REPORT

CHRISTCHURCH CITY COUNCIL

SLOPE HAZARD SUSCEPTIBILITY ASSESSMENT
Akaroa Harbour Settlements

Report prepared for:
CHRISTCHURCH CITY COUNCIL

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Executive Summary

Tonkin and Taylor Ltd (T&T) was engaged by Christchurch City Council (CCC) to undertake an assessment of land stability within 8 defined settlement areas (1900 ha) of Akaroa Harbour. The scope and methodology for this study is outlined in the CCC brief. Key factors in defining the methodology include:

- The requirement to produce susceptibility zoning maps suitable for strategic planning of future growth in the settlement areas. Greater detail and use for functions such as assessing consent applications is not required at this stage.
- To date a review and summary of information regarding slope instability has not been undertaken and presented in an accessible manner. Therefore the information behind the susceptibility zoning should be presented.
- The zoning should be such that additional information can be added and greater levels of sophistication can be developed in the future.

The harbour is the eroded core of a large basalt volcano that formed several million years before present. The erosion and drainage pattern that has formed the valleys and ridges is approximately radial around the 'centre' of the Akaroa Volcano. The 'bedrock' geology consists dominantly of French Hill Formation. The layers of French Hill Formation generally dip at shallow angles (<10^{o}), away from the eruption centre approximately on Onawe Peninsula.

Quaternary Age soil deposits including wind deposited silt (loess) blanket the inner slopes of the harbour and infill the valley floors (Figure C1, Appendix C) and head of the harbour (mudflats). Recent man made fill deposits comprising reclamation and waste disposal (municipal landfill) occur in Akaroa and Duvauchelle settlement areas (see Figures 13, 14, 16).

Groundwater levels and aquifers are complex and related to the layered nature of the volcanic bedrock and draped surface soils. Periods of wet weather, followed by a major rainstorm event has been observed to result in large scale landslides (e.g. Lighthouse Road in 1994) and wide spread development of small scale landslides on loess slopes (e.g. 1975 and 1994).

Our information review and air photo interpretation have identified several types of historic slope instability or slope hazards that can be expected to recur in the future.

Bedrock landslides (Figure 1, Appendix A and Figures C3 to C9, Appendix C) are large to very large failures with a depth to base of movement inferred as 10 to >50m below ground level. The shape and distribution of the landslides suggest that they are ancient features, most likely formed during the initial erosion of the volcano, with subsequent periods of activity related to sea level changes, erosion and deposition cycles, and earthquakes.

Active Gully is a term coined for this study to describe mappable units of geomorphology (Figure 2, Appendix A and Figures C3 to C9, Appendix C) that encompass almost all of the tunnel erosion, surface erosion and small to medium scale landslides that can be identified on the harbour slopes. About one third of the settlement land area is mapped as active gullies.

Large loess/bedrock landslides have dimensions in the 100 to 300m scale and are inferred to be moving at depths of 5 to 15m at, or near the interface between loess and weathered bedrock.

Future instability will be subject to natural trigger events (rainfall and earthquakes) and potentially exacerbated by human development Active gully and large landslide activity are expected to continue into the future in a similar manner to the recent past. The role of bedrock landslides is less certain, but they do add to the complexity of the slope and the potential for slope movements and require specific consideration for any future developments.

In Akaroa Harbour the only areas assessed as being possible of liquefaction are in the valley floors adjacent to the coast where head-of bay 'mudflat' type sediments and areas of landfill/reclamation are likely to occur.

Review of the available information indicates that the slope hazard susceptibility zoning requires significant input from detailed air photo interpretation. The air photo interpretations as shown in Figures 1 and 2 and Figures C3 to C9 (Appendix C) form the basis of the relative susceptibility zoning. The 1975 small landslides were used to count slope angle, slope aspect, slope position and slope length for input to susceptibility ranking/zoning. The breakdown of the assessment of 1975 small landslides is provided in tables in Appendix D.

The basis for the susceptibility zones is a ranking or classification that includes relevant factors that contribute to slope instability as summarised by the tables in Appendix B. A total of 440 zones have been established. The zone score and rankings are listed by settlement area in Appendix B. Zone boundary accuracy is estimated at +\- 30m.

In general, active gullies rank as Locally Significant susceptibility, general slopes rank as Intermediate susceptibility, and valley floors rank as Minor to Negligible susceptibility. Identified large loess/bedrock landslides are assigned a ranking of Significant.

Liquefaction potential is based on our judgement and experience from elsewhere, in the absence of any useful site information. We have provided 2 zones (Unlikely and Possible) for liquefaction potential shown in Figures 10 to 16 (Appendix A). Zone boundary accuracy is estimated at +\- 30m.

The slope hazard susceptibility zoning and assessment of liquefaction potential provided in this report are tools for consideration in strategic planning. In general a higher susceptibility zone indicates relatively greater difficulty (and therefore cost) for development. The long term risk (and cost) to Council of providing reticulated services and access is also likely to be proportionally greater for higher susceptibility zones.

Caution should be exercised in excluding any area from future development based on slope hazard susceptibility alone, as there is not necessarily a direct relationship between susceptibility and ability to develop on any given site. The slope stability risk for development of a specific site must include an assessment of hazard susceptibility, likelihood and consequences to arrive at a defensible conclusion.

Final decisions on development consents should not be made on the basis of the slope hazard susceptibility zoning alone. It is recommended that the zoning be used as a guide to developing consenting 'rules' that require more rigorous investigation, design and peer review conditions for higher susceptibility zones.

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1 Introduction

1.1 General

Tonkin and Taylor Ltd (T&T) was engaged by Christchurch City Council (CCC) to undertake an assessment of land stability within defined settlement areas of Akaroa Harbour. This work was undertaken based on CCC's project brief of 22 May 2007 and T&T's proposal of 25 May 2007.

CCC's project aim provided in the brief is "to delineate areas most suitable for development in the defined study areas in terms of slope and ground stability". Slope instability/landslide susceptibility and potential for liquefaction are two constraints to be considered by CCC in potential future growth of existing settlements.

The brief provides a detailed methodology for the development of slope hazard susceptibility and liquefaction potential maps based on a scope limited to a desk study of available information and a drive-by field check.

The CCC brief required consideration of various factors in developing slope hazard susceptibility zones, including:

- Geology.
- Slope angle.
- Slope aspect.
- The distribution of existing instability.
- Hydrological conditions (groundwater and surface water conditions).

Hazards to be considered in the susceptibility zoning are landslides (including rockfalls), tunnel gullying and run out from movement upslope.

Liquefaction potential was assessed from mapped geology, groundwater inferences, and field observations of alluvial material and local topography.

CCC has provided T&T with settlement boundaries in electronic format. The locations of the settlement boundaries are shown on Figure 1.

The following settlement areas are identified:

- Akaroa
- Takamatua
- Robinsons Bay
- Duvauchelle
- Barrys Bay
- French Farm
- Tikao Bay
- Wainui

1.2 Report Structure

This report describes a desk top study (with field check) of slope hazard susceptibility in the Akaroa Settlements areas. The structure of the report is an introduction, a description of the study area, an assessment of the hazards and the application of susceptibility zoning.

The report Figures, presented in Appendix A include 2 summary figures of slope hazards, followed directly by the susceptibility zoning figures for each settlement area.

The basis for the zoning and derivation of each zone is tabulated in Appendix B.

Supporting information, in the form of Figures and Tables, which is considered primarily of use to geotechnical professionals is provided in Appendices C and D.

Figures to support the description of the study area and hazard assessment, such as geology and air photo interpretation are presented in Appendix C.

Summaries of information used in assessment of hazards and developing criteria for susceptibility zoning are presented in Appendix D.

1.3 Methodology

The scope and methodology for this study is outlined in the CCC brief. Key factors in defining the methodology include:

- The requirement to produce susceptibility zoning maps suitable for strategic planning of future growth in the settlement areas. Greater detail and use for functions such as assessing consent applications is not required at this stage.
- To date a review and summary of information regarding slope instability has not been undertaken and presented in an accessible manner. Therefore the information behind the susceptibility zoning should be presented.
- The zoning should be such that additional information can be added and greater levels of sophistication can be developed in the future.

The study has involved the following stages:

- Meeting with CCC and Environment Canterbury (ECan) to discuss the objectives and obtain available information from these sources.
- Literature search for information in scientific publications, Government, Universities.
- Review of information, initial air photo assessments and development models for slope instability in the area.

- Meeting with CCC and Dr Mark Yetton[1] to discuss findings and scope to complete the study.
- Detailed air photo assessment.
- 1 day drive-by field check around the settlement areas.
- Confirm models for slope instability.
- Assess relative importance of contributing factors (slope angle, aspect etc.), based on our assessments of small scale landslides and large loess/bedrock landslides.
- Develop a relative susceptibility ranking system for Akaroa Harbour Basin.
- Assign susceptibility zones to the settlement maps based on existing instability, slope aspect, slope angle and geology.
- Assign liquefaction potential zones based on geology and slope.
- Present findings in a draft report for CCC and external peer review.

1.4 Sources Of Information

Information for this study has been collected from a number of sources including:

- Historic and recent aerial photographs held by ECan;
- Existing geological publications (soil and geological maps and memoirs);
- Reports and publications sourced from CCC, ECan and Geotech Consulting Ltd;
- Unpublished Theses held at the University of Canterbury Library;

A bibliography is provided in Section 9 of this report.

1.5 Limitations

The information contained in this report and on the accompanying maps has been prepared specifically for CCC as inputs to be considered by CCC in strategic planning for potential future growth of the existing Akaroa Harbour settlements. The maps/GIS data have been prepared at a scale of 1:10 000.

Limitations to the accuracy and 'completeness' of the maps include:

- The ability to identify existing slope instability from air photos and field checking limited to 2 days.
- Knowledge of historic slope instability gained from published information.
- Transfer of air photo interpretation from 1:23,000 photos to 1:10,000 maps.
- The use of 20m contour topography. Contours at 2m intervals are only available for part of the study area.

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[1] Dr Yetton of Geotech Consulting Ltd has been a geotechnical practitioner on Banks Peninsula for >20 years, and is conducting a peer review for this study.

- Generalisations made in developing the susceptibility zoning system.

No liability is accepted for the accuracy of any of the information presented from this study of slope hazards in the settlement areas of Akaroa Harbour. Due to the preliminary nature of the study (limited detail of the assessment), limited information available in the area and the inherent complexity of the geological environment (accuracy of the assessment), site specific conditions may be classified differently from that shown on the maps. Properties that straddle two zones should be initially assessed based on the higher susceptibility category.

The information provided in this report and accompanying maps should not be used as a replacement for site, or area specific geotechnical assessments. The site specific hazard and risk of land instability should be assessed by a suitably experienced geotechnical practitioner.

2 Mapping

Production of maps for this study has used Autodesk software (Auto CAD 2004) to create the images as .dwg files, and has involved the combination of various existing 'GIS layers', digitised air photo mapping and digitised susceptibility zones onto existing cadastral bases. The map features are exportable as individual layers.

T&T received the following files from CCC and ECan to include in our database for the study.

- Settlement boundary maps;
- Consent stability investigation maps;
- Historical and active soil erosion data files.

Sources of information used in the map compilation, along with relevant comments, are listed on Table 1.

Table 1: Map Inputs

Data source	Map Feature	Comments
Terraview database	Cadastral, Roads and major drainage	• Base accuracy assumed, other data scaled to fit. Checked against T&T cadastral database.
Terraview database	Topographic contours, 20m[1]	• Fit to cadastral data.
CCC	Settlement boundary plans	• Fit to cadastral data.
T&T Air Photo Interpretation[2]	Bedrock Landslides	• Digitised and fit to cadastral data. General outline interpretation, boundary accuracy approximately +\- 30m.
	Large Loess/Bedrock Landslides[3]	• Digitised and fit to cadastral data. Location accuracy approximately +\- 30m. Known historically active landslides and others recognised in air photo assessment.
	Active Gullies	• Digitised and fit to cadastral data. Interpretation accuracy approximately +\- 20m, digitising +\- 10m. Total boundary accuracy +\- 30m.
	Small loess landslides	• Digitised and fit to cadastral data. Location accuracy approximately +\- 30m. Actual size down to 5m by 5m recorded, digitised as minimum 10m by 10m.
T&T Slope Aspect Interpretation	Slope aspect boundaries	• Digitised and fit to cadastral data. Division hand drawn to define major valley sides and faces.
T&T Susceptibility Zones	Zone Boundaries	• Digitised and fit to cadastral data. Boundary accuracy approximately +\- 30m. Hand drawn based on slope angle and geology where not defined by existing slope aspect and air photo interpretation boundaries.

Akaroa West 1:50 000 Geology Sheet	Geology	• Scanned and enlarged geology intended as an illustration only. Not accurate.
Banks Peninsula District Plan/CCC	Mass Movement hazard plans	• Not used for this study.
ECan	Soil erosion plans	• Not used for this study.

Notes: 1. 2m contour information is available for most of Wainui, Akaroa and parts of Duvauchelle.

2. Interpretation from 1975 air photos at 1:23,000 scale, sketched onto rectified prints of 1995 air photos at 1:10,000 scale.

3. Additional unmapped large loess/bedrock landslides may exist (mainly within active gully areas?) within the study area. They are not identified due to the difficulty in recognising subtle geomorphology from the air photos and possible locations that do not impact on existing development.

3 Overview of Akaroa Harbour

3.1 Study Area Site Description

The Akaroa Harbour Basin Settlement land stability study covers a number of settlement areas totalling approximately 1900 ha. The study area comprises 8 settlement areas within Akaroa Harbour, as shown in Figure 1 (Appendix A). Generally the settlements are located in inlets and bays at the mouths of valleys adjacent to the coastline of Akaroa Harbour.

The project brief dictated that the study area also include any land outside of the settlement areas which is likely to impact on land within the study areas through instability.

Land use within the settlement study areas is predominantly rural, with small settlement areas along the main highway and valley roads. The Akaroa area is predominantly residential. Existing development results in a 'patchwork' landscape of pasture, horticulture, dwellings, forest and scrub.

Table 2: Figure References for Settlement Areas

Area	Figure		
	Existing Land Instability	**Landslide susceptibility**	**Liquefaction potential**
Wainui	1, 2, C3	3	10
Tikao Bay and French Farm	1, 2, C4	4	11
Barrys Bay	1, 2, C5	5	12
Duvauchelle	1, 2, C6	6	13
Robinsons Bay	1, 2, C7	7	14
Takamatua	1, 2, C8	8	15
Akaroa	1, 2, C9	9	16

3.2 Topography

The topography of the study areas varies from flat to gently sloping valley floors, to moderately and steeply sloping valley sides and headlands, and gently to moderately sloping ridge lines. The erosion and drainage pattern that has formed the valleys and ridges is approximately radial around the 'centre' of the Akaroa Volcano, with the harbour forming the major N-S trending valley that has breached to the sea.

Existing settlement areas are generally centred on gently sloping land adjacent to the harbour at the head of a bay or inlet. Development has tended to avoid moderate to steep slopes, apart from Akaroa Township and some strip holiday home developments along the coastline at Wainui, Robinsons Bay and Takamatua.

3.3 Geology

The geology of Akaroa Harbour is described on the Geology of Akaroa West Area, 1:50,000 scale geological map (Sewell et.al., 1990). The harbour is the eroded core of a large basalt volcano that formed several millions year before present.

The geological map (see Figure C1) shows the underlying 'bedrock' geology to consist dominantly of French Hill Formation, a blue black, medium to fine grained basalt, with interlayered tuff, ash and paleosol (fossil soil) deposits accumulated and eroded between eruptions of the basalt lavas. Tikao Trachyte, a dark green coarse to fine grained trachyte occurs under Tikao Bay settlement, and Lushington Breccia, a cream to light grey, matrix to clast supported, angular to sub-rounded breccia occurs on part of Takamatua peninsula.

The layers of French Hill Formation generally dip at shallow angles (<10°), radially away from the eruption centre approximately on Onawe Peninsula. Erosion of gully and hill topography between eruptions means that locally, and at up to settlement scale the dip direction and thickness of layers can vary significantly from that expected for the overall volcano.

Quaternary Age soil deposits blanket the inner slopes of the harbour and infill the valley floors (Figure C1, Appendix C) and head of the harbour (mudflats). Recent man made fill deposits comprising reclamation and waste disposal (municipal landfill) occur in Akaroa and Duvauchelle settlement areas (see Figures 13, 14, 16).

Generally the soils overlying the bedrock of the harbour are composed of (Bell & Trangmar, 1987):

- Weathered volcanic bedrock, typically <1m thick;
- Volcanic Colluvium, typically <1m thick;
- Loess, wind deposited sand and silt, typically <16m thick;
- Mixed Loess and Volcanic Colluvium, typically <20m thick;
- Alluvium, in valley floors and the harbour head.

Loess and mixed colluvium occur as thicker blankets below 250mRL.

Two different types of loess have been identified in the Banks Peninsula area; the calcareous Birdlings Flat Loess and the non-calcareous Barrys Bay Loess. Barrys Bay Loess is more common in all but the most western extents of the peninsula and is generally found at the heads of inlets and bays, on some lower valley slopes and on ridge crests around Akaroa Harbour (Griffith, 1973).

Colluvium is soil and rock material that has been shifted from its original location, usually by gradual down slope creep of materials, combined with discrete landslide type slope instability.

Alluvium comprises layers of sandy gravel (volcanic derived) and sandy silt (loess derived) deposited by fluid flow in the valley floors and harbour headwaters.

No sub-surface investigation to define the thickness or extent of the overlying soils was undertaken as part of this study.

3.4 Groundwater

Groundwater levels and aquifers are complex and related to the layered nature of the volcanic bedrock and draped surface soils. Bedrock aquifers daylight on the hill slopes where higher permeability volcanic layers underlie the surface soils, resulting in the typical observation of 'lines' of springs at particular elevations along a valley slope. Flows in perched soil aquifers are seasonal, related to preceding periods of rainfall, and tend to daylight at breaks in slope (mid slope and toe of slope) and in the base of gullies.

Groundwater is a major factor in episodic and creep movements of larger scale landslides. Charging of perched aquifers and wetting of the upper soil profile from periods of wet weather, followed by a major rainstorm event has been observed to result in large scale landslides (e.g. Lighthouse Road in 1994) and wide spread development of small scale landslides on loess slopes (e.g. 1975 and 1994).

4 Assessment of Slope Instability

4.1 Background

In assessing existing information it must be noted that there are significant differences between slope instability on the Port Hills and Akaroa harbour. These differences are attributable to geology, historic forest cover and climate (among others).

Significant study and publication about slope instability on Banks Peninsula occurred in the 1970s and 1980s. The work was concentrated on the Port Hills and related to development pressures, and resulting problems with infrastructure in the erodible, tunnel gully prone loess soils. Rainstorm triggered events in the 1970's, with wide spread small scale landsliding, were also studied.

The only major studies in Akaroa harbour have been University of Canterbury Theses (see Section 9, Buckner 1998, Mackwell 1986, and Sanders 1986) and the summary paper by Bell and Trangmar (1987). There are no specific studies or observations of major rainstorm related events in Akaroa harbour, and site specific information is not readily available from Council records.

The generally accepted ideas on slope instability on the Port Hills include:

- Soil creep/shallow landslides generally occurring in loess and mixed colluvium occurring on 15 to 40° southerly facing slopes. Typically shallow landslides are triggered by specific rainfall events and result in down slope runout of semi-fluid debris.
- Tunnel gullies occurring on 5 to 30° northwest facing loess slopes.
- Large scale landslides absent.
- Bedrock landslides absent.

Akaroa is known to have a wetter climate and more complex slopes. In addition to shallow landslides and tunnel gullies, large scale landslides have been studied at Wainui (Mackwell, 1986) and Pipers Valley Road (Buckner, 1998). References to large scale landslide movements in Akaroa on Lighthouse Road (1994) and La Clare subdivision (1975) have been provided for this study by Geotech Consulting Ltd. It is understood that very large bedrock landslides are known of by local practitioners, but there appears to be no published information.

4.2 Existing Slope Instability In Akaroa Harbour

Our information review and air photo interpretation have identified several types of historic slope instability or slope hazards that can be expected to recur in the future.

4.2.1 Bedrock Landslides

Bedrock landslides (Figure 1, Appendix A and Figures C3 to C9, Appendix C) are large to very large failures that are inferred from air photo geomorphology. They occur predominantly on south and southwest facing slopes, forming steep faces and gentle benches that break up the otherwise 'smooth' valley and ridge slopes of the harbour. Depth to base of movement is inferred as 10 to >50m below ground level.

The shape and distribution of the landslides suggest that they are ancient features, most likely formed during the initial erosion of the volcano, with subsequent periods of activity related to sea level changes, erosion and deposition cycles, and earthquakes.

The underlying stratigraphy of the French Hill Formation is inferred to be a major contributor to the number of bedrock landslides, as by comparison the Lyttelton Harbour slopes are almost free of bedrock failures.

Some bedrock landslides or portions may show current and future activity.

4.2.2 Active Gullies

Active Gully is a term coined for this study to describe mappable units of geomorphology (Figure 2, Appendix A and Figures C3 to C9, Appendix C) that encompass almost all of the tunnel erosion, surface erosion and small to medium scale landslides that can be identified on the harbour slopes. About 95% of the counted small landslides occur within active gullies. Several of the large loess/bedrock landslides inferred from air photo interpretation also occur within active gullies.

About one third of the settlement land area is mapped as active gullies, as summarised in tables in Appendix D.

Typical active gullies occur on valley side slopes (unmodified by bedrock landslides) as down slope linear features with lobate head areas (e.g. Takamatua, Pipers valley, Barrys Bay). The surface of the gully is almost entirely covered by existing slope instability (gullies and landslides) that have been superimposed and progressively developed from repeated trigger events over period of time. Current activity is often seen around the over-steepened margins of the gully. Depth to base of movement is inferred to be 1 to 5m below ground level.

Steep coastal faces and bedrock landslide scarps are also mapped as active gullies if they exhibit signs of recent small scale slope instability.

Small landslides are typically slip circle and translational failures, about 3 to 10m wide, occurring in the upper few metres of loess soil. They tend to occur in groups, triggered by near surface soil saturation in intense rainstorm events. Run out of semi fluid silt debris for a distance of about 3 to 10 times the slip circle dimensions is a common feature, the distance being greater with greater confinement into a gully or stream channel. Recent events include rainstorms in 1975 and 1994. Figures C3 to C9 (Appendix C) show small landslides >3m across that occurred in the 1975 rainstorm event, as identified from the 1975 air photo assessment. Characteristics of the counted small landslides are summarised in tables in Appendix D. In any given rainstorm event it appears that about 3 to 10% of the active gully areas are affected by slope movement and debris. On areas outside of active gullies the proportion of land affected in any one storm event is much less than 1%. In addition the proportion of activity can vary around the harbour related to locally higher rainfall in the west, north or east of the harbour.

Medium landslides are similar to small landslides, but nominally 10 to 50m across, prone to episodic and creep movements and less common debris run out.

Tunnel gullies form in highly erodible loess layers below the more resistant surface layers and eventually collapse to form steep sided erosion gullies. Tunnel gully development in Akaroa is not a dominant landform compared to Port Hills and Lyttelton Harbour hill slopes. This is probably due to more stable soil moisture and the history of loess formation including micro climate and prehistoric soil development under forest cover.

Tunnel gullies are particularly noted where surface gullies, landslide scarps and man made cuttings result in undercut soil profiles.

4.2.3 Large Loess/Bedrock Landslides

Large landslides have dimensions in the 100 to 300m scale and are inferred to be moving at depths of 5 to 15m at, or near the interface between loess and weathered bedrock. Typically they occur on moderate to gentle slopes, associated with groundwater seepage and undercut toe slopes (by natural processes or human development).

Figure 1 shows named large landslides that are known to have been recently active, and several inferred from air photo interpretation. Characteristics of these landslides are summarised in Appendix D. There may be more large landslides not recognised by this study, especially in the lobate heads of active gullies. The main defining characteristic would be episodic movement at depths from 5 to 15m (with other active gully instability occurring at <5m depth).

4.3 Future Slope Instability

Future instability will be subject to natural trigger events (rainfall and earthquakes) and potentially exacerbated by human development.

Generally the bedrock landslides are considered ancient and inactive, but portions are known to be active and there are likely to be many more areas, as yet unrecognised, that are subject to episodic movement. Development modifications, particularly in the toe and margins, may lead to reactivation. We do not have a good understanding of the response of bedrock landslides during any future large earthquake loading, but relative displacement will be important and this can occur at slide margins, on active frontal lobes and in debris lobes found on many of the bedrock complexes.

Active gully areas are subject to ongoing episodic movements and debris run out, in particular triggered by rainstorm events when 3 to 10% of the gully area may be affected by fresh movements. The margins of the gully areas are expected to gradually retrogress up and across slope.

Large loess/bedrock landslides can occur on almost any slope. A combination of deep soil profile (often including bedrock ash beds), groundwater seepage and toe modification are required to result in movement.

In summary active gully and large landslide activity are expected to continue into the future in a similar manner to the recent past. The role of bedrock landslides is less certain, but they do add to the complexity of the slope and the potential for slope movements and require specific consideration for any future developments.

5 Assessment of Liquefaction

Liquefaction can occur in saturated, loose, granular soils under cyclic seismic loading from large earthquakes. Effects can include settlement of the ground surface, and lateral spreading movements.

In the Akaroa area locations of potential liquefaction include valley floor and head-of-bay sediments. There is no significant information available on subsurface conditions to assist in assessing liquefaction potential. We are not aware of any historical reports of liquefaction in past earthquakes.

Field observations indicate that valley alluvium occurs on gentle slopes and comprises layers of bedrock derived gravel and loess derived silt/sand. The only 'flat' areas are in the valley floors adjacent to the coast where head-of bay 'mudflat' type sediments are likely to occur. In addition, landfill reclamation is known in Duvauchelle and Akaroa (see figures 13 and 16, Appendix A), with highway road embankment fill likely over soft sediments in Robinsons Bay (Figure 14, Appendix A).

Given our limited knowledge of subsurface conditions the following relative liquefaction potential categories are proposed.

Liquefaction Potential	Area	Factors in Assessment
Unlikely	Loess and bedrock slopes Valley alluvium Effectively all areas that are not zoned as Possible	Silt, clay and gravel soils with limited scope for liquefiable lenses. Unsaturated soils and seasonal perched groundwater aquifers on sloping ground.
Possible	Valley flats, head-of-bay flats	Silt and sand sediments, unconsolidated, near surface groundwater level at approximate sea level.
Likely	None identified	

6 Slope Hazard Susceptibility Zoning

6.1 Introduction

The factors to consider in developing susceptibility maps for Akaroa Settlements have been described in the CCC brief, based on studies and research in other regions. The basic information required for landslide susceptibility maps includes:

- Location of existing slides;
- Soil and bedrock type;
- Vegetation cover (extent and type);
- Slope angle/aspect;
- Groundwater levels and hydrogeology.

The CCC brief for this study requires exclusion of vegetation cover in consideration of susceptibility to slope hazards. This particularly relates to the issue of reduced susceptibility because of dense vegetation cover, therefore all susceptibility is considered as if the slopes were typical farm pasture, or had been cleared for development.

6.2 Susceptibility Inputs

Review of the available information indicates that a slope hazard susceptibility zoning of the Akaroa settlement requires significant input from detailed air photo interpretation. Physical counts of landslides are necessary to be able to derive relative weightings for the contributing factors.

Considering the scope of this study and the fact that no earlier work had been carried out (or at least reported) it was decided to take a 'first pass' approach to the air photo interpretation as follows:

- Detailed review of the 1975 air photos due to the detail visible (scale, resolution, lighting) and the timing of the photos only months after the 1975 rain storm event that was well documented on the Port Hills.
- Check review of 1995 air photos, which are about 1 year after the 1994 rainfall and small landslide event. Air photo interpretation was sketched onto 1:10,000 rectified versions of the 1995 photos.
- Bedrock landslide outlines were recorded. Internal geomorphology was observed but not recorded.
- Small landslides and debris run out visible as very light coloured scars were recorded. The grey scale photos with almost white slide scars means that bias towards specific slope aspects in the count due to differential/low angle lighting is unlikely.
- Open gullies and evidence for tunnel gullies was observed, but individual gullies were not recorded owing the detail, complexity and the issue of a potentially poor sample from the air photo interpretation.

- Large loess/bedrock landslide outlines were recorded where identifying geomorphology was evident (which can be dependent on the resolution and lighting of the air photos).
- Active gully areas were recognised as significant as the detailed assessment continued. They encompass almost all evidence for small to medium scale landslides, debris run out and gully formation. About 95% of 1975 small landslides occur within active gully areas. The density of 1975 small landslides is about 3 to 8% of land area in active gullies compared to <<1% in other areas.

The air photo interpretations as shown in Figures 1 and 2 and Figures C3 to C9 (Appendix C) form the basis of the relative susceptibility zoning. The 1975 small landslides were used to count slope angle, slope aspect, slope position and slope length for input to susceptibility ranking/zoning. The breakdown of the assessment of 1975 small landslides is provided in tables in Appendix D. The results were checked and compared with similar assessments for large loess/bedrock landslides (tables Appendix D). The slope factors considered are described below.

Slope angle

The slope angle was derived by measuring the horizontal distance between two adjacent 20 m contour lines or, where 2 m contour data was available (see figure C17), by measuring the entire elevation change over the horizontal length of the instability feature. The difference between the slope angle calculated by the 20 m contour data and the slope angle calculated by the 2 m contour data was determined (see Appendix D for chart comparison).

The 20 m contour data (See histogram chart in Appendix D) showed that 50% of the small scale landslips identified, occurred on slopes between 16 and 25˚. An additional 28% of small scale landslides occurred on slopes between 26 and 35˚ and 13% of failures on slopes between 11 and 15˚, accounting for 91% of failures in the 11 to 35˚ division.

Comparing 2 m contour data a total of 60% of all landslides were recorded on slopes between 21 and 30˚ with a further 21% falling in the 16 to 20˚ division. Therefore the 20m contour data is underestimating slope angles by about one 5^{o} division (see chart comparing 2m and 20m contour data in Appendix D).

Slope angles having the greatest susceptibility to landsliding include slopes between 16 and 25˚. The slope angle divisions either side of this range, including 11-15˚ and 26-30˚ also have a significant susceptibility.

Slope Aspect

The slopes of the study area were divided into 53 different areas, with each area being assigned one aspect from the following, N, NE, E, SE, S, SW, W, NW, based on the overall aspect of each slope area. Generally small scale variations in slope aspect were overlooked in classifying the aspect of each area. Long thin headlands and spurs were typically divided into two aspect areas while wider spurs and headlands were divided into 3 or 4 different areas. Figure C2 shows the division of the slopes into the aspect areas.

472 small scale landslips were identified. Of that total, 349 were identified to have occurred on slopes with North, Northeast or Easterly aspects (179 = N, 95 = NE and 74 = E respectively).

Normalisation of the data provided the number of landslips expected in each aspect division, assuming each of the eight aspect divisions was represented by an even amount of land area within the whole study area. Analysis of the normalised data showed that while the northern (N) aspect had more than twice the expected number of landslip occurrences, the eastern (E) and northwest (NW) aspects both had less than half of those expected. The remaining aspect divisions all actually had within +- 30% of the number of landslips expected.

Slopes of higher than average susceptibility to small scale land sliding are therefore the northern slopes of the study area, while the slopes that have below average susceptibility to small scale land slides are the slopes with eastern and north western aspects.

Location on the Slope

The slope location was calculated by dividing the observed reduced level (RL) of the instability feature by the reduced level of the crest of the slope on which the instability occurred. The slope location figure is therefore a decimal value, with a maximum value of 1.0 indicating that an instability feature observed at the top of the local slope, while 0.5 indicates the feature is half way up the slope.

The landslides were divided into the following four slope location categories; 0 – 0.24, 0.25 – 0.49, 0.5 – 0.74 and 0.75 – 1.0. 72% of all landslides counted occurred at a slope location between 0.25 and 0.74 with 43% occurring between 0.25 and 0.49. Therefore land located between a quarter and half way up a slope is more susceptible to landsliding than other land. This is generally expected as the middle section of a soil mantled slope is typically the steepest section. Therefore slope angle is likely to be the more important contributing factor.

Elevation

The elevation of the upper extent of each landslide was noted. Each landslide was divided into one of the following four categories based on the elevation recorded; 0 – 50 , 51 – 100m, 101 – 150m and >151m. 61% of the landslides occurred in the 0 – 100 m elevation range, with a further 24% of landslides occurring between 101 and 150 m elevation. The results are likely influenced by the large proportion of settlement areas below the 100m contour.

Up-slope length (groundwater factor)

The up-slope length is the distance of the landslide from the toe of the slope, and was determined as a relative approximation of the amount of groundwater and surface water that was likely to have influenced each instability feature, based on the premise that a longer slope above the landslide allows for greater influence of water in initiating the failure. The up-slope length was calculated using a slope angle of 22˚, the average angle of ground on which landslides occurred, and the change in elevation between the instability feature and the crest of the slope on which the feature was located.

The data showed that 69% of all landslides had an upslope length of between 0 and 400 m with 41% having an up-slope length between 100 and 300 m. The results are likely influenced by the large proportion of settlement areas below the 100m contour.

The other factors used as inputs are geology and debris run out including rockfall. In the definition of the geology alluvium has been restricted to 'flat' land harbour alluvium and reclamation areas. Stream alluvium (as shown on Figure C1) has been included in the loess category for geology.

6.3 Susceptibility Ranking

The basis for the susceptibility zones is a ranking or classification of zones that includes relevant factors that contribute to slope instability. The basis for zones table in Appendix B summarises the ranking system developed. The key features of the ranking system include:

- The ranking of susceptibility is relative and the scoring system is designed to allow key cases to fall in to certain relative zones. The scores are not comparable on a linear scale (i.e. a score of 50 is not a 10% higher susceptibility than a score of 40).
- Existing large loess/bedrock landslides are considered to be active and deep seated, and therefore have a Significant susceptibility ranking. Indicating that all areas of the zone can be affected in any landslide movement event.
- Active gully areas are weighted to provide a Locally Significant susceptibility ranking. Indicating that some parts of the zone will be affected in any given landslide movement event, but it is not possible to specifically predict where the affected parts will be within the zone.
- Similar slopes to those where large loess/bedrock landslides are currently identified can rank from Locally Significant to Minor.
- Slopes between active gullies can rank Intermediate to Negligible.
- Gentle and flat alluvial areas should rank Minor to Negligible, possibly as high as Intermediate where debris run out is possible or likely.
- The presence of bedrock landslides is identified as an overlay to the ranking to alert readers to the requirement for extra care in site specific assessments of these areas.

6.4 Zoning Maps

The zoning maps (Figures 3 to 9, Appendix A) have been developed from the following:

- The 20m contour base (Figures C10 to C16, Appendix C) divided in the slope angle ranges shown in Appendix B.
- The slope aspect areas as defined on Figure C2 (Appendix C).
- The active gully areas, bedrock landslides and large loess/bedrock landslides from Figures C3 to C9 (Appendix C).
- Geology, especially the change from loess (and colluvium) to fine sediment alluvium (on 'flat', near sea level areas).

A total of 440 zones have been established. The zone score and rankings are listed by settlement area in Appendix B.

Zone boundaries were checked against the 2m contour data where available for accuracy of change in slope, especially along the valley floors. Some boundaries were moved by 20 to 40m.

Zone boundary accuracy is estimated at +\- 30m.

In general active gullies rank as Locally Significant susceptibility. General slopes rank as Intermediate susceptibility. Valley floors and some gentle ridge crests rank as Minor to Negligible susceptibility.

7 Liquefaction Potential

Liquefaction potential is based on our judgement and experience from elsewhere, in the absence of any useful site information. We have provided 2 zones for liquefaction potential shown in Figures 10 to 16 (Appendix A) as follows:

- Unlikley – loess, colluvium and bedrock slopes, valley alluvium.
- Possible – Valley flat areas on head-of-bay harbour infill sediments

Zone boundary accuracy is estimated at +\- 30m.

8 Implications for Future Development

The slope hazard susceptibility zoning and assessment of liquefaction potential provided in this report are tools for consideration in strategic planning. In general a higher susceptibility zone indicates relatively greater difficulty (and therefore cost) for development. This is illustrated by the observation that the vast majority of existing settlement development falls within minor and intermediate susceptibility zones.

The long term risk (and cost) to Council of providing reticulated services and access is also likely to be proportionally greater for higher susceptibility zones. Although dependent on the quality of initial design and construction demanded.

Caution should be exercised in excluding any area from future development based on slope hazard susceptibility alone, as there is not necessarily a direct relationship between susceptibility and ability to develop on any given site. The slope stability risk for development of a specific site must include an assessment of hazard susceptibility, likelihood and consequences to arrive at a defensible conclusion.

Final decisions on development consents should not be made on the basis of the slope hazard susceptibility zoning alone. It is recommended that the zoning be used as a guide to developing consenting 'rules' that require more rigorous investigation, design and peer review conditions for higher susceptibility zones.

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10 Applicability

This report has been prepared for the benefit of Christchurch City Council with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

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