



LANDSLIDES AND LAND USE PLANNING

No. 135

Building Regulations

43—(1) Where, in a landslip area—

(a) any trench or hole, excavation made, or the filling of any such trench or hole, or any disturbance of the ground, or any operation of alteration or addition to a building, shall be carried out in accordance with the requirements of this regulation.

(2) Any filling back, or alteration of, or addition to, a building, shall be carried out in accordance with the requirements of this regulation.

(3) Where any permanent excavation is made or filling is carried out in connection with the erection of, or alteration or addition to, a building, the excavation shall not be made into the ground to a depth greater than 1 m below the ground level, and shall be compacted and graded so as not to create landslip conditions.

(4) Where any permanent excavation is made or filling is carried out in connection with the erection of, or alteration or addition to, a building, the excavation shall not be made into the ground to a depth greater than 1 m below the ground level, and shall be compacted and graded so as not to create landslip conditions.

(5) Where any permanent excavation is made or filling is carried out in connection with the erection of, or alteration or addition to, a building, the excavation shall not be made into the ground to a depth greater than 1 m below the ground level, and shall be compacted and graded so as not to create landslip conditions.

(6) Where any permanent excavation is made or filling is carried out in connection with the erection of, or alteration or addition to, a building, the excavation shall not be made into the ground to a depth greater than 1 m below the ground level, and shall be compacted and graded so as not to create landslip conditions.

(7) Where any permanent excavation is made or filling is carried out in connection with the erection of, or alteration or addition to, a building, the excavation shall not be made into the ground to a depth greater than 1 m below the ground level, and shall be compacted and graded so as not to create landslip conditions.

45 No person shall remove for or in connection with the erection of, or alteration or addition to, a building in a landslip area any vegetation, other than those necessary for that purpose.

Land owners blast council

Slip 'high priority' LANDSLIP TEST

LIFETIME'S INVESTMENT WIPED OUT

Owners shocked by landslip costs order

PANIC ON LANDSLIP

Clamour at zone hearing

LANDSLIP AREA BUILDING BANS

Landslip controls now law

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LANDSLIDES
and land use planning

by A. L. Telfer

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PREFACE

The author was employed for two years from January 1985 with a grant from the National Soil Conservation Programme co-sponsored by the Tasmanian Department of Mines. The National Soil Conservation Programme is a scheme funded by the Federal Government and administered by the Department of Primary Industry. The Programme provides funds for approved projects throughout Australia and when the present project was started was one of eight Tasmanian projects.

The brief of the project was to study landslides in Tasmania. Seven landslides in northern and north-western Tasmania were studied in detail and the results of these studies used to improve the understanding of failure mechanisms, particularly in Tertiary materials.

During May and June 1986 the author looked at landslides in Queensland, New South Wales, Victoria and South Australia to determine if a publication on Tasmanian landslides could be expanded to encompass mainland landslides also. It very quickly became obvious that such a publication was beyond the author, given the time and financial constraints of the project, because of the enormous range of landslide styles, materials and failure mechanisms.

However, it was pointed out by Warwick Willmott (Queensland Geological Survey) that people at local government level need a publication which provides information and advice on urban development of landslide-prone land. This need was apparent, to a greater or lesser extent, in each of the States subsequently visited. The National Soil Conservation Programme is an appropriate platform from which to address this need.

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LANDSLIDES

and land use planning

by A. L. Telfer

ABSTRACT

This publication provides information and advice on landslide-prone land for local government personnel. Background information is presented in tabular form for ease of reference. The methodology, mechanics, and mathematics of slope stability assessments are described, as well as remedial measures for the rehabilitation of landslides. A case study of a Tasmanian landslide, using a range of assessment tools described in the text, is included.

Local government authorities have three lines of defence against the consequences of urban expansion over landslide prone land; the acquisition and use of landslide zone maps at land use planning stage, the assessment of the stability of problem areas, and if all else fails, legislative control. The processes of landslide zoning and slope stability assessment are described, and a summary is included of the landslide investigative and legislative procedures in each state. Some building practices for steep slopes are suggested.

It is hoped that the publication will be widely used by local government organisations, and other similarly interested parties, where landslides and urban development overlap.

1 INTRODUCTION

Landslides are usually only studied when they threaten, or have damaged, man-made structures. The structures which can and are occasionally threatened range from large industrial and civic structures such as dams, roads and bridges to small privately-owned structures such as houses. This publication is aimed at the latter end of this range.

Landslides threaten houses in many places in Australia, however this problem can be circumvented if landslide problems can be recognised at the planning stage and effective land use plans drafted. Also, house sites suspected of being threatened by landslides can be examined to determine their stability before building approval is given. Local government authorities are responsible for issuing building permits in all States, however their personnel do not usually have training in the earth sciences. This publication is designed to fill the gap in knowledge, though not the gap in training. It is hoped the targeted audience will gain an appreciation of the problems and processes of site assessment and landslide zone map acquisition, and will appreciate the benefits of proper planning in landslide-prone regions.

This publication addresses the problem of slope movements in engineering soils. By definition these are materials which can be excavated with a shovel, and include unconsolidated sediments and weathered mantles as well as true soils. Landslides in these materials can propagate at very low slope angles, and the causes of failure may not be obvious. The study is restricted to engineering soils because most urban development takes place on such materials. Landslides in rock are usually restricted to steep slopes where urban development is minimal.

The following three sections provide information on the identification, examination and renovation of landslides. Landslide classifications, definitions, nomenclature, and failure styles and their recognition are discussed in Section 2. The methods of landslide examination, including site assessment techniques, soil strength and its measurement and mathematical slope stability analysis are dealt with in Section 3, and in Section 4 the remedial measures of use in the control of landslides, emphasising the use of vegetation for slope stabilisation, are examined.

The remaining sections address the role of local government in the urban development of landslide-prone land. An investigation of a slope stability problem in northern Tasmania, in which most of the techniques previously discussed are used is presented in Section 5. The acquisition of landslide zone maps, the assessment of landslide-prone land, landslide legislation, and suggested building practices on hill slopes are presented in Section 6.

2 DEFINITION, CLASSIFICATION AND NOMENCLATURE OF LANDSLIDES

2.1 INTRODUCTION

The information in this section is in tabular form and thus provides a ready reference to the background information needed to understand landslides and associated technical reports.

The definitions, classification, and nomenclature of landslides, together with descriptions of the basic landslide styles, the common causes of failure, and the effects of time on landslide shape are set out in this section.

2.2 DEFINITION OF A LANDSLIDE

'A landslide constitutes the group of slope movements wherein shear failure occurs along a specific surface or combination of surfaces' (Schuster and Krizek, 1978).

2.3 LANDSLIDE CLASSIFICATION

The following classification of landslides in engineering soils (table 2.1) modified from Schuster and Krizek (1978), will be used in this publication. The classification is based on landslide shape.

Table 2.1
LANDSLIDE CLASSIFICATION (after Schuster and Krizek, 1978)

TYPE OF FAILURE		TYPE OF MATERIAL (see Table 2.2)		
		Engineering soils		Bedrock
		20-80% fragments >2 mm diameter, remainder <2 mm	20-80% fragments <2mm	
FALLS		Debris fall	Earth fall	Not examined in this publication
TOPPLES		Debris topple	Earth topple	
SLIDES	ROTATIONAL	Debris slump	Earth slump	
	TRANSLATIONAL	Debris block slide	Earth block slide	
		Debris slide	Earth slide	
LATERAL SPREADS		Debris spread	Earth spread	
FLOWS		Debris flow	Earth flow	
COMPLEX		Combination of two or more of the above		

2.4 DEFINITION OF MATERIAL TYPES

This publication is concerned with landslides in (engineering) soils, and does not cover those in bedrock. These two materials are defined in Table 2.2. Soil descriptions should accord to the Unified Soil Classification System (table 2.3, after Selby and Lindsay, 1982), a standard soil logging system in almost universal use.

Table 2.2
DESCRIPTION OF LANDSLIDE MATERIALS

Term	Description
(Engineering) soil	Any loose, unconsolidated or poorly cemented aggregate of solid particles (generally of natural origin) either transported or residual which can be excavated with a spade. The material can be described using the Unified Soil Classification System (see table 2.3)
Bedrock	Any material which is intact, is in its natural place before the initiation of movement, and cannot be excavated with a spade

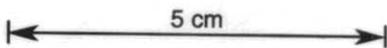
2.5 LANDSLIDE NOMENCLATURE

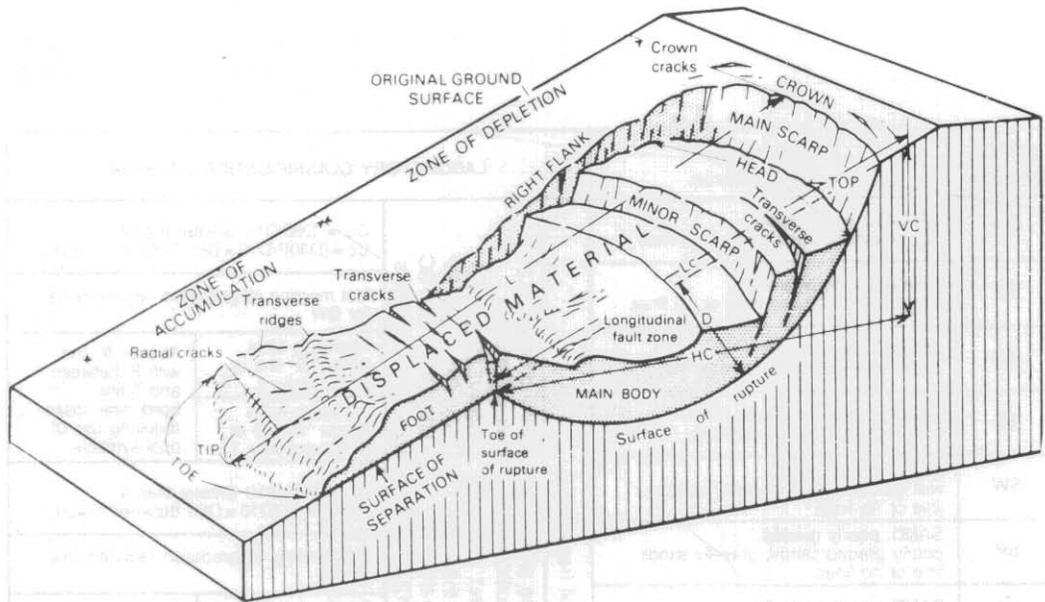
The following nomenclature is applicable to most types of failure, and will be used throughout this publication.

Table 2.3
THE UNIFIED SOIL CLASSIFICATION SYSTEM

		FIELD INVESTIGATION PROCEDURES						GROUP SYMBOL
		Excluding particles larger than 75 mm and basing fractions on estimated weights						
COARSE-GRAINED SOILS More than 50% of material is larger than No. 200 B.S. sieve size	GRAVELS More than 50% of the coarse fraction is larger than 2 mm (retained on B.S.7 sieve)	CLEAN GRAVELS Little or no fines	Wide range in grain sizes, and substantial amounts of all intermediate particle sizes				GW	
			Predominantly one size or a range of sizes, with some intermediate sizes missing				GP	
		DIRTY GRAVELS Appreciable amount of fines	Non-plastic fines—for identification see ML below				GM	
			Plastic fines—for identification see CL below				GC	
	SANDS More than 50% of the coarse fraction is smaller than 2 mm (passing B.S.7 sieve)	CLEAN SANDS Little or no fines	Wide range in grain sizes, and substantial amounts of all intermediate particle sizes				SW	
			Predominantly one size or a range of sizes, with some intermediate sizes missing				SP	
		DIRTY SANDS Appreciable amount of fines	Non-plastic fines—for identification see ML below				SM	
			Plastic fines—for identification see CL below				SC	
FINE-GRAINED SOILS More than 50% of material is smaller than No. 200 B.S. sieve size	FIELD INVESTIGATION PROCEDURES on fraction smaller than 0.4 mm. (passing B.S. 36 sieve)						GROUP SYMBOL	
	SILTS AND CLAYS Liquid limit less than 50	SOIL CAST (soil wet)	SOIL THREAD	SHINE	DILATANCY	ODOUR		DRY STRENGTH
		Forms fragile cast Cracks form when kneaded while moist	Thick crumbly thread easily broken	None to very dull	Distinct	Not significant	None to slight	ML
		Cast may be handled freely without breaking. Can be kneaded moist without cracking. Material adheres to the hand	Thread can be pointed as fine as a lead pencil but is fragile	Moderate	None to slight	Not significant	Moderate	CL
		Cast fragile to cohesive material will adhere somewhat to the hand	Soft, weak thread	None to very dull	Slight to distinct	Decayed organic matter	Low	OL
	SILTS AND CLAYS Liquid limit more than 50	Moderately plastic and cohesive Material adheres somewhat to the hand	Weak to medium thread. May be crumbly	Dull	None to slight	Not significant	Moderate Powdered soil feels floury	MH
		Very plastic and cohesive Material very sticky to the hand Greasy to touch	Very tough thread can be rolled to a pin point	Very glossy	None	Strong earthy	High to very high Cannot be powdered by finger pressure	CH
		Plastic and cohesive Feels slightly spongy Greasy to touch	Weak to medium thread. Often soft and fibrous	Moderate to very glossy	None	Decayed organic matter	Moderate to high Powdered soil may be fibrous	OH
	Readily identified by colour, odour, spongy feel and frequently by fibrous texture							Pt
	NOTE: BOUNDARY CLASSIFICATIONS: Soil possessing characteristics of two groups are shown as a combination of two group symbols, eg. GW—GC, well graded gravel with clay binder.							

GROUP SYMBOL	GROUP NAME and typical materials	LABORATORY CLASSIFICATION CRITERIA		
GW	GRAVEL, well graded; gravel and mixtures, little or no fines	Coarse grained soil classified on basis of percentage of fines, as follows PER CENT OF FINES Less than 5 More than 12 5 to 12 borderline cases, use 2 symbols	Cu = D60/D10 Greater than 4 Cc = (D30) ² /D10 x D60 Between 1 and 3	
GP	GRAVEL, poorly graded; gravel sand mixtures, little or no fines		Not meeting all gradation requirements for GW	
GM	GRAVEL, excess silty fines; poorly graded gravel-sand-silt mixtures		Atterberg limits below 'A' line or PI less than 4	Above 'A' line with Pi between 4 and 7 are borderline cases requiring use of dual symbols
GC	GRAVEL, excess clayey fines; poorly graded gravel-sand-clay mixtures		Atterberg limits above 'A' line or PI greater than 7	
SW	SAND, well graded; well graded sands, gravelly sands, little or no fines		Cu = D60/D10 Greater than 4 Cc = (D30) ² /D10 x D60 Between 1 and 3	
SP	SAND, poorly graded; poorly graded sands, gravelly sands, little or no fines		Not meeting all gradation requirements for SW	
SM	SAND, excess silty fines; poorly graded sand-silt mixtures		Atterberg limits below 'A' line or PI less than 4	Above 'A' line with Pi between 4 and 7 are borderline cases requiring use of dual symbols
SC	SAND, excess clayey fines; poorly graded sand-clay mixtures		Atterberg limits above 'A' line or PI greater than 7	
GROUP SYMBOL	GROUP NAME and typical materials	GRAIN SIZE CURVES to be used to identify soil fractions	<p style="text-align: center;">PLASTICITY CHART For laboratory classification of fine-grained soils</p>	
ML	SILT SOIL, low plasticity; inorganic silts and very fine silty or clayey sands, rock flour			
CL	CLAY SOIL, low plasticity; inorganic clays of low to medium plasticity, gravelly clay, sand, clays, silty clays, lean clays			
OL	ORGANIC SOIL, low plasticity; organic silts and silt clays of low plasticity			
MH	SILT SOIL, high plasticity; inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts			
CH	CLAY SOIL, High plasticity; inorganic clays of high plasticity, fat clays			
OH	ORGANIC SOILS, high plasticity; organic clays of medium to high plasticity			
Pt	PEATY SOIL; Peat and other highly organic soils			
<p>Based on 'The Unified Soil Classification System' United States Department of the Interior, Bureau of Reclamation 'Earth Manual' First edition, Denver, Colorado 1960 (after Selby, L. J. and Lindsay, J. M., 1982)</p>				





NOMENCLATURE

MAIN SCARP—A steep surface on the undisturbed ground around the periphery of the slide, caused by the movement of slide material away from undisturbed ground. The projection of the scarp surface under the displaced material becomes the **SURFACE OF RUPTURE**.

MINOR SCARP—A steep surface on the displaced material produced by differential movements within the sliding mass.

HEAD—The upper parts of the slide material along the contact between the displaced material and the main scarp.

TOP—The highest point of contact between the displaced material and the main scarp.

TOE OF SURFACE OF RUPTURE—The intersection (sometimes buried) between the lower part of the surface of rupture and the original ground surface.

TOE—The margin of displaced material most distant from the main scarp.

TIP—The point on the toe most distant from the top of the slide.

FOOT—That portion of the displaced material that lies downslope from the toe of the surface of rupture.

MAIN BODY—That part of the displaced material that overlies the surface of rupture between the main scarp and toe of the surface of rupture.

FLANK—The side of the landslide.

CROWN—The material that is still in place, practically undisplaced and adjacent to the highest parts of the main scarp.

ORIGINAL GROUND SURFACE—The slope that existed before the movement which is being considered took place. If this is the surface of an older landslide, that fact should be stated.

LEFT AND RIGHT—Compass directions are preferable in describing a slide, but if right and left are used they refer to the slide as viewed from the crown.

SURFACE OF SEPARATION—The surface separating displaced material from stable material but not known to have been a surface on which failure occurred.

DISPLACED MATERIAL—The material that has moved away from its original position on the slope. It may be in a deformed or undeformed state.

ZONE OF DEPLETION—The area within which the displaced material lies below the original ground surface.

ZONE OF ACCUMULATION—The area within which the displaced material lies above the original ground surface.

(after Schuster and Krizek, 1978).

2.6 LANDSLIDE DESCRIPTIONS

Table 2.4 describes the style and method of failure of the landslide types outlined in Table 2.1. Most failures will contain elements of two or more of the classic failure types, and are described as complex landslides.

Table 2.4
DETAILS OF LANDSLIDE TYPES

Landslide type	Description
FALL TOPPLE	A mass which is detached from a steep slope or cliff, and descends mostly under the action of gravity and the forces exerted by any fluids in cracks. Movement is rapid to extremely rapid. A topple is tilting without collapse.
SLIDE	Consists of shear strain and displacement along one or more surfaces. Movement may not necessarily occur everywhere along the shear surface(s) at one time.
<i>Rotational</i>	The failure surface curves concavely upward, exposed cracks are arcuate and concave toward direction of movement, and movement is roughly rotational about an axis parallel to the slope. The heel moves downward and the top surface of each block commonly tilts backward. Water may pond on backtilted blocks, promoting further failure by allowing the ingress of water into the slip. Any high scarps may be unstable and subsequently fail. Classic rotational slides are uncommon. If the rupture surface dips into the hill at the toe of the landslide, the rotational movement of the landslide will tend to restore equilibrium to the unstable mass. The driving movement will decrease and the slide may stop moving.
<i>Translational</i>	The failure surface is roughly planar or gently undulating, with little rotational movement or backtilting. Material will commonly slide onto the original land surface below the slip. Movement commonly controlled by surfaces of weakness (e.g. bedding planes, or the contact between bedrock and overlying weathered material). Movement is slow to rapid, and may continue indefinitely if the driving forces continue to be greater than the resisting forces (i.e. stress > strength).
LATERAL SPREAD	Lateral extension accommodated by shear or tensile fracturing. The failure can involve elements of rotation, translation and flow. Movement generally starts suddenly and proceeds rapidly.
FLOW	The boundary between the moving mass and the material in place may be one or more shear plane. Flows have the appearance of a body which has behaved as a fluid. They are usually wet, but can be dry. Water heavily laden with sediment, perhaps 60-70% solids by mass, can transport boulders weighing one tonne or more. Flows generally follow existing drainage channels and may extend many kilometres before coming to rest on a slope of lower gradient. Movement is generally rapid.
COMPLEX	Complex slides exhibit more than one of the major modes of failure. For example it is not uncommon to find rotational failure at the heel with translational failure and/or flow further down the slip. Most slides are complex.

2.7 RECOGNITION OF LANDSLIDES

Table 2.5 describes the features that aid in the recognition of common types of slope movements. Failures in both soil and rock are described to show the differences and similarities.

2.8 CAUSES OF LANDSLIDES

Some landslides occur under unique conditions, but more often they form under the influence of geologic, topographic, climatic and cultural controls common to a large area. The causes of failure can be divided into historic causes (table 2.6) and trigger mechanisms (table 2.7).

The correct diagnosis of the trigger mechanisms and historic causes of slope failure is essential in formulating remedial and preventative measures.

2.8.1 Historic causes

Historic causes (table 2.6) are those conditions of geologic materials, slope morphologies and climates which are conducive to the formation of potential and active landslides.

Table 2.5

FEATURES WHICH AID IN THE RECOGNITION OF COMMON TYPES OF SLOPE FAILURE (from Schuster and Krizek, 1978)

Type of Motion	Kind of Material	Parts Surrounding Slide		
		Crown	Main Scarp	Flanks
<i>FALLS, TOPPLES</i>	Soil	Has cracks behind scarp	Is nearly vertical, fresh, active, and spalling on surface	Is often nearly vertical
<i>SLIDES</i>				
Rotational	Soil	Has numerous cracks that are mostly curved concave toward slide	Is steep, bare, concave toward slide, and commonly high; may show striae and furrows on surface running from crown to head; may be vertical in upper part	Has striae with strong vertical component near head and strong horizontal component near foot; have scarp height that decreases toward foot; may be higher than original ground surface between foot and toe; have en echelon cracks that outline slide in early stages
Translational	Rock or Soil	Has cracks most of which are nearly vertical and tend to follow contour of slope	Is nearly vertical in upper part and gently to steeply inclined in lower part	Has low scarps with vertical cracks that usually diverge downhill
<i>FLOWS</i>				
Dry	soil	Has no cracks	Is funnel shaped at angle of response	Have continuous curve into main scarp
Wet				
<i>Debris avalanche Debris flow</i>	Soil	Has few cracks	Typically has serrated to V-shaped upper part; is long and narrow, bare, and commonly striated	Is steep and irregular in upper part, may have levees built up in lower parts
<i>Earth flow</i>	Soil	May have a few cracks	Is concave toward slide, in some types is nearly circular and slide issues through narrow orifice	Is curved; have steep sides
<i>Sand flow Silt flow</i>	Soil	Has few cracks	Is steep and concave towards slide, may have variety of shapes in outline: nearly straight, gentle arc, circular, or bottle shaped	Commonly diverge in direction of movement

Parts That Have Moved

Head	Body	Foot	Toe
Is usually not well defined; consists of fallen material that forms heap of rock next to scarp	Is irregular	Is commonly buried; if visible, generally shows evidence of reason for failure, such as prominent joint or bedding surface, underlying weak rock, or banks undercut by water	Is irregular
Has remnants of land surface flatter than original slope or even tilted into hill, creating at base of main scarp depressions in which perimeter ponds form; has transverse cracks, minor scarps, grabens, fault blocks, bedding attitude different from surrounding area, and trees that lean up-hill	Consists of original slump blocks generally broken into smaller masses; has longitudinal cracks, pressure ridges, and occasional overthrusting; commonly develops small pond just above foot	Commonly has transverse cracks developing over foot line and transverse pressure ridges developing below foot line; has zone of uplift, no large individual blocks, and trees that lean downhill	Is often a zone of earth flow of lobate form in which material is rolled over and buried; has trees that lie flat or at various angles and are mixed into toe material
Is relatively undisturbed and has no rotation	Is usually composed of single or few units; is undisturbed except for common tension cracks that show little or no vertical displacement	Has none; and no zone of uplift	Plows or overrides ground surface
Usually has none	Is conical heap of soil, equal in volume to head region	Has none	
May have none	Consist of large blocks pushed along in a matrix of finer material; has flow lines; follows drainageways and can make sharp turns; is very long compared to breadth	Is absent or buried in debris	Spreads laterally in lobes; if dry, may have a steep front about a meter high
Commonly consists of a slump block	Is broken into many small pieces; shows flow structure	Has none	Is spreading and lobate; consists of material rolled over and buried; has trees that lie flat or at various angles and are mixed into toe material
Is generally under water	Spread out on underwater floor	Has none	Is spreading and lobate

Table 2.6
HISTORIC CAUSES OF LANDSLIDES

Historic causes	Description
Geology	<ul style="list-style-type: none"> • <i>Minerals present.</i> Soft platy minerals will shear and slide easily while hard angular minerals will not. • <i>Defects in layers of material.</i> Discontinuities such as faults, joints, desiccation cracks and slickensides usually reduce the shear strength of the mass. • <i>Alternation of layers of different strengths.</i> Massive, competent layers will tend to slide on underlying soft or plastic layers. • <i>Alternation of layers of different permeabilities.</i> Impermeable layers may be uplifted by pore water pressure in underlying permeable layers. • <i>Orientation of layers.</i> Layers inclined toward the slope are susceptible to failure along the bedding plane.
Topography and climate	Landforms formed in previous climates may not be stable in the present.

2.8.2 Trigger mechanisms

Trigger mechanisms (table 2.7) are those factors which can transform a potential slope failure into a landslide in a short period of time.

Table 2.7
TRIGGER MECHANISMS OF LANDSLIDES

Mechanism	Description of destabilising influence
Changes in water content	<ul style="list-style-type: none"> • <i>Increase:</i> water penetrating shrinkage cracks and joints produces hydrostatic pressure and uplift. Moisture content increases of clay change the soil's consistency usually reducing its shear strength. • <i>Decrease:</i> desiccation of clay in drought conditions breaks up soil and facilitates the ingress of water. • <i>Rapid drawdown:</i> Abrupt lowering of reservoir levels causes an equally rapid decrease in the confining pressure on the reservoir flank and dam materials. The resulting excess pore pressures may precipitate failure
Groundwater effects	<ul style="list-style-type: none"> • Confined groundwater acts to uplift overlying impervious beds, increasing the level of shear stress closer to the failure threshold. • Soil below the water table weighs less (because of buoyancy effects), so the shear stress necessary to initiate failure is reduced. • Soluble cements can be washed from the soils, decreasing their strength. • Moving water may wash sands or silts from the soil.
Weathering	Mechanical and chemical weathering destroys molecular bonds, usually decreasing shear strength
Deforestation	<ul style="list-style-type: none"> • Destruction of strength imparted by tree roots. • Water levels will rise because trees are no longer adsorbing and transpiring water.
Change of slope gradient	<ul style="list-style-type: none"> • Erosion of toe of slope by river or coastal processes. • Excavation of toe of slope by man (e.g. road cutting). • Previous slope movements. • Tectonic forces resulting in subsidence or uplift
Increased load	<p>Significant loading will increase the unit mass of the soil. This will increase the shear stress and may increase pore pressure. The risk of failure increases with the loading rate. Increased loads may be applied by;</p> <ul style="list-style-type: none"> • natural surcharge of water, vegetation or scree. • excess load by embankments, fills and waste dumps. • excess water from leaking reservoirs, pipelines, sewers, etc.
Shocks and vibrations	Earthquakes, large explosions and machinery vibration produce oscillations of different frequencies in earth materials, and may disturb the equilibrium of the slope.

2.9 LANDSLIDES AND TIME

Landslide morphology changes with time, and recognising old landslides often takes a practiced eye. The stability of a landslide also changes with time. Inactive and fossil slopes are presumed to be more stable than active slopes, however the increase in stability with time is difficult to measure.

2.9.1 Age classification

Landslides can be classed according to their state of activity (table 2.8).

Table 2.8
LANDSLIDE AGE CLASSIFICATION

Landslide status	State of activity
ACTIVE	Slope that is currently moving or has moved in recent history. Landslide fractures are fresh and not modified by erosional processes
INACTIVE	Slope that was previously active but that has not moved in recent history.
Dormant slope	—inactive slope for which the causes of failure still remain and movement may be renewed
Stabilised	—inactive slope from which the causes of failure have been removed.
FOSSIL	Slope that has been inactive for a long time, and has been modified by erosion and weathering or covered by vegetation. Fossil landslides are commonly developed under different climatic conditions and are stable at present.

2.9.2 Landslide morphology and time

The morphology and vegetation of a slope which is undergoing and has undergone failure will change with time. Table 2.9 describes these changes, though the time periods specified are approximate only and will vary depending on geologic, climatic and topographic conditions.

Table 2.9
LANDSLIDE MORPHOLOGY AND VEGETATION WITH TIME*

Stage of movement	Slope morphology
BEFORE FAILURE	<ul style="list-style-type: none"> • arcuate cracks in slope (tension cracks) • vegetative differences (water loving plants)
IMMEDIATELY AFTER FAILURE	<ul style="list-style-type: none"> • trees, fences, poles etc. inclined from the vertical • houses cracked, damaged, destroyed • fresh scars in soil (headscarp, flanks) • live vegetation over-ridden by earth materials • trees, bushes displaced
SOME TIME AFTER FAILURE (e.g. ten years)	<ul style="list-style-type: none"> • steep and sharp edges rounded • new growth on inclined vegetation will grow straight • weeds and opportunistic plants take hold • movements parasitic to the main movement may have developed • there may still be areas with no vegetation • landslides on arable land may be cultivated and sown, or bulldozed
CONSIDERABLE TIME AFTER FAILURE (e.g. 50-100 years)	<ul style="list-style-type: none"> • mostly completely revegetated, may be difficult to recognise • will be difficult to distinguish from ancient landslides
ANCIENT	<ul style="list-style-type: none"> • light at low angles highlights hummocky topography of ancient landslides • rotational slides are most evident since they leave tell-tale backtilted blocks and (usually) bulbous toes • translational slides may not be recognisable since they do not alter the slope morphology greatly

* It is very difficult to guess the age of old and ancient slope movements, and scientific dating is rarely successful.

3 ASSESSMENT OF LANDSLIDE RISK

The assessment of landslide risk involves the development and evaluation of a geological, morphological, and hydrological model. The earliest stages of landslide risk assessment are concerned with the examination of existing information. Further surface and subsurface information can be obtained to supplement existing data and to refine the model. Soil testing may be conducted on samples of the slope materials, and mathematical slope stability analyses used to check the plausibility of the slope stability model employed to explain the observed facts.

3.1 GEOLOGIC AND TOPOGRAPHIC ANALYSIS

3.1.1 REVIEW OF EXISTING INFORMATION

3.1.1.1 Maps

It is unwise to conduct a site assessment without also examining the regional setting of the site. Most geologic and topographic maps are published at a small scale, and are examined in the office to determine the regional setting of a site. The range of maps available will vary from site to site, but most areas likely to face urban expansion in the foreseeable future will be covered by published topographic and geologic maps at scales ranging between 1:50 000 and 1:100 000. It is unlikely that a published map will be of a scale large enough to show detail of individual land parcels.

Geological maps show the rock types which occur in the vicinity of the site, and local experience will enable the assessor to determine the engineering soils likely to be developed over the rocks. This in turn will indicate the range of stability problems that could exist.

Topographic maps show the topography of an area, and give some idea of the gross morphology. Previous slope instability may be interpreted from the morphology and surface drainage patterns. For example, water courses diverging downslope or traversing across a slope indicate that old drainage lines have been blocked by landslides. Alternate divergent and convergent contour intervals, swampy or marshy areas and high overall slope complexity all point to the disruption and alteration of the original slope profile by landslide activity.

Combining and overlaying geologic and topographic maps will show any relationships between geologic materials and particular slope angles or slope segments. This information may be useful at later stages of assessment. Large landslides may be marked on both geologic and topographic maps.

Finally, landslide zone maps at intermediate scales (e.g. 1:25 000) present the results of previous slope stability work. This means that a preliminary assessment of the site has, in effect, been made. No further assessment of the site will be needed if the maps show that the slope has been classed as stable, however sites within stable zones but close to unstable or suspect zones should be treated with caution. Sites mapped as being within suspect zones must be investigated.

3.1.1.2 Remote sensing

Overlapping aerial photographs, when viewed with a stereoscope, give a three-dimensional, birds-eye view of the land surface. From these the interrelations between geology, morphology, drainage and land use can be determined. Most populated areas will have been photographed at least once, and many will have been photographed several times over the years. If several sets of photographs are available they will show the pattern of landscape alteration, which may provide clues as to existing or potential instability (e.g. patterns of forest clearing). Most photograph sets are in black and white, but colour photographs are becoming more common. Although more expensive to purchase, the colour photographs provide much more detail. The photograph scale will usually not be sufficient to provide intimate detail of the site, however aerial photograph interpretation can be combined with field inspection to verify and refine rock and soil boundaries. The quality of the interpretation will be proportional to the interpreter's knowledge of the geology, soils, and vegetation of the area in question.

Orthophotographs are undistorted, true scale aerial photographs over which are superimposed topographic contours and cultural features. They are usually available at a larger scale than the topographic maps. The combination of photography and topography can be very useful in determining slope morphology.

Remote sensing techniques can be used if applicable. These include special aerial photography flights to capture the landscape when the sun is low, highlighting surface irregularities. Oblique aerial photographs can be taken professionally, or with a hand camera from a light aircraft. Infrared imagery and satellite (LANDSAT) imagery may also be useful.

3.1.1.3 Literature

Previous investigations, both published and unpublished, may throw some light on the area in question. General references can include the explanatory notes accompanying geological and landslide zone maps. Where closer settlement has already occurred in the vicinity of the site in

question it is likely that land parcels in that area have already been assessed. If this is the case then any results or conclusions drawn from the previous investigations may apply to the current site, and coworkers and others may be able to supply information which would otherwise have to be won by experience.

3.1.2 TOPOGRAPHIC MAPPING

3.1.2.1 Base Maps

A base map is used as an underlay for field mapping. The accuracy of any slope class, morphological or geological map of the land parcel and environs will depend on the accuracy of the base map. The land parcels will commonly have been surveyed, and the site plan supplied to the assessor will usually be adequate as a base map for slope class and geologic maps. Morphological maps may require the use of surveying techniques to obtain accurate height and location datum so that surface features can be accurately located. Modern electronic distance measurement (EDM) surveying equipment makes this a relatively quick and very accurate operation.

The case study discussed in Section 5 utilises an effective surveying system employed by the author.

A detailed base map was prepared with the aid of a surveyor using a theodolite and an electronic distance measurer. The height and horizontal datum of over 200 identifiable locations were recorded to prepare the base map for Figure 5.2. The surveyor and the author used an identical numbering system to record the readings and identifiable features respectively of the stations chosen by the author. The location, height, and number of the stations were drafted on the base map at 1:1000 scale. The recorded identifiable features of each location were used for field orientation so the position of the morphological features evident in the field could be accurately mapped (fig. 5.2). The map is less accurate in the heavily vegetated upper slopes (fig. 5.3) because it was difficult to find clear lines of sight in those areas. Preparation of the base map took the surveyor and author approximately five man-days.

3.1.2.2 Slope morphology

Slope class and slope morphology are the most easily assessable of the factors influencing slope movement, because no subsurface exploration is required.

Slope class maps compare measured slope angles and threshold slope angles for a particular geologic material. The slope angle and slope direction of the individual slope segments within the land parcel are measured and mapped. Previous regional assessments may have pinpointed threshold slope angles above which it is assumed that the slope is unstable. The mapped slope angles are compared with the threshold slope angles of the geologic materials involved. This delineates those areas of land which are potentially unstable and should not be developed.

Morphological maps are used to show the shape of the land surface. Symbols are used to describe the convexity and concavity of the land surface, and to show the location of scarps, water courses and other pertinent morphological features. Figure 5.2 shows an example of a detailed morphological map. Ground surveys will improve the morphological detail gleaned from aerial photography, however very accurate maps can be constructed if surveying techniques are used to prepare the base map. The morphological detail and accuracy of the map will depend on the method of mapping used.

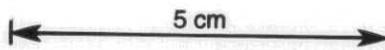
A relationship between surface features and slope movement processes may be recognised which can be used to delineate existing or potentially unstable areas of land. A practised eye can pick up the tell-tale shape of dormant landslides and of morphologically complex slopes indicative of ancient landslides, and distinguish them from undisturbed geologic features. Distinctive vegetative types and patterns may also be indicative of slope movements. The distribution of water-loving plants can indicate areas of poor drainage, and the occurrence of kinked trees indicates previous slope movement.

The morphological and drainage patterns outlined in Section 3.1.1.1 may be more pronounced in the field, and if recognised should be included on the map.

The examination of the morphology of a slope will lead to an understanding of the slope history, which in turn gives an insight into the processes active in the formation of the slope. Prediction of future slope stability may be improved given these insights.

3.1.2.3 Cultural indicators

Some of the tell-tale cultural signs of slope disturbance are leaning telegraph poles and fences, taut fence wires, and damaged buildings. Buildings will quickly show the effects of the smallest movements. Cracked walls, doors and windows which do not close or cannot be opened, faulty drainage pipes, inclined fences, cracked paths and a history of repeated structural repairs indicate the existence of either expansive soils or slope movements. Slope movements will tend to affect



a number of adjacent structures whereas expansive soils may affect only a single structure where excessive garden watering may have exacerbated the problem. In many cases it will be difficult to differentiate between problems caused by slope stability and those caused by expansive soils. In urban areas these cultural clues may be the only visible indicators of slope movement.

3.1.3 GEOLOGIC MAPPING

3.1.3.1 Surface geology

Published geologic maps can be refined and the engineering properties of the materials evaluated by inspecting the surface geology and soils, rock outcrops, and road cuttings and embankments. The materials, if soils, should be described using the Unified Soil Classification System (table 2.3). All geologic boundaries and materials should be mapped, and any potential aquifers and aquicludes noted.

The gross geologic structure and the geologic history of the land parcel and environs on slope stability should be considered, as the geologic history of the slope materials will affect their current and future behaviour (see Section 2.8).

3.1.3.2 Subsurface geology

The subsurface geology can be explored using a variety of drilling and excavating techniques. The type, layout, and depth of drillings and excavations will depend on site conditions and finances. The subsurface materials should be geologically and geotechnically logged, using the Unified Soil Classification System where possible. Detailed examination of the materials will improve the geologic model used to describe the slope. The geologic materials should be examined for indications of inherent instability within the geologic sequence (see Section 2.8), and for potential aquifers and aquicludes which may affect slope stability.

Any drillings or excavations on a landslide should attempt to determine the depth to and shape of the failure plane. The failure plane is often very difficult to recognise, but may be characterised by a softened, wet zone in the sequence. Some information can be gained from the rate of progress of drilling. For example, differences in soil penetration rates indicate soil strength variations and possibly moisture content variations.

3.1.3.3 Sampling, testing and stability analyses

The subsurface materials are examined and their characteristics logged. Samples of the subsurface materials should be collected from any drillings or excavations for strength and soil properties determinations. Table 3.1 compares a range of drilling and excavating methods and describes the procedure, type of sample retrieval, applications, and limitations of each. The choice of sample type will depend on site conditions and the equipment available, the requirements of the testing method used, and the time and cost restrictions on the investigation.

Tables 3.2 and 3.3 detail a range of field and laboratory tests. The quality of the results of any testing programme will depend on the quality of the sample taken, hence high precision testing requires samples which are in as near to their natural state as possible. Undisturbed samples provide more mechanical and geological information than the disturbed samples of the same material, but usually cost more to obtain. There is an Australian Standard on Site Investigations.

Test results are used in mathematical stability analyses, as outlined in Section 3.3. The quality and accuracy of an analysis will depend directly on the quality and accuracy of the information input to it, but the analysis is still only a simplified version of the real world, and its results should be used as only one input into the final decision on slope stability.

3.1.4 HYDROGEOLOGY

3.1.4.1 Water

Surface water drainage systems can be mapped onto the base map. Indicators of previous landslide activity include diverging stream channels, swampy areas, surface water disappearing underground, and drainage lines traversing across slope.

Underground water conditions will be difficult to determine unless bores or wells are conveniently located. A careful study of vegetative patterns may indicate where larger quantities of water are available to the vegetation, and seasonal changes in near surface water levels may be reflected by differential growth among grasses and small annual plants.

3.1.4.2 Hydrogeology and piezometers

Piezometers are used to measure water level fluctuations and to determine the maximum water level elevation of an aquifer. A simple and effective piezometer (fig. 3.1) can be cheaply installed if geologic logging of a hole indicates an aquifer or permeable interval in the subsurface. Clays will often have measureable piezometric surfaces, and apparently dry holes can make water over a period of a few days.

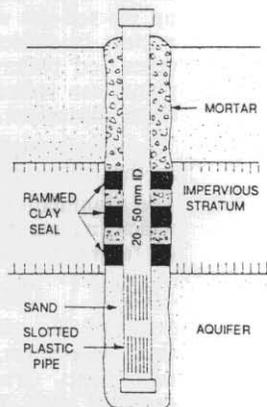


Figure 3.1 Simple piezometer
(from Schuster and Krizek, 1978).

Regular measurements of the water level in the piezometer over seasonal cycles will indicate the range of groundwater levels applicable for stability analyses. These measurements are important because the height of the peak groundwater level in a slope is usually unknown, even though this peak level has a major effect on the calculation of the factor of safety. In many cases there is a direct correlation between abnormally heavy or long rainfall events, water-table rise, and slope failure.

Special attention should be paid to confined water which can exert upward pressure on overlying impervious beds.

3.1.5 GEOPHYSICAL METHODS

Geophysical methods use detecting and recording instruments at the surface to measure the physical properties of subsurface materials.

Although individual site conditions may favour the use of any of a range of geophysical methods, two methods in particular are worth noting; refraction seismic and resistivity.

Refraction seismic methods measure the time taken for a shock wave to travel through the ground from its point of origin to a detector. Materials of different densities transmit shock waves at different seismic velocities. Each material in the subsurface will usually have an identifiable seismic velocity, and the results of the testing can be used to indicate the strength and character of the materials and the depth to material interfaces.

Resistivity methods measure the electrical resistance of the soil by applying a current to the ground and measuring the resultant voltages between a pair of electrodes. The soil resistivity is commonly dependent on the quantity and salinity of water in the soil. This method can be used to quickly examine large areas, but interpretation of the results is often difficult.

Interpretation of the results of both methods is improved if the results can be correlated with a drilled or excavated geologic sequence.

3.1.6 PREPARATION OF LANDSLIDE ZONE MAPS

Landslide zone maps broadly define groups of slopes which have similar potentials for slope failure, and are prepared at a scale convenient for the coverage of the afflicted area in reasonable time (e.g. 1:20 000 scale). Zone maps are commonly based on a three zone system, with slopes classed as stable, unstable, or suspect. The three zone system can be refined and subdivided if field relationships between landslide occurrence and combinations of morphology, geology and hydrogeology can be recognised and mapped. This will reduce the range of hazards associated with any one landslide zone.

The most appropriate method for constructing landslide zone maps is to group together slopes that have similar ranges of slope stability, slope angle, morphology, geology and potential groundwater conditions. Aerial photograph interpretation and field traversing are combined to refine and delineate geologic and morphological boundaries and identify hydrogeological regimes likely to affect stability. Each group defined by this process will then have a similar range of slope stability problems and a comparable probability of failure. This information is presented on appropriate geologic and topographic base maps.

Although it is not possible to predict with absolute certainty the future stability of a slope without detailed geotechnical investigations, these investigations are usually neither warranted nor economic when constructing these medium to large scale zone maps.

3.2 SOIL STRENGTH PROPERTIES AND THEIR MEASUREMENT

3.2.1. INTRODUCTION

This section details some of the strength properties of soils and the theories describing their behaviour.

3.2.2 DEFINITION OF TERMS

cohesion (c)	that part of the shear strength of a material which does not depend upon interparticle friction. The resistance of a material to shear along a surface which is under no pressure
compressive strength	the internal resistance offered to normal stress. It is the maximum normal stress, based on the original cross-section, that can be sustained without failure
internal friction (ϕ)	that part of the shear strength of a material which depends on interparticle friction
normal stress (s)	component of stress perpendicular to a plane

shear strength	the internal resistance offered to shear stress. It is the maximum shear stress, based on the original cross-section, that can be sustained without failure
shear stress (τ)	a stress causing or tending to cause two adjacent parts of a solid to slide past one another parallel to the plane of contact
strain	deformation resulting from an applied force. Within elastic limits strain is proportional to stress
strength	the limiting stress that a solid can withstand without failing by rupture or continuous plastic flow
stress	pressure; force per unit area

3.2.3 FAILURE CRITERION

The criterion most widely used to define failure is the Mohr-Coulomb criterion;

$$s = c + \sigma \tan \phi \dots \dots \dots (1)$$

where s = shear strength, c = cohesion, σ = normal stress on slip surface and ϕ = angle of internal friction (see Section 3.1 for further definition of terms).

3.2.4 EFFECTIVE AND TOTAL STRESS ANALYSIS

The calculation of total stress gives a measurement of the total applied pressure, however the shear strength of a soil is strongly influenced by the rate at which porewater pressures (u) within the soil dissipate when the soil is subjected to stress. The principle of effective stress (s') is used to allow for the effect of porewater pressures on the shear strength of the soil, hence;

$$s' = \sigma - u \text{ and}$$

$$\sigma = \text{total stress.}$$

Therefore the shear strength can be expressed in terms of effective stress;

$$s = c' + \sigma \tan \phi'$$

$$= c' + (\sigma - u) \tan \phi' \dots \dots \dots (2)$$

where c' and ϕ' are the strength parameters of effective stress. The use of the effective strength parameters requires that the porewater pressure be known so that s' can be evaluated.

The results of soil strength measurements are dependant on the magnitude of porewater pressures in the soil, and on their rate of dissipation during the test. In general, there are two components of porewater pressure; hydrostatic pore pressure determined by the location of the point of measurement in relation to the groundwater level, and excess pore pressure due to applied loads. The first component is relatively easy to measure, however the second can be rather more complex. The tendency of a soil to change volume when it is loaded under undrained or partially drained conditions causes a pore pressure change. This excess pore pressure may be negative or positive, depending on the type of soil and the stresses involved. Under undrained conditions the excess pore pressures are not given time to dissipate, and these elevated porewater pressures reduce the total stress required to promote failure. Under fully drained conditions the excess pore pressures are given time to dissipate. Partially drained soils allow partial dissipation of the excess pore pressures.

In the long term and under fully drained conditions the excess pore pressure is zero, and the pore pressure due to groundwater levels can usually be determined without difficulty. Analyses of this type use the effective stress description of shear strength (equation (2)).

For partially drained and undrained conditions the evaluation of field excess pore pressure is often difficult. In some cases the total stress description of shear strength may be used (equation (1)).

The soil shear strength determined from the undrained loading of saturated soils is commonly used to determine the short term stability of excavations in soils to determine a safe batter angle. This is commonly called the $\phi = 0$ method.

The shear strength of a soil usually changes as water drains from it. If the change results in a higher strength, the short-term, undrained stability is critical but can be expected to improve with time. If drainage decreases the strength, the undrained shear strength can be used only for the analysis of short-term or temporary situations.

3.2.5 STRESS-STRAIN CHARACTERISTICS

Two stress-strain curves are shown in Figure 3.2. In common practice, the strength of a soil is defined as the peak strength (points a and b) measured in a test. When this peak strength value is used in a stability analysis it is assumed that the peak strength is attained simultaneously along the entire slip surface. However, many soils demonstrate strain softening behaviour, as illustrated

by curve A, and it is important in analysis and design to take account of this decrease. For such soils it is unreasonable to assume that all soil along the failure surface reaches its peak strength simultaneously. In fact, the magnitude of strain and displacement may vary over the entire slip surface until such time as a large failure takes place. At this stage the strain-softened strength of the soil will apply to analyses of the failure.

Any of several phenomena may explain the strength decreases mentioned above. The lower limit to strength (point *c*) may be called the fully softened strength, remoulded strength or residual strength, depending on the type of soil involved (the terms are not synonymous).

3.2.6 DRILLING, EXCAVATING AND SAMPLING METHODS

The following table (table 3.1) details a range of drilling and excavating methods which can be used to obtain samples of subsurface materials. The choice of method will depend on the equipment available and the type of test required.

Table 3.1
DRILLING, EXCAVATING AND SAMPLING METHODS

Method	Procedure	Type of Sample	Application	Limitations
Auger boring	Dry hole drilled with hand or power auger; samples usually recovered from auger flutes; hollow augers sometimes used	Auger cuttings; disturbed and ground up, partially dried from drill heat in hard materials. Undisturbed samples from hollow augers	Shallow holes in soil and soft rock; to identify geologic units and water content above water table	Soil stratification destroyed, and sample mixed with water below water table in disturbed samples
Rotary coring	Outer tube with diamond bit on lower end rotated to cut annular hole in rock; core protected by stationary inner tube; cuttings flushed upward by drill fluid, water, or air; core and stationary inner tube retrieved from outer core barrel by lifting device or 'overshot' suspended on thin cable (wire line) through large diameter drill rods and outer core barrel	Relatively undisturbed sample, 50-200 mm wide and 0.3-1.5 m long in inner tube	The recovery of continuous samples in most materials	Sample may twist in soft clays; sampling loose sand below water table difficult; success in gravel seldom occurs
Rotary or cable tool drilling	Toothed cutter rotated or chisel bit pounded and churned	Rock chips and cuttings	To penetrate boulders, coarse gravel; to identify hardness from drilling rates.	Identifying soils or rocks difficult. Progress difficult in wet clay
Percussion drilling (jack hammer or air track)	Impact drill used; cuttings removed by compressed air	Rock dust	To locate rock, soft seams, or cavities in sound rock	Drill becomes plugged by wet soil

Tube sampling	Tube forced into soil with static force, or driven in soft rock; retention of sample helped by drilling mud	Relatively undisturbed sample, length 10-20 diameters	In soft to firm clays, short (5-diameter) samples of stiff cohesive soil, soft rock and, with aid of drilling mud, firm to dense sands. Various refinements of method used	Cutting edge wrinkled by gravel; samples lost in loose sand or very soft clay below water table; more disturbance occurs if driven with hammer
Pits and trenches (backhoe)	Pit or trench excavated to expose soils and rocks	Chunks cut from walls of trench; size not limited	To determine structure of complex formations; to obtain samples of thin critical seams such as failure surface- <i>in situ</i> shear tests (vane shear, pocket penetrometer etc.)	Moving excavation equipment to site, stabilising excavation walls, and controlling groundwater may be difficult

3.2.7 FIELD AND LABORATORY TESTS

Field tests (table 3.2) are conducted in *in situ* samples so that the tests are performed on material which is at, as near as possible, its natural state. Testing is more commonly conducted in the laboratory (table 3.3) on samples obtained from the field.

Table 3.2
FIELD TESTS (after Schuster and Krizek, 1987)

Method	Procedure	Sample	Applications	Limitations
Dynamic sounding	Enlarged disposable point on end of rod driven by weight falling fixed distance in increments of 100-300 mm. The number of blows is recorded for a standard depth of penetration	None	To identify significant differences in soil strength or density	Misleading in gravels or loose saturated fine cohesionless soils. Coarse gravels cannot be penetrated
Static penetration	Enlarged cone forced into soil; force measured at regular intervals	None	To identify significant differences in soil strength or density; to identify soil by resistance of friction sleeve	Stopped by gravel or hard seams
Standard penetration	A tube of standard size and shape is driven with hammer blows. The number of blows is recorded for a standard depth of penetration	Undisturbed sample	To identify significant differences in soil strength and density	Stopped by gravel or hard seams
Borehole dilation	Borehole dilated by fluid under pressure, fluid volume measured and converted to change in borehole radius	None	To measure in place shear strengths	Interpretation largely empirical

Borehole shear	Expanding plug forced into wall at known pressure, walls sheared by pulling device up hole	None	Measure shear strength of annular zone surrounding borehole	Shearing direction perpendicular to failure surfaces. Smeared soil on annulus may affect results
Vane shear	Vertical vanes on thin rod rotated to give a cylindrical shear plane	None	Measure shear strength in bottom of borehole, test pit etc.	Shear strengths up to 30% higher than other methods
Pocket penetrometer	Small rod forced a standard depth into soil. Force measured	None	To identify significant differences in soil strength or density	Results relative only
Load test	Large plate loaded in increments until soil shears	None	Shear strength along curvilinear surface	Many different interpretations
Large scale direct shear test	Large block of soil left unexcavated in base of pit. Load placed on top, force needed to shear block horizontally measured	None	<i>In situ</i> shear test of suspected failure plane(s) using a representative sample	Subject to site conditions
Borehole camera	Inside of core viewed by circular photograph or scan	Visual representation	To examine stratification, fractures, and cavities in hole walls	Best above water table or when hole can be stabilised by clear water

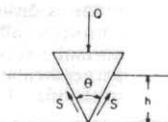
Table 3.3
LABORATORY TESTS (after Schuster and Krizek, 1978)

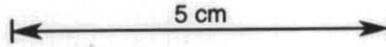
Method	Procedure	Applications	Limitations
Atterberg limits	In clay soils the moisture content is determined at which the clay changes from a brittle to a plastic state (plastic limit) and from a plastic to a liquid state (liquid limit). The plasticity index (P.I.) is the liquid limit minus the plastic limit	Engineering classification of soils. General correlations with other soil properties	Results can vary from operator to operator.
Unconfined compression test	A laterally unconfined cylindrical sample of length/diameter = 2:1 is compressed axially to failure (fig. 3.3a). Shear strength = $0.5 \times$ compressive strength	Saturated cohesive soils under undrained conditions. Measures total stress	Test should be rapid. Degree of strength change through sample disturbance unknown. Orientation of failure surface and potential shear plane not the same
Cone test	A cone with known cone angle is forced into soil (fig. 3.3b)	As above	As above

Fig. 3.3a



Fig. 3.3b

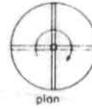




Vane shear test

Vertical vanes on a thin rod rotated to give a cylindrical shear plane (fig. 3.3c)

As above



As above



Fig. 3.3c

Triaxial test

A cylindrical sample is subjected to vertical loading while restrained by a lateral hydraulic load applied by hydraulic pressure. Pore water pressure, volume change, compressive and axial stress are measured (fig. 3.3d). Various types of triaxial test may be undertaken:

Highly versatile, and a variety of stress and drainage conditions can be used.

- Consolidated-drained test is slow. Sample is consolidated and sheared with drainage to allow pore water pressures to equilibrate during shearing. Effective stress measured

- Consolidated-undrained test is quicker. Sample is consolidated with drainage and sheared without drainage. Pore water pressures affect the shear strength measured. Effective stress measured.

- Unconsolidated-undrained test at mercy of pore water pressures. Consolidated and sheared without drainage - similar to simple tests above. Total stresses used for interpretation.

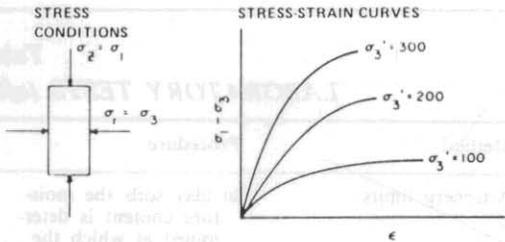
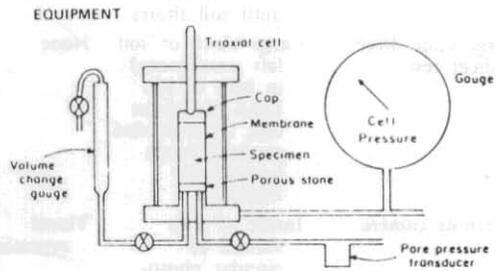
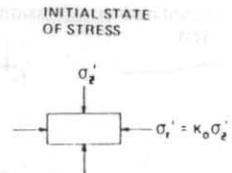


Fig. 3.3d

Direct shear test

Soil is enclosed in box having two halves, porous stones top and bottom for drainage. Consolidated under normal stress, sheared slowly so soil drains. Repeated at greater loads. Ring shear devices allow soils to be continuously sheared

Shear plane orientation is controlled by orientation of sample in box



Simple shear test

Cylindrical specimen encased in wire reinforced rubber membrane. Consolidated anisotropically under normal stress, sheared perpendicular to that stress (fig. 3.3e)

Shear deformation distributed uniformly through sample

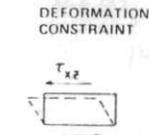


Fig. 3.3e

3.3 STABILITY ANALYSES

Stability analyses are used to calculate the stability of slopes.

3.3.1 THE 'FACTOR OF SAFETY' CONCEPT

Slope stability can be calculated using the factor of safety (FS) concept. A commonly used definition is:

$FS = \frac{\text{the sum of the restraining forces on the slope}}{\text{the sum of the driving forces in the slope}}$

The restraining forces in the above equation include the strength parameters (c and ϕ or c' and ϕ'), and the mass of that part of the soil resisting movement (usually in the toe of a landslide). The driving forces include pore pressures, loads on the soil and the mass of that part of the soil provoking movement (usually the head and body of the landslide).

From the above equation it can be seen that the driving and restraining forces are equal when the FS equals one. The FS becomes less than one when the driving forces predominate and failure occurs. When the restraining forces predominate the FS is greater than one.

The factor of safety concept is of most use when FS values lie between 0.5 and 2.0. Outside this range the FS values have less meaning, though they still demonstrate the extreme instability or stability respectively.

Stability analyses are usually simplistic and do not take into account the variability of natural materials. Their imprecise nature requires that value judgements be made on the validity of input data and the applicability of results. Blind faith in the infallibility of numbers must be overcome.

Site knowledge and previous experience must be applied to the results so that unrealistic answers can be recognised and discarded.

3.3.2 APPLICATIONS OF STABILITY ANALYSES

Stability analysis can be used for forward, back and sensitivity analyses.

3.3.2.1

Sensitivity analyses are used to determine the effect the parameter value changes on the FS. This indicates which parameters have the greatest effect on the FS, and so indicates where care must be taken in determining or choosing values for those parameters. If, as is often the case, a range of values seems applicable for any one parameter, then the extreme values of the range should be used to calculate maxima and minima for the FS.

3.3.2.2 Forward analysis

Forward analyses are used to calculate the FS of a slope, whether existing or planned. All available information is used to calculate the FS or the range of the FS appropriate to the measured or expected parameter value ranges.

3.3.2.3 Back analysis

Back analyses are used to reconstruct the conditions extant at the time of failure. Since the FS equals one at failure, the calculation can be used to determine the value of one parameter if the others are known. Back analysis can be used to check the results of laboratory tests of landslide materials, or to determine the theoretical water table height in the slope at failure, since this is seldom known.

3.3.2.4 $\phi = 0$ analysis

A $\phi = 0$ analysis assumes that there is no interparticle friction on the shearing plane during failure, and hence the failed material slides on water released from the intergranular pores. This method of analysis is commonly used to calculate the short-term (end-of-construction) stability of a proposed cutting.

3.3.2.5 $c = 0$ analysis

The $c = 0$ analysis is used to determine the long term stability of a slope. The assumption is that small movements of parts of the potential landslide mass over long periods of time tend to reduce the internal cohesion to zero.

3.3.3 TYPES OF STABILITY ANALYSES

Stability analyses have been derived for a range of failure styles. Table 3.4 details some stability analysis equations, appropriate references and some comments as to their applicability. Careful examination of the mathematical treatment of the slope stability problem will show the degree to which the real world has been simplified, and once again it must be emphasised that the interpretation of the results must be tempered with wisdom.

Table 3.4

TYPES OF STABILITY ANALYSES

Stability analyses are approximations of the real world, and hence the derived factors of safety may be in error.

Type of analysis	Equation, references and comments
PLANAR SLIP SURFACE - algebraic method	$F = (c'/\delta d)\sec\alpha\csc\alpha + (\tan\phi'/\tan\alpha) [1 - r.\sec^2\alpha]$ <p>where $r_s = (\delta.h/\delta d)$ δ = soil density δ_w = water density c' = effective cohesion ϕ' = effective angle of friction</p> <p><i>Comments:</i> Easily calculated by hand</p> <p><i>Reference:</i> Schuster and Krizek (1978)</p>
CIRCULAR SLIP SURFACE - algebraic method	$F = \Sigma\{[c' + W(1 - r_s)\tan\phi'](1/m_s)\}/\Sigma W\sin\alpha$ <p>where $m_s = \cos\alpha[1 + (\tan\alpha\tan\phi')/F]$ W = mass of slice u = pore pressure</p> <p><i>Comments:</i> Accurate for most purposes. Iterative calculation since F occurs on both sides of the equation. Converges rapidly</p> <p><i>Reference:</i> Bishop (1955)</p>
CIRCULAR SLIP SURFACE - using charts	<p>COUSINS' METHOD</p> <p><i>Comments:</i> Can be used to locate the critical circle</p> <p><i>Reference:</i> Cousins (1978)</p> <p>BISHOP AND MORGENSTERN'S METHOD</p> <p><i>Comments:</i> Uses average porewater pressures</p> <p><i>Reference:</i> Bishop and Morgenstern (1960)</p>
NONCIRCULAR SURFACE SLIP	<p>JANBU'S METHOD</p> $F = f_0\Sigma\{[c'b + (W - ub')\tan\phi'](1/\cos\alpha m_s)\}/\Sigma W\tan\alpha$ <p>where m_s is as previously listed f_0 = a function of the curvature of the slip surface and the type of soil</p> <p><i>Comments:</i> A convenient approximate method</p> <p><i>References:</i> Janbu (1973), Janbu <i>et al.</i> (1956)</p>
HOMOGENEOUS ISOTROPIC - using charts	<p>TAYLOR'S METHOD</p> $F = c.R^2\theta/WX$ <p>where c = undrained cohesion</p> <p><i>Comments:</i> W is a function of slope slope angle and slope height. Restricted to soft clays. Charts are used to rapidly locate critical circle</p> <p><i>References:</i> Taylor (1937), Taylor (1948)</p>
METHOD OF SLICES - algebraic	$F = \Sigma(c.L)/\Sigma(W\sin\alpha)$ <p><i>Comments:</i> Assumes that the soil is saturated, there is no volume change, there is no dissipation of pore pressures, the mode of failure is a slip circle and shear strength along the slip surface is the only factor contributing to resistance. Complex slopes can be modelled</p> <p><i>Reference:</i> Schuster and Krizek (1978)</p>

4 REMEDIAL MEASURES

Both vegetative and engineering solutions are discussed. Vegetative solutions are emphasised as the benefits of planting trees to stabilise landslides have to some extent been neglected in the literature. Combinations of both methods will often prove advantageous.

Section 4.1 is written with the help and co-operation of N. J. Parker and P. Fazackerley of the Private Forestry Division, Forestry Commission of Tasmania.

4.1 VEGETATIVE MEASURES

A large number of landslides are triggered by the removal of vegetation. Re-establishment of vegetation can improve slope stability in the following ways:

- (1) Root networks are formed which increase the stability of a slope, especially if the landslide failure plane is shallow enough to be within reach of the roots.
- (2) Plants dry out the ground, improving slope stability. Some plants (phreatophytes) can remove large volumes of water. For example, *Eucalyptus globulus* can transpire over two cubic metres of water per square metre of ground per year (Greenwood, 1986).
- (3) Plant canopies intercept rainfall, increasing evaporation and decreasing surface infiltration rates. This reduces the intensity and magnitude of rises in the water-table, and so decreases the likelihood of slope failure.

The cause of slope failure must not be neglected when planning remedial measures. It is important to identify where and how water is entering the landslide so tree plantings will reduce the rate and quantity of inflow.

4.1.1 PLANT LIST

The plants of Table 4.1 have been selected for Tasmanian conditions from Grow What Where (1980). The list is not exhaustive, and there are plants not listed which will also serve the purpose. Plant availability is another consideration. The range of ground conditions listed below is appropriate for most landslide areas, and most of the plants will tolerate light to moderate frost conditions (-3° to -6°). Similar lists can be drawn up for specific areas of the mainland so that local conditions and plant availability can be taken into account.

The use of native plants is recommended because of their availability, their suitability to local conditions, and their ability to remove water from the site over the entire year. The use of deciduous trees is not generally recommended, since they are dormant during winter when water levels can be expected to be at their highest.

The last two plants of Table 4.1 are useful exotics. *Populus alba* is a colonising plant useful in wet, soft, muddy conditions where it is difficult to establish other plants. Cuttings of *Populus* may be stuck in the difficult area, and a thicket with a dense root network should establish itself.

Pinus radiata is a quick-growing and thirsty tree which can be systematically harvested and replanted.

4.1.2 GUIDELINES FOR TREE SELECTION AND PLANTING

These guidelines are not exhaustive nor all-embracing, but are written for Tasmanian conditions. Similar guidelines and plant lists could be requested of the Forestry Commission or equivalent body in each State.

4.1.2.1 Selection

In selecting tree species the main factors to be taken into account, in approximate order of importance, are:

- (1) Ability to cope with the existing soil water content, and adaptability to a progressively drying site.
- (2) High early vigour, enabling the trees to take command of the site as quickly as possible.
- (3) Maximum year-round drying capacity (by including species regarded as phreatophytes, i.e. 'pumping plants', but excluding deciduous trees).
- (4) Strongly pioneering, spreading and/or deep root systems (with potential suckering as a desirable attribute, though not altogether consistent with the choices available under (1) and (2)).
- (5) One contrary set of properties, to some extent inseparable from high vigour and water extraction capabilities, is height, bulk and wind resistance of the crown, which may eventually transmit destabilising forces to the ground. This can be tackled by selecting some species to be removed in the course of management, and others which can be rejuvenated by periodic coppicing (i.e. felling and regrowth from the cut stump).

Table 4.1
PLANT LIST FOR LANDSLIDE CONDITIONS

Genus			Species		Common name	Plant size, origin availability
	Ground wet in winter, dries out in summer	Permanently boggy	Permanently wet ponded	and Water absorbing		
<i>Acacia</i>	<i>dealbata</i>	-	-	-	Silver Wattle	tsTn
	<i>floribunda</i>	<i>floribunda</i>	-	-	Gossamer Wattle	smn
	<i>longifolia</i>	-	-	-	-	sTn
	<i>retinodes</i>	-	-	-	-	sTn
	<i>verticillata</i>	<i>verticillata</i>	-	-	Prickly Mimosa	tsTn
<i>Bauera</i>	-	<i>rubioides</i>	-	-	-	sTn
<i>Banksia</i>	<i>marginata</i>	-	-	-	Honeysuckle	tsTn
<i>Callistemon</i>	<i>pallidus</i>	<i>pallidus</i>	-	<i>pallidus</i>	Lemon Bottlebrush	sTn
<i>Eucalyptus</i>	<i>camaldulensis</i>	<i>camaldulensis</i>	-	-	River Red Gum	tm
	<i>globulus</i>	<i>globulus</i>	-	<i>globulus</i>	Blue Gum	tTn
	<i>kitsoniana</i>	<i>kitsoniana</i>	-	<i>kitsoniana</i>	Black Gum	tm
	<i>ovata</i>	<i>ovata</i>	<i>ovata</i>	<i>ovata</i>	Cabbage Gum	tTn
	<i>pauciflora</i>	-	-	-	-	tTn
	<i>perriniana</i>	-	-	-	-	tTn
	<i>pulchella</i>	<i>pulchella</i>	-	-	White Peppermint	tTn
	<i>risdonii</i>	-	-	-	Risdon Peppermint	tTn
	<i>tenuiramis</i>	<i>tenuiramis</i>	-	-	Silver Peppermint	tTn
	<i>Hakea</i>	<i>sericea</i>	<i>sericea</i>	-	-	Silky Hakea
<i>Leptospermum</i>	<i>lanigerum</i>	<i>lanigerum</i>	<i>lanigerum</i>	-	Woolly Tea-tree	sTn
	<i>scoparium</i>	<i>scoparium</i>	-	-	Manuka	sTn
<i>Melaleuca</i>	<i>armillaris</i>	<i>armillaris</i>	<i>armillaris</i>	<i>armillaris</i>	Bracelet Honey-myrtle	smn
	<i>ericifolia</i>	<i>ericifolia</i>	<i>ericifolia</i>	<i>ericifolia</i>	Swamp Paperbark	tsTn
	-	<i>gibbosa</i>	-	<i>gibbosa</i>	-	sTn
	-	<i>squamea</i>	<i>squamea</i>	<i>squamea</i>	-	-sTn
	-	<i>squarrosa</i>	<i>squarrosa</i>	<i>squarrosa</i>	Scented Paperbark	sTn
<i>Sprengelia</i>	-	<i>incarnata</i>	<i>incarnata</i>	-	-	sTn
	-	<i>sprengelioides</i>	-	-	-	sTn
<i>Pinus</i>	<i>radiata</i>	-	-	-	Monterey Pine	ten
<i>Populus</i>	-	<i>alba</i>	<i>alba</i>	-	Silver Poplar	ten

s = shrub; ts = tall shrub; t = tree; T = Tasmania; m = mainland; e = exotic; n = nursery; FC = Forestry Commission.

4.1.2.2 Planting

Recommended procedure for establishment is as follows:

- (1) Fence securely against all stock, and against vermin if possible.
- (2) Spot-spray the planting places on a diameter of 600 to 800 mm with 1% 'Roundup', avoiding particularly waterlogged places.
- (3) Spraying should precede planting by about three weeks, at which time the spots will be quite evident and clear of competing vegetation.
- (4) Spraying can be along lines marked by pairs of sighting poles. Lines may be straight or random according to choice and site conditions.
- (5) The number of plants required will be indicated by a count of the sprayed places two weeks after spraying.
- (6) Tease out or prune pot-bound roots. Firm trees in and water to ensure that roots make contact with soil.
- (7) Plastic sleeves provide protection from animals, winds and sprays while condensing dew and fog and providing a valuable greenhouse effect. Younger plants can be used and faster growth may result. Four stakes are preferable to three to maintain tightness of plastic and growing space for the plants.

(8) On poor soils the application of fertiliser is advisable, but where soil fertility is adequate the fertiliser may promote top-growth at the expense of root development.

(9) Finally, attention is drawn to the need for continued inspections, and for weed control in the first two years. A second spraying with 'Roundup' in the spring is recommended, along with hand-pulling of weeds from within the sleeves. Note that this herbicide should not in any way be allowed to contact the plants. Subsequent sprayings will require the use of a shield.

4.1.3 GUIDELINES FOR TREE LAYOUT

(1) Phreatophytes (table 4.1, column 4) should be planted on and around springs and swampy places, both in the slip and above or adjacent to it. This will dry the land and improve stability.

(2) Plants tolerating progressively dryer conditions should be placed where the phreatophytes will affect the soil moisture. This may include the entire landslide area.

(3) Trees planted for timber should be accessible, and should be harvested in rotation to avoid the clearing of large areas at one time.

(4) Tall trees on the edges of scarps should be coppiced to reduce the risk of them toppling in strong winds.

4.1.4 COSTS

Costs associated with planting and maintenance are steadily increasing. The following figures are estimates of current prices and should be used as a guide only.

Estimated costs at September 1986 are as follows:

Fencing	standard	\$2500/km
	electric	\$1500/km
Spraying	per application	30c/spot
	plastic sleeves	55 to 75c each
Protection	stakes	50c/set of 4
	pipe and dripper	\$1.00 to \$1.50/tree
Irrigation	tube stock	50c to \$1.50/tree
Trees		

4.1.5 CASE STUDY—SLOPE MOVEMENT AT HERRICK, NORTH-EASTERN TASMANIA

A landslide threatened a railway line, and it was recommended that tree plantings be used to stabilise the movement. The following is extracted from communications between N. Parker (Private Forestry Division, Forestry Commission) to Australian National Railways.

The following recommendations are based on the premise, first, that immediate stability will be gained through engineering techniques. Secondly, trees will be established for the drying and soil strengthening properties of their root systems, but only on the actual area of instability below the tracks.

On the basis of the area to be fenced of 3390 m², an average spacing of 3 m x 3 m and a planting distance of 2 m from the three paddock side fences, a total of 400 paper-potted trees have been tentatively reserved at Perth nursery, comprising:

- 90 *Acacia melanoxylon* (Blackwood)
- 90 *Eucalyptus globulus* (Blue Gum)
- 90 *Eucalyptus ovata* (Black Gum)
- 130 *Pinus radiata* (Monterey Pine)

The cost of the above stock at the nursery, providing it is not necessary to substitute for some of the paper-potted plants or to make up numbers with some additional pines as suggested below, will be \$98.20.

The high-vigour, high-uptake trees are the pine and blue gum, the former to be regarded mainly as temporary elements, that is until significant drying has been effected, and to be removed before they become too large. They should be considered for thinning or removal at about eight years. The Blue Gum can be managed almost indefinitely on a coppice system, by cutting, possibly every 8 to 10 years.

The Blackwood and Black Gum are included for their tolerance of the wet site in the early stages, also for their long term drying effect. Blackwood also has a propensity to suckering.

4.1.5.1 Disposition of tree species

It is suggested that the top row, or the two top rows if one is outside the enclosure, be planted with pine. Similarly, all the outer plants, that is those at the ends of each row, plus the bottom row, being on drier ground, should be pines.

Blue Gum should next be distributed throughout the remaining drier sites, generally around the inner fringe. Blackwood and Black Gum can then be randomised through the body of the block in the remaining prepared places.

This should work out reasonably according to plan if some thought is given to the arrangement at the time of counting, preparatory to making the final order for plants.

4.2 MECHANICAL MEASURES

4.2.1 *Surface drainage*

Landslides usually move only when abnormal quantities of water are present in the subsurface. Surface drainage is used to intercept and direct surface water away from the slope failure, decreasing the volume of water available for slope destabilisation. Watercourses flowing into the affected area should be diverted, and springs, swamps and ponded water within the area should be drained. In some cases it may be wise to fill surface depressions and tension cracks to prevent water from being channelled to the failure plane.

Disposal of water should be into an established stream beyond the extent of current or potential movement. Surface drains are more effective if lined. This decreases the volume of water seeping into the subsurface. Drain linings include concrete and polythene pipes, and tapered interlocking U-shaped concrete tiles. Flexibility in the drainage system means it will remain effective after small slope movements. Unlined drains should be of a constant gentle slope to minimise gully erosion within the drain. Deep open drains should be avoided as they are likely to become the site of a new tension crack particularly if the drain is relatively close to the headscarp. All drainage lines should be periodically checked and maintained to ensure continued effectiveness.

4.2.2 *SUBSURFACE DRAINAGE*

Groundwater is a major cause of slope instability, and the successful interception and drainage of the groundwater improves the stability of a slope.

4.2.2.1 *Excavated and French drains*

Shallow aquifers can be intercepted and near-surface drainage affected with excavated trenches backfilled with either coarse aggregate (French drain) or coarse aggregate and a basal perforated plastic drainage pipe. A herringbone network of drains can be used to drain the top level of a landslide, and will concentrate water to a point for ease of disposal. Drain excavation by backhoe is quick and they can be used in most terrains.

The drains, if properly constructed, can be used to intercept and drain surface water before it enters the landslide and to drain the toe of the landslide. However, if poorly constructed, the intercepting drains will pond water and contribute to slope instability.

Drainage systems have been installed with some success in a number of Tasmanian landslides, however these have mostly been constructed by individuals. Their construction is often recommended when houses are being erected. French drains had mixed results in the Lawrence Vale landslide stabilisation in Launceston (Knights, 1977) because few of the drains intercepted appreciable quantities of groundwater.

4.2.2.2 *Vertical and horizontal bores*

Vertical and horizontal bores perform the dual function of providing geologic and hydrogeologic information in addition to their groundwater removal capacity. Vertical holes may be drilled both outside and within the failure. Those outside the failure can be sited to intercept water entering the slide, and because they will be little affected by slope deformations they may be of greater long-term value than those sited in and dewatering the body of the slide. Holes should be large enough (100 to 200 mm diameter) to accommodate down-hole pumps in screened steel casing. Construction is similar to piezometer construction.

Horizontal holes or drains do not require pumping if angled uphill. Casing may be plastic, with hacksaw slots or small diameter holes perforating the pipe where water enters the bore. This may be determined from water flow during drilling or by examination of material from the borings.

Subhorizontal drain holes are being used at Rokeby, near Hobart, in an attempt to stabilise a landslide threatening a house on a steep waterfront block. The drain holes have intercepted the suspected failure plane, and some water is draining from it (Moore, 1987). Their long term effectiveness is still unknown.

4.2.3 *TREATMENT OF SLOPE SHAPE*

Slope stability may be substantially increased by reducing the weight on the head and/or increasing the weight on the toe of a slope failure. Zaruba and Mencl (1969) indicate that a 10% increase

in the factor of safety will result if approximately 4% of material is displaced from the head of a rotational movement to the toe. Toe loading is commonly used in appropriate circumstances to increase the resisting forces of the failure.

Toe loading principles are used by the Tasmanian Department of Main Roads when batter failures occur. An example is outlined in the following section.

4.2.4 *RETAINING WALLS AND SIMILAR STRUCTURES*

Retaining walls and similar structures are used in vehicular cuttings and for similar applications where space is limited. They provide enough dead weight or artificially reinforced restraint near the toe of an unstable slope to prevent movement. All retaining walls must resist overturning, sliding at or below their base, and internal shearing, and they must be designed to allow the drainage of groundwater.

Retaining walls can be constructed in a large range of materials and styles. Some commonly used types are: rock buttresses; timber bulkheads; timber, metal and concrete cribbing; and rubble, masonry, concrete and reinforced earth retaining walls. Rock buttresses use high specific gravity rock-fill to replace slope materials or to form embankments emplaced against suspect slopes. This increases the weight and hence the restraining forces at the toe of a potential or existing slope movement. Crib walls are useful for retaining shallow slope failures. Interlocking beams are used to form a wall inclined toward the slope and fill is placed behind the wall as construction proceeds, tying the wall into the fill. Retaining walls combine buttressing and crib wall effects. The walls are precast or formed, and various materials emplaced between them and the slope. They are used to restrain forces greater than those which can be handled by crib walls.

Retaining walls and similar structures are commonly used by the Tasmanian Department of Main Roads to prevent landslides and improve the stability of potentially unstable slopes. Landslides of highly weathered Tertiary basalt in a high road batter near the Forth River, Tasmania have been excavated and backfilled with dolerite boulders to prevent further failure.

4.2.5 *PILES*

Piling has been successful in restraining shallow active slope movements. Deep-seated landslides are difficult to restrain with piles as they must be emplaced far enough below the slip plane to ensure that they remain in place when slope movements occur. Piles can be strengthened if their tops are tied back to earth anchors outside the active failure.

Several shallow landslides affecting roads in the Tamar Valley have been successfully restrained with a closely spaced row of large diameter wooden piles.

4.2.6 *CHEMICAL TREATMENT*

Cation exchange has been successfully used to increase the stability of clay by changing its chemical composition. Calcium, injected into the soil as lime, is used to replace lower valance cations, chiefly sodium. An extensive network of holes is needed to ensure the cation exchange affects a significant proportion of the clay.

The Department of Main Roads used quicklime to stabilise Tertiary sediments near Glen Huon, Tasmania. Some 150 holes were drilled and charged with the quicklime in a three metre square grid. Movement of the landslide appears to have abated, although part of the stabilisation may be due to the extensive perforation of a confined aquifer and consequent release of pore pressures (B. D. Weldon, pers. comm.).

4.2.7 *ELECTRO-OSMOSIS*

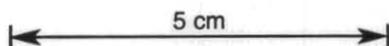
The action of an electric field induces water to migrate from anode to cathode, where collectors and pumps can dispose of it. This property can be used to increase drainage of clays in which permeability is low, and is usually restricted to the drainage of relatively small sites.

4.3 *CONCLUSIONS*

Any remedial measures will need to be tailored to suit the requirements of individual landslides. The choice of vegetative or engineered solutions will depend on site conditions, and present and future land use. Drainage and diversion of surface, and if possible subsurface, water should be tackled as soon as is practicable.

In some cases it is not practicable to attempt any remedial measures. For example, mud flows in the Strezlecki Ranges in Victoria can be up to 200 m wide and over one kilometre long, and it is doubtful whether any stabilisation schemes would work.

Both vegetative and engineering measures are used in urban areas. Engineering solutions can be employed to preserve buildings and roads, and vegetative solutions wherever practicable. Vegetative schemes have particular application in rural areas where plantings of commercial timbers can be used to stabilise slope movement. These may provide a long term investment if the trees can be progressively harvested and replanted at maturity.



5 WINDERMERE - A CASE STUDY

5.1 INTRODUCTION

The Windermere area (fig. 5.1) is located some 15 km north-west of Launceston in the Tamar Valley, overlooking a picturesque stretch of the estuarine River Tamar. There is a potential for slope stability problems along the length of the slope within the Tertiary colluvium.

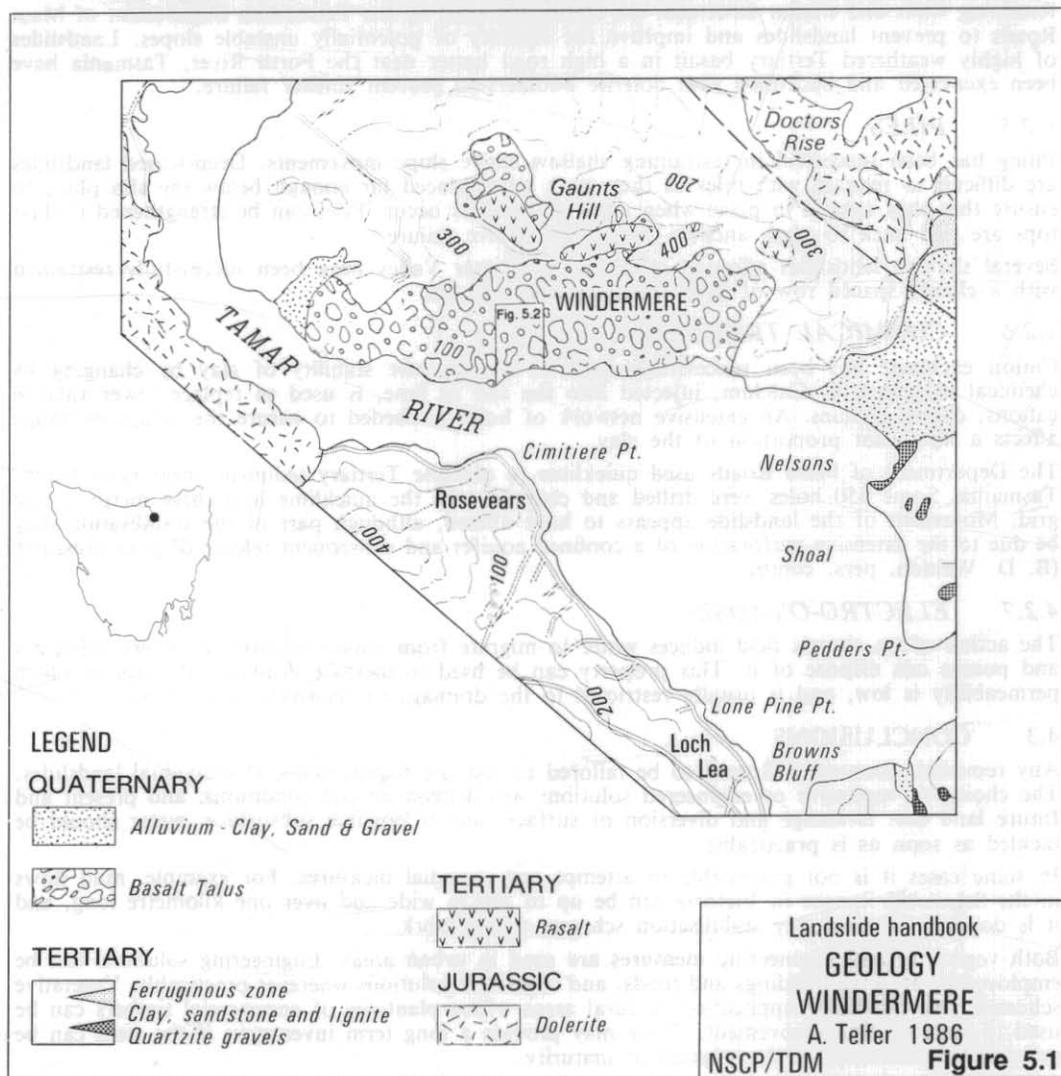
Land use is presently a mixture of rural land and small-acreage residential blocks. Subdivision pressure on this land is constant as the area is within commuting distance of Launceston.

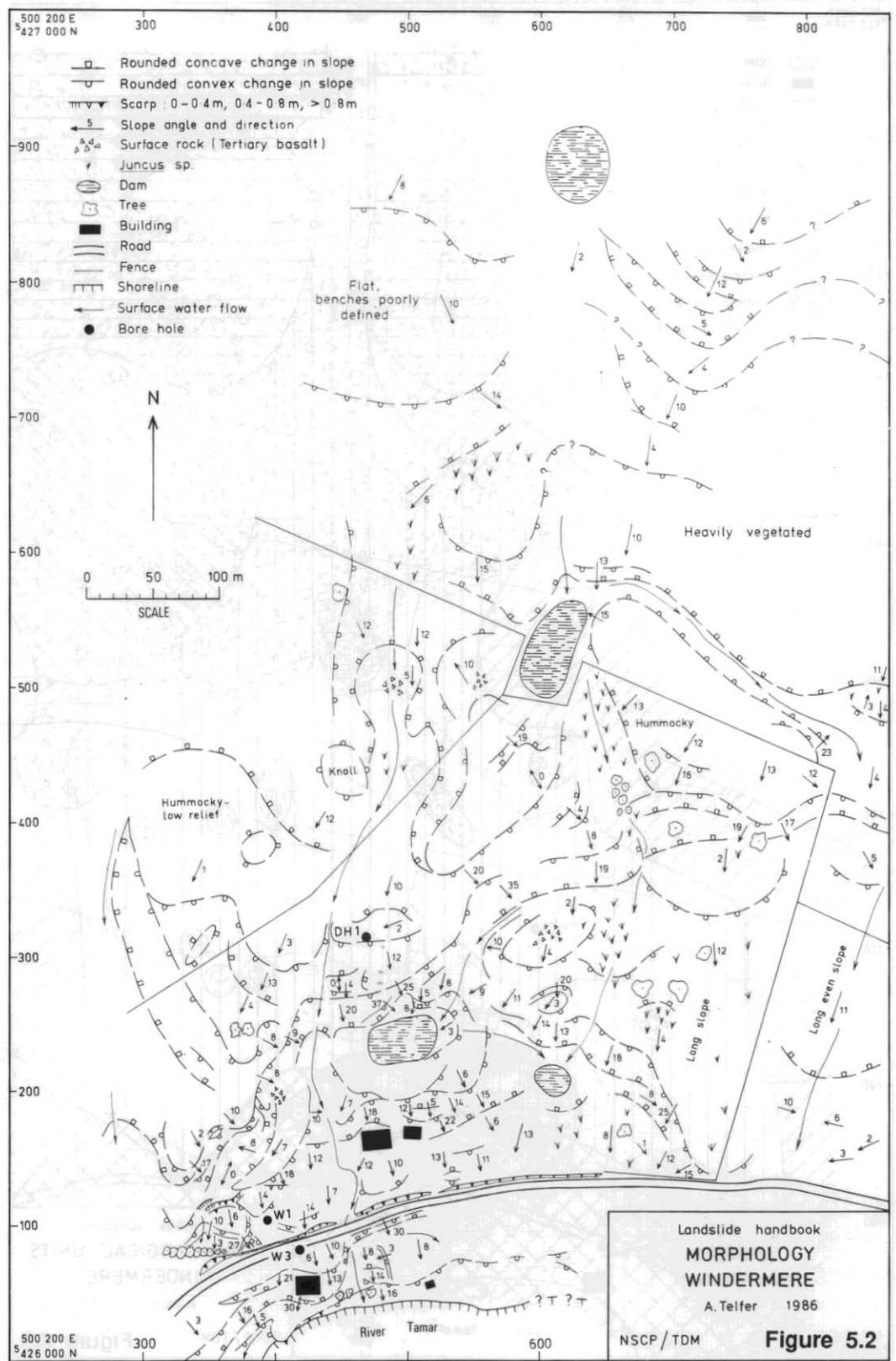
5.2 SURFACE INVESTIGATION

5.2.1 SITE INSPECTION

A house was destroyed on a river frontage allotment with a 13° slope at Windermere (fig. 5.2, EQ00422605). Opinions as to the cause of destruction included poor building practices, landslide activity, and expansive soil. When the author visited the site there remained only a 75-100 mm concrete slab from the floor of the garage, and the 2-3 m high brick retaining wall forming the rear of the garage and presumably supporting the house above. Neighbours testified that the garage was excavated after the house proper had been erected. A concrete drive on the western side of the house terminated at the shoreline, where now exists a 0.3 m high undercut river bank. A small retaining wall downslope from the house was tilted downslope.

The floor and wall showed the effects of the disturbance which had caused the destruction of the dwelling (figure 5.4). The floor had bulged upward some 100-300 mm, and the wall and





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MORPHOLOGY
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 NSCF/TDM **Figure 5.2**

associated pillars were extensively cracked. The magnitude of the destructive forces involved was demonstrated by the bisection of two of the pillars by vertical cracks. The width of the cracks was greatest at the base of the pillars.

The destruction appears to have been a gradual process with problems attributable to movements of the foundations occurring from the time of first occupation of the house. The house was not abandoned for several years.

During the site investigation it became apparent that the role of local geology in potential slope movement was poorly understood, and the scope of the investigation broadened to a determination of the geology, morphology and slope stability of the Quaternary alluvium (fig. 5.1).

5.2.2 PREPARATION OF A BASE MAP

The existing Tamar 1:100 000 topographic map is not detailed enough for use as a base map and although orthophotographs at a scale of 1:5000 are better, they still lack sufficient detail. Aerial photographs at 1:22 000 are useful for an overview of the morphology of the site and surrounds.

5.2.3 TOPOGRAPHY AND MORPHOLOGY

The Windermere slope has a southerly aspect. Slope angles range from zero to 37° with an overall slope angle of approximately 8°. The slope profile is hummocky and irregular, and slope reversals are not uncommon. Aerial photographs of the area show the surface morphology to be dominated by bulbous lobate forms some tens of metres across near their downslope extremity. This morphology is typical of a slope which has been modified by slope movements.

Examination of the environs of the destroyed building located a small scarp some 80 m north of the building (fig. 5.2, EQ04002613). The scarp is relatively recent, and the landowner is of the opinion that its formation roughly coincided with the destruction of the building. A convex morphology, characteristic of the toe of a landslide is apparent in the area bounded by W3, the shoreline, and points [EQ00402606], and [EQ00462607].

5.2.4 GEOLOGY

The site and adjacent areas fall on the western boundary of the Launceston sheet (Longman *et al.*, 1964) and the eastern boundary of the Frankford sheet (Gulline *et al.*, 1973) of the 1:63 360 scale Geological Atlas Series produced by the Tasmania Department of Mines. Figure 5.1 is a compilation of these maps drafted after consultation with the geologists responsible for the original mapping. The map shows a Tertiary basalt cap on part of Gaunts Hill, underlain by Tertiary clay, siltstone and lignite with quartzite gravels and ferruginous zones. A mantle of Quaternary basalt talus is mapped as overlying the Tertiary sediments over most of the problem area at Windermere.

Field inspections of the site and surrounds revealed that the published geologic maps are essentially accurate. Some fine white (SP) sand occurs immediately below the basalt on Gaunts Hill, while most of the near surface material is a high plasticity grey or mottled grey-brown to yellow-brown clay. Basalt blocks, boulders and cobbles shed from the top of Gaunts Hill mantle the upper slopes at Windermere, and basalt talus is common on or near the surface over the entire slope length.

Sutherland (1971) has mapped basalt flows below an elevation of 100 m within the area represented as Quaternary basal talus on Figure 5.1, however subsequent site investigations at various locations at Windermere (Knights, 1973; Matthews, 1976; Moore, 1981; Moore 1982; Stevenson, 1974) have failed to prove the location of *in situ* basalt at elevations below this level.

Inspection of the foreshore below the destroyed house [EQ00432604] revealed a contorted Tertiary sediment layer dipping steeply northward.

5.3 SUBSURFACE INVESTIGATION

5.3.1 DRILLING

Three shallow holes were drilled using augering methods to determine the near surface geology. W2 (abandoned) and W1 were drilled using a hand held Stihl auger while W3 was drilled with a trailer mounted Triefus auger. Figures 5.6 shows the geologic logs of the holes.

Hole W1 encountered 0.4 m of red-brown top-soil over high plasticity, yellow-brown to brown-grey (CH) clay to 5.4 m depth. A trace of fine sand was present in places. Hole W2 was abandoned due to drilling difficulties after passing through 0.4 m red-brown top-soil and 0.5 m grey and yellow-grey high plasticity (CH) clay. Hole W3 encountered 0.9 m of roadforming material over a yellow-brown (mottled grey) high plasticity (CH) clay to 3.0 m depth. Fine sand and gravel occurred between 3.0 and 4.2 m depth, with a soft, wet zone occurring between 4.0 and 4.2 m.

A diamond hole (WDH1) was drilled behind the suspected landslide (fig. 5.2) to determine the undisturbed stratigraphy and to look for aquifers which may contribute to slope instability; it encountered 7.5 m of basalt underlain by clay to 53 m. The clay is dark brown and carbonaceous with numerous coalified plant remains intercalated. Little or no sand occurs in the top 40 m of the hole, and only minor sand and clayey sand interbeds occur below this depth. There were approximately 1.2 m of core loss at the interface of the basalt and the clay. The drilling fluid washed out a quantity of montmorillonite rich clay aggregations from this interval. The clay and sandy clay sequence is of Middle or Late Early Eocene age (upper *M. diversus* zone or *P. asperopolus* zone - S. Forsyth pers. comm.).

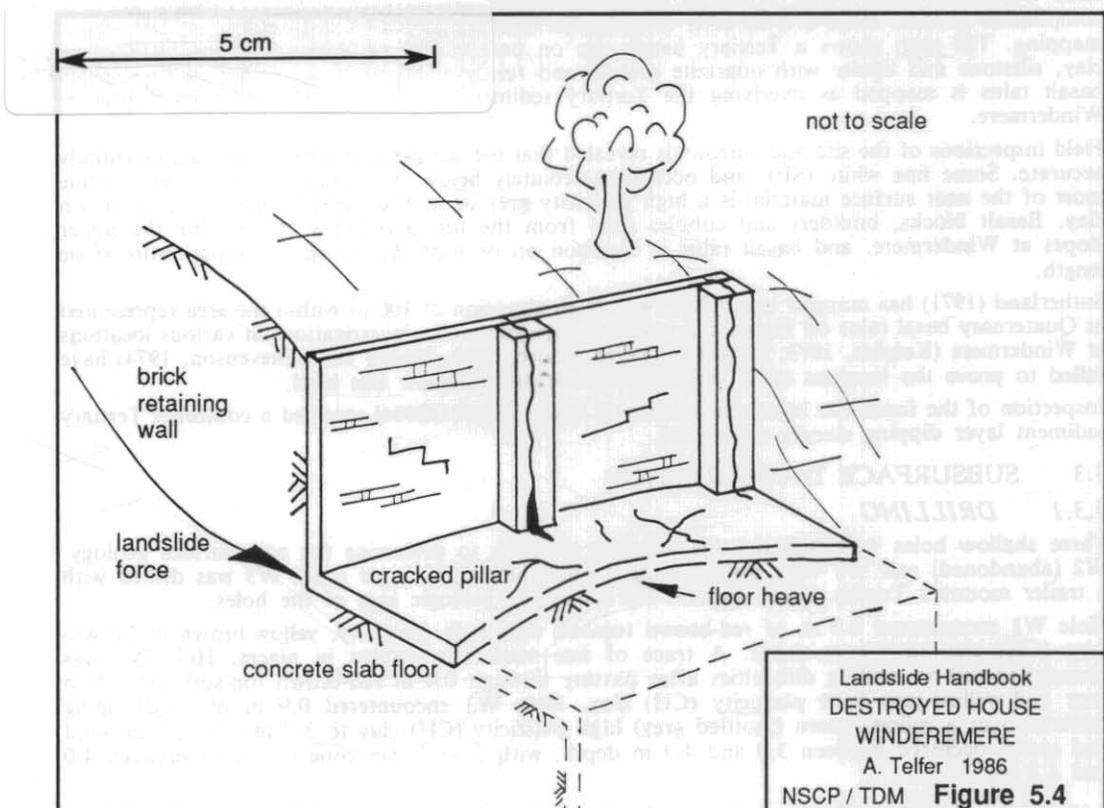
5.3.2 PIEZOMETERS

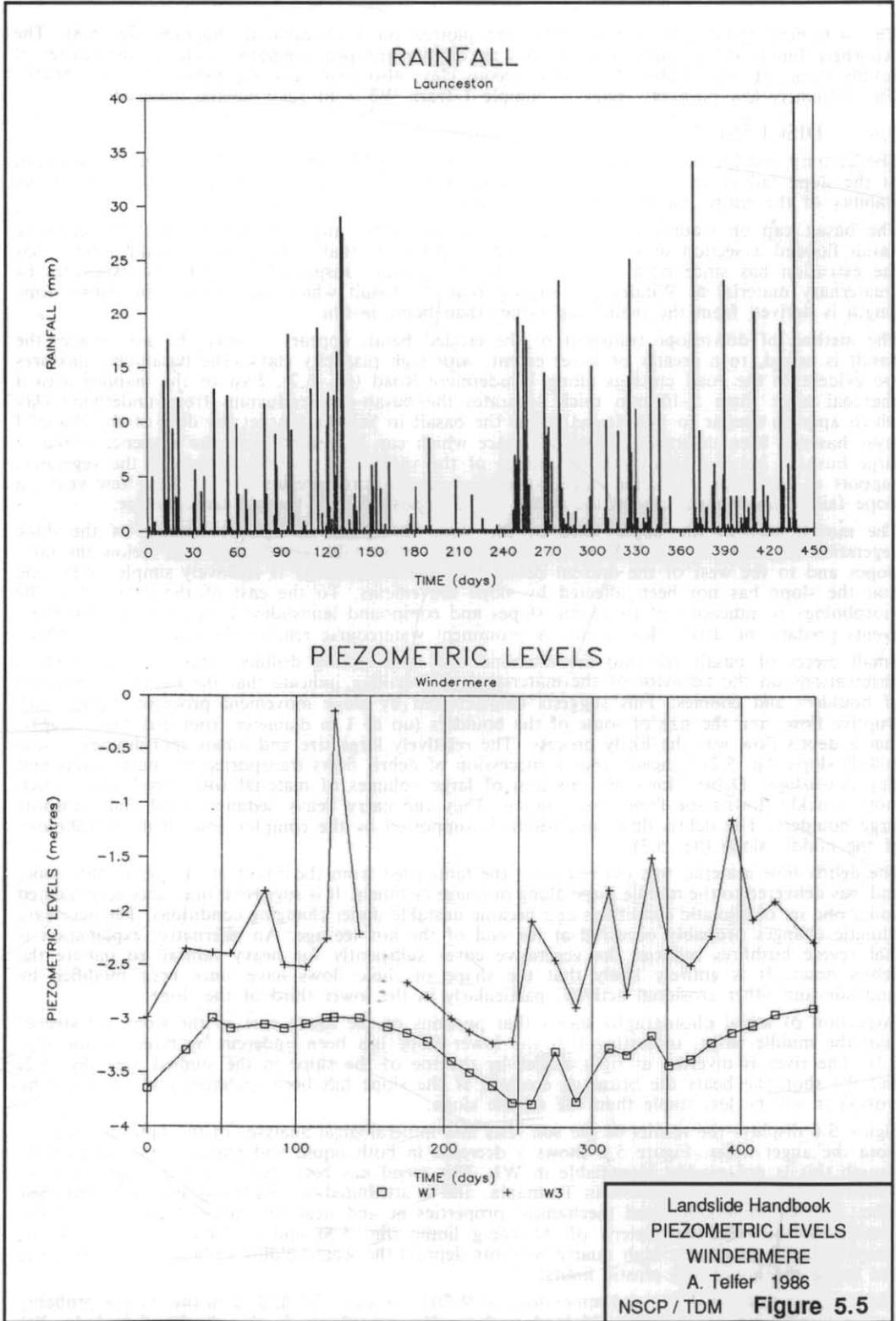
A piezometer was installed in WDH1 in the interval between 7.5 m and 8.6 m at the basalt-clay interface. The piezometer was rendered inoperative during installation. Operative piezometers are installed at the bottom of both W1 and W3. Water level measurements were recorded on a weekly to fortnightly basis from the 12 August 1985, and are compared with the rainfall records for Launceston over the recording period (fig. 5.5).

The piezometers were constructed in all cases from 20 mm UPVC, slotted and screened over a 300-450 mm interval which was positioned at the bottom of the hole (W1) or adjacent to the water-bearing layer (W3 and WDH1). The annulus between screen and hole wall was filled with gravel or sand and the hole sealed above the screened section to ensure that water levels in only one aquifer are measured.

5.3.3 SAMPLING AND TESTING

Samples of subsurface materials were collected from all holes drilled. All holes were logged, and all samples subjected to Atterberg tests and X-ray diffraction analyses to determine their plasticity characteristics and approximate mineralogical composition respectively. The test results from the three successful holes are plotted on figures 5.6 and 5.7. The mineralogy of the clays in WDH1 (fig. 5.7) between 7.5 m and 15 m is irregular, although deeper in the hole the mineralogy is relatively constant. A sample collected from the suspected failure zone of W3 was tested in a shear box, and the results of this and similar tests previously conducted on samples from the area were used in the slope stability analyses.





5 cm

The Atterberg test results for all holes are plotted on a Casagrande diagram (fig. 5.8). The Atterberg limits of the carbonaceous clays are tightly grouped compared with the scatter of results from the other holes. The carbonaceous clays also have generally lower plasticity indices. The extremely low plasticity index of sample 1 from W3 is of road-making materials.

5.4 DISCUSSION

The Tertiary and Quaternary geology the slope stability at Windermere, therefore an investigation of the slope failure at the site of investigation cannot be divorced from a consideration of the stability of the entire mapped Quaternary slope.

The basalt cap on Gaunts Hill is underlain by fine sand, and it is possible that the erupting basalt flooded a section of the ancestral Tamar River. If that is the case it would appear that the extrusion has since been reduced in size by erosion. Inspection of available exposures of Quaternary material at Windermere suggest that the basalt which occurs over the entire slope length is derived from the basalt cap rather than being *in-situ*.

The method of downslope transport of the eroded basalt appears to vary. In most places the basalt is mixed, to a greater or lesser extent, with high plasticity clays. The basalt-clay mixtures are evident in the road cuttings along Windermere Road (fig. 5.2). East of the mapped area a charcoal layer some 5-10 mm thick separates the basalt-clay colluvium from underlying clay which appears similar to that found below the basalt in WDH1. As yet the date of the charcoal layer has not been determined. One inference which can be drawn from the sequence is that a large bushfire burnt a significant percentage of the vegetation, thereby decreasing the vegetative support of the slope. At some stage postdating the bushfire, presumably within a few years, a slope failure mechanism caused the debris to be deposited over the old land surface.

The morphology of the upper third of the slope is difficult to analyse because of the thick vegetation (fig. 5.3). Rockfall from the basalt cliffs forms talus slopes (fig. 5.2). Below the talus slopes and to the west of the ancient debris flow the morphology is relatively simple, indicating that the slope has not been affected by slope movements. To the east of the debris flow the morphology is indicative of rotational slopes and compound landslides. It is proposed that these events predate the debris flow event. A prominent watercourse reaches the flanks of the talus.

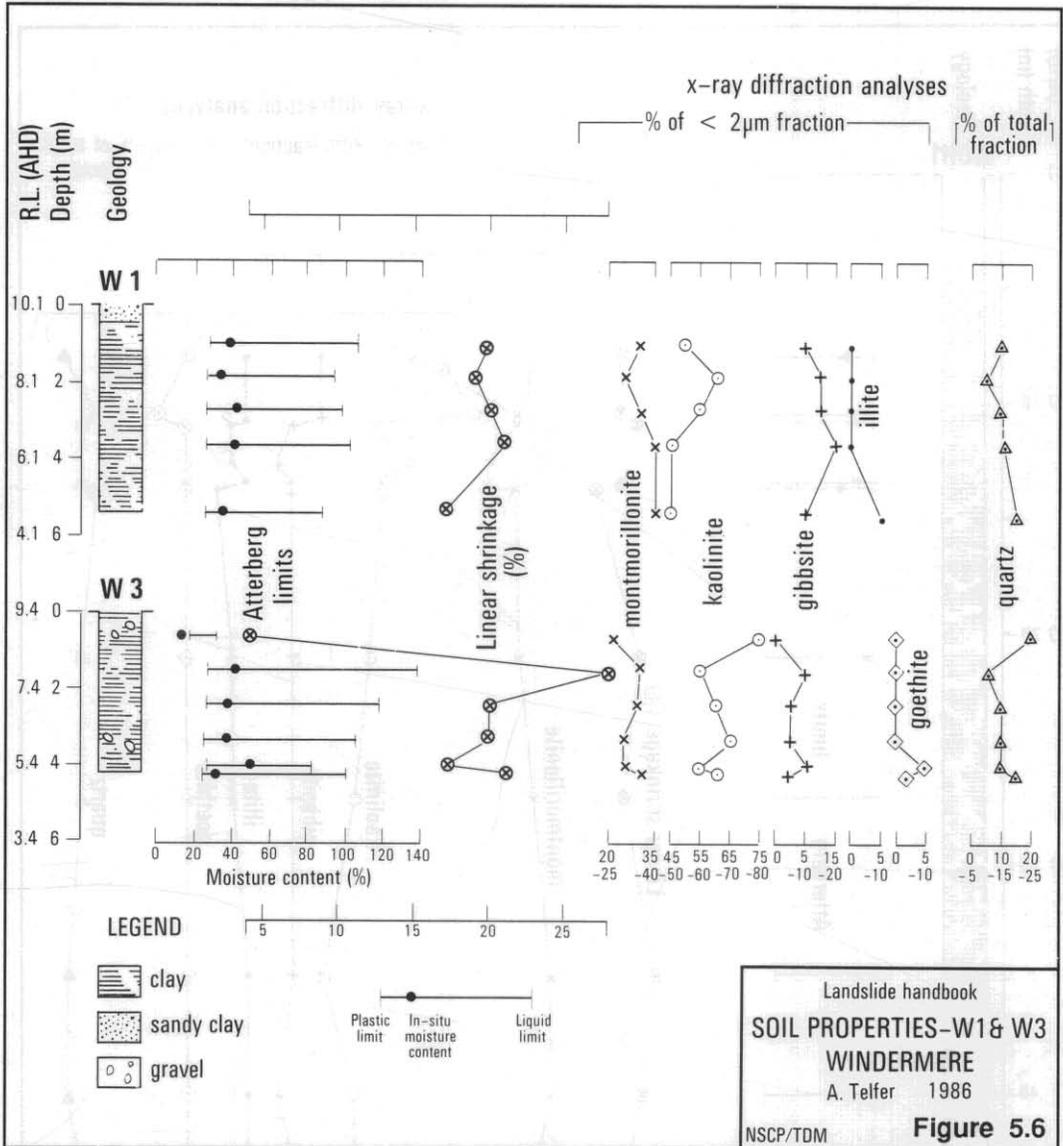
Small pieces of basalt fell into the diamond drill hole during drilling. This, and the driller's observations on the behavior of the material during drilling, indicate that the basalt is composed of boulders and cobbles. This suggests emplacement by slope movement processes rather than eruptive flow, and the size of some of the boulders (up to 1 m diameter from drill logs) suggest that a debris flow was the likely process. The relatively large size and lobate morphology of the middle slope (fig. 5.2) indicates that a succession of debris flows transported the basalt talus and clay downslope. Debris flows are mixtures of large volumes of material with some water which move quickly downslope from their source. They can carry heavy sediment load and transport large boulders. The debris flow supposition is supported by the complex and lobate morphology of the middle slope (fig. 5.2).

The debris flow material was derived from the talus shed from the basalt at the top of the slope, and was delivered to the middle slope along drainage channels. It is suggested that talus accumulated under one set of climatic conditions and became unstable under changing conditions. The necessary climatic changes probably occurred at the end of the last ice age. An alternative explanation is that severe bushfires reduced the vegetative cover sufficiently for heavy rainfall to initiate the debris flows. It is entirely likely that the shape of these flows have since been modified by landslide and other erosional activity, particularly in the lower third of the slope.

Inspection of aerial photographs shows that portions of the lower part of the slope are steeper than the middle slope, indicating that the lower slope has been undercut by river erosion (fig. 5.3). The river is diverted at right angles by the toe of the slope in the studied area (fig. 5.2) and the shoreline bears the brunt of erosion. If the slope has been undercut and steepened by erosion it will be less stable than the middle slope.

Figure 5.6 displays the results of the soil tests and mineralogical analyses of the samples collected from the auger holes. Figure 5.6 shows a decrease in both liquid and plastic limits with depth, though this is not readily identifiable in W1. This trend has been noted in many shallow holes drilled in clay at other locations in Tasmania, and is attributed to weathering processes and their effect on clay mineralogy and mechanical properties at and near the surface. There is a loose relationship between the pattern of Atterberg limits (fig. 5.8) and the quartz content of the samples (fig. 5.6) because high quartz contents depress the waterholding capacity of the material and hence the liquid and plastic limits.

The irregular soil properties and mineralogy of WDH1 between 7.5 and 12 m (fig. 5.7) is probably due to weathering beneath the old land surface. The irregularity is also displayed in holes W1 and W3 (fig. 5.6). This alteration of the mineralogy and soil properties is thought to exert some influence on the depth of failure planes. Most small landslides in Tasmania have failure planes

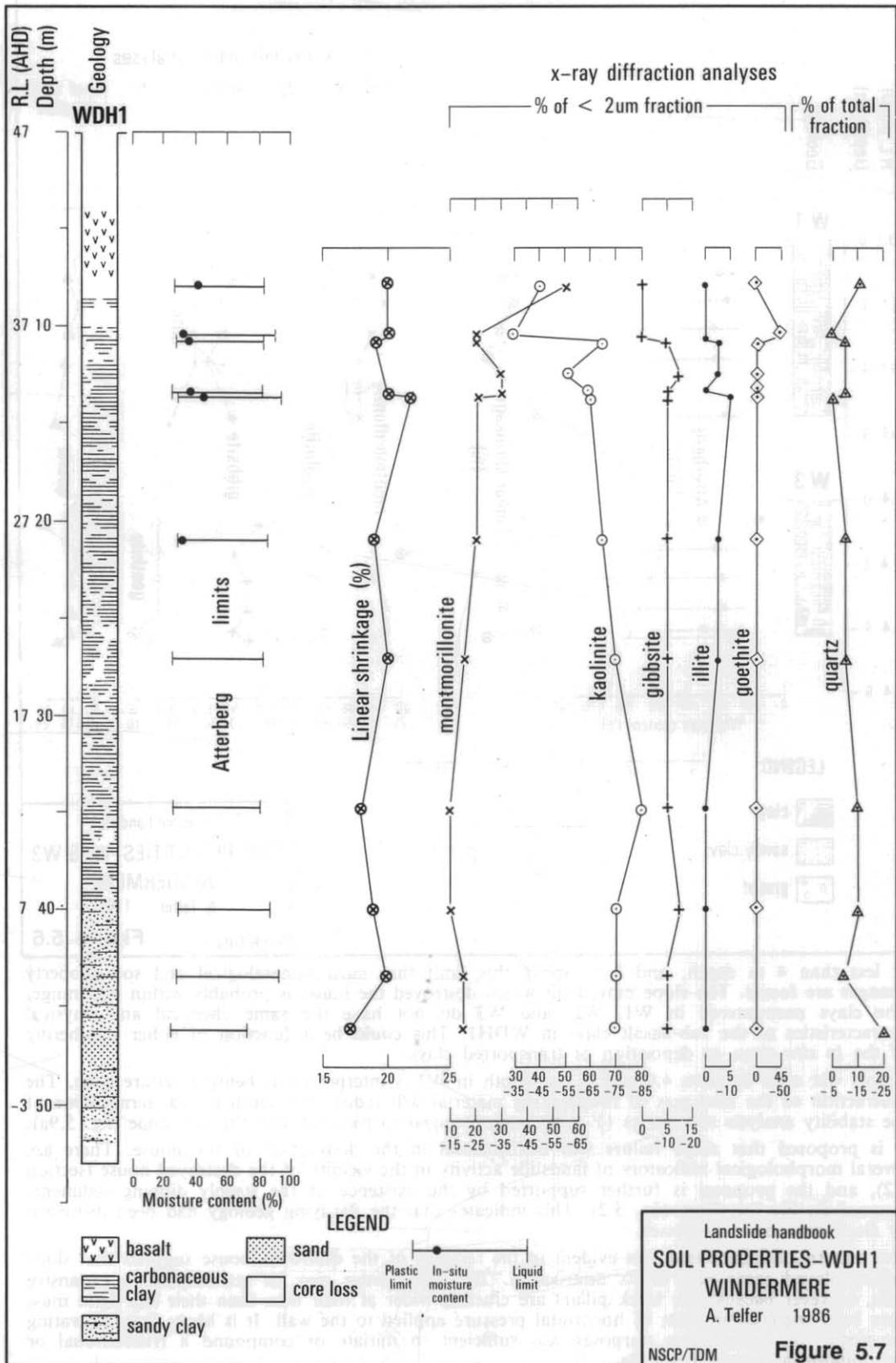
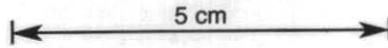


at less than 4 m depth, and it is above this limit that most mineralogical and soil property changes are found. The slope movement which destroyed the house is probably within that range. The clays encountered in W1, W2, and W3 do not have the same chemical and physical characteristics as the sub-basalt clays in WDH1. This could be a function of either weathering of the *in situ* clays or deposition of transported clays.

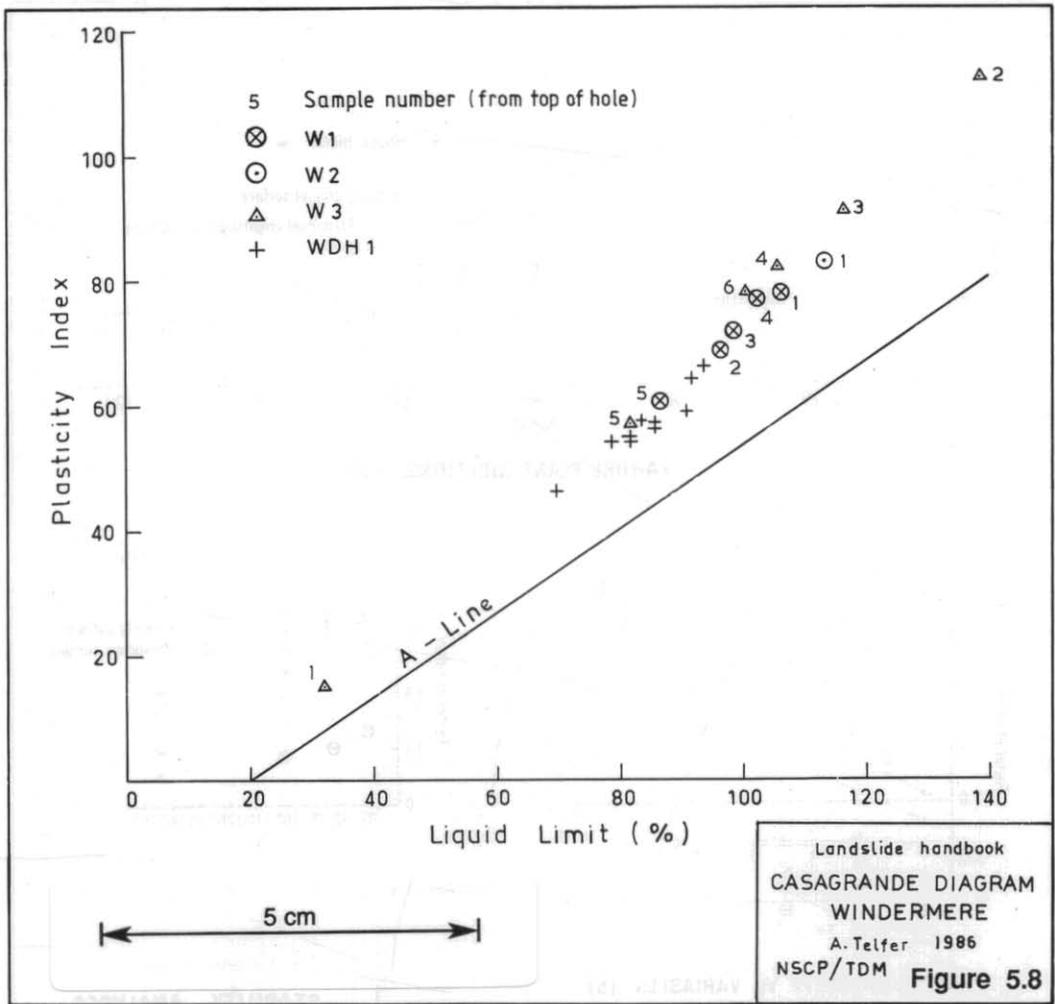
A soft wet zone between 4.0 and 4.2 m depth in W3 is interpreted as being a failure zone. The subtraction of the thickness of roadmaking material will reduce the depth in real terms. One of the stability analysis slip circles ($Y_c = 71$) is constructed to pass through the soft zone (fig. 5.9a).

It is proposed that slope failure was instrumental in the destruction of the house. There are several morphological indicators of landslide activity in the vicinity of the destroyed house (section 5.2), and the proposal is further supported by the existence of the steeply dipping sediments exposed on the foreshore (fig. 5.2). This indicates that the flat-lying geology had been disturbed by slope movement processes.

The pattern of failure that was evident in the remains of the destroyed house suggests that slope failure played some part in its destruction. The floor heave may be attributable to expansive soils, however because the brick pillars are cracked wider at their base than their top there must have been some component of horizontal pressure applied to the wall. It is likely that excavating the slope for construction purposes was sufficient to initiate or compound a translational or rotational-translational landslide.



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SOIL PROPERTIES-WDH1
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Figure 5.7



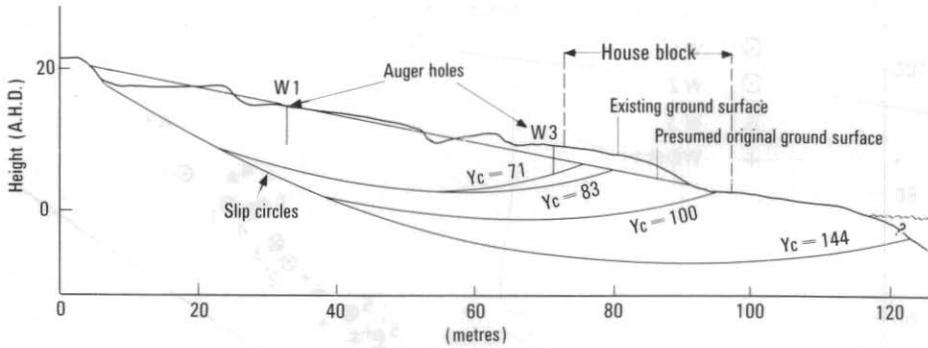
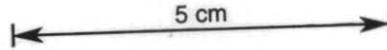
5.5 STABILITY ASSESSMENT

Mathematical stability analyses were performed to check the slope failure model. The cross-section runs between the shoreline below the destroyed house and [EQ00402614] (fig. 5.9a). Analyses for $Y_c=83$ and $Y_c=100$ were performed for both the existing ground surface and a presumed original surface of constant slope between the head scarp and the base of the toe. The analysis $Y_c=144$ was performed only for the existing ground surface and $Y_c=71$ only for the presumed surface. Figure 5.9c shows the changes in FS which result from the alteration of surface shape, and it can be seen that the existing surface gives a higher FS. This is to be expected because the slope movement has depleted the head and loaded the toe of the landslide.

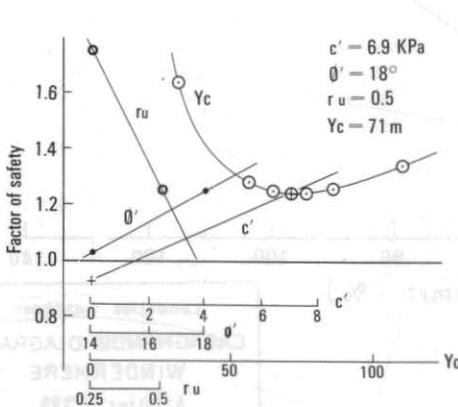
The slip circle considered most likely to represent the existing situation is $Y_c=71$. Here the failure plane daylights under the toe of the landslide and intercepts the softened zone in W3. The FS of the $Y_c=71$ slip circle is 1.26. This value is determined using the measured soil strengths from the softened zone in W3 ($c'=6.9$ kPa, $\phi'=18^\circ$) and assuming that the water level will reach the ground surface at failure. This assumption is justified since water levels have been measured at very close to this level (fig. 5.6).

This value of FS (1.26) demonstrates that the slope is only marginally stable, and examination of Figure 5.9b will show that small variations in the values of any of c' , ϕ' and r_u are sufficient to significantly decrease the FS value. Small variations of two or more parameters simultaneously can compound the decrease in FS.

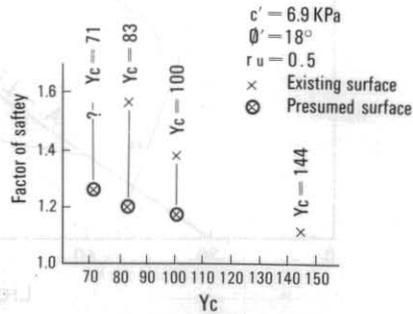
It can also be seen from Figure 5.9b that FS is very sensitive to changes in r_u , and that small artesian pressures would significantly contribute to slope destabilisation.



FAILURE PLANE LOCATIONS (a)



FACTOR OF SAFETY Vs. VARIABLES (b)



FACTOR OF SAFETY Vs. SURFACE SHAPE (c)

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STABILITY ANALYSES

WINDERMERE

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Figure 5.9

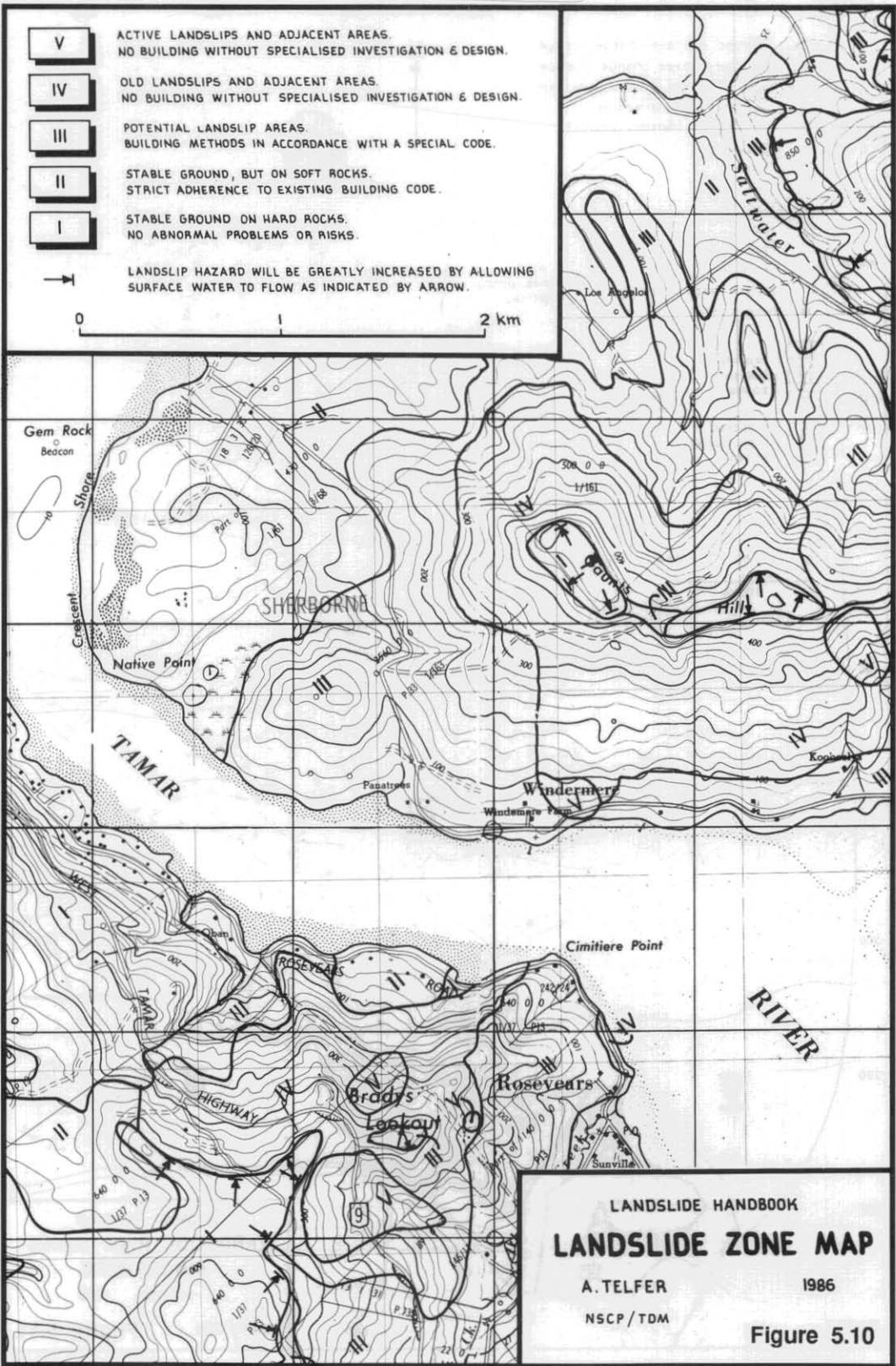
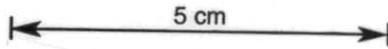
The stability analysis is an approximation of the real world. The location of the failure plane is not known with any certainty, however its shape and depth are unlikely to be as modelled. Experience has shown that most failures in Tertiary sediments in Tasmania have a roughly circular failure plane below the head scarp, merging into a planar or undulating shear zone parallel to the surface of the slide. The shear zone may be approximately circular near the toe.

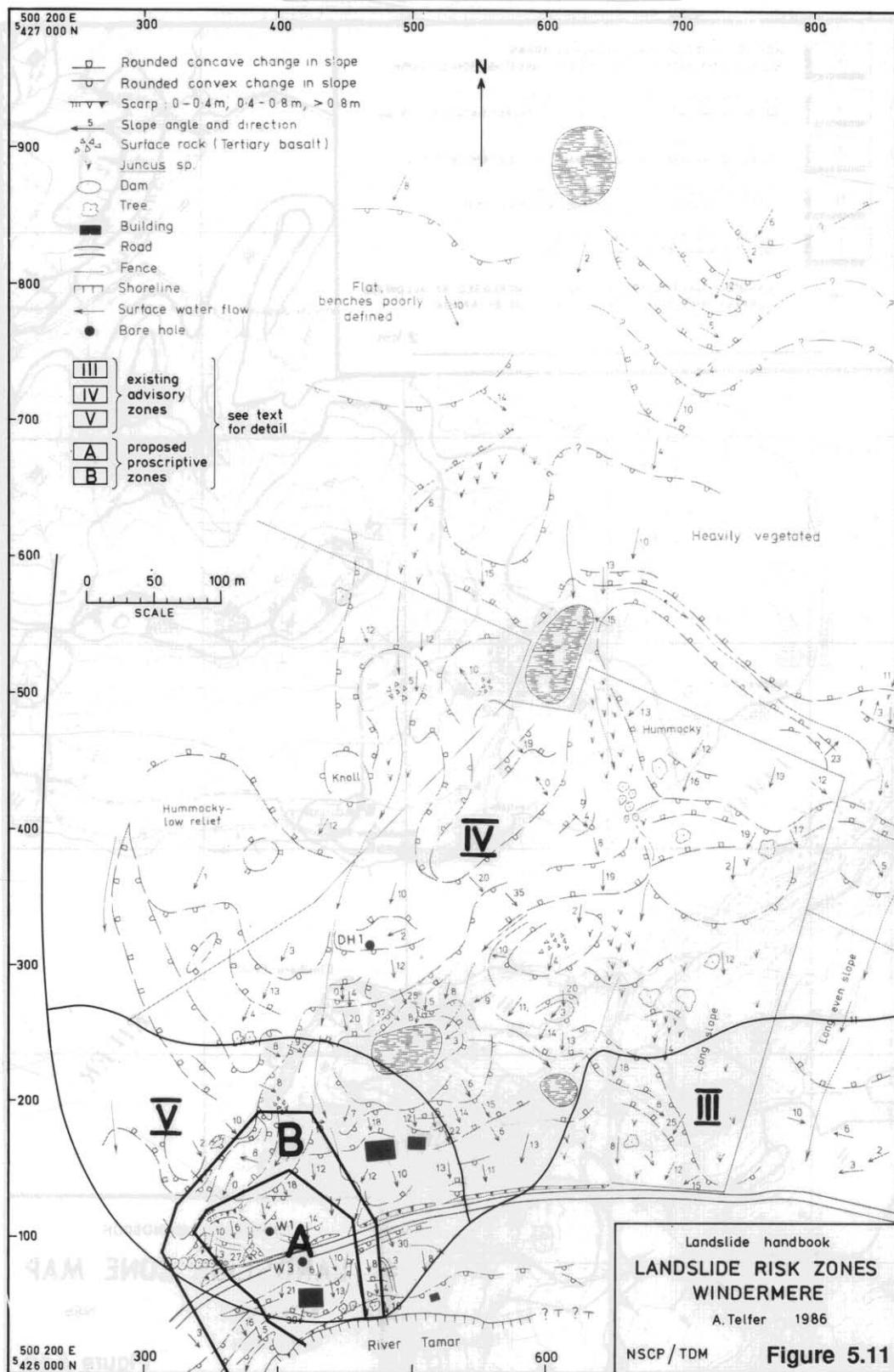
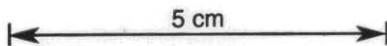
The road and its effect on drainage and slope integrity is not considered, nor are variations in slope material properties.

5.6 LEGISLATION AND ZONING

The Windermere area was zoned as part of the Tamar Valley Zone Maps (fig. 5.10). Figure 5.11 shows the location of the existing landslide zone boundaries superimposed on the morphological map. The investigations outlined above indicate that the Class III area should be rezoned as Class IV, because almost the entire slope appears to have been affected by slope movements in the past.

During the investigation the land parcel in question was bought by a member of the public, despite having been warned of the dangers. He intended to construct a house over the site of the destroyed house. The Tasmanian government has the legislative power to enable it to proclaim the area under Section 431A of the Local Government Act (1962), and it is proposed that this





be done. Figure 5.11 shows the proposed proscriptive zones A and B. While this may appear to impinge on the rights of individuals, it is the opinion of the Government that it is unwise and unsafe to place a dwelling on the block.

5.7 CONCLUSIONS

It appears that the slope at Windermere is mantled with a basalt-clay talus derived from the basalt cap at the top of the slope. It is the author's opinion that debris flow processes are responsible for the morphology of Figures 5.2 and 5.3. This opinion is based on the geology revealed in road cuttings and from samples retrieved from subsurface investigations, from inspection of surface morphology, and from aerial photograph interpretation. The lower third of the slope appears to have been undercut and oversteepened by the River Tamar.

The construction of the dwelling on the investigated site probably led to the reactivation of an old landslide originally caused by the undercutting of the slope. The reactivation of the slope appears to have destroyed the building, and the Government has proposed that the slope failure and adjacent areas be zoned as A and B landslip areas under Section 431A of the Local Government Act 1962 to prevent the construction of any dwelling on that site.

Slope stability and its prediction is not an easy task, and this case study provides an example of problems which may be faced and some of the methods of inspection and investigation applied by the author to the problem. It can be seen that the causes of instability in a slope are not always obvious, and that a qualified engineering geologist or geotechnical engineer is best equipped to deal with the range of geological and engineering influences likely to affect slope stability.

6 STATE LEGISLATION AND LOCAL GOVERNMENT

There are three facets of landslides and land use planning which must be considered by local government:

- (1) The acquisition and use of landslide zone maps to assist land use planning over large areas of landslide prone land facing pressure from closer settlement.
- (2) The assessment of the stability of land parcels identified by means of the zone maps as having a slope stability problem.
- (3) The judicious use of legislative powers to regulate the development of sites deemed unstable by the investigations of stage two.

6.1 ACQUISITION AND USE OF LANDSLIDE ZONE MAPS

Landslide zone maps are essential for effective land use planning in areas where land demonstrably prone to landslide activity faces pressure from closer settlement. The acquisition and use of landslide zone maps will ensure that such settlement does not promote slope instability. This will prevent acrimony from ratepayers when their investment is threatened or destroyed by slope failure.

The maps should be prepared before subdivision pressure develops so that land use plans can take into account the landslide potential of landslide prone regions. However, the identification of a need for the zone maps may be a slow process, and it will usually require the loss or threatened loss of a structure or structures before local government will recognise the need for action.

If it is recognised that slope stability is likely to be a land use problem then the local government will be well advised to seek the advice of professional geotechnical personnel. The first avenue of questioning should lead to the Engineering Geology Branch of the State Geological Survey (or its equivalent).

Landslide zone maps provide a quick and ready means of differentiating between those regions which can support denser settlement, those in which further development is possible if detailed assessments (usually of individual allotments (Section 6.2.2)) are favourable, and those which are unsuitable for settlement. It must be emphasised that each zone within a zone map encompasses land having not merely a single level of landslide hazard, but rather having a comparable range of hazards. Also, since lines on a map must be drawn somewhere, boundaries between zones are usually representative of gradational changes in landslide hazard. Hence caution must be exercised in stable land adjacent to the boundaries of unstable land.

Further study will be required where land is zoned as suspect so that subdivision layouts and densities can be designed to avoid unstable and potentially unstable areas. If blocks are created which are unsuitable for development then new owners have little option but to abandon the investment, sell to another unsuspecting buyer or embark on expensive remedial measures, the success of which is not guaranteed.

The zone maps should be made available to the general public as well as to local government authorities. Any attempt to restrict the circulation of the maps will alienate the general public and ratepayers and make the achievement of public acceptance of the system much more difficult.

The bottom line is that effective planning can neutralise the risk of slope failure and the destruction of property.

6.1.1 TAMAR VALLEY ZONE MAPS - A TASMANIAN EXAMPLE

The Tamar Valley in northern Tasmania is an elongate depression in which abundant clay with interbedded sand, gravel and basalt were deposited during the Tertiary period. The clay has a high strength when dry, but becomes plastic and is prone to failure when wet. The interbedded sand lenses act as localised aquifers which serve to keep the clay wet and can exert destabilising hydraulic pressures on the overlying materials. The Tertiary materials are underlain by older Permian mudstones and Jurassic dolerite.

The thickness of Tertiary sediment in the Tamar Valley was greater in the past than it is at present. The current fluvial system has eroded the Tertiary materials, and the banks of the river and some of its tributaries are quite steep. Landslides rarely occur in those parts of the Tamar Valley under natural vegetative cover, however stresses caused by deforestation, cut and fill operations, septic tank systems, alteration of drainage patterns etc. have reduced the stability of slopes, and in some cases this reduction in stability has been sufficient to cause the slopes to fail.

Several towns and cities are situated in the Tamar Valley. Launceston is located at the southern end of the River Tamar, and urban expansion of the city and other towns is encroaching on

land previously used for farming. Landslide zone maps are needed in the Tamar Valley because of the effect on land use planning of the combination of steep slopes, landslide prone subsurface materials, scenic views and urban expansion. Tertiary sediments form some steep slopes in Launceston, and sections of some of the smaller towns are built on steep slopes overlooking the river. Approximately 40 houses have been destroyed by slope movements between the early 1950s and 1974, however the preparation of the zone maps did not commence until the late 1960s. A provisional series of maps was produced to cover the Tamar Valley from Launceston northward to the coast, an area of over 800 km².

A five-tiered zoning system (table 6.1) was devised by Tasmania Department of Mines personnel. The five landslide zones were drafted onto existing 1:15 840 scale base maps after extensive field traversing and aerial photograph interpretation had delineated the slope classes and the zone boundaries. Figure 5.10 is a portion of one of these maps covering the Windermere area. This area has been discussed in some detail in Section 5.

Table 6.1

LANDSLIDE ZONES IN THE TAMAR VALLEY

Landslide Zone	Description	Potential Stability
Class I	Stable ground on hard rock	stable
Class II	Stable ground on engineering soils	stable
Class III	Potential landslip area	suspect
Class IV	Old landslips and adjacent areas	suspect
Class V	Active landslips and adjacent areas	unstable

Class I zone is restricted to sites underlain by rock of Permian or Jurassic age. The distinction between Class II (stable) and Class III (potentially unstable) land is based on slope angle criteria. The lowest recorded slope angle of an active landslide in Tertiary materials is 7°, and so slopes of less than 7° are zoned Class II and those greater as Class III. Those slopes which have a morphology indicative of past slope failure (see Section 6.2.2) are zoned Class IV, and active slope movements and adjacent areas are zoned Class V, irrespective of underlying geology.

The provisional zone maps have been distributed to the local government authorities involved, and have since been used extensively by them to determine the need for site assessments on the basis of their location within the zoning system. The maps are also freely available to interested parties, and have been sent on request to real estate agents, solicitors and State government authorities. The public have accepted the validity of the zone maps, and make frequent reference to them.

There is scope for the existing maps to be upgraded and refined. Orthophotographs are now available for the Tamar Valley at 1:5000 scale and are ideal for use as base maps because of their combination of topographic and photographic detail. The urban growth areas of the Tamar Valley have changed since the maps were first compiled, and revised maps would address the new problem areas and include minor revisions brought about by the continuing accumulation of information.

6.2 ASSESSMENT OF STABILITY OF PROBLEM AREAS

The aim of this publication is to provide local government authorities with sufficient background information on landslides to enable them to critically examine reports of slope stability assessments.

This section examines the processes which are commonly used to assess the stability of those problem areas which are identified as having the potential to develop slope stability problems with a change in land use. Stability assessments can range from quick, simple and cheap to lengthy, complicated and very expensive. Office research will almost always need to be supplemented by morphological or slope-class mapping and geological reconnaissance of the site and environs. Subsurface exploration will be needed where this level of assessment proves insufficient to determine the long-term stability of a land parcel. This third stage of assessment can become very expensive, and in some cases the cost of conducting the assessment will be greater than the benefit gained.

Reports on land parcel assessments should detail the work done, the results obtained and conclusions on site stability. If the site is proved to be marginally stable then recommendations of preventative and remedial measures should be presented.

These assessments should be conducted by engineering geologists or geotechnical engineers experienced in slope stability assessments and who, for preference, have an understanding of local conditions.

6.2.1 OFFICE RESEARCH

Researching available information is the first stage of a slope stability assessment. Research should include the examination of relevant geologic, topographic, and landslide zone maps, a literature search for any reports relevant to the site, and communication with co-workers and others to gain the benefit of their experience and local knowledge. In some cases the information gleaned at this stage will obviate the need for further work.

The examination of all available information, whether printed or oral, will give the assessor an overview of the setting of the site and may provide sufficient information on which to base a decision (Section 6.2.1.1). However, the information available will not usually be sufficient to enable a stability assessment to be made without visiting the site.

6.2.1.1 Case study - 180 Wilson Street, Burnie

Dear Sir,
180 WILSON ST, BURNIE

As the land at the above address is relatively flat, there is little risk of it being affected by landslip. It is situated on debris from ancient landslips that developed on the slopes behind but there are no known signs of this particular area becoming unstable in recent times.

Yours faithfully,
DIRECTOR OF MINES

6.2.2 FIELD INSPECTION AND MAPPING

Field inspection of the surface features of the site and adjacent areas is the second stage of a slope stability assessment. The inspection is aimed at obtaining information on slope angle, surface morphology, surface geology, and surface hydrology additional to that gleaned from the office assessment. Cultural features will be inspected for signs of slope movement. This information should be presented on a base map of suitable scale.

The benefits of mapping are twofold. Firstly, the characteristics of the site are distilled onto a small plan which can be examined for patterns not discernable on the ground or in published maps. Secondly, the mapping process forces the geotechnical engineer or engineering geologist to critically and systematically examine the area with a thoroughness which may not otherwise be achieved.

Land parcel inspection is relatively quick and inexpensive, and may provide sufficient information to enable the assessor to make a decision on the stability of the land parcel. Detailed surface morphology and slope classing are completed at this stage, however if the slope stability is still unresolved it may be necessary to consider subsurface investigations to obtain more information.

This stage of assessment will usually be adequate for determining subdivision density and layout planning, and for some individual land parcels.

6.2.2.1 Case study - Queechy Rd, Launceston

This study by W. R. Moore was originally issued as Unpublished Report 1984/78.

6.2.2.1.1 Introduction

The owner proposes to subdivide into two lots his block at 2 Queechy Road, Launceston [EQ143109]. The block is situated close to the junction of Penquite Road and Queechy Road, and is on the western section of the Queechy scarp. The block overlooks the lagoon and flood plain of the Kings Meadows Rivulet at its confluence with the North Esk River (fig. 6.1).

An examination of the block was undertaken on 27 September and 10 October and a preliminary report was written in October. This is the formal report requested for the council.

6.2.2.1.2 Slope Stability

Most of the block is very steep, with slopes of 20-25°, and is situated on the lower section of the 30 m high Queechy scarp. A sharp break in slope occurs at the foot of the slope, 10 m from the road along the eastern boundary of the block, where a 17° slope eases to 3°. The 17° slope is only short (11 m long). The slope then increases rapidly to 20° for the remainder of the eastern boundary of the block (fig. 6.2).

The relatively flat area adjacent to the road pinches out westwards and the slope of the western boundary is a uniform 20°, with only a 2 m wide low sloping (2°) area. It is on this flatter

section that the owner proposes to site the house on the eastern half of the subdivided block. The house is to be sited on a flat section 11 m wide with a slope of 5° . Siting the house in this position gives no stability problems, particularly as it is proposed to build a retaining wall at the rear of the house. A well-drained retaining wall would, by its weight and position at the toe of the slope, add to the stability of the steep slope.

Translational movement is known to have occurred on the steep section of the Queechy Road scarp causing minor cracking of the houses and their surrounds. In spite of the steepness of the slope, no major failures are known to have occurred along the western section of the scarp.

On the Tamar Valley Landslip Zone Map the proposed subdivision is shown as a Class III area, which is defined as a potential landslide zone (fig. 6.3). Even the low sloping $3-5^\circ$ area on which it is proposed to build the house is classified as Zone III. This classification should remain, even though the risk for this particular area is low. A major slope failure on the steep slope at the rear would damage a house on the proposed site. Therefore, by definition, this area should remain in the potential risk zone.

On the steep slope ($17-25^\circ$) of the subdivision the potential risk of failure is far greater. From other site investigations in this area, the old river terrace forming the Queechy scarp is capped with gravel, sand and silt. These river sediments have been deposited on Tertiary sediments (Launceston Beds), dominantly clay with minor soft sandstone beds or lenses (Longman, 1966). The clay of this area is highly plastic with a low shear strength. It is the minor sandstone beds or lenses within the clay, combined with the free-draining properties of the overlying river terrace gravel and sand, that are considered to give the higher slope stability to the Queechy-Sandown Road area than would otherwise occur if the Tertiary sediments were all clay (Moore, 1984).

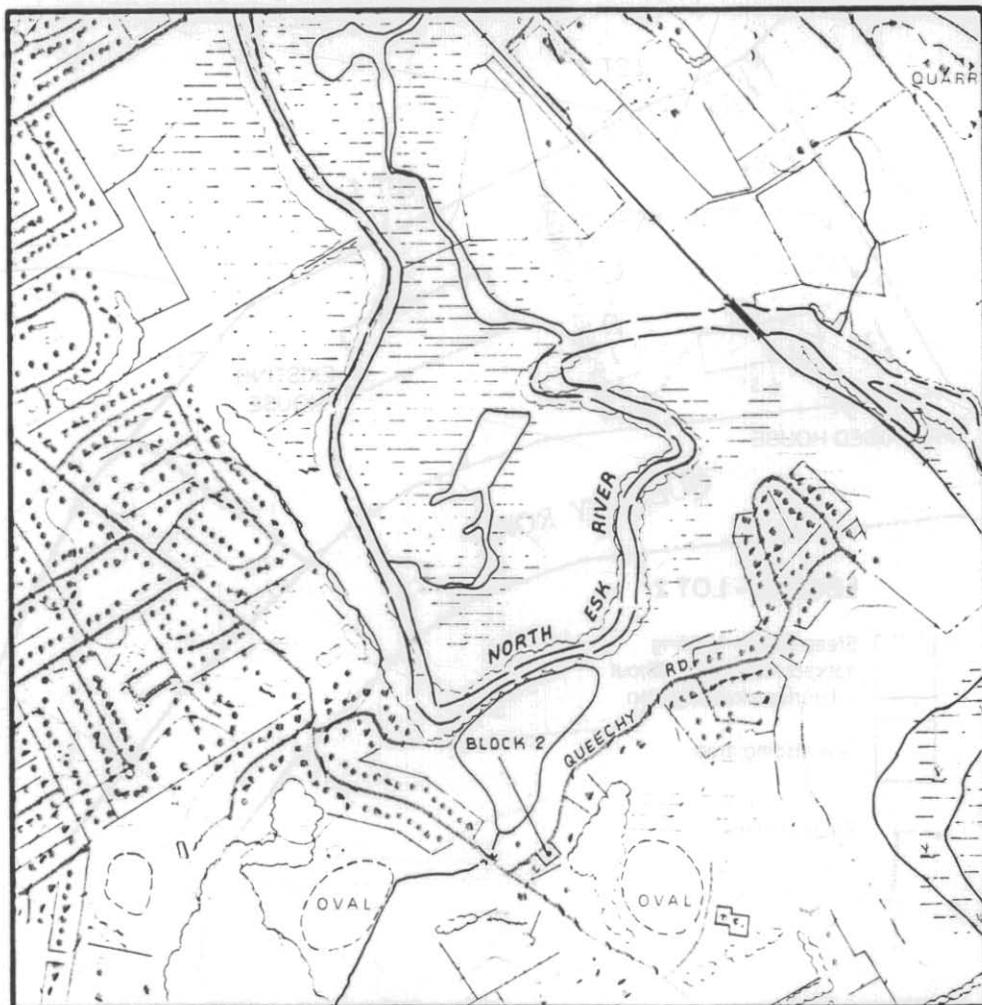


Figure 6.1 Location map of Queechy Road area.

5 cm

If building were to be permitted on this steep slope, a very detailed subsurface investigation would appear to be necessary to find out how much sandstone was present and the properties of the sediments. To consider building on the clay of the Launceston Beds where slopes were 20–25° would require long term shear box testing of the clay samples plus Atterberg Limits testing etc. The results of soil laboratory testing and subsurface investigation should be included in an accurate geological model of the slope for analysis (Moon, 1984a). The analysis should include all the Queechy scarp for possible failure, as well as the proposed subdivision slope (Moon, 1984b).

Such an investigation appears far too expensive for house building, and it would appear preferable to recommend that no building occur on the steep slope of this proposed subdivision.

6.2.2.1.3 Recommendations

- (1) A single house can be sited on the low sloping section of the subdivision adjoining the road.
- (2) No further building is recommended on the steep 20–25° slope area.
- (3) No undercutting of the toe of the slope to widen the proposed house site be permitted.
- (4) A retaining wall with adequate drainage provision be built at the back of the house on the toe of the steep slope.
- (5) The planting of trees and shrubs on the steep slope should be encouraged and any watering of these kept to a minimum.

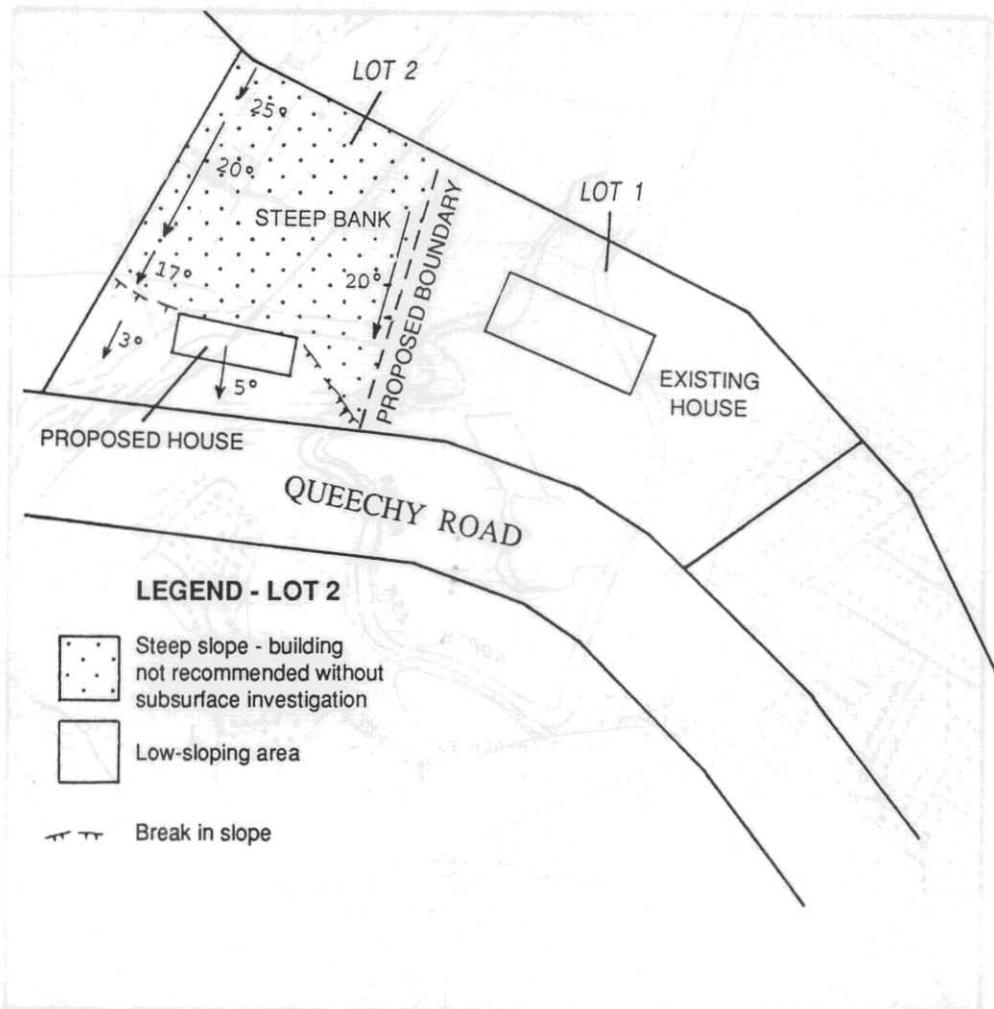


Figure 6.2 Sketch plan of proposed subdivision, Queechy Road, Launceston.

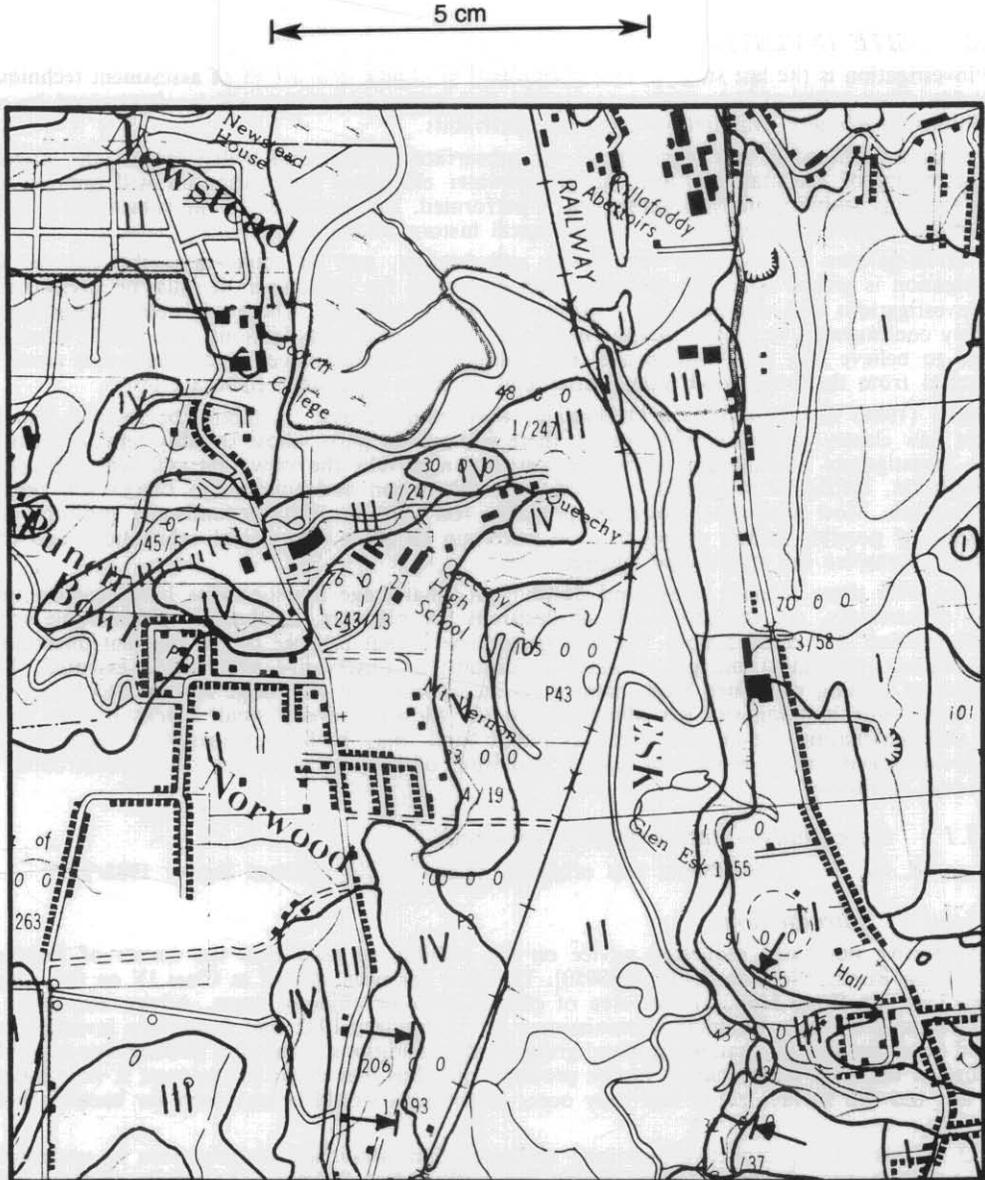


Figure 6.3 Landslip zone map, Queechy Road area.

- Zone V - Active landslips and adjacent areas.
No building without specialised investigation and design.
- Zone IV - Old landslips and adjacent areas.
No building without specialised investigation and design.
- Zone III - Potential landslip areas.
Building methods in accordance with a special code.
- Zone II - Stable ground, but on soft rocks.
Strict adherence to existing building code.
- Zone I - Stable ground on hard rocks.
No abnormal problems or risks.

6.2.3 SITE INVESTIGATION

Site investigation is the last stage of site assessment, and there is a wealth of assessment techniques available. The choice of investigative, sampling and testing techniques will be determined by site conditions, machinery availability, and cost constraints.

Information gathered at this stage about the subsurface geology and hydrogeology, the strength characteristics of the materials and the groundwater elevations and variations will improve the quality of any stability analyses subsequently performed. Interpretation of the subsurface geology will improve the understanding of the geological history of the site.

The investigations can become very costly and lengthy, and in some cases the cost of the investigation is greater than the perceived gain or loss to the landowner. It must be stressed that site investigations will not necessarily prove that a site is stable. There will remain sites whose stability continues to be suspect despite extensive geotechnical investigations. The public must not be led to believe that tests will 'prove' the stability of a land parcel, and landowners must be dissuaded from throwing good money after bad on more and more elaborate tests.

Willmott (1984) in a report to a Queensland shire council says: 'It should be realised that no matter how closely an area is investigated, there will remain parts whose stability remains suspect. Some investigators with an engineering background may take the view that sufficient subsurface investigation, testing of materials, mathematical calculation and foundation design will resolve the situation. Most geologists, however, probably feel that the likely groundwater pressures and positions of possible failure planes are too uncertain to allow meaningful calculation, and thus unlikely to resolve the stability of suspect areas.

'Dealing with these suspect areas, and deciding at what stage investigations have reached their limits of certainty, are the most difficult decisions for planners, as there is considerable scope for disputation and court action. The geological view is that because of the inherent uncertainty of subsurface geological and groundwater conditions, a conservative approach is essential. Two methods of dealing with such land, namely (1) incorporating it into large acreage blocks with at least one stable building site per allotment, or (2) allowing several small blocks on the stable sites and designating the suspect areas as public land, may both be appropriate depending on the circumstances, such as ease of access, provision of services, and ease of administration by the Local Authority'.

6.2.3.1 Case study—Station Road, Norwood

This study, by, W. L. Matthews, was originally issued as Unpublished Report 1982/21.

6.2.3.1.1 Introduction

A prospective purchaser requested advice on the stability of land near the corner of Penquite and Station Roads, Norwood [EQ15250950]. The land has been classed as Class IV on the Tamar Valley Landslip Zone Map, *i.e.* an area of old landslips or adjacent areas. Advice was given to the Town and Country Planning Commissioner on 13 January 1982 that subsurface investigations should be undertaken to examine soil and groundwater conditions at the site. Drilling was suggested because of the deep seated nature of the probable old slips that occur in the area; it was thought that any old slip surface zones that may occur in the area would be too deep for backhoe holes to reach.

On 23 February the prospective purchaser requested that subsurface investigations be undertaken and five holes were drilled (fig. 6.4) during the week ending 9 April. The results of these holes are given in Figure 6.6. As the holes were auger drilled, the logs must be regarded as only indicating the approximate levels of the various materials. These holes were used to select zones for taking undisturbed samples for strength measurements from further holes drilled nearby.

6.2.3.1.2 Relief and Geology

The proposed subdivision is situated on slopes formed between an elevated, relatively flat, terrace area and the flood plain of the North Esk River. Average slope angles directly beneath the terrace are up to 18°, with local slopes greater than 20°. The rear boundary of the proposed subdivision extends around the middle of this slope. At the foot of the slope the land surface flattens to about 6° over most of the subdivision, although near the south boundary there is a small area of internal drainage. The slope angles on the front of the lots towards Penquite Road increase to 10–12°.

The material underlying the subdivision is composed of Tertiary clay and sandy clay with minor fine-grained clayey quartz gravel horizons. The sand in some locations is composed mainly of quartz, while in others it has some quartz but is mainly of clayey material (possibly weathered feldspar grains). The terrace top has quartz gravel at some locations.

Table 6.2
RESULTS OF X-RAY ANALYSIS

Sample No.	Hole	Depth (m)	Montmorillonite	Illite	Kaolinite	Gibbsite	Quartz %	>63um
1	1	5.5-6.4	F			S		S
2	1	9.1-10.0	F		M		S	
3	2	6.7	F		F	F	F	
4	2	7.9-8.2	F?		M		S	30
5	3	2.7-3.7			M-S		M-S	
6	3	7.3-8.2	F		S		S	7
7	4	5.5-7.3	VF?		F-M		S	30
8	4	2.7-4.6	F		S		S	
9	5	0.9-1.8	F		S		S	
10	5	2.7-5.5	F?		S	M	VS	33
11	1	3.7	F		VS		VS	21
12	1	8.2	F?		S		VS	26
13	2	4.1-4.6	F?		S	S	M-S	18
14	3	4.6	F-M	F-Mt	S		S	
15	3	7.3	M	M	S		VS	

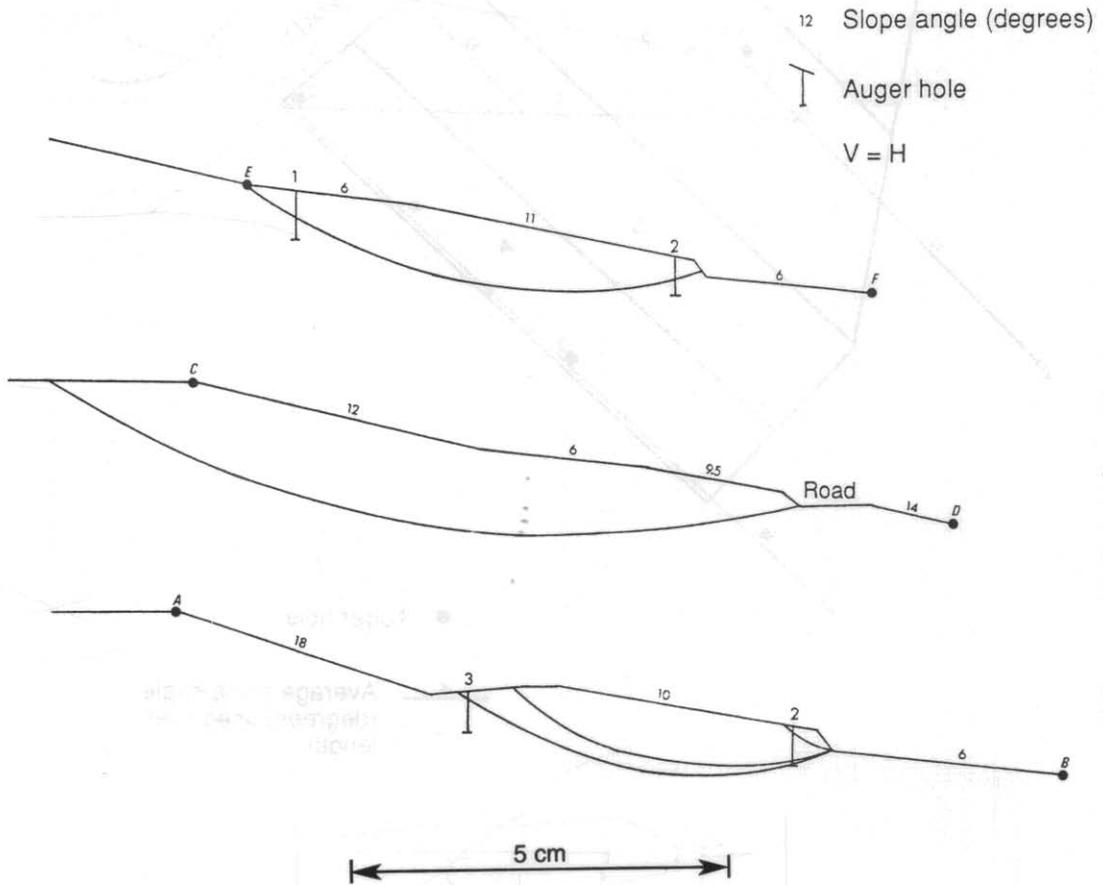


Figure 6.5 Cross sections used in stability analysis, showing possible slip circles used.

TASMANIA DEPARTMENT OF MINES

ENGINEERING LOG - BOREHOLE

borehole no. 1

sheet 1 of 1

penetration		support	water	notes samples, tests	metres		graphic log	classification symbol	material soil type: plasticity or particle characteristics, colour, secondary and minor components.	moisture condition	consistency density index	hand penetr- ometer kPa 25 50 750 200 400	structure, geology
1	2				3	RL							
project A.E. Wilkes' subdivision location Penquite Road, Norwood													
co-ordinates EQ15250950		drill type Proline auger drill		hole commenced -									
RL -		drill method -		hole completed -									
inclination Vertical		drill fluid -		drilled by -									
bearing -				logged by W.L.M.									
				checked by -									
							CL	Soil - silty clay, light grey. Underlain by clay, greenish brown	D	F			Soil
					1		CH						
							CL or CH	Sandy silty clay - brown, fragmented	M	S-F Fb			Unconsolidated Tertiary sediments
					2		CH CL	Silty clay - red and grey mottled, fragmented	M	S-F Fb			Unconsolidated Tertiary sediments
					3		CH CL	Sandy silty clay - red and grey, fragmented	M	S-F Fb			Unconsolidated Tertiary sediments
					4		CH CL	Sandy silty clay - light brown, fragmented, some quartz grit fragments in clay, occasional quartz pebbles up to 15 mm across	M	S-F Fb			Unconsolidated Tertiary sediments
					5								
					6		CH CL	Sandy silty clay, red, fragmented, some pebbles - may be contamination from ground above	W	S Fb			Unconsolidated Tertiary sediments
					7		CH CL	Sandy silty clay, brown fragmented occasional pebbles - may be contamination from gravel above.	W	S Fb			Unconsolidated Tertiary sediments
					8								
					9		CH CL	Sandy clay light grey, plastic	M	F			Unconsolidated Tertiary sediments
					10								

Figure 6.6 Engineering log of borehole 1.

5 cm

To give an indication of the quantity of material of sand size or greater some samples were sieved with a 63 μm screen to separate the silt and clay sizes from the larger fractions. Most of the material greater than 63 μm in each sample consists of quartz grains, mainly of fine sand size, together with small quantities of ilmenite and magnetite of similar size and a few larger limonite fragments.

6.2.3.1.3 STRENGTH TESTS

Because there is some doubt about the continued stability of the area, samples were selected for strength measurements. These measurements were performed in a shear box and approximate peak and residual values for angle of internal friction (ϕ) and cohesion (c) have been determined in each case.

Hole 1 (8.2 m depth)

$c'_p = 19 \text{ kPa}$	$\phi'_p = 24^\circ$
$c'_r = 13.6 \text{ kPa}$	$\phi'_r = 18.5^\circ$

Hole 2 (4.1-4.6 m depth)

$c'_p = 13.5 \text{ kPa}$	$\phi'_p = 23.5^\circ$
$c'_r = 7.11 \text{ kPa}$	$\phi'_r = 16.5-21^\circ$

6.2.3.1.4 Stability Analyses

Using the above information on factors of strength and a study of the plots used to obtain the above values, A. Moon of the Department of Mines undertook stability calculations. The residual values were used on the assumption that a slip surface may already exist. Plots of strength data are seldom perfect straight lines and a range of values for cohesion (down to 5 kPa) and a slightly lower angle of internal friction (16°) were used in the analyses. Two methods of analysis for sections CD and EF (fig. 6.5) were used - infinite slope and Cousins' stability charts. Calculations from the infinite slope method using the worst test results ($c' = 5 \text{ kPa}$ and $\phi' = 16^\circ$) and a high water level (one metre below the surface) show that the land along these sections is only marginally stable. Similar results are obtained using Cousins' stability charts. Stability becomes more certain with higher strength values and lower water levels.

Two methods of analysis were used for section AB - Bishop's simplified method and Cousins' charts. Again, analysis using Cousins' charts shows that for the lowest strength factors and the highest water levels, stability is only marginal, taking a large slip circle into consideration. Bishop's method for a similar slip circle and using similar strength values indicates that the area along this section could be stable.

Analysis of the steep cutting above Penquite Road shows an unstable situation if residual strength values are considered. It is probably inappropriate to use residual values in this case and if peak values are used, the stability situation is much better. Only small shallow slumps are likely in this area (as have occurred in the recent past).

6.2.3.1.5 Discussion of Stability

Using the results obtained from strength tests, the stability analyses show that with very high subsurface water levels, unstable conditions involving large sections of the land could occur. There is no record of the level the water table reaches during wet periods, but the highest water levels used in the analysis may not occur in practice or may only occur in extremely rare situations. It should be possible to decrease the chance of the water table rising to levels where the stability is endangered by ensuring good surface drainage and the cutting of french drains 2 m or more deep in three equally spaced locations down the slope (from the flattish area towards Penquite Road). If the water table can be kept to a low level, there is a greater likelihood that stability will be maintained.

Another factor that could influence stability is the removal of material from the slopes near the road. This material is helping maintain stability and any removal will increase the risk of instability over a large part of the subdivision.

6.2.3.1.6 Conclusions and Recommendations

Investigations show that the area could become unstable if water levels rise towards the surface. This assumes that a slip surface is already present (thus the use of residual strength values in the stability analyses) and that the surface passes through material of similar strength to that tested. Use of the higher values of residual strength determined from the strength tests suggests that the area should be stable. If no slip surface (from an old slip) exists, strength values approaching the peak values would be used in stability analyses and these would suggest stable conditions.

It cannot be said that there is no risk of landslip affecting the subdivision, but even taking the lowest possible strength factors indicated from the tests, measures can be taken to minimise the risk. This would involve drainage measures to ensure the water level does not approach the surface. Surface storage of water, such as in swimming pools from which leaks could occur, is not recommended.

Removal of material from the area immediately above Penquite Road should be avoided, as this will have a destabilising effect. If, as planned, access roads will be cut in this area, specially designed land drained retaining walls, which will provide the support that is removed, should be installed. An access road parallel to Penquite Road with an entrance to each lot would avoid excavations and steepening of existing slopes.

If the lots are developed, houses should be sited on the flatter portions away from the steeper slopes. Lot 1 takes in some of the steeper land with only a narrow flat area along the northern boundary. A house on this lot, as outlined at present, would only be recommended near Penquite Road and on the most northerly part. Here a house would be far enough from the steep slope so as not to be affected in the event of a landslip occurring. An alternative would be to move the boundary of the lot 15-20 m to the north; it should then be possible to safely build a house on low sloping land at any point over the whole length of the northern boundary.

The presence of montmorillonite in the clay suggests that the clay may have expansive properties as in some other parts of the Tamar Valley. Foundations of houses should be designed so that the effects of drying and wetting are reduced. This is usually achieved by extending the foundations to depths where these fluctuations are only small.

In conclusion, although some risk exists of unstable conditions developing, with the above precautions, it should be possible to reduce this to an acceptable level to allow development to proceed.

6.2.4 REPORTING RESULTS

This is the final stage of site assessment, and it is that part of the assessment with which local government is most often involved.

All information on which recommendations are based should be presented so an independent assessment of the results can be made. The report should present the methods and results of all work carried out, and should include copies of maps, geological and hydrogeological logs, strength test results, and the values used for any stability analyses. The conclusions reached should be supported by reasoning based on site observation and test results.

In many cases building applications are granted conditional to the landowner conforming to a number of preventative and remedial measures to control and improve slope stability. The measures outlined may include foundation and house design, drainage system and septic tank layouts, limitations on the height of cut and fill operations, banning in-ground pools, planting of water adsorbing trees, retention of native or existing vegetation and modest garden watering schemes.

6.3 SUGGESTED BUILDING PRACTICES

Table 6.3 and Figure 6.7 are reproduced from Walker *et al.* (1985). The paper was written specifically for the Newcastle-Sydney-Wollongong area, but the information reproduced here is more widely applicable.

The guidelines of Table 6.3 are to be considered as such, as each site will have its own particular problems.

6.4 LEGISLATION

There is no coherent policy addressing the landslide problem in Australia. Each State has formulated a system which works within the public and legal constraints of that State. Most States have legislative powers vested in one or another level of government which can be used to prevent the construction of habitations on land parcels deemed to be unsafe. Consultants, landowners and local government authorities have to address the problem of legal liability in slope stability assessments.

The following section outlines the use of zone mapping, site inspection and legislative powers employed in each Australian State.

6.4.1 TASMANIA

Tasmania has a large landslide problem despite the fact that individual landslides are usually relatively small.

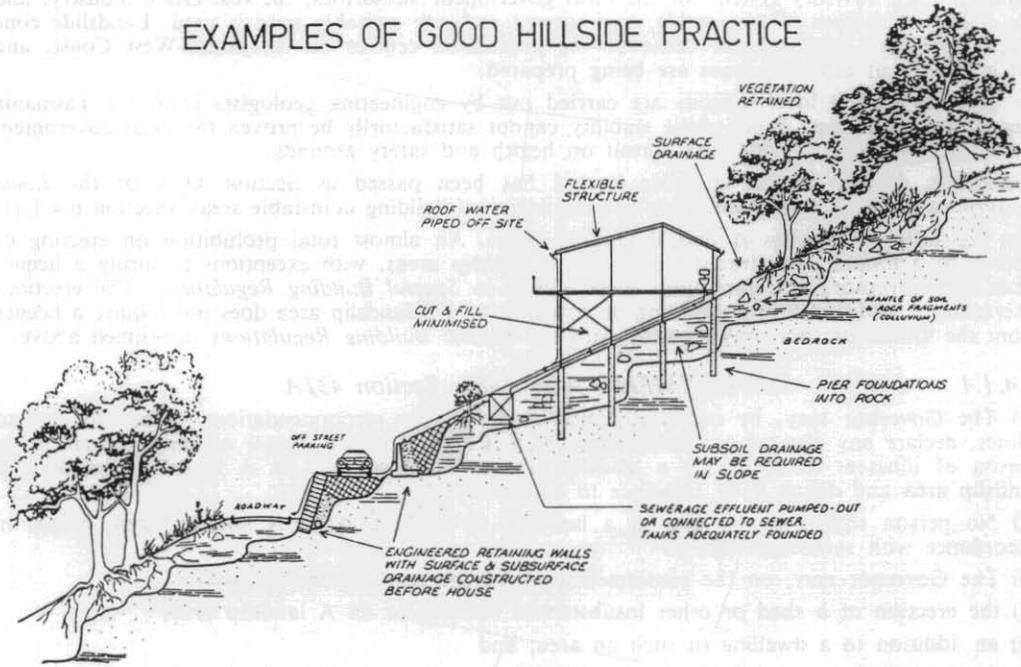
Landslide zone maps have been used in the Tamar Valley since their compilation by the Tasmania Department of Mines in the 1970s. The maps cover an area of over 800 km², providing a

Table 6.3
SOME GUIDELINES FOR HILLSIDE CONSTRUCTION

	GOOD ENGINEERING PRACTICE	POOR ENGINEERING PRACTICE
ADVICE		
GEOTECHNICAL ASSESSMENT	Obtain advice from a qualified, experienced geotechnical consultant at early stage of planning and before site works.	Prepare detailed plan and start site works before geotechnical advice.
PLANNING		
SITE PLANNING	Having obtained geotechnical advice, plan the development with the Risk of Instability and Implications for Development in mind.	Plan development without regard for the Risk of Instability.
DESIGN AND CONSTRUCTION		
HOUSE DESIGN	Use flexible structures which incorporate properly designed brickwork, timber or steel frames, timber or panel cladding. Consider use of split levels. Use decks for recreational areas where appropriate.	Floor plans which require extensive cutting and filling. Movement intolerant structures.
SITE CLEARING	Retain natural vegetation wherever practicable.	Indiscriminately clear the site.
ACCESS & DRIVEWAYS	Satisfy requirements below for cuts, fills, retaining walls and drainage. Council specifications for grades may need to be modified. Driveways and parking areas may need to be fully supported on piers.	Excavate and fill for site access before geotechnical advice.
EARTHWORKS	Retain natural contours wherever possible.	
CUTS	Minimise depth. Support with engineered retaining walls or batter to appropriate slope. Provide drainage measures and erosion control.	Large scale cuts and benching. Unsupported cuts. Ignore drainage requirements.
FILLS	Minimise height. Strip vegetation and topsoil and key into natural slopes prior to filling. Use and compact clean fill materials. Batter to appropriate slope or support with engineered retaining wall. Provide surface drainage and appropriate subsurface drainage.	Loose or poorly compacted fill. Block natural drainage lines. Fill over existing vegetation and topsoil. Include stumps, trees, vegetation, topsoil, boulders, building rubble etc in fill.
ROCK OUTCROPS & BOULDERS	Remove or stabilise boulders which may become unstable. Support rock faces where necessary.	Disturb or undercut detached blocks or boulders.
RETAINING WALLS	Engineer design to resist applied soil and water forces. Found on rock where practicable. Provide subsurface drainage within wall backfill and surface drainage on slope above. Construct wall as soon as possible after cut/fill operation.	Construct a structurally inadequate wall such as sandstone flagging, brick or unreinforced blockwork. Lack of subsurface drains and weepholes.
FOUNDATIONS	Support on or within rock where practicable. Use rows of piers or strip foundations oriented up and down slope. Design for lateral creep pressures. Backfill foundation excavations to exclude ingress of surface water.	Found on topsoil, loose fill, detached boulders or undercut cliffs.
SWIMMING POOLS	Engineer designed. Support on piers to rock where practicable. Provide with under-drainage and gravity drain outlet where practicable. Design for high soil pressures which may develop on uphill side whilst there may be little or no lateral support on downhill side.	
DRAINAGE		
SURFACE	Provide at tops of cut and fill slopes. Discharge to street drainage or natural water courses. Provide generous falls to prevent blockage by siltation and incorporate silt traps. Line to minimise infiltration and make flexible where possible. Special structures to dissipate energy at changes of slope and/or direction.	Discharge at top of fills and cuts. Allow water to pond on bench areas.
SUBSURFACE	Provide filter around subsurface drain. Provide drain behind retaining walls. Use flexible pipelines with access for maintenance. Prevent inflow of surface water.	
SEPTIC & SULLAGE	Usually requires pump-out or mains sewer systems; absorption trenches may be possible in some low risk areas. Storage tanks should be water-tight and adequately founded.	Discharge sullage directly onto and into slopes.
EROSION CONTROL & LANDSCAPING	Control erosion as this may lead to instability. Revegetate cleared area.	Failure to observe earthworks and drainage recommendations when landscaping.
DRAWINGS AND SITE VISITS DURING CONSTRUCTION		
DRAWINGS	Building Application drawings should be viewed by geotechnical consultant.	
SITE VISITS	Site Visits by consultant may be appropriate during construction.	
INSPECTION AND MAINTENANCE BY OWNER		
OWNER'S RESPONSIBILITY	Clean drainage systems; repair broken joints in drains and leaks in supply pipes. Where structural distress is evident seek advice. If seepage observed, determine cause or seek advice on consequences.	

(from Walker *et. al.*, 1957)

EXAMPLES OF GOOD HILLSIDE PRACTICE



EXAMPLES OF POOR HILLSIDE PRACTICE

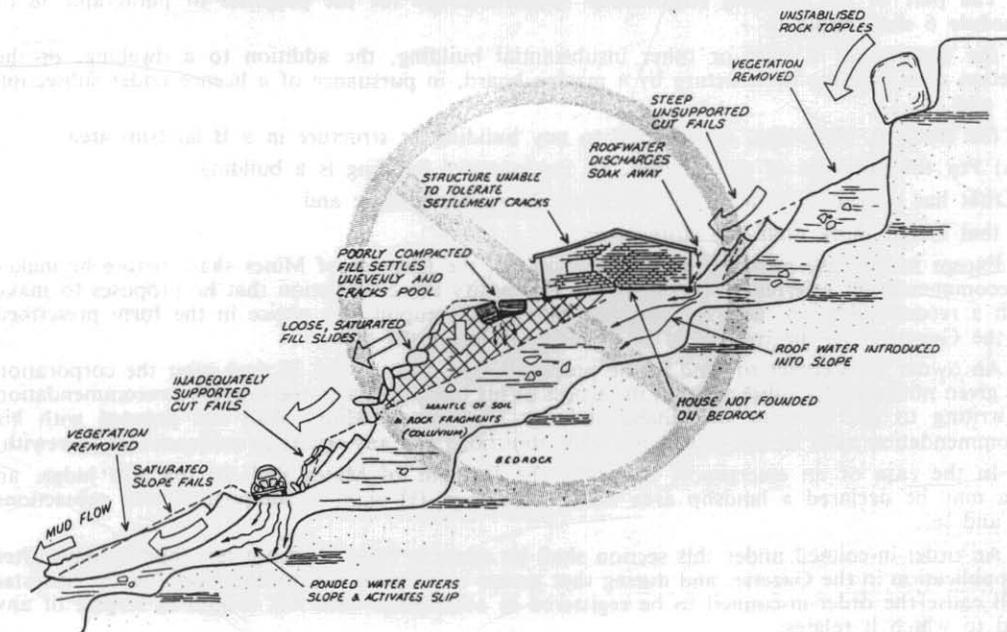


Figure 6.7 Illustrations of good and poor hillside practice (from Walker *et al.*, 1985).

regularly used advisory system for the local government authorities, the real estate industry, and the public. A system of two stable, two suspect and one unstable zone is used. Landslide zone maps have been prepared for some of the population centres on the North-West Coast, and further maps of adjacent areas are being prepared.

At present, all site investigations are carried out by engineering geologists from the Tasmania Department of Mines. When slope stability cannot satisfactorily be proven the local government authorities withhold the building permit on health and safety grounds.

Legislation specific to the landslide hazard has been passed as Section 431A of the *Local Government Act 1973* as 'Prohibition and regulation of building in instable areas' (Section 6.4.1.1).

The legislation recognises A and B landslip areas. An almost total prohibition on erecting or adding to a building or structure exists in A landslip areas, with exceptions requiring a licence from the Governor. The exceptions must adhere to *Special Building Regulations*. The erection, alteration or addition to any building or structure in a B landslip area does not require a licence from the Governor, but must comply with the *Special Building Regulations* mentioned above.

6.4.1.1 LOCAL GOVERNMENT ACT 1962, Section 431A

- (1) The Governor may, by order-in-council made on the recommendation of the Director of Mines, declare any area of a municipality which is subject to the danger of earth movement by reason of inherent instability as a landslip area to be known as an A landslip area or a B landslip area and define it by reference to a plan.
- (2) No person shall erect or add to a building or structure in an A landslip area, except in accordance with subsection (3).
- (3) The Governor may, on the recommendation of the corporation, license -
 - (a) the erection of a shed or other insubstantial building in an A landslip area;
 - (b) an addition to a dwelling in such an area; and
 - (c) the erection by a marine board of a building or structure within the boundaries of a wharf in such an area (being a building or structure that is subject to the Building Regulations pursuant to section 459A).
- (4) The part of the Building Regulations which is made for the purposes of paragraph 38 of Schedule 6 shall apply to -
 - (a) the erection of a shed or other insubstantial building, the addition to a dwelling, or the erection of a building or structure by a marine board, in pursuance of a licence under subsection (3); and
 - (b) the erection, alteration, or addition to any building or structure in a B landslip area.
- (4A) For the purposes of this section, an insubstantial building is a building -
 - (a) that has a total floor area not exceeding 25 square metres; and
 - (b) that is not more than one storey high.
- (5) Except in the case referred to in subsection (7), the Director of Mines shall, before he makes a recommendation referred to in subsection (1), notify the corporation that he proposes to make such a recommendation, and the corporation shall thereupon give notice in the form prescribed by the Governor to the owners of all land in the proposed area.
- (6) An owner or occupier of land in the proposed area may, within 30 days after the corporation has given notice under subsection (5) in respect of his land, object to the proposed recommendation in writing to the Director of Mines, and the Director of Mines shall not proceed with his recommendation until he has considered such objections and any report or evidence sent therewith.
- (7) In the case of an emergency, of which the Director of Mines shall be the sole judge, an area may be declared a landslip area under subsection (1) without compliance with subsections (5) and (6).
- (8) An order-in-council under this section shall be made to take effect not less than 30 days after its publication in the Gazette, and during that period or as soon as possible thereafter the Minister shall cause the order-in-council to be registered in accordance with this section in respect of any land to which it relates.
- (9) The registration of an order-in-council in respect of any land is effected -
 - (a) if the land is land under the *Real Property Act 1862*, as provided by subsection (10); or
 - (b) if the land is not land under the *Real Property Act 1862*, by causing the order-in-council to be registered under the *Registration of Deeds Act 1935*, as if it were an instrument to which the Minister is a party.

(10) Where any land affected by an order-in-council is under the *Real Property Act 1862*, the Minister shall lodge with the Recorder of Titles a copy of the order-in-council, accompanied by a statement signed by the Minister specifying the titles affected thereby; and thereupon the Recorder of Titles shall record particulars of the order-in-council upon those titles, and the order-in-council shall be deemed to be registered for the purposes of this section.

(11) Where an order-in-council is recorded upon the title to land under the *Real Property Act 1862*, the order-in-council shall be deemed to be an encumbrance for the purposes of section 40 of that Act.

(12) Subsection (10) does not apply to land that is not subject to the *Real Property Act 1862* and has not been conveyed or alienated for a legal estate by or on behalf of the Crown and registration of an order-in-council in respect of any such land is effected by endorsement of a certified copy of that order-in-council with a certificate signed by or on behalf of the Commissioner of Crown Lands stating that the order-in-council has been registered under this section.

(13) Where an order-in-council has been registered under subsection (12) the relevant documents shall be filed and kept by the Director of Lands in such manner as the Commissioner of Crown Lands may approve.

(14) Where buildings and structures are erected in an A landslip area or a B landslip area after an order-in-council in respect thereof has been registered in accordance with subsections (9), (10), or (12), the Crown will give no compensation or other relief for any damage caused by earth movement to such buildings or structures.

(15) The Governor may -

- (a) revoke an order-in-council;
- (b) change the category of a landslip area to the landslip area of the other kind; or
- (c) alter the boundaries of a landslip area,

and, if he does, the Minister shall forthwith cause the revocation, the change of category, or the alteration of boundaries to be registered in respect of any land to which it relates in the like manner as is registered an order-in-council declaring an area as a landslip area.

(16) If, in pursuance of subsection (15), land that is not part of a landslip area becomes part of one or land in a B landslip area becomes part of an A landslip area, subsections (5) and (6) shall be complied with in respect of that land.

6.4.2 VICTORIA

Advisory landslide zone maps have been produced by the Department of Industry, Technology and Resources (DITR) for an area of several hundred square kilometres within the Otway Ranges adjacent to the coast. Zoning is based on the three zone system previously discussed.

In the Otway Ranges and other areas the DITR are invited by local government authorities to inspect land parcels suspected as having slope stability problems, though there is no obligation for the local government to do so. Engineering geologists from DITR will conduct an inspection of the site and provide an informed judgement of slope stability. If site investigation is deemed necessary the DITR recommend to the local government that the landowner retain a qualified and experienced geotechnical consultant to conduct the investigation. The cost of this investigation is borne by the landowner. The DITR will help the local government evaluate the report if so required. The local government can withhold a building permit on safety grounds.

The system aims to avoid disaster while taking into account the interests of landowners.

No legislation exists though it has been contemplated.

6.4.3 QUEENSLAND

Landslide zone maps have been prepared by the Geological Survey of Queensland at the request of several shire councils. The areas mapped include the foothills of the Toowoomba Range (Willmott, 1984), the Mapleton-Maleny Plateau (Willmott, 1983) and the Cairns area (Hofmann, 1984). The zoning systems are tailored to local conditions, and expand the three basic zones to five or more.

The Geological Survey of Queensland has little involvement at site assessment level, however local government Town Planning Schemes and Strategic Plans must be submitted to the Department of Local Government for approval. The Geological Survey then has the opportunity to comment on slope stability potential. Their role is advisory, but the comments are usually taken seriously. Site assessments are instigated by and presented to the local government authorities.

Building permits for land parcels can be refused by the local government if slope stability cannot be proven.

6.4.4 NEW SOUTH WALES

The extent of the landslide problem in areas where slope movement is a hazard has been broadly identified at 1:25 000 to 1:100 000 scale by geologists of the Department of Mineral Resources at the request of regional planning and local government authorities. Subsequently some river catchments and large subdivisions have been the subject of urban capability studies by the Soil Conservation Authority and consultants.

Local government usually requests that a stability report be submitted with development plans. Site assessments are carried out at the request of the local government authorities by qualified foundation or geotechnical engineers. Court rulings on negligence cases have tended to leave most of the onus for negligence on the council because of their access to previous site records.

Some legislative control using 'scenic preservation' (landscape) zoning has been employed by planning authorities to restrict the development of land known or suspected as being unstable.

6.4.5 SOUTH AUSTRALIA

The potential for landslides in South Australia is low because of the low rainfall, and so no landslide zone maps have been produced.

The Groundwater and Engineering Services Division of the South Australian Department of Mines and Energy can request that an engineering report be submitted to the local government if a proposed subdivision has a landslide risk. After the report has been submitted SADME can suggest recommendations to the State Planning Authority who pass them on to the local government. These recommendations do not have to be accepted by the local government. Every application for a building permit must be accompanied by an Engineer's Site Report.

There has been no legislation enacted specifically addressing the landslide problem.

6.4.6 WESTERN AUSTRALIA AND THE NORTHERN TERRITORY

No reply to a request for information was received from either Western Australia or the Northern Territory.

6.4.7 CONCLUSION

The legislative approach to the control of construction activity over unstable land is variable from state to state. Tasmania has the most control, having the legislative powers of Section 431A of the Local Government Act 1962 directly addressing these problems. All states that have a landslide problem employ sections of their respective Local Government Acts to withhold the granting of Building Licence if slope stability can not be proved.

In conclusion, it is left to the local government authorities to act on the problem of slope stability and urban or suburban development using the best information available.

7 CONCLUSIONS - LANDSLIDES AND LOCAL GOVERNMENT

Landslides are commonly addressed from a technical and scientific viewpoint, with publications written by and for earth scientists who are familiar with the terminology and concepts involved. However, local governments bear the brunt of decision making on urban development over land which has slope stability problems, and it is unlikely that their personnel have any training in the earth sciences. This publication has attempted to address this problem by providing as much information as possible on the terminology and assessment of landslides, and by describing the inputs to decision making.

Landslides are usually studied only when they pose a threat to, or have damaged, manmade structures, however slope movements are difficult to stop once initiated. This problem is compounded in urban areas where the houses at risk simultaneously disguise the surface morphology. Local governments are advised to take into account landslide potential when planning or examining subdivision proposals to prevent urban construction on unstable slopes. In most cases a qualitative estimate of the landslide potential of subdivisions will reveal problem areas, and the plans can be altered to accommodate those problems. Similarly, site assessments of individual blocks within a problem area will usually indicate those which may continue to be unstable. These stability assessments should be conducted by qualified engineering geologists or geotechnical engineers.

The consultants' role is that of detective. They must examine the available evidence and formulate a model which best fits the known facts. This model is then used for predictive purposes. If vital clues are disguised or unobtainable because of financial or temporal constraints, the model may fit the known facts but still not be representative of the truth. In this case the predictions of the consultant may be in error, however it would be difficult to determine the truth without the benefit of more clues.

Legal liability is a problem facing the consultants retained to conduct slope stability assessments. Geotechnical personnel cannot predict the future of a slope. At best they can examine an area for indications of past or present slope instability to determine the range of stability conditions likely to develop in the future. Hence the role of the consultant is advisory rather than predictive.

It is hoped the publication will be widely used by local government organisations, and other similarly interested parties, where landslides and urban development overlap.

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