the contractor completing the investigations.

Soil and / or rock logs, as well as accompanying investigation records, should be compiled for the investigation, in accordance with the recommendations outlined in the latest edition of the NZGS field classification and description guideline (NZGS, 2005).

TABLE 19: Summary of applications and limitations of various intrusive methods for landslides.

Investigation	Application and advantages	Limitations	Relative cost
Dynamic Cone Penetration tests (DCP, Scalas)	<ul style="list-style-type: none"> Fast, efficient and low cost. Can complete many Scalas in one day. Continuous penetration over shallow depth. Can be used to define density of shallow soils, and for investigations of shallow landslides comprising loose to dense soils. 	<ul style="list-style-type: none"> No samples for inspection. Cannot penetrate very dense soils or rock. Limited applicability for depths >2 m. Data quality can be significantly affected by incorrect use. 	Low
Hand augers	<ul style="list-style-type: none"> Fast, efficient and low cost. Can complete several hand augers in one day. Provides continuous ground profile in granular soils above the groundwater table and in firm or stronger clayey soils above and below the groundwater table. Allows for the collection of disturbed samples at desired depths. Can be used for the investigation of surficial soils and shallow landslides. Allows for installation of instruments in the hand auger hole for ongoing monitoring. Scala penetrometer and shear vane tests can be completed for field testing of the soils. 	<ul style="list-style-type: none"> Samples are disturbed. Cannot penetrate below groundwater table in granular soils. Penetration in stiff or dense soils is difficult. Cannot penetrate very dense soils or rock. Limited investigation depth: generally, 3 - 5 m below ground level. Sampling is generally restricted to disturbed samples. Installation of downhole instrumentation can be limited by hole diameter and / or collapsing holes. 	Low
Test pits and trenches	<ul style="list-style-type: none"> Can complete several test pits in one day. Provides a visual 'three dimensional' exposure of the geology, lateral extent of the geology (limited to the pit extent), groundwater, soil / rock interface, discontinuities and potentially the failure surface (if exposed within the test pit), which is unachievable by other intrusive methods. Detailed logging of trenches and test pits can aid in providing more accurate interpretations of samples from boreholes (Baum et al., 2008). Very useful for landslides of moderate depth, and near the edges of deep landslides (Baum et al., 2008). Allows for disturbed or undisturbed samples to be collected at desired depths. Scala penetrometer and shear vane tests can be completed for field testing of the soils. 	<ul style="list-style-type: none"> Limited investigation depth: generally, 3 - 5 m below ground level. Pit sides can be smeared. Potential health and safety issues related to pit wall stability. Limited use below water table. Largest area of ground disturbance when compared to other methods. Care needs to be taken by the geoprofessional that the excavation does not lead to (further) slope instabilities (e.g. do not excavate the toe of a landslide). The pit should not be entered below 1.2 m depth. 	Moderate
Window sampler	<ul style="list-style-type: none"> Portable, enables intrusive investigations at sites which are difficult to access using larger drill rigs. Can penetrate deeper than hand augers in suitable ground conditions. Allows for the collection of disturbed samples at desired depths. 	<ul style="list-style-type: none"> Limited investigation depth: often 2-6 m below ground level but can reach up to 10 m below ground level. Samples are disturbed. Uncertainty about the nature and type of refusal layer, unless deeper investigations are available. 	Moderate

TABLE 19: Summary of applications and limitations of various intrusive methods for landslides. (continued).

Investigation	Application and advantages	Limitations	Relative cost
Cone Penetration Tests (CPTs)	<ul style="list-style-type: none"> • Fast and efficient. Can complete several CPTs in one day. • Provides near-continuous measurements (generally every 10 mm) of the soils. • As CPTs provide near-continuous measurements they can be effective in detecting the presence of weak or sheared zones that need further investigation/sampling, as well as boundaries between soil types (Baum et al., 2008). • Collects data on dynamic pore pressures as the CPT advances. Dissipation tests can be completed to assess the hydrostatic pressure at a given depth. Note the CPT holes should still be dipped following completion to measure the groundwater level. • Depending on the ground conditions and rig used, can penetrate to significant depths. • CPT data can be used to derive multiple different soil parameters. • Can be completed as a seismic CPT (sCPT) to collect shear wave data at nominal intervals. • Allows for installation of instruments in the CPT hole for ongoing monitoring. • Size of rigs varies from hand portable through to tracked and truck rigs, allowing various options depending on access requirements. 	<ul style="list-style-type: none"> • Provides no soil samples for inspection unless a sampler (e.g. MOSTAP) is used. • CPTs cannot penetrate very dense /stiff soils or rock. • The presence of cobbles and boulders in landslide debris can limit the applicability of CPTs as the CPT can refuse on these. • The maximum depth of penetration can be limited by rig size. • Data quality can be affected by incorrect use or damaged equipment (see MBIE & NZGS, 2021 for common errors and anomalies). As no samples are collected it can be difficult to easily identify erroneous data. • Installation of downhole instrumentation can be limited by hole diameter and/or collapsing holes. • May require pre-drill near the surface to penetrate harder layers. • May require consent depending on its depth, location and local Council requirements. It is recommended that the geoprofessional checks with their planner to determine if a consent is required. 	Moderate
Boreholes	<ul style="list-style-type: none"> • Boreholes can generally be drilled to the desired depth so long as the correct rig is used. • Provides a continuous profile through the landslide and into underlying intact material, thereby allowing the geoprofessional to log the full soil and / or rock profile (including the failure surface and any discontinuities). • Boreholes can be drilled on various inclinations. • Allows for disturbed or undisturbed samples to be collected at desired depths. • Most suited investigation method for the installation of instruments in the borehole for ongoing monitoring. • Allows for various downhole tests to be completed during or following drilling to determine soil / rock properties. Examples include SPTs, permeability tests, pressuremeter tests, pumping tests, etc. (see Section 7.5 for field testing methods). • Tools can be used to recover oriented cores to determine true orientations of discontinuities and the failure surface. • Optical and/or Acoustic Televiewers (OTV/ATV) can be lowered down the borehole to observe borehole sidewalls and determine true orientations of discontinuities and the failure surface. • Size of drill rigs varies from hand portable through to large tracked rigs, allowing various options depending on access constraints. 	<ul style="list-style-type: none"> • Depending on the site access to set up the rig can be difficult meaning investigation locations may be limited (e.g. by number of locations, drill rig used, etc.). • Generally, more expensive than other methods. • Depth of borehole can be limited by rig size. The geoprofessional should specify that an appropriate drill rig is used to be able to drill to the desired depth. • May require consent depending on borehole specifications, testing proposed to be carried out, location of the borehole, and local Council requirements. It is recommended that the geoprofessional checks with their planner to determine if a consent is required. 	High

5.3.3 Boreholes

Boreholes are commonly used for, and form a critical component of, landslide investigations. The primary purposes of boreholes for landslide investigations are to:

1. Enable the geoprofessional to identify the subsurface distribution of materials by recovering and engineering geological logging of continuous core samples. This includes the ability to identify the landslide depth and failure surface(s).
2. Enable testing of the soil and rock to determine geotechnical parameters. This includes:
 - a. recovering representative soil and / or rock samples for laboratory testing;
 - b. completing in situ field testing; and
 - c. completing downhole geophysical testing.
3. Allow the acquisition of groundwater information through observations during drilling and monitoring using piezometers following drilling.
4. Enable monitoring of subsurface movement through the installation of inclinometers or ShapeArrays following completion of drilling.

Given the range of purposes and their versatility, boreholes are one of the most widely applicable methods for the investigation of landslides. Choosing the correct drilling method is important to ensure that as much information as possible is obtained from the investigation. As such, methods which do not allow for continuous samples to be retrieved (i.e. percussion drilling or augering) are not recommended for landslide investigations as key information would likely be missed using these methods. Wash drilling should only be used for the purposes of installing additional instrumentation adjacent to a cored borehole. The drilling of boreholes should be completed in accordance with the NZ Ground Investigation Specification (NZGS, 2017) and New Zealand Standard NZS4411.

The two most common drilling methodologies used in landslide investigations are rotary core drilling and sonic drilling. Detailed descriptions of these drilling methods are provided in NZGS & MBIE Module 2 (2021), and both are summarised below:

- **Rotary coring:** In New Zealand, rotary coring typically involves the triple tube technique where the two outer barrels rotate as the drilling advances, while the inner barrel does not. Rotary coring can be accomplished with either conventional or wireline equipment. Conventional drilling requires the entire rod string and core barrel to be brought to the surface after each run, while wireline drilling allows the inner core tube to be uncoupled from the outer tube and raised to the surface with a wireline hoist. This enables a more efficient removal of the core from the hole and can provide improved quality of core. Casing is typically installed to the required depths as drilling proceeds.
- **Sonic drilling:** Sonic drilling uses high-frequency vibrations (resonance), generated by two counter rotating weights in the sonic head and transferred down the drill string, to advance the drill bit and casing through the ground. Rotation can also be added if required. Casing is advanced as drilling proceeds. A typical sonic drilling sequence is shown in Figure 18.

The advantages, applications and limitations of the drilling methods are summarised in Table 20.

5.3.3.1 Information to be recorded

The geoprofessional supervising the drilling should record all relevant information including, but not limited to:

- Logging of soil and rock in accordance with the NZGS (2005) guidelines. This includes logging of discontinuities.
- RQD values in rock.
- Core recovery for each core run.



FIGURE 18: Typical sonic drilling sequence (NZGS & MBIE, 2021).

- Field testing data (see section 7.6).
- Depths of any voids encountered.
- Gain or loss of drilling fluids during drilling (including volumes of fluid, rise/fall of the drilling fluid in the hole, depth of hole and casing).
- Measurements of water levels at the start and end of the day, noting borehole and casing depth. While these only provide indicative groundwater levels as the borehole has not yet been developed and may be affected by drilling muds, these measurements can provide important preliminary information about the groundwater at the site and assist with choosing the optimal piezometer installation depths following drilling. An example of how water level measurements may be recorded during drilling is provided in Figure 21.

5.3.3.2 Common mistakes when drilling boreholes

Some common mistakes that can occur while drilling boreholes, and how to avoid them, are listed in Table 21.

SPEAKING WITH DRILLERS

Communication is critical to the success of projects. Many of the common mistakes listed here can be avoided by conversations between the geoprofessional and drillers leading up to, and during, the course of the site investigations. Clear communication between the geoprofessional and the drillers will provide both parties with critical information and improve the outcomes of the project.

TABLE 20: Advantages, applications and limitations of common drilling methodologies for landslide investigations.

Method	Advantages and Applications	Limitations
Rotary core drilling	<ul style="list-style-type: none"> • Generally does not disturb samples or surrounding ground. • Best method for coring rock. • Can preserve soil and rock structure, including the landslide failure surface(s). • Versatile and retrieves good quality samples in various strata. • Generally preferred for landslide investigations as it minimises the risk of any changes in the nature of the strata being sampled and tested. 	<ul style="list-style-type: none"> • Drill fluids required. In fractured rock or landslide deposits drilling fluid use can increase dramatically, thereby increasing time. • Slower than sonic drilling. • Can have poor recovery rates in loose granular soils and collapsible soils.
Sonic drilling	<ul style="list-style-type: none"> • Faster than other drilling methods. • Usually has very good core recovery rates and allows for high recovery rates in soils which are typically difficult to recover using rotary drilling. Examples include loose granular soils or collapsible soils, especially where a high groundwater table or artesian pressures are present. • Typically requires less drilling fluids than rotary drilling. Boreholes can be drilled with little or no drill fluids. This can be advantageous in landslide investigations as it avoids adding / losing water into the slope. • Hole is cased to the full depth. • Sonic capable drill rigs are frequently equipped with a dual head, allowing the operator to switch between sonic and rotary methods. • Generally suitable for deep landslides (>10 m depth), or in the body of the landslides to allow for recovery of a continuous sample up to 5 m above the anticipated failure surface depth. 	<ul style="list-style-type: none"> • By definition produces disturbed samples (Bratton, 2012), and the vibratory action of directing the sample into the sample barrel and then vibrating it back out can cause distortion of the strata being sampled. • Not recommended for drilling through rock. In softer rocks the resonance of the core barrel tends to open fractures and round off edges, preventing attainment of RQD (Bratton, 2012). • Sonic drilling can cause core to dry out and appear 'cooked' leading to over-estimation of cohesive soil strength. • Shear vane testing is not recommended within the core due to the disturbed nature. • Can destroy the fabric / structure of soil and of rock, making correct interpretation of the recovered sample difficult. • Can fracture boulders and rock when drilling through them, potentially leading to misinterpretation of the recovered core. • Sonic drilling may affect SPT results. • Samples collected by the dry sonic coring method may be subjected to drilling induced heat. • Not recommended for shallow landslides, or within 5 m of the anticipated depth of the failure surface, as the drilling method can disturb the core sample.
Wash drilling	<ul style="list-style-type: none"> • Fast and economic method to drill an additional borehole for instrument installation. • Only recommended for installation of additional instrumentation adjacent to an existing cored borehole. 	<ul style="list-style-type: none"> • No core recovery. • Not recommended for any other uses other than installing instrumentation adjacent to an existing cored borehole.
Percussion drilling	Not recommended for landslide investigations.	
Auger drilling	Not recommended for landslide investigations.	

TABLE 21: Common mistakes when drilling boreholes, and how they can be avoided.

Common mistake	How it can be avoided
Choosing the wrong drilling method leading to non-recovery or disturbance of materials across critical depths	It is important to choose the correct drilling method depending on the anticipated geology (see Table 20).
Disturbance of the landslide failure surface	It is important to recover and log the landslide failure plane with as little disturbance as possible. As such, SPTs should not be completed within 5 m of the anticipated depth of the failure surface, and any sonic drilling should be ceased (and switched to rotary) at least 5 m prior to the anticipated depth of the failure surface. If the landslide failure surface depth is unknown the geoprofessional may elect to complete a cored borehole without any SPTs to minimise the risk of disturbance (assuming SPTs can be completed in other boreholes at the site).
Misinterpretation of the geology, resulting in not drilling sufficiently deep to intersect the basal failure surface of the landslide, and recover in situ material	Boreholes should extend sufficiently below the inferred basal failure surface depth to confidently identify in situ material which has not been displaced or disturbed. This requires a good understanding of the engineering geological model, thorough logging of the cores, and engineering geological judgement. The borehole should extend at least 5-10 m below the failure surface.
Insufficient drill rods available to drill sufficiently deep to intersect the basal failure surface of the landslide, and recover in situ material	The geoprofessional should clearly communicate the anticipated drill depth to the drilling contractor, so that the contractor can supply the required number of drill rods. A nominal number of spare rods should be supplied as contingency to enable the borehole to be drilled deeper than anticipated if required.
Not recording sufficient information during drilling	When completing boreholes, it is important that the geoprofessional not only logs the borehole but also records other observations as drilling proceeds (such as return or loss of drilling fluids), as this can provide valuable details about subsurface conditions (McGuffey et al., 1996).
Not identifying a suitable water source for drilling fluids prior to the investigation	Borehole locations can be located significant distances from suitable water sources, and significant volumes of water may be required for drilling, depending on the ground conditions, depth of borehole and drilling method used. If a suitable source is not identified prior to the site work this can cause delays to the drilling programme. The drilling contractor and geoprofessional should identify a suitable water source for drilling fluids prior to the investigation commencing.
Misinterpreting drilling induced defects as natural defects	The drilling process can cause drilling induced defects, which can be difficult to differentiate from natural defects. Drilling induced defects can occur on various angles, but some of the more commonly encountered drilling induced defects are (sub-)horizontal defects which are sometimes referred to as diskings. Drilling induced defects will not have any clay infill or striations. The geoprofessional needs to carefully identify which defects are drilling induced, and which are natural. If OTV/ATV is used in the borehole, this may be able to be used to confirm if some of the defects observed in the core are drilling induced.
Misinterpreting the location of core loss	Correctly identifying the zone of core loss can be very important in interpreting the subsurface conditions. When core loss is encountered, the geoprofessional should identify where core loss is likely to have occurred. This should involve conversations with the driller. A guide on identifying common locations of core loss is provided in Figure 19.
Misinterpreting the cause of core disturbance and poor recovery	If a zone of poor core recovery is encountered, or if the recovered core appears disturbed, it is important that the geoprofessional correctly assesses this was caused by the drilling process or because of natural, variable ground conditions. Correctly identifying the cause of core loss or disturbed appearing core can be important in correctly assessing the subsurface ground profile.

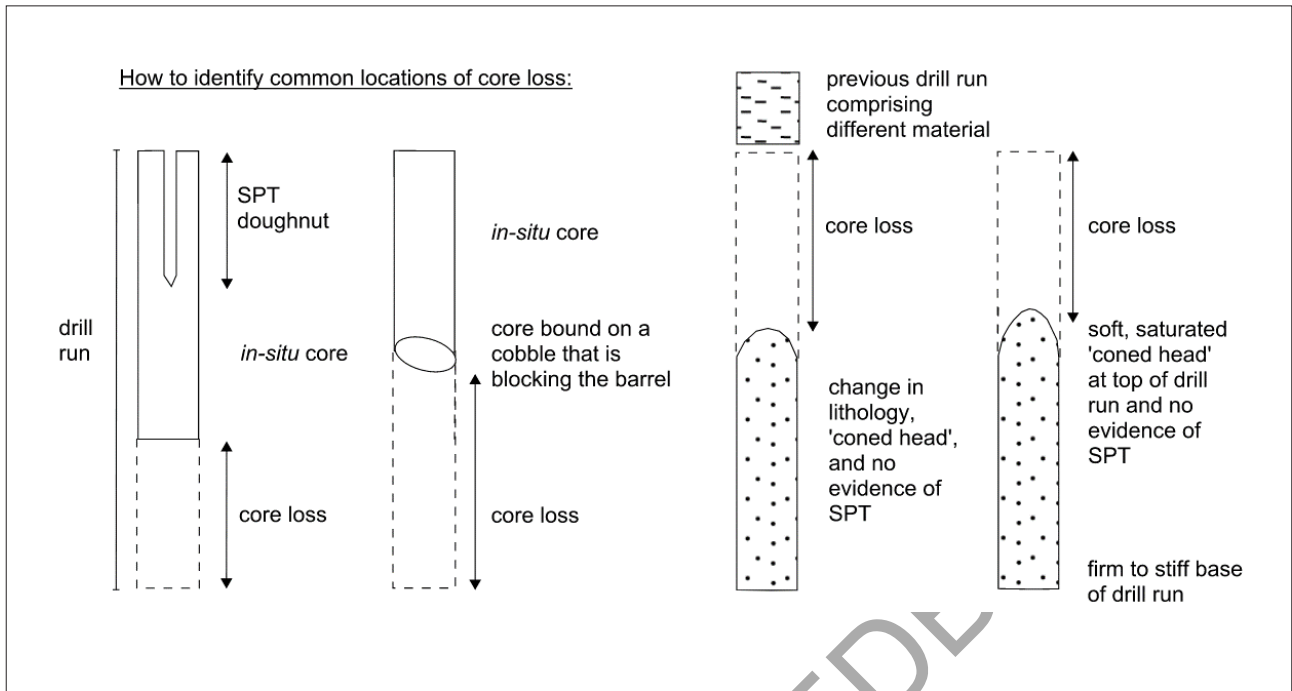


FIGURE 19: Identifying common locations of core loss (figure courtesy of Jacqui Coleman, Beca).

5.3.4 Ground Surface Geophysics

The characterisation of the subsurface of a landslide is a critical step in developing ground models that inform planned mitigation measures, remediation works or future early warning of instability. The most widespread landslide investigation techniques involve the drilling, sampling at discrete points, and *in situ* or laboratory testing. With such investigations, only a very small proportion of the volume of soil and rock that will affect the stability of a slope can be sampled and tested. This affects the reliability of the EGM.

Geophysical surveys are able to rapidly acquire data across large areas of the subsurface at the slope-scale. Geophysical methods rely on detecting significant contrasts between the physical properties of different material types (lithological units) and / or moisture content. However, sometimes the data may be difficult to interpret or the methodologies available may have limitations on inclined ground. Traditionally common geophysical methods for other geotechnical problems, have not been widely used in landslide investigations.

Carefully used, geophysical techniques offer the chance to overcome some of the problems inherent in the more conventional ground investigation techniques. In particular, geophysical investigations, used as a complement to mapping and drilling, allow:

- The investigation of the landslide geological configuration.
- The investigation of the groundwater (determining

the level and its fluctuation with time) as a landslide formation factor.

- The study of the physical properties and status of the landslide deposits and their changes with time.
- The investigation of the landslide displacement process.

The main advantages of applying geophysical methods to landslide investigations are:

- The rapid and relatively cost-effective investigation of large areas, collecting a larger number of sample points than those acquired by geological engineering techniques.
- The determination of the mechanical properties of wet and dry soils based on the measurements of large rock volumes directly involved in the processes; dynamic properties of the materials can be also measured with some of the methods (refer MBIE, NZGS Module 2).
- The measured parameters reflect the combined geological and hydrological characteristics, which sometimes cannot be identified separately.
- The measurements can be repeated any number of times without disturbing the environment.

General limitations of the geophysical methods include (Jongmans & Garambois, 2007):

- The decreasing resolution with depth.
- The non-unique interpretation of the retrieved sets of data; therefore, calibration with intrusive investigations is required.

- The indirect information they yield (physical parameters instead of geological or geotechnical properties).
- The performance of geophysical techniques is strongly dependent on the signal-to-noise ratio.
- Landslide material can be highly disturbed and consequently lead to electrical current injection difficulties or strong seismic wave attenuation. High level understanding of the slope geology and collaboration with a geophysicist is always required before designing a survey.

Collaboration with an experienced engineering geophysicist is the most important consideration when selecting geophysical methods for a landslide investigation. To get the best possible results the geoprofessional needs to

- Ensure that the geophysicist understands the specific objectives of the proposed investigations.
- Provide the geophysicist with relevant geological information (outcrop maps, core logs).
- Understand what the geophysical method(s) will produce.
- Involve the geophysicist in the interpretation of the data and its application to the EGM. It is essential that the geophysical data be correlated with drillhole and / or mapping data for control purposes.

The relative benefits and detailed limitations of the geophysical methods most commonly used in New Zealand for landslide investigations (seismic reflection and refraction, SRT, MASW, ERT and GPR) are summarised in Table 22.

5.4 IN SITU TESTING

In situ testing of soil and rock in intrusive investigations takes the form of downhole physical and geophysical tests. *In situ* tests are used to obtain the properties of soils and rocks (refer Table 23 and Section 5.4.1 below). Laboratory testing is not discussed in this Unit.

Groundwater conditions are also important aspects and considerations for most landslides in New Zealand, and adequate and appropriate instrumentation and testing is required to understand groundwater conditions. These are also discussed in Section 5.4.2 below.

5.4.1 Material characterisation tests

In addition to understanding the geometric characteristics of landslides (e.g. thickness of landslide mass, depth to failure plane and volume of soil mobilised), it is also vital to understand the material properties to appropriately and accurately model landslides. Material characterisation is an important step in correctly understanding landslide behaviour and mechanism. *In situ* testing also helps the geoprofessional distinguish landslide material from the underlying more competent soil or rock and thus help determine the depth and geometry of the landslide.

Specific material properties or ground conditions may trigger instability or are key considerations for slope stability modelling. *In situ* testing becomes an important undertaking in identifying these properties and conditions. In addition to *in situ* testing, laboratory testing may also be required in some cases (e.g., particle size distribution testing, shear strength testing of basal slip plane, UCS testing of rock samples, age-dating, etc.).

The choice of physical and geophysical field-testing methods can be dependent on a number of factors, such as the information sought, applicability for the ground conditions expected, advantages and disadvantages and limitations or pitfalls of the method. Table 23 identifies the most common methods of field investigations of soils and rocks to better understand their properties and summarises the key advantages and limitation.

Downhole and cross hole seismic testing is not discussed in detail in Table 23. For the *in situ* testing suitable for determining the dynamic parameters of the soil refer to MBIE-NZGS Module 2 (2021).

TABLE 22: Summary of applications and limitations of various geophysical methods for landslides.

Method	Application and advantages	Limitations
Seismic Reflection	<ul style="list-style-type: none"> Measures the reflection of P- and S- seismic body waves on surfaces with sufficient contrast in acoustic impedance (reflectors). Able to image multi-layered systems. Applicable for imaging the geometry of the landslide structure, such as the internal bedding or the sliding surface(s). Less common for landslide investigations (see limitations). 	<ul style="list-style-type: none"> Bigger effort to deploy geophone layouts in rugged topography, could be time consuming and costly. Careful survey design based on landslide characteristics is required; maximum depth depends on length of the geophone array, and frequency and wavelength of source. Better suited for horizontal reflectors. For dipping reflectors interpretation may be more complex and surfaces may appear shallower than they actually are. Shallow seismic reflection requires a good signal to noise ratio and the recording of high frequency waves to reach the desired resolution. This may be difficult to achieve in landslides.
Seismic Refraction	<ul style="list-style-type: none"> Measures the refraction of P- and S- seismic body waves when they arrive at a critical angle of incidence on a surface with sufficient contrast in wave velocity. Generally applicable for landslides, especially for investigating the landslide shape and where there is strong contrast in both shear and compressional wave velocities between the landslide body and the unaffected ground. 	<ul style="list-style-type: none"> Requires relatively long profile (three to five times the penetration depth). Can be difficult to interpret due to wave attenuation within disturbed landslide material. Strong wave generators may be required to impart enough energy in the ground. If layers with higher seismic velocities exist above the sliding surface, there is a risk that the sliding surface may not be identified. The depths to underlying layers with higher velocities will be overestimated.
Seismic Refraction Tomography (SRT)	<ul style="list-style-type: none"> A variety of refraction technique that provides an image of P-wave velocity distribution in the ground, regardless of the determined seismic interfaces. Most commonly, the P-wave is analysed. Provides better diagnosis and location of landslide zones of potential slip surfaces. In rock materials can distinguish the weathering zones. 	<ul style="list-style-type: none"> Compared to seismic refraction, the technique requires more travel-time data and field effort.
Multichannel analysis of surface waves (MASW)	<ul style="list-style-type: none"> Measures the refraction of P- and S-waves on surfaces with sufficient contrast in acoustic impedance (reflectors). Applicable for landslides, can detect contrast of surface waves between the unstable and stable mass. Can be used to determine the mechanical properties of soils. Is efficient in environments with high background noise. Can be used for determining dynamic parameters of the soil and seismic site classification and liquefaction analysis. 	<ul style="list-style-type: none"> Receivers on sloping ground violate some of the assumptions made in a typical MASW test owing to a complex attenuation and amplification regime (Vishwakarma et al., 2024). May require sophisticated analysis for interpretation. Applicability of the method for a slope should be confirmed with a geophysicist.
Electrical Resistivity Tomography (ERT)	<ul style="list-style-type: none"> Transmits a direct electric current through the ground and measures the resistance of geological materials. For landslides 2D or 3D imaging are more applicable. Sensitive to various factors like the nature of material (particularly clay percentage), the water content and its conductivity, as well as the rock weathering and fracturing. Based on available literature it can target the location of the slip surface successfully. 	<ul style="list-style-type: none"> Needs careful configuration of array of electrodes to achieve the desired penetration depth vertical and lateral resolution and ambient electrical noise. Interpretation of obtained images may be complex.
Ground Penetrating Radar (GPR)	<ul style="list-style-type: none"> Low applicability for investigations of landslides. 	<ul style="list-style-type: none"> Provides information at shallow depths only, unless special equipment has been utilised. GPR signals can be highly attenuated in high conductive formations, thus preventing any application in soil landslides or when water saturation is higher than the target. Heterogeneities like fractures and blocks create diffractions decreasing dramatically the penetration depth.

TABLE 23: Overview of in-situ field investigation methods for landslides

Testing standards	Applicability	Similar alternatives or variants	Outcome(s)	Advantages	Disadvantages	Things to note
<p>Standard Penetration Test (SPT)</p> <p>SI2.1 of NZGS, 2017 (NZ Ground Investigation Specification) ASTM D 1586</p>	<p>Preferred method for cohesionless soils (non-plastic silts and coarser)</p>	<p>Although not equivalent alternatives or variants, hammer blow type tests are sometimes used in some cases in lieu of SPT-N and where sample collection is not vital, or borehole construction is difficult. These methods include Dynamic Cone Penetrometer test (DCP, or Scala) and dynamic probe heavy and super heavy (DPSH).</p>	<p>SPT resistance in terms of blow counts per mm length (last 300 mm run).</p>	<p>Readily available and common method of testing. Able to collect soil samples. Applicable to a wide range of soils and soft rocks. Wide range of theoretical background to correlate SPT-N (blow numbers). Can be used to distinguish landslide material from more competent undisturbed material below, bedrock or a key geological setting where the presence of other obstruction (e.g., boulders and floaters) are not vital.</p>	<p>Results can be highly variable and non-repeatable. Samples are disturbed (can be used for index testing). This can result in critical information (like the basal shear surface) being missed. Result requires correction before use. Not applicable to soft and plastic cohesive soils.</p>	<p>Calibration of test tool to get the energy transfer ratio is key (refer ASTM D 4633). Consider the effect of drilling disturbance to SPT-N values and select drilling method carefully. If closer SPT test depth is specified the quality of sample recovery from the borehole will be affected. Consider doing a second nearby borehole with full core run if this is the case to pick up critical landslide features.</p>
<p>Vane Shear Test (VST)</p> <p>SI2.3-12.4 of NZGS, 2017 ASTM D 2573</p>	<p>Preferred method for cohesive soils (silts and clays)</p>	<p>Field vane shear test method can be done with a rectangular of a tapered vane apparatus. Vane testing is also either handheld or large diameter testing.</p>	<p>Undrained shear strength Sensitivity.</p>	<p>Simple equipment and test procedure. Enables the direct assessment of the undrained shear strength. Measures the remoulded shear strength or sensitivity of cohesive soils directly. Long history of application.</p>	<p>Limited only to weak cohesive soils (soft to stiff clays / silts). Test can be time consuming and slow. Results are not directly usable in raw form, i.e., require corrections. Test results may not be accurate if the failure profile is non-horizontal (i.e., if failure is on a non-horizontal plane, the measured values may not represent that).</p>	<p>Using this method to test fissured clay layers, as is sometimes the case for landslides, can lead to inaccurate results. High sand and silt content and laminated clay layers can lead to inaccurate results. Landslide debris can have disturbed bedding which can lead to similar issues. Use with caution if there are thick peaty layers (results in fibrous peat can be overestimated).</p>

TABLE 23: Overview of in-situ field investigation methods for landslides (continued).

Testing standards	Applicability	Similar alternatives or variants	Outcome(s)	Advantages	Disadvantages	Things to note
<p>S12.2 of NZGS, 2017</p> <p>ASTM D 5778</p>	Generally applicable to both cohesive and cohesionless soils.	<p>Piezocones (with piezometric sensor and porous media) are the most commonly used cones.</p> <p>Cones also come in either 10 cm² or 15 cm² base area, the bigger ones being more suited to gravelly soils.</p> <p>A similar (but completely different) test apparatus is the flat plate or Marchetti dilatometer test (DMT, based on ASTM D 6635).</p>	<p>Direct measurement of end cone resistance, sleeve friction and pore pressure.</p> <p>Derived parameters include shear strength, unit weight, soil classification, permeability, shear wave velocity, OCR, etc.</p>	<p>Fast and productive testing method (typical penetration progress rate of 20 mm/sec).</p> <p>Continuous and full profile of soil layers obtained.</p> <p>Groundwater information is possible with the piezocene (including permeability of cohesive layers).</p>	<p>Test requires expertise to calibrate and to carryout.</p> <p>Sample collection is not possible (although most CPT rigs can also be used for push tube soil samples).</p> <p>Results require quality checks before use.</p> <p>Common issues are no / low sleeve friction, uncalibrated pore pressure, large inclination, and noise.</p> <p>Early refusal due to intermediate stiff layers or obstructions.</p>	<p>Use with precaution in gravels or where the soils can contain coarse gravels, cobbles and boulders.</p> <p>Early termination or refusal is possible due to intermediate stiff layers.</p> <p>It is recommended to use CPTs in addition to boreholes in to have a fuller picture of geology.</p> <p>Rig selection and termination criteria setting important to avoid refusal due to rig limitations.</p>
<p>S12.16 NZGS, 2017</p> <p>ASTM D 4719</p>	Generally applicable to all soil and rock types.	<p>Tests in rock usually utilise the Menard PM test inside a pre-bored hole.</p> <p>In soils, where ground disturbance is a concern, self-boring PM test is preferred.</p> <p>When borehole stability is more critical than disturbance effects in soils, push-in or full-displacement PM tests are also an option.</p>	<p>Elastic of Young's modulus</p> <p>Shear strength</p> <p>Limiting pressure</p> <p><i>In situ</i> horizontal stress, or K_0</p>	<p>Tests or mobilizes a larger zone compared with other tests (four to six times the probe diameter).</p> <p>Provides unique and specific results that is not directly measured by other tests.</p> <p>Long track record of successful application in soils and rocks with strong theoretical background.</p>	<p>Test setup is delicate and requires high level of expertise.</p> <p>Testing procedure is complicated and requires careful calibration.</p> <p>Test is time consuming and can be expensive.</p>	<p>Correct matching of borehole diameter and pressuremeter test setup is important.</p> <p>Boreholes that are too big or too small can lead to shape anomalies.</p> <p>Presence of weak and thick layers, bedding or discontinuities in rock can lead to probe bulges and membrane rupture.</p> <p>Borehole disturbance during probe lowering can lead to misinterpretations.</p>

TABLE 23: Overview of in-situ field investigation methods for landslides (continued).

	Testing standards	Applicability	Similar alternatives or variants	Outcome(s)	Advantages	Disadvantages	Things to note
Borehole Televiewer	ASTM D 5753	To be used in boreholes in rock formations.	Typically used are either acoustic televiewer (which uses ultrasonic waves) or optical televiewer (borehole camera).	Discontinuity detection and mapping. Discontinuity dip and orientation and character.	Provide continuous, oriented and high-resolution representation of borehole wall. Can be a useful information gap filling method for depth control and core orientation, especially when core recovery is incomplete.	Acoustic method requires fluid filled boreholes. Thick slurry may affect readings. Optical televiewer requires boreholes that is clean (air) or clear water filled.	Investigation equipment is usually very costly. Collapse of material into boreholes can wedge and trap testing equipment, resulting in costly recovery or loss of gear. Use with caution. Although these methods provide a plethora of useful data, highly fractured zones can result in failed or incomplete orientation of discontinuities.
Velocity logging	ISRM Suggested methods for borehole geophysics (2005)	To be used in boreholes in rock formations.	Includes downhole, up-hole and sonic methods. Includes P-wave velocity logging, or PS logging for both P- and S-waves. Sonic logging uses much higher frequency P-waves to obtain a much more detailed P-wave velocity profile.	Dynamic elastic properties of the rock mass. Physical and mechanical properties of the rock, degree of weathering, and fracturing around the borehole. Site specific seismic parameters when the S-wave velocity is measured.	Flexible depth ranges and intervals for the measurements and can be as frequent as 0.1 m if the sonic method is used. Can overcome borehole instability risks or anomalies by using the up-hole or downhole method. Can locate and map stratigraphic boundaries in the borehole. Provide continuous measurement of rock mass P- and S- waves and seismic properties of the rock mass and by inference mechanical characteristics of the rock formations.	Orientation of structural features cannot be determined through this method. Suspension PS and sonic logging cannot normally be undertaken in cased holes. Poorly set casing may affect the quality of the data, even for the down-hole method. Suspension PS and sonic logging cannot be undertaken in dry holes	The most appropriate method (downhole or up-hole) should be selected on the basis of the survey objectives and site conditions. The depth range and intervals for the measurements can be determined in consideration of the requirements for the survey. Borehole-related conditions, which may affect the data quality, should be known in advance so that countermeasures can be taken.

TABLE 23: Overview of in-situ field investigation methods for landslides (continued).

Testing standards	Applicability	Similar alternatives or variants	Outcome(s)	Advantages	Disadvantages	Things to note
<p>Electric and electromagnetic logging</p> <p>ISRM Suggested methods for borehole geophysics (2005)</p>	<p>To be used in boreholes in soil and rock formations.</p>	<p>Spontaneous Logging (SP).</p>	<p>Provide resistivity profiles of geological formations along a borehole. Evaluation of water bearing zones and aquifer/leakage zones. Correlation of geological stratification. Detection of weathering zones. Estimation of true formation resistivity. Evaluation of porosity and water saturation.</p>	<p>Suitable for hydrogeologic or groundwater investigations, since resistivity is strongly affected by characteristics of conductivity or saturation of the formation water. Useful to obtain information of a water bearing layer or an aquifer on slopes. Suitable for identifying stratigraphy and lithology investigations, since resistivity varies depending on types of soils, mineral compositions, and degree of weathering of a rock.</p>	<p>Electric logging requires borehole water for measurement (the SP method should be considered for dry boreholes). Resistivity values can be influenced by the resistivity of borehole water. Hence, the apparent resistivity may not represent the true resistivity of the formation. The influencing factors should be considered in the data presentation and interpretation.</p>	<p>During the measurement, the resistivity and the temperature of the drilling fluid should be measured and noted.</p>
<p>Nuclear logging</p> <p>ISRM Suggested methods for borehole geophysics (2005)</p>	<p>To be used in boreholes in soil and rock formations</p>	<p>Active methods (γ-γ logging, neutron logging): a radioisotope is used as a radioactive source and induced radiation due to the formation is measured. Passive method (Natural γ logging): only natural radiation is measured.</p>	<p>γ-γ logging estimates the bulk density and elastic constants. Neutron logging estimates the water content and porosity. Natural γ logging measures the natural γ-ray intensity and natural γ-ray spectral logging measures the energy spectrum of the natural γ-ray.</p>	<p>γ-γ logging can be applicable for various types of ground from soils to rocks. Neutron logging can be employed in dry boreholes. This method, in combination with acoustic logs, can detect fractured zones and the degree of weathering for rocks. Natural γ logs reflect the shale and clay contents of most sedimentary rocks and can be used for lithology identification. Permeability and rock strength can be also derived.</p>	<p>Methods sensitive to borehole stability. If casing is used, large voids or water behind the casing may affect the measurement. Heavy drilling muds may affect the measurements. γ-γ logging probe must be suitable for the range of densities and borehole diameters (use calibration charts). Borehole diameters must be <120 mm.</p>	<p>Natural γ logging is recommended to be conducted together with γ-γ logging. Changes in the borehole diameter affect the measurement. It is better to conduct caliper logging to measure the borehole diameter and apply diameter corrections to the density logs obtained with γ-γ logging. Neutron and natural γ logging can be employed in a steel cased borehole but corrections are required.</p>

5.4.2 Investigating groundwater conditions

Groundwater level / pressure is a contributor to, or major trigger of, many landslides. Identifying groundwater conditions and understanding how and why they vary is a critical aspect of any subsurface investigation.

Due to the disturbance of the soil and rock materials, groundwater conditions within a landslide can be complex. Landslide movement can affect and change groundwater level, groundwater flow directions and volumes. Observations and engineering geological mapping should identify surface expressions of groundwater such as springs, seeps, natural ponds and marshy ground as well as the relative levels of nearby streams, rivers, lakes or coastlines. These can be used to help determine the position and complexity of the water table(s) and the saturated zone(s) of the landslide.

Observations of seeps at the toe of the landslide may indicate that the landslide is draining or, in most cases, that there is potential for groundwater to recharge during rainfall events. A reduction or cessation of groundwater flows at the toe may be a sign that there is a potential for further instability.

Considerations when designing investigations targeting groundwater include:

- Groundwater conditions in small landslides might be straight-forward but groundwater conditions should always be considered as complex for larger landslides.
- Groundwater conditions within a landslide may change over time due to ongoing landslide movements, rainfall or seasonal changes.
- Disturbance of materials within the landslide mass (sheared soils and rocks, loosened debris, entrained plant material etc.) can lead to juxtaposed materials with different permeabilities and the development of perched groundwater levels. Isolated zones of

saturated permeable material containing groundwater under elevated pressures can be also developed.

- Groundwater pressures may differ at different depths at the same location (see Figure 20) due to the presence of perched and / or confined groundwater.
- Groundwater in a landslide may be directly or indirectly affected by rainfall (see Figure 20).
- Groundwater in a landslide may be fed by surface water discharge, typically poorly controlled surface water runoff and the geoprofessional should check if this is a contributor.
- Generally, increases in groundwater pressure with depth indicate an upward flow of groundwater, whereas pressure reduction with depth indicates a downward flow. These changes may also be indicators of multiple aquifers within the slope that are not interconnected.

Drilling in large, complex landslides may encounter a wide range of groundwater conditions due to the disturbance of the materials and the resulting presence of impersistent, perched or confined aquifers within the landslide that are separate from the basal water table but can influence the behaviour of the slide mass. Investigations in the very complex schist landslides in the Cromwell Gorge for the Clyde Power Project made use of the DVD (depth v depth) plot described in Dick (1976) which plots the depth of the drillhole against the recorded water levels at the beginning and end of each day (see Figure 21). The method was suitable in those slopes because the materials were of low to medium permeability, the holes were commonly deep (> 100 m) and drilling was slow, which allowed more data points to be obtained. On that project the DVD plot allowed the identification of possible internal aquifers and their depth range, determination of their nature (confined or not) and assisted with optimally locating piezometers within and beneath the landslides (Macfarlane, Pattle & Salt, 1992).

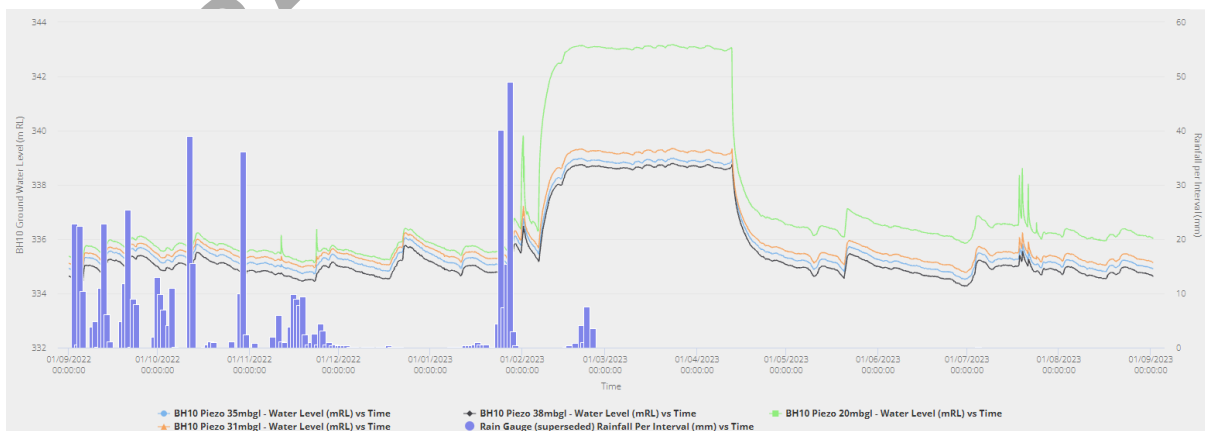


FIGURE 20: Different water pressures recorded by vibrating wire piezometers at different depths in a landslide borehole versus rainfall. The piezometers in the landslide (10.7mbgl, 15.7mbgl, 20.7mbgl) show increasing water pressure with depth within the landslide mass. The piezometer at 30.2mbgl is below the landslide in an undisturbed sandstone bed indicating the sandstone is relatively free draining as the water pressures are low.

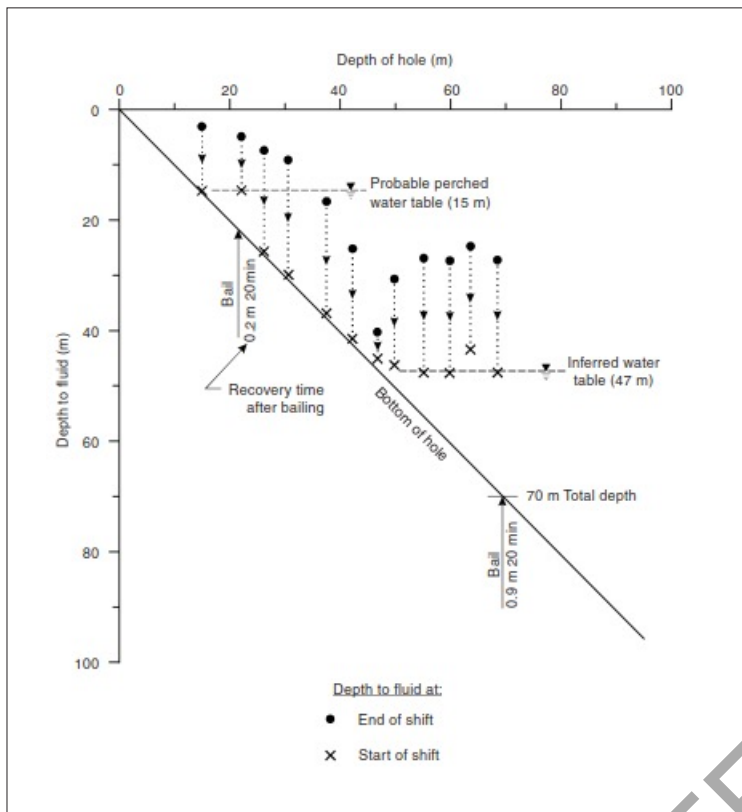


FIGURE 21: Example of a depth vs depth plot identifying multiple aquifers within the drillhole. From Fell et al (2015, Figure 5.33)

Although landslides are complex features and generalisations should be considered carefully, a list of useful points regarding groundwater conditions are provided below as a guide when undertaking investigations and assessments:

- Surface observations are essential.
- Seasonal changes in groundwater will not be detected unless monitoring is undertaken over a period of at least one year and preferably many years.
- Considering a steady-state condition in the geotechnical stability assessments is common. Although for most applications this may be suitable, there could be certain scenarios where a more comprehensive hydrogeological assessment becomes necessary. Examples of such conditions include the presence of perched groundwater conditions, presence of artesian groundwater pressures and landslides with complex water boundaries (e.g., bounded by rivers / streams, precipitation over a significant watershed abutting the landslide, and complex evapotranspiration considerations).
- Consideration should be given to measurement of temporary or transient groundwater pressures resulting from intense rainfall, e.g. percolating groundwater fronts, which may not connect with underlying long term groundwater tables.
- Landslide movement can result in the formation of

open cracks in the ground that can facilitate access of water into the landslide mass.

- Ponding of water or the disruption of surface water channels anywhere on or adjacent to the landslide can increase surface water infiltration into the landslide.
- Landslide movements may block groundwater flow paths through more permeable areas of the landslide, resulting in increased water pressures and further instability.
- Low permeability materials in landslides respond more slowly to changing groundwater conditions that can only be observed and understood through long term monitoring.

Groundwater investigations can either be observation type (direct determination of groundwater levels) or measurement type (determination of permeability or transmissivity). Refer to Table 24 for a summary of the groundwater investigation and testing methods for landslides.

In addition to the methods described in Table 24, further testing can be considered if the groundwater conditions in the underlying in-situ rock affect the landslide. The testing can include water pressure and / or permeability testing in the underlying rock mass (e.g., packer or lugeon testing).

TABLE 24: Summary of the groundwater investigation and testing methods for landslides

	Description	Testing standards	Applicability	Variants or similar alternatives	Outcome(s)	Advantages	Disadvantages	Things to note
Observation types	Open bores		All types of geology	-	Groundwater level	Early information on groundwater can be obtained. Drilling observations can be vital (e.g., water loss during drilling, or artesian pressure during drilling, etc.).	Readings can be inaccurate due to the effects of drilling. Groundwater level from different piezometric conditions (e.g., perched or aquifer water pressures) cannot be differentiated.	Readings should ideally be taken after a prolonged interruption in drilling (e.g., early morning, after the weekends). Care should be used where drilling used drilling mud or slurry, as this will give inaccurate groundwater level readings.
	Standpipe piezometer in boreholes (with manual reading)	SI3 of NZGS, 2017	All types of geology	Push-in or drive-point type piezometers are available.	Groundwater level	Simple and cost effective. Can easily be replaced if damaged.	Requires manual and recurrent effort to collect data. Data is slow, infrequent and can be inaccurate or misleading.	Not ideal when the landslide geology and hydrogeology is complex.
	Standpipe Piezometers in boreholes (with logger)	SI3 of NZGS, 2017 ASTM D 7764	All types of geology	Piezometers can be either pneumatic or vibrating-wire piezometers; the latter being the most common in NZ.	Groundwater level or pressure	Continuous data collection is possible.	Requires a borehole to be nested in. Requires specialist for installation, maintenance and upkeep.	Piezometer may initially require development. Very detailed information can be obtained using multi-port piezometers, but these are very expensive and usually difficult to justify.

TABLE 24: Summary of the groundwater investigation and testing methods for landslides (continued).

	Description	Testing standards	Applicability	Variants or similar alternatives	Outcome(s)	Advantages	Disadvantages	Things to note
Measurement types	Permeability test	S12.12-S12.13 of NZGS, 2017 BS EN ISO 22282-2	All types of geology	Falling head, rising head or constant head methods.	<i>In situ</i> permeability	Good for all types of soils.	Uncased sections of the borehole can contribute to the water inflow / outflow. These tests can be time consuming and can sometimes be inaccurate if readings are not taken at appropriate time intervals.	Drill holes for these tests should use clean water. Careful selection of the hydraulic gradient is recommended (too high a gradient can cause the test hole to be deformed).
	Dissipation test	S12.2.5 of NZGS, 2017 ASTM D5778	Silts and clays	-	Calculated (horizontal) permeability	Can be conducted at the same time as a CPT test being carried out.	Limited use for landslides due to narrow applicability.	Opportunity for testing can be missed if geology of the site is not known beforehand.
	Pumping test	S12.15 of NZGS, 2017 BS ISO 14686	All types of geology	Can be carried out as a step test or constant drawdown test.	<i>In situ</i> permeability or transmissivity of geological units and aquifer systems	Accurate determination of hydrogeologic conditions. Test reflects the global groundwater conditions, compared to other tests that are generally local.	Requires significant instrumentation and monitoring. Requires time to setup and carry out the test. Can be costly and therefore limited in use to large landslides where dewatering is considered as a stabilisation option.	An array of piezometers around the pump test borehole is required. These require good positioning and instrumenting to capture the groundwater response to the pumping test.

6 FIELD INSTRUMENTATION FOR LANDSLIDE MONITORING

Field instrumentation can provide valuable information on the distribution and rate of movement of incipient and fully developed landslides. Instrumentation is commonly installed either on the ground surface or in boreholes and provides supplementary information to that collected from surface observations and other subsurface investigation techniques. Instrumentation can be used in the following situations to obtain specific information including:

- Determination of baseline conditions.
- Locating active failure surfaces within the landslide.
- Determining the rate of landslide movement.
- Determining the depth and shape of the landslide to support the calculation of strength parameters at failure and the design of remedial measures.
- Monitoring marginally stable natural or cut slopes, or embankments and the effects of construction work or rainfall on the slopes.
- Monitoring groundwater levels or porewater pressures.

Some benefits of a well-planned monitoring system include:

- Allowing the installation of remote monitoring and alarm systems that can send alerts and alarms indicating potential, imminent or actual movements.
- Allowing the monitoring and evaluation of the performance and effectiveness of landslide control measures.
- Enhanced safety outcomes.
- Feedback into construction control.
- Demonstrating compliance with consent conditions.
- Providing public or stakeholder assurance.
- Advancements in understanding.

Instrumentation and monitoring can play a vital role in the understanding of landslide behaviour when well-planned and executed. When a system is unreliable in either data capture or data veracity, confidence in the system is eroded and the value is missed.

“Full benefit can be achieved from geotechnical instrumentation programs only if every step in the planning and execution process is taken with great care” (Dunncliffe, 1993).

6.1 PLANNING A LANDSLIDE MONITORING SYSTEM

The design of a landslide monitoring system needs to take the following considerations into account:

1. Engineering geological model – Determined following the techniques and methods to investigate the landslide set out in this Unit and prepared using guidance set out in Part 5 of Unit 1.
2. Landslide mechanism/s – This may be known or suspected through the surface and subsurface

investigation methods, such as engineering geological mapping and boreholes; instrumentation may be required to gain sufficient certainty.

3. Purpose of the instrumentation – e.g., Establish baseline conditions, verify assumptions, provide early warning system, monitor performance of mitigation measures.
4. Parameters to be monitored – Determined by understanding of the critical factors affecting the landslide movement and the effects of the landslide on potentially affected parties.
5. Expected rate of movement – Determined by landslide mechanism and engineering geological model.
6. Environmental factors – e.g., Extreme (high or low) temperatures, vandalism, dust / mud, power supply, potential for damage from construction plant, corrosive soil or groundwater, humidity.
7. Accessibility – Remote location vs urban areas, unsafe conditions, access to control / reference points.
8. Risk / Stakeholders / affected parties – What are the consequences of failure and what or who is affected by this? How quickly does information need to be gathered, processed and reported.
9. Availability and accessibility – What monitoring sensors are readily available, and, based on site accessibility, what power and communications options are suitable?
10. Communication of data – Does the sensor information need to be integrated into a Trigger Action Response Plan (TARP) or other alert / alarm-based system with formalised protocols for action if trigger levels are exceeded? Consider end users, usability and longevity of any data communications or data display system.

Once all these variables are recorded, assessed and understood, the task of instrument selection can begin. Over the course of a project the elements that need to be understood or the interpretations may change so ongoing review is required to ensure that the monitoring system remains fit for purpose.

Figure 22 illustrates the generalised locations of instrumentation on a typical landslide, see section 6.4 for further details on instrument types.

6.2 MONITORING METHODS CONSIDERATIONS

Instrumentation typically aims to measure crack opening, landslide movements and groundwater levels or porewater pressures. The types of instrumentation, instrument layout and monitoring requirements will be determined by the type and scale of the landslide, the needs and stage of the project, structures / infrastructure impacted (or potentially impacted) and the available budget. Instrumentation varies greatly in cost and degree of sophistication.

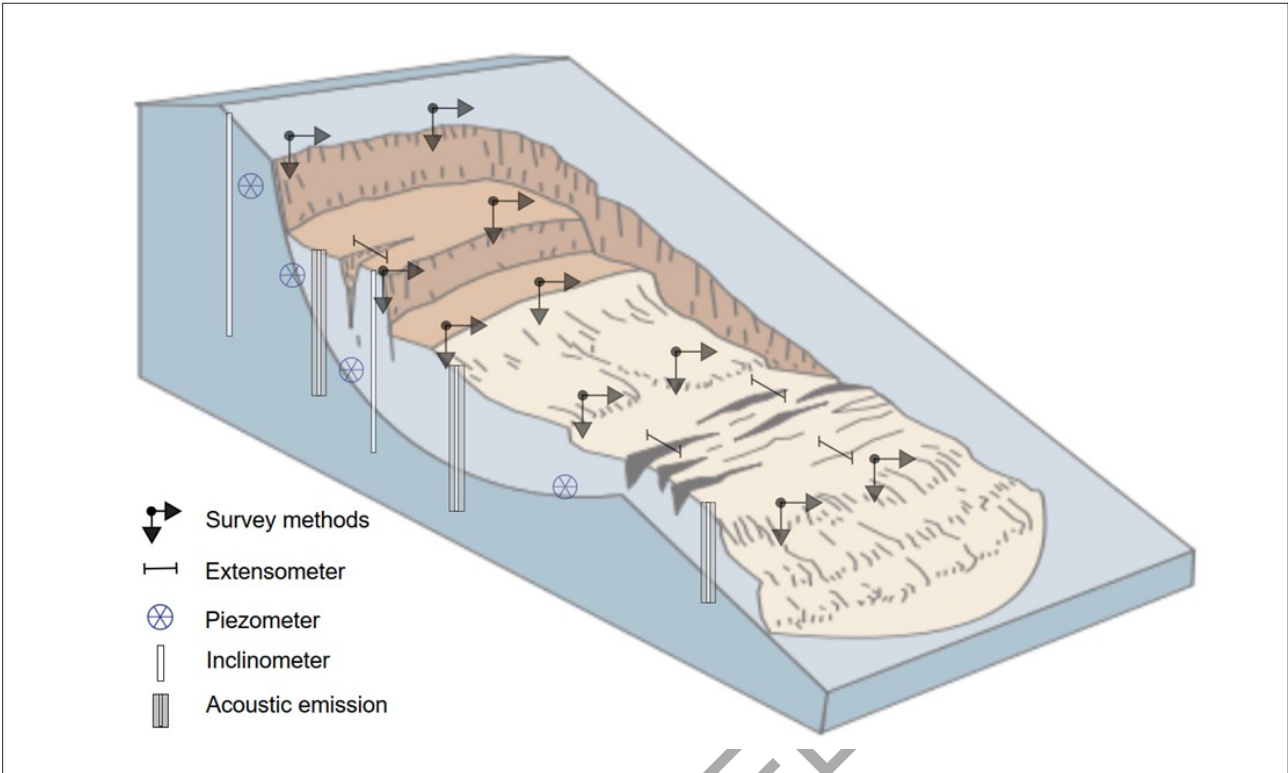


FIGURE 22: Schematic of typical landslide monitoring installation locations

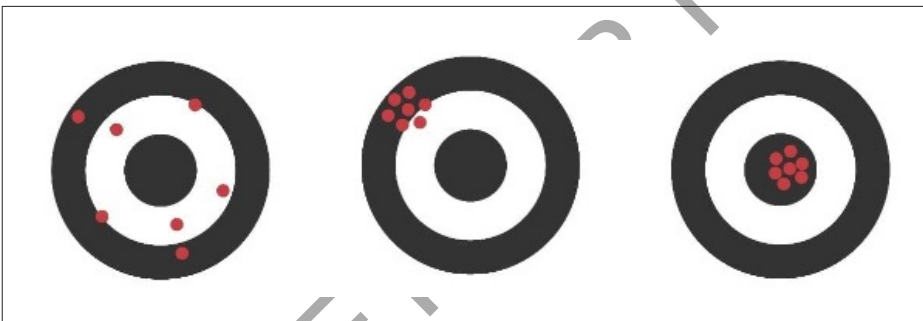


FIGURE 23: Accuracy vs Precision (Left: Not precise but accurate on average, centre: precise but not accurate - even when averaged, right: accurate and precise)

In the early stages of a landslide investigation, simple surface located survey marks and crack- or tilt-meters and a rain gauge might be installed to help understand the way the slope is behaving and its sensitivity to rainfall. This may help the development of the engineering geological model.

The location of instrumentation for long term monitoring needs to be based on a good understanding of the engineering geological model and groundwater conditions so that meaningful and useful information can be obtained. For example, if movements are large or the shear surface is well defined then crude and simple movement instrumentation could be used, whereas if movements are small and the depth of movement is uncertain, then more precise

instrumentation should be considered. Depending on the project and need for precise instrumentation, a well-defined landslide with ongoing movement could also warrant the need for precise telemetered instrumentation to be installed.

The following sections outline considerations in the instrument selection process.

6.2.1 Accuracy vs Precision vs Resolution

A sensor or type of monitoring device will have inherent accuracy based on the technology of that instrument. Precision can also be affected by environmental factors and potential user error. Figure 23 shows the relationship between accuracy and precision.

Accuracy can be defined as a measure of how close to the true value a measurement actually is.

Precision is a measure of the repeatability of readings obtained by a method.

Resolution relates to the range over which a value can be applied. For landslide monitoring this can apply to a number of considerations.

6.2.1.1 Measurement range

Measurement range is defined as the range of movement a particular sensor or instrument is able to detect. High-precision geotechnical instruments are more suited to slower moving landslides or parts of landslides with smaller overall movements predicted. Landslides with larger predicted movements require instruments that can operate over the larger scale. Often, different parts of the landslide will require different ranges.

6.2.1.2 Spatial Resolution

A measure of the area over which the observation can be made. Individual precision instruments provide a small area of application, whereas a wide network of survey targets, for example, can provide a much higher resolution. Multiple-precision instruments can be installed to increase the spatial resolution of the overall system; however, this should be balanced by the cost and overall benefit.

In a landslide context, it is beneficial to use instruments with different spatial resolutions, for instance, photogrammetry methods allow overall trends across the whole area of the landslide as opposed to specific widening of a tension crack as detected by an extensometer. Spatial resolution can apply in plan view, for example the density of prism targets across a landslide, in section or locally such as in the case of closely spaced shape array nodes installed within a borehole.

6.2.1.3 Temporal Resolution

The smallest amount of time between readings at an exact same location. Whilst it is possible to manually monitor geotechnical instrumentation hourly on an ongoing basis, this is onerous and expensive, and it is therefore considered that manual monitoring has low temporal resolution. Automated systems, normally connected to telemetry can provide very high temporal resolution, however, this has cost and other implications. A slow-moving landslide may only require

periodic monitoring of a parameter that is not expected to vary a great deal in response to environmental factors. For fast moving landslides or ones which are sensitive to rapidly changing environmental conditions a system with higher temporal system is required.

6.2.2 Absolute Vs Relative

Relative monitoring refers to data that is related to other observed points, e.g., distance between two points on the ground. Absolute monitoring is related to a grid reference system, e.g., prisms and total station monitoring. In many cases, monitoring relative movements is sufficient as this provides rates and magnitude of movement, however, these readings are taken in isolation and do not necessarily relate to other features of the landscape.

By relating measurements to a grid reference system, appropriate to the scale of the landslide, absolute displacements can be obtained. Absolute displacements enable a more thorough overview of the landslide to identify areas of interest and any changes occurring within them. Determination of absolute movements requires reference stable points outside the influence of the landslide. Whilst this generally relates to surface monitoring, sub-surface relative monitoring can also be linked to surface survey methods to provide absolute monitoring data.

6.2.2.1 Automated vs Manual

There are obvious advantages for the use of automated systems coupled with telemetry to remotely monitor landslides, such as increased temporal resolution, rapidity of receiving and reviewing data, reduced long term costs, improved health and safety outcomes and lower environmental impact due to fewer site visits.

The benefit of manual systems is that they allow important information to be collected by the site operatives undertaking the work. Landslides are often identified by dynamic observations on any changes to seepage, tension cracks etc. Subtle changes on the slope may not be picked up by the instrumentation unless it is designed and located to do so. An experienced engineering geologist with knowledge of the site is likely to identify these changes during routine site observations.

“An instrument too often overlooked in our technical world is a human eye connected to the brain of an intelligent human being.” Peck (1972)

6.3 SPECIFICATIONS FOR MONITORING

Robust specifications for the monitoring instruments should be completed prior to the installation phase. The specifications should cover the following, as a minimum:

- Installation procedures.
- Monitoring procedure.
- Maintenance programmes.
- Calibration requirements.
- Data format.
- Baseline period.
- Frequency of monitoring.
- Any trigger values and alert mechanisms.
- Reporting requirements.
- Decommissioning requirements.
- Ancillary event-based data to collect (potential causes of movement).

6.4 INSTRUMENTATION SELECTION

In general terms, when monitoring landslides, the parameters that require measuring are related to deformation and groundwater / pore pressure. The options for measuring these can be further subdivided into surface and subsurface monitoring techniques, with various options within each category.

Each technique has its own merits and disadvantages, and some are better suited to different landslide types. Understanding the techniques is critical in the development of the monitoring strategy, and it is often recommended to have multiple complementary monitoring systems installed to address the limitations. Complementary systems provide a backup to the primary system in the case of potentially erroneous results or in the event of instrument failure. No single technique or instrument can provide complete information about a landslide and therefore various combinations are usually employed (Uhlemann et al., 2016).

6.4.1 Surface deformation measurement instrumentation

Surface deformation measurement instrumentation ranges in cost and precision and common methods are summarised in Table 25. Other methods are available and may be considered once researched and the benefits and limitations are understood for the landslide being assessed. Generalised relative ratings of attributes are included in Table 25 using a Low (L), Medium (M), or High (H) framework. Automated (A) and manual (M) options are also indicated in the table. Figure 22 illustrates the generalised locations of instrumentation on a typical landslide.

6.4.2 Subsurface deformation measurement instrumentation

Subsurface ground displacement instrumentation is usually installed in boreholes and can range in precision and cost. Commonly used subsurface deformation measurement instrumentation is summarised in Table 26. Boreholes drilled with the intent of installing inclinometers should be extended several metres below the landslide and into undisturbed ground so that the basal shear surface can be identified and the rate of movement along it measured, while attaining base fixity for the inclinometer (i.e. a stable zone against which deformations can be calibrated). The base fixity zone should be several meters long.

Many of the errors prevalent in inclinometer data can be attributed to issues during drilling or installation. Drilling of boreholes for inclinometer installation should be supervised by an experienced engineering geologist or geotechnical engineer familiar with the context of the landslide being monitored. Careful logging should be undertaken to identify any potential shear surfaces. A specification should be issued to the contractor that provides details of grout stiffness and tube orientation. Installation of inclinometer tubing should be supervised by the geologist or engineer to issues such as minimise tube curvature, inclination, groove misalignment and introduction of debris.

TABLE 25: Summary of surface deformation measurement instrumentation

Category	Type	Attribute							Typical applications
		Temporal	Spatial	Range	Accuracy	Precision	Cost	Auto/Manual	
Survey (See section 4.3, Table 14 for further details)	Manual	L	L	H	M	L	L	M	Cost effective way to monitor slow-moving, lower risk landslides. Data collected as part of manual survey can be affected by errors that may not be picked up until the data is processed leading to uncertainty in data interpretation. The low temporal resolution means that environmental effects and trends may not be discernible in the data.
	Total station (TS) using electronic distance measurements (EDM)	H	M	H	H	H	H	A/M	The method comprises a series of prisms or targets installed across the landslide, which are measured using a total station. Total station measurements must be referenced to multiple stable points outside the zone of movement. Errors can result from prisms being knocked, atmospheric conditions, incorrect setup of the total station, or if reference points are not located outside of the zone of movement. This can be an automated total station method (ATS) to provide near real-time survey of prisms. This method has been used successfully on the monitoring of the Ngaio Gorge Road Rockslide as part of an early warning system used during landslide remediation works (Stewart, 2022).
	GPS/GNSS	H	M	H	H	H	M	A	Production of lower cost receivers in recent years has made the use of GPS / GNSS more viable on a wider scale. They can therefore be used as alternative to TS. Clear line of sight to the sky is required which would preclude their use in built up or vegetated areas. Horizontal accuracy is more reliable than the vertical which is impacted by slope angle, satellite coverage and environmental factors. TS and GPS / GNSS systems require various processing and correction routines and are normally provided by specialist suppliers.
	Spatial Change Detection, e.g. Drone	M	H	H	M	L	M	M	Spatial change detection methods, for example, multi-temporal drone photogrammetry and / or LiDAR surveys can be a very effective method of mapping overall landslide movement over a wide area. It is often used to corroborate expected behaviour or help to understand complex landslide mechanisms and direct sub-surface deformation monitoring installations.
Extenso-meters	Tape	L	L	M	L	L	L	M	Extensometers can be used at all scales within various parts of a landslide, but most have limited range. At their most basic, manual variants are often deployed across observed tension cracks to provide data on progressing or stalled landslides. The choice of measuring device will be influenced by the expected rate of movement. Measurements are subject to gross error in poor reading practices or by failing to use the same measuring device on each visit. Sensitive landslides or structures can be monitored using electrical versions that can provide real time monitoring.
	Calliper	L	L	L	H	H	L	M	
	Wire	L	L	M	M	M	L	M	
	Mechanical - Tape	L	L	M	L	M	M	M	
	Mechanical - Wire	L	L	M	M	H	M	M	
	Mechanical - Rod	L	L	L	H	H	M	AM	
Electrical	H	L	L	H	H	M	A		
Tilt-meters	Mechanical	L	L	H	H	L	L	M	Best used across scarps or on blocks or stakes within a landslide mass. They are lightweight, easy to interpret and of relatively low cost. Can be manually connected to data collection platforms to record and relay information in real time and provide alerts to phones. Mechanical versions are unlikely to be used due to the low-cost and prevalence of accelerator-type sensors. For higher accuracy applications, it is recommended that the Electrolytic sensors are specified. Tiltmeters can be installed as single nodes on existing structures or blocks. They can be mounted on a beam across a landslide head where a rotational component is suspected. They may also be mounted on shallow stakes within the head, main body or foot to derive general movement characteristics.
	Accelerometer (MEMS)	H	L	M	M	M	M	A	
	Electrolytic	H	L	H	H	H	H	A	

TABLE 26: Summary of sub-surface deformation measurement instrumentation

Category	Type	Attribute							Typical applications / considerations
		Temporal	Spatial	Range	Accuracy	Precision	Cost	Auto/Manual	
Shear Probe	Steel rod	L	L	L	L	L	L	M	Provides approximate position of shear surface as measured in a standpipe installed within a borehole. Can be used to quantify amount of movement but with low accuracy and limited range. Effective at determining target depth for further analysis using more sophisticated means.
Inclinometers	Traversing Probe	L	L	M	H	M	M	M	Traverse probes can be lowered down the borehole to measure horizontal displacements at nominated depth intervals. This data is analysed in a variety of ways, either by individual movement at discrete depths over time or by accumulating the movement to provide a profile of apparent horizontal deformation with depth. These are the most widely used instruments for measurement of small amounts of ground creep or shear zone movement. Better suited for determining baseline conditions and for slow moving landslides. May be used to identify shear zone locations before installing an automated system to monitor more dynamic situations.
	In-Place	H	L	M	H	M	H	A	In-place inclinometers (IPI) provide more accurate measurements and continuous readings which can be relayed remotely. These are more appropriate to use where the depth of the shear surface is known, and the goal is to determine the rate of movement. Provision of regular (hourly / daily) data allows for correlations to other triggering factors. Limited range of movements mean that these are better suited to landslides or parts of landslides that exhibit slower rates of movement.
	Shape Array	H	L	H	H	H	H	A	Shape accelerometer arrays (SAA) are essentially a chain of rigid segments connected by flexible joints that are designed to resist twisting but allow the segments to tilt in any direction. They were historically inserted into a small diameter plastic pipe before being installed down the borehole, but more recently most systems are designed to be installed inside conventional inclinometer casing. Their flexibility is a significant benefit when compared to other sub-surface deformation sensors. This allows for a large range of movement to be detected. Provision of regular (hourly / daily) data allows for correlations to other triggering factors SAA have an advantage over IPI in sensor spacing allowing for finer vertical resolution. Cost is the main disadvantage of the SAA system. As such they are often best suited to landslides where large movements are expected and where the risks justify the costs of installing the system. Sensors may be re-used if they remain undamaged over the course of the project.
Acoustic Emission Monitoring		H	L	H	H	L	M	A	Acoustic emissions (AE) are generated in a landslide setting due to frictional forces at soil particle interfaces. AE monitoring is designed to detect these subsurface movements by installing a steel tube “waveguide” within a borehole backfilled with a granular medium (gravel or sand). An AE sensor is attached to the top of the tube. AE monitoring systems can be sensitive, and it is recommended that a suitable baseline period is specified to determine background noise errors which can be filtered. AE systems are primarily used as displacement rate sensors to provide an activity status for the slope and are therefore useful in the context of early warning systems for early predictions of slope movements. Lower costs than IPI and shape arrays means that more monitoring locations can be considered, increasing overall spatial resolution.

6.4.2.1 Other options

Other movement measurement methods that can be installed in boreholes could include extensometers or strain meters and these may be considered by the geoprofessional if the ground model, landslide mechanism and project budget allow. For example, borehole extensometers installed across the slide base have been used to monitor the slow-moving landslides of the Clyde Dam reservoir, utilising drainage tunnels for access (Macfarlane, 2009).

6.4.3 Groundwater and rainfall monitoring

The specification of groundwater monitoring on a landslide is often an iterative process and may follow a period of investigative monitoring to determine the location of shear surfaces around which it would be desirable to install vibrating wire piezometers to monitor changes in porewater pressure.

Often, the primary triggering mechanism for landslides within New Zealand is rainfall. Developing an understanding of the hydrogeological factors influencing landslide movement is key to most mitigation solutions and trigger action response plans. Whilst regional and local rainfall data may be available for the area of interest, consideration should be given to installing weather stations including rain gauges to monitor site-specific conditions for the most accurate representation of the potential triggering mechanisms.

Using methods described in Section 5.4.2, groundwater levels and pressures can be recorded over long periods to determine changes in groundwater levels in response to rainfall. This data can be used to observe at what critical level or pressure the landslide reactivates. For example, groundwater monitoring at

two large landslides in the central North Island has been effectively used to help determine trigger levels for landslide movement as well as the effect of rainfall events and antecedent rainfall on landslide stability.

6.5 DATA ANALYSIS

Once installed, it is vital that instrumentation is constantly monitored to identify trends in data that could indicate movement or potential error. More often than not, instrumentation is designed to observe trends and therefore, sudden, unexpected changes may often be attributed to errors. These errors could be systematic (inherent to instrument), gross (user or processing) or environmental.

Understanding that these issues exist is key to resolving them. Incorporating them into the planning phase is an important fail safe and another reason for adopting multiple instrument types within a monitoring system to help corroborate observations and provide redundancy in the case of failed or compromised instruments.

Some common issues with data are listed in Table 27. Given the potential for all monitoring systems to generate erroneous observations, it is recommended that post processing and assessment of data is undertaken on readings before the issuing of alerts to stakeholders on automated “real-time” systems.

For early warning systems, the LANDAWARE community (international network on landslide early warning systems) have developed a set of resources that may be of use when designing such systems <https://www.landaware.org/>

TABLE 27: Common sources of error in monitoring systems

Type	Root cause	Detail	Example
Environmental	Diurnal fluctuation	Cyclic changes from day to night mostly attributed to temperature changes	Optical systems often display cyclic behaviour, manual readings should target similar conditions. Automatic systems will clearly display the effect
	Humidity	Most electronic equipment has a specified tolerance for humidity, site conditions outside this range may affect performance of devices.	A data logger enclosure without ventilation may experience condensation, potentially affecting operation.
	Seasonal fluctuation	Cyclic changes related to seasonal fluctuation of temperature or groundwater	Pore pressures or groundwater levels will naturally vary with the seasons. Establishing these fluctuations is an important part of the baselining period
	Vibration	Vibration can damage instrumentation or cause erroneous readings	Acoustic emission monitoring is likely to detect vibrations within the monitoring area. Potential sources of vibration should form part of a monitoring system data collection specification.
	Physical	Damage to instrument from external elements (e.g. construction plant, animals, vandalism)	Monitoring prisms and tiltmeters can be knocked leading to sharp, unexpected changes.
	Atmospheric pressure	Example of a variable that may not be accounted for in sensor data	Fluctuations in atmospheric pressure may affect the “apparent level” in a well with some sensor types if there is no local measurement of atmospheric pressure to carry out a correction.
Systematic	Linearity	The assumption that an instrument retains the same level of precision or accuracy at all ranges	Manual and mechanical extensometers are likely to produce less accurate readings over greater distances.
	Calibration	Assumption that the calibration remains constant across time	Water pressure transducers will often exhibit drift over time.
	Precision	The inherent spread of results native to the instrument or system	The repeatability of manual survey data is often reported as being within the bounds of precision. This may be affected by the type of instrument but also by survey practice and environmental factors. Trends should be monitored rather than individual readings.
	Unstable reference points	Monitoring relates all readings to a stable reference point to base movement from a baseline. Where this assumption is incorrect, total movements may be misrepresented.	Inclinometer that does not extend deep enough to ensure the base is stable as a reference point.
Gross error	Poor data collection	Inconsistent readings of instrument, normally manual reading.	Dip meter readings in standpipes are subject to user error due to simple mistakes by users.
	Processing error	Raw units from sensors are processed into engineering units via a system, often “black box”. Errors here are normally widespread and do not just affect one sensor in isolation.	Missed observations of reference prisms by the ATS can lead to a shift in all survey targets. This should be apparent in all survey targets and should be identified in post processing before issuing of alerts.
	Poor installation	Data interpretation is undertaken on the assumption that the installation has been undertaken as specified, errors may be present if this is not true.	Curvature of inclinometer tubing or incorrect orientation of tube groves leading to over or under-representation of movement.
	Cumulative error	For sensors configured to work in series, any error (systematic, environmental or gross) can be compounded.	Borehole inclinometer readings are often depicted as cumulative profiles providing a potentially erroneous impression of the shape of the inclinometer tubing due to cumulative error. Individual tilt may be more indicative of zones of movement.

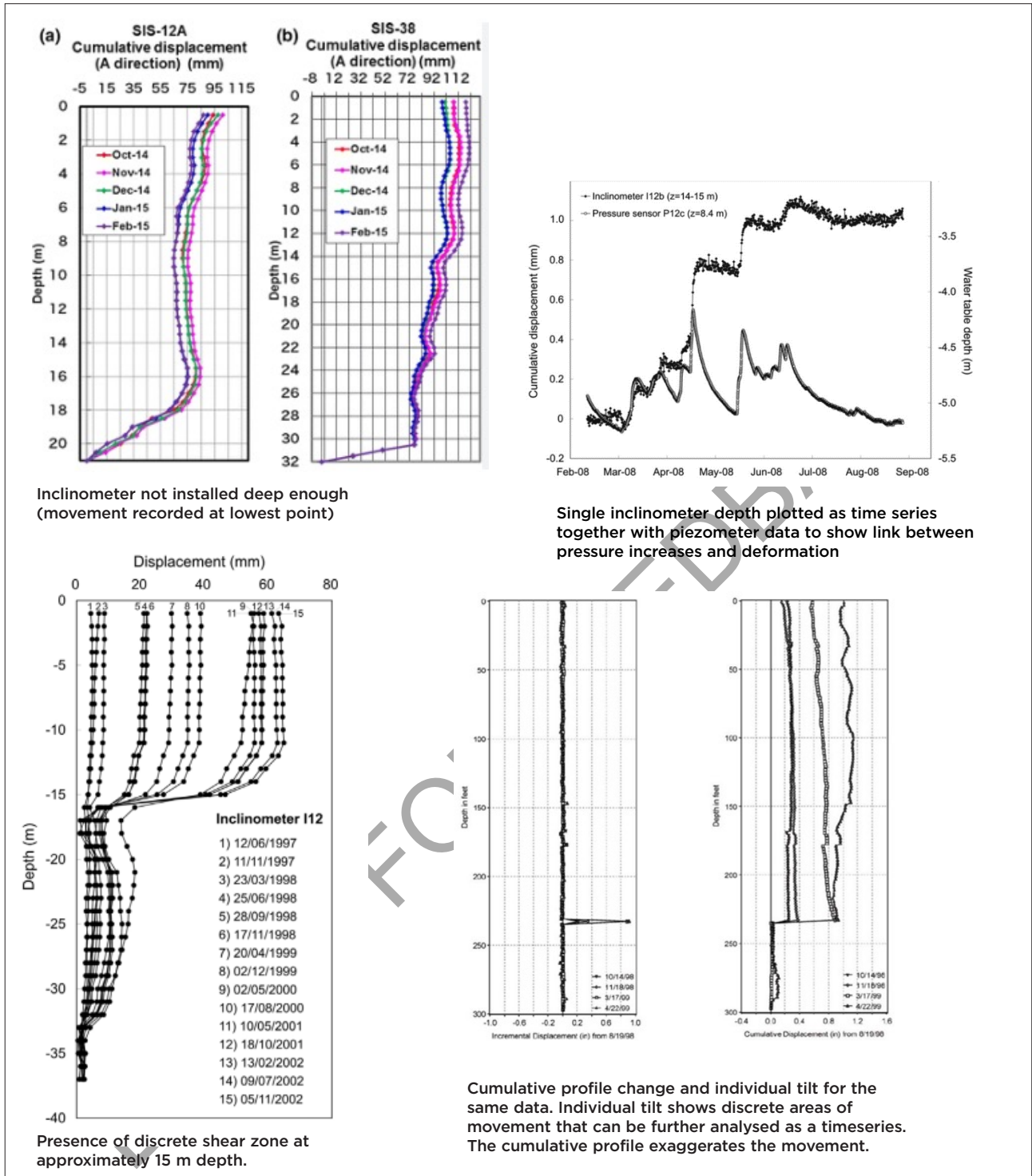


FIGURE 24: Inclinometer data plots; some good; others symptomatic of error

The interpretation of monitoring data should be undertaken or overseen by an experienced individual that has a thorough understanding of the following:

- Limitations of the system (accuracy, precision, range, etc)
- The EGM
- Context of the landslide
- Any ongoing events that may affect the ground response or sensor readings

Inclinometers are perhaps the most widely used subsurface deformation measurement method. They are also the most prone to misinterpretation due to issues with installation, errors in reading or in presentation of data. A thorough guide on inclinometer data analysis is presented in Stark & Choi (2008).

Common inclinometer data issues are shown in Figure 24.

6.6 DURATION OF MONITORING

The duration of the monitoring period for the types of instruments described in Section 6 is usually dependent upon project size and complexity. Small landslides affecting residential development are less likely to be monitored over long time periods than large landslides affecting infrastructure or transport corridors that may need to be monitored over a much longer period of time, or in some cases, indefinitely (the Lake Dunstan landslides for example).

Because of the relatively low cost to install loggers into boreholes it is becoming more common that they can be left to collect groundwater readings over a longer period. Likewise, prisms can be installed on the ground surface to allow total station or remote monitoring to be undertaken at relatively low cost.

It is important to allow time for “baselining” of sensors to be carried out. This can be used to define not only the starting conditions of the landslide but also to understand the effects of potential errors within the system.

7 REFERENCES

- Alhalaby, N., & Whyte, I. (1994). The impact of ground risks in construction on Project finance. London: Thomas Telford Services Ltd.
- Auckland Council (2023). The Auckland Code of Practice for Land Development and Subdivision. Chapter 2: Earthworks and Geotechnical. Version 2.0, May 2023. Auckland Council. <https://www.aucklanddesignmanual.co.nz/media/ujnl3q4u/cop-chapter-2-v2.pdf>
- AGS (2007a). Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning. Journal and News of the Australian Geomechanics Society, Vol. 42, No. 1. <https://landsliderisk.org/resources/guidelines/>
- AGS (2007b). “Commentary on Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning. Journal and News of the Australian Geomechanics Society, Vol. 42, No. 1. <https://landsliderisk.org/resources/guidelines/>
- AGS (2007c). Practice Note Guidelines for Landslide Risk Management 2007. Journal and News of the Australian Geomechanics Society, Vol. 42, No. 1. <https://landsliderisk.org/resources/guidelines/>
- AGS (2007d). Commentary on Practice Note Guidelines for Landslide Risk Management 2007. Journal and News of the Australian Geomechanics Society, Vol. 42, No. 1. <https://landsliderisk.org/resources/guidelines/>
- AGS (2007d). The Australian GeoGuides for Slope Management and Maintenance. Journal and News of the Australian Geomechanics Society, Vol. 42, No. 1. <https://landsliderisk.org/resources/guidelines/>
- Baum, R.L., Galloway, D.L., and Harp, E.L. (2008), Landslide and land subsidence hazards to pipelines: U.S. Geological Survey Open-File Report 2008-1164, 192 p. https://pubs.usgs.gov/of/2008/1164/pdf/OF08-1164_508.pdf
- Bayer B, Simoni A, Mulas M, Corsini A, Schmidt D (2018) Deformation responses of slow moving landslides to seasonal rainfall in the Northern Apennines, measured by InSAR. *Geomorphology* 308:293-306. <https://doi.org/10.1016/j.geomorph.2018.02.020>
- Bazin, S (2012). SafeLand guidelines for landslide monitoring and early warning systems in Europe - Design and required technology. Work Package 4.3 – Evaluation and development of reliable procedures and technologies for early warning. Rev no 1, March 2012
- Buxton, D. (2021). Let the Terrain Do The Talking - Understanding Landscapes from Aerial Photos and LiDAR (Australian Geomechanics Society) <https://www.nzgs.org/event/online-webinar-let-the-terrain-do-the-talking-understanding-northland-landscapes-from-aerial-photos-and-lidar-terrain-models/>
- Battulwar, R., Zare-Naghadehi, M., Emami, E., & Sattarvand, J. (2021). A state-of-the-art review of automated extraction of rock mass discontinuity characteristics using three-dimensional surface models. *Journal of Rock Mechanics and Geotechnical Engineering*, 13(4), 920-936.
- Baynes, F. J and Parry, S (2024). Guidelines for the Development and Application of Engineering Geological Models on Projects. Version 2.0. IAEG Commission 25 Publication No. 1, 81 pp. <https://iaeg.info/wp-content/uploads/2024/09/IAEG-C25-EGM-Guidelines-v2.0-4-9-August-2024.pdf>
- Bratton, S. (2012). Sonic drilling in support of geotechnical investigation and geo-construction. *Geo-Strata—Geo Institute of ASCE*, 13(2), pp. 24-31.
- Colesanti C, Wasowski J (2006) Investigating landslides with space-borne Synthetic Aperture Radar (SAR) interferometry. *Engineering Geology* 88(3-4): 173-199. <https://doi.org/10.1016/j.enggeo.2006.09.013>
- Crosetto, M., Monserrat, O., Cuevas-González, M., Devanthery, N., & Crippa, B. (2016). Persistent scatterer interferometry: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, 115, 78-89.
- Daghigh, H., Tannant, D. D., Daghigh, V., Lichti, D. D., & Lindenbergh, R. (2022). A critical review of discontinuity plane extraction from 3D point cloud data of rock mass surfaces. *Computers & Geosciences*, 169, 105241. <https://doi.org/10.1016/j.cageo.2022.105241>
- De Vilder, S.J. and Massey, C.I. (2024). Guidelines for natural hazard risk analysis on public conservation lands and waters – Part 2: preliminary hazard and exposure analysis for landslides. GNS Science Consultancy Report 2024/36. Prepared for Department of Conservation.
- de Vilder, S.J., Kelly, S.D., Buxton R.B., Allan, S., Glassey, P.J. (2024) Landslide planning guidance : reducing landslide risk through land-use planning. Lower Hutt, NZ: GNS Science. GNS Science miscellaneous series 144. 84 p.. doi: 10.21420/R2X8-FJ49

- Feng, Q., Röshoff, K. (2015). A Survey of 3D Laser Scanning Techniques for Application to Rock Mechanics and Rock Engineering. In: Ulusay, R. (eds) *The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014*. Springer, Cham. https://doi.org/10.1007/978-3-319-07713-0_25
- Ferretti A, Monti-Guarnieri AV, Prati CM, Rocca F, Massonnet D (2007) *INSAR Principles B*. ESA publications.
- Ferretti, A., Prati, C., Rocca, F., 2001. Permanent scatterers in SAR interferometry. *IEEE TGRS* 39 (1), 8-20.
- Ferretti A (2014) *Satellite InSAR Data: Reservoir Monitoring from Space (EET 9) (1st ed.)*. EAGE. [10.1109/MGRS.2015.2398392](https://doi.org/10.1109/MGRS.2015.2398392)
- FHWA (2014). *Distress Identification Manual for the Long-Term Pavement Performance Program (Fifth Revised Edition)*. Report No. FHWA-RD-03-031. Federal Highway Administration. Office of Infrastructure Research and Development, 142p. <https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/13092/13092.pdf>
- Gkeli, E. X., Efraimidis, C.F., Argyriadi, D., (2015). Geotechnical challenges during design and construction of high rock cuts in mountainous terrain - The case of Egnatia Odos vertical axe 75 in Greece. *Proceedings Australia New Zealand Conference on Geomechanics*, Wellington, 2015, 468-475.
- Griffiths, J.S. (2005). Landslides. In (eds.) Fookes, P.G., Lee, E.M. and Milligan, G., *Geomorphology for Engineers*. pp.173-217. Whittles Publishing.
- Highland, L.M., and Bobrowsky, P. (2008). *The landslide handbook—A guide to understanding landslides*. Reston, Virginia, U.S. Geological Survey Circular 1325, 129 p. https://pubs.usgs.gov/circ/1325/pdf/C1325_508.pdf
- Hu J, Li Z, Ding X, Zhu J, Zhang L, Sun Q (2014) Resolving three-dimensional surface displacements from InSAR measurements: A review. *Earth Science Reviews* 133:1-17. <https://doi.org/10.1016/j.earscirev.2014.02.005>
- Hungr O, Leroueil S, Picarelli L (2014) The Varnes classification of landslide types, an update. *Landslides* 11(2):167-194. <https://doi.org/10.1007/s10346-013-0436-y>
- ISRM, I. (1978). Suggested methods for the quantitative description of discontinuities in rock masses. *Int J Rock Mech Min Sci Geomech Abstr*, 15(6), 319-368. [https://doi.org/10.1016/0148-9062\(79\)91476-1](https://doi.org/10.1016/0148-9062(79)91476-1)
- Jongmans, D., & Garambois, S. (2007). Geophysical investigation of landslides : a review. *Bulletin de la Societe Geologique de France*, 178(2), 101-112 <http://dx.doi.org/10.2113/gssgfbull.178.2.101>
- Khalil RZ (2018) InSAR coherence-based land cover classification of Okara, Pakistan. *The Egyptian Journal of Remote Sensing and Space Science* 21:S23-S28. <https://doi.org/10.1016/j.ejrs.2017.08.005>
- Lato, M., Bobrowsky, P. T., Roberts, N., Bean, S., Powell, S., McDougall, S., Brideau, M. -A., Stead, D. & VanDine, D. (2016). Site investigation, analysis, monitoring and treatment, Canadian technical guidelines and best practices related to landslides: a national initiative for loss reduction. Geological Survey of Canada, Open File, 8114. <https://doi.org/10.4095/299117>
- Macfarlane, D. F. (2009). Observations and predictions of the behaviour of large, slow-moving landslides in schist, Clyde Dam reservoir, New Zealand. *Engineering Geology*, 109(1-2), 5-15. <https://doi.org/10.1016/j.enggeo.2009.02.005>
- Massey, C. I., Petley, D. N., McSaveney, M. J., & Archibald, G. (2016). Basal sliding and plastic deformation of a slow, reactivated landslide in New Zealand. *Engineering Geology*, 208, 11-28. <https://doi.org/10.1016/j.enggeo.2016.04.016>
- McGuffey, V.C., Modeer Jr., V.A., & Turner A.K. (1996). Subsurface Exploration. In (eds.) Turner, A.K. and Schuster, R.L. *Landslides Investigation and Mitigation*. Transportation Research Board Special Report, (247). Washington DC. <http://onlinepubs.trb.org/Onlinepubs/sr/sr247/sr247.pdf>
- Moreira A, Prats-Iraola P, Younis M, Krieger G, Hajnsek I, Papathanassiou KP (2013) A tutorial on synthetic aperture radar. *IEEE Geoscience and remote sensing magazine* 1(1): 6-43. [10.1109/MGRS.2013.2248301](https://doi.org/10.1109/MGRS.2013.2248301)
- MSU (2023). Mole Drains. Michigan State University Extension Bulletin E3452. Michigan State University. <https://www.egr.msu.edu/bae/water/drainage/mole-drains>
- NSW RMS (2014). *RMS Guide to Slope Risk Analysis, Version 4*. New South Wales: NSW Transport Roads and Maritime Services.
- NZGS (2005). *Field description of soil and rock. Guideline for the field classification and description of soil and rock for engineering purposes*. New Zealand Geotechnical Society. <https://fl-nzgs-media.s3.amazonaws.com/uploads/2022/06/NZGS-2005-Field-description-of-soil-and-rock-3.pdf>
- NZGS (2017). *New Zealand Ground Investigation Specification. Volume 1 – Master Specification*. New Zealand Geotechnical Society. <https://www.nzgs.org/libraries/nz-ground-investigation-specification/>
- NZGS & MBIE (2021). *Earthquake Geotechnical Engineering Practice: Module 2. Geotechnical investigations for earthquake engineering. Revision 1, November 2021*. New Zealand Geotechnical Society (NZGS) and Ministry of Business Innovation & Employment (MBIE). <https://www.building.govt.nz/building-code-compliance/b-stability/b1-structure/module-2-geotechnical-investigations>
- NZGS (2024). *Slope Stability Geotechnical Guidance Series. Unit 1 - General Guidance*. New Zealand Geotechnical Society (NZGS).
- Piroton V, Schlögel R, Barbier C, Havenith HB (2020) Monitoring the recent activity of landslides in the Mailuu-Suu Valley (Kyrgyzstan) using radar and optical remote sensing techniques. *Geosciences* 10(5):164. <https://doi.org/10.3390/geosciences10050164>
- Qin Y, Hoppe E, Perissin D (2020) Slope hazard monitoring using high-resolution satellite remote sensing: Lessons learned from a case study. *ISPRS International Journal of Geo-Information* 9(2): 131. <https://doi.org/10.3390/ijgi9020131>

- Ramsey, N. (2010). Some issues related to applications of the CPT. 2nd International Symposium on Cone Penetration Testing, Huntington Beach, CA, USA, May 2010. https://www.geoengineer.org/storage/publication/18455/publication_file/2694/KN3Ramsey.pdf
- Rib, H. T., & Liang, T. (1978). Recognition and identification. In (eds.) Schuster R.L and Krizek R.J. *Landslides Analysis and Control*. Transportation Research Board Special Report, (176). Washington DC. <https://onlinepubs.trb.org/Onlinepubs/sr/sr176/176.pdf>
- Ritchie, A.M (1958). Recognition and identification of landslides – Chapter four of Landslides and Engineering Practice, Highway Research Board Special Report, Issue 29 published by Highways Research Board, 1958. <https://onlinepubs.trb.org/Onlinepubs/sr/sr29/29-004.pdf>
- Rosi A, Tofani V, Tanteri L, Tacconi Stefanelli C, Agostini A, Catani F, Casagli N (2017) The new landslide inventory of Tuscany (Italy) updated with PS-InSAR: geomorphological features and landslide distribution. *Landslides* 15(1):5-19. <https://doi.org/10.1007/s10346-017-0861-4>
- Singh, S. K., Banerjee, B. P., & Raval, S. (2023). A review of laser scanning for geological and geotechnical applications in underground mining. *International Journal of Mining Science and Technology*, 33(2), 133-154. <https://doi.org/10.1016/j.ijmst.2022.09.022>
- Simons M, & Rosen P A (2007) Interferometric synthetic aperture radar geodesy. *Geodesy* 3:391-446. [10.1016/B978-044452748-6.00059-6](https://doi.org/10.1016/B978-044452748-6.00059-6)
- Standards New Zealand (2003). NZS 4411:2001. Environmental standard for drilling of soil and rock. Amendment 1. Standards New Zealand.
- Stark, T.D. and Choi, H. (2008). Slope inclinometers for landslides.
- Stewart, D.L. (2022). Monitoring technologies to manage landslide risk to transportation routes in the Lower North Island. Paper 134. Proceedings of the 2022 New Zealand Society for Earthquake Engineering Annual Technical Conference. <https://repo.nzsee.org.nz/handle/nzsee/2506>
- Takahashi, T., Takeuchi T., Sassa K. (2006). ISRM Suggested Methods for borehole geophysics in rock engineering, *International Journal of Rock Mechanics and Mining Sciences*, Volume 43, Issue 3, 2006, 337-368, ISSN 1365-1609, <https://doi.org/10.1016/j.ijrmms.2005.09.003>.
- Tensor (2021). Types of road cracks and how to avoid them. <https://www.tensor.co.uk/resources/articles/what-are-the-types-of-cracking-in-roads>
- Vishwakarma, P., Bora, S. S., & Prashant, A. (2024). Analysis of shear wave velocity estimation using MASW on sloping grounds. *Acta Geophys.* <https://doi.org/10.1007/s11600-024-01382-8>
- Wasowski J, Bovenga F (2021) Chapter 11 - Remote sensing of landslide motion with emphasis on satellite multi-temporal interferometry applications: an overview. In *Landslide Hazards, Risks, and Disasters* (2nd ed., pp. 365–438). Elsevier. <https://doi.org/10.1016/B978-0-12-818464-6.00006-8>
- Wasowski J, Bovenga F (2014) Investigating landslides and unstable slopes with satellite Multi Temporal Interferometry: Current issues and future perspectives. *Engineering Geology* 174:103–138. <https://doi.org/10.1016/j.enggeo.2014.03.003>
- Wei, X., Gao, C., & Liu, K. (2020). A review of cracking behavior and mechanism in clayey soils related to desiccation. *Advances in Civil Engineering*, 2020(1), 8880873.
- Wyllie, D. C., & Mah, C. (2004). *Rock slope engineering*. CRC Press.
- Yang, R., Huang, J., Griffiths, D., Meng, J., & Fenton, G. (2019, October). Optimal geotechnical site investigations for slope design. *Computers and Geotechnics*, 114(103111).
- Xu Y, Schulz WH, Lu Z, Kim J, Baxstrom K (2021) Geologic controls of slow-moving landslides near the US West Coast. *Landslides* 18(10):3353–3365. <https://doi.org/10.1007/s10346-021-01732-3>
- Zangerl, C., Strauhal, T. (2020): Investigations and monitoring of deep-seated rock slides in feasibility studies for dam reservoirs. *AUC Geographica* 55(2), 210–217 <https://doi.org/10.14712/23361980.2020.15>
- Jongmans, D., & Garambois, S. (2007). Geophysical investigation of landslides : a review. *Bulletin*, 178(2), 101-112.
- Vishwakarma, P., Bora, S. S., & Prashant, A. (2024). Analysis of shear wave velocity estimation using MASW on sloping grounds. *Acta Geophys.* [doi:https://doi.org/10.1007/s11600-024-01382-8](https://doi.org/10.1007/s11600-024-01382-8)

APPENDIX A - MAPPING SYMBOLS

GEOLOGY

GEOLOGICAL CONTACTS

	Accurate
	Approximate
	Inferred

FAULTS AND FOLDS

FAULT

- Fault (ticks on downtown side)
- Thrust (teeth on overthrust side)
- Ductile shear

Accurate Approximate Inferred



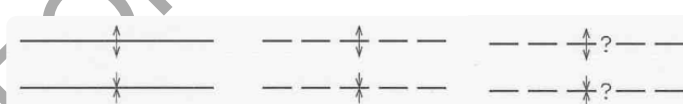
ACTIVE FAULT

- Fault (ticks on downtown side)
- Thrust (teeth on overthrust side)



FOLD

- Anticline
- Syncline

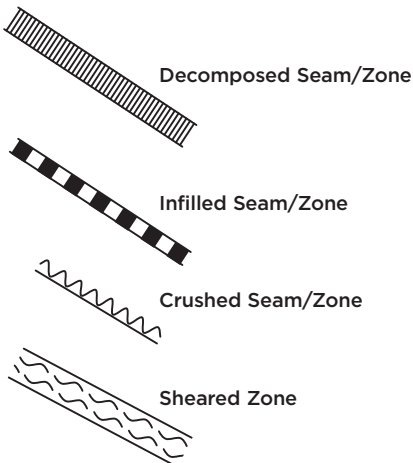
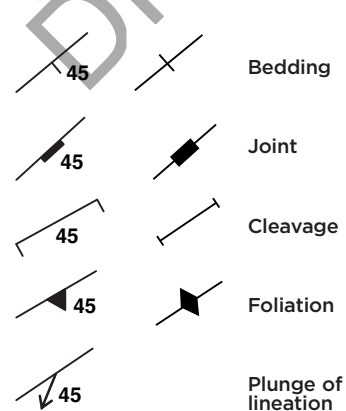


Notes for fault symbols:

- Can use arrows to show displacement direction for strike/slip faults:
- Can use U/D notation to denote upthrown and downthrown sides of the fault:

DEFECTS

Dipping Vertical Defects



Colours of geological units:

Where colours are used for geological units, they should generally match the colours used in the QMap 1:250,000 and 1:50,000 maps.

GEOMORPHOLOGY












	Crest of cut or embankment		Tension crack
	Active scarp		Lineament
	Inactive scarp		Bench
	Cliff		Landslide boundary (accurate)
	Break of slope		Landslide boundary (approximated or inferred)
	Convex break of slope - sharp		Lateral shear or flank of landslide
	Convex break of slope - rounded		En echelon cracks indicating shear direction
	Concave break of slope - sharp		Toe thrust or Bulge
	Concave break of slope - rounded		Hummocky ground
	Measured slope angle		Horst and graben
	Concave slope		Depression or sinkhole
	Convex slope		Cave
	Gully axis		Mound
	Rounded ridgeline		Landslide
	Sharp ridgeline		Rock fall
	Soil creep		Debris flow
	Scattered or fallen boulders		Gully erosion
	Cut slope		Landslide runout extent
	Fill slope		

SURFACE AND GROUNDWATER







	Water flow Permanent		Standing surface water body (shown in blue)
	Water flow Intermittent		Damp/wet ground or area with hydrophilic vegetation
	Outflow Inflow		
	Seepage		
	Seepage line		
	Water flow - permanent (shown in blue)		
	Water flow - intermittent or ephemeral (shown in blue)		
	Water in/out flow (shown in blue)		
	Seepage (shown in blue) - can be annotated with flow rate (x L/min)		

ANTHROPOGENIC FEATURES




Services and utilities

-  **Manhole**
- Culverts**
 -  **Single cell culvert**
 -  **Multi cell culvert**
-  **Stormwater pipe (show flow direction)**
-  **Wastewater pipe (show flow direction)**
-  **Water pipe (show flow direction)**
-  **Gas pipe**
-  **Communications cable (telecom or fibre optic)**
-  **Electricity cable (underground)**
-  **Overhead power lines**
-  **Power pole (if leaning can annotate with degrees from vertical)**

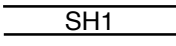
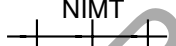

Mining and quarrying

-  **Mine**
-  **Quarry, aluvial mine or dredge**
-  **Gravel pit - selected, active or abandoned**
-  **Mine tunnel entrance**
-  **Mine shaft**
-  **Tailings or sluiced gravels**





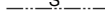

Buildings and structures

-  **Building (shape varies and the geoprofessional should outline the footprint of the building)**
-  **Reservoir or tank**
-  **Retaining wall (note the type of wall)**



Transport

-  **Roads (annotated with road or highway name)**
-  **Railway line (annotated with railway line name)**
-  **Walking or biking trail (annotated with railway line name)**

Investigation locations

-  **Borehole or well location (annotated with ID number)**
-  **Test pit location (annotated with ID number)**
-  **Hand auger location (annotated with ID number)**
-  **CPT location (annotated with ID number)**
-  **Geophysical survey line (annotate the line with a letter to denote the type of survey, e.g. S for seismic)**
-  **Ground survey mark (annotated with ID number)**

Mapping references locations

-  **Location of notebook reference, with reference number**
-  **Location and orientation of sketch or photo, with reference number (sketches denoted with an S before the number, photos denoted with a P before the number).**

REFERENCES

- AGS (2007c). Practice Note Guidelines for Landslide Risk Management 2007. Journal and News of the Australian Geomechanics Society, Vol. 42, No. 1. <https://landsliderisk.org/resources/guidelines/>
- Dackombe, R.V. Gardiner, V. (1983). Geomorphological Field Manual. George Allen & Unwin, London, 1983.
- de Vilder, S.J. and Massey, C.I. (2020). Guidelines for Natural Hazard Risk Analysis on Public Conservation Lands and Waters. Part 4: A commentary on analysing landslide risk to point and linear sites. Lower Hutt, N.Z. GNS Science. GNS Science Consultancy Report 2020/53.
- GNS Science 1:250,000 QMap Series
- LINZ Topo50 Map Series
- NSW RMS (2014). RMS Guide to Slope Risk Analysis, Version 4. New South Wales: NSW Transport Roads and Maritime Services.
- Otago University (2016). Geological Mapping Symbols. <https://blogs.otago.ac.nz/si-geology/files/2013/08/Symbol-Sheet-2016.pdf>
- Standards Australia (2017). AS 1726:2017 Geotechnical site investigations. <https://store.standards.org.au/product/as-1726-2017>
- Townsend, D.B., Massey, C.I., Lukovic, B., Rosser, B.J., de Vilder, S.J., Ries, W.F., Morgenstern, R., Ashraf, S., Jones, K.E., Carey, J.M. 2020. SLIDE (Wellington): geomorphological characterisation of the Wellington urban area. Lower Hutt, N.Z. GNS Science. GNS Science report 2019/28 [194] p.
- USGS (2005). Topographic map symbols: U.S. Geological Survey Unnumbered Series, GIP, 4 p.. Topographic Map Symbols. <https://pubs.usgs.gov/gip/TopographicMapSymbols/topomapsymbols.pdf>
- USGS (2006). Federal Geographic Data Committee (FGDC) Digital Cartographic Standard for Geologic Map Symbolization; Reston, Va., Federal Geographic Data Committee Document Number FGDC-STD-013-2006, 290 p., 2 plates. Prepared for the Federal Geographic Data Committee by the U.S. Geological Survey. https://ngmdb.usgs.gov/fgdc_gds/geolsymstd/fgdc-geolsym-all.pdf

DRAFT FOR FEEDBACK



**NEW ZEALAND
GEOTECHNICAL
SOCIETY INC**
www.nzgs.org