West Coast Lifelines

Vulnerability and Interdependency Assessment

Supplement 2: Earthquakes

West Coast Civil Defence Emergency Management Group

August 2017

IMPORTANT NOTES

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Hazard Maps

The hazard maps contained in this report are regional in scope and detail, and should not be considered as a substitute for site-specific investigations and/or geotechnical engineering assessments for any project. Qualified and experienced practitioners should assess the site-specific hazard potential, including the potential for damage, at a more detailed scale.

Cover Photo: Railway at Oaro after 2016 Kaikoura earthquake (I McCahon)

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1 INTRODUCTION

The West Coast Region lies across the Australian – Pacific tectonic plate boundary, and is thus subject to earthquakes as these two plates move relative to each other. The major fault line in the West Coast Region is the Alpine Fault, but there are several active faults in the region or close enough to cause damaging shaking. Figure 1.1 shows the active faults in the central South Island as included in the National Active Fault Database (GNS Science). Not shown on this map are the 13 faults recently identified within 30km of the coastline between Cape Farewell and Milford. As recently demonstrated in both the 2010 – 2011 Canterbury earthquakes and the 2016 Kaikoura earthquake, the fault database is not complete and earthquakes can also occur on unknown faults.

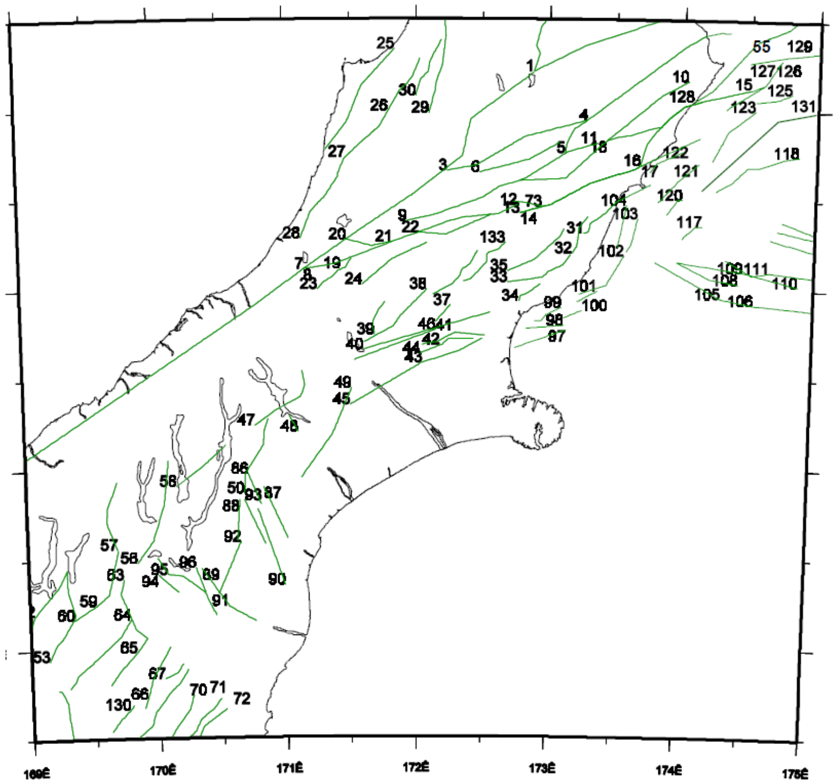

Figure 1.1 Active Faults in central South Island (GNS Science)

Main faults in West Coast Region are:

7	Alpine Fault (Fiord – Kelly)	27	MaiMai
8	Alpine Fault (Kelly – Tophouse)	28	Brunner Anticline
20,21	Hope Fault	29	White Creek
25	Paparoa Range Front	30	Lyell
26	Inangahua		

The more active faults are the Alpine Fault south of the Taramakau River and the complex of faults including the Hope Fault passing diagonally across the island to Kaikoura. A probabilistic hazard analysis (GNS Science) shows the pattern of earthquake shaking expected for a 475 year return period in Figure 1.2. The light green representing Modified Mercalli Intensity[1] shaking of 8 to 9 covers the whole of the northern part of the West Coast Region, whereas shaking of 9 to 10 intensity follows the more active faults and covers all of Westland and inland Grey Districts. Intensity 8 – 9 shaking is very damaging; 9 – 10 is approaching catastrophic.

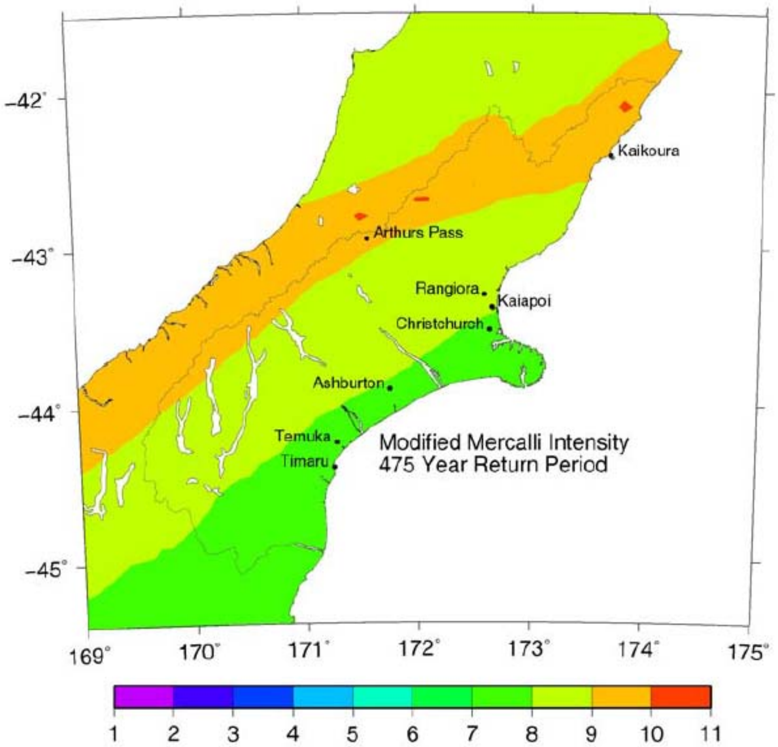

Figure 1.2. Probabilistic seismic hazard map of the central South Island for 475 year return period shaking
(Stirling et al 2007, Figure 5w)

Figure 1.1 and 1.2 both illustrate that although the Alpine Fault is a focus of earthquake awareness, the whole region is exposed to damaging earthquakes. Historically, the largest earthquakes affecting the West Coast Region were both in Buller (1929 Buller or Murchison M7.8 earthquake and the 1968 Inangahua M7.1 earthquake). The recent 2010 – 2011 Canterbury and 2016 Kaikoura earthquakes were distinguished by rupture on unknown faults (Canterbury) or on a completely unanticipated combination of faults (Kaikoura). The Canterbury earthquakes also occurred in an area of lower probability. It is important to keep this in mind, and not equate being a long distance from the Alpine Fault with no need for earthquake preparedness.

The probabilistic approach as shown in Figure 1.2 is useful in assessing the relative likelihood of damaging earthquake shaking across an area, but is less helpful in assessing what any one particular event might be like (compare Figures 1.2 and 2.1). For this, a scenario approach is better.

[1] Modified Mercalli (MM) scale of shaking intensity. This is a descriptive scale, which reflects the intensity of shaking according to the resulting damage and felt effects, and a full description of it is included as Appendix A

Two earthquake scenarios have been used to illustrate the type of damage to infrastructure that could occur. The first is an earthquake on the Alpine Fault. We have used the rupture scenario as adopted for the Project AF8, with rupture starting in Fiordland and progressing north to end close to Lake Kaniere. Although this is a length of about 280km, the rupture remains in Westland District. The rupture direction does mean that strong shaking will be experienced throughout Grey and Buller Districts, but not to the extent that would really test the infrastructure. To illustrate an alternative event in the north of the region, we have taken the 1968 Inangahua Earthquake and attempted to update the damage scenario to match existing infrastructure.

2 ALPINE FAULT EARTHQUAKE

2.1 Alpine Fault

The Alpine Fault is the largest active fault in New Zealand and extends over 650km on land from Milford Sound to Blenheim. It runs virtually the whole length of the West Coast Region, with the high mountains to its east and the lower hill lands and alluvial flats to its west. South of Ross, effectively all of the inhabited areas within the district are within 15km of the fault.

The fault and the likely rupture are well documented in the Alpine Fault Magnitude 8 Hazard Scenario (Orchiston et al) prepared for Project AF8. Reference should be made to that document for more detailed background information.

Movement on the fault is both vertical, with the east side rising relative to the west side and hence uplifting the Southern Alps, and horizontal with geological rock types matching across the fault but offset by about 470km. Field evidence suggests that the horizontal offset is episodic and each movement of several metres is accompanied a large earthquake.

The most active part of the fault is the central section, which forms the western boundary of the Southern Alps from Haast to Inchbonnie, i.e., the length of Westland District. Further north the fault becomes progressively less active as movement is spread to numerous branch faults within Marlborough (refer to Figure 1.1). The AF8 scenario is for a rupture of more than 400km of the fault, generating a M8.2 earthquake with up to 9m of lateral displacement. This event has a likely recurrence interval of about 340 years, although recent research suggests this may be shorter at 270 – 290 years, and the last such rupture is thought to have been in 1717. There is an estimated 30% to 50% probability of an earthquake in the next 50 years.

For the purposes of this study, the AF8 scenario of rupture starting from south of Milford Sound north to the Toaroha River (south of Lake Kaniere) has been adopted. The rupture does not extend further north to enter the Taramakau Valley. This is just one of many scenarios possible with the Alpine Fault, but appears to be one of the more likely, and there is advantage in retaining consistency with the AF8 work. The fault rupture from the south end and propagating to the north east is significant as there is a "piling up" of seismic energy which intensifies the shaking at, and well beyond, the north end of the rupture length. Increased shaking and resulting damage is expected in the Grey and Buller Districts than a distance-only perspective would indicate. A rupture of the same length of fault from north to south would have very different impacts away from the area close to the rupture itself.

Direct effects of the earthquake will include:

- Ground rupture destroying buildings, road and pipelines on or crossing the fault, and
- Shaking damage to buildings, bridges and infrastructure such as water supplies, sewerage, power and telephone.

Secondary effects from earthquake shaking include:

- Liquefaction in sandy areas within river valleys, in low swampy ground near lakes, and in the coastal areas around river mouths, estuaries and lagoons.
- Landslides, particularly close to the fault line and in the mountains, some of which are likely to create dams across rivers. Landslides may cause local damage to parts of urban areas. Slips and landslides will cause considerable damage to roads.
- Seiches (water waves generated by seismic oscillations) could be produced on lakes.

Indirect and longer-term impacts will result from the large volumes of landslide material entering rivers, particularly those with catchments in the Southern Alps. The increased sediment load will result in high river water turbidity, river aggradation and channel avulsion with implications for drinking water quality, river control, stopbanking and bridging. These effects will alter the environment in the area subject to the strongest shaking, and some will result in totally new infrastructure being required to accommodate the new landscape. Water supply and sanitation services in some towns will be disrupted for weeks and potentially for many months resulting in a significant increase in public health risks. Aggrading riverbeds will affect some bridges for many years.

2.2 Earthquake Scenario

The scenario that follows is only one of a large range of possible combinations of damage resulting from an Alpine Fault earthquake. It is NOT a prediction, but merely an illustration of the sort of damage that might occur. An actual earthquake will be different from that assumed, and we have only a limited knowledge of the various networks and components and their vulnerabilities. The scenario is not intended to be predictive with respect to the precise lifeline impacts or the exact locations of any impact. The impacts listed are intended to help focus thinking on the way that lifelines systems can be affected by a strong earthquake and suggest some of the interdependency issues between lifelines.

The scenario also includes possible damage that may occur to the main lifeline links within the West Coast Region and to the remainder of the South Island. This is because impacts outside the Region will have a direct and significant effect on the ability and speed with which the West Coast Region can respond to the earthquake and the consequential damage.

2.2.1 Ground Rupture

The Alpine Fault runs in the main through undeveloped land where ground rupture will not impact directly on infrastructure. The exceptions are Franz Josef where the fault passes through part of the township, and a number of important roads which cross the fault. Rupture will cause a dramatic dislocation at these points with typically 5 – 8m of lateral displacement and 0.5 – 1.5m of vertical offset. Apart from some minor district roads, rupture damage will occur on:

- SH 6 at Wanganui Bridge, near Harihari,
- SH 6 a short distance both north (Parker Creek) and south of Whataroa River Bridge,
- SH 6 at Franz Josef, in the town and to the south of the Waiho River,
- SH 6 in the Cook Saddle area, at least two and possibly more locations,
- Access road to Fox Glacier
- SH 6 at Karangarua River, and
- SH 6 to Haast Pass, a few kilometres east of Haast Township – near Snapshot Creek.

2.2.3 Ground Shaking Hazard

The most widespread and predominant effect of earthquakes is ground shaking experienced as seismic waves generated by the release of energy from the fault rupture surface propagate through the earth. These waves are modified by the underlying geology, soils and terrain, and generally reduce with distance from the earthquake source. The shaking hazard can be defined in terms of the maximum accelerations caused by the seismic waves, or indirectly in terms of effects. The scale of effects used in New Zealand is the Modified Mercalli (MM) scale of shaking intensity. This is a descriptive scale, which reflects the intensity of shaking according to the resulting damage and felt effects, and a full description of it is included as Appendix A.

The whole of the Westland and much of the Grey District will experience very strong shaking, and all but the far north of the Buller District will also be shaken strongly. It will be most intense closest to the Southern Alps and the fault trace, but wave propagation effects suggest that the area around Hokitika and Greymouth will also be intensely shaken. The townships of Harihari, Whataroa, Franz Josef and Fox Glacier and the rural communities of Kowhitirangi – Kokatahi, Te Taho and north Franz Josef are all very close to the fault trace and can expect the most intense shaking. However, with the exception of the far north of Buller District, nearly the whole of the region will all experience Modified Mercalli Intensity shaking of MM VII or greater.

Figure 2.1: Modified Mercalli Intensity for an Alpine Fault rupture *(from Figure 9(c) Bradley et al, 2017)*

Green	IV
Yellow	V
Light orange	VI
Dark orange	VII
Red	VIII+

Fault rupture is from south to north

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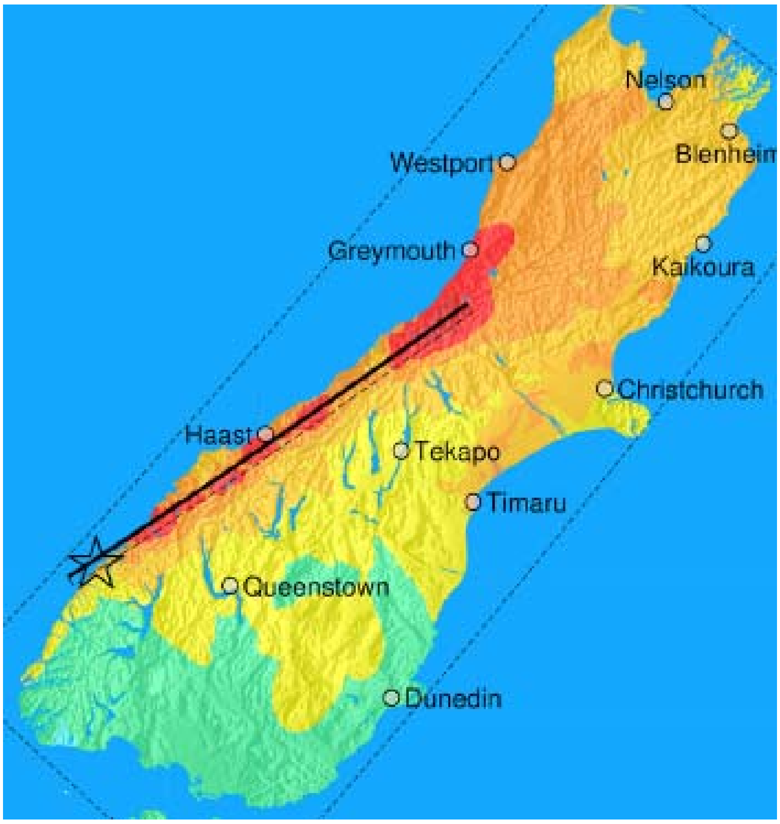

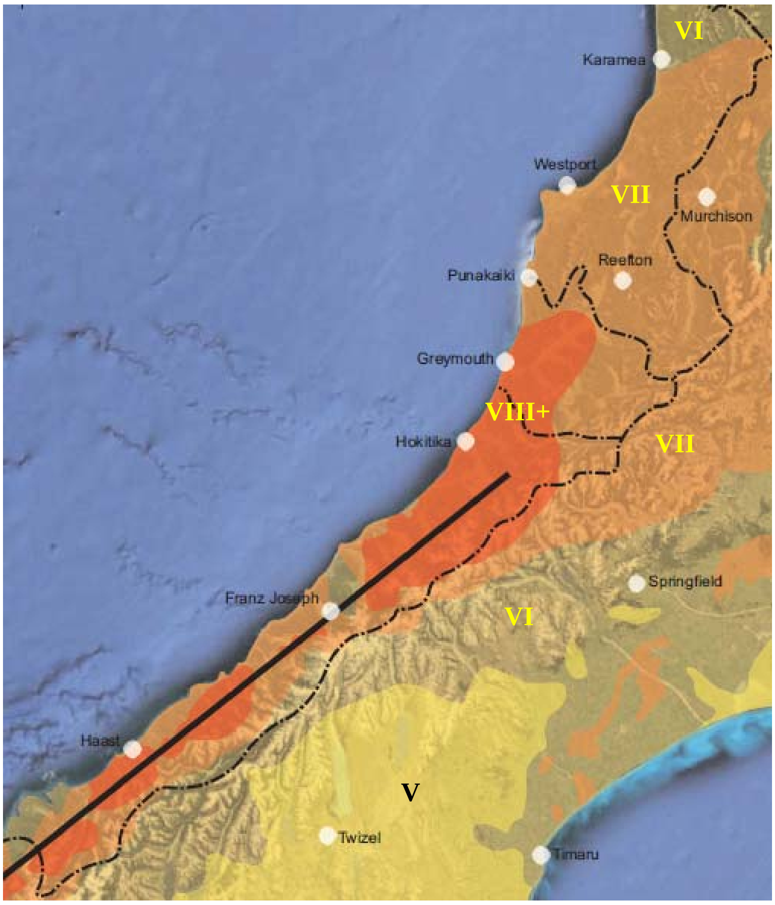

Figure 2.2: Modified Mercalli Intensity within West Coast Region for an Alpine Fault rupture *(from Figure 9(c) Bradley et al, 2017, Enlargement of part Fig 2.1)*

Figures 2.1 & 2.2 are based on sophisticated modelling techniques but do not reflect variations in near surface ground conditions. There will be some additional variation due to local site conditions such as the nature of the underlying rock and soils, their relative thickness and their depths. This is discussed in more detail in the Regional and District Study reports of 2006 (Elms et al, 2005, 2006(a), (b), (c)). The ground shaking as modelled is quite different from older simple models with attenuation related to distance from the rupture, and there is a pronounced directivity of the shaking. This results in stronger shaking in the Greymouth area than in some locations along the rupture itself.

There is little doubt that the shaking will be the strongest experienced anywhere within Grey and Westland Districts since settlement of the district. Shaking Intensities likely to be experienced with the Alpine Fault AF8 scenario earthquake are shown in Table 2.1 for centres within and beyond the West Coast Region. Parts of Buller District have been subjected to as strong or stronger shaking in 1929 with the Buller earthquake and in 1968 with the Inangahua earthquake as listed in Table 2.2.

Table 2.1: Shaking Intensities at Selected South Island Centres

Intensity	West Coast Localities		Other South Island Localities	
MM IX +	Kokatahi Harihari Whataroa	Franz Josef Fox Glacier		
MM VIII	Greymouth Hokitika Ross Ahaura Blackball	Kumara Lake Paringa Haast Bruce Bay		
MM VII	Westport Reefton Punakaiki Springs Junction Inangahua	Moana Rotomanu Otira Okuru Jackson Bay	Murchison Arthur’s Pass	
MM VI	Karamea		Mt Cook Springfield Hanmer Nelson	Blenheim Kaikoura Christchurch Timaru
MM V			Queenstown Wanaka	Twizel Oamaru

Table 2.2: Comparison of Historical Shaking Intensities

Locality	Modified Mercalli Shaking Intensity		
	1929 Buller EQ	1968 Inangahua EQ	Alpine Fault EQ
Karamea	IX	VII	VI
Westport	VIII	VIII	VII
Punakaiki	VII	VII	VII
Inangahua	VIII	X	VII
Reefton	VIII	IX	VII
Springs Junction	VII	VII	VII
Greymouth	VII	VII	VIII
Hokitika	VI	VI	VIII
Franz Josef	V	V	IX
Haast	IV	IV	VIII

Associated with shaking intensity is ground acceleration. The 2006 study included maps of possible peak ground acceleration (PGA), but the recent modelling indicates that these contours are overly simplistic. At the time of compiling this report, no better modelling of PGA is available and reference can be made to the 2006 work where necessary, with the proviso that these are very approximate only.

2.2.4 Liquefaction Hazard

The 2010 – 11 Canterbury earthquakes graphically demonstrated the damage that can result from liquefaction. In the last 2 years, a nationwide geotechnical database has been established, but to date there is only a small amount of additional data available that could assist in refining the liquefaction hazard in the West Coast Region as described in the 2006 reports. The New Zealand Geotechnical Database shows one CPT[2] and one borehole in Hokitika, 4 CPTs and 6 boreholes in Greymouth, clustered around the hospital area, and 6 CPTs and 4 boreholes in Westport, with all but one at the hospital site. (Hand auger and test pits have been ignored as the lack of in-situ testing makes these of limited value for liquefaction assessment).

Other accessible data not on the NZGD includes limited testing in three sites in Greymouth: the area on the east side of Erua Lagoon, and a site in the CBD. This suggests that liquefaction is likely, but in looser sandy layers interspersed between gravel, finer grained or under fill, resulting in limited surface expression and settlement. Shear wave velocity measurement on 3 sites also concluded that liquefaction was not so extensive. In Hokitika we have access to CPT tests on two sites. One, located on the beachfront, indicated limited liquefaction was possible but at over 5m depth with no surface expression likely as a result. The other test, on Gibson Quay by the river, showed fill and soft silt grading into sand overlying gravel at 3 – 3.5m depth. The sand, and some sandy lenses at greater depth, was identified as being liquefiable but with limited settlements (less than 100mm) and surface expression.

This additional information is insufficient to warrant a full review of the 2006 mapping in Hokitika and Greymouth, as it generally conforms to the zoning as drawn. No update has been carried out and the 2006 reports should be referred to with respect to the areas of greatest likely susceptibility.

Hokitika is about 25km from the end of the earthquake rupture, Greymouth about 47km and Westport about 130km. All these centres can expect to experience liquefaction, at least in the more susceptible soils, even at these distances. Karamea, at 195km away is marginal in terms of liquefaction triggering in the AF8 scenario.

[2] CPT – Cone Penetration Test pushes a cone fitted with a load cell into the ground to give a near continuous record of penetration resistance, which can be related to various soil parameters and susceptibility to liquefaction

2.2.5 Landslides

Landslides are a common effect of earthquakes where shaking occurs in steep terrain, as graphically shown in the 2016 Kaikoura earthquake. A high number of landslides can be expected given that the combination of the steepest and most elevated area of relief in New Zealand coincides with the epicentral region of strongest earthquake shaking. The landslide hazard is discussed more fully in the 2006 reports. Since then research has extended knowledge in this field. T. Robinson has produced a map of relative probability of slope failure co-incident with an Alpine Fault earthquake, as shown in Figure 2.3. It indicates a high probability of landsliding over a very large area along the length of the fault.

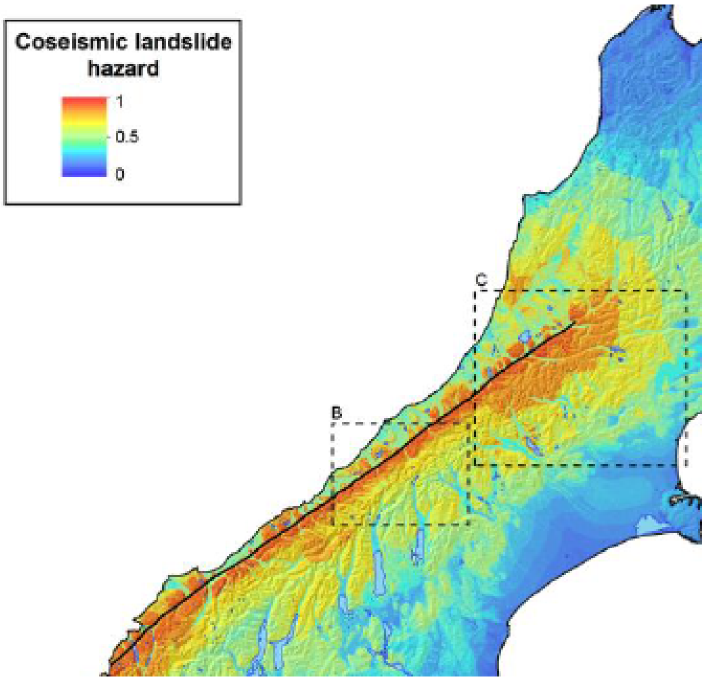

Figure 2.3. Co-seismic landslide model for an Alpine Fault earthquake scenario
(Robinson et al, 2015)

The 2016 M7.8 Kaikoura earthquake resulted in an estimated 100,000 landslides, with at least 200 of these forming landslide dams across rivers. The most severe occurred over an area of about 3,500km^2 (120km by 30km), with less severe landsliding over 10,000km^2 (about 200km by 50km), which roughly corresponds to the area of shaking intensity MM VI or greater. The rupture length for this event was about 160km. Using this as a crude calibration, rupture of 400km of the Alpine Fault could generate something like 250,000 landslides and 500 landslide dams, but this ignores the directional effects to the north. If landsliding is likely within shaking intensity MM VI or greater, then landslides can be expected throughout the region, including as far north as Karamea.

2.2.6 Seiches and Tsunami

Strong seismic shaking can induce water in lakes to oscillate (or “slop”) at a particular frequency determined by the lake size and depth. These oscillations are referred to as seiches. Seiches were reported at both Lake Brunner and Lake Rotoroa in the 1929 Buller earthquake. Seiches can be expected in all the lakes in the region. Damaging waves can also be caused in lakes from large landslides entering a lake suddenly, or from submarine landslides.

The risk of a tsunami being triggered by an Alpine Fault earthquake, large enough to cause damage along the coast, is considered to be very low. The offshore section of the fault is remote from inhabited areas and the movement is likely to be largely horizontal with limited vertical displacement of the water column. Some fluctuations in sea level must be expected, but are assumed to remain within normal spring tide levels along the coast and within river mouths and lagoons, for the purpose of this scenario.

2.3 Infrastructure Damage Scenario

We stress that the following is only one many possible outcomes from the earthquake. We have not done any rigorous analysis or examination of all the many variables that contribute to which structure gets damaged, or which hillside may collapse. The intent of the following is to create what we hope and intend is a credible "story" to illustrate the type of damage and impact an Alpine Earthquake is likely to have. One important measure of damage is the time taken to recover, which is also the prime measure for community recovery. The times indicated in this scenario are very much speculative and subjective, but we contend that there is no reliable way of forecasting this. We have tried to allow for the wider setting as well – the fact that much of the South Island will be affected by the earthquake, and will inevitably take resources (manpower, machinery, spare parts, funding) which might otherwise be directed to the most severely affected region – the West Coast. This is different from any of the recent earthquakes in New Zealand where access and support from the rest of New Zealand has been almost immediate, and must extend recovery times. It may also result in political decisions on where resources are to be directed, or even if some damaged infrastructure is to be repaired at all.

We note that this scenario remains based on the one used in the 2006 lifelines study, adapted somewhat to reflect the shorter rupture length to the north (in 2006 we used the northern end of the rupture at the Matakitaki Valley, about 120km north of Lake Kaniere where the AF8 rupture scenario finishes) and greater length to the south (the AF8 rupture starts in Fiordland whereas in 2006 the rupture was assumed to start at Paringa, about 100km north of the south end of the region).

2.3.1 One Week

(a) Transport

The situation in the fault rupture zone close to the Alpine Fault between Haast and Lake Kaniere is one of widespread devastation with most roads effectively blocked and most bridges damaged, but damage extends throughout the region. All road links connecting the region to the rest of the South Island are cut, and significant landslide or bridge damage effectively divides the region into a series of isolated areas. Between these major road blockages, there is still significant damage in places, or batter failures, liquefaction damage, bridge and bridge abutment damage, fallen trees or poles etc, which severely limit immediate access and use of the roads.

At a time of **one week** after the earthquake, the situation could be as follows:

SH 6 has been re-opened between Murchison and Nelson and Springs Junction for controlled emergency and resident access. Slips in the Upper and Lower Buller Gorge and on the Rahu Saddle are expected to be cleared within a few days. SH 7 over the Lewis Pass is also expected to be reopened within 2 – 3 weeks. Westport is isolated with rock fall and small landslides on SH 6 in the Buller and south of Charleston, as is the Karamea Highway north of Mokihinui.

Most local roads in the Greymouth and Hokitika areas are negotiable by four wheel drive vehicles. There is damage to the overbridges at South Beach and in the Brunner Gorge. The first has been bypassed with a temporary road and the second has closed the road between Dobson and Stillwater. SH 6 is blocked north of Rapahoe. SH 73 is extensively damaged between Jacksons and Cass, with several large landslides.

South of Ross, SH 6 remains blocked at the major crossings throughout South Westland. SH 6 damage includes several fault ruptures, bridge collapse at the Wanganui and Whataroa Rivers, bridge failures at Waitangitaona, Fox and Karangarua Rivers, extensive landslides over the Cook Saddle and at Knights point, and landslips and bridge damage at other locations. Roads on the flats immediately adjacent to Whataroa and Harihari are negotiable by four wheel drive, but there is no access beyond the immediate area. The road between Whataroa and Franz Josef is closed at the Waitangitaona River and close to Lake Wahapo. .

The Haast Pass section of SH 6 is extensively damaged with several bridges destroyed or badly damaged and large rock falls and landslides bury the road in many places, including to the east as far as Wanaka. SH 6 is severed by the fault rupture inland from the Haast Township. The Haast River bridge suffers partial collapse, as does the Pleasant Flat Bridge and the district bridges are all significantly damaged. The Arawhata Bridge loses one span. A large landslide south of Knights Point entirely destroys 300m of SH 6 with the whole coastal escarpment collapsed into the sea. Several large slips bury the road to Jackson Bay. There is extensive liquefaction damage to the roads inland of Neils beach and near Okuru.

The railway is extensively damaged between Cass and Jacksons, with other damage throughout the region. A coal train is derailed near Inchbonnie.

The airports at Hokitika and Westport suffer little damage, other than building contents damage, but the Greymouth aerodrome is damaged by liquefaction under part of the runway causing distortion and fissuring.

Greymouth harbour wharves are deformed and damaged in part by liquefaction and failure of the banks behind them. Westport harbour suffers damage in the fishing harbour due to liquefaction and lateral spread of banks. The Jackson Bay wharf is badly racked and is unsafe.

It is clear that the State Highway links of SH 7 between Reefton and Springs Junction will be closed for some days yet and the West Coast remains effectively isolated by road. The focus is on clearing the slips off SH 6 through the Upper and Lower Buller Gorges which will then allow access to Westport, Greymouth and Hokitika. Fuel supplies throughout the region are of concern, and are available to essential vehicles and plant only. The other external road links across the three alpine passes are all damaged with re-opening times of at least some weeks for the Lewis Pass and much longer for the Haast and Arthur's Passes.

(b) Drainage

There are large landslide dams throughout the region and particularly east of the Alpine Fault in the steep mountain valleys. Significant dams in about 25 rivers present a dam break hazard.

Liquefaction has damaged some lengths of the embankments around the fishing basin at the north end of Westport. Some lengths of stopbank at Karamea are damaged with longitudinal cracking and slumping caused by lateral spread of the foundation material. The Greymouth floodwall has been damaged by liquefaction under some short lengths, in conjunction with dislodgement of rock on the steep batter resulting in some lengths having longitudinal fissures and the crest lowered by up to a metre. Large portions of the floodwall around the lagoons are damaged by liquefaction-induced lateral spreading and fissuring.

Liquefaction under some short lengths has damaged the Hokitika River stopbank within the town. This has also broken two of the storm water outlet pipes to the river. Stopbanks throughout the district, including that in the Kowhitirangi and Kokatahi areas, on the Wanganui, Waitangitaona and Waiho Rivers are damaged with slumping of the batters and rare liquefaction-induced spreading. The stopbank on the south bank of the Waiho is destroyed on the fault trace by the rupture.

(c) Sewerage

Sewerage systems in the urban areas are all damaged. The oxidation ponds at Hokitika, Moana, Blackball, Franz Josef, Fox Glacier and Haast are all damaged with distortion of the embankments and cracking of wave band concrete. Liquefaction in sands under portions of the three main towns causes some gross pipe displacement. All pump stations are stopped due to power supply interruption, and pump stations in Greymouth, and Hokitika are damaged by liquefaction, resulting in sewerage flowing on the ground in a few locations. Temporary drains are planned to be excavated in places to take sewerage into the rivers from the areas of damaged pipes and pump stations in Hokitika and Greymouth. The sewer system at Franz Josef is significantly damaged. All pipes crossing the fault are destroyed and most of the system suffers severe damage with breaks at junctions and manholes. The Haast township system is damaged, as are the oxidation ponds.

Seepage into damaged banks at the Hokitika and Moana oxidation ponds causes bank failures, and within a short time the north Hokitika pond has drained and effluent is covering the paddock to the north the Moana pond has discharged almost directly into the Arnold River.

(d) Water supply

Water supply to all the major towns is disrupted. All pumps stop, and breaks in the gravity systems mean that supply from the intakes is lost. There is widespread damage to the reticulation in Greymouth and Hokitika, and some liquefaction damage at the north end of Westport. Damage to the smaller schemes also occurs and with the exception of some small supplies in the coastal area of Buller, all public water supplies fail.

The breaks in the main pipes into and out of the Hokitika reservoirs and in the reticulation drained the reservoirs and the whole systems have no pressure. Similar draining of reservoirs occurred at virtually all the smaller schemes south of Reefton. Slopping in the Blackball reservoir damaged the bladder roof and 30% of the stored water was lost. Earthquake valves at most of the Greymouth reservoirs limited loss from the system, but the Omoto reservoir failed due to landslide movement and some parts of the reticulation have had to be isolated due to leakage from pipe damage. Greymouth, Hokitika and Reefton all had some days without water as well as 15% of Westport, with a progressive extension of the area served[3].

The main Greymouth intake has been checked and pumps manually turned on with power from a portable generator. Repairs to the water supply systems are continuing, and tankers are ferrying water to the Civil Defence posts at the schools and the hospital in both Greymouth and Hokitika. Water is reinstated to 50% of Greymouth at reduced pressure, and 60% of Reefton. Ross remains serviced with standpipes, as repairs to the distribution system and intake pipe have to wait until more urgent repairs are done. At Franz Josef, water is being sourced by tanker from the local streams. Other than this, all systems remain inoperative.

(e) Power Supply

Power supply is lost throughout the whole region. All links into the region have lost supply, all the local generation is shut down by the earthquake, and there is significant shaking damage at substations. The Transpower line through Arthur’s Pass is cut in several places by loss of poles and near Otira by a landslide destroying a transmission towers. There is extensive damage to the Electronet distribution system with poles down and other breakages. A pylon on the north bank of the Wanganui River is destroyed, dropping the wires into the river. The line between Franz Josef and Fox Glacier is destroyed for 40% of its length.

[3] In the Kaikoura earthquake, Renwick had water restored to at least a partial service within a week. Kaikoura experienced a complete loss of supply but some streets had supply restored one day later. Water stations were set up by day 45, and by day 11, supply was sufficiently restored to allow restricted use throughout the town (Hughes et al 2017).

The power stations at Dillmanstown escape significant damage, although there is movement to the dams. Trustpower have checked the scheme and could restart it, but are unable to do so in isolation as it needs the grid for synchronisation to control the frequency. The Arnold scheme appears little damaged (as does that at Fox) but a batter failure on the tailrace prevents operation. The Amethyst Scheme is badly damaged by movement in the tunnel rupturing the penstock and by rock fall over the intake. The Turnbull station at Okuru suffers a penstock failure and subsequent damage from released water. The distribution system between Haast and Jackson Bay is damaged, but there are no resources to check the plant and repair the power lines.

Power remains off throughout the whole region. Backup generators at the hospitals and Council offices are working, but reliant on a diminishing fuel supply.

(f) Telecommunications

The fault rupture cuts the fibre optic cable over Arthur's Pass, and the fibre optic cable to Nelson is also cut in three places due to bridge abutment settlements and road dropout. This results in complete loss of service (land line and cell phone) within the whole of the West Coast except for local calls via the local exchanges where lines are not damaged and back-up generators function to maintain power supply.

2.3.2 Two weeks

(a) Transport

All state highways and essential routes north of Greymouth are reopened, with the exception of SH 6 between Rapahoe and Charleston, and SH 7 over the Lewis Pass[4] which is scheduled to reopen for restricted use in a few days. The roads are only open to essential traffic at reduced speed and often with single lane width only. Rain during the second week triggered a large number of slips within earthquake weakened ground, and temporary closures were needed on SH 6 in the Buller Gorge. Access to the south is possible as far as the Wanganui River where the bridge damage stops the connection to Harihari. SH 73 remains closed between Jacksons and Cass, as does SH 6 west of Lake Hawea across the Haast Pass.

Most Westland District roads close to the Alpine Fault remain closed with no intention for reinstatement in the near future. Haast remains isolated. Most tourists have been evacuated from the Franz Josef area, along with many of the permanent residents. This has been achieved by the army erecting cableways across the lost spans on the Wanganui and Whataroa Rivers with vehicles used between them. With restricted helicopter availability, many tourists and residents remain at Fox Glacier as the roads out are impassable. Plans to airlift the remaining people out are in hand and should

[4] The Lewis Pass is 100 km north of the fault rupture in this scenario, and even with the directivity of the seismic energy, landsliding and damage will be reduced in this area. With a different earthquake scenario, the time to reopen this route could be much longer.

be accomplished within a few days, weather permitting. Some residents have elected to stay on in Okarito, Whataroa and Harihari. Ongoing aftershocks compound the difficulties faced by both residents and those attempting to restore lifeline services. Most aftershocks are of a size such that, while felt and alarming, result in little damage beyond the immediate fault rupture zone, and thus have no real impact in Grey and Buller Districts.

The Greymouth runway has been cleared and repaired and the airport reopened.

(b) Drainage

Intermittent heavy rain during the second week caused all the main rivers in the Grey and Westland Districts to rise. The landslide dam on the Whitcombe River breached on day 13. The resulting flood wave down the Hokitika River caused local flooding on its floodplain but no major damage. The flood further downstream was large but not exceptional and did not breach the damaged stopbanks.

The landslide dam on the Kokatahi River breached on day 12. The resulting flood wave caused flooding in the flats downstream, destroying some farmland and killing stock, but caused no problem to infrastructure. A dam break on the Poerua River on day 10 resulted in the north abutment to the bridge being washed out. The landslides in the Tatare River and Callery River breached on day 12. The Tatare dam break resulted in a debris flow onto the head of the fan which caused the river to change course and wash out SH 6 about 300m south of the bridge, destroy the airstrip and narrowly miss damaging the school. The Callery dam break impacted immediately on the Waiho River. Fortunately the flood wave did not impact significantly on the north bank, but took out the damaged SH 6 bridge, washed out the stopbank on the south bank where the rupture had breached it, resulting in a major portion of the flow following down SH 6 to and around the south and west sides of Canavans Knob before returning to the riverbed.

Stopbank damage resulted in flooding problems in Vine Creek, along the Wanganui River near Harihari, on the Poerua, where the dam break exacerbated the issues resulting in two houses being flooded on the north bank. The damaged SH 6 embankment upstream of the Haast Bridge was washed out in one location resulting in local flooding and the cutting off of Haast Township from Okuru for 3 days.

(c) Sewerage

The rain has exacerbated the effects of the sewer damage in Hokitika, with isolated pockets of sewage flow on the ground surface. The floods in the Grey and Hokitika Rivers caused problems with outflow from the business areas due to the damaged pump stations.

(d) Water supply

Repairs to the water supply systems are continuing, with water reinstated to 80% of Greymouth, 70% of Hokitika, and 90% of Reefton, although at a reduced pressure. The outlying systems remain as they were at week 1. Repairs to the water supply systems are continuing, although a large aftershock caused further pipe breaks delaying work as the repair crews had to go back over sections that had been repaired. Repair work is continuing in Greymouth and Reefton.

The main pipe from Lake Kaniere to Hokitika has been temporarily repaired and full water supply to the Hokitika reservoirs was reinstated on day 9. The water is turbid as a result of landslides into and within the lake, as well as into tributary creeks.

(e) Power

Repair to distribution lines is happening, but is constrained in part by road damage restricting access.

Transpower has reinstated supply from the north, and the main centres north of Hokitika are on reduced power. Power supply has been reinstated to 80% of the area and 90% of the habitable properties north of and including the Waitaha Valley. There is no power south of the Waitaha.

(f) Telecommunications

The fibre-optic cable link to Nelson was repaired on day 8. Most telecommunications north of Ross are now operable to an acceptable level[5].

2.3.3 One month

(a) Transport

The roading network within the region north of the Wanganui River is largely functional again, although there are many areas with metalled surface, one way sections and weight and speed limitations on bridges. The only significant route still closed in this area is SH 6 between Rapahoe and Barrytown because of slip and bridge damage. The situation south of the Wanganui River remains unchanged, although a start has been made on a temporary vehicle link across the destroyed spans of the Wanganui Bridge. SH 6 remains severed at the Wanganui and Whataroa Rivers, dependent on fords on the Poerua, Waitangitaona and Tatare Rivers, and closed between Franz Josef and Haast.

The Arthur’s Pass route remains closed between Jacksons and Cass, due to landslips. The damage and repair strategy is still being assessed with no immediate plans of repairing the remaining length, due to other priorities for resources.

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[5] Kaikoura was completely isolated from the national network due to 6 breaks in the East Coast fibre-optic cable, although local calls were possible on the local copper network. The fibre link was re-established after 2 days but only because of the ability to connect into an offshore cable that comes onshore at Kaikoura. Repairs to the East Coast cable were expected to take weeks or possibly months. Text services resumed after 5 days. (Giovinazzi et al 2017)

No repair has started on the railway network, as politicians have asked for a detailed damage assessment and cost of repair before committing funds to its reinstatement. Indications are that the major problem is several landslides in the Otira Valley, and that there is little severe bridge or track damage beyond this area.

(b) Drainage

It has already become apparent that aggradation of the rivers draining the alpine areas is occurring. In the most affected fault rupture zone south of the Kokatahi River, virtually all the local catchments are choked with landslide debris. During heavy rain, debris flows and the streams carry material onto the outwash fans. The lower stream channels have become unstable and are changing course virtually every time the steams are in spate. The roads in the immediate area of the range front, badly damaged by the earthquake, are now being covered by debris, which has effectively buried some of the damaged bridges. Heavy rain has produced debris flows in many catchments, overwhelming any training work that may have existed. Similar problems are also occurring in some locations away from the fault area, such as at Fergusons Farm south of the Mikonui with resultant flooding of SH 6.

(c) Sewerage

The sewer reticulation is functioning although still damaged, with repairs to the obstructed points, but discharge is still to the river, and the local waters are polluted.

(d) Water supply

Repairs to the water supply systems are continuing, with water reinstated to 90% of the greater Greymouth area and Hokitika. The Ross intake and pipe have been reinstated and the upper part of the town has a restricted water supply. The lower part is still requiring repair and water is being tankered in to a series of temporary tanks and standpipes.

(e) Power

A temporary line has been strung across the Wanganui River to supply power to Harihari. There is no power south of Harihari Township.

2.3.4 Three Months

(a) Transport

All roads north of Ross are open, except for a few district roads close to the fault line and mountains in the Kokatahi – Lake Kaniere area because of the degree of damage, ongoing debris flow issues and lack of major economic benefit in repair. SH 6 to Punakaiki was opened after 6 weeks. SH 73 remains closed between Jacksons and Arthurs Pass, but the government is committed to re-opening the route. A temporary vehicle bridge has been placed across the damaged sections of the Wanganui River to give access to Harihari and allow work to continue on the road to Whataroa. Work has started on re-opening the Haast Pass, at least for essential four wheel drive vehicles[6].

The government has decided to reinstate the Midland railway, and KiwiRail are working on repairs between Jacksons and Ngakawau, with the Jacksons to Cass section through Otira pending agreement on how to clear the line in conjunction with work on SH 73.

(b) Drainage

Problems ongoing as outlined for one month above.

2.3.5 One Year

(a) Transport

The roading network north of Ross is essentially back close to pre-earthquake condition, although with many speed and weight restrictions in place, and with local roads close to the fault remaining closed. SH 73 was reopened 10 months after the earthquake but is still subject to delays at several sections still being worked on, and sometimes closure when heavy rain remobilises slips and debris[7].

SH 6 south of Ross was reopened as far as Franz Josef with a temporary bridge over the Whataroa River after 5 months. There are weight restrictions on many bridges, and some fords. The road is single lane with a metalled surface in many places and is subject to frequent closure due to instability and flooding at bridge sites. In places, debris flow and stream aggradation issues close the road after nearly every heavy rainstorm. From Haast, the road over Haast Pass was reopened for controlled essential access after 4 months, but the road remains suitable for four wheel drive only. Ten months after the earthquake, the government announced that it was delaying the decision on rebuilding the road between Franz Joseph and Haast for another 12 months. Further assessments were being conducted and the response of rivers and even small catchments following the earthquake changes was to be observed as part of this.

The railway system was re-opened along with SH 73 six months after the earthquake (three months before the road), with Government funding for its reconstruction, but remains subject to severe speed restrictions in many places and occasional closure due to landslips and flooding.

(b) Drainage

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[6] Four wheel drive access only is planned to provide land access into Haast, The additional work needed to provide a road suitable for normal heavy vehicle use is considered too ambitious at this stage.
[7] SH 1 south of Kaikoura was closed for 72 out of 150 days in the first 5 months of its re-opening after the 2016 earthquake

Problems with aggradation are ongoing. The areas most affected are close to the hills and mountains throughout South Westland. Major rivers are aggrading and flooding and depositing sediment over land that was hardly ever flooded previously. Smaller streams are disgorging large quantities of sediment over fans. There are concerns that as aggradation continues, maintenance of the stopbanks and clearance to bridges will become increasingly difficult and expensive.

The Alpine Fault rupture produced a 1m step in all the riverbeds between Fox Glacier and the Hokitika River, resulting in local channel instability. Initially this produced degradation upstream of the fault, but this was rapidly reversed to aggradation as slip debris is worked down river. Smaller streams are disgorging large quantities of sediment over fans. Aggradation is threatening the future of Haast, and has already made it impossible to rebuild Franz Josef on its original site.

3 REGIONAL EARTHQUAKE

The Alpine Fault earthquake is clearly the most damaging event for the whole of the West Coast Region, but there are other earthquake sources in the region (see Figure 1.1). Fault lines offshore could produce strong shaking in coastal areas, but the greater effect could be tsunami, which is covered in *Supplement 4:Tsunami*. Onshore active faults and folds are generally located north of Hokitika and thus affect the Grey and Buller Districts. Rather than create a scenario, a real event has been chosen to represent a non-Alpine Fault earthquake. Two large earthquakes have occurred historically; the M7.8 Murchison earthquake of 1929, and the M7.1 Inangahua earthquake of 1968. The latter has been used as a representative scenario.

3.1 1968 Inangahua earthquake

The earthquake was a M7.1 event with an epicentre about 15km north of Inangahua Township. It occurred at 5:24 am on 23 May 1968. There were three deaths (two by landslide) and widespread damage from Karamea to Hokitika. Communications were affected, such that initial reports suggested that Greymouth was worst affected, and it was 3 hours after the earthquake that the first radio communication from Inangahua was achieved.

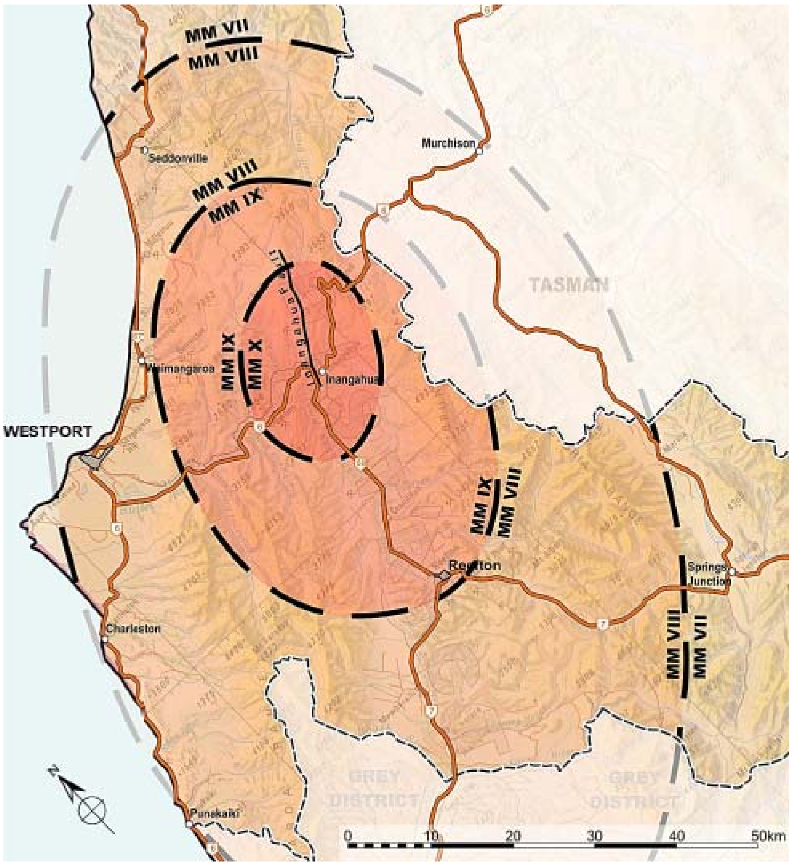

Figure 2.4. Isoseismals showing shaking intensities from the 1968 Inangahua earthquake

Aerial reconnaissance by helicopter began later in the morning. By 9:30pm, 196 people had been evacuated from Inangahua area by helicopter to Rotokohu and thence by bus to Reefton. A state of emergency was declared in Reefton and Westport, and maintained in place until 30 May. The following information has been taken mainly from Adams et al, 1986.

It is important to note that this was a "local" earthquake impacting on part of the region. The Inangahua earthquake fault rupture was about 15km, compared with the overall length of 160km in the 2016 Kaikoura earthquake and 400km for the Alpine Fault AF8 scenario. Even Westport at 25km from the epicentre was only lightly damaged, and thus there was immediate and rapid response from the surrounding area as well as from the rest of the country. This clearly affects the scale of the damage and the response and restoration times.

3.2 Roads

There was widespread damage to roads from landslides, slumping and fissuring. Spreading of embankments, particularly at bridge approaches, caused longitudinal cracking. Differential movement and slumping caused transverse cracking at terrace faces. Subsidence of bridge abutment fills was particularly large in the Inangahua – Rotokohu area, but extended as far south as Reefton and west to Westport. Subsidence of a high fill at the Camp overbridge near Runanga (about 85km from the epicentre) resulted in the death of a driver who drove into the abutment shortly after the earthquake. Approaches to the Orowaiti Bridge at Westport and the Waimangaroa overbridge were lowered by 0.2 – 0.3m.

Access between Reefton and Inangahua was initially gained along the Brown Creek Road two days after the earthquake for heavy and four wheel drive vehicles only. The main road was reopened three weeks after the earthquake, following repairs to the Landing road-rail bridge and clearance of a large slip. The Lower Buller Gorge Road was damaged by landslides and rock falls at Whitecliffs, 5km west of Inangahua. It was reopened 3 weeks after the quake, with a low level road built over a flood channel to by-pass the rock falls. The Upper Buller Gorge Road was extensively damaged with several sections completely carried away by landslides. Temporary reconstruction allowed it to be reopened after 10 weeks.

Structural damage to bridges was substantial within about 7km of Inangahua, but minor to none beyond this distance. Damage and cracking to piers was typical. Generally the bridges could be used after comparatively minor repairs and once the abutment slumping had been remedied. The Landing Bridge suffered failure of a concrete abutment and tilting of one pier and could not be used for about 3 weeks until temporary repairs had been effected.

Comment: Similar damage could be expected. Subsidence at bridge abutments should not be the same obstacle because bridges built in the last 30 years will all have settlement slabs (it is not known how many older bridges have been retrofitted, if any). The Landing Bridge has been replaced with a new structure, and depending on the extent of slips, SH 69 could be reopened within 2 – 3 days.

The Whitecliffs section of SH 6 has been rebuilt since 1968, away from the bluffs, and reopening of the Lower Buller Gorge could be expected to occur with a few days. However, similar damage to that in 1968 could be expected through the Upper Buller Gorge. Although the forty years since the 1968 earthquake have seen huge advances in machinery and technologies that might be thought to result in large reductions in time to clear slips and reinstate roads, that period has also seen a large increase in traffic volumes, traffic speeds and safety awareness. The type of preparation work seen prior to any large scale slip clearance on SH 1 on the Kaikoura Coast after the 2016 earthquake would most likely be needed on slip clearance in the Buller. The standard of road expected on re-opening would also be higher and concerns about safety from any on-going instability more pronounced. For these reasons we consider that no improvement on re-opening times for the Upper Buller Gorge could be expected, and it could even take considerably longer than the ten weeks in 1968.

3.3 Railway

Movement of the surface fault traces damaged the line with buckling due to compression and lateral displacement. Much more significant was lateral spreading of embankments with pronounced distortion to the track in both vertical and horizontal alignment. One train was derailed about 2km south of Rotokohu through embankment spreading. A number of slips blocked the line in the Buller Gorge, including a 1,900m^3 rock fall and collapse of a river bank below the line needing 2,300m^3 of fill to rebuild the line. The railway was reopened with severe speed restrictions about 3 weeks after the earthquake.

Comment: *Similar damage could be expected, with a similar time to reopen.*

3.4 Drainage

A major effect was a rock fall avalanche, which blocked the Buller River 3km upstream of Lyell. Material was carried down the whole 600m height of the southern valley side and 50m up the northern side. The slide dammed the river flow, forming a lake about 8km long. It overtopped the dam within a short time (the references are unclear about the duration taken) and the dam eroded out without causing any significant flood.

Comment: *Similar events could be expected in any large earthquake in the area, but next time the dam break might not be so fortuitous and there could be downstream flooding.*

3.5 Telecommunications

Telecommunication was all wire based in 1968. Subscribing telephones that lost connection ranged from 8% in Hokitika to 39% in Westport. A problem in these local lines was the twisting together of aerial lines during the earthquake shaking. Local calls were apparently able to be made within Inangahua Township on the manual exchange shortly after the earthquake, but all lines away from the township were cut by fallen trees, slips and the spreading of road and rail embankments displacing poles. About 2.5km of underground cabling was badly damaged by 80 ground subsidences and cracks and was replaced with aerial cable on existing poles.

The Inangahua exchange building was damaged and the risk of a large slip resulted in it being relocated within 2.5 weeks. The Reefton exchange building was badly damaged and demolished. The replacement exchange was installed in a relocatable building in Christchurch and transported to site. The Reefton to Greymouth line was re-connected by the end of day 1, the toll line from Inangahua to Westport reopened the day after the road (3 weeks), and a temporary repair enabled the Upper Buller line to open several weeks in advance of the road re-opening. The peak number of staff engaged in the repair work in the area was 67.

Comment: The technical advances in telecommunications since 1968 will have alleviated many of the vulnerabilities, but damage to cables from ground damage and moving of equipment through inadequate fixing remain relevant.

3.6 Electricity

Damage was not significant other than at Inangahua substation, where equipment was disconnected and bypassed allowing the restoration of supply after only 3 hours. However, landslides threatened several transmission towers, and a partial rerouting of the line was carried out after the earthquake in the Upper Buller Gorge to bypass the unstable areas.

Comment: Landslides from this earthquake came very close to destroying some transmission towers. Re-routing the lines will have mitigated the 1968 problem, but the lines across the steep topography must remain somewhat vulnerable.

3.7 Water and Sewer

There is little information reported:

"Cemented glazed sewer pipes suffered severe damage in the Inangahua earthquake. …. In Westport some underground pipes were broken." (p36 Adams et al, 1968). "All the services (to Westport) were cut with the exception of the gas which continued to flow as usual through pipes that had been damaged in the 1929 earthquake." (p46 MacDonald, 1973).

Reconnection of a broken water main in Derby Street near Kilkenny Park required the addition of 1.2m of pipe, indicating that lateral extension of the ground from liquefaction had occurred here (Carr, 2004).

Comment: There appears to have been less damage in Westport in 1968 than in 1929 although shaking intensities were similar (MM VIII). The direction and duration of strong shaking may have had some influence, but further research may reveal more damage in 1968 than reported in the references used. Some pipe damage was obviously the result of liquefaction.

Much of the pipework in critical sections of the water supply, stormwater and sewer is constructed of rigid and old material. Failure of critical pipework would be expected for all three services.

3.8 Conclusion

The Inangahua earthquake illustrates the type of damage that can occur with a moderately large earthquake but centred in a sparsely inhabited area. Major transport routes were closed for up to three weeks, but the damage was so located that alternative routes were available (albeit with long detour distances). A similar earthquake at a different location could have a much greater impact such as severing all land access to centres such as Westport or Karamea for an extended period of time, or of course, if close to an urban centre such as Westport or Greymouth, have much greater impacts on urban infrastructure.

REFERENCES

Adams, R.D., Eiby, G.A., Lowry, M.A., Lensen, G.J., Suggate, R.P., Stephenson W.R., 1968, *Preliminary Reports on the Inangahua Earthquake, N.Z., May 1968*, NZ Department of Scientific and Industrial research, Bulletin 193.

Butcher, G., Andrews, L., Cleland G., 1998, *The Edgecumbe Earthquake*. Report prepared for the Centre of Advanced Engineering, University of Canterbury.

Carr, K.M., 2004, *Liquefaction Case Histories from the West Coast of the South Island, New Zealand,* MSc thesis, Dept of civil engineering, University of Canterbury, Research report 2004-04.

Davies,A.J. et al, 2017. *Transport Infrastructure Performance and Management in the South Island of New Zealand, during the first 100 days following the 2016 M_w 7.8 "Kaikoura" Earthquake*. Bulletin of the New Zealand Society for Earthquake engineering, Vol 50, No.2, June 2017.

Dowrick, D.J., Rhoades, D.A., Davenport, P.N., 2003, *Effects of microzoning and foundations on damage ratios for domestic property in the magnitude 7.2 1968 Inangahua, New Zealand Earthquake*, Bulletin NZ Society for earthquake engineering, Vol 36, No.1.

Elms, D., McCahon, I., Dewhirst., 2005 *Alpine Fault Earthquake Scenario & Lifelines Vulnerability Assessment for Grey District Council*, Report for Grey District Council.

Elms, D., McCahon, I., Dewhirst., 2006 (a) *Alpine Fault Earthquake Scenario & Lifelines Vulnerability Assessment,* Report for West Coast Engineering Lifelines Group.

Elms, D., McCahon, I., Dewhirst., 2006 (b) *Alpine Fault Earthquake Scenario & Lifelines Vulnerability Assessment for Buller District*, Report for Buller District Council.

Elms, D., McCahon, I., Dewhirst., 2006 (c) *Alpine Fault Earthquake Scenario & Lifelines Vulnerability Assessment for Westland District*, Report for Westland District Council.

Giovinazzi S., Austin A., Ruiter R., Foster C., Nayyerloo M., Nair N., Wotherspoon L., 2017, *Resilinace and Fragility of the Telecommunication Network to Seismic Evenets: Evidence after the Kaikoora (New Zealand) Earthquake,* Bulletin of the New Zealand Society for Earthquake engineering, Vol 50, No.2, June 2017.

Hancox, G.T., Perrin, N.D., Dellow, G.D., 2002, *Recent studies of historical earthquake-induced landsliding, ground damage, and MM intensity in new Zealand*, Bulletin of the NZ Society for Earthquake Engineering, Vol 35, No.2.

Hancox. G.T., Cox, S., Turnbull, I.M., Crozier, M.J., 2003, *Reconnaissance studies of landslides and other ground damage caused by the Mw 7.2 Fiordland earthquake of 22 August 2003,* Institute of Geological and Nuclear Sciences science report 2003/30.

Hughes M.W., Nayyerloo, M., Bellagamba, X., Morris, J., Brabhaharan P., Rooney, S., Hobbs, E., Wooley, K., Hutchison, S., 2017, *Impacts of the 14th November 2016 Kaikoura Earthquake on Three Waters Systems in Wellington, Marlborough and Kaikoura, New Zealand: Preliminary Observations,* Bulletin of the New Zealand Society for Earthquake engineering, Vol 50, No.2, June 2017.

Liu Y., Nair N., Renton A., Wislon S., 201, *Impact of the Kaikoura Earthquake on the Electrrical Power System Infrastructure*, Bulletin of the New Zealand Society for Earthquake engineering, Vol 50, No.2, June 2017.

Stirling, M., Gerstenberger, M., Litchfield, N., McVerry, G., Smith, W., Pettinga, J., Barnes, P., 2007, *Updated Probabilistic Seismic Hazard Assessment for the Canterbury Region*, GNS Science Consultancy Report 2007/232; Ecan Report U06/6.

Suggate,R.P., Waight, T. 1998: *Geology of the Kumara-Moana area*. Geology of the Greymouth Area, Institute of Geological and Nuclear Sciences geological map 24.

Transit New Zealand, 2000, *Manual for Seismic Screening of Bridges*, Revision 2.

Transit New Zealand, 2000, *Seismic Screening of Bridges, Region 11, Canterbury.*

Transit New Zealand, 2000, *Seismic Screening of Bridges, Region 12, West Coast.*

APPENDIX A: Modified Mercalli Intensity Scale

Construction Categories for Damage Assessment as Used in Modified Mercalli Intensity Scale

<table>
<tr><th>After Eiby (1966)
Categories of non-Wooden Construction</th><th>After Study Group (1992)
Categories of Construction</th></tr>
<tr><td>Masonry A
Structure design to resist lateral forces of about 0.1g, such as those satisfying the New Zealand Model Building Bylaw, 1955. Typical buildings of this kind are well reinforced by means of steel or ferroconcrete bands, or are wholly of ferro-concrete construction. All mortar is 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 comers, but neither designed nor reinforced to resist lateral forces.
Masonry D
Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick and rammed earth. Weak horizontally.
Windows
Window breakage depends greatly upon the nature of the frame and its orientation with respect to the earthquake source. Windows cracked at MM5 are usually either large display windows, or windows tightly fitted to metal frames.
Water Tanks
The "domestic water tanks" listed under MM7 are of the cylindrical corrugated-iron type common in New Zealand rural areas. If these are only partly full, movement of the water may burst soldered and riveted seams.
Hot water cylinders constrained only by supply and delivery pipes may move sufficiently to break the pipes at about the same intensity.</td><td>Buildings Type I
Weak materials such as mud brick and rammed earth; poor mortar; low standards of workmanship (Masonry D in other MM scales).
Buildings Type II
Average to good workmanship and materials, some including reinforcement but not designed to resist earthquakes (Masonry B and C in other MM scales).
Buildings Type Ill
Buildings designed and built to resist earthquakes to normal use standards, i.e. no special damage limiting measures taken (mid –1930's to c. 1970 for concrete and to c. 1980 for other materials).
Buildings and bridges Type IV
Since c. 1970 for concrete and c. 1980 for other materials, the loadings and materials codes have combined to ensure fewer collapses and less damage than in earlier structures. This arises from features such as "capacity design" procedure, use of elements (such as improved bracing or structural walls) which reduce racking (i.e. drift), high ductility, higher strength.
Windows
Type I – Large display windows, especially shop windows.
Type II - Ordinary sash or casement windows.
Water Tanks
Type I - External, stand mounted, corrugated iron water tanks.
Type II - Domestic hot-water cylinders unrestrained except by connecting pipes.
H - (Historical)
Important for historical events. Current application only to older houses, etc.
General Comment
“Some” or a “few” indicates that the threshold of a particular effect has just been reached at that intensity.</td></tr>
</table>

INTENSITY SCALES

MODIFIED MERCALLI (MM) INTENSITY SCALE (Table from Downes, 1995)

	After Eiby (1966)	After Study Group (1992)
MM 1	Not felt by humans, except in especially favourable circumstances, but birds and animals may be disturbed. Reported mainly from the upper floors 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, reservoirs etc. may be set into seiche oscillation.	*People* Not felt except by a very few people under exceptionally favourable circumstances.
MM 2	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.	*People* Felt by persons at rest, on upper floors or favourably placed.
MM 3	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 the duration, but not the direction. Hanging objects may swing slightly. Standing motorcars may rock slightly.	*People* Felt indoors; hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognised as an earthquake.
MM 4	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 frame of buildings are heard to creak. Doors and windows rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock, and the shock can be felt by their occupants.	*People* Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic or to the jolt of a heavy object falling or striking the building. *Fittings* Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock. *Structures* Walls and frame of buildings, and partitions and suspended ceilings in commercial buildings may be heard to creak.

	After Eiby (1966)	After Study Group (1992)
MM 5	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.	*People* Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed. Direction of motion can be estimated. *Fittings.* Small unstable objects are displaced or upset Some glassware and crockery may be broken. Hanging pictures knock against the wall. Open doors may swing. Cupboard doors secured by magnetic catches may open. Pendulum clocks stop, start or change rate (H*). *Structures* Some window type I* cracked. A few earthenware toilet fixtures cracked (H)
MM 6	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 moved. Unstable 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.	*People* Felt by all. People and animals alarmed. Many run outside. Difficulty experienced in walking steadily. *Fittings* Objects fall from shelves. Pictures fall from walls (H*). Some furniture moved on smooth floors. Some unsecured free-standing fireplaces moved. Glassware and crockery broken. Unstable furniture overturned. Small church and school bells ring (H). Appliances move on bench or table tops. Filing cabinets or “easy glide" drawers may open (or shut). *Structures* Slight damage to Buildings Type I*. Some stucco or cement plaster falls. Suspended ceilings damaged. Windows Type I* broken. A few cases of chimney damage.

	After Eiby (1966)	After Study Group (1992)
MM 7	General alarm. Difficulty experience 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 on sand and gravel banks.	*People* General alarm. Difficulty experienced in standing. Noticed by motorcar drivers who may stop. *Fittings* Large bells ring. Furniture moves on smooth floors, may move on carpeted floors. *Structures* Unreinforced stone and brick walls cracked. Buildings Type I cracked and damaged. A few instances of damage to Buildings Type II. Unbraced parapets and architectural ornaments fall. Roofing tiles, especially ridge tiles may be dislodged. Many unreinforced domestic chimneys broken. Water tanks Type I* burst. A few instances of damage to brick veneers and plaster or cement-based linings. Unrestrained water cylinders (Water Tanks Type II*) may move and leak. Some Windows Type 11* cracked. *Environment* Water made turbid by stirred up mud. Small slides such as falls of sand and gravel banks. Instances of differential settlement on poor or wet or unconsolidated ground. Some fine cracks appear in sloping ground. A few instances of liquefaction.

	After Eiby (1966)	After Study Group (1992)
MM 8	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 foundation 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.	*People* Alarm may approach panic. Steering of motorcars greatly affected. *Structures* Buildings Type II damaged, some seriously Buildings Type Ill damaged in some cases. Monuments and elevated tanks twisted or brought down. Some pre-1965 infill masonry panels damaged. A few post-1980 brick veneers damaged. Weak piles damaged. Houses not secured to foundations may move. *Environment* Cracks appear on steep slopes and in wet ground. Slides in roadside cuttings and unsupported excavations. Small earthquake fountains and other manifestations of liquefaction.

	After Eiby (1966)	After Study Group (1992)
MM 9	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 alluviated areas, with the formation of earthquake fountains and sand craters. Underground pipes broken. Serious damage to reservoirs.	*Structures* Very poor quality unreinforced masonry destroyed. Buildings Type II heavily damaged, some collapsing. Buildings Type III damaged, some seriously. Damage or permanent distortion to some buildings and bridges Type IV. Houses not secured to foundations shifted off. Brick veneers fall and expose frames. *Environment* Cracking of ground conspicuous. Landsliding general on steep slopes. Liquefaction effects intensified, with large earthquake fountains and sand crater.
MM 10	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 in rivers, lakes and canals thrown up the banks	*Structures* Most unreinforced masonry structures destroyed. Many Buildings Type II destroyed. Many Buildings Type Ill (and bridges of equivalent design) seriously damaged. Many Buildings and Bridges Type IV have moderate damage or permanent distortion.
MM 11	Wooden frame structures destroyed. Great damage to railway lines and underground pipes.	

	After Eiby (1966)	After Study Group (1992)
MM 12	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.	