

Brief report of fatal rainfall-triggered landslides from record-breaking 2023 storms in Auckland, New Zealand



Abstract The aim of this paper is to report on fatal landslides resulting from two extraordinary storm events in January and February 2023, in Auckland, New Zealand, including the characteristics of the terrain, the site geology, and the storms. The January 27 Auckland Anniversary storm was from an “atmospheric river,” dumping Summer’s worth of rain (265 mm) in one day. This was the highest 24-h total on record, estimated a 1 in 200-year event, with a peak 2-min rainfall of 4.2 mm, coinciding with Friday’s evening “rush hour.” This led to widespread landsliding throughout Auckland, including a fatal landslide in Parnell, central Auckland. Notably, this occurred only meters from a similarly destructive landslide in 1997. With January 2023 Auckland’s wettest January on record, and with the region still in a state of emergency, Tropical Cyclone Gabrielle crossed the region on February 13–14. This also caused widespread landsliding, including a fatal landslide at Muriwai on the west Auckland coast. Fatal landslides from the same escarpment had occurred in 1965, close to the February 13, 2023, fatal landslide. Taken together, both storm events caused > 140,000 landslides across the North Island, and flooding, making hundreds of people homeless, with damage estimates of > US\$8.6 billion (3.4% of NZ’s GDP). For future disaster risk reduction, attention should be paid to revising legislation and local planning, which currently allows people to legally build (and re-build) houses in landslide-prone areas of New Zealand.

Keywords Landslide · Fatal · Rainfall-triggered · New Zealand · Gabrielle

Introduction

Even though numerous studies globally over the last few decades have focused on landslide susceptibility and monitoring, landslides remain a major risk to people in many parts of the world (Alcántara-Ayala and Sassa 2023). In New Zealand, given its mid-latitude maritime climate, on a convergent plate boundary, large parts of the country are at risk from multiple occurrences of regional landslide events, MORLEs (Crozier 2005). This is where tens of thousands of landslides can occur across a region over a short timeframe (< 24 h), causing fatalities and damaging property and infrastructure. Such events create particular challenges for disaster response agencies (e.g. Roberts 2023). Often, such widespread landsliding in New Zealand occurs due to earthquakes, but region-wide landslide events also occur due to severe rainfall. Indeed, since 1843, more people have been killed by landslides in New Zealand (> 600 deaths) than from any other natural hazard (Rosser et al. 2017). Herein is a brief report on two remarkable, record-breaking rainfall-triggered MORLEs that occurred on the

North Island of New Zealand (Fig. 1), in consecutive months in January and February 2023, that resulted in fatalities and are New Zealand’s costliest storm events ever (Pullar-Strecker 2023). The rainfall events occurred on January 27, 2023, and February 13–14, 2023. The focus here is on the Auckland region, which contains one-third (~ 1.7 million) of the total population (5.2 million) of New Zealand (Fig. 1) and where both rainstorm events (Fig. 2) proved fatal. Collectively, across the North Island, both rainfall events caused billions of dollars of damage to property and infrastructure, from which the country is still recovering.

Auckland (Fig. 1) has rather varied geology and geomorphology, with much of the region on slopes formed on either Miocene-age sediments and volcanics, or more recent Pleistocene Quaternary Auckland Volcanic Field cones and flows (Edbrooke et al. 2003). Thus, much of Auckland is at high or moderate risk from landslides (Hancox and Nelis 2009). The purpose of this short report is not to provide a comprehensive analysis of landsliding across Auckland and the North Island; ongoing research will report on that in the coming years. Rather, the aim is to report a summary of the respective storm events, terrain and geological characteristics of two specific fatal landslides in the Auckland region. The methods include the application of LiDAR digital elevation model data and the investigation of soil index and strength properties. The results are contextualized alongside some aspects of the impacts and response, legislation, and insurance implications, specific to New Zealand’s public natural disaster insurance scheme (Earthquake Commission Act 1993).

Study area

Landslides across Auckland (Fig. 1) generally are shallow (< 10 m), formed in soils and weathered rock. Typically in the region, surface materials become saturated, decreasing effective stress and causing failure via slumping and flows, across more competent underlying bedrock (Palma et al. 2020). The soils across Auckland vary, with residual soils forming from parent rocks of Miocene Waitemata Group sediments and Waitakere Group volcanics (central-west Auckland), as well as on more recent, Pleistocene Auckland Volcanic Field materials in central Auckland (Fig. 1). In addition, colluvium deposits from reworking of residual soils and former landslides exist on slopes, while late Pleistocene and Holocene fluvial deposits occupy valley floors (Edbrooke et al. 2003). To the southwest and west of Auckland, Plio-Pleistocene Awhitu Group sediments, predominantly moderately-to-poorly consolidated, large-scale, cross-bedded dune sands, form hilly topography up to 285 m high in the Awhitu Peninsula (Fig. 1). During the January and February 2023

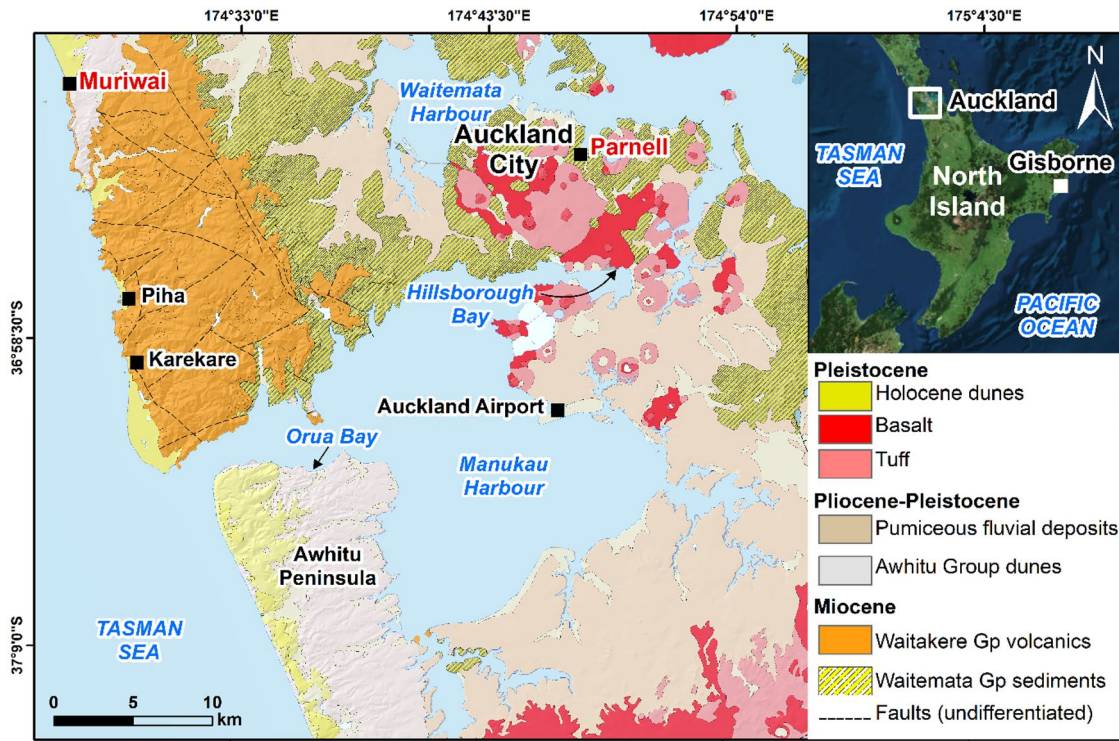


Fig. 1 Generalized regional geology of Auckland with fatal landslides in Parnell (January 27, 2023) and Muriwai (February 13, 2023) highlighted in red

storms, landslides occurred on all of these materials (e.g., Fig. 3). Shallow slumps that transition into highly mobile flows occurred in Awhitu Group sands (Fig. 3A), while other mobile slump-flows occurred in Waitemata Group East Coast Bays Formation residual soils, damaging the North Auckland main trunk line near Wellsford (Fig. 3B). Slumping of residual soils and colluvium formed on Waitakere Group Volcanics at Karekare and destroyed

houses (Fig. 3C), while several landslides on steep slopes on Awhitu Group sands damaged houses at Orua Bay (Fig. 3D). Around central Auckland, hundreds of landslides occurred on the Waitemata Group East Coast Bays Formation residual soils and weathered rocks, which compose most of the cliffs around Manukau Harbor and Waitemata Harbor. Many houses around the coastal cliffs often have minimal “setback” (<10 m) from cliff edges (e.g., Fig. 3E).

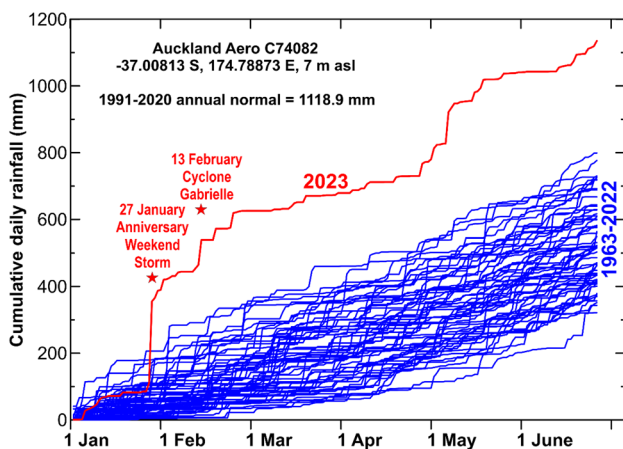


Fig. 2 January to June cumulative daily rainfall for Auckland airport for 2023 (red line), compared with years from 1963 to 2022 (blue lines). Total annual “normal” rainfall (mean of 1991–2020 annuals) is 1118.9 mm, and in 2023, 50% of this had already fallen in the first 6 weeks of the year

Methods

Digital elevation models (DEMs) and long profiles of both the Parnell and Muriwai sites were created from LiDAR captured for Auckland Council and then provided by Land Information New Zealand (LINZ). Vertical accuracy specification is ± 0.2 m, and horizontal accuracy specification is ± 0.6 m. Field testing of Waitemata Group residual soils and Awhitu Group sands was undertaken using a Geonor H60 hand-held shear vane tester and Eijkelkamp hand-held penetrometer, to ascertain in situ soil strength. Soil samples were crushed and subsampled for particle-size distribution analysis using a Malvern Mastersizer 2000 (Malvern 2007). Atterberg limits were obtained on the <0.425 μm fraction of soils using procedures outlined in BS 1377-2 (BSI 1998).

Results

January 27 “Auckland Anniversary” storm and Shore Road landslide, Parnell

The first storm event outlined here was from a long band of rain brought by a tropical “atmospheric river,” which crossed Auckland

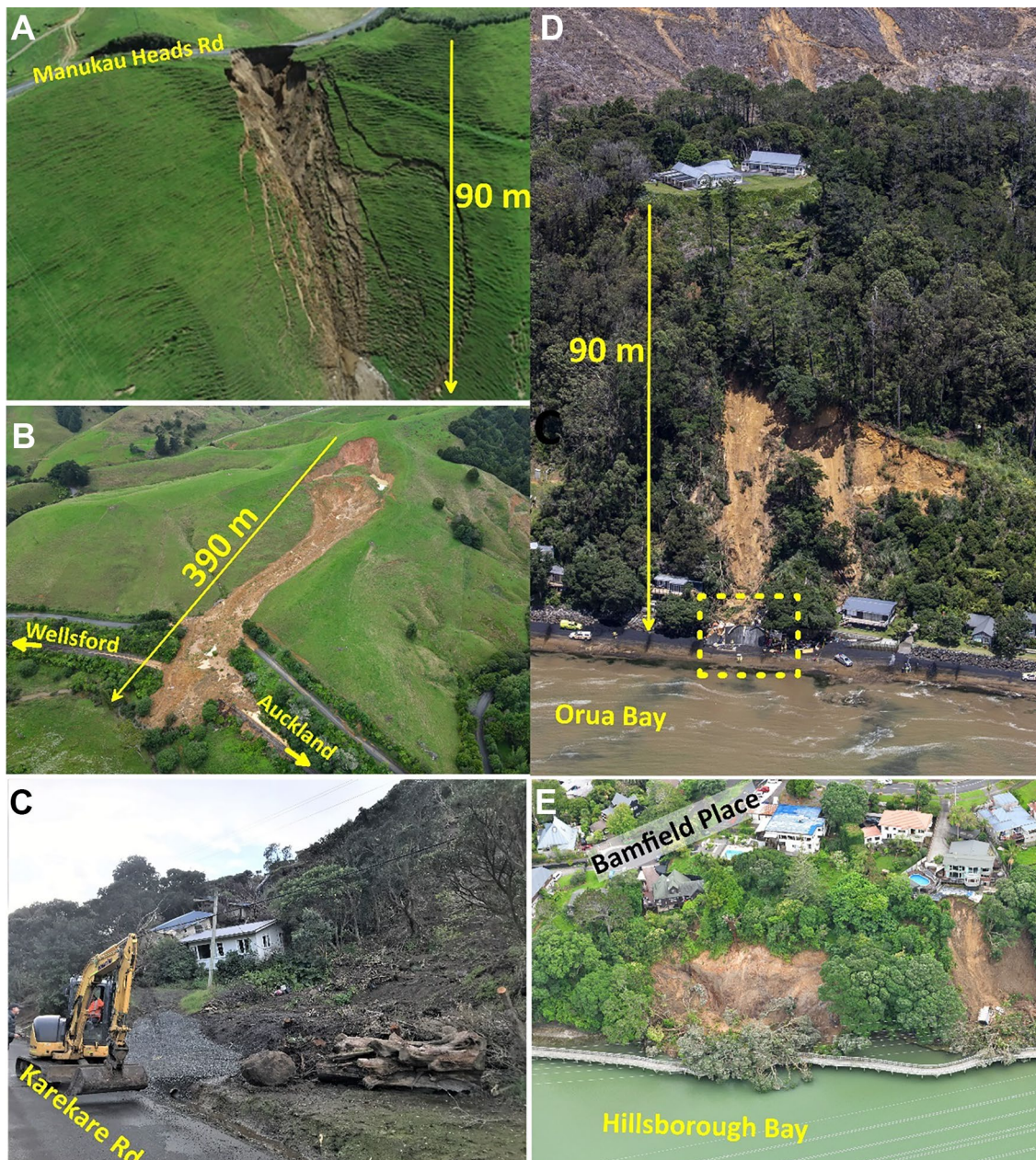


Fig. 3 Example damaging landslides from the 2023 rain events in the Auckland region: **A** ~90,000 m³ slump-flow “underslip” in Awhitu Group sands, Awhitu Peninsula; **B** earthflow across the Auckland-Wellsford railway line in East Coast Bays Formation residual soils; **C** displaced houses in Karekare from slumps in Waitakere Group residual soils; **D** damaged house (yellow outline) in Awhitu Group sands at Orua Bay; **E** slumping in coastal cliffs in East Coast Bays Formation sediments and residual soils, Hillsborough Bay

on the afternoon and evening of Friday, January 27, 2023, on the Auckland Anniversary public holiday weekend. It caused flash flooding and widespread landsliding (Roberts 2023), including a fatal landslide in the central suburb of Parnell (Fig. 1 for location). Beginning on Friday, January 27, 2023, regions across the upper North Island of New Zealand experienced widespread catastrophic floods caused by heavy rainfall, with Auckland being the most significantly affected as the holiday weekend began (NIWA 2023). An entire summer of rain falling in one day is estimated to be a 1 in 200-year event (NIWA 2023). The peak 2-min rainfall

in Māngere close to Auckland Airport was 4.2 mm (24-h total of 265 mm), causing flash flooding around 5 pm, and cancellation of the Elton John rock concert, leaving many people stranded near the Mt Smart stadium venue. The storm meant that January 2023 was the wettest month ever (539 mm) in central Auckland, easily exceeding the previous record of 420 mm in February 1869 (NIWA 2023). The upper North Island had already experienced a wetter than average summer. Indeed, heavy rain had fallen on northern and eastern areas of the North Island through most of January, with flooding events soon after New Year, followed by the passage of

Recent Landslides

Cyclone Hale on January 10–11. Thus, soils were already exhibiting high antecedent moisture conditions prior to the January 27 storm. This caused ~200 houses to be “red stickered” under section 124 of the Building Act (2004), whereby the territorial authority deems a building is dangerous, and so entry is prohibited.

At Parnell in central Auckland, a fatal landslide occurred at 33 Shore Road (Fig. 4). This was a slump within the upper cliff, formed of Waitemata Group East Coast Bay Formation residual soil and weathered rock. Following the classification of Hungr et al. (2014), this was probably initiated as a clay/silt rotational slide that transitioned downslope into an earthflow, with a *Fahrböschung* angle of ~32°. This landslide inundated the house below, which had been constructed on colluvium formed from prior slope failures, and extended onto Shore Road itself. The house was subsequently

removed (Fig. 4D). Such slump failures that transition downslope into flows typify rainfall-triggered landslides in Waitemata Group residual soils (e.g., Moon et al. 2003). The site is a ~30-m high Holocene sea cliff, with the land in front of the cliff toe reclaimed, on which Shore Road was built. Houses were then constructed in a narrow zone (~30 m) of accommodation space between the cliff and Shore Road itself (Fig. 4A). An engineering geological model of the site and fatal landslide is provided in Fig. 4F, and example soil index properties are reported in Table 1. Given liquid limit (LL) and plasticity index (PI) values (Table 1), the ECBF residual soils would typically plot just above the A-line on a Casagrande chart and can be characterized as fat clays (ASTM D2487-06), unsurprising given their high smectite content (Moon et al. 2003). They exhibit high plasticity, are firm to stiff, of moderate strength, and have a

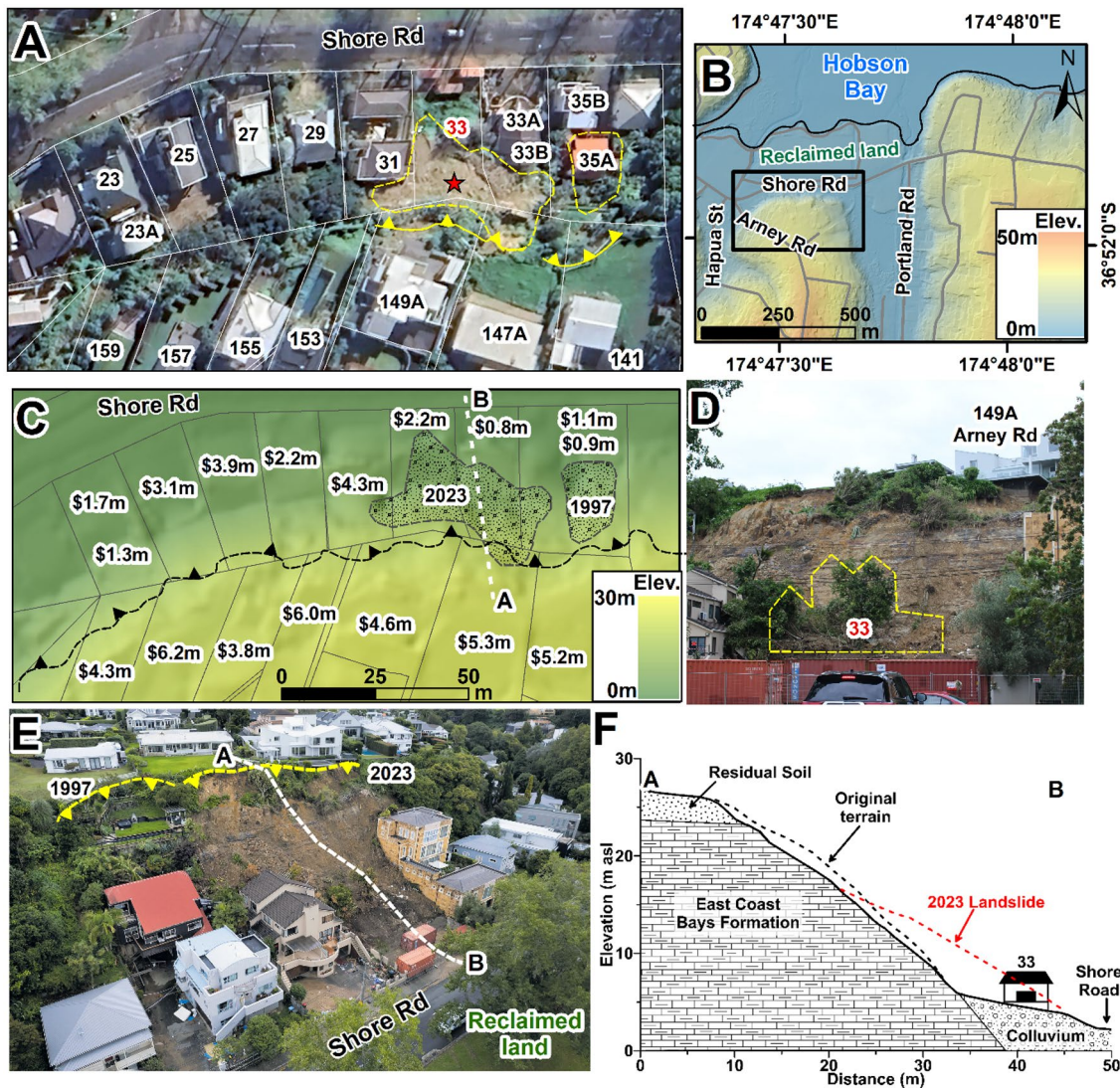


Fig. 4 January 27, 2023, fatal landslide at 33 Shore Road, Parnell. **A** Post-landslide satellite image with extents of 2023 landslide (red star) and 1997 landslide at 35A Shore Road shown; **B** topography of area on Holocene cliff line; **C** LiDAR DEM with cliff edge, land parcels with capital values in US\$ (as of July 2022), cross-section in **F** denoted by A-B; **D** post-landslide photo of 33 Shore Road site (house removed), and East Coast Bays Formation strata visible in cliff, with overlying residual soil; **E** oblique post-landslide image with A-B cross-section in **F** shown; **F** generalized geological cross-section (A-B) of landslide

Table 1 Characteristic soil index properties of Awhitu Group (AG) and East Coast Bays Formation (ECBF) residual soils, including liquid limit (LL), plastic limit (PL), plasticity index (PI), effective particle size (D_{10}), coefficient of uniformity (Cu), coefficient of curvature (Cc), field unconfined compressive strength (UCS), and undisturbed (S_u) and disturbed (S_d) shear vane strength

	Clay %	D_{10} μm	LL	PL	PI	Cc	Cu	UCS kPa	S_u kPa	S_d kPa	SI
ECBF	26	1.52	51	25	26	0.9	6.3	198	84	18	4.7
AG	6.7	46	48	28	20	1.0	2.5	249	106	42	2.5

sensitivity index ($SI = S_u/S_d$) of 4.47, indicating they are “sensitive” (Skempton and Northey 1952). As can be seen from Fig. 4, houses in the vicinity are constructed either directly above the cliff with minimal (< 5 m) setback from the cliff edge, or are at the foot of the cliff, on previously failed material. Indeed, the area is a known landslide zone, and a house was destroyed by a landslide at 35A Shore Road in 1997 (Fig. 4C).

Severe Tropical Cyclone Gabrielle on February 13–14, 2023

The second remarkable rainstorm event of early 2023 was severe Tropical Cyclone (TC) Gabrielle, which crossed the Auckland region on 13 and 14 of February 2023 (Fig. 2). TC Gabrielle has become the costliest tropical cyclone on record in the Southern Hemisphere, with total damages estimated to exceed NZ\$14.5 bn (US\$8.7 bn). The Auckland region was still under a State of Emergency from the Auckland Anniversary weekend storm on January 27, with the State of Emergency extended pending TC Gabrielle’s landfall. TC Gabrielle had earlier affected parts of Vanuatu and Australia and, after devastating parts of Auckland, caused major damage across the North Island (Molnar 2023), damaging roads, destroying bridges, displacing > 10,000 people, and causing > 140,000 landslides (Geonet 2023). In the Auckland region, 244 buildings were evacuated and entrance prohibited (“red stickered”) by the territorial authority, with 130 of these houses in the west Auckland town of Muriwai, comprising nearly one-third of homes in the town (Fig. 1). The rain gauge at Muriwai failed due to inundation of floodwater, but west Auckland region recorded ~248 mm of 24-h rainfall, with winds gusting at 150 km/h, and the deaths of two volunteer firefighters at Muriwai (Roberts 2023).

The tragic deaths of the two firefighters occurred during inspection of a house on Motutara Road around 10 pm on February 13 (Fig. 5), to investigate flood damage (FENZ 2023). Muriwai is an interesting location because much of the town lies below a ~80-m high escarpment formed within soft, Pleistocene Awhitu Group sands (Fig. 5). These are poorly-cemented dune sands and silts (Table 1), with fines typically exhibiting liquid limit (LL) and plastic limits (PL) of 48 and 28, respectively, during laboratory testing (Table 1). In situ, the Awhitu Group sands have a tendency to dilate when wetted but are firm to stiff ($S_u \sim 100$ kPa) and can sustain steep (~40°) slopes in drained conditions. However, the crenulated ridgeline immediately west of Oaia Road indicates that several landslides have occurred in the past along the escarpment above the town (Fig. 5A). Indeed, in August 1965, 2 fatal landslides occurred on consecutive days at Domain Crescent, in the form of slides that transitioned to rapid (90 km/h) flows, which inundated houses,

following substantial (220 mm) rainfall (Wright 1966). While landslides from TC Gabrielle did inundate the Domain Crescent houses that were rebuilt after the 1965 fatal landslides, Domain Crescent was evacuated during TC Gabrielle on February 13 at 9–10 pm (FENZ 2023). The actual fatal landslide occurred ~1 km northeast of Domain Crescent, along the escarpment at 132–136 Motutara Road, after 10.40 pm (Fig. 5B). At Motutara Road, as with Domain Crescent, the Awhitu Group sands unconformably overly the relatively impermeable Nihotupu Formation volcanoclastic sediments of the Miocene Waitakere Group (Fig. 5D). As outlined by Wright (1966), groundwater tends to flow downwards through the permeable Awhitu Group dune sands, until it reaches the erosional contact with the underlying Waitakere Group Nihotupu Formation, which acts as an aquiclude, increasing porewater pressure within the overlying Awhitu Group. During the passage of TC Gabrielle, landslides in the Awhitu Group occurred at several places along the escarpment, inundating houses below (e.g., Fig. 5E), but the fatalities were limited to 132–136 Motutara Road. The landslide there was initiated in the slope above the evacuated house at ~130 m asl (Fahrböschung angle = 26°), which inundated the house, while firefighters were digging a trench to divert floodwater. The inundated house was transported by the landslide into the roadway below, while further landslides occurred nearby (FENZ 2023). One firefighter died at the scene, while a second (rescued) firefighter died in hospital on February 16 (FENZ 2023). From the Hungr et al. (2014) classification, the Motutara Road and Domain Crescent landslides due to TC Gabrielle can be classified as sand/silt/debris flowslides, because they are rapid, and also entrain trees and surficial material from prior slope failures.

Discussion

Triggering rainfall events

In the Auckland region, rainfall-triggered MORLEs are not infrequent (Palma et al. 2020), and most of Auckland is at moderate to high risk of landslides (Hancox and Nelis 2009). Indeed, in 2017, the “Tasman Tempest” storm led to a 24-h rainfall total of 210 mm in Auckland on March 8, while on April 5 of the same year, Tropical Cyclone Debbie brought 157 mm of rainfall in 24 h (Palma et al. 2020). Both of these storms led to widespread landsliding across the region (Palma et al. 2020). However, the early 2023 Auckland storms were part of unprecedented monthly rainfalls in the Auckland region, since records began in 1853 (Fowler 2021). Indeed, January 2023 was Auckland’s wettest month since records began, with 539 mm recorded at Albert Park, Auckland CBD, which had previous monthly maximums of 420 mm in February 1869 and 393 mm in July 1988 (NIWA 2023). The January 2023 total was due to

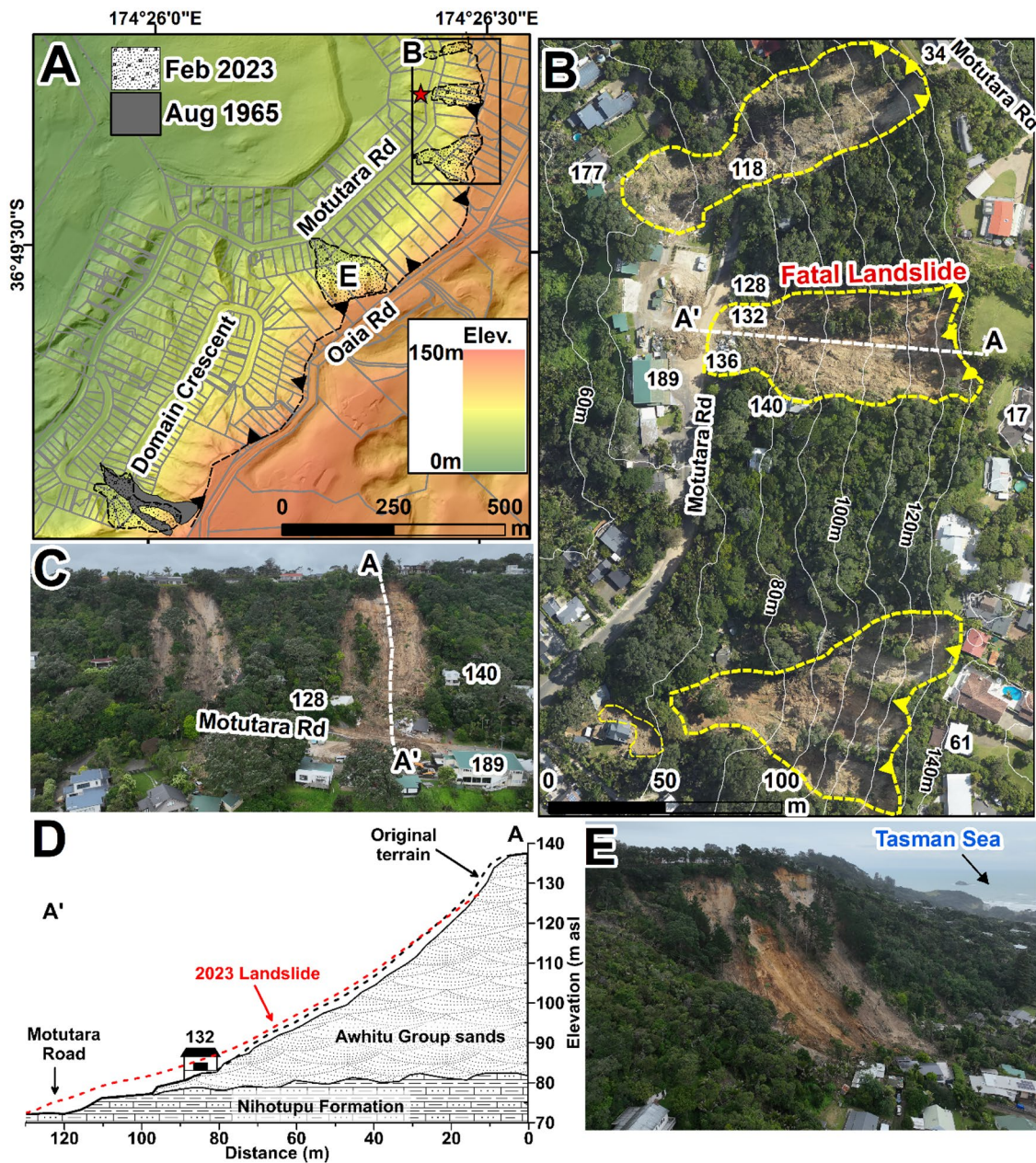


Fig. 5 February 13 fatal landslide at Motutara Road, Muriwai, on Auckland's west coast: **A** LiDAR DEM of Muriwai showing land parcels, the escarpment formed in Awhitu Group sands, the locations of 2023 landslides (red star in inset is 2023 fatal landslide), as well as the 1965 fatal landslides at Domain Crescent (dark gray); **B** post-landslide aerial image of 2023 fatal landslide (middle landslide) at Motutara Road; **C** aerial image of 2023 landslide and long-section A-A'; **D** geological section A-A'; **E** oblique image of large (non-fatal) landslide (labeled in panel A)

prevailing wet weather over the 2022/2023 summer, influenced by (1) strong marine heatwave conditions with sea surface temperatures (SSTs) several degrees warmer than average and (2) the positive El Niño Southern Oscillation conditions, with rainfall anomalies more than 30% above average (Harrington et al. 2023). Thus, wet soil conditions were prevailing when the Auckland Anniversary storm (January 27) occurred and even more so when TC Gabrielle arrived (February 13). Both events caused a reduction of effective stress due to rainfall-induced excess porewater pressure (e.g., Cruden

and Varnes 1996). Because of the low number of extreme rainfall events ($n = 2$), the extreme rainfall maximums associated with the landslides, and the prevailing wet soil conditions prior to the events, it is difficult to derive meaningful rainfall triggering thresholds (e.g., Sidle and Ochiai 2006) for the occurrence of landslides. Indeed, of more importance are pre-conditioning factors such as material properties (Cruden and Varnes 1996; Parker et al. 2015; Varnes 1978), which have been explored in the literature previously, as well as land use planning.

Material properties and landsliding

The fatal landslide at Parnell on January 27 (Auckland Anniversary Storm) and the fatal landslide that occurred on February 13 (TC Gabrielle) at Muriwai were on different geological materials and in contrasting geomorphological settings (Fig. 1). The Parnell landslide occurred in Waitemata Group residual soils and underlying weathered rock and was not particularly mobile, as signified by the runout distance of ~40 m and Fahrböschung angle of ~32° (e.g., Legros 2002). At this landslide, permeability contrasts between the residual soil and the underlying Waitemata Group weathered rock were probably an important factor (e.g., Moon et al. 2003). Previous direct shear and ring shear testing (Moon et al. 2003) indicate Waitemata Group rocks weather into very high clay content soils (Adhikary 2001), commonly including swelling clays and limiting permeability (Moon et al. 2003). The Waitemata Group rocks in this area of Auckland are rather flat-lying with widely spaced joints. Residual soils that formed above this parent rock exhibit moderate plasticity for materials of high clay content but are generally weak in shear. The residual soils thus easily become saturated, lie upon a gently dipping surface, and have low shear strength (Moon et al. 2003). Failure along a basal shear surface defined by the regolith-bedrock contact, entraining particles of the underlying rock as the material moves downslope, is a likely model of the process.

In contrast with the above, the fatal landslide at Muriwai during TC Gabrielle was not associated with residual soils but was formed in Awhitu Group Pleistocene sands and showed more mobility (Brook et al. 2023). Indeed, the Fahrböschung angle of ~26° indicates increased mobility (e.g., Legros 2002), and this was evidenced by the runout of the material across Motutara Road. At Ohuka coastal landslide 75 km south of Muriwai, landslides within Awhitu Group sands appear to be facilitated by the presence of halloysitic tephra layers (Bevan et al. 2022). These are typically ~1-m thick beds of ~1-Ma old Kidnappers Tephra, from rhyolitic eruptions in the Taupo Volcanic Zone (Bevan et al. 2022). These low-permeability clay layers are highly sensitive, and their low permeability reduces water infiltration into the slope, therefore increasing pore water pressure in the overlying aquifer (e.g., Kluger et al. 2020). Sensitivity is the ratio of maximum shear strength to post-failure residual shear strength, where a value of >30 is defined as highly sensitive (Skempton and Northey 1952). However, sensitivity is much lower in Awhitu Group soils at Muriwai (SI = 2.5, Table 1) than in the Awhitu Group sands at Ohuka (SI = 8.9), and the Kidnapper's Tephra has not been identified within Awhitu Group sands as far north as Muriwai. Therefore, a different model of failure is likely to that at Ohuka, and probably accords with the 1965 fatal landslides in Muriwai, from the same escarpment (Wright 1966). Indeed, at Muriwai, the unconformity with the underlying Waitakere Group volcanoclastic sediments forms an aquiclude, and this is evident from the water seeps that are usually visible, marked by a rich growth of vegetation (Wright 1966). An increase in pore water pressure causes a reduction in effective stress and, consequently, a reduction in shear strength to the critical level, and landslides are triggered. The seemingly rapid failure without warning of the 2023 fatal landslides closely mirrors the 1965 landslides, where the source areas formed similarly large "amphitheaters" in the escarpment, and the reports of "spontaneous liquefaction" of the failing material by Wright (1966). Moreover, the escarpment LiDAR DEM indicates the presence of a multitude of

existing headscarps from older landslides, illustrating that highly mobile, hazardous landslides are part of the long-term geomorphic evolution of the landscape.

Planning and legislation

Economic impacts of landslides (and floods) have been brought to the fore in 2023 because the impact of the two storms exceeds NZ\$14.5 bn (Pullar-Strecker 2023), which is 3.4% of New Zealand's 2023 projected GDP of \$417 bn (US\$249 bn). To put this into context, Rosser et al. (2017) estimated that typical annual costs associated with landslides in New Zealand are NZ\$250–\$300 million/year, or 0.1–0.12% of GDP. Thus, the economic and social impacts of the storm events this year are profound. Given that both Parnell and Muriwai fatal landslides occurred close to previous major landslides within living memory, it may seem surprising that houses have been re-constructed on land that has failed in the recent past. Indeed, the fatal Auckland Anniversary storm landslide occurred only a few meters from a landslide in 1997 that destroyed a house (which was rebuilt in 1998). At Muriwai, the TC Gabrielle event also triggered landslides over the same land parcels where fatal landslides had occurred in 1965 (note the 2023 fatal landslides were ~1 km along the escarpment). In particular, given Muriwai's history of fatal landslides (Wright 1966), the interplay of land development, central government legislation, and local planning decision-making is intriguing. Indeed, several reasons promote building on unstable land in New Zealand, which may intrigue international landslide experts. First, after the 1965 Muriwai landslides, local council engineers stated that no new houses would be developed in the landslide "footprints." Indeed, by the Local Government Act 1974, s 641(2), councils were forbidden to grant a permit for the erection or alteration of any building if, within its useful life, it was likely to be damaged by "...erosion, subsidence, slippage or inundation..." However, on October 23, 1981, that Act was amended, and s 641A(1) then allowed councils to permit buildings on land subject to "erosion, subsidence or slippage" if they were designed to be relocatable and the council was satisfied they could be relocated (many New Zealand houses are "relocatable" in that they are timber-piled, timber-framed, covered with weatherboard cladding and steel panel roofs). For similarly vulnerable existing properties, consents were also possible under s 641A(2) for alteration of an existing building or erection of *any other building* consistent with the use and occupation of the existing building. Finally, the councils were absolved from civil liability for issuing consents under these subsections (s 641A(3)). Soon after the s 641A requirements were relaxed (1981), the plots of land on Muriwai's Domain Crescent that had remained vacant since the 1965 landslides were re-developed. Unfortunately, several of these "new-builds" were subsequently inundated and destroyed during the 2023 TC Gabrielle event (Fig. 1). Note that the present building laws are broadly similar in effect (s 71 to s 74, Building Act 2004).

Second, the Earthquake Commission Act (1993) provides New Zealand homeowners with up to NZ\$300,000 (US\$187,000) compensation for several natural hazards including landslides, floods, and earthquakes. It is a statutory scheme administered by the Earthquake Commission (EQC), part-funded by levies on homeowners who have fire insurance cover over their dwellings. Indeed, it is a precondition to their EQC cover that they have fire insurance,

although most homeowners' policies obtained on the domestic market cover a package of other home ownership-related risks and are not restricted to fire. However, these levies (collected by the fire insurer and passed onto EQC) are not the true actuarial price of the individual risk. There is a large degree of cross-subsidization because the levies are not calculated with geographical location in mind and geography in New Zealand is a significant risk factor with natural hazards. EQC cover for landslides includes the dwelling and, since shortly after the 1979 Abbotsford Landslide disaster (Hancox 2008), damage to the land. This is because land cover was and is not available on the domestic insurance market. The land component of EQC cover for landslides is limited to land on which the house rests and an 8-m buffer around the dwelling. There is an element of "moral hazard" here (e.g., Hudson and Thieken 2022), because people who pay for someone else to accept their risk (insurance) or who know they will receive a largely taxpayer-funded benefit for less than its actuarial cost are less likely to reduce risk on their own initiative—they do not care for their property as much as if were their "own insurer." Thus, if the government's state "safety net" (New Zealand's EQC Act) is not carefully designed with reciprocal, measurable obligations of the householder to take reasonable steps to avoid risk or to reduce the effects of unavoidable risk, self-help is reduced and the cost to the taxpayer is, sometimes unsustainably, increased. Notwithstanding this, landslide hazards in the vicinity of the 1997 landslide appear to have been partly recognized by the housing market, because lower house and land valuations exist in the area of the 1997 landslide (Fig. 4C). Indeed, houses above the cliff at Arney Road, with views across Hobson Bay, average US\$5.06 million (July 2022), while houses below the cliff on Shore Road average much less, US\$2.15 million (July 2022). This may indicate "price discounting" effects (e.g., Yi and Choi 2020), due to specifications on the property title regarding landslide hazards, as designated under New Zealand's 2004 Building Act. Alternatively, the higher house prices above may simply reflect the higher demand (hence value) of houses with more impressive views, even though the building setback from the cliff edge is in some cases, zero meters, and therefore is of increased risk (e.g., AGS 2007) of being affected by slope failure.

Conclusions

Rainfall-triggered landslide events that generate tens of thousands of landslides (MORLEs) present a challenge to many countries, including New Zealand. Indeed, the first 2 months of 2023 saw two severe storm events, the Auckland Anniversary Storm and Cyclone Gabrielle, cross New Zealand's most populous city, causing fatal landslides in weak materials. Our work shows that some of these landslides occurred in the same locations as where fatal landslides had occurred in recent decades. An element of such fatal landslides in Auckland (and New Zealand) is the legacy of previous building laws (Local Government Amendment Act 1974) as well as the current building legislation (Building Act 2004), whereby houses are legally constructed in areas that are known to be susceptible to damaging landslides. Global best practice shows that region-wide landslide susceptibility mapping and monitoring of hazardous slopes with techniques such as InSAR is an important component of landslide risk assessment. Nevertheless, the hazardous situation in parts of Auckland almost entirely exists due to existing planning legislation, coupled with legacy historic planning decisions.

As it stands, the New Zealand legal and institutional framework for land-use planning does not facilitate coordinated decision-making for resilience-building. Policies and laws (including private insurance and the state's natural hazard safety net) need to be better-aligned, promoting effective and integrated natural hazards planning, because policy levers are dispersed across various statutes with inevitable overlaps, voids, and incongruence. Only then will New Zealand translate legal directions into practical realities such as managed retreat and realistic building setback distances from hazardous slopes.

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Data availability

All data is provided within the article.

Declarations

Competing interests The authors declare no competing interests.

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