The Mw 7.1 Sept 4 2010 and Mw 6.3 Febr 22 2011, New Zealand Eqs. Comparison of EMS_{1998} and ESI_{2007} Data

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SUMMARY:
Two major earthquakes struck the city of Christchurch and the broader Canterbury region, the magnitude Mw 7.1 on the 4th of September 2010 and the Mw 6.3 on the 22nd of February 2011. The two earthquakes caused significant damage to the urban environment and infrastructure as well as induced changes to the natural environment such as surface fissures, lateral spreading and slope failure. For both seismic events the intensity scales EMS_{1998} and ESI_{2007} were estimated, based on the observed structural damage and the impact on natural environment respectively. Both EMS_{1998} and ESI_{2007} scales resulted in similar maximum intensity values. For the September earthquake the comparison was achieved by normalizing the EMS_{1998} intensity values, observed in Christchurch city, to epicentral ones, using well established formulas. The convergence of the two methodologies for each event and the complement of their values based on different data, are important for seismic hazard and risk assessment in a region particularly since data from historical and recent earthquakes can be compared.

Keywords: Christchurch, Canterbury, Earthquake, EMS_{1998}, ESI_{2007}

1. INTRODUCTION

Christchurch is the largest city of New Zealand's South Island and the second largest urban area of the country. It lies within Canterbury Region and has a population of 375.000. Prior to the September 4th earthquake the city of Christchurch was not considered as a high seismic risk area and the major seismic hazard was associated with the Alpine fault zone, located approximately 150 km from the city, along the west coast of the South Island. The faults responsible for the two major earthquakes were both unknown hidden structures without surface expression, covered by recent thick deposits (fluvial and coastal).

On the 4th of September 2010 the city of Christchurch and the broader Canterbury region were hit by a magnitude Mw 7.1 earthquake with epicenter 40 km west of the Central Business District (CBD) of the city, close to the town of Darfield, in a depth of about 10 km, see Fig. 1. This was the largest seismic event since the Mw 7.8 Hawk's Bay earthquake in 1931. Despite the fact that no deaths occurred during the earthquake, it caused extensive damage to the built environment and infrastructure. The event produced a 29 km dextral strike-slip surface rupture with an approximately E-W orientation. Unprecedented residential losses due to liquefaction and lateral spreading represent a considerable portion of total losses estimated 3 billion USD, (EERI 2010).

Five months later, on the 22nd of February 2011 a second earthquake of magnitude Mw 6.3 occurred with epicenter 6 km south of CBD and depth of about 5 km. Although lower magnitude compared to the first earthquake it caused about 200 deaths while it severely damaged different types of buildings and infrastructure, affecting the broader Christchurch area and particularly the CBD. The event induced extensive liquefaction, lateral spreading and slope failures whereas no surface rupture was observed. The total losses are estimated over 15 billion USD, (EERI 2011).

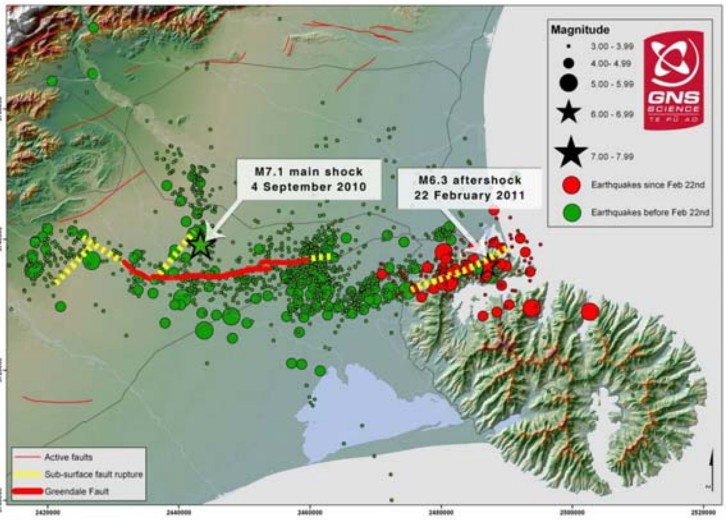

Figure 1. Earthquake sequences of September 4th, 2010 and February 22nd, 2011 and the fault zones that were activated (GNS 2011).

Both seismic events of September 4th and February 22nd provide an excellent opportunity to apply the EMS_{1998}, (Grünthal 1998) and ESI_{2007}, (Michetti et al. 2004, Michetti et al. 2007) intensity scales and compare their results as i) there is significant impact on the built environment which is characterized by a great diversity of structures and ii) there is a distinct surface expression of the fault rupture (of the September 4th earthquake) as well as different consequent geodynamic phenomena such as liquefaction, lateral spreading and landslides.

The impact on the built environment is used in estimating the EMS_{1998} intensity degrees whereas the occurrence of surface faults and other co-seismic geodynamic phenomena are used in the intensity assessment according to the ESI_{2007} scale.

The correlation of the two scales in estimating seismic intensities based on different data is very interesting, considering that each scale supplements the other regarding recent events, reducing the inherent uncertainties of each methodology. Ultimately, historical and even pre-historical earthquakes can be associated with recent events aiming to enhance the seismic hazard and risk assessment in a region, (Papanikolaou et al. 2009, Lekkas 2010).

2. THE Mw 7.1 DARFIELD (CANTERBURY) EARTHQUAKE

On the 4th of September 2010 at 4:35 am NZ local time (16:35, 3 September UTC) a magnitude Mw 7.1 earthquake occurred 40 km west of Christchurch, close to the town of Darfield, in the flat area of Canterbury Plains. The focal depth of the earthquake was approximately 10 km and produced a surface rupture of about 30 km length with horizontal dextral component up to 5 m and up to 1 m vertical, (Quigley et al. 2012). The surface rupture extends west from the town of Rolleston to just southwest of Greendale and then it trends northwest. Hundreds of lower magnitude aftershocks followed the main earthquake, mainly arranged along an elongated region with E-W orientation, coinciding with the surface rupture trace.

2.2. Estimation of $I_{EMS-1998}$

Extensive damage occurred to a large part of the built environment, which consists of different types of structures, due to the seismic shaking. Particularly, based on the guidelines of EMS_{1998} scale

(Grünthal 1998) to estimate the intensity per different construction type, the following damages were observed:

- Unreinforced Masonry. Structures of this type suffered significant damage and especially many buildings with Vulnerability Class A suffered damage of grade 4 and a few of grade 5. Furthermore, buildings with Vulnerability Class B suffered damage of grade 3 and a few of grade 4. Indicatively, over 160 of the 958 URM buildings suffered more than 10% damage and many of these have since been demolished (Ingham and Griffith 2010).
- Reinforced Concrete. Suffered comparatively less damage than the previous category. In particular, many buildings with Vulnerability Class C suffered damage of grade 2 and a few of grade 3. In addition, many buildings with Vulnerability Class D suffered damage of grade 2.
- Reinforced Masonry. Many buildings with Vulnerability Class D are estimated to have suffered damage of grade 2 and a few of grade 3.
- Timber Structures. A few buildings with Vulnerability Class D sustained damage of grade 2.

According to the above observations maximum values in Christchurch urban area are estimated up to $VIII_{EMS-1998}$.

As already mentioned, the epicentral distance of Christchurch city is about 40 km. The estimation of the $I_{ESI-2007}$ values, as it is described below, refers to the seismic effects on the natural environment in the epicentral region. In order to compare the values of the two scales it was necessary to normalize the above derived values of EMS_{1998} to epicentral ones.

According to Mc Guire (1976) the intensity at a site

$$I_S = I_e + 3.08 - 1.34 \bullet \ln D \qquad (2.1)$$

where I_e is the epicentral intensity in the MMI scale and D is the epicentral distance. For D=40 km:

$$I_e = I_S - 3.08 + 1.34 \bullet \ln(40) = I_S - 3.08 + 4.94 = I_S + 1.86 \qquad (2.2)$$

which mean that the epicentral intensity, I_e, is about two degrees higher in MMI scale than that observed in Christchurch city, I_s. With an acceptable approximation we could assume that the same difference is yielding for both MMI and EMS_{1998} scales. Therefore, the epicentral intensity based on EMS_{1998} scale data is about X degrees.

On the other hand it is interesting to determine the epicentral EMS_{1998} intensity values, using recorded peak ground accelerations in both sites. That, around the epicentre the peak ground acceleration was about 700 $cmsec^{-2}$, while that in Christchurch city was about 200 $cmsec^{-2}$.

Based on Trifunac and Brady (1975) formula:

$$\log a = 0.14 + 0.3 \bullet I \qquad (2.3)$$

Therefor:

$$I_S = \frac{\log(200) - 0.14}{0.3} = 7.20 \qquad (2.4)$$

$$I_e = \frac{\log(700) - 0.14}{0.3} = 9.0 \qquad (2.5)$$

The ratio I_e/I_s=9.0/7.2=1.25. This means that the normalized I_e=8·1.25=10.

2.3. Estimation of $I_{ESI-2007}$

In order to estimate the $Imax_{ESI-2007}$ according to the ESI_{2007} guidelines, (Michetti et al. 2007) different types of environmental effects were used such as the length of the surface fault rupture, the spatial distribution and severity of liquefaction and lateral spreading in the broader area, the total affected area and major hydrogeologic effects.

The earthquake produced a surface rupture of approximately 29 km length and displacement of the order of few meters (D_{max} = 5.3 ± 0.5 m and $D_{average}$ = 2.5 ± 0.1 m, Quigley et al. 2012), see Figs 1 and 2. Widespread liquefaction and lateral spreading occurred in various parts of Christchurch significantly affecting the eastern suburbs along the Avon river that meanders through the city (Avonside, Dallington, Burwood and Bexley), localized areas to the north and southwest of the city, the town of Kaiapoi and the beachside settlements near the Waimakariri River, (Allen et al. 2010). The co-seismic geodynamic phenomena are observed in an area of more than 1,000 km^2. The diameter of the sand volcano cone formations reached several meters in areas close to river channels and surface subsidence was measured about 1 m, often due to lateral spreading. Additionally, subsidence of the east-side on the NW-striking western segment of the fault resulted in partial diversion of the spring-fed Hororata River, (Allen et al. 2010). Based on the above data the resulting maximum intensity is estimated up to $X_{ESI-2007}$.

Figure 2. Horizonthal displacement of approximately 5 meters caused by the Greendale fault.

3. THE M_W 6.3 CHRISTCHURCH EARTHQUAKE

On the 22nd of February 2011 at 12:51 pm NZ local time (23:51, 21 February UTC), a second major earthquake of magnitude Mw 6.3 occurred close to the city of Christchurch. The focal depth of the earthquake was just 5 km and its epicenter is located 6 km south of CBD in Port Hills area, see Fig. 1. The earthquake is considered as an aftershock of the main Mw 7.1, September 2010 earthquake and occurred on a fault without surface expression. Both major earthquakes and the hundreds of aftershocks, that followed, are arranged in an elongated region with E-W orientation which comprises the activated fault zone, (GeoNet 2011).

3.1. Estimation of $I_{EMS-1998}$

The February earthquake caused much more extensive damage to a large part of the built environment, which consists of different types of structures, due to the strong seismic shaking. Particularly, based on the guidelines of EMS_{1998} scale, (Grünthal 1998), in order to estimate the seismic intensity per different construction type, official data records (Kam et al. 2011, Data source: Christchurch City Council) were used and the following impact was observed, see Figs 3, 4 and 5.

- Unreinforced Masonry. Classified in Vulnerability Class B. Many buildings suffered damage of grade 5.
- Reinforced Masonry. Classified in Vulnerability Class C. Many buildings suffered damage of grade 4 and a few of grade 5.
- Reinforced Concrete. Classified in Vulnerability Class D. Many buildings suffered damage of grade 3 and a few of grade 4.
- Steel Structures. Were classified in Vulnerability Class E. Many buildings suffered damage of grade 2 and a few of grade 3.
- Timber Structures. Classified in Vulnerability Class D. Many of these structures suffered damage of grade 3 and a few of grade 4 and 5.

Figure 3. a) Three storeyed traditional corner building. It is an unreinforced masonry structure with higher storey heights. It is functioning as a shop in the CBD. Therefore the structure (floors and non load bearing structural members, the materials and workmanship) is strong enough. On the other hand the openings inside the building must be larger than common residential buildings. Nevertheless the facades present a robust structure. The vulnerability is estimated to be class C. The upper part and the corners of the building are damaged. It seems as if the roof had hammered over the lower part of the building. A large part of the roof collapsed. No horizontal displacements or diagonal cracks are noticeable. The observed pattern of damage is indicative of the strong vertical seismic component, a fundamental characteristic of the seismic action in epicentral regions of shallow focus earthquakes. The damage is grade 3 (substantial to heavy damage); b) Three storeyed unreinforced traditional masonry corner building. The building is functioning as a shop in CBD of the city. Each floor of the building is symmetrical along the two horizontal axes. There is also symmetry along the height. Also, it is quite well built, composing a robust structure. The plan of the building is trapezoidal having its shorter dimension perpendicularly to the facade. The stiffness along its shorter dimension is much smaller than along its facade. The vulnerability is estimated to be between class C and class D. The third storey suffered quite symmetric damage. The corner elements of the top, third, storey at the facade collapsed, while the roof is still standing up. Not any diagonal crack or any lateral displacement is noticeable. The only reason for the damage is due to the effects of the dominance of the vertical seismic motion. The damage grade is 4 (very heavy damage).

Figure 4. a) Two storeyed building with a reinforced concrete load bearing system. The ground floor is taller than the second floor. It seems to be quite robust and stiff. Its plan is orthogonal with the one dimension quite long. It seems as if it has been strengthened and probably the second storey has been added later. The

vulnerability is estimated to be of class D. The damage is concentrated in the column to beam joints of both levels and especially more in the mass of the columns and less in the mass of the beams. The elongated side of the building suffered more damage. There is not any horizontal displacement of the building nor any diagonal crack. The damage may be attributed to the strong vertical seismic component. Based on the observation that there are no damages in the column to beam joints along the short side of the building (except the one at the corner) the following point of view might be expressed: Due to the strong vertical seismic motion the framing beams of both levels vibrated vertically. The beams compose frames with the columns. These frames are functioning along the short side of the building. Due to the vertical vibration these beams functioned as levers against the joints. The damage grade is grade 2 (moderate damage); b) Multistoreyed building with a reinforced concrete load bearing system with frames. The level of earthquake resistance design and construction is of a low to moderate level. The vulnerability is estimated to be between class B and class C. The building has totally collapsed. There is no offset of the penthouse, that in despite of the total collapse maintains the same inclination of the below standing storeys. Small appendices, lightly connected to the penthouse stand intact. The building seems to have collapsed at two or three parallel and separated blocks. It is not possible to identify and assess the exact reason of the damage. Nevertheless, the non-uniform vertical loading of the structure due to multi-storey penthouse, combined with the gap along the vertical axis between the above mentioned blocks, together with the rather prevailing immobility of the penthouse, guide us to infer that besides the earthquake inefficiency of the structure a strong vertical seismic component was dominating and greatly contributed to that damage. The damage grade is 5 (destruction).

Figure 5. Five storeyed building, rather old, following traditional architecture. The last (fifth) storey looks as if it has been added after the completion of the lower four storeys. Most probably the load bearing system is reinforced concrete (slabs, beams and columns). Due to the estimated period of construction, most probably the building may be characterized as of low earthquake resistance. But due to the rather thick and strong masonry exterior wall paneling the stiffness and earthquake resistance of the whole building is increased. The vulnerability is estimated to be class C. The damage is concentrated in the first up to the fourth storeys. The fifth storey is intact. (Perhaps the added fifth storey is constructed with different materials and technology. It seems that it is stiffer than the other storeys). The heaviest damages are in the first (ground) storey and in the fourth storey. The damages give the impression as if the four storeys have been smashed. The vertical elements of the windows have been buckled. There is neither any horizontal displacement nor any diagonal cracking. The appearing diagonal cracks are due to an excess vertical loading that surpassed the strength of the vertical load bearing elements during the earthquake. The whole structure stands absolutely vertical. The whole damage might be attributed to the strong vertical seismic component that dominated the seismic action. The lack of any horizontal displacement, in despite of the almost equally strong horizontal ground motion, it is probably due to the above mentioned type of damage and due to an increase of the horizontal period of the structure. The damage grade is grade 3 (substantial to heavy damage).

By considering the above observations the maximum intensity values in the worst affected areas of Christchurch urban environment and its suburbs is estimated of up to $X_{EMS\text{-}1998}$.

3.2. Estimation of $I_{ESI\text{-}2007}$

The estimation of $Imax_{ESI-2007}$ according to the ESI_{2007} guidelines, (Michetti et al. 2007) was mainly based on the occurrence of liquefaction, lateral spreading and slope failures since there was no surface rupture during the February 2011 earthquake.

Despite its lower magnitude, the Christchurch earthquake also induced widespread environmental effects in Canterbury region. The most severely affected by liquefaction and lateral spreading suburbs after the February earthquake were yet again areas along the Avon River to the east and northeast of CBD such as, Avonside, Dallington, Avondale, Burwood, and Bexley, (Cubrinovski & Taylor 2011, Cubrinovski et al. 2011a, GEER Report 2011). The liquefaction manifested as sand boils and large amount of sand / silt ejecta as a result of low cohesion soils, high water table (< 5m) and the intensity of the ground shaking (up to 2.2 g in Heathcote valley close to the epicenter and up to 0.8 g in the CBD (Kaiser et al. 2012). The severity of liquefaction, although predominantly of moderate intensity was not uniform, reflecting the complex and highly variable soil conditions even within the CBD area, (Cubrinovski et al. 2011b). The diameter of sand volcano cones which was several meters in the worst affected areas and measured subsidence of > 1m, often associated with the occurrence of lateral spreading, indicate maximum intensity value of the order of $X_{ESI-2007}$, see Fig. 6.

Figure 6. Views of liquefaction phenomena in the area of Christchurch after the earthquake of February 22, 2011.

Furthermore, observed surface fissures of > 1m width and up to few hundred meters length are also indicative of a maximum intensity value of $X_{ESI-2007}$, see Fig. 7a. Finally, extensive slope failures were triggered by the strong seismic shaking of the February 22 earthquake, see Fig. 7b, causing human losses and injuries, and damaging residential houses and infrastructure in RedCliffs, Mt Pleasant, Sumner, Lyttelton, Cass Bay and Rapaki areas (Hancox et al. 2011). The estimated landslide deposit volumes of the order of 10^5 m^3 and even > 10^5 m^3 in some locations suggest a maximum intensity value of $IX_{ESI-2007}$.

Figure 7. a) View of surface ruptures caused by the earthquake of February 22nd, 2011 in suburban area of Christchurch; b) View of co-seismic landslides triggered by the February 22nd earthquake along Sumner road, Lyttelton.

4. CONCLUSIONS

As mentioned above, both seismic events of September 4th and February 22nd provide an excellent opportunity to apply the EMS_{1998}, (Grünthal 1998) and ESI_{2007}, (Michetti et al. 2004, Michetti et al. 2007) intensity scales and compare their results as i) there is significant impact on the built environment which is characterized by a great diversity of structures and ii) there is a distinct surface expression of the fault rupture (of the September 4th earthquake) as well as different co-seismic geodynamic phenomena such as liquefaction, lateral spreading and landslides.

Correlation of the two scales based on different data is very interesting, since results from each scale can complement the other, allowing the comparison of recent earthquakes with historical or pre-historical seismic events in an effort to enhance the seismic hazard and risk assessment in a region, (Papanikolaou et al. 2009, Lekkas 2010). Furthermore the distribution of ESI_{2007} intensities can be potentially useful in land use planning as it provides insight on the impact of recent and historical earthquakes in currently undeveloped areas where future development might take place, see Figs 8 and 9. During both major earthquakes in Christchurch significant damage to residential properties, buildings and infrastructure occurred not only as direct result of seismic shaking but due to liquefaction, lateral spreading, landslides and river flooding. Therefore, information on the spatial distribution and severity of co-seismic environmental effects induced by recent and historic seismic events might be beneficial in land use planning in the context of sustainable seismic hazard mitigation.

The application of both EMS_{1998} and ESI_{2007} scales for the two seismic events of September 4, 2010 and February 22, 2011 and comparison of their results illustrate the following main conclusions:

a. Intensity values according to ESI_{2007} scale for the September earthquake are equal to X, while those according to EMS_{1998} are equal to VIII. This is mainly because of the epicentre's distance from the Christchurch urban area, which was approximately 40 km. Additionally, the maximum values of ESI_{2007} were observed close to the epicentre as well as in areas in close proximity to rivers streams, old (abandoned) river channels, lagoons and wetlands, where unconsolidated alluvial deposits (gravels, sand and silt) constitute the main soil types. Nevertheless, by normalizing the values of EMS_{1998} to the epicentre, the two values of the different scales perfectly coincide.

b. Intensity values according to EMS_{1998} and ESI_{2007} for the February 2011 earthquake are similar, as the greater impact on the built environment and greater environmental effects are clustered in the Christchurch urban area. This also indicates that the co-seismic environmental effects such as liquefaction, lateral spreading and slope failure in addition to the strong seismic shaking were responsible for the extensive structural damage.

c. The coincidence of the intensity values between the two scales, EMS_{1998} and ESI_{2007}, after the normalization for the September case, proves that both are stable, presenting insignificant sensitivity against various factors such as: a) the different depth of the earthquake and b) the different direction in which the energy was released, (Fry et al. 2011, Webb et al. 2011) and c) the different data on which are based.

d. The maximum epicentral intensity is rather independent of the Magnitude of the earthquake, while the corresponding area is a function of many parameters, the most important of which is the Magnitude. Both conclusions are yielding for shallow focus events.

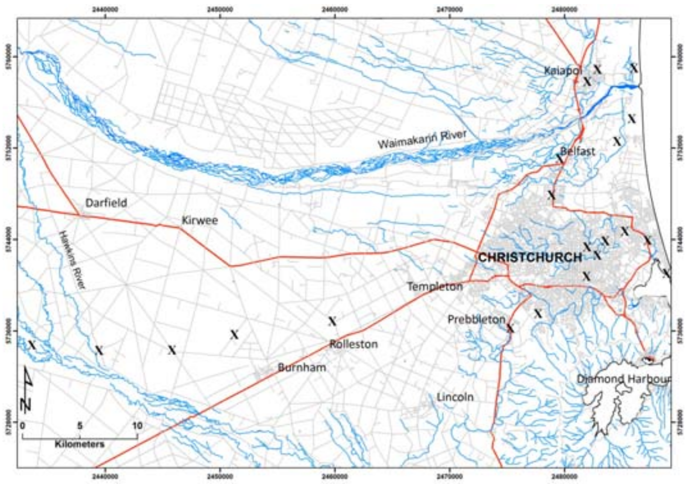

Figure 8. Distribution of $I_{ESI\text{-}2007}$=X for the September 4th earthquake based on surface faulting, the spatial distribution and severity of liquefaction, lateral spreading and ground subsidence.

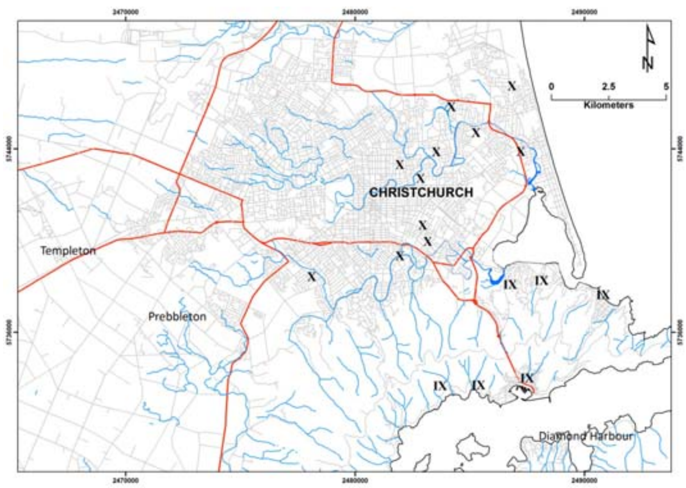

Figure 9. Distribution of $I_{ESI\text{-}2007}$=X and $I_{ESI\text{-}2007}$=IX for the February 22nd earthquake based on the severity and spatial distribution of liquefaction, lateral spreading, ground subsidence and volume of mass movements.

REFERENCES

Allen J, Cubrinovski, M., Green, R., Ashford, S., Bowman, E., Bradley, B.A., Cox, B., Hutchinson, T., Kavazanjian, E., Orense, R., O'Rourke, T., Pender, M., Quigley, M. and Wotherspoon, L. (2010). Geotechnical Reconnaissance of the 2010 Darfield (Canterbury) Earthquake. *New Zealand Society for Earthquake Engineering Bulletin*, December Special volume, Preliminary Assessment of Initial Observations of the Darfield (Canterbury) Earthquake Sequence.

Christchurch City Council (2011). Christchurch Earthquake 22 Feb. 2011. http://www.ccc.govt.nz

Cubrinovski, M., Bradley, B., Wotherspoon, L., Green, R., Bray, J., Wood, C., Pender, M., Allen, J., Bradshaw, A., Rix, G., Taylor, M., Robinson, K., Henderson, D., Giorgini, S., Ma, K., Winkley, A., Zupan, J., O'Rourke, T., DePascale, G. and Wells, D. (2011a). Geotechnical aspects of the 22 February 2011 Christchurch earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, **22:4**, 205-226.

Cubrinovski, M., Bray, J.D., Taylor, M., Giorgini, S., Bradley, B., Wotherspoon, L. and Zupan, J. (2011b). Soil Liquefaction Effects in the Central Business District during the February 2011 Christchurch Earthquake, *Seismological Research Letters*, **82:6**, 893-904.

Cubrinovski, M. and Taylor, M. (2011). Liquefaction Map - Drive-through Reconnaissance, University of Canterbury NZ. www.nzsee.org.nz

EERI (2010). The Mw 7.1 Darfield (Canterbury), New Zealand Earthquake of September 4, 2010. *EERI Special Earthquake Report*, November 2010

EERI (2011). The M 6.3 Christchurch, New Zealand, Earthquake of February 22, 2011. *EERI Special*

Earthquake Report, May 2011.

Fry, B., Benites, R., Reyners, M., Holden, C., Kaiser, A., Bannister, S., Gerstenberger, M., Williams, C., Ristau, J. and Beavan, J. (2011). Strong Shaking in Recent New Zealand Earthquakes. EOS, Transactions, *American Geophysical Union*, **92:41,**:349-360.

GeoNet (2011). Canterbury Quakes. http://www.geonet.org.nz

GNS Science (2011). Canterbury Quakes. http://www.gns.cri.nz/

Geotechnical Extreme Events Reconnaissance - GEER (2011). Geotechnical reconnaissance of the 2011 Christchurch, New Zealand Earthquake. Report of the National Science Foundation-Sponsored Geotechnical Extreme Events Reconnaissance (GEER) Team. Version 1: November 8, 2011. (www.geerassociation.org)

Grünthal, G., (Editor) (1998). European Macroseismic Scale 1998, *Conseil de l' Europe* **15**, 99.

Hancox, G., Perin, N. and VanDissen, R. (2011). Immediate report: Report on Landslide Reconnaissance Flight on 24 February (2011) following the Mw 6.3 Christchurch Earthquake of 22 February 2011. GNS science immediate report, 2 March.

Ingham, J. and Griffith, M. (2010). Performance of Unreinforced Masonry Buildings during the 2010 Darfield (Christchurch, NZ) Earthquake. NZSEE Clearinghouse. http://db.nzsee.org.nz:8080/en/web/chch_2011/home

Kaiser, A., Beavan, J., Beetham, D., Benites, R., Celentano, A., Collet, D., Cousins, J., Cubrinovski, M., Dellow, G., Denys, P., Fielding, E., Fry, B., Gerstenberger, M., Holden, C., Massey, C., Motagh, M., McVerry, G., Pondard, N., Ristau, J., Stirling, M., Thomas, J., Uma, SR. and Zhao, J. (2012). –The Mw 6.2 Christchurch Earthquake of February 2011: Preliminary Report, New Zealand Journal of Geology and Geophysics. DOI:10.1080/00288306.2011.641182

Kam, W.Y., Akguzel, U. and Pampanin, S. (2011). 4 Weeks on: Preliminary Reconnaissance REPORT FROM THE CHRISTCHURCH 22 Feb 2011 6.3M_w Earthquake. New Zealand Society of Earthquake Engineering. http://db.nzsee.org.nz:8080/en/web/chch_2011/home

Lekkas, E. (2010). The 12 May 2008 Mw=7.9 Wenchuan Earthquake, China. Macroseismic Intensity Assessment Using the EMS1998 and ESI2007 Scales and their Correlation with the Geological Structure. *Bulletin of the Seismological Society of America*, **100:5B**, 2791-2804.

McGuire, R.K. (1976). Methodology for Incorporating Parameter Uncertainties into Seismic-Hazard Analysis for Low Risk Design Intensities, *Proceedings, International Symposium on Earthquake Structural Engineering*, St. Louis Rolla, Mi, 1007-1022.

Michetti, A. M., Esposito, E., Gurpinar, A., Mohammadioun, B., Mohammadioun, J., Porfido, S., Rogozhin, E., Serva, L., Tatevossian, R., Vittori, E., Audemard, F., Comerci, V., Marco, S., McCaplin, J. and Morner N.A. (2004). The INQUA scale: An innovative approach for assessing earthquake intensities based on seismically-induced ground effects in natural environment, *Spec. Pap. Mem. Descr. Carta Geologica D' Italia* **LXVII,** APAT, Rome, Italy, 118 pp.

Michetti, A. M., Esposito, E., Guerrieri, L., Porfido, S., Serva, L., Tatevossian, R., Vittori, E., Audemard, F., Azuma, T., Clague, J., Comerci, V., Gürpinar, A., McCalpin, J., Mohammadioun, B., Mörner, N.A., Ota, Y. and Roghozin, E. (2007). –Environmental Seismic Intensity Scale 2007—ESI 2007, *Memorie Descrittive della Carta Geologica d'Italia*, **74**, 7-54, L. Guerrieri and E. Vittori (Editors), Servizio Geologico d'Italia—Dipartimento Difesa del Suolo, APAT, Roma, Italy, 1–41.

Papanikolaou, I.D., Papanikolaou, D.I. and Lekkas, E.L. (2009). Advances and limitations of the environmental seismic intensity scale (ESI 2007) regarding near-field and far-field effects from recent earthquakes in Greece: Implications for the seismic hazard assessment, *Paleoseismology: Historical and Prehistorical Records of Earthquake Ground Effects for Seismic Hazard Assessment*, **Special Publication 316**, Geological Society of London, K. Reicherter, A.M. Michetti, and P. G. Silva (Editors), Geological Society of London, London, 11–30.

Quigley, M., Van Dissen, R., Litchfield, N., Villamor, P., Duffy, B., Barrell, D., Furlong, K., Stahl, T., Bilderback, E. and Noble, D. (2012). Surface rupture during the 2010 Mw 7.1 Darfield (Canterbury, New Zealand) earthquake: implications for fault rupture dynamics and seismic-hazard analysis, Geology 40:1, 4p.

Trifunac, M.D. and Brady, A.G. (1975). On the correlation of seismic intensity with peaks of recorded strong motion. *Bulletin of the Seismological Society of America*, **65**, 139-162.

Webb, T.H., Bannister, S., Beavan, J., Berryman, K., Brackley, H., Cousins, J., Fry, B., Gerstenberger, M., Holden, C., Kaiser, A., McSaveney, E., McVerry, G., Pettinga, J., Reyners, M., Rhoades, D., Somerville, P., Stirling, M., Van Dissen, R., Villamor, P., Wallace, L. and Zhao, J. (2011). The Canterbury Earthquake Sequence and implications for Seismic Design Levels, *GNS Science Consultancy Report* 2011**:183**, 88p.