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Field Trip Guides

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Tararua Wind Farm – Manawatu Destination

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Field Trip 3

LANDSLIDE AND SLOPE INSTABILITY HAZARDS AFFECTING PAEKAKARIKI, THE SH1 COASTAL HIGHWAY, AND THE PROPOSED TRANSMISSION GULLY MOTORWAY ROUTE

Sunday 3 December 2006

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1. INTRODUCTION

Landslide problems affecting the State Highway 1 Coastal Highway from Pukerua Bay to Paekakariki and the proposed Transmission Gully motorway route have received considerable attention in the News Media over the last 12 months. The main issue of debate has centred over whether a Coastal Route Upgrade or building the Transmission Gully Motorway should be pursued for the long term northern road access to Wellington. Geological hazards (landslides and rock falls, debris floods and flows, fault rupture, liquefaction, and tsunamis) that could potentially affect these two routes became one focus in this debate.

After lengthy hearings of submissions on the proposed Western Corridor Plan for Greater Wellington, the report of the Regional Land Transport Sub Committee issued in March 2006 came out in favour of building the Transmission Gully Motorway (TGM) within 10 years (Transit New Zealand and Wellington Regional Council, 2006). The TMG project is still in its early stages of planning and development. In the meantime Transit NZ will not do any further work on proposals for upgrading the existing State Highway 1 Coastal Route. Plans are currently underway for Transit NZ to carry out initial geotechnical investigations, and cost, risk, and value engineering assessments along the TGM route, prior to design and construction.

On this field trip we will look at some of the landslide hazards affecting the existing SH1 Coastal Highway, debris flood problems and remedial works at Paekakariki and Paekakariki Hill Road, slope instability and active faulting hazards that could affect the northern section of the proposed TGM route. The route for the field trip and main stops are shown in Figure 1. Stop locations and points of interest are also shown on many of the accompanying figures. Text and figure references and information relating to those stops is summarised in Appendix 1.

The effects of landslides and debris floods (as defined in Appendix 2) were well illustrated by flood and landslides at Paekakariki in 2003 and 2004. State Highway 1 was again closed at Paekakariki during a rainstorm on 26 August 2006 by gravel and debris from a landslide on Paekakariki Hill Road, which is still closed to repair damage caused by that storm.

Figure 1. Map showing the location of SH 1 north of Wellington (the Coastal Route) and the proposed Transmission Gully Motorway. This field trip will begin at Paekakariki Railway Station and head south to the top of Pukerua Bay Hill for the first stop (S1). We will travel north up the coast, stopping where possible to view features of interest (locations are limited by road works). Stops along SH 1 and the Paekakariki Hill Road are as shown (S2-9). We will then proceed up Te Puka Stream, along the northern end of the TGM route to Wainui Saddle, crossing the Ohariu Fault in the upper valley (Figure 2). This will allow us to look at and discuss the potential geotechnical difficulties for construction of the TGM highway in the narrow fault-controlled valley.

2. REVIEW OF GEOLOGY AND GEOLOGICAL HAZARDS

2.1 Geology and rock condition

The regional geology of the northern Wellington area where the Coastal Highway and the proposed Transmission Gully Motorway route are located is shown in Figure 2 (from Begg and Johnston 2000). This shows that the hills and coastal slope from Pukerua Bay to Paekakariki across to the Transmission Gully route are formed of 'greywacke' bedrock – hard, interbedded sandstone and argillite (siltstone). The greywacke rocks have been folded and faulted by several phases of deformation, and as a result are sheared and closely jointed (100-500 mm spacing). Bedding is variable throughout the region, but north of Pukerua Bay it generally dips steeply (50°–80°) to the east and northeast into the coastal slope (Figure 3). There are extensive bedrock exposures on the rock platform along the coast foreshore and in road cuts along SH 1and the railway line *[STOPS 1b and 2]*.

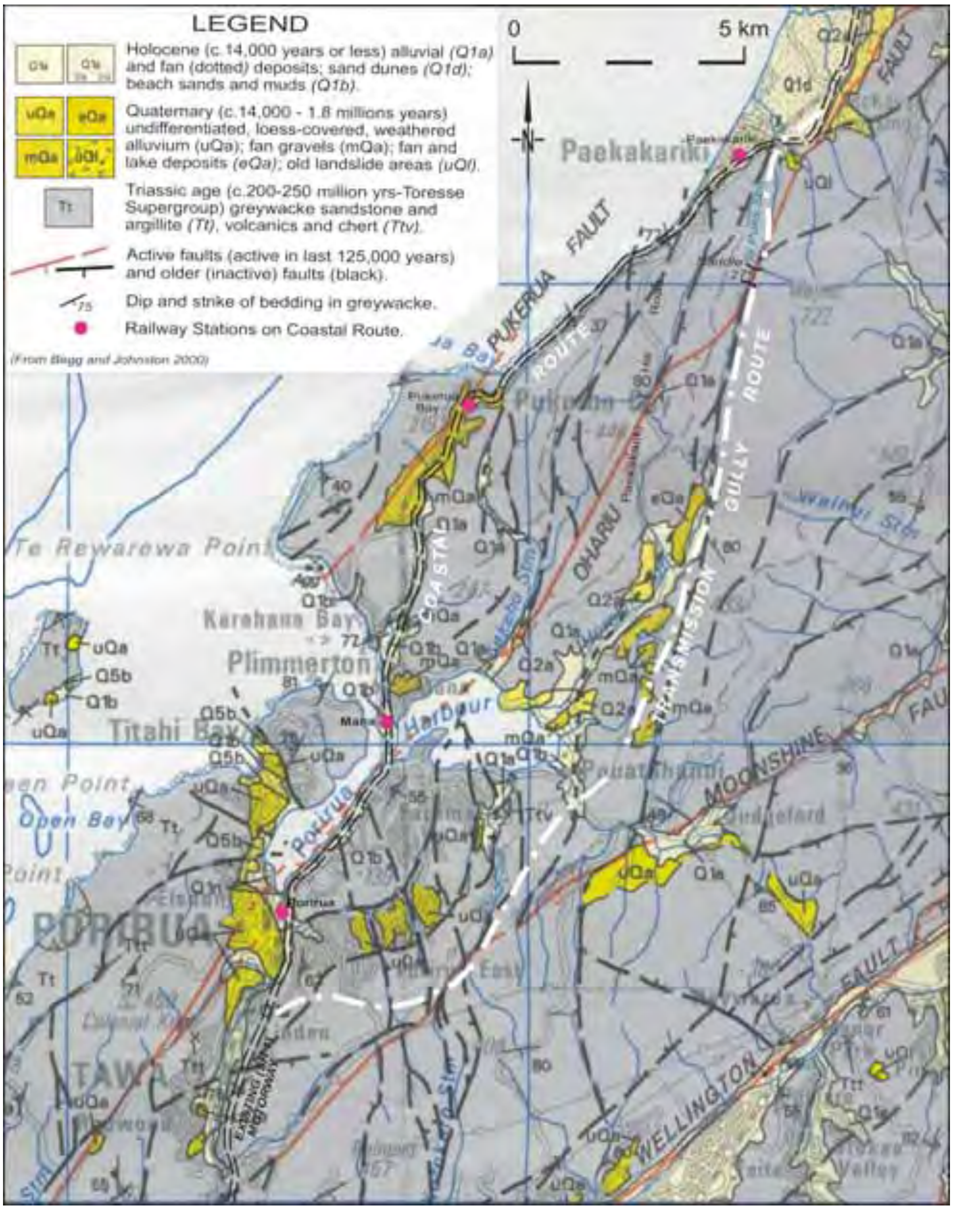

Figure 2. Geological map of the northern Wellington area showing main rock types, areas of recent and older alluvium, loess, and fan gravels, and geological structures in relation to the Coastal and Transmission Gully Motorway routes. Note that both routes are aligned along major active faults that are considered to be potential areas of fault rupture hazard that must be taken into account *(after Begg and Johnston 2000[8])*.

The near-surface rock of the lower slopes along and immediately above the highway and railway line is slightly weathered to unweathered, but is generally closely jointed and fractured. On the upper slopes the rock is moderately to highly weathered and is overlain by a thin (200–400 mm) surface layer of soil, loess (wind deposited silt) and colluvium ~3–6 m thick, which exhibits widespread superficial soil creep and incipient slumping in places. Similar bedrock occurs along the TGM route, although rocks forming hill slopes in the area are more (moderately to completely) weathered, overlain by colluvium, loess, and alluvial fans of variable thickness (weathered rock and overlying soils often referred to as 'regolith').

Superficial colluvium and scree deposits of variable thickness are present over most of the coastal slope, except where there are steep (~50–60°) rocky bluffs. Along the foot of the slope below and above the railway line there is a thick wedge of old rock scree, now covered in grass and low coastal scrub. This material (coarse, loose angular gravel), up to 10 m thick under the railway embankment and ~1–3 m thick above it, has a natural angle of stability of about 35°. Scree deposits extend up to ~50–70 m up the slope in many places and infill depressions and gullies at the bottom of the slope (Hancox 1981a, 1982b), At higher levels, thick deposits of old solifluction gravels are widespread, especially in the heads of gullies from which recent debris flood deposits were derived (Figure 4). Areas of loess and sand occur in the valley south of Pukerua Bay, and deposits of old bedded beach gravels and weak loess and dune sand outcrops in the high road cut along SH 1 on the north side of the Pukerua Bay hill.

2.1.1 Geological structure

The main geological structures in the region are active faults***** and old faults (Figure 2). Two major active faults are mapped in the area. The Pukerua Fault passes through Pukerua Bay and is inferred to continue offshore. The Ohariu Fault extends from Porirua Harbour through the hills to the north, and at the northern end along Te Puka Stream on the western side of the TGM route. The TGM would cross the Ohariu Fault on the northern side of Wainui Saddle (Figure 3), either on a bridge or cut and fill (discussed later).

Both the Ohariu and Pukerua Bay faults are capable of generating earthquakes of M 7.2–7.5 at intervals of about 2000 to 5000 years (Begg and Johnson, 2000; Langridge et al. 2005), resulting in shaking intensities of MM9–MM10 in the Kapiti area, as is the Wellington Fault. There are also other inferred active faults offshore (such as the continuation of the Wairau Fault west of Kapiti Island) that are capable of causing MM9 intensity shaking in the area, as will be discussed later.

Most of the major geological structures in the area are old faults which do not show recent movements. Preferential erosion along zones of crushed and sheared rock has formed topographic lineaments by the alignment of gullies and linear stream courses. An example of one such lineament will be seen at Stop 3 (Figure 1), where a deep gully has been eroded along the crush zone of an old fault mapped to the west of the Ohariu Fault (see Figures 2 and 3). Crushed rock associated with a similar old fault 1 km to the south was responsible for a large slope failure in 1981 (Hancox 1981a).

** **Active Faults** are defined as faults that have moved in the last c.125,000 years, and are likely to move again in the foreseeable future causing a large earthquake (~ ≥ M 7) and possibly ground surface rupture. The active fault classifications referred to in this report are those defined in Appendix 1 of the MFE Active Fault Guidelines (Kerr et al. 2003).*

Figure 3. Aerial view looking south along the coast from Paekakariki *(P)* to Pukerua Bay *(PB)*. It clearly shows the marked geomorphic differences between the Coastal Route, with the steep coastal cliff above *SH 1*, and the proposed Transmission Gully Motorway route, the northern part of which follows the strongly linear valley of Te Puka Stream. Others features shown here that will be seen on the field trip include the Fly-by-Wire Gully *(fg)*, Reservoir Creek *(rc)*, Wainui Saddle *(ws)*, and the topographic lineament *(l)* near the Fisherman's Table Restaurant *[S3-6 - locations of STOPS 3, 4, 5, 6]*.

2.1.2 Geomorphology

The coastal section of SH1 between Pukerua Bay and Paekakariki lies at the foot of a steep wave-cut slope, which rises to a height of about 150–250 m at an average slope of about 40°. However, there are also many very steep (50–60°) rocky bluffs and spurs (Figures 3 and 4). The slope is dissected by several deeply incised streams which extend from the ridge crest to the coast, where they have discordant junctions due to geologically recent uplift. The streams are separated by steep bedrock spurs with broad truncated triangular ends, through which railway tunnels have been excavated. The lower slope has also been modified in places by fills for the NIMT railway line and road embankments, near-vertical unsupported rock cuts between the tunnels, along SH 1, and in two places near Paekakariki by quarrying for railway line ballast (Figure 4). The slope is now mainly grass-covered, but was formerly clad in native scrub and bush, of which a few small remnant areas remain. The toe of the slope has been protected from wave erosion since the road and concrete sea wall was completed in the late 1930s.

North of Pauatahanui the TGM route follows the linear courses of Horokiri and Te Puka streams, rising from near sea level to about 275 m at Wainui Saddle (Figures 3 and 4). Slopes along the TGM route extend up to 200 m above proposed road level at an average slope of about 25°, more gently than along the coastal highway. Apart from superficial soil and debris slides there are no identified large bedrock slides along the TGM route. The very large (about 4 million m^3) prehistoric landslide at the northern end near SH 1 (Figure 4) may have occurred as result of the last movement on the Ohariu Fault about 1000 years ago (Begg and Johnson, 2000; Langridge et al. 2005). This old landslide is inactive, and does not impact on and will not be affected or modified by the proposed motorway.

2.2 History of slope instability on the Paekakariki Coast

The steep coastal slope between Pukerua Bay and Paekakariki has a recent history of landsliding and slope instability problems, and is mapped as having high to very high earthquake-induced landslide (EIL) susceptibility (Brabhaharan et al. 1994; Wellington Regional Council, 1995). Figure 4 shows the locations of the main areas where landslides problems have occurred in the last 25 years. Figure 5 show areas of EIL susceptibility in the area, including possible 100 m high cut slopes (with moderate to high EIL susceptibility) along the TGM route

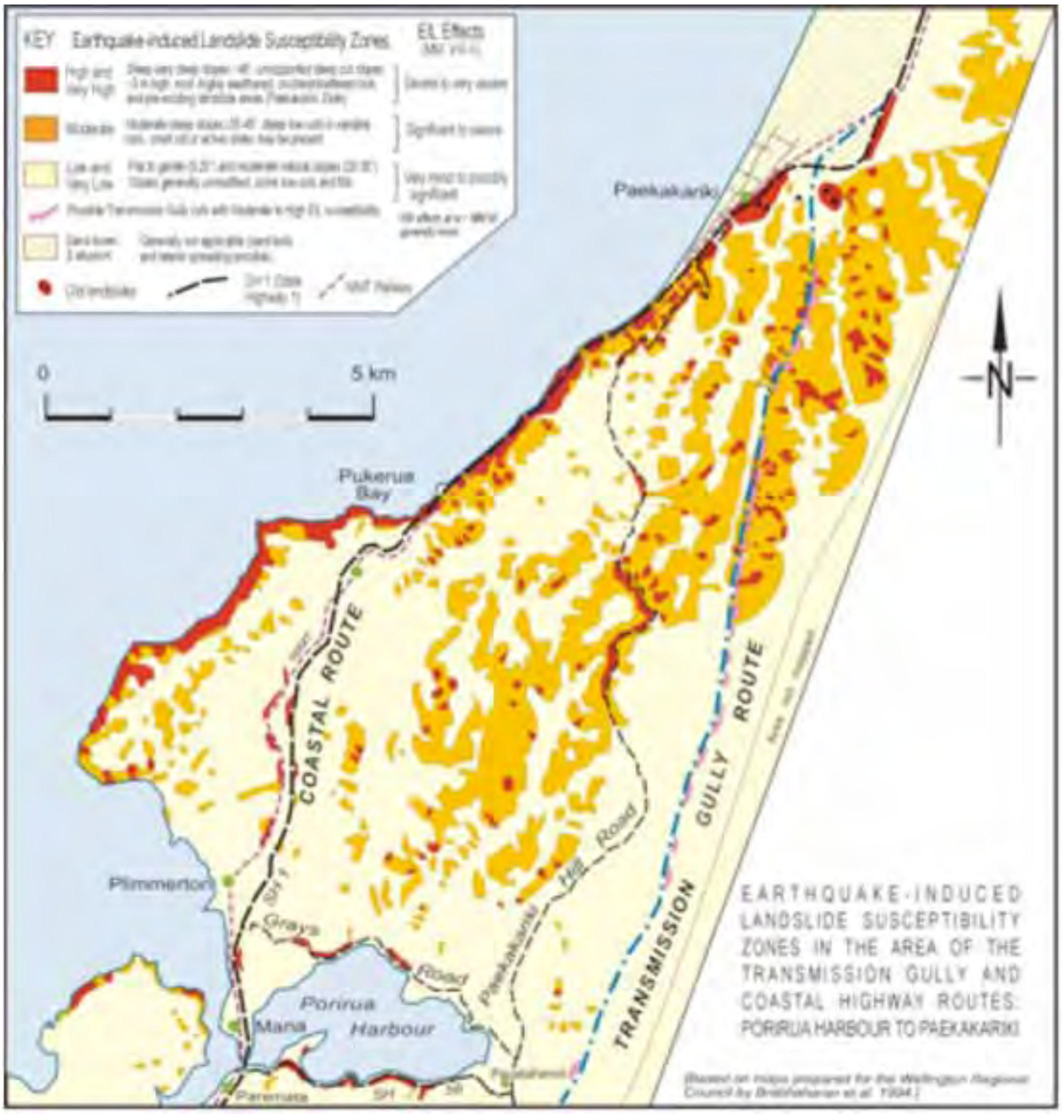

Figure 5. Map showing earthquake-induced landslide susceptibility in the area of the Coastal Highway and proposed Transmission Gully Motorway route from Porirua Harbour to Paekakariki area *(after Brabhaharan et al. 1994; Wellington Regional Council, 1995).*

Several geomorphic features on the coastal slope appear to be the scars of large prehistoric landslides which may have been caused by large earthquakes. One such feature on the southern side of the Beanpole Corner landslide (Figure 4) has an eroded arcuate head scarp with a shallow gully extending 200 m from ridge crest to the coast, where the rock platform appears to have been displaced and replaced by a boulder beach in a small bay (Figure 6). Other old failure scars are present at the top of the slope c. 500 m northeast of Beanpole Corner (Figure 7). Incipient slumping along the edge of the cliff suggests this is one of several possible locations where large landslides could occur on the coastal slope in the future, particularly during a large earthquake on the Wellington Fault or another nearby active fault (see Figure 4).

The coastal slope has not undergone MM9 or MM10 shaking in the last 150 years, over which time large sections of its toe have been undercut and destabilised by cuts for railway and SH 1 construction, and quarrying, leaving it potentially more vulnerable to slope failures.

Figure 6. Aerial photo of the coastal slope at Beanpole Corner, where extensive stabilisation work was completed in 1990. Also shown are protective debris fences (*df*), rock shelter *(rs)* at tunnel portal, 1980 debris slide scar, steep, and a possible prehistoric landslide *(pls, note displaced rock platform at coast and gravel beach),* and scree *(sc)* deposits along the base of the slope *[STOPS 1 and 2].*

Figure 7. Aerial view of coastal slope south of Tunnel 7 *(T7)* showing old landslide scars *(ols)*, incipient slumping at the top of the slope, and areas where large landslides could occur *(pfa)* in the future, particularly during a large (MM9-MM10) earthquake on the Wellington Fault. The site of a 1999 rock fall from the northern portal of Tunnel 7 is also shown *[STOP 2].*

Looking back to the time of early European settlement, there is no evidence of any significant slope failures in the Wellington area from the 1848 Marlborough earthquake even though building damage was severe (Hancox et al. 1997, 2002). Shaking intensities of MM7–8 in the Kapiti area would have been strong enough to cause failures of cut slopes during the 1848 earthquake, but little slope modification had been undertaken that early in the history of the region. Although there are no records of such failures, small slides and rock falls may have occurred on the steep slopes along the coast, but were not reported.

Historical earthquake-induced landslides in the area resulted primarily from the Wairarapa earthquake in 1855 (Hancox 2005), by which time small cuts had been made for roads. Slope failures caused by the 1855 earthquake were reported to be common along the Paekakariki Hill Road, which was constructed in 1849 utilising many cuts and fills and served as the main route north until the present SH 1 opened in 1939. There were no reports of landslides on the coast south of Paekakariki as there was no road in that area (Hancox et al. 1997, 2002; Hancox 2005). However, there are old rockfall deposits on the coast south of Pukerua Bay which may date from the 1855 earthquake, suggesting that similar landslides probably occurred north of Pukerua Bay as well. Unfortunately, proof of these failures (rock fall deposits) is likely to have been obliterated by road construction in the 1930s. The large landslide reported at Paekakariki after the earthquake is inferred to have been the cause of the prominent scar high on the cliff above the old quarry near the Paekakariki railway station (Figures 4 and 8). It is unlikely that was the only large landslide on coastal slopes in the area – just the only one that was reported.

Figure 8. Aerial view of the site of 1855 landslide and former quarry at Paekakariki, and possible large future EIL failure areas *(pfa)* and debris runout areas *(dra)* near the Railway Station *[STOP 5]*. Also shown are soil slides *(sl)* and erosion gullies *(g)* in the Fly-by-Wire Gully, the motel *(m)* that was inundated by debris flood gravel, and the SH 1 culvert *(c)* blocked by gravel during storms in 2003, 2004, and 2005 *[STOP 4 - see Figures 10 and 13 also]*

The shaking intensity from the two Masterton earthquakes in 1942 was only MM 6 to 7 in the Wellington area, which is not high enough to trigger large slope failures. However, a moderately large debris slide at Goat Point at Plimmerton during the 24 June 1942 earthquake blocked both lines of NIMT railway. A few small soil slides also occurred along the road and railway between Plimmerton and Paekakariki. These slope failures were minor, and the railway was reopened about 7 hours after the event.

The Pukerua Bay-Paekakariki section of the NIMT railway has been prone to instability problems since completion in 1886, with slope failure processes apparently accelerated by cuts for railway construction, and also removal of native bush cover (Hancox 1981a, 1982b). A number of slope failures have occurred along this section of the railway line in the last 50 years. There have been several local rock and debris falls from steep cuts (~¼H:1V, ~76°) and tunnel portals - for example at the southern portal of No 6 tunnel, where a rock fall shelter was constructed (Figure 6). A significant rock fall also occurred at the north portal of No 7 tunnel in 1999 (Figure 7), disrupting trains and SH 1 traffic for several days while debris was cleared and a protective fence erected *[STOP*

2]. Most of these failures were relatively small rock and scree falls which occurred during or after heavy rainfall. However, some slope failures have also occurred during dry weather, without any triggering event or failure history. The rock and debris fall on 19 November 1980 which derailed a south-bound train (see Figures 4 and 6) is one example of such an event.

2.2.1 Beanpole Corner Landslide

The most serious landslide problem to have affected the Pukerua Bay-Paekakariki railway and potentially SH 1 in the last 25 years is the large (~30,000 m^3) rock and debris slide at Beanpole Corner about 2 km north of Pukerua Bay. Problems at this location began after the railway was realigned around a tight bend, when the old (No 12) tunnel was abandoned in 1890 after a brick from the tunnel lining blinded an engine driver. It was speculated that deformation of the tunnel due to rock mass creep caused the lining failure (old NZ Railway records Ref 259/24). Beanpole Corner was a well known trouble spot that caused problems for at least 40 years from 1942 to 1990 (Hancox 1981b). Increased activity of the slide area occurred in the early 1960s when falls of surficial rock debris blocked the line on several occasions, most notably on 19 September 1961 when a goods train was derailed (NZR files). Between 1958 and 1961 the line was blocked on 11 separate occasions, as result of which a 4 m high rail and sleeper debris fence was constructed to protect the line in 1962.

Following several periods of heavy rainfall in 1979 a large slumped area developed 120 m up the slope (Inset A Figure 4, and Figure 6). After extensive site investigations and ongoing concern about landslide risk to the railway and SH 1 at this site, the slope was stabilised in 1990 by removal of 31,000 m^3 of material from the head of the slide (Saul 1992). The upper slopes have been stable since those works were completed, and although minor surface ravelling failures of loose debris have continued on the lower slopes, this material has been effectively contained behind the debris fence. However, because of the poor rock condition at this site and its long history of instability, there are still concerns about the long term stability of the Beanpole Corner slope, especially during strong earthquake shaking.

2.2.2 Debris floods and flows

Debris inundations (debris flood gravel deposits – see Appendix-2) have also affected the railway periodically. The gully 500 m north of tunnel No 7 is one area that was affected several times by debris flood deposits in the last 40 years, following a series of slope failures from a steep spur of crushed and weathered rock near the mouth of the gully (Figures 4 and 9). Although this area has not been very active since 1981, and is now covered with vegetation, the scar area is unstable, with a large incipiently slumped area above it (Figure 9). Other debris flood deposits have occurred in gullies near Beanpole corner in the 1970s and 1980s (Hancox 1981a, 1982b).

More recently, flooding and debris flood gravels blocked SH 1 and stopped trains during the October 2003 Paekakariki floods (Figure 10). Other parts of the railway to the south of Paekakariki were also affected by gravel inundations during that event, but no significant rock falls were reported (Hancox 2003).

Figure 9. Aerial photo of the gully 500 m north of Tunnel 7 (see Figure 4) where debris flood deposits *(df)* caused problems for the railway from 1973 to 1981 (lower right). This material was derived from debris slides of weathered crushed rock (associated with major fault in gully) on the spur end. Note slumping *(slu)* above slide scar, and also in old scree along top of railway cut *(s)* - below older landslide area *(ols)*. These and other potential EIL slope failure areas *(pfa)* are indicated.

Figure 10. Aerial photo showing the gravel *(g)* from the Fly-by-Wire gully *(fg)* deposited around the Belvedere Motel *(M)* at the bottom of the Paekakariki Hill Road *(HR)*, and across SH 1 during the rainstorm on 3 October 2003. A new stream channel *(sc)* was dug the day after the flood. The hill road was unaffected by the flood as the debris passed through the culvert *(c)* below the road. The BP Service Station *(BP)* was flooded but was largely unaffected by gravel inundation. A small soil flow slide *(sf)* spilled on to the hill road ~70 m south of the gully exit. *[STOP 4 - see Figures 8 and 13 also]*

2.2.3 October 2003 Rainstorm at Paekakariki

The rainstorm that hit Paekakariki on Friday 3 October 2003 affected many parts of the Wellington region causing flooding and slips that closed roads, with the Kapiti Coast being one of the worst affected areas. Rainfall appears to have been much heavier in the Paekakariki area, where it was probably in excess of 100 mm in 24 hours, causing severe flooding and extensive landsliding, gully erosion and debris flood damage on the steep coastal hills (Hancox 2003). The area of greatest ground damage coincides with the area of maximum rainfall accumulation indicated by radar imagery. This shows that the heaviest rainfall occurred in a narrow band about 10 km wide and extending from just south of Kapiti Island and directly across Paekakariki towards Upper Hutt (Figure 11). Data provided by NIWA suggests that the average return interval of rainfall in the most damaged area (>82 mm in 4 hours) is estimated from nearby rain gauges to be greater than 125 years. In other areas where there was less rainfall the landsliding and flood damage was generally minor.

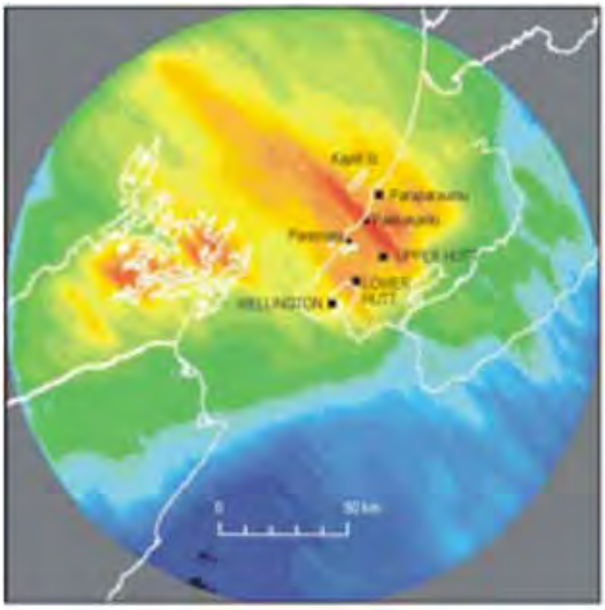

Figure 11. Radar-derived rainfall accumulation image for Friday 3 October 2003, showing total rainfall over the Wellington region for the period 6:45 am to 10:00 pm. Red is the heaviest rain and blue is the lightest. The band of heaviest rainfall coincides with the severe landsliding and flood damage observed in the Paekakariki area *(Image from MetService)*

The areas most affected by landslides and debris floods were around the junction of the Paekakariki Hill road with State Highway 1, and across the hills ~2 km south of Paekakariki, especially in the Fly-by-Wire gully above the BP Service Station and Belvedere Motel, and the Hill Road gully ~700 m to the south (Figure 12). About 3000 m^3 of gravel from the flooded Fly-by-Wire gully was deposited around the Belvedere Motel buildings and across SH 1 at the bottom of the Paekakariki Hill Road (Figures 3 and 4). All of the flood water and gravel was passed through the culvert under the hill road, which was not affected at this site. Based on the lack of damage to buildings, and supported by TV coverage during the event, the gravel was deposited gradually as a debris flood over several hours, not as a single debris flow. The buildings on the east side of SH 1 at the bottom of the Paekakariki Hill Road are built on an old debris fan formed at the gully exit. This makes it potentially a dangerous site for future flooding, debris floods, and possibly debris flows which can cause much more damage.

The Fly-by-Wire and Hill Road gullies were severely damaged by numerous shallow slumps and deep erosion gullies (Figures 12 and 14). Geomorphic evidence suggests that the flood was a very rare local event with a return period of more than 100 years, or possibly several hundred years. A large amount of soil and gravel from steep slopes and gullies was transported down the stream and deposited on the debris fan around the motel buildings and across SH 1. Gravel from these gullies and deposited in stream channels has continued to be transported downstream during severe rainstorms in February 2004, January 2005, and August 2006.

Figure 12. Map showing landslides, erosion gullies, and debris flood deposits resulting from the October 2003 Paekakariki flood. The main areas affected were the Fly-by-Wire gully and Hill Road gullies. Gravel from the former caused damage to a Historic Building and motel located on the debris fan at the bottom of the gully. Sites 4–7 were the most damaged parts of the hill road were *[STOPS 8 & 9].* The total cost for road repairs was about $500,000, and the road was not reopened until early November 2003. A similar event in February 2004, prompted construction of debris fences to control gravel deposits. Removal of gravel deposited at the SH 1 culvert in the two events cost around $750,000.

Figure 13. At the bottom of the Paekakariki Hill Road debris flood gravel from the Fly-by-Wire Gully was deposited slowly around the Belvedere Motel, buried cars and infilled a swimming pool. However, the gravel did little damage to the buildings and was eventually removed. A gravel bund now protects the site, and the motel has since reopened, despite similar debris flood events in 2004 and 2005 *[STOP 4]*.


Figure 14. Typical erosion gully formed in the hills above Paekakariki during the October 2003 rainstorm *[STOP 9]*. Gravel blocked culverts and caused extensive washouts on Paekakariki Hill Road. There are no historical examples of such gullies, nor are they seen elsewhere in the area. It is inferred that the rainfall intensity that caused these gullies (in old periglacial gravels) has not occurred in the Paekakariki area since the clearance of native forest about 150 years ago. The top photo taken after the Jan 2005 rainstorm shows the effectiveness of simple debris fences.

Damage to the northern end of the Paekakariki Hill Road was the result of deposition of debris flood gravels, which blocked culverts in several places (Figure 14), and sent flood water surging down and over the edge of the road. Road cuts on the hill road were generally not affected, with only a few small rock and soil falls observed north of the summit. Gravel trapped behind undamaged fences and gates above the road suggests that this material accumulated slowly. Most of the silt and sand was carried away in flood water, which flowed over the road, washing out road edge fills and undermining the road in several places. This mechanism suggested that steel catch fences above the road and culvert entrances could be used to trap gravel during floods, while allowing water to pass through culverts (Hancox 2003).

After a second storm in February 2004 caused similar damage, simple debris fences (consisting of rails and old rubber tyres) were erected in three of the hill road gullies (Figure 15). These fences effectively trapped and retained gravel during further rainstorms in January 2005 and August 2006, and generally prevented further damage to the road, except at the northern gully *(Stop 8, Figure 12)* where gravel escaped under the fence (because of poor maintenance after the previous flood). Gravel again blocked the culvert at this location, sending flood water down the road and causing collapse of the road edge fill *(Stop 7, Figure 12),* and spilling debris on to and closing SH 1. The Paekakariki Hill Road was closed from 26 August to early November 2006 to allow the damage to be repaired *(Stops 7-9)*.

Geomorphic evidence shows that deep gully erosion has not occurred in the Paekakariki area in the last few thousand years (Hancox 2003). Removal of forest cover in the last 150 years has made it possible for gullying to occur, and it will continue now that erosion scars have formed. Debris floods will continue to cause problems for SH1 at and north of Paekakariki unless measures are taken to stop the erosion and trap the gravel in the heads of streams. Similar but much less severe debris flood problems occurred in October 2003 along Te Puka and Horokiri streams at the northern end of the Transmission Gully route (Figure 12). Such events will occur in those areas in the future and protective measures will be needed along the TGM route to deal the problem. There is no evidence of debris flows in the Paekakariki area, but they could occur along both routes in the future given the right conditions (e.g. landslide into flooded stream).

Figure 15. Debris fences (railway iron and old tyres) were recommended after severe rainstorms in October. 2003 and February 2004. These fences were finally constructed in April 2004 (after the 2nd '100- year storm' in 6 months) and prevented damage during a storm in January 2005 (see Figure 14).

2.3 Earthquake-induced landslides in the Paekakariki area and TGM route

Over the last 65 years earthquake-induced landslides have caused few problems for the NIMT railway and SH 1 from Pukerua Bay to Paekakariki. However, the earthquakes that have occurred since the railway was completed in the late 1880s are at the lower shaking intensity threshold where landslides occur (MM6– 7, see Appendix-3). Landsliding on the coastal slopes south of Paekakariki is likely to be much more extensive during future strong earthquake shaking (MM8–10). The EIL hazard along in this section of coastline is rated as high, with relatively large rock and debris falls expected to affect both the railway and SH 1, possibly causing significant damage, during an earthquake on the Wellington Fault or another nearby active fault, locally producing MM 9-MM10 shaking

In the early 1990s the Wellington Regional Council commissioned a series of studies to assess seismic hazards in five study areas in the region, including those resulting from earthquake-induced slope failure (Brabhaharan et al. 1994; Wellington Regional Council, 1995). The methodology used to assess EIL susceptibility involved integration of factor maps for: slope angle, geology, slope modification, and existing landslides to determine different classes of EIL susceptibility, as shown in Figure 5 for the Paekakariki area simplified into three classes, in which the expected effects during strong earthquake shaking (MM8–10) are as follows:

(1) High -Very High: - Severe to very severe (widespread large landslide, 10^4–10^6+ m^3).

(2) Moderate: - Significant (small to moderate failures - 10^3–10^4 m^3).

(3) Low - Very Low: - Minor and very minor (< 10^3 to a few boulders).

Landslide effects at MM7 or less are likely to be minor (Appendix 3) as they were in 1942 (Note: terms used to describe landslide size are also defined in Appendix 3).

Figure 5 shows that most of the area south of Pukerua Bay has low and very low EIL susceptibility, with only small areas of high susceptibility (red) on the Coastal Route north and south of Plimmerton.

On the TGM route south of Pauatahanui there are several areas rated as moderate (orange). Along the TGM route, areas where cuts 50–100 m high would be required for the 'earthworks option' are rated moderate–high (pink areas), but as low–moderate for the 'viaduct option' (most cuts are 30 m high or less; 13 cuts ~30–52 m high)4.

The northern sections of both the coastal highway and the Transmission Gully Motorway routes from Pukerua Bay north have notably higher earthquake-induced landslide susceptibility (Figure 5). The steep coastal slope from Pukerua Bay and Paekakariki on the Coastal Route has mainly high to very high susceptibility, with only short sections rated as moderate. By contrast, the natural slopes along the

Transmission Gully route in Te Puka and upper Horokiri streams have much lower EIL susceptibility- mainly rated as moderate, with only a few small areas of high susceptibility. This is consistent with the generally lower overall slope height, flatter average slope, and lack of deep seated landslides along the TGM route (Figures 16 and 17).

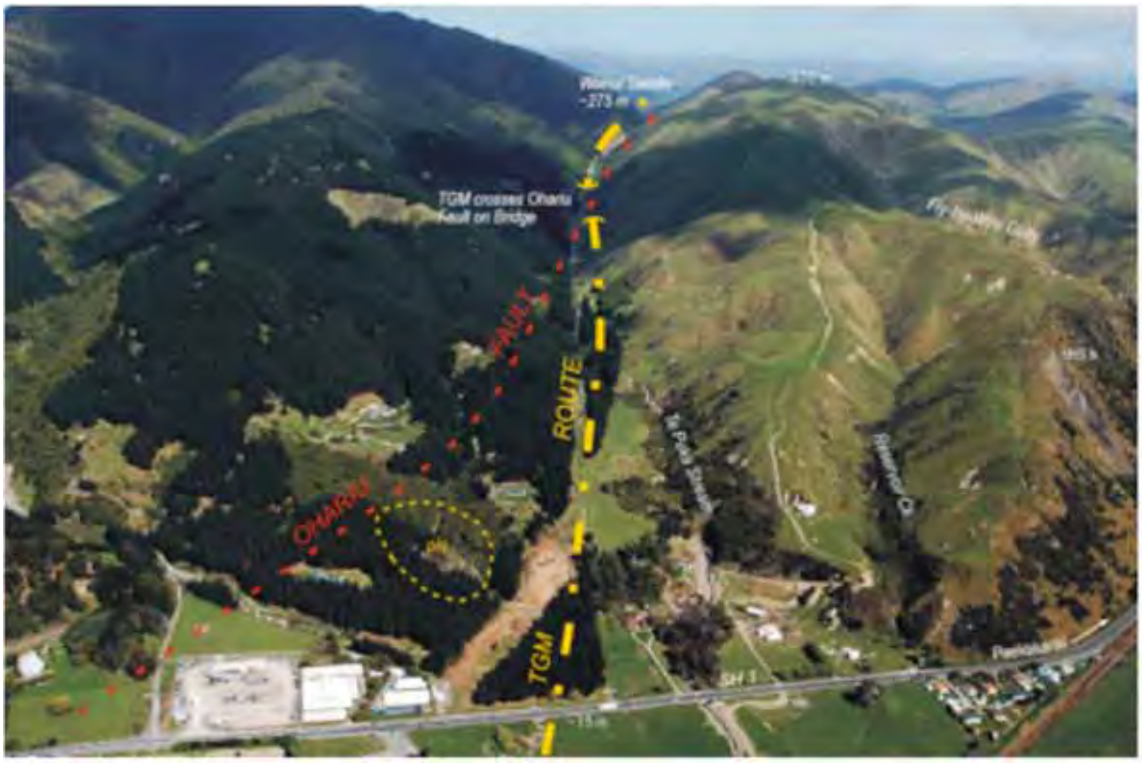

Figure 16. Aerial view looking south along proposed Transmission Gully Motorway Route, showing its position in relation to the Ohariu Fault (crossed by a bridge, or possibly on a cut and fill in the forested area on the east side of Te Puka Stream), and an inactive prehistoric landslide area *(pls) [STOPS 10+]*. Note that the slopes along the TGM route are lower and less steep than those along the coastal highway, with few landslide areas except for shallow soil slides *(sl)* formed in recent storms - during which culverts *(c)* under SH 1 were blocked by gravel *[STOP 6]*.

On almost all the steeper slopes (>35°) of the coastal cliff from Pukerua Bay to Paekakariki, and above the former quarry areas landslide susceptibility is rated as high to very high (Figure 5). Unsupported steep cuts for the NIMT railway and SH 1 at the toe of the slope contribute to this rating, making the overall slope more vulnerable to failure in strong earthquake shaking of MM9 and MM10. Shaking of this intensity could trigger moderate to large landslides from the top of the slope in several places along the Paekakariki coast. The possible locations of these landslides are shown in Figure 4. Volume estimates for such failures range from about 20,000 to 450,000 m^3, and even 1 million m^3 or greater at one location (Hancox et al. 2005). They include several areas above or adjacent to historical slope failures (Figures 6 and 7), and areas of oversteepened (>60°) rock slopes above former quarry sites at Paekakariki (Figure 8).

Estimates suggest that it could take up to 2–3 months or possibly longer to clear landslide debris from the Coastal Highway after a MM9–10 earthquake. A very large ridge crest collapse at only one of several possible sites could take several months to clear, especially if there were continued failures from the head scarp. The 3-month closure of the Manawatu Gorge by a 100,000 m^3 landslide triggered by the February 2004 rainstorm (Hancox and Wright, 2005) demonstrates the potential for large landslides to cause long road closures.

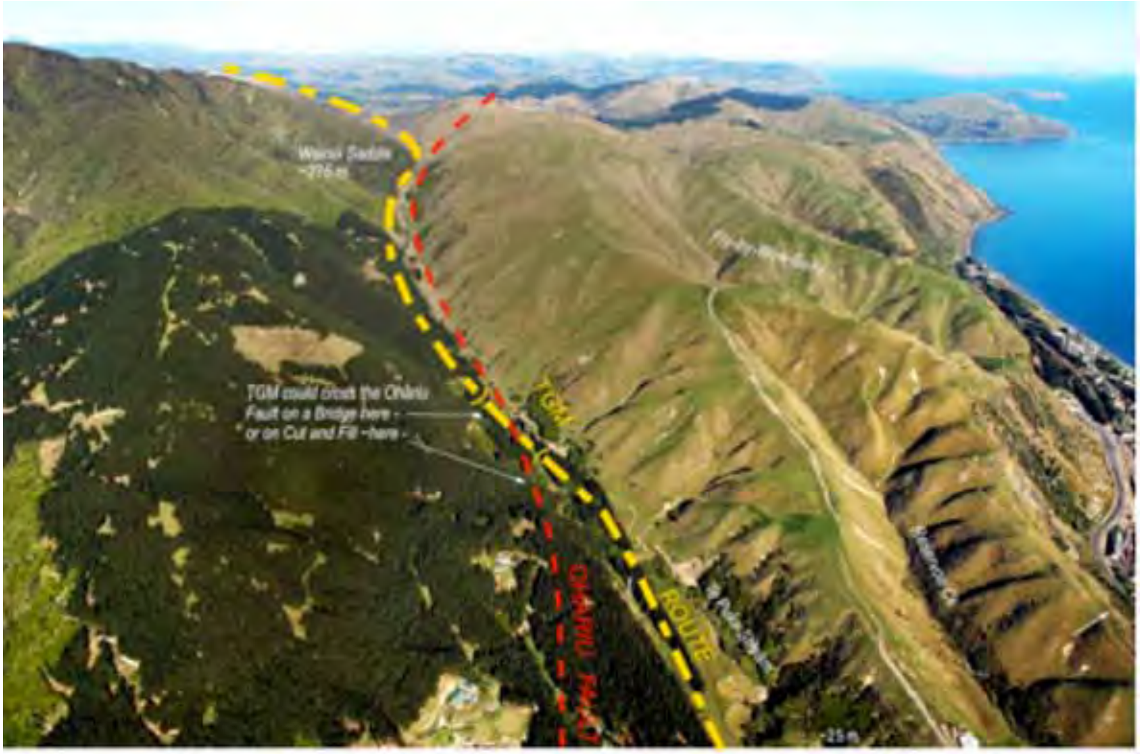

Figure 17. Closer view (looking south) of the northern section of the TGM Route up Te Puke Stream, showing its position in relation to the Ohariu Fault - which could be crossed on a bridge, or on a cut and fill. This view shows the Field Trip route up Te Puke Stream (on 4WD track lower right) *[STOPS 10+]*.

Although there are currently no modified slopes along the Transmission Gully route (apart from farm tracks), construction of the proposed motorway would result in cuts with either moderate to high or low to moderate EIL susceptibility (pink areas in Figure 5). Earthquake-triggered slope failures expected from proposed TGM cuts could range from small to moderate, depending on their height and support measures used. Only small to very small failures are expected on natural slopes with moderate and low EIL susceptibility.

Because the natural slopes along Transmission Gully are lower and less steep than those along the coast, no large landslides are expected along the TGM route during an MM9–10 earthquake. However, small to moderate failures (c.1,000–20,000 m^3) could occur, even on well designed cut slopes (no steeper than 45° and generally less than 50 m high), but few failures are expected on cuts of 35° or less. Debris clearance times for such failures could range from 2–5 days or possibly slightly longer. However, a closure of several weeks or months is most unlikely as there is little potential for very large landslides to occur.

Major engineering works are often used to protect highways from ongoing slope failures at some critical sites, but generally this is not done to mitigate effects of large landslides that might occur during very strong earthquakes. Although such events might trigger only one large landslide (at several possible sites) on the coast, the debris could take several months to clear. This needs to be considered in planning transportation routes, as it is generally not cost effective to mitigate the effects of such large-scale failures before they occur, unless it can be done by minor route realignment. Extensive and costly slope protection works to reduce landslide risk are more difficult to justify if an acceptable alternative route, such as Transmission Gully is available. Although both routes can be considered viable with respect to geological hazards, the alternative TGM route appears to offer better long-term route security, given the potentially greater vulnerability of the existing SH 1 coastal highway to large landslides.

2.4 Earthquakes and ground shaking

Earthquake-induced landslides, liquefaction effects and other ground damage occur when shaking intensities reach or exceed MM7. Earthquake scenarios used in early Transmission Gully studies (Perrin and Van Dissen, 1995; Beca 2004) indicate that both an Ohariu Fault earthquake and a Pukerua Fault event would yield intensities of MM 9 to 10 in the area of the Coastal Highway and the TGM route. Shaking of intensity MM9 to 10 could be expected from earthquakes on the Wellington Fault, the Wairarapa Fault (similar to the 1855 earthquake), and probably also the Wairau Fault offshore. Less well constrained is a Subduction Zone earthquake, which could also result in MM 9 to 10 intensities in the Kapiti coast area.

The mean return periods previously estimated for various shaking intensities in the Kapiti area1 were calculated from the old Smith and Berryman (1986) model to be: MM6 – 6 years; MM7 - 21 years; MM8 - 67 years; MM9 - 220 years; and MM10 - >1000 years. More recent modelling of MM intensity return periods in the Kapiti area using a probabilistic seismic hazard model and active fault catalogue (Stirling et al. 2002), yields somewhat longer return period, as follows: MM6 - 10 years; MM7 - 45 years; MM8 - 180 years; MM9 - 800 years; MM10 - 8000 years (pers. comm. Warwick Smith, 2005).

However, the longer return periods currently estimated for stronger shaking (MM8–10) in the Kapiti area should not be taken to imply that the seismic risk is considered to be lower now than it was in the past. Shaking intensity is only one, rather imprecise measure of seismic hazard, and does not take account of other factors such as ground and spectral accelerations, time history data, fault fling and directivity for specific earthquake events. These are all vital parameters that are needed for the dynamic analysis of interchange and retaining structures, bridges, and viaducts required for both the Coastal and TGM routes, and they would need to be determined by further detailed studies.

Although dynamic analysis to simulate earthquake effects is normally carried out for the design and construction of man-made structures (such as buildings, bridges, and viaducts) it is generally not thought to be applicable to assessing the performance of unsupported, non-homogeneous rock mass, in which failure will probably be controlled by randomly spaced and oriented rock mass defects (Ramsay 1997). For assessing the likely behaviour of rock slopes during earthquakes, qualitative assessments of slope stability and performance based on observations and precedent evidence from natural and cut slopes in the area are considered to provide appropriate data for cut slope design. Shaking duration is also important for landslide initiation, so larger, long-duration earthquakes tend to be much more damaging to slopes.

2.5 Fault rupture

Previous studies (Perrin and Van Dissen, 1995; Beca, 1996, 2004) have assessed possible fault rupture hazard to the present SH1 coastal highway and the proposed TMG route, and concluded that both routes could be directly damaged by ground surface rupture only on the Ohariu Fault. Recent studies suggest that the Ohariu Fault has average single event dextral horizontal displacements of about 3.7 m at a mean recurrence interval of about 2000 years, and last moved around 1000 years ago (Langridge et al. 2005). However, in any future studies the possibility of fault rupture on the less active Moonshine Fault at the southern end of the TGM route (Figure 2) would also have to be considered.

On the coastal route such ground surface fault displacement could cause the loss of the SH 1 bridge at Paremata, and possibly damage to motorway embankment fills between Porirua and Paremata along the east side of Porirua Harbour. Bridges, interchange structures, and road fills for the Transmission Gully Motorway can be designed to allow for fault displacement without total failure, but this does not necessarily apply to the present Coastal Route.

In the upper Te Puka Stream southeast of Paekakariki, the Ohariu Fault lies on the western side of the Transmission Gully Motorway route (Figure 2; Figure 17). To allow for the possibility of future fault movement, the proposed motorway could cross the fault on a bridge structure on the northern side of Wainui Saddle. This would require detailed seismic design consideration to reflect the close proximity of the Ohariu Fault, and to determine the exact position of the fault, and likely displacement values. However, although significant damage might occur, the possibility of catastrophic failure of such structures is considered to be low if modern design standards are applied (Beca 1996; Beca 2004; Ramsay 1997). Crossings of active faults on cuts and fills would probably be safer and less costly and may eventually be the preferred option.

2.6 Geological Hazard Summary

A summary of the landslide hazards described above and their effects on the Coastal and Transmission Gully Motorway routes is presented in Table 1. This allows the damage that could potentially result from landslides on both routes to be compared.

Table 1. Summary of landslide hazards and effects along the Paekakariki SH1 Coastal Highway and Transmission Gully Motorway routes *(after Hancox et al 2005).*

Geological Hazard	Coastal Route	Transmission Gully Motorway Route
Earthquakes-induced landslides	Very high steep slope from Pukerua Bay to Paekakariki has long history of instability. Earthquake-induced landslide susceptibility rated *high to very high*. Large failure at Paekakariki in 1855 Eq. Slope stability reduced by rail and road cuts, and removal of forest cover. During MM9-10 earthquake very large landslides are possible in several places; moderate-small slides in many places. Debris clearance and road closure times longer than anticipated - 10-30 days or possibly 2-3 months or more. MM 7-8 earthquake is likely to cause smaller and fewer slides, with shorter closure time (1-3 days). *Mitigation options:* Rock shelters or stabilisation works are possible but very expensive. Difficult to justify. Debris disposal likely to be a problem; disposal into sea likely to cause concern.	Transmission Gully slopes lower and less steep, with no history of instability except for small failures, despite loss of forest cover. Earthquake-induced landslide susceptibility at northern end is *moderate to low* with few high areas. High *(100 m)* TGM cuts could have *moderate to high* EIL susceptibility; *Low-moderate* susceptibility for currently proposed low cuts *(up to 30 m , 13 to 30-50 m)*. During MM 9-10 shaking small to moderate failures of natural slopes or cuts expected, depending on height and support measures. Debris clearance times likely to range from 2-5 days, considerably shorter than for the Coastal Route. *Mitigation options:* No large failures expected in cuts of ~45°; flatter cuts (< 35°) in weak rocks and soils will minimise slope failure potential. Debris disposal sites need to be identified.
Rainfall-induced landslides, debris floods and flows	The coastal slope from Pukerua Bay to Paekakariki has a history of storm-related landslide and debris flood events. Effects, damage, and closure times possibly significant, but much less than during a large earthquake.	Relatively minor effects from landslide and debris floods during recent rainstorms. Effects, damage, and closure times likely to be minor if correct design and construction measures are used.

Table 1 shows that the Coastal Route is exposed to more landslide hazards than the proposed Transmission Gully Motorway route, which has several advantages. Natural slopes along the TGM route are lower and less steep, and they do not have a history of landsliding or instability, except for a few small shallow failure areas. Earthquake-induced landslide susceptibility is rated as *moderate to low*, with only a few high areas. Any very high cuts (c.100 m) could have *moderate to high* EIL susceptibility, and would have to by carefully designed and constructed to reduce their vulnerability to failure during MM9 and 10 earthquakes.

However, the lower cuts that were proposed (most are less than 30 m high and a dozen or so are 30-50 m in height) in the 2004 cost estimate (Beca 2004) would have *low to moderate* susceptibility. During an MM9-10 earthquake small to moderate failures (1,000–20,000 m^3) of natural or cut slopes are expected, depending on their height and support measures. Most of the areas where higher cuts might be required are located occur along Te Puka Stream section of the TMG route, north of Wainui Saddle. Some of these areas will be inspected during the Field Trip up Te Puka Stream *[Stops 10+, see Figure 17]*.

3. FUTURE STUDIES FOR TRANSMISSION GULLY MOTORWAY

Now that the Transmission Gully route has been approved as the preferred northern highway access in the Wellington area, Transit New Zealand has discontinued work on the Coastal Route Upgrade and begun planning for the investigation design and construction of the Transmission Gully Motorway. Transit NZ has recently called for Registrations of Interest for professional services for several TGM contracts that will be undertaken in the next year or so. Included in these studies is a Preliminary Geotechnical Assessment which will determine the technical feasibility, risks and costs of constructing an 'earthworks' option for TGM, refine the risks and costs of a viaduct option, and quantify trade-offs between costs and route security benefits.

Investigations for the 'earthworks' option will probably include looking more closely at the feasibility of safely constructing 45º cuts in greywacke up to 100 m high, which has not previously been done before in New Zealand. However, since 45º is about the stable angle of natural greywacke slopes in the Wellington region, this may not be an impossible task. The planned geotechnical investigations (which could include drill holes, test pits, shafts, and trial excavations in critical areas) are likely to focus on this aspect, as well as the effects of the nearby Ohariu Fault on rock condition and performance of cut slopes, and the possibility of future fault rupture. The full scope of the investigations will not be known until the contract has been awarded in early 2007.

4. REFERENCES

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Appendix - 1

GSNZ-NZGS Joint Conference - Field Trip 3

List of planned Stops and Features of Interest

STOP	Location and Features of Interest	Text Reference	Figures
1a	Lookout at top of Pukerua Bay Hill *(0.0 km)*: General view north along coastal slope from Pukerua Bay to Paekakariki – Introduction to the area and what we will see along the coast.	2.1.1; 2.1.2	1, 2, 4
1b	Car park at bottom of Pukerua Bay Hill (0.7 km): Better view of coastal cliff, Beanpole corner, and coast to the north.	2.2	4, 5, 6, 7
1c	Possible Stop *(2.1 km if space available)*: Beanpole corner	2.2.1	4, 5, 6, 7
2	Stopping Bay *(3.3 km)*: View potential failure areas on steepest part of slope to the south; 1999 rock fall area at No 7 tunnel.	2.2; 2.3	4, 5, 7
3	Fisherman's Table Car Park *(5.2 km)*: Views of old quarry and potential slope failure area; gully eroded along fault zone.	2.2; 2.3	2, 4, 12
4	Belvedere Motel (6.7 km): Area of debris flood damage on the Fly-by-wire gully debris fan at bottom of Paekakariki Hill Road.	2.2.3	4, 10, 12, 13
5	Car Park "Steam Inc" *(7.3km)*: View of 1855 landslide area and old quarry c.300 m north of the Paekakariki Railway Station.	2.2	4, 8
6	Reservoir Creek *(8.3 km)*: Site of debris flood damage and new SH 1 culvert and debris protection structures.	2.2.3	4, 3, 12, 16
7-9	Paekakariki Hill Road *(c.9.5-11 km)*: Several stops to view the debris flood damage and protection works on the Paekakariki Hill Road. *Stop 7* – Site of August 2006 road fill failure (still under repair); *Stop 8* – debris fence in gully and new culvert protection works; *Stop 9* – Erosion gullies and debris fences at the 'Hairpin' Gully; *Stop 9a* – Paekakariki Hill Lookout – for general overview of area (time permitting).	2.2.3	12, 13, 14, 15
10 +	Transmission Gully: Back to Stop 6 area – Take 4WD track up Te Puke Stream to view terrain along the northern section of the TGM route as far as Wainui Saddle. Several stops to look at and discuss: the Ohariu Fault and proposed TGM crossings, slopes along route, and possible cut and fill vs viaduct option.	2.3; 2.5; 2.6	4, 12, 16, 17

Notes: (1) Stop locations along SH 1 on the Coastal Highway are indicative and may be subject to change due to construction activities

(2) The Field Trip will start and end at the Paekakariki Railway Station car park, beginning at 930 am and ending around 4 pm, or possibly earlier. Cut lunch and drinks provided, with lunch stop at Te Puke Stream or Wainui Saddle – weather permitting.

APPENDIX - 2

Definitions of landslides and associated features

The following definitions are provided for those who are unfamiliar with landslides and slope movements to explain the terms that are used and issues discussed in these notes.

Landslide is a general term for gravitational movements of rock or soil down a slope (as a mass along discrete shear surfaces). In this context, 'soil' includes both earth (material smaller than 2 mm) and debris (material larger than 2 mm); rock is a hard or firm intact mass and in its natural place before movement. Landslides are most often triggered by heavy rainfall or strong earthquakes, but they can also occur 'spontaneously', without an obvious triggering event. Such failures are often caused by undercutting the toes of slopes (by natural erosion or man-made slope modification), combined with long-term weathering and weakening of slopes. Shaking of Modified Mercalli intensity MM7 can cause small failures (<103 m3), but MM8 or greater is generally required for larger landslides ($\geq 10^3$–10^6 m^3 – see Appendix 3).

Landslides are usually classified or described in terms of: (a) the type of material involved (rock, earth, debris, or sometimes sand, mud etc.), and (b) the type of movement – fall, topple, slide, flow, spread, which are kinematically-distinct modes of movement. Combining these two terms gives a range of landslide types such as: rock fall, rock slide, rock topple, debris fall, debris slide, debris flow, earth flow etc. Landslides involving soils and bedrock are often called slips or landslips, while small failures with rotational slide surfaces are generally referred to as slumps. Small landslides often do little damage, but very large failures of thousands or millions of cubic metres moving bodily downslope can overrun and bury buildings and roads, or cause foundation collapse at the tops of slopes. Effects of landslides can range from minor deformation of foundations and structural failures to total destruction of sites and all buildings, lifelines and infrastructure above or below slopes.

***Debris flows and debris floods*:** These are both hydrological mass-transport phenomena but have different hazard and risk implications. *Debris floods* are very rapid hyper-concentrated flows in stream channels of water charged with sediment. *Debris flows* are a type of landslide: they have much higher sediment concentrations than debris floods, with a consistency rather like wet concrete. Debris flows have the ability to transport large boulders, and are therefore potentially much more hazardous and destructive. A debris flood is not a landslide, but is a mass-transport phenomenon with destructiveness similar to that of water, but less than debris flows. Objects impacted by debris floods are surrounded or buried by flood debris but are often largely undamaged, as seen during the 2003 Paekakariki storm (Hancox, 2003)

Appendix - 3

Landslide and Environmental Criteria for N Z Modified Mercalli Intensity Scale [4]

MODIFIED MERCALLI (MM) INTENSITY SCALE – Landslide and Environmental Criteria	
MM 6	▪ Trees and bushes shake, or are heard to rustle. Loose material dislodged on some slopes, e.g. existing slides, talus and scree slope. ▪ A few very small (<10^3 m^3) soil and regolith slides and rock falls from steep banks and cuts. ▪ A few minor cases of liquefaction (sand boil) in highly susceptible alluvial and estuarine deposits.
MM 7	▪ Water made turbid by stirred up mud. ▪ Very small (<10^3 m^3) disrupted soil slides and falls of sand and gravel banks, and small rock falls from steep slopes and cuttings common. ▪ Fine cracking on some slopes and ridge crests. ▪ A few small to moderate landslides (10^3 –10^5 m^3), soil/rock falls on steep slopes (>30°) on coastal cliffs, gorges, road cuts/excavations etc. ▪ Small discontinuous areas of minor shallow sliding and mobilisation of scree slopes in places. Minor to widespread small failures in road cuts in more susceptible materials. ▪ A few instances of non-damaging liquefaction (small water and sand ejections) in alluvium.
MM 8	▪ Cracks appear on steep slopes and in wet ground. ▪ Significant landsliding likely in susceptible areas. ▪ Small to moderate (10^3-10^5 m^3) slides widespread; many rock and disrupted soil falls on steer slopes (terrace edges, gorges, cliffs, cuts etc). ▪ Significant areas of shallow regolith landsliding, and some reactivation of scree slopes. ▪ A few large (10^5-10^6 m^3) landslides from coastal cliffs, and possibly large to very large (>10^6 m^3) rock slides and avalanches from steep mountain slopes. ▪ Larger landslides in narrow valleys may form small temporary landslide-dammed lakes. ▪ Roads damaged and blocked by small to moderate failures of cuts and slumping of road-edge fills. ▪ Evidence of soil liquefaction common, with small sand boils and water ejections in alluvium, and localised lateral spreading (fissuring, sand and water ejections) and settlements along banks of rivers, lakes, and canals etc.
MM 9	▪ Landsliding widespread and damaging in susceptible terrain, particularly on slopes steeper than 20°. Cracking on flat and sloping ground. ▪ Extensive areas of shallow regolith failures and many rock falls and disrupted rock and soil slides on moderate and steep slopes (20°-35° or greater), cliffs, escarpments, gorges, and man-made cuts. ▪ Many small to large (10^3-10^6 m^3) failures of regolith and bedrock, and some very large landslides (10^6 m^3 or greater) on steep susceptible slopes. ▪ Very large failures on coastal cliffs and low-angle bedding planes in Tertiary rocks. Large rock/debris avalanches on steep mountain slopes in well-jointed greywacke and granitic rocks. Landslide-dammed lakes formed by large landslides in narrow valleys. ▪ Damage to road and rail infrastructure widespread with moderate to large failures of road cuts slumping of road-edge fills. Small to large cut slope failures and rock falls in open mines and quarries. ▪ Liquefaction effects widespread with numerous sand boils and water ejections on alluvial plains, and extensive, potentially damaging lateral spreading (fissuring and sand ejections) along banks of rivers, lakes, canals etc). Spreading and settlements of river stop banks likely.
MM 10	▪ Landsliding very widespread in susceptible terrain[(3)]. ▪ Similar effects to MM9, but more intensive and severe, with very large rock masses displaced on steep mountain slopes and coastal cliffs. Landslide-dammed lakes formed. Many moderate to large failures of road and rail cuts and slumping of road-edge fills and embankments may cause great damage and closure of roads and railway lines. ▪ Liquefaction effects (as for MM9) widespread and severe. Lateral spreading and slumping may cause rents over large areas, causing extensive damage, particularly along river banks, and affecting bridges, wharfs, port facilities, and road and rail embankments on swampy, alluvial or estuarine areas.

NOTES:

(1) "Some or 'a few' indicates that threshold for an effect or response has just been reached at that intensity. Effects below MM 6 generally insignificant in NZ.

(2) Intensity is principally a measure of damage. Environmental damage (response criteria) occurs mainly on susceptible slopes and in certain materials, hence the effects described above may not occur in all places, but can be used to reflect the average or predominant level of damage (or MM intensity) in a given area.

(3) Environmental response criteria have not been suggested for MM11 and MM12, as those levels of shaking have not been reported in New Zealand. However, earlier versions of the MM intensity scale suggest that environmental effects at MM11 and MM12 are similar to the new criteria proposed for MM9 and 10 above, but are possibly more widespread and severe.

(4) Appendix 3 is based on Hancox et al. 1997, 2002.