

ANALYSIS OF THE MECHANISM OF LANDSLIDING, GARIE ROAD, ROYAL NATIONAL PARK, NSW

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ABSTRACT

Once landslide movement is identified, it is important to employ the necessary investigation techniques to characterise the landslide type and analyse the mechanism of mass movement. Defining the geometry of the landslide slip surface and presenting this with confidence within the engineering geological model is fundamental to the development of the appropriate remedial design solution.

A large landslide developed along Garie Road, Royal National Park in March 2022 following a series of intense rain events. Tension cracking along the centreline of the road progressed quickly to large scale deformation as a slow-moving landslide developed retrogressing to the south and west. This paper presents a case study of the engineering geological and geotechnical assessment of the Garie Road landslide using various investigation techniques including drone terrain evaluation, landslide mapping, detailed core logging and instrumentation review. The data collected to analyse the landslide mechanism is presented and validated through a literature search and comparison of a similar Illawarra escarpment landslide. The comparative study was fundamental in identifying similar basal sliding in close proximity to the interface between the Bald Hill Claystone and the Bulgo Sandstone.

1 INTRODUCTION

1.1 SITE LOCATION

Garie Road is situated approximately 30 km south of Sydney CBD within the Royal National Park. The landslide location is located along a north-south trending section of Garie Road that is approximately 400 m to the west of Garie Beach. The landslide location is presented in Figure 1.

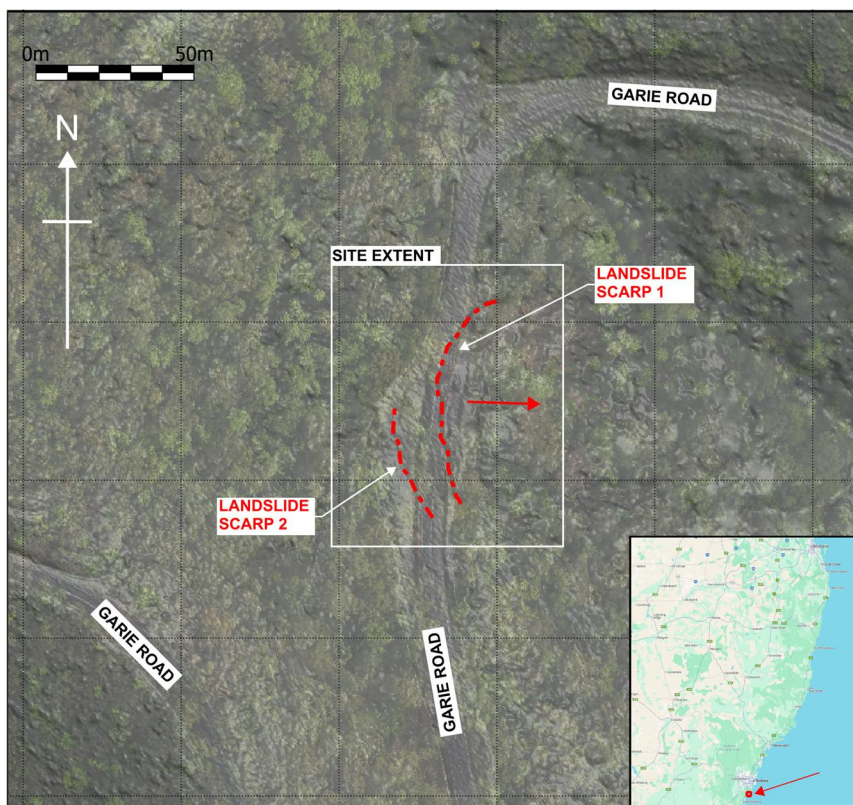


Figure 1: Location and scarp extents of the Garie Road landslide

1.2 SITE GEOLOGY AND GEOMORPHOLOGY

Reference to the Seamless NSW Geological Maps (Colquhoun, et al., 2021) indicates that the site geology comprises (from an upslope to downslope direction) the Hawkesbury Sandstone, Newport Formation, Bald Hill Claystone and Bulgo Sandstone (Figure 2). The landslide site is directly underlain by the Bald Hill Claystone and the top of the underlying Bulgo Sandstone is between ~12 m to 17 m below road level.

An Unmanned Aerial Vehicle (UAV) drone survey was flown over the failed extent of the road and surrounding upslope and downslope areas. An output from the UAV survey was a LiDAR Digital Terrain Model (DTM) that is utilised as the topographic surface in Figures 2, 3, 6, 8 and 10.

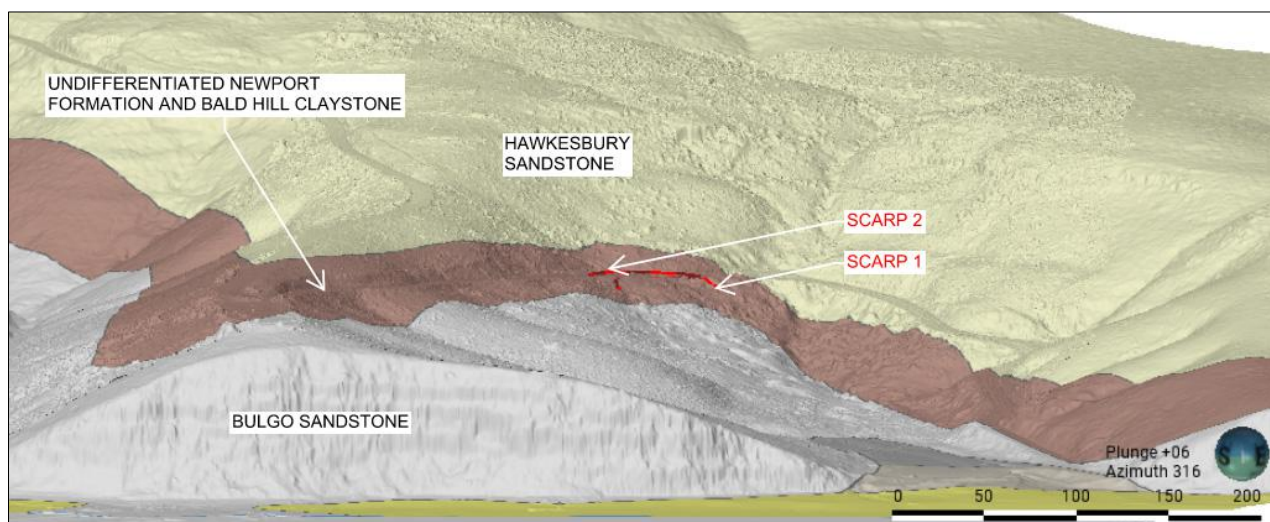


Figure 2: View of the Seamless NSW Geological Maps (Colquhoun, et al., 2021) overlain on the DTM (MES, 2022) of the Garie Road landslide and coastal cliffs. Note: no differentiation is provided on the Seamless NSW Geological Maps between the Newport Formation and the Bald Hill Claystone however the Bald Hill Claystone was mapped as an individual unit on site.

Descriptions of the geological units are presented Table 1.

Table 1: The geological units present in the vicinity of the Garie Road landslide site (Colquhoun, et al., 2021) and (Pells, 1994).

Sub-group	Formation	Map Unit	Period	Description
Hawkesbury Sandstone		Tuth	Middle Triassic	Medium to coarse grained quartz sandstone with minor shale and laminate lenses.
Gosford Sub-group	Newport Formation	Tng_b	Early Triassic	Interbedded shale and sandstone sequence. The unit has a gradational boundary to the underlying Bald Hill Claystone and is interbedded with the overlying Hawkesbury Sandstone.
Clifton Sub-group	Bald Hill Claystone			Chocolate brown to red-brown kaolinitic claystone with silty and sandy grey and mottled grey-brown zones, with minor laminated and thinly bedded siltstones and sandstones ranging up to 3 m thick. The Bald Hill Claystone is primarily kaolinite (50% to greater than 75%) with quartz and feldspar as the remainder. Hematite is the primary secondary mineral and source of the red-brown colour.
	Bulgo Sandstone	Tncu		Fine to medium grained grey-brown to green quartz-lithic sandstone with lenticular brown shale/claystone and siltstone interbeds, sporadic minor polymictic pebble conglomerates.

Garie Road traverses an undulating hillside that slopes at approximately 20-30° to the east. The road corridor is typically 10 m wide and was constructed using cut and fill techniques. The embankment on the downslope side of the road is ≤5 m in height with a gradient of 20° to 40°. At the landslide location, the road corridor widens to approximately 30 m, where the toe of the natural slope to the west is set back from the western edge of Garie Road. It is understood that this widened area is where the previous alignment of Garie Road existed prior to being straightened in the 1960's with the introduction of fill to span the valley.

Site topographical and drainage features are illustrated in Figure 3, which presents an oblique view of the Garie Road landslide site illustrating the topography and incised drainage channels and immediate surrounding area.

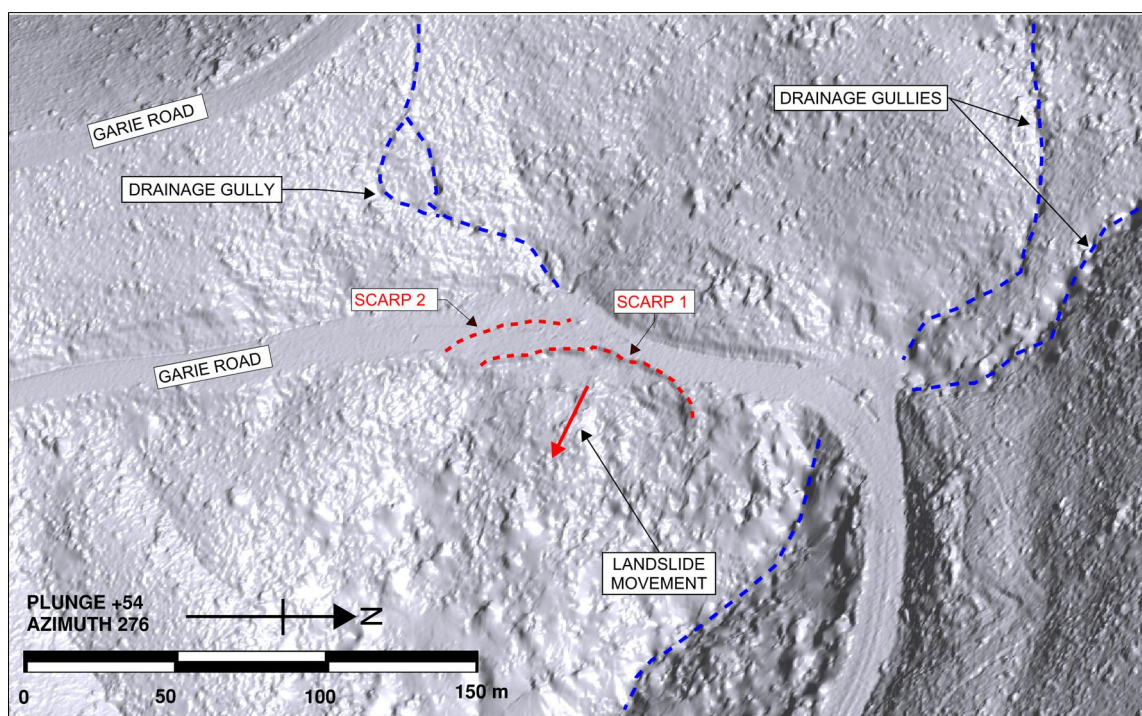


Figure 3: View of the DTM (viewing west) of the Garie Road Landslide site and surrounding area. Source of DTM is MES (2022).

1.3 DEVELOPMENT OF THE LANDSLIDE

The east coast of New South Wales (NSW) experienced severe rainfall in early to mid-2022 associated with the La Nina weather cycle resulting in widespread flooding and significant landslide damage to road and rail infrastructure across the state networks (Flentje, et al., 2022).

In early March 2022, a large landslide developed on Garie Road with the movement direction downslope and to the east. With additional heavy rain events, the landslide grew, retrogressing across the road to the west and some distance to the south between March 2022 and October 2022 (Figure 4). The landslide eventually encompassed the entire road, rendering it impassable by any vehicle.



Figure 4: Photos showing the development of the Garie Road landslide. Top left - vertical and horizontal displacement along road centreline (30 March 2022). Top right - significant progression of the deformation (4 April 2022). Middle - landslide retrogressed south (early July 2022). Bottom - Scarp 1 condition (July 2022).

Within 24 hours of the initial ground instability, a series of surface survey monitoring points at various locations were installed above and below the observable scarps to record the ground movement. The movement and rainfall observations are summarised below and in Figure 5:

- **Early March 2022:** 268 mm of rainfall was recorded within two consecutive days. Site observations recorded longitudinal cracking along the centre line of the road and crescent shaped cracking at the northern and southern end of the developing zone of instability.
- **Early April 2022:** 352 mm of rainfall was recorded in five days. This resulted in progression of the instability and a significant landslide backscarp was now evident with ~1 m of vertical displacement.
- **April to July 2022:** Scarp 1 increased to 2.7 m vertical displacement.
- **Early July 2022:** 755 mm of rainfall was recorded within seven days. This resulted in additional vertical displacements of up to 160 mm in the areas surrounding Scarp 1 and the landslide retrogressed to the south. Movement at Scarp 1 slowed and stabilised at ~3 m of vertical displacement.
- **Early to mid-October 2022:** 287 mm of rainfall was recorded in 13 days, resulting in additional instability and a retrogression of Scarp 1. A secondary Scarp 2 (Figure 1) opened to the west of Scarp 1 with vertical displacement ranging from 300 mm to 400 mm with creep of surrounding areas. Survey data recorded 3.3 m of maximum vertical displacement at Scarp 1 in October 2022.
- **November 2022 to April 2023:** The landslide movement stabilised and the surface survey monitoring was terminated in April 2023 due to early construction activities on site.

The above summary is presented graphically in Figure 5 which illustrates the rainfall data near Garie Road (sourced from the nearest Bureau of Meteorology station, Darkes Forest, Kintyre) and the resulting vertical slope movement recorded by the survey monitoring points.

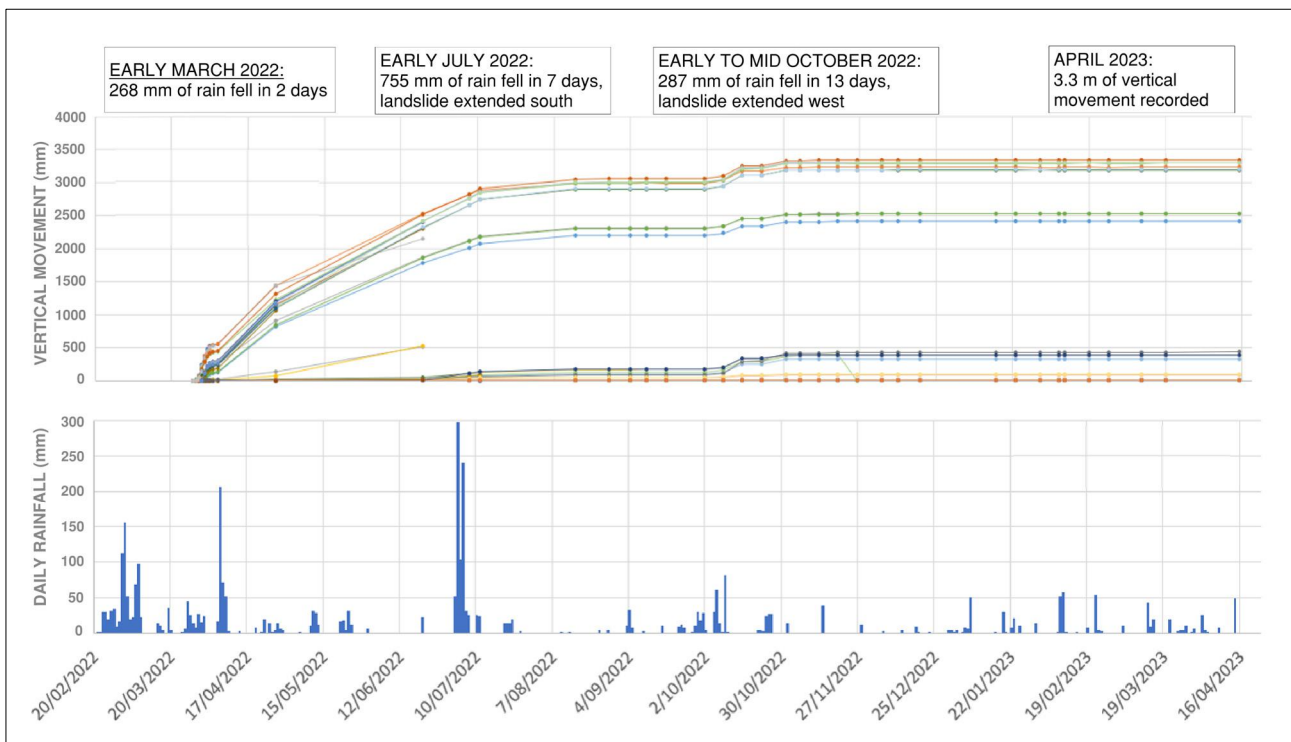


Figure 5: Landslide vertical movement plotted from key survey monitoring points (coloured lines) installed below Scarp 1 and rainfall plot from March 2022 to April 2023. The rainfall data is taken from the BOM database for the Darkes Forest, Kintyre rain gauge.

2 ASSESSMENT METHODOLOGY

Various intrusive and non-intrusive investigation techniques were employed at the Garie Road landslide site to provide the required data to create an Engineering Geological Model (EGM) and characterise the landslide and its mechanism of mass movement:

- **UAV drone survey:**
Flown over the failed extent of the road and surrounding upslope and downslope areas. The outputs from the UAV survey were high resolution photogrammetry and a LiDAR generated DTM.
- **Engineering geological and geomorphological mapping:**
Mapping of the zone of instability and surrounding areas including the upslope and downslope (limited access) to the landslide. The mapping assessed the extent and key features of the landslide, key geomorphological features and soil and rock exposures/outcrops.
- **Intrusive geotechnical investigation:**
A phased geotechnical investigation was undertaken comprising:
 - Twelve cored boreholes.
 - Five (5) seismic refraction lines totalling 450 m in total length, one (1) along the road, one (1) along the toe of the road/landslide and three (3) perpendicular lines in a down slope direction, intersecting boreholes where possible for calibration purposes.
- **Instrumentation installation and monitoring:**
Geotechnical monitoring instruments were installed in selected boreholes:
 - Four (4) manual inclinometers (refer Figure 8).
 - One (1) Vibrating Wire Piezometer (VWP).
 - Three (3) standpipe piezometers.
 - Four (4) boreholes allocated for downhole imaging with Optical Televiewer (OTV) and Acoustic Televiewer (ATV) methods.
- **Literature Review:**
A literature review was undertaken on any known documented slope instability within the Bald Hill Claystone, particularly within the Illawarra Escarpment which the Garie Road landslide site forms the escarpments northern limit.
- **Engineering Geological Model:**
The factual data from the intrusive and non-intrusive investigations was presented in an EGM (produced in Leapfrog software by Seequent). The EGM presents the distribution of the assigned engineering geological units within 3D space and assisted in the characterisation and interpretation of the landslide and its mechanism of mass movement.

3 INVESTIGATION RESULTS

3.1 UAV DRONE SURVEY

The UAV survey produced high quality orthomosaic photos of the landslide and its features, particularly the downslope inaccessible area to the landslide. A key observation from the orthomosaic photos was the identification of the extent of felled trees on the downslope that had been uprooted due to the landslide movement. The lower limit of the felled trees was taken to be the toe of the landslide daylighting from the slope face. This point was georeferenced and inputted into the EGM.

The DTM was a valuable output from the UAV survey and was interrogated to assess additional scarps that could not be observed during the mapping due to steep inaccessible slopes or dense vegetation. In addition, the DTM provided information relating to the geomorphology and drainage characteristics of the site (Figure 3).

3.2 ENGINEERING GEOLOGICAL MAPPING

The engineering geological and geomorphological mapping is presented in Figure 6 and a typical mapped outcrop of the Bald Hill Claystone is presented in Figure 7.

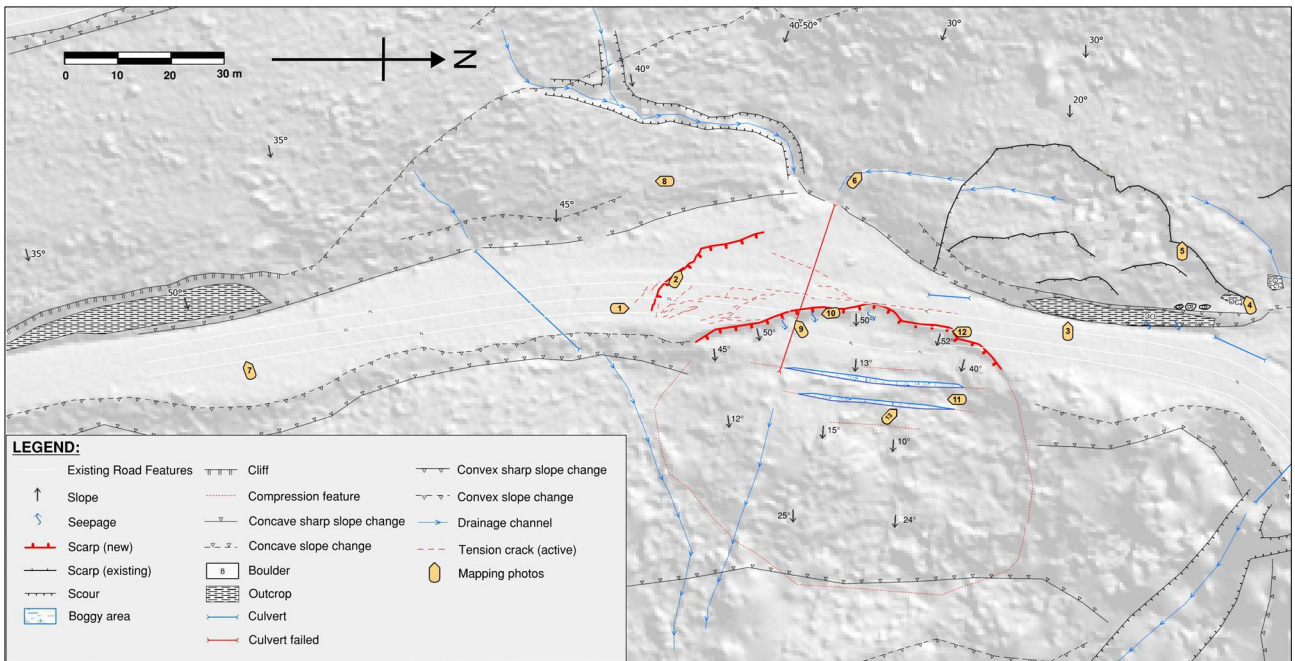


Figure 6: Engineering geological map of the landslide and surrounding area. Source of DTM is MES (2022).

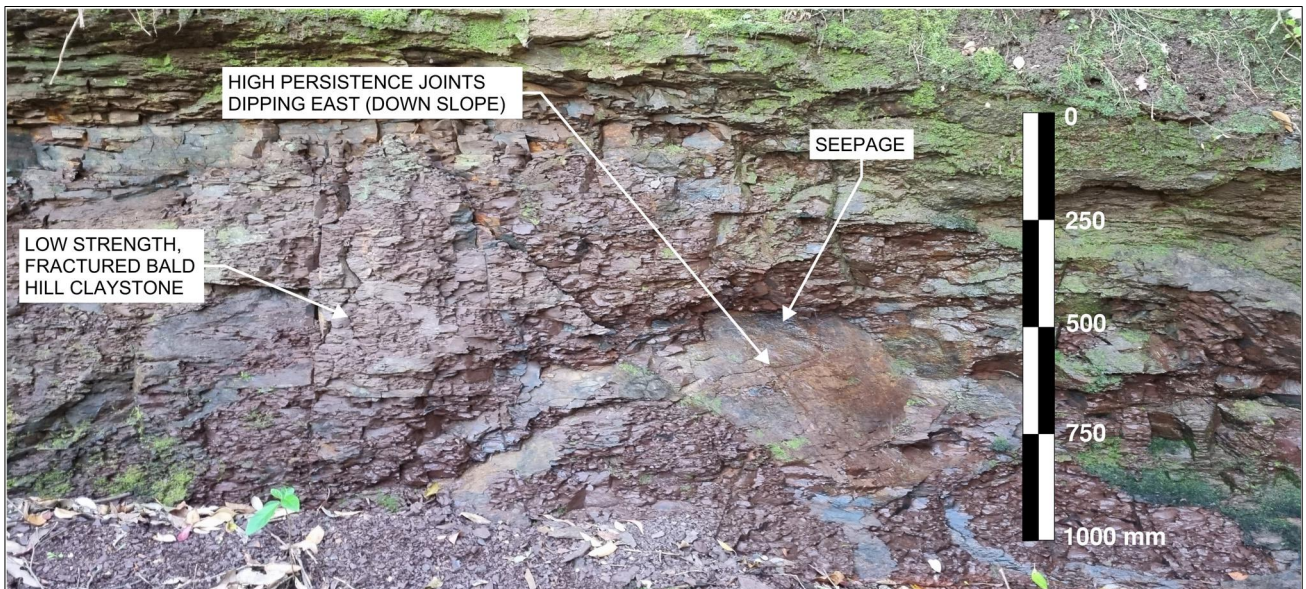


Figure 7: Typical Bald Hill Claystone rock cutting present on the upslope of Garie Road immediately to the north of the landslide

The following is a summary of the key features mapped:

- The landslide was relatively large; the dimensions were assessed to be approximately 80 m in width and 60 m in length from landslide backscarp to toe. The landslide toe extended significantly beyond the road reserve into the National Park to the east.

- The landslide backscarps in the road and road reserve were inclined relatively steep, dipping $\sim 65^\circ$ to the east.
- A historic scarp was mapped on the immediate downslope to the main landslide with approximately ~ 2 m of vertical displacement. This historic scarp was less obvious due to compression features resulting from the recent instability.
- Some historic scarps were also mapped on the upslope above the road cutting that is present at the northern end of the site, but with no recent displacement or instability observable.
- The Bald Hill Claystone outcrops are typically highly fractured with their surface being comprised of angular interlocking gravel and cobble sized claystone fragments, separated by clay infilled defects.
- A key outcrop observation was a number of higher persistence smooth joints with groundwater seepage, dipping approximately 60° east (general slope failure direction).

3.3 BOREHOLES AND GEOPHYSICS

A site plan indicating the locations of the exploratory holes, inclinometer locations and seismic refraction lines is presented in Figure 8.

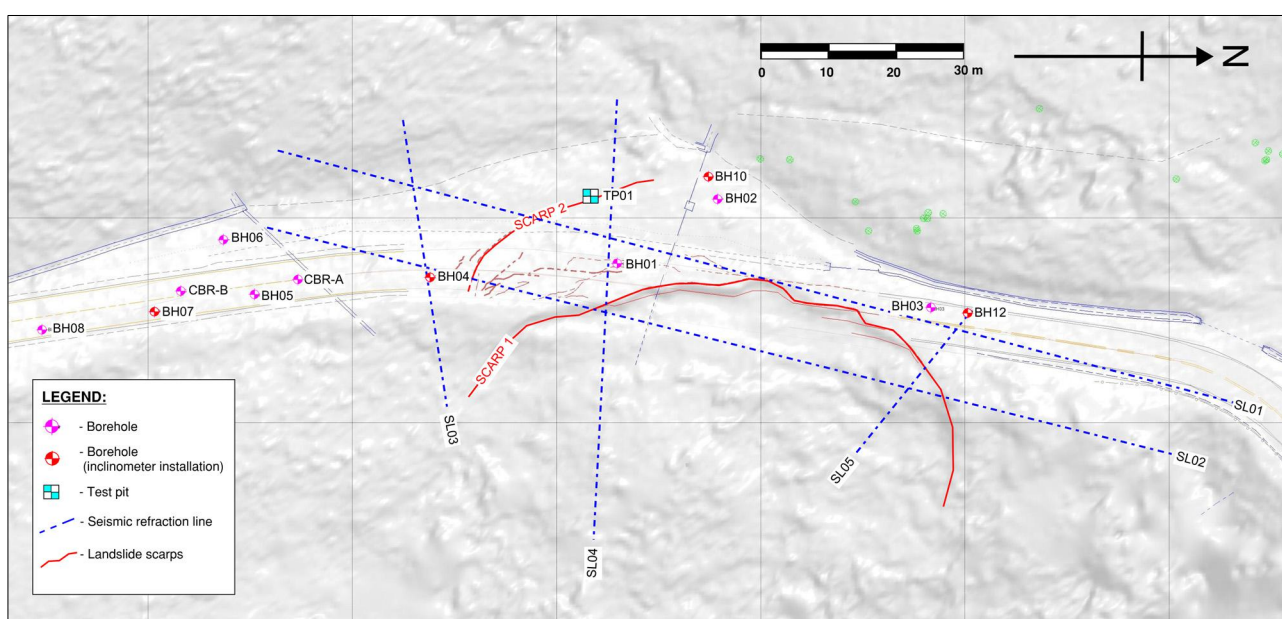


Figure 8: Geotechnical investigation site plan at the Garie Road landslide site. Source of DTM (MES, 2022).

The following presents a summary of the key conclusions from the borehole and geophysical investigation:

- The ground profile generally comprised variable depths of fill, typically underlain by colluvium. These surficial soils were underlain by varying weathering grades of the Bald Hill Claystone, underlain by the more competent Bulgo Sandstone.
- The colluvium comprised highly variable cohesive soils with a significant silt, sand and gravel component, generally stiff to very stiff.
- The residual soil and extremely weathered rock of the Bald Hill Claystone generally comprised very stiff clays with gravel of extremely weathered to highly weathered claystone, siltstone and sandstone. This unit was sometimes difficult to distinguish from the overlying colluvium.
- The highly weathered or better Bald Hill Claystone was typically claystone with siltstone and minor ($<10\%$) sandstone beds (typically highly fractured with weathered joints). This unit ranged from very low to medium strength with an assessed Geological Strength Index (GSI) ~ 40 .
- A pale weathered zone of reduced strength (named ‘weak zone’ from here in) was encountered in boreholes BH06, BH08, BH10 and BH12 within the Bald Hill Claystone in close proximity (within ~ 1 to 2 m) to the underlying interface of the Bulgo Sandstone (Figure 9). This weak zone was logged varying from 350 mm to 800 mm thick where the material had been recovered.

- The Bulgo Sandstone was fine to medium grained, competent sandstone (in contrast to the nature of the overlying Bald Hill Claystone) typically high to very strength with an assessed GSI ~70. The sandstone has a clay/silt matrix between the sand grains hence a relatively low permeability. In some of the logged core, the interface of the Bald Hill Claystone and the underlying Bulgo Sandstone was transitional with an interbedded zone (Pells, 1994).

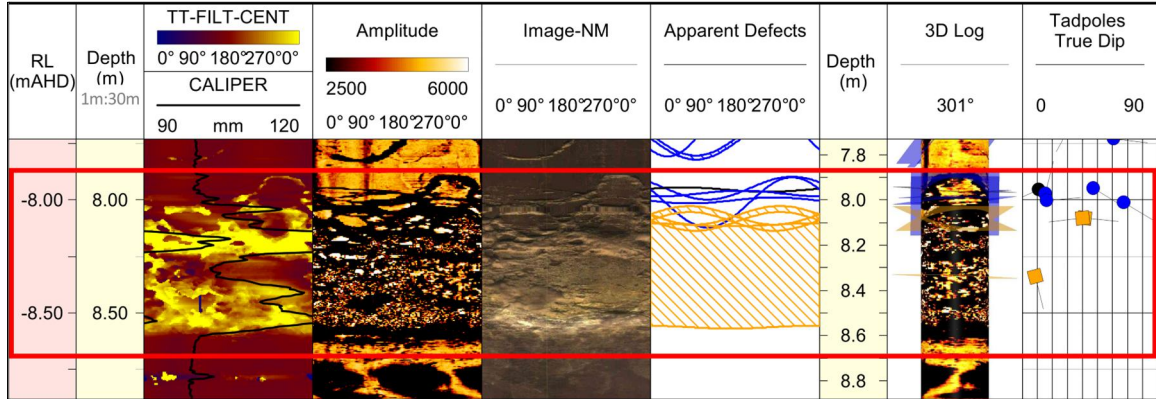


Figure 9: Weak zone clearly identified in the downhole OTV and ATV logs between 8.05 m to 8.5 m depth in BH12

3.4 INSTRUMENTATION REVIEW

The installed inclinometers and standpipe piezometers were monitored manually at fortnightly intervals post installation and then increased to weekly after intense rain events. Initially, only minor movements (<2 mm) within the zone of error were recorded from the relatively dry period from April 2023 to April 2024.

Due to initial construction activities on site only two inclinometers BH10 and BH12 remained operational. In early May 2024, 344 mm of rain fell over twelve days and inclinometer monitoring of BH10 and BH12 was undertaken on a weekly basis. In BH10 which was located towards the western edge of the landslide where no instability had been previously recorded, 55 mm of displacement was recorded on 12 June 2024 at ~9 m depth (Figure 10). The recorded movement within the BH10 inclinometer was within a zone of core loss ~1 m above the upper logged ‘weak zone’ observed in BH10 (Figure 12).

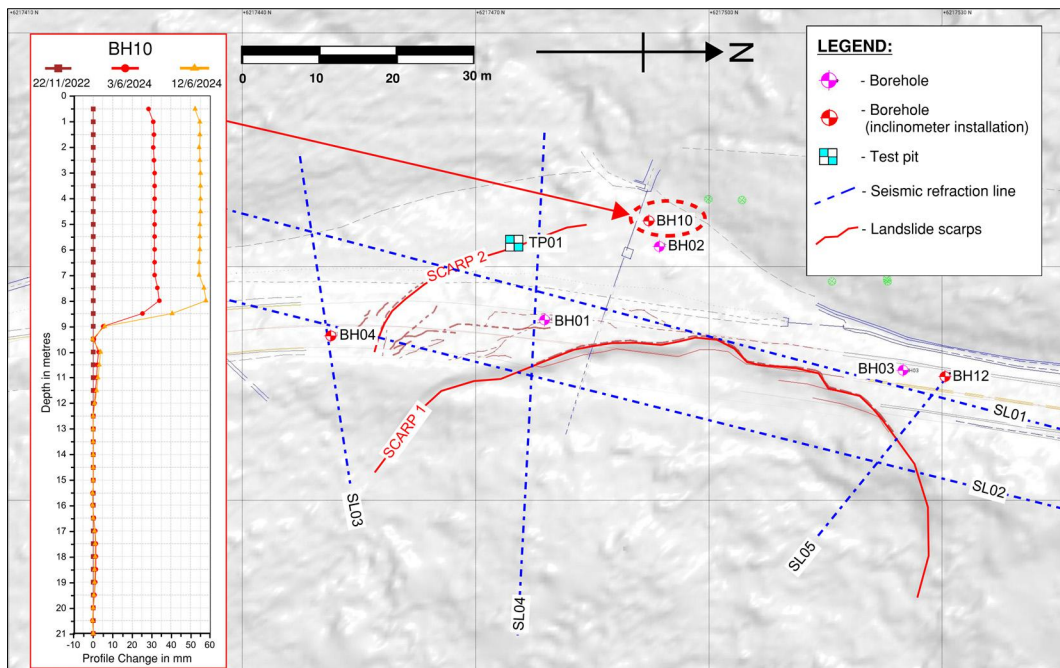


Figure 10: Ground movement at ~9 m depth recorded in BH10 inclinometer in June 2024.

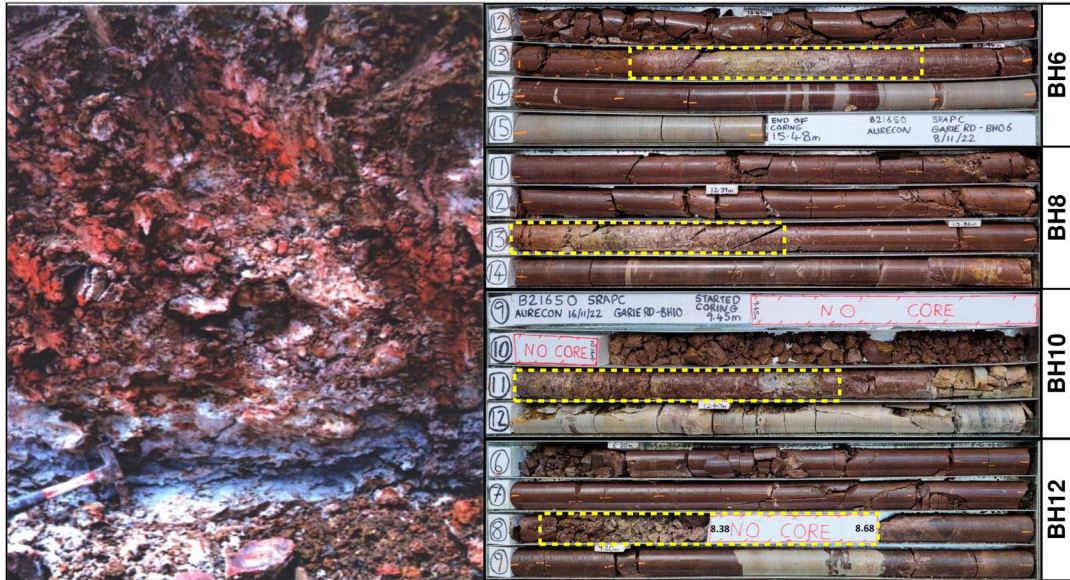


Figure 12: Left image - pale white clay ‘gouge’ associated with a zone of sliding in the Bald Hill Claystone at Site 43 (Stone, 2012). Right images - BH06, BH08, BH10 and BH12 core displaying a similar pale white weathered clay zone (yellow dashed boxes) within the Bald Hill Claystone, 1 to 2 m above the interface with the underlying Bulgo Sandstone.

5 ENGINEERING GEOLOGICAL MODEL

The data collected during the investigation was assessed and used to develop the EGM. Engineering geological units were assessed at an appropriate scale largely based on rock weathering grades or type of deposit (e.g. colluvium and fill). The ‘weak zone’ was assigned an individual project engineering geological unit given its importance within the ground model and landslide mechanism.

A 3D cross section of the EGM is presented in Figure 13.

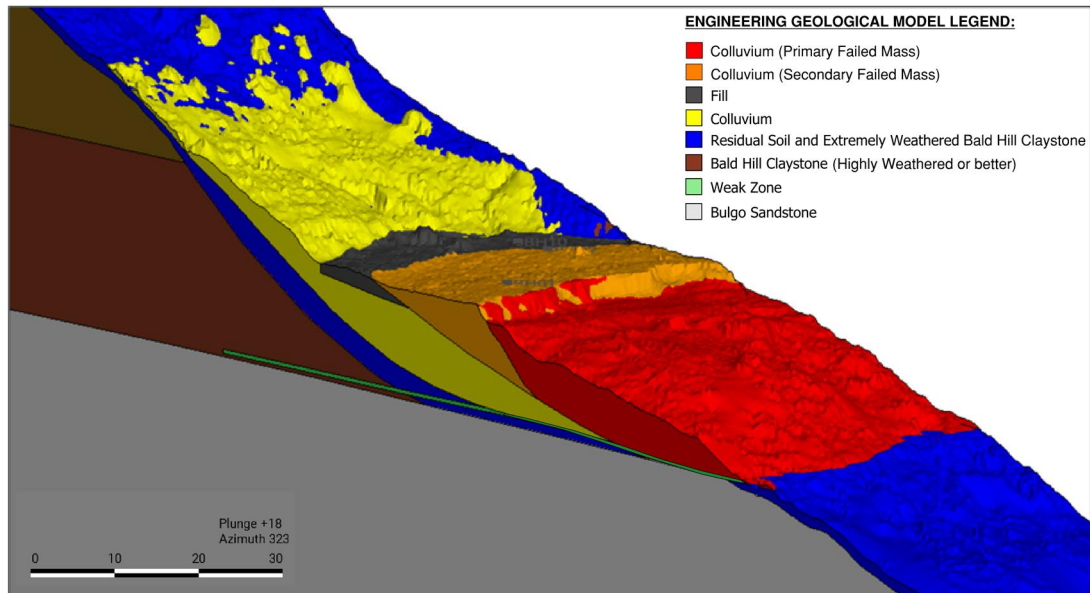


Figure 13: Cross section through the Leapfrog developed EGM. Source of DTM (MES, 2022).

In the EGM, the landslide was interpreted to have a backscarp in the order of $\sim 65^\circ$ dip and an assessed planar basal sliding plane ~ 13 m below ground level at the Scarp 1 location. The geometry of the landslide was defined based on the engineering geological mapping, intrusive investigation results and comparison with the published literature (Flentje & Leventhal, 2012; Stone, 2012).

6 DISCUSSION

The characteristics and mechanism of mass movement of the Garie Road landslide have been assessed by a number of instructive and non-intrusive investigation techniques, a literature review and the development of an EGM. The following is a summary of the landslide characteristics and the components of the mechanism of mass movement:

- The landslide is a pore pressure driven; slow moving ‘stick-slip’ landslide as demonstrated by the rainfall vs ground monitoring data (Figure 5). Ground movements accelerated subsequent to intense rain events with retrogression of the landslide and slowed or ceased during periods of dry weather.
- The mechanism of mass movement is a large slide with both a rotational and translational component. The backscarp to the landslide is assessed to be semi-rotational measured dipping at $\sim 65^\circ$ to the east at the ground surface. The basal slide plane is the translational component of the landslide mechanism sliding on the weak zone within the Bald Hill Claystone close to the interface of the underlying Bulgo Sandstone. The assessed dip of the basal slide plane is just $\sim 5^\circ$ to the east, approximately parallel to the sub-horizontal top of the Bulgo Sandstone.
- The Garie Road landslide has a number of close similarities to the Site 43 South Coast Railway landslide site, namely the same zone of sliding within the white clay gouge ‘weak zone’ is common to both landslides (Figure 12). In addition, both landslides have similar backscarp and basal slide plane geometry, the presence of superficial instabilities on the upslope and progressive movement was experienced until the onset of dry weather (Flentje & Leventhal, 2012; Stone, 2012).
- The ground movement recorded in the BH10 inclinometer at ~ 9 m depth in June 2024 is assessed to be a retrogression of a new backscarp trending up at a similar geometry to the existing Scarp 1 and 2 from the ‘weak zone’ basal slide plane. This inclinometer movement further validated the landslide movement is within the identified ‘weak zone’.
- The steep joints with high persistence dipping approximately 60° to the east (general slope failure direction) mapped within the Bald Hill Claystone road cuttings are assessed to provide a preferential weak surface for the formation of backscarps during high intensity rainfall events.
- In addition, the steep dip high persistence joints are assessed to provide a preferential pathway for surface water infiltration into the lower Bald Hill Claystone. During intense rain events groundwater is concentrated at the interface of the relatively low permeability Bulgo Sandstone where degradation of this zone occurs forming the ‘weak zone’ that is prone to landsliding.
- The mechanism of landsliding presented is an example of the Illawarra Escarpment retreat (Flentje, 2012).

The components of the mechanism of landsliding comprising a semi-rotational backscarp and a sub-horizontal basal slip plane formed at the location of the ‘weak zone’ is presented in Figure 14.

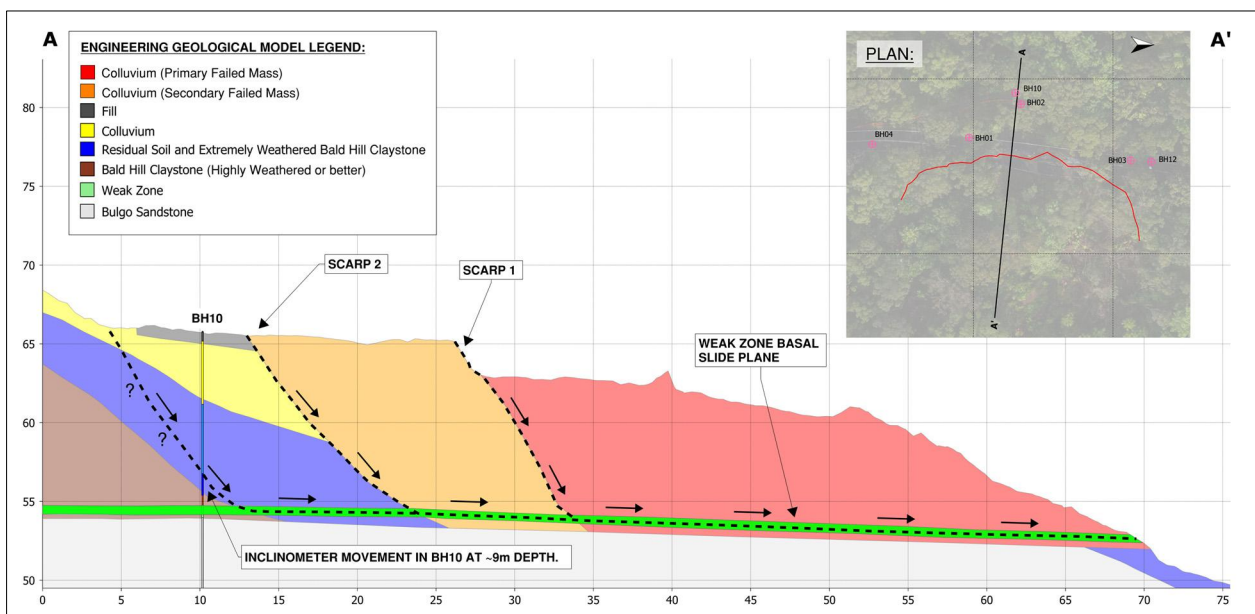


Figure 14: Cross section A-A' through the EGM displaying the assessed mechanism of landsliding at Garie Road.

7 CONCLUSIONS

The Garie Road landslide was triggered by 268 mm of rain that fell in two consecutive days in early March 2022. The landslide was slow moving, retrogressing to the south and west over the subsequent months in response to further intense rain events. The landslide demonstrated ‘stick-slip’ style movement in response to periodic elevated pore water pressures.

This paper presents a case study of the assessment of the landslide through the various investigation techniques including drone terrain evaluation, landslide mapping, detailed core logging and instrumentation trends. The data collected was inputted into an EGM which allowed an interpretation of the components of the mechanism of mass movement, comprising a steep semi-rotational backscarp and a translational basal slide plane ~60 m in length dipping at just ~5° to the east. The location of the basal slide plane was interpreted to be at the location of the identified ‘weak zone’ within the Bald Hill Claystone in close proximity to the underlying Bulgo Sandstone.

The assessed landslide mechanism has been validated through comparison of the similar Illawarra escarpment landslide at Site 43 on the South Coast Railway (Flentje & Leventhal, 2012). At this landslide site, a trench excavation revealed white slide plane clay gouge identified to be the failure surface at the Bald Hill Claystone / Bulgo Sandstone interface. This case study builds on the previous knowledge of known landsliding at the interface of the Bald Hill Claystone / Bulgo Sandstone; allowing better understanding and mitigation of similar landslides on Australia’s civil infrastructure network.

8 REFERENCES

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