Liquefaction ejecta clean-up in Christchurch during the 2010-2011 earthquake sequence

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ABSTRACT: The Canterbury earthquake sequence in New Zealand's South Island induced widespread liquefaction phenomena across the Christchurch urban area on four occasions (4 Sept 2010; 22 Feb; 13 June; 23 Dec 2011), that resulted in widespread ejection of silt and fine sand. This impacted transport networks as well as infiltrated and contaminated the damaged storm water system, making rapid clean-up an immediate post-earthquake priority. In some places the ejecta was contaminated by raw sewage and was readily remobilised in dry windy conditions, creating a long-term health risk to the population. Thousands of residential properties were inundated with liquefaction ejecta, however residents typically lacked the capacity (time or resources) to clean-up without external assistance.

The liquefaction silt clean-up response was co-ordinated by the Christchurch City Council and executed by a network of contractors and volunteer groups, including the '*Farmy-Army*' and the '*Student-Army*'. The duration of clean-up time of residential properties and the road network was approximately 2 months for each of the 3 main liquefaction inducing earthquakes; despite each event producing different volumes of ejecta. Preliminary cost estimates indicate total clean-up costs will be over NZ$25 million. Over 500,000 tonnes of ejecta has been stockpiled at Burwood landfill since the beginning of the Canterbury earthquakes sequence.

The liquefaction clean-up experience in Christchurch following the 2010-2011 earthquake sequence has emerged as a valuable case study to support further analysis and research on the coordination, management and costs of large volume deposition of fine grained sediment in urban areas.

1 INTRODUCTION

Disasters can generate large volumes of waste and debris. In extremely short periods, 15-20 years worth of a community's normal solid waste production may be generated (Brown et al. 2011). This can severely stretch waste collection and management resources in the aftermath of a disaster. Recent disasters in New Zealand and internationally highlight that disaster waste management is a critical element for lifeline organisations and municipalities to consider in disaster management plans. A recent study by Brown et al. (2011) found that:

- The large volume of solid waste generated after a disaster has the potential to overwhelm day-to-day solid waste operations, create public and environmental health issues and lead to years of disruption;
- Disaster debris can impede rescuers and emergency services reaching survivors;
- Double handling of waste, uncoordinated organisations, legal hurdles, poor quality control, poor communication, or poor funding mechanisms can each lead to higher costs for collection, treatment and disposal of disaster wastes; and

- The slow management of solid waste can also impede economic recovery by inhibiting rebuilding activities and lead to significant community frustrations.

Disaster waste commonly includes building debris from collapsed and demolished buildings and other structures, but it may also include large volumes of fine grained sediment deposited by natural hazards such as liquefaction ejecta, flood silt, landslide/mudflow debris or volcanic ash fall.

The paper examines the management of cleaning up liquefaction ejecta in Christchurch city during the Canterbury earthquake sequence in New Zealand's central South Island. On four occasions, 4 Sept 2010; 22 Feb, 13 June and 23 Dec 2011 (as at 28th of March 2012), large earthquakes induced widespread liquefaction phenomena across the Christchurch urban area that resulted in widespread ejection of silt and fine sand, particularly in eastern and northern suburbs. Impacts to lifelines, including roads and storm water systems, and to urban communities were severe and the clean-up response was extensive, prolonged and expensive. This paper investigates the logistics, resources and financial costs needed to conduct a large-scale fine grained sediment clean-up operation in urban areas. Overall >500,000 tonnes of sand and silt ejected by liquefaction processes was collected from streets and properties. This is in the context of approximately 4 million tonnes of demolition waste from both the Central Business District (2 million tonnes) and residential-suburban-commercial (2 million tonnes) zones in addition to 4 million tonnes of demolition waste from repair of roads plus water and sewer pipes.

1.1 Methodology

A series of semi-structured interviews were held with organisations (Christchurch City Council, Fulton-Hogan Ltd, City Care Ltd) and two main volunteer groups ('*Farmy-Army*' – a group organized by rural organizations and made up mainly of farmers and rural workers; and the '*Student-Army*' – a group organized by the University of Canterbury Student Association and made up mainly of tertiary students at first but anyone was welcome to join) involved in the clean-up and management of liquefaction ejecta from Christchurch. A list of questions was prepared based on review of disaster waste literature and framed in the Christchurch context. They focused on costs breakdown, time, volume, resources, coordination, planning and priorities. Interviews were conducted face to face, by email or by phone and included guided visit to Burwood landfill, the main liquefaction disposal site. The interviews were supported with review of relevant literature and media reports.

1.2 Liquefaction Ejecta

Liquefaction occurs when saturated, typically fine-grained, unconsolidated soils are subjected to an applied force (such as earthquake shaking) and the increase in pore pressure causes the soil to lose strength and behave like a liquid. Examples include the 1868 Hayward earthquake (San Fransisco Bay Area, USA), 1989 Loma Prieta earthquake (San Fransisco Bay Area, USA), 1995 Great Hanshin earthquake (Kobe, Japan), 1999 Kocaeli earthquake (Izmit, Turkey), 2001 Peru earthquake (Arequipa, Peru), 2010 Haiti earthquake (Port-au-Prince, Haiti) and 2010 Maule earthquake (central Chile); (RMS 2010b, Boulanger & al. 1997, Kitagawa & Hirishi 2004, Ozcep & Zarif 2009, Audemard et al. 2005, RMS 2010a, Saragoni 2010). Similarly, it has been identified as a potential hazard in many large cities exposed to high seismic risk such as Wellington (New Zealand), Salt Lake City (USA) and Vancouver (Canada); (Hancox 2005, Anderson et al. 1994, Onur & al. 2005).

It has been well established that liquefaction causes damage to poorly design structural foundations and critical infrastructures such as bridges, roads and buried services (Kitagawa & Hiraishi 2004). However, earthquake engineers and emergency managers have paid less attention to the widespread ejection of fine-grained sediments at the surface during a liquefaction event. Such phenomena can cause significant disruption to transport infrastructure, storm- and wastewater networks, pose physical and mental health hazards for the exposed community and clean-up of the ejecta creates a significant demand on resources and time in a post-disaster environment (Sakr and Ansal 2012).

Despite the potential impacts and management issues, there have been no known previous studies which investigate the logistics, costs and strategies of liquefaction clean-up from an urban environment. An analogous study which investigates fine grained sediment clean-up from an urban

environment is a study on volcanic ash clean-up by Johnston et al, (2001). This study provides a pre-planning guide, prioritization list and best method for clean-up that can be used for tephra removal. It highlights the importance of coordination between the clean-up teams and the public.

2 CANTERBURY EARTHQUAKE SEQUENCE: 4 SEPT 2010-PRESENT

2.1 Tectonic Setting and the 4 September 2010 – present Canterbury Earthquake Sequence

New Zealand is located on a convergent plate boundary where the Australian and the Pacific plates move obliquely relative to each other (Walcott, 1998) (Fig. 1). This movement is mostly accounted by the Alpine Fault (70-75 %) and the Marlborough Fault zone (Howard et al. 2005), but it is also transferred to the surrounding region such as the Canterbury plains. These faults present a significant and poorly understood hazard that requires further research (Pettinga et al. 2001).

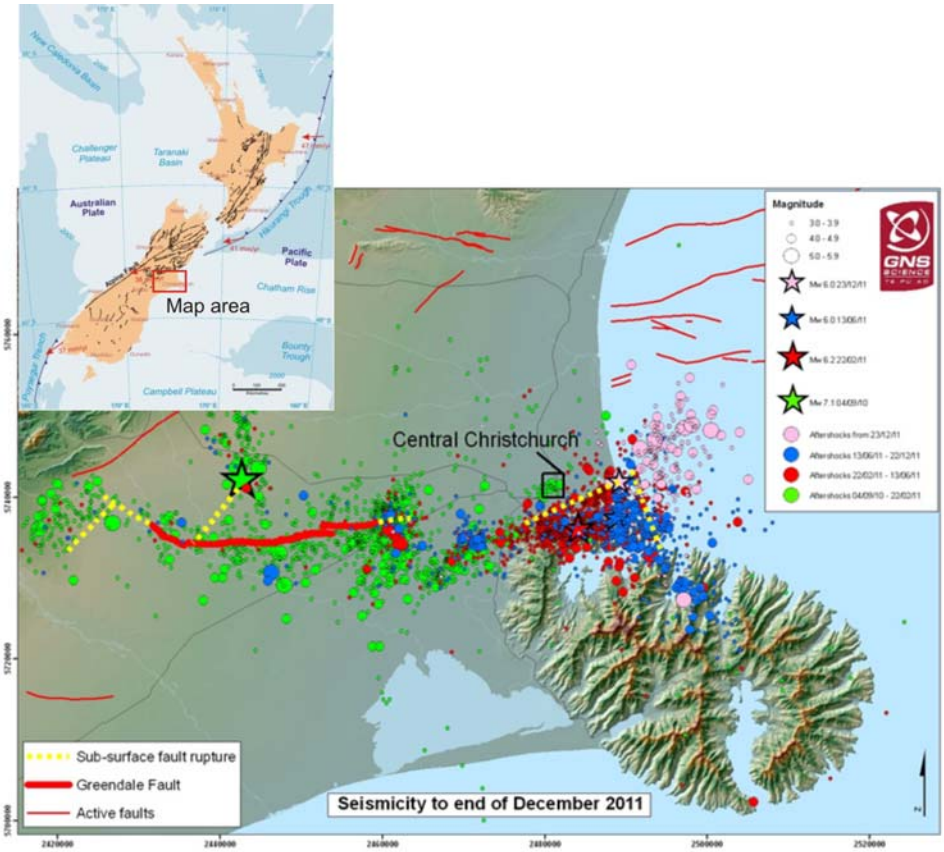

Figure 1: New Zealand tectonic setting and aftershock map showing epicentre locations of significant earthquakes of the 2010-present Canterbury earthquake sequence (source: GNS Science)

On 4 September 2010, the Mw7.1 Darfield earthquake occurred along the previously unknown Greendale Fault. It produced a ≥28 km long surface rupture with an E-W trending through low relief farmland 40 km west of Christchurch, leading to widespread damage and disruption (Quigley et al., 2012). Since then, a large number of aftershocks with strike-slip and reverse faulting components have continued to affect the central Canterbury and Christchurch region. Significantly, the aftershock pattern has moved progressively eastward towards and beyond the Christchurch urban area (Fig. 1). These earthquakes include the Mw6.2 Christchurch earthquake on 22 February 2011 (which lead to 185 deaths and widespread damage throughout Christchurch city), Mw6.0 on 13 June 2011 and Mw6.0 earthquake on 23 December 2011 (although the December event clean-up is not considered in this paper). As of 28 March 2012, the ongoing sequence counts over 10,000 recorded earthquakes, with 43 larger than Mw 5 (GeoNet 2011).

Each of the four major earthquakes induced significant ground-shaking in Christchurch area and resulted in widespread liquefaction, particularly in the eastern suburbs of Christchurch (Bradley &

Gubrinovski, 2011). These regions are built upon soft, saturated and uncompacted (Kaiapoi or Tai Tapu) soils (Recent and Recent Gley Soils respectively) which act to amplify the effects of ground shaking and are highly susceptible to liquefaction. The areas that experienced the greatest liquefaction included many low-lying eastern suburbs with a concentration along the Heathcote and Avon rivers (Fig. 2).

3 LIQUEFACTION EJECTA

3.1 Liquefaction Ejecta Impacts

It was well established that much of eastern and central Christchurch was constructed on soils which would likely liquefy during strong ground shaking (CELG 1997). However, the volume and scale of liquefaction ejection across the city was a surprise.

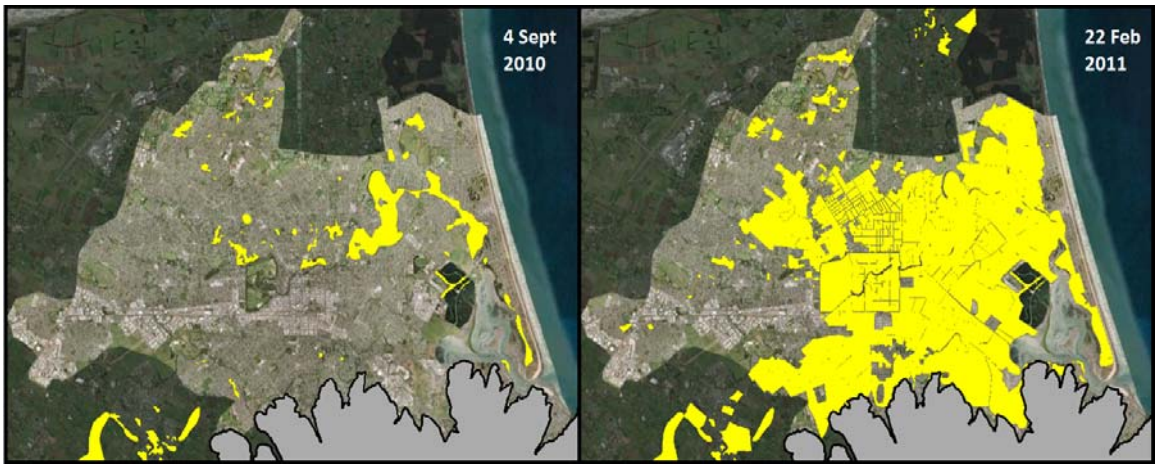

Figure 2: "Observed liquefaction overview map" in Christchurch for 4 Sept 2010 and 22 Feb 2011 earthquakes Yellow areas show observed liquefaction (source: EQC and Tonkin and Taylor Ltd).

The liquefaction ejecta created unique impacts to Christchurch city. In each event, road networks were badly affected by liquefaction induced ground deformation which created features such as domes, cracks, holes, lateral spreading, differential settlement, ejection of fine grained sediments at the surface and ponding/pooling water. Roads in the eastern parts of the city were difficult to transit or sometimes impassable for two-wheel drive traffic. The poor state of roads contributed to significant traffic congestion on major arterial roads, the central business district closure and significant internal population migration within and out of the city. The poor access and congestion would have affected the initial speed of the clean-up operations after each liquefaction event. This problem was reflected at the Burwood disposal site where low numbers of trucks were seen in the first few days (Harris pers comm., 2011).

Unmanaged liquefaction ejecta also caused damage to urban infrastructure. The ejecta continually eroded over time, creating a sediment source which could infiltrate and contaminate the damaged storm water system and the urban waterways. From a human health point of view, the liquefaction ejecta posed several hazards. Due to the extensive damage to the sewage disposal networks from lateral spreading and differential settlement, there was the risk that much of the liquefaction ejecta had been contaminated with raw sewage creating a long-term health risk to the population (McDonald pers comm., 2011). During hot and windy conditions, the dry finer portions of silt was mobilised by the wind creating a possible respiratory health hazard. Following the February earthquake the Ministry of Health suggested that personal protection such as gloves, gumboots and masks should always be worn when dealing with liquefaction silt.

With thousands of residential properties inundated with liquefaction ejecta, residents were eager to remove it from their properties to restore household functionality, remove the depressing grey deposits and retain a sense of control and normality. However, with hundreds of thousands of tonnes of sediment to clean, many residents lacked the capacity (time or resources) to clean-up their properties without external assistance.

3.2 Clean-up

The liquefaction silt clean-up response was co-coordinated by the Christchurch City Council (CCC). Silt removal from private property was primarily carried out by private property owners and volunteers using hand tools and some small earthmoving plant. Silt collection from public areas (including silt moved from private property to kerbside) was executed by a network of road maintenance contractors (including Fulton-Hogan Ltd and City Care Ltd) who were required under the emergency section of their maintenance contracts to respond and supply plant and personal as required. In addition, sewage and stormwater network maintenance contractors had to hire specialist silt and sewage "sucker" trucks to clear blocked stormwater and sewage pipes.

The first occurrence of liquefaction ejecta on 4 Sept 2010 was less voluminous than in the February and June 2011 earthquakes and proved to be a valuable learning experience (McDonald; Hautler pers comm., 2011). Clean-up strategies developed in September, such as definition of clean-up zones, prioritizations and methods, equipment/resources and connections provided a strong foundation that evolved during subsequent events (McDonald; Chapman; Rutherford pers comm., 2011). The general strategy for ejecta clean-up identified through the interviews is presented in Figure 3. The amount of time per volume of collected sediment decreased as the chosen method, communication and coordination between the involved parties improved.

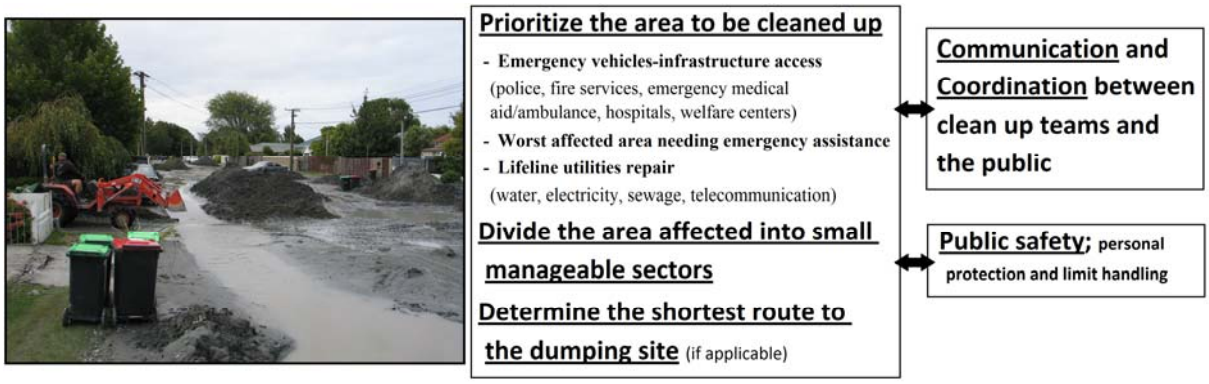

Figure 3: General strategy for Christchurch liquefaction clean-up. Photo: piles of liquefaction ejecta cleaned from residential properties and roads, ready for removal by heavy earth moving machinery at Bracken Street in the suburb of Avonside following the 22 Feb 2011 earthquake (Photo credit: Jarg Pettinga)

The optimal liquefaction clean-up process was found to include the following five steps (McDonald pers comm., 2011, Scott pers comm., 2012):

1) Contractor undertakes an initial inspection, defines small working zones on the basis of volume of sediment and local conditions, and identifies priority zones.
2) Contractor undertakes an initial silt removal from the street and pathways to facilitate transport - typically using heavy earth moving machinery.
3) Contractors, volunteers and property owners/residents remove silt by hand (i.e. shovel and wheelbarrow) from difficult to reach areas that machinery can't reach, including private properties, areas around vehicles, gardens, driveways and schools (Fig. 3). Material is accumulated in the street away from the curb (for easy pick up by diggers or loaders) and away from drains (to avoid sediment ingestion into waste water networks).
4) Silt is collected by contractors with machinery and either a) transported to disposal site at Burwood Resource Recovery Park (former city landfill) (Figs. 4, 5b) or b) stored in a temporary strategic location, prior to transport to disposal site (Fig. 5a).
5) Final cleaning via water-carts (truck mounted water tank and sprinkler system) to suppress windblown silt from the roads and to clean the silt possibly left into the storm water system.

This general method would be varied according to severity of sedimentation and access to available resources.

3.3 **Disposal**

Due to the contaminated state of some deposits and the extremely large volumes (> 500,000 tonnes), it was necessary to store the collected sediment outside of the city for storage and secure decontamination. The majority of liquefaction ejecta were disposed of at the Burwood Landfill (also known as the Burwood Resource Recovery Park) in Bottle Lake Forest following each earthquake (Fig. 4). The Burwood landfill had been operational from 1984-2005 serving Christchurch's solid waste disposal needs and at the time of the earthquake was undergoing a final stages of restoration and remediation work (started in 2010). The site had been identified as a storage area for solid disaster waste during disaster resilience planning in the 1990's and 2000's due to its proximity to the city (~10 km) and presence of a natural fine-grained barrier between the landfill and the shallowest aquifer that protects local groundwater resources (Harris pers comm., 2011).

The severity of road damage following the February quake and the huge volumes of silt led to stock piles being created in strategic locations in the city before being transported to Burwood (Fig. 5a) (Harris; Hautler pers comm. 2011, Scott pers comm. 2012). In addition, small quantities were disposed of by Fulton Hogan at their quarry in Pound Road due to proximity (Haulter pers comm. 2011). Future uses for liquefaction ejecta have been suggested for construction of concrete blocks or bricks, and engineering fill for levelling ground for sports fields and parks, however, to date the final uses have not been determined.

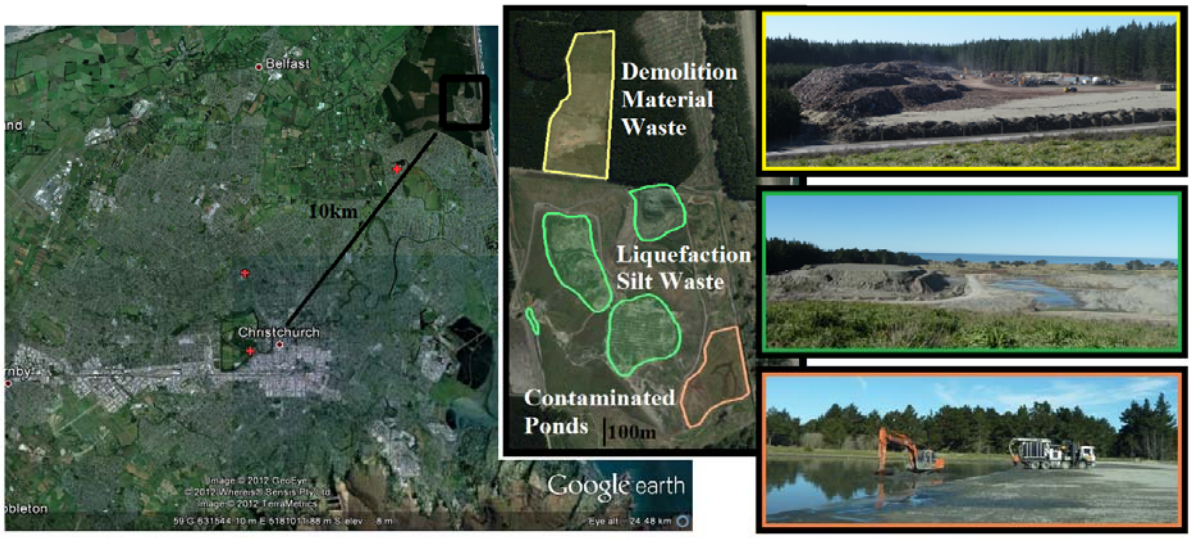

Figure 4: Burwood Resource Recovery Park location to Christchurch centre and simplified map of staging areas for different type of waste. Photo: staging areas on 25 August 2011.

3.4 **Coordination and Communication**

The liquefaction clean-up operation involved many different organisations and its effectiveness relied on extensive and well managed coordination and communication. During peak clean-up after the 22 February 2011 earthquake, over 2000 contractors were working on the clean-up along with approximately 1000-2000 *Student-Army* and *Farmy-Army* volunteers per day (Hautler; Fulton; Rutherford; Chapman pers comm. 2011, Scott pers comm. 2012). During this period, the Burwood landfill was accepting one truck every 20 seconds into the waste disposal area (Harris pers comm. 2011).

Clean-up managers noted the importance of a clear strategy which was underpinned at all times by clear and concise communication and coordination between council, contractors, volunteers, the public and other stakeholders, such as Civil Defence and other lifeline organisations who might require access to specific sites (e.g. for repairs). Initially communication between groups was poor, leading to

confusion and double handling (McDonald; Russell; Chapman; Rutherford pers comm. 2011). For example, information such as where to dispose of cleared silt was not transmitted to volunteer groups, leading to stock piles at inappropriate locations (e.g. private car parks).

All organisations stated that local knowledge, trust, contacts and existing informal relationships significantly enhanced the effectiveness of the clean-up management. In fact, the contacts and relationship established between different agencies involved and lessons from the first clean-up following the September 2010 earthquake made the mobilisation a lot more effective in the following events (Hautler; Rutherford pers comm. 2011).

Figure 5a: Aerial Photo 655 Breezes Road Bexley, showing temporary storage area for liquefaction silt 25/02/11 (Source: Koordinates 2011); Figure 5b: Estimated >500,000 tonnes of liquefaction silt removed from the Christchurch urban area after the 22 February 2011 earthquake at the Burwood landfill disposal site.

The large number of volunteers and the different level of skills and resources available between each of the groups involved in the clean-up operations made for challenges. Ensuring coordination of groups to limit multiple clean-ups of the same road in sequence with contractors took significant planning, but ultimately proved a powerful partnership. Initially, clean-up managers were concerned about health and safety amongst the volunteers, particularly in terms of operating around heavy machinery and access to sufficient food and water. However, this was remedied through briefings and strong leadership in each of the volunteer organisations. Coordination was further significantly enhanced when a job dispatch and mobile workforce management system, GeoOp system, was offered to the *Student-Army* with no usage cost. It was successfully used to coordinate the work of volunteers around the city (GeoOp 2012, Rutherford 2011).

3.4.1 *Coordinated Incident Management System (CIMS)*

The use of an incident management system (IMS) and staff trained in its use was essential for managing the clean-up (McDonald pers comm. 2011). New Zealand Civil Defence and Emergency Management (CDEM) uses the Coordinated Incident Management System (CIMS) which provides a unified, scalable and integrated system designed to enhance and empower on-site incident managers and communication. It is based on distributed accountability, which puts the people closest to the incident in charge and responsible in order to facilitate decision making and accelerating response time. Clean-up organisations reported there were significant benefits from having a common IMS structure in place, which was familiar from previous CDEM exercises in addition to snow and flood clean-up operations (Fig. 6). Some challenges were encountered when national CDEM began to relieve local CDEM, adding “unnecessary complications and poor situational awareness”.

CIMS was used effectively to communicate between the different clean-up organisations and with the public. The uniformity and control of the information was essential to avoid misunderstandings. The CIMS structure created one unique source of information for: road closure and opening, evolution of clean-up, identifying what had been done and what still had to be done. This information was available on a unique website where everybody would get the same and the most up to date information (McDonald pers comm. 2011).

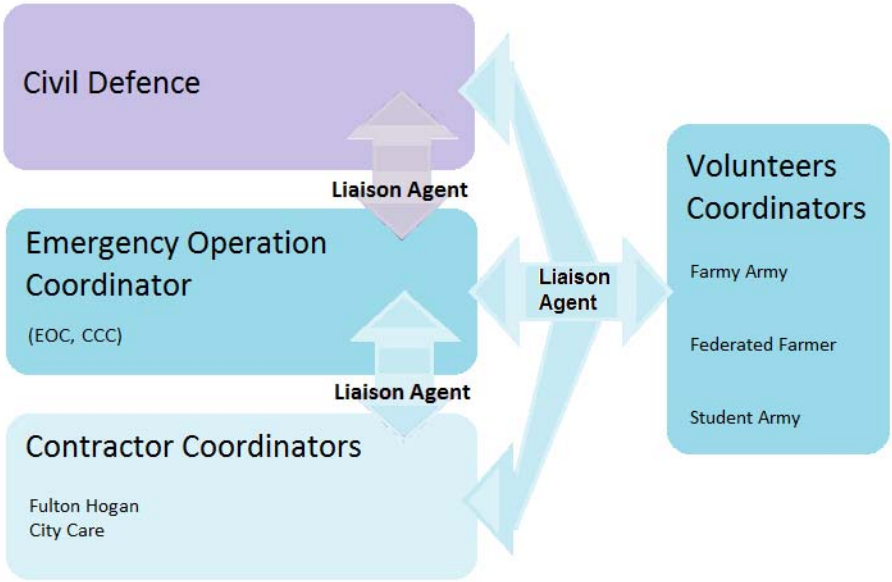

Figure 6: Emergency Clean-up Chain of Command from Christchurch liquefaction clean-up

3.4.2 *Volunteer Management*

It is well established in disaster literature that volunteers can have a significant positive impact on disaster victims by reducing stress, assisting in recovery activities and providing guidance throughout healing process (Fernandez et al. 2006). However, spontaneous volunteerism also represents a management problem for emergency management organisations not prepared to receive them, which can lead to major ineffectiveness of the response operations. This occurred during the early days of the clean-up operations, as the voluntary force from the *Student Army*, the *Farmy Army* and others were slowed down at first due to lack of preparedness (McDonald; Rutherford 2011). A team of project managers was rapidly put in place to co-ordinate all the efforts. The volunteer team evolved from two independent forces in February, where there was limited communication between them, to a joined organisation under the *Farmy Army* to work as a single body in June (Chapman pers comm. 2011). The joint effort and sharing of information was recognised to have great potential (Rutherford pers comm. 2011). The volunteer set-up could have been more rapid and efficient if there had been better provisions for managing volunteers in CDEM plans (Russell pers comm., 2011).

The *Farmy-Army* formed after the February 2011 event and was active again in the June 2011 event. They contributed 10-14 days of voluntary work after the February quake with thousands of workers and around five days volunteered for the June clean-up effort, partially because of the smaller scale and a sense of volunteer fatigue (Chapman pers comm. 2011). A significant contribution was made by the *Farmy-Army* with the use of equipment including tractors, trucks and human resources.

The total volunteer resources from *Student-Army* were difficult to ascertain due to the transient nature of the volunteer effort. Over 10,000 people had already joined their *Facebook* group *Student Volunteer Army* on the 24 February 2011 (One News 2011) and thousand of *Student-Army* volunteers are thought to have worked an estimated 75,000 hours (Webster pers comm. 2011). It was calculated that they offered over $1M worth of labour only during the first week after the February quake and help went on until the 20th of March (Rutherford pers comm. 2011). The Internet, social media and the coordination system GeoOp, were powerful tools for the *Student-Army*. Their *Facebook* page provided a useful way to communicate to the wider community of any needs they had and responses were rapid and very generous from local to international business and individuals.

3.5 Duration and estimated Clean-up Cost

Despite the volume of liquefaction ejecta being significantly different for each event, the duration of clean-up time was approximately 2 months following each event with most of it being completed during an intense period of cleaning lasting 2-3 weeks after each event. Interviewees indicated this reflected an ability of contractors and volunteer groups to scale their response to the need required. Although following the June 2011 event there were indications of groups suffering volunteer fatigue. Table 1 shows the estimated liquefaction silt volumes and time to remove the materials.

Table 1: Estimated mass of silt removed in Christchurch between September 2010 and August 2011

	Fulton Hogan	City Care	**Total**
Sept 2010 - Feb 2011	31,000 tonnes	No information	31,000 tonnes
Feb - June 2011	315,655 tonnes	81, 370 tonnes	397,025 tonnes
June - Aug 2011	87,364 tonnes	No information	87,364 tonnes
Total	434,019 tonnes	100,000 tonnes	**534,000 tonnes**

During the period of data collection the final financial cost of the clean-up effort to contractors was not available. However, from available sources the estimated cost of clean-up at March 2012 is approximately NZ$30,000,000.00.

4 SUMMARY

The prompt removal of liquefaction ejecta after an earthquake is essential to restore affected lifelines utilities, facilitate transportation and relieve the stress and disruption within affected communities. However, it is complex, time consuming and expensive, representing a major social, economical and even political challenge for the clean-up management team. Lessons from the Christchurch liquefaction clean-up experience agree with guidance from Brown et al. (2011) who note that key element to success include good public communication and public consultation during the disaster waste management process. Both elements can increase public understanding of the necessity for emergency measures, and also increase the authorities' appreciation of publically unacceptable options.

There were a number of similarities to other fine sediment clean-ups (particularly volcanic ash fall) observed during the Christchurch liquefaction ejecta clean-up experience:

- Widespread and thick deposition of fine grained sediment in or on a city requires municipal assistance and coordination.
- Emergency planning and the use of the CIMS system during the emergency were important to facilitate a rapid recovery from the liquefaction hazard.
    - Rapid identification of a disposal site is crucial. Significant benefits were realised in Christchurch by having a pre-selected site close to the city.
- Fine sediment is very difficult to handle when saturated (non-cohesive and heavy) or dry (hardens and is susceptible to erosion by wind). Fine sediment is ideally collected when slightly moisten.

Observations unique, but not necessarily exclusive to the Christchurch experience includes:

- Management of volunteer groups during clean-up operations can be extremely challenging, resource intensive and require their rapid adaption and integration into the incident management system. However, their contribution is invaluable and greatly adds to clean-up effectiveness. There are also a number of social benefits, including community spirit.

- Management of liquefaction silt, generally took around 2 months, despite variable extent and volume of ejecta,
- The financial cost of clean-up is in the order of multiple millions of dollars.
- Light and heavy earth moving machinery is essential for the large scale removal of deposits. However, this is most effective when properly integrated and coordinated with ground teams who clean hard to reach areas.
- Clear communication and coordination between clean-up command and the general public (affected property owners and volunteers) is essential for achieving the most efficient and effective clean-up.

The liquefaction clean-up experience in Christchurch following the 2010-2011 earthquake sequence has emerged as a valuable case study to support further analysis and research on the management, logistics and costs not only for liquefaction related phenomena, but also any kind of hazard which might cause the deposit of large volumes of fine grained sediment in urban areas, (e.g. volcanic ash or flooding; see Johnston et al. 2001).

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