EARTHQUAKE INDUCED SLOPE FAILURE HAZARD HUTT VALLEY

NOTES TO ACCOMPANY

SEISMIC HAZARD MAP SERIES: EARTHQUAKE INDUCED SLOPE HAZARD MAP SHEET 3 HUTT VALLEY (FIRST EDITION) 1:40000

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1. INTRODUCTION

1.1 BACKGROUND

The occurrence of earthquakes in the Wellington Region is inevitable because of its location at the boundary of two crustal plates and the presence of four major active faults (Figures 1 and 2). The Region is frequently shaken by moderate to large earthquakes (Figure 3).

Earthquakes have the potential to cause significant adverse effects in the Region, including damage to buildings and other structures, loss of life and injury, and social and economic disruption. In recognition of these potential effects, the Wellington Regional Council initiated a project in 1988 to:

- Assess the risks posed by earthquakes.
- Identify mitigation options.
- Implement measures to ensure that the level of risk is acceptable.

The first step in the project is to define the characteristics of the hazard. Information on the type and magnitude of possible effects, the probability of these occurring and the location of the effects within the Region was required. For the purpose of the project *earthquake hazard* has been divided into five separate but interrelated components:

- Ground surface rupture from active faulting.
- Ground shaking.
- Liquefaction potential and associated ground damage.
- Slope failure.
- Tsunami.

Although not all the effects will occur during every earthquake, and many will be localised, all components must be considered to obtain a complete picture of earthquake hazard.

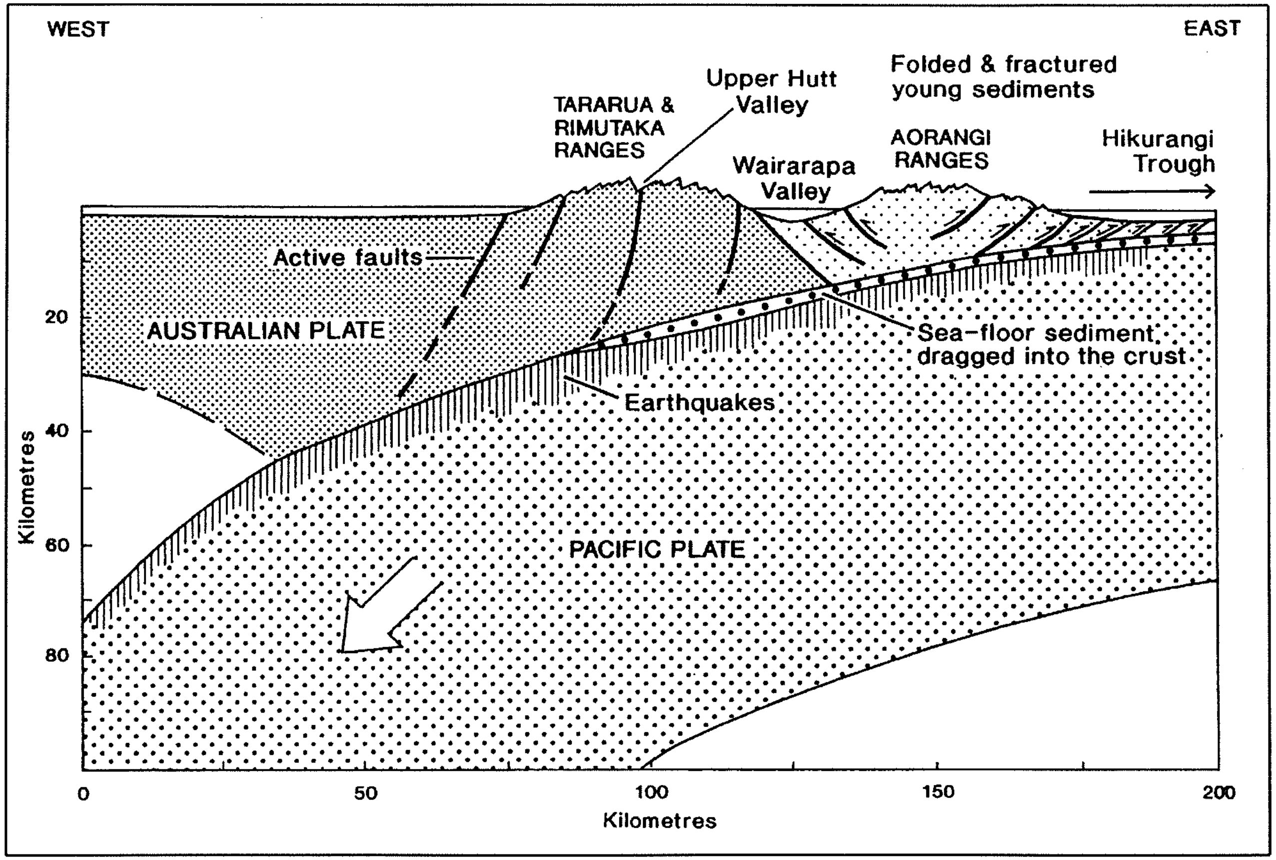


Figure 1: Source of earthquakes at plate boundary and along active faults (after Stevens, 1991).

The Hutt Valley earthquake induced slope failure hazard map and this accompanying booklet have been compiled from a detailed report prepared for the Wellington Regional Council by **Works Consultancy Services Limited.** The **Institute of Geological and Nuclear Sciences Limited** was subconsultant to Works Consultancy Services. Substantial parts of this booklet are taken directly from the report prepared by Brabhaharan *et al* (1994) of Works Consultancy Services Limited.

1.2 PURPOSE OF MAP AND BOOKLET

A series of five map sheets, with accompanying explanatory booklets, has been compiled to describe the *earthquake induced slope failure hazard* for the main urban areas in the western part of the Wellington Region. In addition, State Highway 58 and State Highway 2, from Upper Hutt to Featherston, have been assessed.

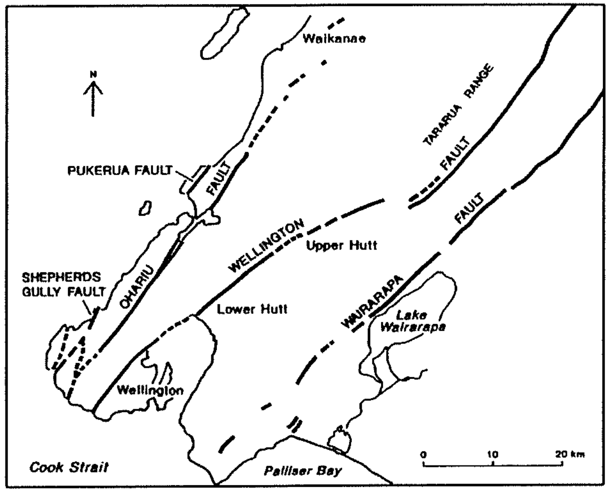


Figure 2: Active faults in the western part of the Wellington Region.

The purpose of the maps is to show the geographic variation in:

- ❑ Slope failure *susceptibility* for parts of the Region.
- ❑ Slope failure *potential* for three earthquake scenarios.

The main purpose of the booklets is to provide information to support the geographic hazard information shown on the maps, and more specifically to:

- ❑ Summarise the Regional Council's earthquake hazard strategy.
- ❑ Explain how the slope failure susceptibility hazard zones shown on the map were derived.
- ❑ Describe the type and nature of slope failures that can be expected to occur in the Region.
- ❑ Outline the qualifications and the limitations of the hazard information.

1.3 HAZARD STRATEGY AND PREVIOUS STUDIES

In recognition of the earthquake hazard in the Region, the Wellington Regional Council is developing a strategy aimed at achieving an *acceptable level of risk* from earthquake and geological hazards. The Regional Council's strategy will promote the use of earthquake and geological hazard information in planning and development, and emergency management. The strategy will also help to raise public awareness of earthquake and geological hazards.

Detailed technical studies on ground surface rupture from active faulting, ground shaking hazard, and liquefaction potential and associated ground damage, have been completed by the Regional Council.

Information on the active faults in the western part of the Region has been published by the Regional Council in a series of three map sheets;

- ❑ Map Sheet 1 Wellington Fault (1:25000)
- ❑ Map Sheet 2 Ohariu Fault (1:25000)
- ❑ Map Sheet 3 Shepherds Gully, Pukerua and Wairarapa Faults (1:25000)

A series of six maps and booklets describing the ground shaking hazard in the Region was published by the Regional Council in 1992:

- ❑ Map Sheet 1 Wellington (1:20000)
- ❑ Map Sheet 2 Porirua (1:25000)
- ❑ Map Sheet 3 Lower Hutt (1:25000)
- ❑ Map Sheet 4 Upper Hutt (1:25000)
- ❑ Map Sheet 5 Kapiti (1:40000)
- ❑ Map Sheet 6 Wairarapa (1:50000)

The liquefaction potential and associated ground damage hazard for the main urban areas of the Region has been summarised in a series of four maps and booklets:

- ❑ Map Sheet 1 Wellington (1:50000)
- ❑ Map Sheet 2 Porirua (1:50000)
- ❑ Map Sheet 3 Hutt Valley (1:75000)
- ❑ Map Sheet 4 Kapiti (1:100000)
- ❑ Wairarapa - booklet only

Tsunami inundation hazard information for Wellington Harbour is also available from the Regional Council.

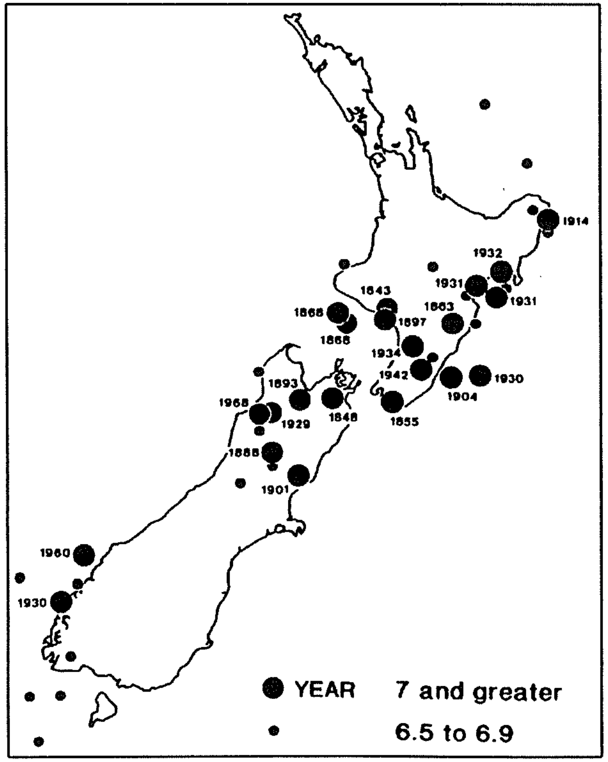


Figure 3: Epicentres of shallow earthquakes of magnitude 6.5 and greater since 1840 (Van Dissen *et al*, 1992.)

SLOPE FAILURE POTENTIAL			
Slope Failure Susceptibility Zones	Earthquake Scenarios		
	Scenario 1 (MM V-VI)	Intermediate Scenario (MM VII-VIII)	Scenario 2 (MM IX-X)
Very Low	Very Minor	Very Minor	Very Minor
Low	Very Minor	Very Minor	Minor
Moderate	Very Minor	Minor	Significant
High	Minor	Significant	Severe
Very High	Significant	Severe	Very Severe

SLOPE FAILURE CLASSES AND TYPICAL SLOPE FAILURES	
	Very Minor: Few very small failures (<100m^3) in alluvium along high river banks and terrace edges, loose rocks dislodged and very small debris/rock slides or falls on steep slopes and high steep cuts.
	Minor: Minor slope failures. Small failures (100m^3-10,000m^3) in alluvium along river and stream banks, loose rocks dislodged on slopes, small debris/rock slides or falls on steep slope and high steep cuts.
	Significant: General as for "Minor" but effects more widespread. Larger masses (10,000m^3-100,000m^3) displaced, with failures along river and stream banks, rocks dislodged on slopes, moderate debris/rock slides or falls on many steep slopes and cuts.
	Severe: Slope failures widespread with large failures (>10,000m^3) along river banks, rocks dislodged on slopes, moderate to large debris and rock slides or falls on many steep slopes, and large failures on cuts. Failures of sidling fills on steep slopes and road edges.
	Very Severe: Slope failures very widespread, with many small to very large failures (>100,000m^3) in most areas. Failures general on steep slopes, with some very large failures of debris and rock, particularly on high steep cut slopes. Many failures of fills and road edges.

EARTHQUAKE SCENARIOS	
Scenario 1:	A large (M 7), distant (= 100 km), shallow (15-60 km) earthquake producing MM V to MM VI on bedrock over much os the Wellington Region. The probability of this event occurring in next 50 years is very high (90 percent or greater).
Intermediate Scenario:	An intermediate size earthquake that produces MMVII to MM VIII on bedrock at any location in the Wellington Region. Estimated probability is intermediate between Scenarios 1 and 2 (about 45 percent in the next 50 years).
Scenario 2:	A large (M 7.5), shallow (<30 km) earthquake centred on the Wellington-Hutt Valley segment of the Wellington Fault, producing shaking on bedrock in the Wellington Region, ranging from MM X near the fault to MM VII, see Figure 3. Probability of occurrence in next 50 years is about 10 percent.

Table 1: Legend for earthquake induced slope failure hazard map.

1.4 BOOKLET STRUCTURE

This booklet is divided into six main parts. Part 1 gives background information on the study. Part 2 describes the slope failure hazard map and the classification developed. The types of slope failures likely to occur during an earthquake and the slope failure hazard assessment methodology used for the study are outlined in Parts 3 and 4 respectively. Part 5 summarises the qualifications and limitations that determine the certainty with which the hazard information can be used. Part 6 defines the three earthquake scenarios used in the study.

Appendix 1 lists the contributing reports and references. Technical words and terms not defined in the main text of the booklet are defined in Appendix 2. The Modified Mercalli Intensity scale and associated masonry structure classification are given in Appendices 3 and 4 respectively. A classification of the various types of slope failure movement likely to occur in the Wellington Region is given in Appendix 5.

2. EARTHQUAKE INDUCED SLOPE FAILURE HAZARD MAP

Earthquake induced *slope failure susceptibility* is shown on the accompanying map sheet. The table on the map (Table 1) is part of the map legend and relates the *susceptibility zones* to three earthquake scenarios. The table is a convenient way of showing both the slope failure susceptibility and the *slope failure potential* on a single map. Furthermore, the legend provides a rapid means of comparing the potential effects at different levels of shaking.

The five slope failure susceptibility zones range from *very low* susceptibility to *very high* susceptibility and the five slope failure potential classes range from *very minor* to *very severe*. The slope failure potential classification includes information on the types and volumes of the various slope failures that may occur.

The index map on the map sheet (Figure 4) shows the five study areas assessed.

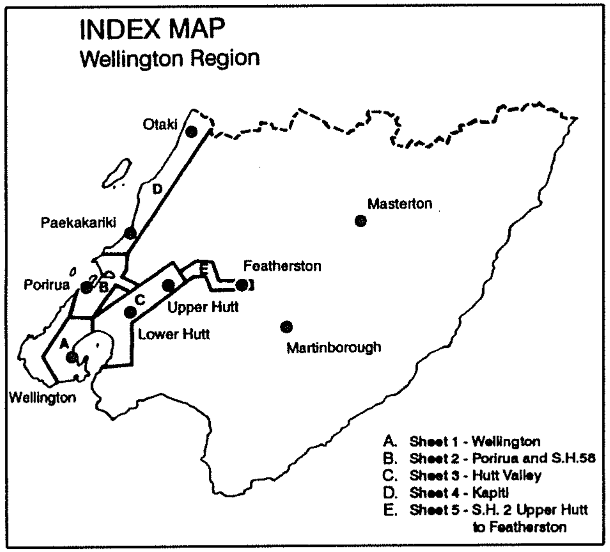


Figure 4: Index map showing earthquake induced slope failure study areas.

3. EARTHQUAKE INDUCED SLOPE FAILURES

3.1 INTRODUCTION

Slope failure includes all types of failures in slopes, including falls, slides, avalanches, flows, and slumps in both soil and rock. Failures caused by liquefaction are excluded from this study. Earthquake induced slope failures are defined as those *caused directly* or *triggered* by earthquakes. The majority of earthquake induced slope failures will occur during earthquake shaking. However, some slopes weakened by earthquake shaking may fail days or weeks after the earthquake. After-shocks or high intensity and/or long duration rainfall may trigger such failures.

3.2 SLOPE FAILURE MECHANISMS

3.2.1 Introduction

The main types of earthquake induced slope failures likely in the Wellington Region are summarised in Table 2. A pictorial representation of the various slope failures is given in Appendix 5.

TYPES OF MATERIAL	TYPE OF MOVEMENT
Bedrock	Rock topple Rock fall Planar slide Rotational slide
Surficial soil	Soil fall Planar slide Rotational slide
Rock or soil debris	Debris flow

Table 2: Slope failure material type and movement type.

3.2.2 Bedrock Failures

Stability of the Wellington greywacke/argillite bedrock is strongly controlled by rock defects such as joints, bedding, crushed and sheared zones, and clay gouge zones. Persistent defects dipping out of slopes control rock slides and wedge failures. Closely jointed and loose rocks are susceptible to rock falls. The most common defects are bedding planes, and the majority of sheared and crushed zones are parallel to these.

Modified slopes (cuttings) in rock can be potentially unstable where there are unfavourably oriented defects, and can be expected to produce deep-seated failures in an earthquake.

Rock topples are likely only in high-relief areas such as gorges and slopes undercut by rivers and coastal erosion. Moderate size failures are expected on the highest bluffs, elsewhere rock topples are likely to be *small* to *moderate* (Table 3).

Rock falls are common in cuts, gorges, fault line scarps and slopes undercut by rivers. They usually occur as block failures with at least one joint set dipping out of the slope, but may occur as wedge failures. Failures range in size from *very small* to *large* (Table 3).

Planar slides can occur in any rock slope where adversely oriented defects occur and can be *very large* failures (Table 3).

Rotational slides are not common in the greywacke/argillite bedrock. The failures are generally up to *moderate* in size (Table 3). *Very large* failures are likely to involve complex mechanisms of which rotational failure is only a part.

SLOPE FAILURE SIZE	TYPICAL VOLUME OF ROCK/SOIL MASS
Very small	<100 m^3
Small	100 m^3 - 1,000 m^3
Moderate	1000 m^3 - 10,000 m^3
Large	10,000 m^3 - 100,000 m^3
Very large	>100,000 m^3

Table 3: Typical volumes of slope failures.

3.2.3 Surficial Soil Failures

Surficial soils overlying the greywacke/argillite bedrock in the Region include top soil, loess, colluvium and alluvium.

Colluvium and loess on steep slopes often fails during high intensity and/or long duration rainfall. The failures are typically retrogressive and occur in the catchments of small drainage channels, or as soil falls with loss of vegetation on steeper slopes. When these materials fail at the bedrock interface and occur in dry ground areas, the failures are likely to be larger. Earthquake induced failures in colluvium and loess are likely to be more severe on naturally or artificially oversteepened slopes.

Soil fall occur mainly in cut slopes or river banks. They range in size from *small* to *moderate* (Table 3), depending on the size of the slope.

Planar slides occur mainly in cuts but also in natural slopes. Failure is generally dependent on an adversely dipping defect such as a bedding plane of low shear strength or the soil/bedrock interface. Planar slides in soil range in size up to *moderate* (Table 3).

Rotational slides occur mainly in higher slopes, especially in large cuts. They may be *moderate* in size (Table 3), and to fail by ground shaking need to be on the point of failure under static conditions.

3.2.4 Rock or Soil Debris Failures

Debris flows may be loose, dry to saturated debris, mobilised by earthquake shaking, but may also occur as an indirect effect of an earthquake. Debris from any type of slope failure may be mobilised by high intensity rainfall, hours or even weeks after an event. Debris flows can be up to *very large* in size (Table 3) and potentially very destructive.

4. SLOPE FAILURE HAZARD ASSESSMENT

4.1 METHODOLOGY

The slope failure hazard assessment methodology was developed following a review of historical records of earthquake induced slope failures and a literature review of similar hazard assessments. The methodology was tailored to suit the geology, topography and seismicity characteristics of the Region.

The main steps of the methodology were:

- Compilation of *factor maps* from available information and site reconnaissance.
- Integration of factors by assigning numeric values and weightings to factors, and summing the products of the factor value and weighting for each factor to derive a *susceptibility rating.*
- Mapping of *slope failure susceptibility* using the factor maps and the *susceptibility rating* derived for common slope characteristics.
- Definition of *earthquake scenarios* from seismicity.
- Appraisal of *potential* for slope failure from susceptibility, earthquake scenarios and data from historical earthquakes.
- Review of slope failure mechanisms.
- Assessment of likely ground damage from slope instability.

4.2 FACTOR MAP COMPILATION

Four *factors* considered important for assessing slope failure susceptibility were mapped at a scale of 1:25000. These are:

- Steepness and extent of natural slopes.
- Slope modification - mainly areas of high steep cuts along major roads and railway lines, quarries, and some areas of cut and fill roads and subdivisions.
- Geology - including rock types, strength and geomorphic features, the location of major fault zones and, where known, engineering geological properties of materials.
- Landslides - including known historical earthquake induced and rainfall induced failures.

Each factor was divided into appropriate *factor classes* (Table 4). Ratings (*factor values*) for factor classes and weightings assigned to each factor are also given in Table 4.

SUSCEPTIBILITY FACTOR	FACTOR CLASS	FACTOR VALUE	FACTOR WEIGHTING	DESCRIPTION
Slope Angle [α] (F_{SL})	$\alpha < 20°$ $20° \leq \alpha < 35°$ $35° \leq \alpha < 45°$ $45° \leq \alpha < 60°$ $\alpha > 60°$	0 2 4 8 10	4	Flat to gentle slopes; Gentle to moderate slopes; Moderate to steep slopes; Steep to very steep slopes; Precipitous slopes.
Slope Height (F_{SH})	0 - 5m 5 - 10 m 10 - 20 m >20 m	0 4 8 10	2	This factor applies only to slopes that are steeper than 35-45° - mainly cuts and some natural slopes.
Slope Modification (F_{SM})	Cut slope Angle 35 - 45° 45 - 60° >60° (for height see factor F_{SH}) Sidling Fills	 4 8 10 10	4	Slope modification applies to cut slopes and sidling fills on steeper slopes.
Geology (F_G)	UW-MW greywacke HW-CW greywacke Crushed and shattered greywacke Colluvium/alluvium	0 4 8 10	2	Applies to variably weathered, crushed and shattered greywacke and argillite, colluvium and alluvium on slopes.
Landslides (F_L)	No slides present Old slides Active slides	0 5 10	2	Factor values broadly based on presence or absence of slope failures (on cuts), or of old or active landslides.
Groundwater (F_W)	Slopes are: Well drained Poorly drained Saturated	 0 5 10	1	Groundwater factor generalised to reflect extreme conditions, with maximum effects during prolonged heavy rainfall. Generally of less importance that the other factors.

Notes:

1. Factor WEIGHTINGS have been subjectively assigned, based on historical and geological precedent evidence of earthquake induced slope failures in the Wellington Region.
2. Weighting for slope height is applied only to slopes (cuts mainly) steeper than 45°. Not considered appropriate for natural slopes of 35-45° (for example, coastal cliffs, slopes along the Wellington Fault Scarp).
3. Compared to other factors vegetation is believed to be relatively unimportant in the Wellington Region and is not considered in the preparation of the slope failure susceptibility maps.
4. See Table 5 for definition of susceptibility zones.
5. See Table 6 for typical characteristics of susceptibility zones.
6. UW - unweathered, SW - slightly weathered, MW - moderately weathered, HW - highly weathered, Cr - crushed, Shat - shattered.

Table 4: Factors affecting slope failure susceptibility.

4.2.1 Slope

Five slope classes were identified as appropriate for the Region (Table 4). In general, these classes are steeper than those used in many published classifications. The classes reflect the relatively high intact strength of the Wellington greywacke bedrock. 1:25000 slope angle maps were generated from a digital terrain model derived from 20 metre contours. The slope maps are the main *factor* for deriving the *slope failure susceptibility zones.*

4.2.2 Slope Modification

Cut slopes along main roads, railways, in subdivisions and quarries were generally mapped at a scale of 1:50000. In urban areas cut slopes were mapped at a scale of 1:10000 and 1:20000.

Apart from the valley floor areas, most of the urban and suburban development has been by means of cut and fill subdivision. Roads in the western hills of the Hutt Valley have been established by means of significant cuts. The Western Hutt Road and the Hutt Road between Horokiwi and the Petone foreshore have been cut into the toe of the scarp of the Wellington Fault in many places. Extensive cuts and fills were required for the Wainuiomata Hill Road, and extensive high cut faces have been excavated around Gracefield-Seaview for industrial development. The road to Eastbourne required high cuts in the steep, wave-cut slope on the eastern side of the harbour. There are several major quarries adjacent to the Western Hutt Motorway and River Road (State Highway 2 Upper Hutt Bypass).

The *factor classes* for slope modification are shown in Table 4.

4.2.3 **Geology**

Although geology is often an important factor in slope failure susceptibility studies, it was less important for this study because of the relative uniformity of bedrock type in the Region. Generally the steep slopes are underlain by greywacke rock with a variable but generally thin (1 to 2 metre) surface layer of colluvium. The lower relief areas are underlain mainly by Quaternary age alluvial materials.

In general the greywacke bedrock material is strong to very strong when unweathered, but the rock mass is significantly weaker because of closely spaced joints and the presence of many sheared zones. The bedrock in the area is highly to completely weathered near the surface on the eastern hills and the higher land on the west side of the valley. Along the scarp of the Wellington Fault, less weathered bedrock is exposed in places near the valley floor.

Much of the area mapped as bedrock is covered by a veneer of colluvium and topsoil (and loess in places) up to a depth of two metres. Fossil gullies, up to 10 metres deep, filled with Pleistocene periglacial colluvium are common. These deposits can have a pronounced effect on stability, particularly when they are encountered by earthworks.

The geology *factor classes* are shown in Table 4.

4.2.4 **Existing Landslides**

Landslide incidence and distribution in the Region is an important factor for defining slope failure susceptibility zones. Landslides known to have formed during earthquakes provide useful information for this study. A review of historical earthquake induced slope failures in the Region provided valuable information for assessing future seismic response of slopes (Hancox *et al*, 1994).

Aerial photographs of the Region were examined and landslides identified. Few large landslides were identified in the study area. A house at Rona Bay was destroyed by a collapse of the modified wave-cut slope in 1990, and it is obvious that this was a partial reactivation of a much larger old slide. Very large scale, probably intermittently creeping, gravity slides are present in the western hills, but these are not considered to be relevant to earthquake induced slope failure.

4.3 INTEGRATION OF FACTORS

Slope angle, slope height, slope modification, existing landslides and geology information were integrated to assess *slope failure susceptibility*. This was carried out by:

- Subjectively assigning a numeric *factor value* (F) for the *factor classes* of each factor on a scale of 1 to 10 (Table 4).
- Assigning a *weighting* (W) for each *factor*, depending on the subjectivity assessed relative importance of the *factors* in causing slope failure (Table 4).
- Multiplying each *factor value* by it's *weighting* (FxW), and adding together the products for all the factors to derive a *slope failure susceptibility rating* (R_S):

$$R_S=[(F_{SL}xW_{SL})+(F_{SH}xW_{SH})+(F_{SM}xW_{SM})+(F_GxW_G)+(F_LxW_L)+(F_WxW_W)]$$

SL = slope angle
SH = slope height
SM = slope modification
G = geology
L = existing landslides
W = groundwater

For the chosen factor weightings, the susceptibility rating therefore becomes:

$$R_S=[(F_{SL}x4)+(F_{SM}x4)+(F_{SH}x2)+(F_Gx2)+(F_Lx2)+(F_W)]$$

x4 = weighting factor

Table 4 shows the factor values used for each factor class, and the weightings shown above.

Table 5 summarises the *susceptibility rating* range for each *susceptibility zone* and Table 6 shows the way the various factors have been integrated to define the *susceptibility zones*.

4.4 MAPPING SLOPE FAILURE SUSCEPTIBILITY

4.4.1 **Methodology**

The *slope failure susceptibility zones* are defined by the susceptibility rating as given in Table 5. The slope failure *susceptibility zones* were checked against historical earthquake induced landslide characteristics and subjectively against known areas of earthquake induced slope failure hazard. The *factor values* and *weightings* were refined to give *susceptibility ratings* and therefore *susceptibility* to slope failure consistent with historical records and consideration of the known slopes. They were then used as a basis for mapping.

Given the regional scale of the study, it was not practical to identify and integrate all the factors influencing the stability of every individual slope. Therefore, typical combinations of factors predominant in the Region were considered and classified in the different susceptibility classes and used for hazard zonation. The key factors with the highest weighting and importance were *slope angle* and *slope modification* (Table 4) and these were used primarily to define the boundaries of the hazard zones on the maps.

SLOPE FAILURE SUSCEPTIBILITY ZONE	SUSCEPTIBILITY RATING [R_S] [Σ(Value x Weighting)]	MAP COLOUR	COMMENTS
Very low	0 - 20	Green	Flat and low lying areas mainly
Low	20 - 60	Yellow	Gentle hill country, low cuts
Moderate	60 - 100	Orange	Gentle - moderate slopes, moderate cuts
High	100 - 140	Red	Steep slopes, high cuts
Very high	> 140	Purple	Very steep slopes and high cuts

Table 5: Slope failure susceptibility zones.

4.4.2 **Discussion**

Slopes above 45 degrees were used as a prime indicator of very high susceptibility to earthquake induced slope failure. The steep slope areas were expanded to include the entire slope they occupy, including an allowance for downslope runout. The assumption is that if a slope contains an extremely steep component, then that will generally control the stability of the entire slope. In some cases these extend to the bottom of the slope onto the valley floor. Where only a small steep area is indicated high up on a gentle slope, then a *tear-drop* shape was zoned to represent the extent of slope failure that might occur.

All areas of *modified slopes* fall within the high or very high susceptibility zone, on the assumption that oversteepened (cut) slopes are generally less stable than unmodified slopes. Quarry slopes are likely to be the least stable, as most have very steep, high cuts (greater than 20 to 40 metres) that are generally not designed for long-term stability.

Natural (unmodified) slopes usually exist at a slope angle depending on their geological, tectonic and environmental history, age, prevailing conditions, and the strength and rock mass properties of the bedrock. Any artificial oversteepening or rapid natural undercutting at the toe of slopes can cause significantly reduced stability, especially during earthquake shaking. However, retained slopes designed to resist seismic shaking or other destabilising factors, such as rainfall, are not included in the high failure risk category. Inadequately designed or constructed crib walls, shotcreted slopes and light concrete walls are not expected to perform as well under strong shaking, and are therefore zoned as moderately to highly susceptible to failure.

In general, any marginally stable slope on the point of failure may be triggered by earthquake shaking. Existing landslides, and areas adjacent to landslides are therefore regarded as highly susceptible to earthquake induced slope failure, and are included in the high hazard zone. The weighting assigned to the landslide factor reflects this importance (Table 4).

The most susceptible slopes are all the major road and subdivision cuts. All steep slopes, including road and rail cuts, quarries and steep natural slopes are zoned as having a high susceptibility.

4.5 EARTHQUAKE SCENARIOS

In assessing earthquake induced *slope failure potential*, the earthquake scenarios represent *slope failure opportunities*. These *opportunities* may be simply defined as a function of the seismic loadings imposed on slopes during earthquakes. Such loadings or opportunity levels may or may not be sufficient to cause slope failure, depending on the complex range of factors that affect slope stability, and expressed here as *slope failure susceptibility*.

For this study, *slope failure opportunity* has been assessed using historical data on earthquake induced landslides in the Wellington Region. Slope failure opportunity links different types and degrees of landslides during earthquakes to Modified Mercalli Intensity (Appendix 3) as well as earthquake magnitude and distance.

Slope failure opportunity in the Wellington Region has been assessed for three earthquake scenarios. The scenarios are defined in Part 6. *Slope failure opportunity* levels for the three earthquake scenarios are defined by Modified Mercalli Intensity values (Table 7). The Modified Mercalli Intensities are those assessed for bedrock. Estimated peak ground accelerations on bedrock are also given in Table 7 for each scenario.

4.6 SLOPE FAILURE POTENTIAL

Earthquake induced *slope failure potential* in the Wellington Region has been determined by the integration of *slope failure susceptibility zones* with different levels of *opportunity* (Modified Mercalli Intensity shaking) given by the three earthquake scenarios. The five classes of *slope failure potential* (Table 1) are based on subjective judgement supported by local engineering geological experience and evidence provided by a review of historical earthquake induced slope failures (Hancox *et al*, 1994).

SUSCEPTIBILITY ZONE	TYPICAL CHARACTERISTICS AND SUSCEPTIBILITY RATING (R_S)		MAIN GENERAL FEATURES
Very Low	• Slope angle flat to gentle (0 - 20°) • Slopes mainly unmodified; 5 - 10 m cuts • Greywacke/colluvium • Generally no slides present • Slopes dry - saturated **Rating: $R_S = \Sigma$ (F x W) = 0-20**	F x W = 0 F x W = 4 F x W = 4 F x W = 0 F x W = 10	Mainly flat low-lying areas and gently sloping hill country. Slopes are generally unmodified with low cuts and small fills.
Low	• Slope angle gentle to moderate (20-35°) • Mainly natural slopes; low 5-10 m cuts • Moderate cut slopes 35-45° • Greywacke/colluvium • Possibly small old slides • Slopes dry - saturated **Rating: $R_S = \Sigma$ (F x W) = 20-60**	F x W = 8 F x W = 8 F x W = 16 F x W = 4 F x W = 10 F x W = 10	Mainly gentle to moderate natural slopes, with a few low cuts in greywacke and/or colluvium.
Moderate	• Slopes moderate to steep (35-60°) • Moderate to steep cuts (35-60°) • Low cuts (5-10 m) • Cr, Shat greywacke/colluvium • Possibly small old and active slides • Slopes dry - saturated **Rating: $R_S = \Sigma$ (F x W) = 60-100**	F x W = 16 F x W = 32 F x W = 8 F x W = 20 F x W = 10 F x W = 10	Moderate to steep slopes with low cuts in variable greywacke and colluvium. Small old or active slides may be present.
High	• Slopes steep to very steep (45-60°) • Steep to very steep cuts (>60°) • Moderate to high cuts (10-20 m) • HW, Cr, Shat greywacke/colluvium • Old and active slides possibly present • Slopes dry - saturated **Rating: $R_S = \Sigma$ (F x W) = 100-140**	F x W = 32 F x W = 40 F x W = 16 F x W = 20 F x W = 20 F x W = 10	Steep to very steep slopes with steep, moderate high cuts. Rock at tops of cuts is usually MW to HW, closely jointed to shattered, often with a variable thickness of colluvium and topsoil. Stronger MW-SW rock at base of cuts. Old or active slides may be present.
Very High	• Slopes very steep to precipitous (>60°) • Steep to very steep cuts (>60°) • Very high cuts (>20 m) • HW, Cr, Shat greywacke/colluvium • Old and active slides possibly present • Slopes dry - saturated **Rating: $R_S = \Sigma$ (F x W) = 140-150**	F x W = 40 F x W = 40 F x W = 20 F x W = 20 F x W = 20 F x W = 10	Very steep and precipitous slopes with very steep, very high cuts. Rock at tops of cuts usually loose, HW, closely jointed to shattered, often with a variable thickness of colluvium and topsoil. Old or active slides may be present.

Notes:

1. Factor WEIGHTINGS have been subjectively assigned based on historical and geological precedent evidence of earthquake induced slope failures in the Wellington Region.
2. Maximum susceptibility rating $R_S = \Sigma$ (factor value x weighting) for all factors is 150. Maximum values only given for examples. See Table 5 for definitions of Susceptibility Zones.
3. Weighting for slope height is applied only to slopes (cuts mainly) steeper than 45°. Not considered appropriate for infinite natural slopes of 35-45° (for example, coastal cliffs, slopes along the Wellington Fault Scarp).
4. UW - unweathered, SW - slightly weathered, MW - moderately weathered, HW - highly weathered, Cr - crushed, Shat - shattered.

Table 6: Typical characteristics of susceptibility zones.

4.6.1 Historical Evidence

The main conclusions from the historical review relevant to the assessment of slope failure potential are:

- In the Wellington Region, felt intensities of MM VIII to X or greater are required for the development of widespread slope failures and that this has occurred only four times since 1840.
- Felt intensity MM VI has occurred about ten times in the Wellington Region since 1840, but no significant landslides are known to have been associated with these events.
- Felt intensity of MM VII and above during past earthquakes have caused significant landslides in the Wellington Region. Therefore, based on the available information, a felt intensity of MM VII is considered to be the threshold for occurrence of significant earthquake induced slope failures in the Region.

4.6.2 Geomorphological Evidence

Geomorphological evidence suggests that most historical earthquake induced slides in bedrock occurred on steep to very steep (30 - 45 degree) mountain slopes, and slopes that had been undercut and oversteepened by river erosion. Many bedrock and regolith failures also developed on steep cut slopes along roads and railway lines. Failures in alluvial materials occurred mainly along river channels, terraces and coastal cliffs. A similar pattern of landslide damage can be expected for future large earthquakes in the Wellington area.

	SLOPE FAILURE OPPORTUNITY		
	SCENARIO 1	INTERMEDIATE SCENARIO	SCENARIO 2
Modified Mercalli Intensity	V-VI	VII-VIII	IX-X
Peak Ground Acceleration on Rock (g)	0.02-0.06	0.1-0.2	0.5-0.8

Table 7: Slope failure opportunity.

4.6.3 Contemporary Studies

An MM VII threshold level is supported by recent studies following the Ormond (Gisborne) Earthquake of 10 August 1993. MM VII was the threshold for earthquake induced landslides in the soft rocks in the Gisborne area. A similar threshold level for earthquake induced landslides has been suggested for the Dunedin area. Few landslides are expected to occur at lower levels of shaking.

5. QUALIFICATIONS AND LIMITATIONS

The earthquake induced slope failure hazard assessment methodology used for the study and the map compilation procedures impose the following qualifications and limitations on the use of the information:

(1) The slope failure hazard assessment is appropriate for regional scale planning and development purposes and **should not be used as a substitute for site specific investigations and/or geotechnical engineering assessment for any project.**

(2) The slope failure hazard information in the booklet and on the accompanying map sheet is based on the best information available at the time of the study and was supplied to the Regional Council under specific financial constraints. **The hazard information may be liable to change or review if new information is made available.**

(3) While zones of slope failure susceptibility have been shown on the accompanying map sheet, **there is no certainty that slope failures will occur in a particular area due to an earthquake of any size.**

(4) Because of specific geotechnical conditions, **there may be small areas within any susceptibility zone shown on the map, that may have a higher or lower slope failure potential than that indicated.** Examples of such areas include small cut slopes or areas of steep slopes that are too small to represent on the regional scale maps.

(5) Detailed engineering geological data on rock mass properties and on overlying surficial deposits is only available in localised areas. Therefore, **the hazard assessment has been based on a generalised engineering geology map, and the rock mass properties or soil conditions at any particular location may result in a hazard different to that shown on the regional scale map.**

(6) **The boundaries between the various slope failure susceptibility zones are approximate and indicative only.**

(7) The slope failure susceptibility and potential classes indicate the relative hazard between different areas of the Wellington Region, and have been specifically developed for the Region's geology, topography and seismicity. Therefore, **they should not be compared with similar hazard maps for other parts of New Zealand or other countries.**

(8) The classification of slope failure potential is indicative of the types of failures likely, **and does not imply any level of damage to particular structures or services in or adjacent to assessed hazard zones.** The sizes of slope failure indicated are only general statements of the likely extent of the slope failures.

(9) There is potential for liquefaction induced failures in the relatively flat floor part of the Hutt Valley. **Liquefaction induced failures have not been presented in this study**, as these hazards have already been identified in the liquefaction hazard study (Brabhaharan and Jennings, 1993).

6. EARTHQUAKE SCENARIOS

6.1 THE SCENARIOS

No single earthquake event adequately describes the potential earthquake induced slope failure hazard in the Wellington Region. Therefore, three earthquake scenarios were adopted to define the hazard. Scenarios 1 and 2 represent a large distant earthquake and a large earthquake on the Wellington Fault respectively. Because a Scenario 1 earthquake is unlikely to cause significant slope failure, an intermediate scenario has been defined. The *Intermediate Scenario* represents regional earthquakes which can cause significant slope failures, and have a probability of occurrence higher than that for the larger Scenario 2 earthquake on the Wellington Fault. The three scenarios in order of increasing intensity are:

- *Scenario 1*: A large, distant, shallow (<60 km) earthquake that produces *Modified Mercalli (MM) intensity* (Appendix 3) of V-VI in bedrock over the Wellington Region. An example of such an event would be a magnitude (M) 7 (Appendix 6) earthquake centred 100 km from the study area at a depth of 15-60 km, perhaps similar to the 1848 Marlborough earthquake. The return period of a Scenario 1 event is 29-80 years. The probability of this event occurring in the next 50 years is very high (90 percent or greater).

- *Intermediate Scenario*: A regional earthquake that produces *Modified Mercalli (MM) intensity* of about VII-VIII in bedrock at any location in the Wellington Region. Such an earthquake will have a higher probability of occurrence (approximately 45 percent in the next 50 years) than a Scenario 2 event.

- *Scenario 2*: A large earthquake centred on the Wellington - Hutt Valley segment of the Wellington Fault. Rupture of this fault segment is expected to be associated with a magnitude 7.5 earthquake at a depth less than 30 km. The mean recurrence interval for such an event is about 600 years, and the probability of it occurring in the next 50 years is estimated to be about 10 percent.

6.2 GROUND MOTION PARAMETERS

In the Wellington Region, most of the slopes likely to be susceptible to earthquake induced slope failure are in the mountains and hills which are formed of bedrock with limited thicknesses of overlying soils and weathering products. Therefore, only the ground shaking in bedrock is of importance to this study.

- *Scenario 1*: The large, distant, shallow earthquake could result in MM V-VI shaking on bedrock. A Scenario 1 event is capable of producing a peak ground acceleration of up to 0.06 g in bedrock areas, where most of the slopes are located (Table 7). For the purpose of hazard assessment, it is assumed that a Scenario 1 event is associated with a constant intensity of ground shaking on bedrock at any location in the Region.

- *Intermediate Scenario*: An Intermediate Scenario event will probably be caused by regional earthquakes, and for the purpose of hazard assessment, it is assumed that it is associated with a constant intensity of ground shaking on bedrock of about MM VII-VIII and a peak ground acceleration of about 0.1 g to 0.2 g at any location in the Region (Table 7).

- *Scenario 2*: The large local Wellington Fault event (Scenario 2) will give a higher level of ground shaking throughout the Region. In general, shaking decreases with increased distance from the source. Most of the Wellington study area is within 5 km of the Wellington - Hutt Valley segment of the Wellington Fault, with Miramar Peninsula within 10 km of the Fault. The isoseismals for Modified Mercalli intensities predicted for a Scenario 2 event are shown in Figure 5.

The felt intensities on bedrock predicted are mostly MM IX-X in the Wellington study area, with peak ground accelerations of 0.5 g to 0.8 g. For the purposes of this study, the ground shaking is assumed to be MM IX-X over the whole study area (Table 7).

APPENDICES

APPENDIX 1: CONTRIBUTING REPORTS AND REFERENCES

Brabhaharan P and Jennings D N (1993). Liquefaction hazard study, Wellington Region. Study area 2 - Hutt Valley. Works Consultancy Services Limited Contract Report prepared for Wellington Regional Council.

Brabhaharan P, Hancox G T, Perrin N D and Dellow G D (1994). Earthquake induced slope failure hazard study, Wellington Region: Study area 2 - Hutt Valley. Works Consultancy Services Limited Contract Report prepared for Wellington Regional Council.

Hancox G T, Dellow G D and Perrin N D (1994). Earthquake induced slope failure hazard study, Wellington Region: Review of historical records of earthquake induced slope failures. Institute of Geological and Nuclear Sciences Limited Contract Report prepared for Works Consultancy Services Limited for Wellington Regional Council.

Stevens G (1991). On shaky ground: A geological guide to the Wellington metropolitan region. DSIR Geology and Geophysics, and the Geological Society of New Zealand, Lower Hutt.

Van Dissen R J, Taber J J, Stephenson W R, Sritharan S, Perrin N D, McVerry G H, Campbell H J and Barker P R (1992). Earthquake ground shaking hazard assessment for Wellington City and suburbs, New Zealand. DSIR Geology and Geophysics Contract Report 1992/23 (prepared for Wellington Regional Council).

Varnes D J (1978). Slope Movement Types and Processes. In: Landslides Analysis and Control. Special Report 176, Transportation Research Board, Washington.

APPENDIX 2: GLOSSARY OF TECHNICAL WORDS AND TERMS

Active fault A fault with evidence of surface movement in the last 50000 years or repeated surface movement in the last 500000 years.

Alluvium Material deposited by streams, including gravel, sand, silt and clay.

Colluvium Loose, unconsolidated material on slopes, the formation of which has involved downslope transport under gravity of the weathered products derived from local bedrock.

g Gravity. For an earthquake which produces a ground acceleration of 0.4g, the actual acceleration is 40 percent of gravity.

Liquefaction Process by which water-saturated sediment temporarily loses strength, usually because of strong shaking, and behaves as a fluid.

Loess Material transported and deposited by wind and consisting predominantly silt size particles.

Pleistocene The *Ice Age*. The period of time that lasted from about 2 million years ago to 10000 years ago.

Tsunami An impulsively generated sea wave of local or distant origin that results from seafloor fault movement, large scale seafloor slides or volcanic eruption on the seafloor.

APPENDIX 3: MODIFIED MERCALLI INTENSITY SCALE

MM I Not felt by humans, except in especially favourable circumstances but birds and animals may be disturbed. Reported mainly from the upper floor of buildings more than 10 storeys high. Dizziness or nausea may be experienced. Branches of trees, chandeliers, doors and other suspended systems of long natural period may be seen to move slowly. Water in ponds, lakes and reservoirs may be set into seiche oscillation.

MM II Felt by a few persons at rest indoors, especially by those on upper floors or otherwise favourably placed. The long period effects listed under MM I may be more noticeable.

MM III Felt indoors but not identified as an earthquake by everyone. Vibration may be likened to the passing of light traffic. It may be possible to estimate duration but not the direction. Hanging objects may swing slightly. Standing motorcars may rock slightly.

MM IV Generally noticed indoors but not outside. Very light sleepers may be wakened. Vibration may be likened to the passing of heavy traffic, or to the jolt of a heavy object falling or striking the building. Walls and frames of buildings are heard to creak. Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock and the shock can be felt by their occupants.

MM V Generally felt outside and by almost everyone indoors. Most sleepers awakened. A few people frightened. Direction of motion can be estimated. Small unstable objects are displaced or upset. Some glassware and crockery may be broken. Some windows cracked. A few earthenware toilet fixtures cracked. Hanging pictures move. Doors and shutters may swing. Pendulum clocks stop, start or change rate.

MM VI Felt by all. People and animals alarmed. Many run outside. Difficulty experienced in walking steadily. Slight damage to Masonry D. Some plaster cracks or falls. Isolated cases of chimney damage. Windows, glassware and crockery broken. Objects fall from shelves and pictures from walls. Heavy furniture overturned. Small church and school bells ring. Trees and bushes shake, or are heard to rustle. Loose material may be dislodged from existing slips, talus slopes or shingle slides.

MM VII General alarm. Difficulty experienced in standing. Noticed by drivers of motorcars. Trees and bushes strongly shaken. Large bells ring. Masonry D cracked and damaged. A few instances of damage to Masonry C. Loose brickwork and tiles dislodged. Unbraced parapets and architectural ornaments may fall. Stone walls cracked. Weak chimneys broken, usually at the roofline. Domestic water tanks burst. Concrete irrigation ditches damaged. Waves seen on ponds and lakes. Water made turbid by stirred-up mud. Small slips and caving in of sand and gravel banks.

MM VIII Alarm may approach panic. Steering of motorcars affected. Masonry C damaged, with partial collapse. Masonry B damaged in some cases. Masonry A undamaged. Chimneys, factory stacks, monuments, towers and elevated tanks twisted or brought down. Panel walls thrown out of frame structures. Some brick veneers damaged. Decayed wooden piles broken. Frame houses not secured to the foundations may move. Cracks appear on steep slopes and in wet ground. Landslips in roadside cuttings and unsupported excavations. Some tree branches may be broken off. Changes in the flow or temperature of springs and wells may occur. Small earthquake fountains may form.

MM IX General panic. Masonry D destroyed. Masonry C heavily damaged, sometimes collapsing completely. Masonry B seriously damaged. Frame structures racked and distorted. Damage to foundations general. Frame houses not secured to the foundations shifted off. Brick veneers fall and expose frames. Cracking of the ground conspicuous. Minor damage to paths and roadways. Sand and mud ejected in alleviated areas, with the formation of earthquake fountains and sand craters. Underground pipes broken. Serious damage to reservoirs.

MM X Most masonry structures destroyed together with their foundations. Some well built wooden buildings and bridges seriously damaged. Dams, dykes and embankments seriously damaged. Railway lines slightly bent. Cement and asphalt roads and pavements badly cracked or thrown into waves. Large landslides on river banks and steep coasts. Sand and mud on beaches and flat land moved horizontally. Large and spectacular sand and mud fountains. Water from rivers, lakes and canals thrown up on banks.

MM XI Wooden frame structures destroyed. Great damage to railway lines and underground pipes.

MM XII Damage virtually total. Practically all works of construction destroyed or greatly damaged. Large rock masses displaced. Lines of sight and level distorted. Visible wave-motion of the ground surface reported. Objects thrown upwards into the air.

APPENDIX 4: CATEGORIES OF NON-WOODEN CONSTRUCTION

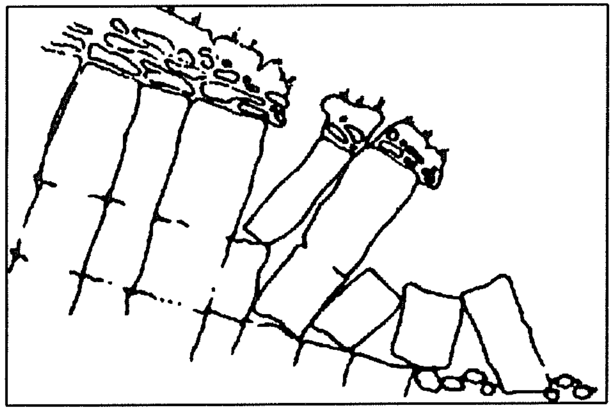
Masonry A. Structures designed to resist lateral forces of about 0.1 g, such as those satisfying the New Zealand Model Building Bylaws, 1955. Typical buildings of this kind are well reinforced by means of steel or ferro-concrete bands, or are wholly of ferro-concrete construction. All mortar is of good quality and the design and workmanship is good. Few buildings erected prior to 1935 can be regarded as in category A.

Masonry B. Reinforced buildings of good workmanship and with sound mortar, but not designed in detail to resist lateral forces.

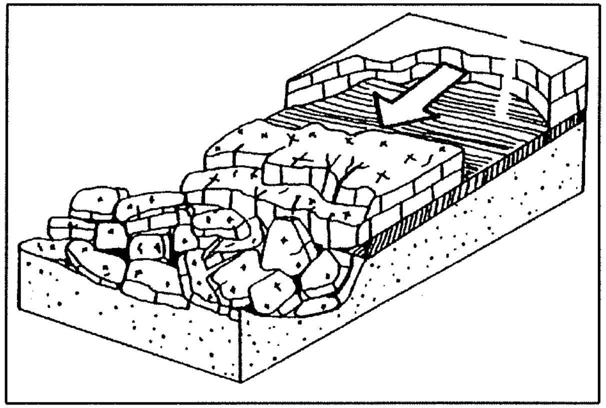
Masonry C. Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces.

Masonry D. Buildings with low standards of workmanship, poor mortar, or constructed of weak materials like mud brick and rammed earth. Weak horizontally.

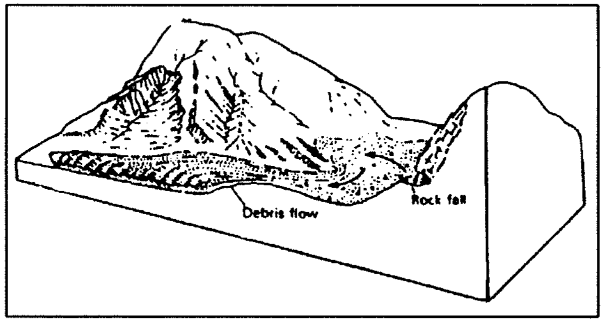
APPENDIX 5: TYPE OF MOVEMENT FOR SELECTED SLOPE FAILURES (AFTER VARNES, 1978)



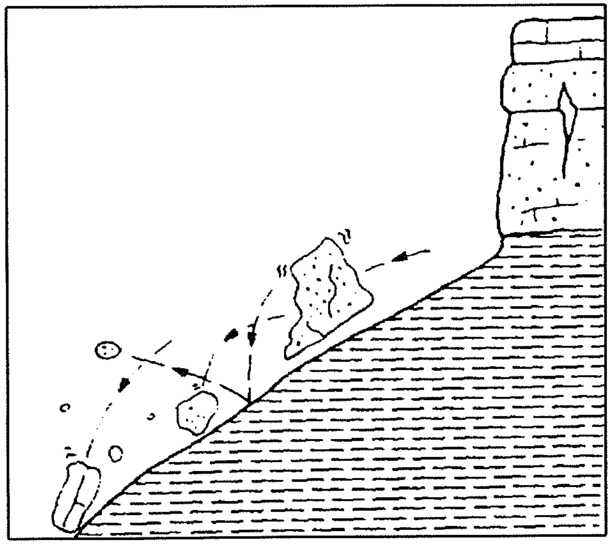
1. Topple



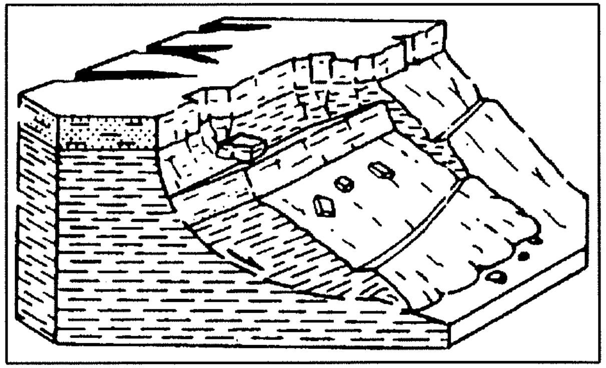
3. Planar slide



5. Debris flow



2. Fall



4. Rotational slide