



**13<sup>th</sup> World Conference on Earthquake Engineering**  
**Vancouver, B.C., Canada**  
**August 1-6, 2004**  
**Paper No. 1325**

## **LIQUEFACTION CASE HISTORIES FROM THE WEST COAST OF THE SOUTH ISLAND, NEW ZEALAND**

**Kirsti CARR<sup>1</sup> and John BERRILL<sup>2</sup>**

### **SUMMARY**

The refinement of liquefaction prediction models is highly dependent on the establishment of precedent provided by case histories to effect improvement in analysis procedures. A study into three earthquakes that have occurred on the West Coast of the South Island, New Zealand, has been undertaken in order to build on existing archival information and to consolidate previous research. It is anticipated that this investigation will provide the basis for selection of sites for the installation of pre-event instrumentation arrays that will lead to a greater understanding of the cause and effects of liquefaction.

### **INTRODUCTION**

The original project objectives were to build upon the current case history database for sites of liquefaction resulting from earthquakes on the West Coast of the South Island of New Zealand since the 1920s. Liquefaction occurrences had been reported in Karamea and Greymouth as a result of the 1929 M7.8 Murchison earthquake and the 1968 M7.1 Inangahua earthquake, two of the three major earthquakes on the West Coast in the 20th Century. Site investigation work was performed at sites which liquefied in selected earthquakes and not in others, to ascertain the variation in soil properties and profiles at these sites. Using the information collected an examination of the current methods for predicting the liquefaction potential were reviewed.

#### **Geology of the Region**

Many of the towns on the West Coast of the South Island are located on geologically young soil. Hokitika, Greymouth, Westport and Karamea are located near river mouths in a mixed fluvial and lagoonal environment while Reefton, Inangahua, and Murchison have been established in river valleys on near level flood plains. These sites are therefore naturally susceptible to liquefaction and when combined with the proximity of the many active faults, including the Alpine Fault, the likelihood of liquefaction is high.

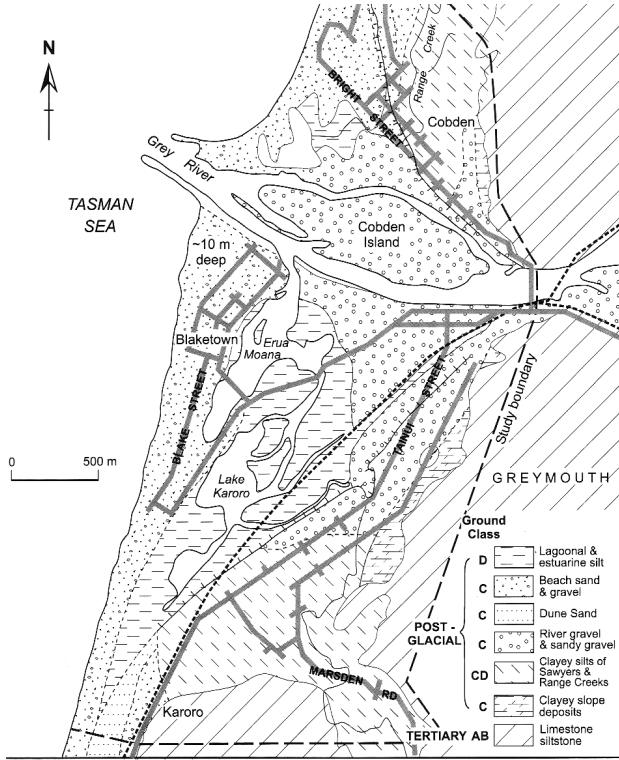
---

<sup>1</sup> Geotechnical Engineer, Tonkin & Taylor Ltd, Auckland, New Zealand (formerly Univ. of Canterbury)

<sup>2</sup> Reader in Civil Engineering, University of Canterbury, Christchurch, New Zealand

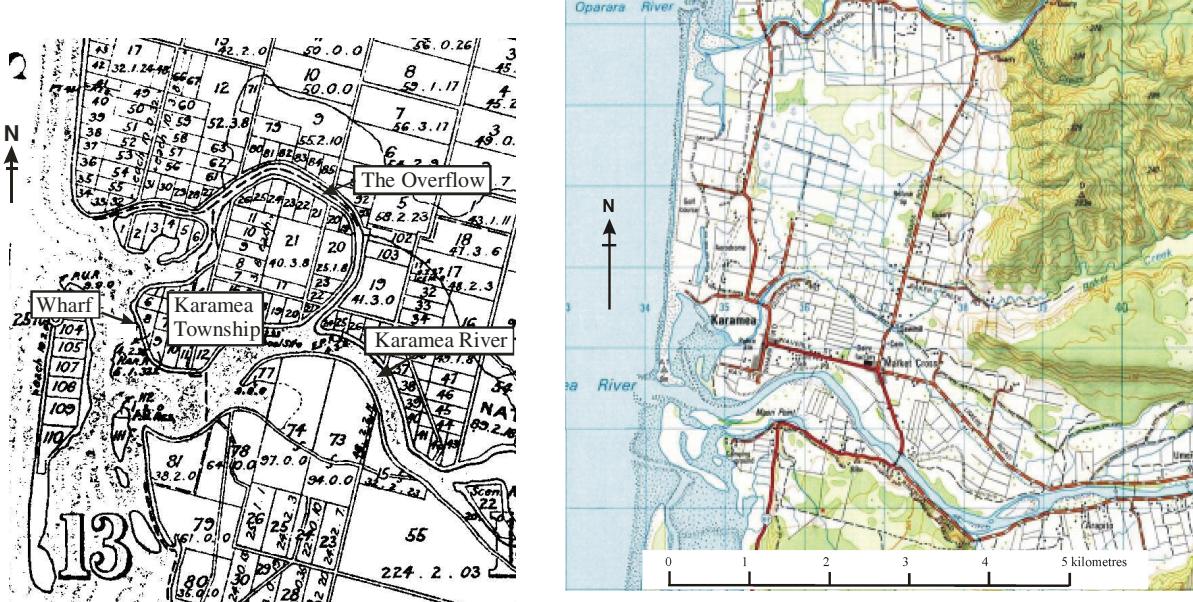
### *Human impact over the past 150 years*

The potential for liquefaction in towns such as Greymouth, Westport and Karamea has been increased by the alterations made to the coastlines due to the training of rivers and the building of wharves. In Greymouth, the construction of the sea wall acting as a groyne combined with longshore drift, has meant that the coast to the south of the river mouth has built up by nearly one kilometre over the past 150 years as shown in Figure 1. Due to the rate of accretion, and the less energetic environment in which the sediment is trapped, the sediments in the Blaketown area are thought to be fairly loose in comparison to sand dunes subject to wave action, and hence more susceptible to liquefaction than is usual for dense sand. It will be seen later that the Blaketown area was indeed one of the worst affected in the 1929 earthquake.



**Figure 1. Microzoning Map of Greymouth (Dowrick *et al.* [1])**

Whereas it was loose sand that liquefied at Greymouth, at Karamea, the other area studied, it was mainly fluvial sands that liquefied. In 1929, the Karamea River took a different path to that taken today, with a now abandoned second channel braiding off to the north and the outlet also to the north and referred to as the Overflow. The map shown in Figure 2(a) was drawn in 1918 and shows that the Karamea Township was situated on what was known as Simpson's Island, which had been formed by the changing course of the braided Karamea River. It is likely to have been built up by the accretion of sand and silt from the river flow, as well as longshore drift along the Karamea Bight. Both the Karamea River and Oparara River mouths have moved considerably over time, as can be seen by comparing the 1918 map with the current map of the area, shown in Figure 2(b). At the river mouth, the river flow rates diminish rapidly as the coast is approached, the river becomes wider and a large amount of sediment is deposited. These deposits are predominantly sand and thus ideally liquefiable materials when saturated. In 1931, the Overflow was blocked off during construction of the flood protection stop banks along the main channel. The overflow channel has since filled in, though is visible from above as a small dip in the farm paddocks.



**Figure 2. (a) 1918 Map of Karamea (Archives New Zealand) (b) 2001 Map of Karamea (Base Map: Topomap [2])**

## LIQUEFACTION CASE HISTORIES

### Previous Research

Three major earthquakes occurred on the West Coast of New Zealand since the 1920s - the 1929 Murchison earthquake, the 1968 Inangahua earthquake and the 1991 Hawks Crag events. These caused significant damage to infrastructure and loss of life. Many studies undertaken into liquefaction on the West Coast using these events as a basis for investigation have been carried out by researchers at the University of Canterbury (Fairless [3]; Ooi [4]; Adlam [5]; Bienvenu [6]). Dou and Berrill [7], conducted reconnaissance studies in the area after the 1991 Hawks Crag earthquake.

In the course of the present study, much additional archival information has been collated from museums, newspapers and from discussions with residents who experienced the earthquakes on the West Coast since the 1920s. This project has greatly extended the University of Canterbury case history database, with sites of liquefaction identified as far north as the Paturau River, and as far south as the Greenstone River on the West Coast as a result of the 1929 Murchison earthquake. These sites are indicated in Figure 3.

The phenomenon of liquefaction was not understood at the time of the 1929 Murchison earthquake and neither was it universally recognised in 1968 when the Inangahua earthquake occurred. Due to this, reports of the following surface manifestations were all used to identify sites of liquefaction and base the study upon:

- sand boils and ejection of water and mud from the ground
- lateral spreading
- subsidence of the ground surface
- tilting or sinking of structures.

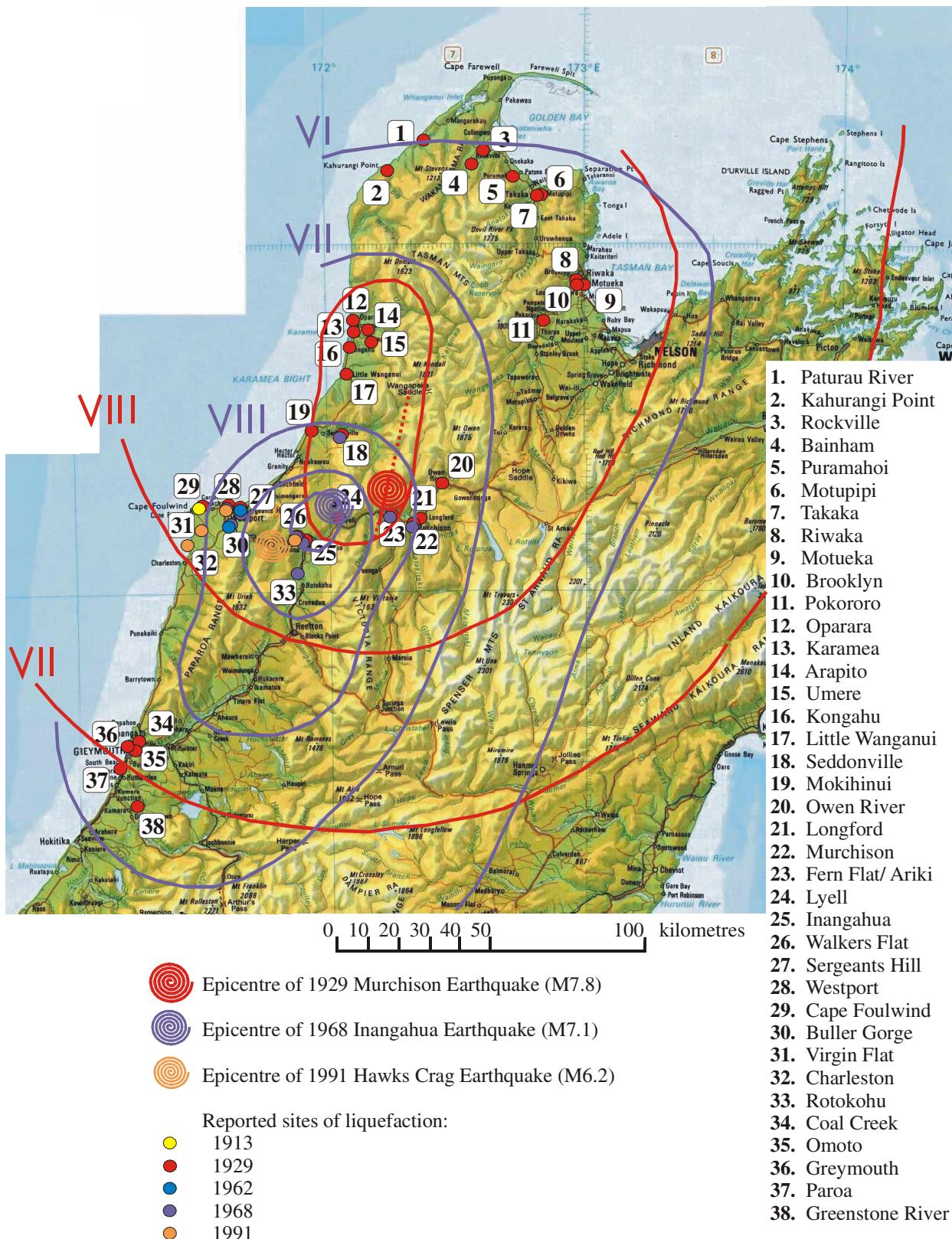


Figure 3. Summary map of all known locations of liquefaction (Base map: Topomap [2])

### *1929 Murchison Earthquake*

The 1929 Murchison earthquake, otherwise known as the Buller earthquake, caused severe damage in the Westland and Nelson regions. The earthquake, which has been assigned a magnitude of 7.8 (Dowrick and Smith [8]) based on intensity reports from 1929, was one of the largest recorded in recent times in New Zealand. Dowrick [9] wrote that the earthquake occurred in the middle of what was a much wetter June than normal. This statement was based on comparisons made of the June 1929 rainfall levels, with average rainfall levels for four weather stations on the northern West Coast. The map shown in Figure 3 indicates the location of the epicentre of the earthquake on the White Creek Fault, near Murchison and the areas where liquefaction is thought to have occurred following the earthquake.

The effects of the earthquake were widespread and included damage to houses, destruction of bridges and roads. In Karamea, the surface manifestations of liquefaction were concentrated between the Karamea River and the Overflow channel. These effects included sand boils with geysers of water gushing to heights of up to 10 m and overall settlement of approximately 0.7 metres. Fissuring was widespread over the area, as were cracks in the road as shown in Figure 4 and the lateral spreading caused the bridges to become arched in shape. Lateral spreading also affected the wharf and the main bridge across the Karamea River, where two years later it was discovered that the piles had fractured.



**Figure 4. Cracks in ground at Quinlans Filling - looking South towards Karamea (photo courtesy of Karamea Museum)**

In Westport, the rupturing of services was noted by the county engineer as were fissures, and sand boils. The towns of Inangahua and Murchison were closest to the epicentre of the earthquake and suffered proportionally increased damage. Occurrences such as lateral spreading, fissuring of roads, sand boils and geysers were all reported. However, this damage was insignificant in the eyes of the community due to the loss of life sustained by the township.

To the south in Greymouth, most liquefaction occurred in areas of reclaimed land, such as the suburb of Blaketown. In this area the land has been built up by the combination of longshore deposition and sand trapped by the effective groyne feature, the wharf and breakwater. Fissuring of roads and paddocks was observed, as was silt and water exuding through cracks in the ground. A number of national newspapers reported the occurrence of a sand boil in Blaketown that resulted in a deposit of sand being spread over an area of 40 square metres and several centimetres deep.

### *1968 Inangahua Earthquake*

The shallow nature of the Inangahua earthquake, assigned a moment magnitude of 7.2, meant that the greatest intensities were felt in the Inangahua district, where few buildings remained undamaged following the earthquake. Photographs taken following the earthquake indicated that landslides and other forms of damage were widespread in the surrounding area, though the effects from liquefaction, such as the formation of sand boils, seemed to be confined to young sediments associated principally with the Buller River, from Inangahua township to the West Coast at Westport. The epicentre was approximately 15 km north of the township and 25 km west of the location of the 1929 Murchison earthquake (Adams *et al.*[10]).

The most commonly observed effects of liquefaction were sand boils and geysers. These were widespread in the alluvial flood plains of Inangahua, and also recorded in Westport. The toppling of power poles were also noted in Westport as were the rupturing of pipes, in similar locations to those that ruptured in 1929.

As a result of the 1991 magnitude 6.1 Hawks Crag earthquake, sand boils and water spouts occurred at a site that had previously liquefied in the same manner as a result of the Inangahua earthquake. Sand boils were also noted in the Westport North School grounds and on the beach at Charleston, and on the coast south of Westport.

### **FIELD WORK UNDERTAKEN**

Soil testing was undertaken at sites in both Greymouth and Karamea. These towns are located a significant distance from the epicentres of the 1929 and 1968 earthquakes, and a number of areas in each town liquefied in the 1929 event but did not do so in the 1968 event. Due to these differences, the results of testing at these localities may be used to help identify the dividing line between potential liquefaction and non-liquefaction of a site.

Preliminary site investigations were carried out at sites that were confirmed to have liquefied as a result of the 1929 Murchison earthquake by a number of residents or by photographic evidence. Hand augering was undertaken to ensure that there were no gravel layers close to the ground surface which may inhibit the cone penetrometer testing and the site assessed for adequate access for the drilling rig.

Some twenty Cone Penetrometer Tests (CPT's) were undertaken using the Civil Engineering Department's drill rig in the towns of Greymouth and Karamea. The CPT was used as it could provide repeatable tests and a detailed interpretation of soil types and soil layers was possible due to the continuous profile obtained. The University of Canterbury drilling rig had a total weight of six tonnes and the cone itself belonged to Fugro's sensitive range, with a tip-force limit of 5 tonnes. These two factors limited the depth to which the cone could be driven. For instance, gravel layers between 1.2 and 1.6 metres and again at 5.6 metres limited the use of the CPT in Greymouth but using flight augers to drill through these gravel layers enabled CPT tests to be made to greater depths.

In Greymouth, standard penetration testing was attempted, though the results were discounted due to boiling of sand into the base of the hollow stem auger. SPT testing was not attempted in Karamea due to the very loose nature of the cohesionless soil beneath the water table which was likely to cause similar problems. Hand augering and flight augering were undertaken in order aid definition of the soil profiles.

## LIQUEFACTION PREDICTION MODELING

A number of different analysis techniques were used in this study to enable the comparison of the different methods available for predicting the occurrence of liquefaction at a site. These methods have been developed, based on either a stress based approach, or energy approach as shown in Table 1 below.

**Table 1. Methods used in this study**

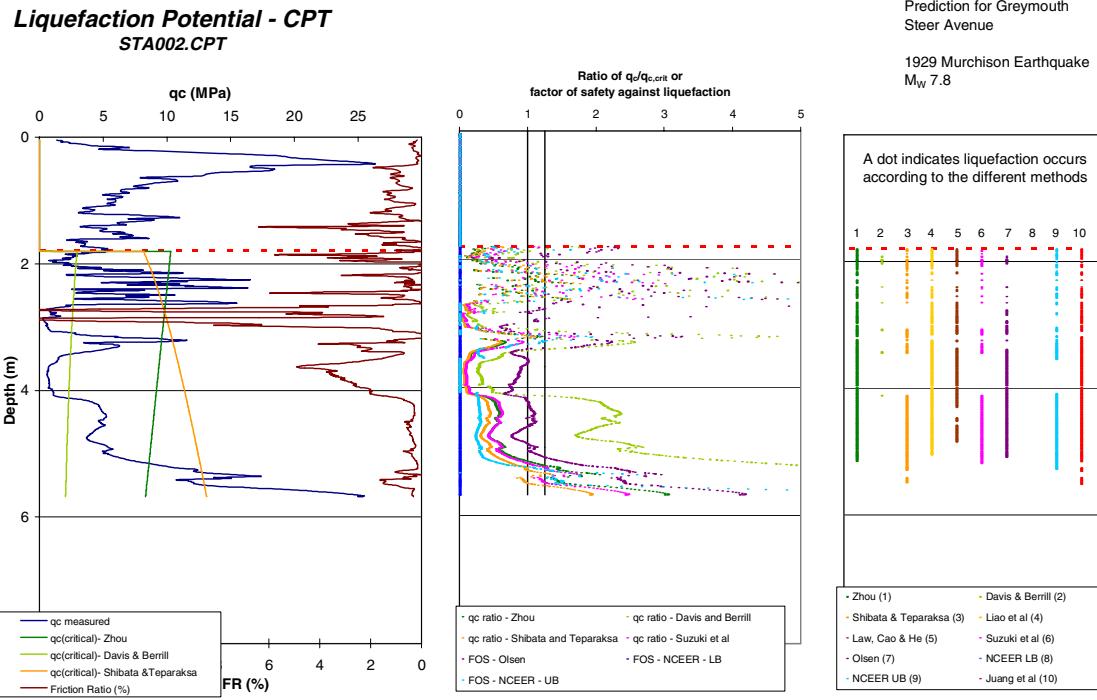
Stress Based Prediction Methods	Energy Based Prediction Methods
Shibata and Teparaksa [11]	Zhou [17]
Suzuki, Tokimatsu, Koyamada, Taya and Kubota [12]	Davis and Berrill [18]
Olsen [13]	Liao, Veneziano and Whitman [19]
Robertson and Wride [14] as NCEER [22]	Law, Cao and He [20]
Juang, Yuan, Lee, Lin [15]	
Toprak and Holzer (2003)	

Peak ground accelerations (PGA) values were calculated at each site for the 1929 Murchison earthquake and at some sites for the 1968 and 1991 earthquakes as few or no instrumental measurements were available. The following PGA values were obtained using the method of Zhou *et al.* [21], discussed further below.

**Table 2. Peak ground accelerations used in this study**

Location	1929 Murchison (M 7.8)		1968 Inangahua ( $M_W$ 7.23)		1991 Hawks Crag (M 6.2)			
	Calculated	Used	Recorded	Calculated	Used	Recorded	Calculated	Used
Oparara	0.228g	0.228g	-	0.135g	0.135g	-	-	-
Karamea	0.250g	0.250g	-	0.148g	0.148g	-	-	-
Arapito	0.269g	0.269g	-	0.150g	0.150g	-	-	-
Murchison	1.134g	1.134g	0.29g, 0.364g	0.425g	0.364g	0.202g, 0.29g	0.070g	0.29g
Inangahua	0.638g	0.638g	-	0.743g	0.6g	0.186g, 0.168g	0.181g	0.186g
Westport	0.279g	0.279g	0.302g, 0.302g	0.338g	0.302g	0.142g, 0.158g	0.246g	0.158g
Greymouth	0.081g	0.4g	0.22g, 0.391g	0.070g	0.391g	0.058g, 0.057g	0.047g	0.058g

For each of the test sites, a chart was compiled to show the results of the cone penetrometer testing and indicating the liquefiable layers, as defined by the different analysis methods. The format is illustrated by the results from the CPT number 2 at Steer Avenue, Greymouth and given in Figure 5. The first of the three charts indicates the measured tip resistance and friction ratio, as well as critical values for  $q_c$  obtained by the methods of Zhou [17], Davis and Berrill [18] and Shibata and Teparaksa [11]. The second chart shows either the ratio of critical tip resistance to the measured resistance, or the factor of safety against liquefaction defined as  $FS = CRR/CSR$ . Vertical lines have been drawn at both a value of 1.00 and 1.25. The third plot indicates, for each of the prediction methods, the layers that are deemed potentially liquefiable. In this plot a dot indicates the layer has the potential to liquefy according to the particular prediction method.



**Figure 5. CPT test results and analysis for Steer Ave, Greymouth.**

## DISCUSSION OF MODELLING

The analysis of the acquired CPT data demonstrated poor agreement between the models themselves and between the model predictions and the historical observations. A number of the prediction methods indicate liquefaction at sites where no surface evidence of liquefaction was recorded. This absence of correlation may be attributed to an adopted lower bound approach in the models examined here. For example, Youd *et al.* [22] writes, when discussing the curve defining the limit between liquefaction and non-liquefaction of sites according to the method of Robertson and Wride [14], that, “*several studies have confirmed that the CPT criteria .. are generally conservative*”. Youd *et al.* [22] also states that the criteria of Suzuki *et al.* [12] are “*slightly more conservative than those of Robertson and Wride (1988)*”.

The liquefaction potential models are predominantly based on case history data from the USA, Japan, and China. The lack of knowledge available, regarding liquefaction effects based on New Zealand earthquakes and the suitability of the models in the context of local soils has implications on the application of these models in New Zealand, with its mixed and complicated tectonics and in this region, exceptionally high rainfall. For example, Zhou *et al.* [21] noted that the New Zealand acceleration attenuation may be different to that in other countries. Ólafsson [23] noted that the attenuation rates in Iceland were different to those appropriate for the Western USA or continental Europe, where it is believed that the thickness of the earth’s crust is an important factor in the attenuation rule. One of the major factors used in all of the prediction models is the intensity of the shaking at the site. This is usually estimated from the magnitude of the earthquake at the epicentre and the attenuation rule of the shaking with distance, and expressed as a single term, the peak ground acceleration, or pair of terms, the earthquake magnitude and distance to the epicentre. It must be noted that in this study, the accelerations at the epicentre are estimated and with the uncertainties in the attenuation for many of the earthquakes on the West Coast, estimates of the site acceleration are therefore difficult. There are also uncertainties in the epicentral distances.

### **Uncertainties in Data**

Additional inaccuracies in the modelling undertaken for this study may stem from uncertainties in the peak ground acceleration values, the distances from the epicentre of the fault rupture to the site in question, the measured cone tip values or in the models themselves.

The peak ground accelerations used in the modelling process for the 1929 Murchison earthquake and for some sites for the 1968 Inangahua earthquake were simply estimated from attenuation equations rather than taken from direct instrumental measurements. These values were based on the attenuation models of Zhou *et al.* [21] and the peak ground acceleration values reported by Zhou *et al.* [21] from scratch plate records. As the magnitude of the 1929 Murchison earthquake is itself an estimate based on felt intensity reports, this adds to the uncertainty and makes any estimate of the peak ground acceleration difficult to apply with any great degree of confidence.

Liquefaction occurred in Blaketown, part of Greymouth, in the 1929 Murchison earthquake but not in the 1968 Inangahua event. In the analysis, the same peak ground acceleration was used for the study of the prediction models for both the 1929 and 1968 earthquakes in Blaketown. This was done as the motion was felt strongly in Greymouth in 1929, as indicated by the isoseismal maps. Even when using this estimated value of PGA, not all the observed liquefaction sites in the Greymouth area were deemed to be potentially liquefiable, under the 1929 conditions using the various prediction models. This may be a result of the simplicity of the models, densification of the soil due to previous shaking, consolidation over the past 74 years, or some other, as yet, undetermined phenomena occurring to the soil prior to testing in 2003. A possible explanation lies in the duration of the 1929 shaking, which would have gone on longer due to the greater magnitude of the earthquake and from the propagation of rupture to the north.

Methods such as Davis and Berrill [18], Berrill and Davis [24] and Liao *et al.* [19], estimate the seismic energy arriving at a site from the magnitude of the earthquake and the epicentral distance. These epicentral distances are only known approximately and the rupture at the epicentre may stretch for many kilometres along a fault, making accurate estimates of the distance very difficult. Another factor to consider is that the Davis and Berrill model also assumes spherical spreading of energy. This assumption, although convenient, is unrealistic for close-in sites and also neglects directivity effects, which can be seen in the isoseismal maps drawn from the felt intensities. However, the model could be adjusted for this. For example, for the 1929 Murchison earthquake, a spheroidal propagation of earthquake energy could be used as the isoseismal contours are ellipsoidal in shape. However, this will require further work on the estimation of the appropriate epicentral distances. This modification would introduce another parameter to the model as the energy radiation pattern varies for each earthquake.

### **Uncertainties in Modelling**

The method of Robertson and Wride [14], which was adopted by the NCEER Workshop Participants as the recommended method of determining the liquefaction potential of a site, does not appear to represent very well the observed behaviour in the Grey-Buller region. Layers of soil were deemed liquefiable at almost every site under the conditions of both the 1929 Murchison earthquake and the 1968 Inangahua earthquake, even though no surface effects due to liquefaction were reported. Since the loose sand layers were generally at shallow depths, it is unlikely that occurrences of liquefaction went unobserved. It is possible that the normalising process used in this method takes insufficient account the properties of alluvial soils i.e. layers of gravel and then silts and sand deposited by successive floods.

The discrepancies in the inferred soil profiles in comparison to those obtained by hand auger borings and the particle size distribution plots suggests that soil profile identification through hand augering and drilling is a necessity rather than an option. It is acknowledged that some thin layers of soil may not be

identified from hand auger bores or drilling due to the disturbed nature of the soil. However, the cone penetrometer probe is likely to disturb the soil for depths of at least 2 to 3 cone diameters ahead of the cone, which is equivalent to a depth of greater than 0.1 metres. This means that the thin layers identified by methods such as Robertson and Wride [14] and Olsen [13] are of dubious confidence as the input parameters are questionable.

Many of the prediction models indicated that a large number of relatively thin layers had the potential to liquefy over the depth of the soil columns studied. It was noted by Pyke [25], that thin liquefiable layers, “*are unlikely to be of practical consequence under level ground, especially when they are well below foundation depth*”, whereas they should be considered of importance on sloping ground. The sites considered in this study were all level ground sites. If a thin layer liquefies the increased pore-water pressure is unlikely to be able to build up to the extent required for the surficial effects of liquefaction, such as sand boils, to be seen. This means that liquefaction may have occurred at lower levels, leaving no surface indication of the occurrence. This also means that the model predictions could be correct, but there is no way of knowing for sure. Thin layers of soil may have liquefied in Karamea due to the 1968 Inangahua earthquake, as was indicated by the different prediction models, yet with no effects observed at the ground surface. If the confining layers between the sand layers are sufficiently porous, the increased pore pressure required for liquefaction may have been dissipated into the surrounding soil. It must also be noted that the tip resistance values measured in the thin layers might be inaccurate due to the well-known thin layer effect. As a result of this, the ascertained properties of these thin layers may not be known with sufficient accuracy for any modelling based on the data to give accurate predictions. This is not a new problem, but it is still a perplexing one

#### *Sensitivity study*

A study was carried out, in order to evaluate the sensitivity of the various models to changes in peak ground acceleration and the distance of the site to the epicentre of the earthquake. As a basis for this work the 1929 Murchison event was used.

The uncertainty of relationships between intensity and magnitude, such as the Gutenberg and Richter expression, has become much more apparent with the growing base of data. Thus, the peak ground accelerations at a site were also varied to observe the sensitivity of the models to such changes. The methods of Shibata and Teparaksa [11], Suzuki *et al.* [12], Olsen [13], Robertson and Wride [14] as NCEER [22] and Juang *et al.* [15] all use the peak ground acceleration to characterise the seismic energy arriving at a site and therefore the potential for liquefaction. The peak ground acceleration values were adjusted by  $\pm 10\%$  of the original estimated value. It was observed that the models of Shibata and Teparaksa, Suzuki *et al.*, Robertson and Wride and Juang *et al.* are all reasonably stable with respect to small variations in the peak ground acceleration values. When the PGA was altered for the method of Olsen, the change in thickness of the potentially liquefiable layers was strongly affected by the critical cone tip resistance.

Three of the liquefaction potential prediction methods use the magnitude of the earthquake and the distance between the site and the source of rupture to characterise the seismic energy arriving at a site. These models include Davis and Berrill [18], Liao *et al.* [19] and Law *et al.* [20]. When the distance between the site and epicentre was decreased it was observed that the methods of Liao *et al.* and Law *et al.* predicted slightly varied thicknesses of the potentially liquefiable layers. This shows that the models require reasonably accurate epicentral distance values in order to achieve accurate identification of the liquefaction potential. However, accurate estimates of the epicentral distances are often difficult as the epicentral distances are only known approximately and the fault rupture may stretch for many tens of kilometres along the fault.

## **Improving the Models**

### *Modelling*

In order to improve the accuracy of the prediction models and to increase the understanding of where the phenomenon of liquefaction will occur, details of the sites which may liquefy are needed before an earthquake so that the properties of the sites can be compared before and after the occurrence of liquefaction in the earthquake.

This means that the data obtained in this study can be used as base line for comparison with information obtained at liquefied and non-liquefied sites following the next large earthquake on the West Coast. An improved model incorporating a greater number of parameters needs to be developed to better represent the complexity of the seismic energy arriving at a site. For example, the thrust events in the Buller region are very different to the strike-slip earthquakes of California, but similar to some events in Japan. As indicated by the results of the analyses, rupture directivity leading to energy focussing is a source characteristic which should also be investigated. The current soil state, in terms of aging effects and particle distribution, also needs consideration as part of the liquefaction model. For example, the simple Oparara site appears to fit the current models better. The improved models should include the associated attenuation rates and duration effects. This needs to replace the current simple models which utilise only the peak ground acceleration value (with a rough correction for duration through magnitude) or the magnitude and epicentral distance pair of parameters.

## **Instrumentation Arrays**

### *The Need for Instrumentation*

There is an immediate need for instrumentation to be installed at key sites on the West Coast. Any information that can be obtained from such an initiative would be invaluable in terms of validating and further refining the liquefaction potential prediction models.

At the simplest level, accurate measurements of the peak ground accelerations should be obtained through the installation of arrays of accelerometers at several sites where future liquefaction is expected and where soil conditions are known before the event.. As well as providing acceleration data for analysis of the behaviour of the particular sites, the overall set of data would shed light on attenuation of strong motion in the region. In addition to installing one accelerograph per site to simply record surface motion, it is also desirable to install down-hole arrays of accelerometers and pore-pressure transducers at one or more key sites. Data from these arrays, from large and small events, could be used to study the initiation of pore-pressure increase, the effect of thin stratification of sandy deposits, discussed above, and their importance relative to thick layers, as well as providing further field testing of the dissipated energy~pore pressure increase hypothesis (Davis and Berrill [27]). Further, the interplay of site response and liquefaction effects could be examined.

### *Locations for the Instrumentation*

Constraints are imposed on the location and type of instruments used in the arrays due to the flood prone nature of many West Coast towns. This means that the instruments need to be able to withstand such events, be accessible and monitored regularly to ensure they are in correct working order. Additionally, they need to be cheap enough so that they can be replaced if needed. The sites selected must be founded on sands and silts as the peak ground accelerations measured at rock sites are very different to those measured on soft soils (Zhou et al. [21]). A number of sites have been suggested in Carr [28].

### *Monitoring*

Monitoring of the site conditions must be undertaken on a regular basis so that the site conditions are reasonably accurately known both before and after a future earthquake event. This includes recording the

variation in the depth to the water table and the use of seismic wave velocity measurements to increase understanding of aging effects on the soil and hence liquefaction potential.

At the sites suggested for instrumentation, knowledge has already been gathered regarding the soil profiles and results from cone penetrometer tests. It would be prudent to undertake further cone penetrometer tests at the sites where the variation in soil profile is unknown. These results should then be extended using other testing methods such as the seismic cone penetrometer test, or geophysical testing and bore logs, obtained adjacent to the test sites. This data would provide a “datum”, and similar testing carried out every five or ten years at each site, could monitor the changes in the soil profiles in terms of effects, such as consolidation and especially water table variations. The water table variations should also be correlated against rainfall records. For instance, Dowrick [9] reported that the winter of 1929 was an unusually wet winter.

This monitoring may also increase understanding of long-term site effects and indicate why the Oparara site is not considered potentially liquefiable, according to the prediction models, under the conditions of the 1929 Murchison earthquake. As noted earlier, the soil at the site may have become denser under the 1929 earthquake shaking or from consolidation over the past 74 years. The water table may also have lowered over the past 74 years due to the Oparara River cutting down, the alteration of the coast line and drainage of the flat land inland from the coast.

## CONCLUSIONS

As a result of this study, the case history database of liquefaction occurrences has been increased. Further sites have been identified as having liquefied in the past and as such are now localities which should be reviewed, following future earthquakes in the Buller Region. Drilling was undertaken at a number of sites in both Greymouth and Karamea and from this base line data and site parameters have been recorded for use in future studies. A number of residents were made aware of the liquefaction phenomena and while the consequences may not be as severe as in highly populated countries such as Japan, risks are still significant.

A review of the current state of prediction modelling was undertaken. This indicated that the simple models may not be as accurate as would be liked and may not be able to capture the complex phenomenon of liquefaction. None of the current prediction models for the boundary between soils likely to liquefy and those not likely to liquefy in an earthquake, appear to perform particularly well in the Grey-Buller Region, with 87 percent correct predictions of liquefaction and 40 percent correct predictions of non-liquefaction. Much of the current data is not very precise as it is based on distant memory and best estimates of parameters such as epicentral distances and peak ground accelerations. This study has indicated the likely reasons for this poor prediction and possible measures to improve both the database and understanding of the liquefaction phenomenon. Small changes in the input data did not have a great effect on the results indicating that the models are not sensitive to variations of the peak ground accelerations within 10%. The study also highlighted the need for soil profile investigations as the models did not correctly interpolate the fluvial nature of the soils in the region.

Installation of arrays of accelerometers, distributed both on the ground surface and down-hole, would be very useful in refining the acceleration attenuation relationships for both the West Coast Region and for New Zealand in general. The measurement of pore pressure changes and the accelerations should improve the future modelling of the liquefaction phenomenon through increased understanding of the effects.

## ACKNOWLEDGEMENTS

We wish to thank the many residents of the Buller and West Coast for their assistance in enthusiastically providing accounts, documents and photographs of the earthquakes, as well as for their hospitality and for allowing us to carry out investigations on their land. We wish to acknowledge, also, the financial support provided by the EQC Research Foundation, as well as the assistance of the Grey and Buller District Councils.

## REFERENCES

1. Dowrick DJ, Rhoades DA, and Davenport PN. "Effects of Microzoning and Foundations on Damage Ratios for Domestic Property in the Magnitude 7.2 1968 Inangahua, New Zealand Earthquake." Bulletin of the New Zealand Society for Earthquake Engineering 2003; 36(1): 25-46.
2. TopoMap [electronic resource]. MapWorld New Zealand, Christchurch, New Zealand, 2001.
3. Fairless G.J. "Liquefaction Case Histories in New Zealand". Research Report 84. Department of Civil Engineering, University of Canterbury, New Zealand, 1984.
4. Ooi ECT. "Investigation of Liquefaction in the Buller Region". Master of Engineering Thesis, University of Canterbury, New Zealand, 1987.
5. Adlam RJ "Engineering Geological Documentation of Seismic Liquefaction Resulting from the 1968 Inangahua Earthquake, West Coast, NZ". Master of Science Thesis, University of Canterbury, New Zealand, 1988.
6. Bienvenu VC "Studies of Liquefaction in the 1929 Murchison and 1968 Inangahua, New Zealand Earthquakes." Master of Engineering Thesis. University of Canterbury, New Zealand, 1988.
7. Dou Y and Berrill JB "Pattern Recognition Approach to Evaluation of Liquefaction Potential: Exploration of Buller Sites". Research Report 92/7, Department of Civil Engineering, University of Canterbury, New Zealand, 1992.
8. Dowrick DJ and Smith EGC 1990. "Surface wave magnitudes of some New Zealand Earthquakes 1901- 1988". Bulletin of the New Zealand National Society for Earthquake Engineering 1990, 23(3): 198-210.
9. Dowrick DJ "Damage Intensities in the magnitude 7.8 1929 Murchison, New Zealand, Earthquake." Bulletin of the New Zealand National Society for Earthquake Engineering 1994, 27(3): 190-204.
10. Adams RD, Eiby GA and Lowry MA. "A Preliminary Seismological Report." Bulletin of the New Zealand Society for Earthquake Engineering, 1969, 2(1): 9- 18.
11. Shibata T and Teparaksa W "Evaluation of Liquefaction Potentials of Soils using Cone Penetration Tests." Soils and Foundations 1988, 28(2): 49-60.
12. Suzuki Y, Tokimatsu K, Koyamada K, Taya Y, Kubota Y. "Field Correlation of Soil Liquefaction Based on CPT Data" IN International Symposium on Cone Penetration Testing, CPT '95 1995, Linköping, Sweden.
13. Olsen RS. "Cyclic Liquefaction based on the Cone Penetrometer Test" IN Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils 1997. Edited by T.L. Youd and I.M. Idriss. Technical Report NCEER-97-0022, National Center for Earthquake Engineering Research, State University of New York at Buffalo, Buffalo, N.Y.
14. Robertson PK and Wride CE "Evaluating cyclic liquefaction potential using the cone penetration test". Canadian Geotechnical Journal 1998, 35: 442-459.

15. Juang CH, Yuan H, Lee D-H and Lin P-S. "Simplified Cone Penetration Test-based Method for Evaluating Liquefaction Resistance of Soils." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE 2003, 129(1):66-80.
16. Toprak S and Holzer TL "Liquefaction Potential Index: Field Assessment." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 2003, 129(4): 315-322.
17. Zhou S "Evaluation of the Liquefaction Potential of Sand by Static Cone Penetration Test." *Proceedings of the 7<sup>th</sup> World Conference on Earthquake Engineering*, Istanbul 1980, 3: 156-162.
18. Davis RO and Berrill JB "Energy Dissipation and Seismic Liquefaction in Sands." *Earthquake Engineering and Structural Dynamics* 1982, 10: 59-68.
19. Liao SCC, Veneziano D and Whitman RV "Regression Models for Evaluating Liquefaction Probability." *Journal of Geotechnical Engineering* 1988, 114(4): 389-411.
20. Law KT, Cao YL, and He GN "An energy approach for assessing seismic liquefaction potential." *Canadian Geotechnical Journal* 1990, 27: 320-329.
21. Zhou JX, Dowrick DJ, McVerry GH. "Attenuation of Peak Ground Accelerations in New Zealand Earthquakes." *Bulletin of the New Zealand National Society for Earthquake Engineering* 1997, 30(2): 133-158.
22. Youd TL, Idriss IM, Andrus RD, Arango I, Castro G, Christian JT, Dobry R, Finn WDL, Harder LF, Hynes ME, Ishihara K, Koester JP, Liao SSC, Marcuson WF III, Martin GR, Mitchell JK, Moriwaki Y, Power MS, Robertson PK, Seed RB, Stokoe KH II "Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE 2001, 127(10): 817-833.
23. Ólafsson S. "Estimation of Earthquake-Induced Response." Ph. D Thesis. Department of Structural Engineering, Norwegian University of Science and Technology, Trondheim, Norway, 1999.
24. Berrill JB and Davis RO. "Energy Dissipation and Seismic Liquefaction in Sands: Revised Model." *Soils and Foundations* 1985, 25(2): 106-118.
25. Pyke R. "Practical aspects of the evaluation of liquefaction potential" IN *Proceedings of the 1<sup>st</sup> Conference on Earthquake Geotechnical Engineering* 1995. Edited by K. Ishihara. A.A. Balkema, Rotterdam, pp 923-926.
26. Davis RO, and Berrill JB "Site Specific Prediction of Liquefaction" *Geotechnique* 1999, 48: 289-293
27. Davis RO and J.B. Berrill, "Correlation of Pore Pressure and Dissipated Energy in Earthquakes – Field Verification ", *Jour. Geotech. Engineering*. ASCE, Vol. 127, pp 269-274, 2001..
28. Carr K. "Liquefaction Case Histories from the West Coast of the South Island, New Zealand" Master of Engineering Thesis. University of Canterbury, New Zealand, 2004.