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Advancing Slope Stability Practice in New Zealand: The NZGS Guidelines and their application in Greywacke

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Abstract

The New Zealand Geotechnical Society (NZGS), in collaboration with the New Zealand Natural Hazards Commission (NHC), is developing a modular Slope Stability Guidance series to support consistent and reliable assessment of landslides and slope instability across New Zealand. This paper presents Unit 7C.2 of the guidance series, which addresses slope stability in Torlesse greywacke, New Zealand's most widespread basement rock and a material commonly associated with landslides triggered by rainfall and seismic loading. Torlesse greywacke is characterised by intense deformation, heterogeneous weathering, and closely spaced, variably persistent discontinuities, resulting in complex slope failure mechanisms that challenge conventional rock slope assessment approaches. The paper demonstrates how the guidance was developed, by synthesising recent New Zealand earthquake case histories, published laboratory test data, and practitioner experience. This approach resulted in practical, engineering-focused guidance for characterising greywacke rock masses, interpreting failure mechanisms and selecting appropriate strength parameters for stability analysis. By addressing the challenges associated with typical site investigation constraints especially in urban environments, Unit 7C.2 streamlines slope stability assessments in New Zealand, while it enhances their reliability and consistency. The principles and approaches adopted in the development of the guidance could be applicable to other similar rock conditions and steep landslide prone terrain worldwide.

Keywords

Slope stability, Landslides, Greywacke, Guidance, New Zealand.

1 Introduction

Landslides represent a significant geotechnical hazard in New Zealand, due to the combination of steep topography, complex geology, high rainfall, and high seismicity. To improve consistency of practice for assessing slope instability, the New Zealand Geotechnical Society (NZGS), supported by the Natural Hazards Commission (NHC), is developing a modular Slope Stability Guidance series. This guidance provides a nationally consistent framework for slope instability, including landslide identification, investigation, modelling, and mitigation presented across seven units. The units cover topics from site investigations to specialised assessments for debris flows and region-specific materials and are available to download from the NZGS website (NZGS, 2025a).

This paper focuses on Unit 7C.2 (NZGS, 2025b), which adapts the general principles and processes established in Units 1 to 4 specifically for slopes developed in Torlesse greywacke, New Zealand's most widespread basement rock. The paper demonstrates how Unit 7C.2 integrates recent studies of coseismic landslides in greywacke, laboratory test data, and practitioner experience into practical guidance for the assessment of slope stability in this highly fractured rock mass. This paper also shows how Unit 7C.2 aims to streamline the application of rock-engineering principles for highly fractured greywacke slopes under real cases with investigation and design constraints.

2 General characteristics of Torlesse greywacke rocks

Torlesse greywacke is a Mesozoic age rock complex part of the Torlesse Composite Terrane that forms the basement across extensive areas of both the North and South Islands, including urban areas such as Wellington, the capital of New Zealand (Fig. 1, left). The rocks consist predominantly of fine- to medium-grained sandstone, siltstone, mudstone and argillite, of marginal marine to sub-marine origin, deposited by turbidity currents and mass-flow processes (Suneson, 1993). Although greywacke strictly describes the fine sandstone, it is commonly used as a colloquial term in New Zealand, to describe the rock complex, as a whole. Low-grade metamorphism and a multi-stage deformation history have produced a structurally complex rock mass with great variability in intact rock strength and intensity of fracturing, ranging from closely jointed rock to melange or broken formation.

An example of a typical interbedded Torlesse greywacke outcrop is shown in Fig. 1, right. Bedding orientations and angles can vary, while persistence is interrupted by randomly oriented jointing. Multiple joint sets, typically more than three, exist in the rock mass with one or two dominant with higher persistence. Closely spaced, low-persistence joints are also present, many of which are incipient and do not form continuous failure surfaces until mobilised by loading or seismic shaking (Singeisen, et al., 2022).The rock mass weathering varies and ranges from completely to highly weathered on slope exposures, to moderately to slightly weathered or unweathered on the high hill ranges, or at lower elevations. The strength of the rock material ranges widely, from extremely weak to very strong, depending on the weathering grade and the lithology.

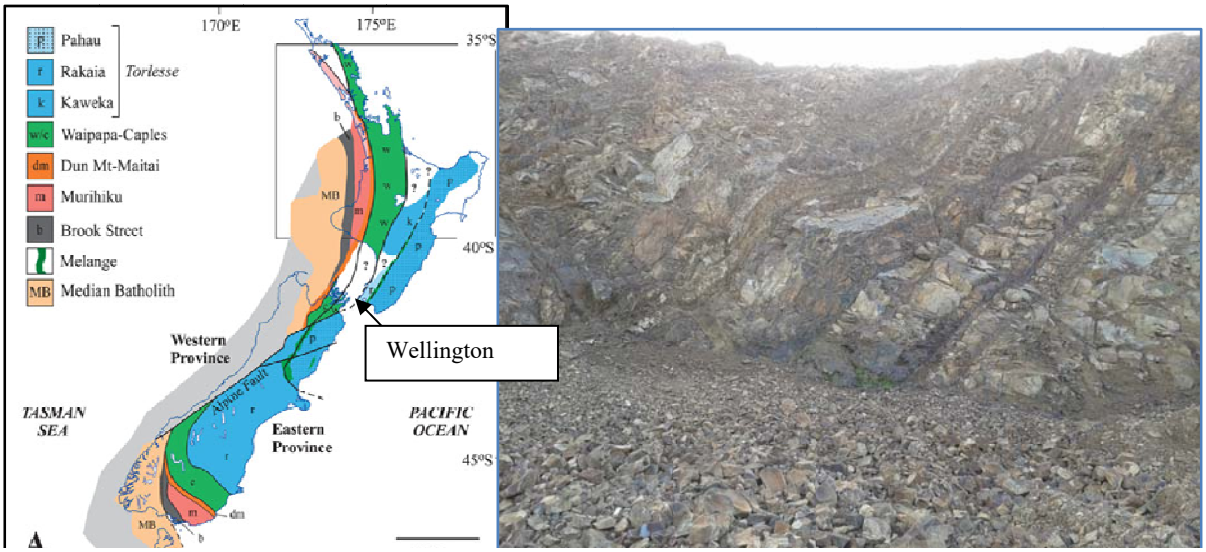


Fig. 1 Left: Extents of greywacke rocks across New Zealand (Price, et al., 2015). The paper covers rocks of the Torlesse terrane. Right: Greywacke rock outcrop – mudstone (dark) and sandstone (light grey) with thin laminated siltstone beds in between (NZGS, 2025b).

3 Modes of slope failure

As a result of the complexity in strength, fracturing, and weathering, greywacke rock slopes can fail by a variety of mechanisms, depending on factors such as the conditions of the rock mass and dominant defects, the geometry of the slope, and the loading conditions. Slope failures in greywacke can be structurally controlled or rock-mass controlled, or a combination of both. Individual slopes may also be affected by more than one failure mode. The modes of failures determined as typical for greywacke slopes in Unit 7C.2 (Table 1) were confirmed in the studies of the landslides triggered by the 2016 Mw 7.8 Kaikoura earthquake (Singeisen, et al., 2022)(Mason & Brabhaharan, 2023).

Table 1. Most common slope failure modes in greywacke rock masses.

Principal Mechanism	**Mode**	**Typical occurrence**	**Typical size and scale (relative to height of slope)**
1. Structurally controlled	Planar, wedge and toppling moderate size failures –	In moderately strong to strong, blocky rock masses with >3 sets of discontinuities.	Small - moderate
	Translational rockslides	In all types of rock masses with at least one persistent discontinuity.	Large
2. Composite (translational and rotational)	Planar with step-path structurally controlled mechanism (en-echelon failures)	In moderately strong to weak, blocky to very blocky rock masses - non-persistent but consistently oriented discontinuities.	Large
	Multi-planar compound slides	In weak rock masses with persistent discontinuity (-ies).	Large
3. Rotational	Circular failure plane	In highly fractured, disintegrated or highly weathered weak to very weak rock mass that can exhibit nearly isotropic behaviour.	Large

4 Assessment of geotechnical parameters

4.1 Intact rock

The intact rock strength of unweathered Torlesse greywacke is generally strong to extremely strong, with reported unconfined compressive strength (UCS) values of up to approximately 350 MPa (Read, et al., 1999). Intact rock strength varies with lithology; sandstone typically exhibits higher UCS values than associated mudstone or siltstone beds. Intact strength decreases markedly with increasing degree of weathering to as low as 1 to 5 MPa. A key difficulty in laboratory determination of intact rock strength in Torlesse greywacke is the frequent presence of hairline or incipient fracturing, which can adversely influence test results and lead to underestimation of true intact strength. Indirect field and laboratory index tests, such as the Schmidt hammer rebound test and Point Load Index test, are useful for estimating intact rock strength and for calibrating laboratory triaxial and UCS test results, particularly where truly fracture-free specimens cannot be obtained.

4.2 Rock mass

Use of the generalised Hoek–Brown failure criterion (Hoek, et al, 2002) for estimating rock mass parameters in slope stability modelling is considered appropriate for very blocky, disintegrated or sheared Torlesse greywacke. As mentioned in Section 4.1, obtaining intact rock specimens for laboratory testing in Torlesse greywacke is inherently challenging. Consequently, best-practice guidance for defining the intact uniaxial compressive strength (σ_{ci}) and the Hoek–Brown material constant (m_i) is provided in Unit 7C.2, based on a combination of published laboratory test data, the authors' experience on New Zealand projects, and available literature. Unit 7C.2 also provides guidance for Geological Strength Index (GSI) assessment, defining typical rock mass classes based on the work of Read et al. (1999). The guidance includes indicative GSI ranges linked to characteristic rock mass appearance on both field exposures and borehole core. Typical rock mass parameters assessed based on the recommendations of NZGS Unit 7C.2 are shown in Table 2. These ranges are provided as starting points and must be validated on a case-by-case basis with appropriate investigation and assessment.

4.3 Discontinuities

The shear strength of discontinuity surfaces is adopted for the assessment of structurally controlled failure modes. For Torlesse greywacke, the Barton–Bandis shear strength criterion (Bandis, 1993) is considered a practical and appropriate approach for estimating discontinuity shear strength,

particularly given the difficulties associated with sampling and laboratory testing in fractured rock mass. To support the calibration of strength parameters derived from the criterion, Unit 7C.2 presents published results from direct shear testing of greywacke joint samples spanning a range of weathering grades. Guidance for recording joint roughness, strength, and weathering discontinuity conditions during engineering geological mapping is provided in NZGS guidance (NZGS, 2005).

Table 2. Typical ranges of rock mass parameters, input to the Hoek-Brown criterion.

Rock mass class	**Rock mass description**	**GSI**	**Unit Weight (kN/m3)**	**m_i**	**σ_{ci} (MPa)**
I	UW or SW – sandstone blocky	50 - 70	26.5 – 27.0	12	100 - 350
II	SW to MW – sandstone very blocky	40 - 60	25.0 – 26.0	12	50 –200 (most common range 50 – 100)
III	MW- HW sheared mudstone, interbedded sandstone / mudstone, blocky disturbed	25 -45	23.0 –25.0	9- 10	5 - 70
IV	CW-HW Interbedded sandstone mudstone, mudstone or very fine sandstone, crushed – disintegrated	15 - 35	22.0 – 24.0	8	3 - 30
V	CW HW Mudstone or fine sandstone (rock material generally sheared) – foliated laminated sheared	10- 20	20.0 – 23.0	8	1 - 10

5 Analysis and Design

Slope stability analysis in greywacke, as in any material, requires a combination of analytical skill, geological understanding, and engineering judgment. Computer modelling using limit equilibrium methods is recommended for slope stability analyses in the guidance. Emphasis is given on the need for a sound engineering geological models to form the basis of these analyses, which are developed by thorough engineering geological mapping of existing outcrops and intrusive investigations where possible, including downhole geophysical investigations.

Observationof existing nearby slopes and evaluation of their past performance are recommended to calibrate the results of computer modelling. Back analysis of failed slopes is recommended for calibrating parameters assumed in the models, recognising its limitations for modelling the exact conditions of failure. Typical slope angles for use in low-risk projects are provided, however the need for review of all designs by experienced geoprofessionals is emphasized. Seismic demand is an important part of most designs that lie within central New Zealand – that area of the country where most greywacke is found. Drawing on past earthquakes, general comments are provided on the expected failure mechanisms in future ones. For greywacke, coseismic landslides typically are disaggregated falls, slides and rock avalanches. As most failures in greywacke are expected to be brittle, and evacuative failure is so common, use of the Newmark sliding block method to estimate seismic displacements of slopes is cautioned against.

6 Unit 7C.2 derived frompractice - Wellington Case History

Landslides of greywacke slopes frequently affect residential properties, transport corridors, and infrastructure in Wellington city. Given the city's steep topography, restricted access, and the close proximity of private property, opportunities for intrusive investigation are often limited. Consequently, slope characterisation is largely dependent on observational methods, supported by experience and engineering judgement. The accumulated experience on successful analysis of slope instabilityin Wellington and elsewhere in New Zealand, underpin the development of the framework presented in Unit 7C.2.

An example of a ~20 m-high slope in a suburb of Wellington city where a landslide occurred is shown in Fig. 2. Engineering geological mapping on the slope aimed to develop the engineering geological model and assist interpreting the failure mechanisms (Fig. 3), a process that is recommended in Unit 7C.2. The mapping identified unfavourably oriented discontinuities and a highly weathered, highly fractured, low-strength rock mass in the upper slope, coincident with the failure zone. The failure took place during very wet conditions, with elevated water content of the slope materials inferred to have

further reduced the strength of both the rock mass and its discontinuities. In this case, the predominant failure mechanism was interpreted to be principal mechanism 2 of Table 1, involving a combination of translational movement along discontinuities and a rotational component through the poor-quality rock mass. Additionally, failure of individual blocks governed by the dip and orientation of discontinuities (principal mechanism 1 of Table 1) was observed at the top of the slope.

The selection of rock-mass and discontinuity parameters followed the methods recommended in Unit 7C.2, employing the generalised Hoek–Brown and Barton–Bandis criteria, and was further refined through back-analysis, a process supported in this case by knowledge of the failure conditions and experience on local slope performance. Stability analysis commenced with the structurally controlled principal mechanism 1, using discontinuity parameters, and the resulting stabilisation measures were then tested and calibrated for the more complex translational failure mechanism 2, modelled using limit equilibrium slice methods and a combination of discontinuity and rock mass parameters. Cases examined include static with normal water pressures, elevated water pressures to simulate high rainfall conditions, and seismic loading. Similar stabilisation strategies as the one followed in this case history, comprising rock anchors, shotcrete facing, and sub-horizontal drainage targeted at the upper slope, are included in the practical, experience-informed methods included in the guidance.

7 Conclusions

The NZGS Slope Stability Guidance series has been developed to address an identified gap in existing guidance for slope stability assessments and analysis in New Zealand. The objective of the guidance series is to transfer accumulated knowledge of experienced local professionals and existing local and international studies to engineering practice, thus ensuring a consistent and structured approach in investigating, analysing and mitigating slope instability, which is a significant geotechnical risk in New Zealand. Unit 7C.2 of the series, provides practical guidance for slopes formed in Torlesse greywacke rock. The recommendations are based on local experience, complemented by published data on failure mechanisms and laboratory testing, and internationally established rock engineering principles. This collective knowledge ensures the guidance remains robust and relevant, offering a consistent and evidence-based approach even in challenging, data-poor settings. By systematically integrating observational methods, engineering geological mapping, back-analysis of failures and modern modelling techniques, the framework supports practitioners in applying consistent methodologies for slope assessment and make informed decisions for remediation strategies tailored to site-specific conditions. The principles of developing the guidance series and their objectives can form a transferable example for developing similar practical and efficient documents worldwide.

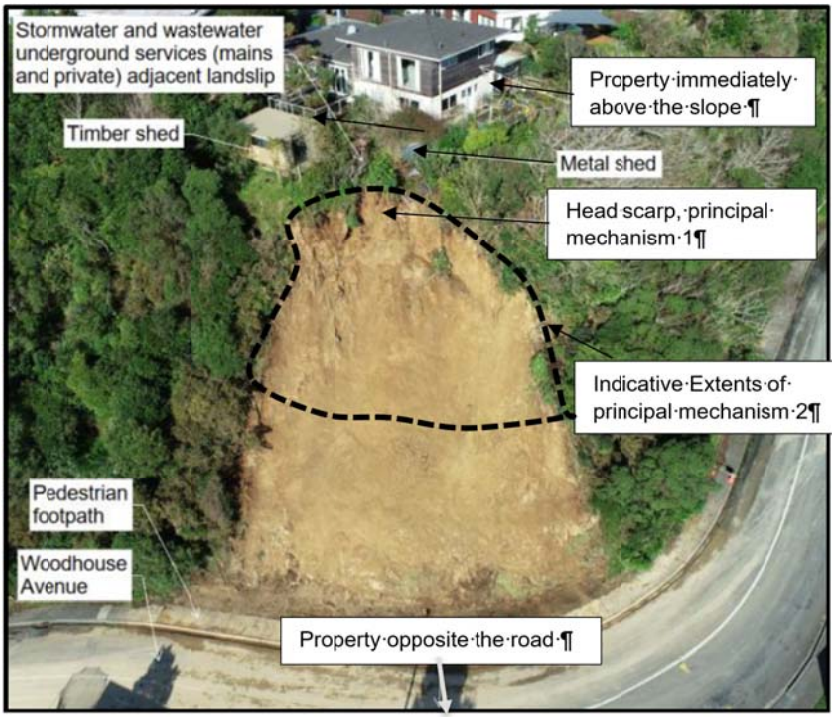


Fig. 2. View of the slope in Wellingtonafter the landslide (Stantec, 2023, modified from Tonkin + Taylor, 2022).

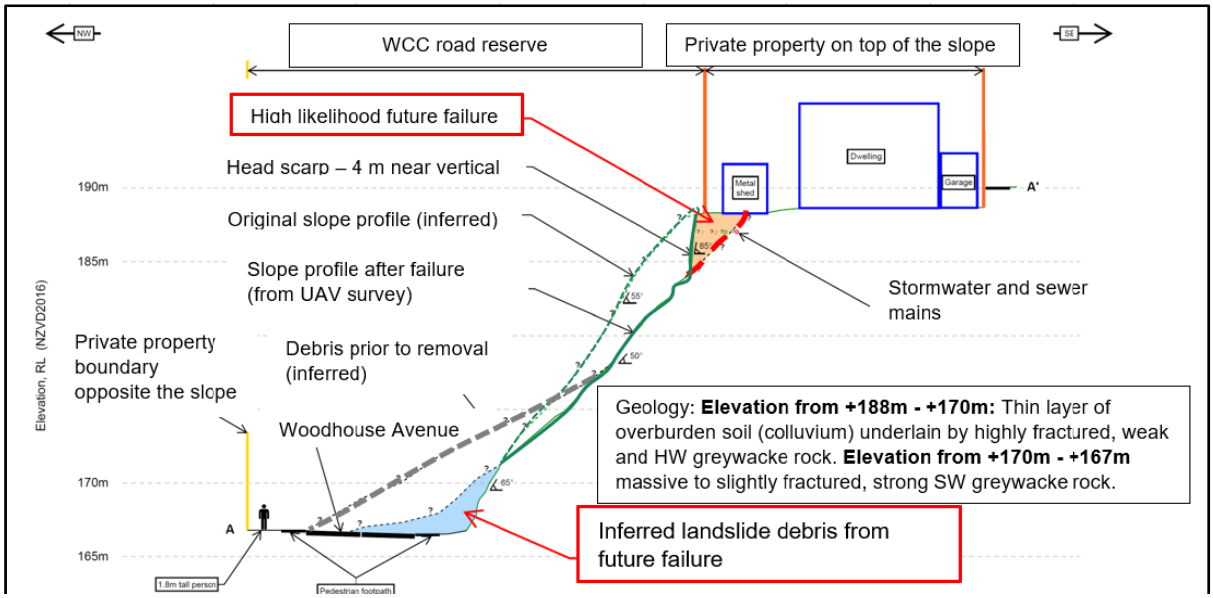


Fig. 3 Engineering geological model and failure mechanisms of the slope (Stantec, 2023, modified from Tonkin + Taylor, 2022).

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