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Evaluating Seismic Effects on a Water Supply Network and Quantifying Post-Earthquake Recovery

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ABSTRACT

This paper summarises the impact of major earthquakes, 2010–2011, on Christchurch's water supply network and what recovery measures have been applied, what worked well, what did not and why. A number of issues related to the open nature of the Christchurch water supply network were identified during earthquakes. It was difficult to manage large water supply pressure zones during the post-earthquake emergency response due to multiple failures of assets. The performance of the post-earthquake, post-rebuild 2017 water supply network was compared with the pre-earthquake water supply network to investigate the success of the post-earthquake rebuild programme. A multi-million dollar repair and rebuild works helped to return the level of service of the network to the pre-earthquake level and the water leakage of the 2017 water supply network was found similar to the pre-earthquake level. Hydraulic model was used for immediate earthquake emergency response, what/if scenarios investigations and earthquake damage assessments. Hydraulic models were built for pre and post-earthquake water network of Christchurch. The performance of pre and post-earthquake hydraulic models were compared and the results are also reported in this paper. Hydraulic modelling was found to be a very powerful tool engineers can use to assess the impact of an earthquake on a water supply network and formulate alternative plans during emergency response.

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1. INTRODUCTION

Any disruption in safe water supply has a major impact on a community's well-being [1]. A water supply network must be safe and sound for an effective, efficient and safe supply of water to customers [2, 3]. In years 2010 and 2011, Christchurch experienced a series of major earthquakes [4, 5].

This paper discusses the impacts of major earthquakes, 2010–2011, on Christchurch's water supply network and what recovery actions have been applied. The paper also outlines the damage to pipes and correlates pipe materials with the extent of the earthquake damage due to three major earthquake events. The performance of post-earthquake, post-rebuild 2017 water supply network was compared with the pre-quake water network and results are reported in this paper.

2. METHODOLOGY

As part of this study, the performance of Christchurch's water supply network was assessed using site inspection documents, water leakage data, customer complaints, and flow and pressure monitoring data taken from different parts of the network. Hydraulic models were built for pre and post-earthquake water network of Christchurch using infoworks WS modelling tool.

3. CHRISTCHURCH WATER SUPPLY NETWORK

Christchurch's current water supply network is divided into a number of large pressure zones. There are multiple pump stations in each zone and water is extracted from confined aquifers under the ground. There are a number of small pressure zones in the hill suburbs to the south of the city. The Christchurch city water system consisted of 175 wells, 57 primary pump station sites, around 1,600 km of water mains and around 1,550 km of sub-mains [6]. The water is extracted from underground aquifers

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that supply high-quality water. As the water quality is good, there is no need for water treatment, resulting cheap water supply to customers. As shown in Figure 1, there are seven major water supply pressure zones in Christchurch. Zone 1 (also called Central Zone) operates with highest operating pressure range of 70 to 80 m. All the other major zones are typically operates between 55 to 65 m pressure range.

4. EARTHQUAKES IN CHRISTCHURCH[a]

Christchurch was hit by an earhquake with a magnitude of 7.1 Richter on 4 September 2010 [4]. It was centred approximately 50 km west of the city centre [4]. A second earthquake with a magnitude of 6.3 hit Christchurch on 22 February 2011 [4]. The second earthquake caused major damage to the water network as its epicentre was near to ground level and closer to the city centre. Another earthquake with a magnitude of 6.3 hit Christchurch on 13 June 2011 [4]. There have been numerous earthquake aftershocks since then.

5. QUANTIFYING EARTHQUAKE EFFECTS

The earthquakes caused widespread liquefaction, lateral spreading and ground deformation [3]. Christchurch's water supply network was damaged mainly due to the February 2011 earthquake. The eastern suburbs of Christchurch – such as Wainoni, Aranui, New Brighton, and Bexley – suffered the most due to the earthquake.

5. 1. Impact on the Operation of Pressure Zone

In Christchurch, there are large water supply zones; for example, the central zone (zone 1) supplies water to around 60% of Christchurch customers. There are a number of small pressure zones in the hills that supply water to around 7% of Christchurch customers. The earthquakes of 2010–2011 highlighted a number of issues related to the operation of water supply zones and the vulnerability of the network due to the open nature of the supply zones. It was difficult to manage large water supply zones during the emergency response immediately after the earthquake given the multiple failures of assets (pumps, pipes and reservoirs). It took a long time to return relatively undamaged areas to full service by isolating the area from the large pressure zone (damaged significantly). Smaller zones were found to be more manageable and it was easier to restore full service during the emergency response time. In reality, large water pressure zones were converted to smaller zones for efficient management of water supply network during post-earthquake emergency. [7]

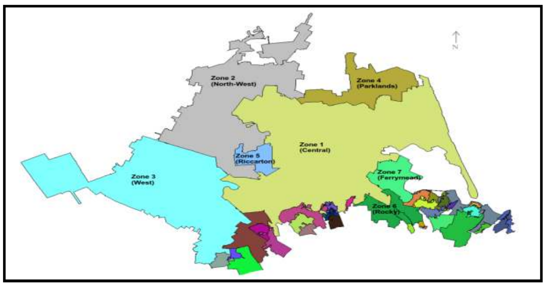

Figure 1. The pressure zones currently comprising Christchurch's water supply (Seven major pressure zones)

5. 2. Water Supply Pipelines

It was estimated that approximately 240 km of water supply mains and 320 km of sub-mains needed to be replaced or repaired due to the earthquakes [6]. The water supply pipes were damaged due to cracks, breaks and joint failures. During post-earthquake recovery works, SCIRT (Stronger Christchurch Infrastructure Recovery Team) developed a number of damage criteria to define which pipes require repair and/or replacement. In some areas, the network was operating with reduced delivery pressure and capacity due to pipe damage. In Christchurch, pipe materials also varied considerably. Some of the predominant pipe materials are polyvinyl chloride (PVC), polyethylene (PE), steel (St), galvanised iron (GI), and asbestos cement (AC). As shown in Figure 2, asbestos cement and PE were the dominant pipe materials in Christchurch's water supply network.

The impact of the three major earthquakes on different pipe materials was assessed. As shown in Figure 3, the February earthquake had significant effects on pipe damage and AC pipe was found to be the most vulnerable pipe material during ground movements. Flexible pipe materials such as PVC and PE performed much better than other pipe materials such as steel, GI, and AC.

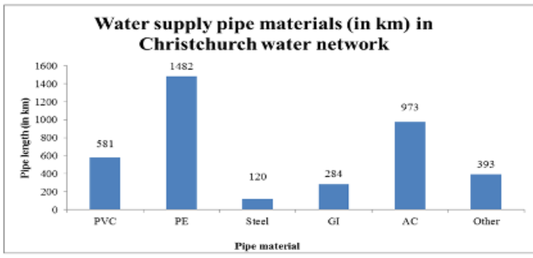

Figure 2. Water pipe materials (in km) in Christchurch

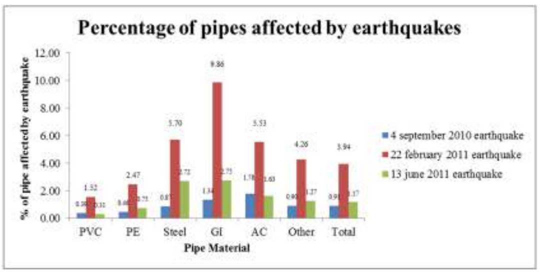

Figure 3. Water supply pipe affected by earthquakes

The choice of appropriate pipe materials can make a significant difference on the performance of pipes during seismic activities.

5. 3. Pump Stations, Wells and Reservoirs There were 57 pump station sites in pre-earthquake Christchurch. Of these, two water pump station sites were damaged significantly and needed to be rebuilt. Damage to pump stations was related to the structural damage to the building and floor slabs due to liquefaction [6, 7]. There were a total of 175 wells in the city and, of these, 110 wells were damaged due to the earthquakes [6, 7]. Of the damaged wells, 25 had to be either rehabilitated or redrilled. The remaining 85 damaged wells required minor repairs to make them fully functional [6]. In pre-earthquake Christchurch, there were eight main storage reservoirs and 37 service reservoirs. Of these, 12 reservoirs needed repairs whereas two reservoirs needed to be rebuilt [6].

5. 4. Customer Complaints Pre-earthquake 2009 (June 2009 to May 2010) customer complaints related to water supply network is compared with the 2011 (June 2011 to May 2012) post-earthquake customer complaints. All the customer complaints have been broadly categorized into four major categories: a) Low pressure complaints, b) Pipe-burst/water leakage complaints, c) Water quality complaints, d) Other water service related complaints. Figure 4 outlines the customer complaints comparison in graphical format. Low water pressure and pipe burst related complaints had increased by around 200% in 2011. Overall, there was a significant increase in customer complaints during the post-earthquake 2011/2012 time period. It also needs to be noted that the post-quake customer complaint data may not be a true reflection of reality as a lot of customer complaints were not documented properly immediately after the earthquake.

6. WATER NETWORK MODEL AND POST-EARTHQUAKE RECOVERY IN CHRISTCHURCH[b]

Water network model (also called as water network hydraulic model) is a very powerful tool to assess the

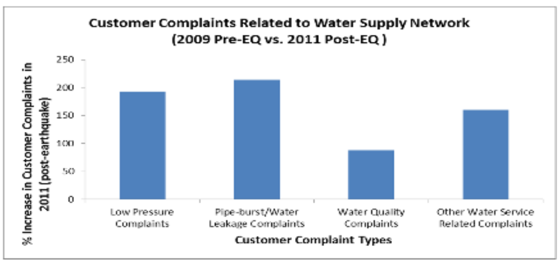

Figure 4. Customer complaints related to water supply network 2009 pre-earthquake vs. 2011 post-earthquake

performance of a water supply network [8-10]. Water network modeling is a modern technology that has been adopted by many water authorities in New Zealand to assess different what/if operational and future planning scenarios of a water network. There are a number of sophisticated software available in the market where the real water supply network can be replicated and visualized using different GIS and hydraulic modeling calculation engine. Asset data (pipe network, pump stations, nodes, water meter etc) are imported in the modeling files and then extensive calibration and validation works are carried out so that the water network model replicates the reality (water pressure, operation of the network etc).

6. 1. Water Network Model Development Method Hydraulic models were built for pre and post-earthquake water supply network of Christchurch. Water network asset data (pipes, pumps, reservoirs, wells, nodes etc.) were imported into hydraulic modelling simulation software Infoworks WS. Infoworks modelling software is one of the most popular hydraulic modelling softwares available in the market [9]. Once water network asset data were imported, asset data verfication and connectivity checks were carried out. The operating features of the water network is replicated in the model by changing control information of different water assets (valves, pumps, reservoirs etc.). Water supply network model development methodology has been outlined in Figure 5.

The pre-earthquake and post-earthquake models were calibrated/validated with pre and post-earthquake flow data respectively. Data for pre and post-earthquake water network models are further explained in section 6.1.1 and 6.1.2. As part of this research, the performance of the pre-earthquake hydraulic model was compared with the December 2011, post-earthquake hydraulic model to understand earthquake damage

6. 1. 1. 2010 Pre-quake (Pre-Q) Model This model was developed to assess and understand the performance of Christchurch's water supply network before the

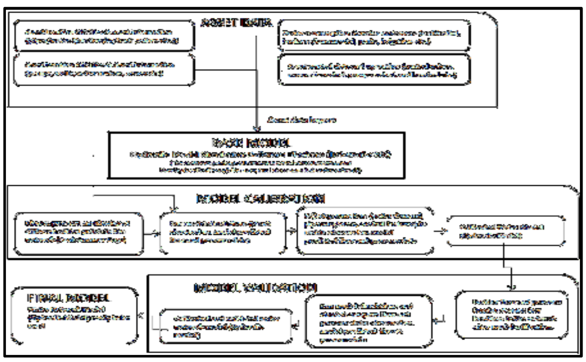

Figure 5. Hydraulic model building and calibration method

September 2010 earthquake. The model was developed by taking pre-earthquake information such as network survey files, GIS files, billing and demand data, pressure and flow-monitoring data and as-built files (as also shown in Table 1).

6. 1. 2. 2011 Post-quake (Post-Q) Model This model was developed to assess post-earthquake performance of the network and also to test emergency response activities in Christchurch. Please refer to Table 1.

6. 2. Performance notes 2010 Pre-Q Network Model vs. 2011 Post-Q Network Model Hydraulic modelling simulations were run to assess the performance of Christchurch's water network immediately after the June 2011 earthquake. Both pre and post-earthquake water supply models were run for a peak summer day and the results are compared.

6. 2. 1. Minimum and Maximum Pressure In case of 2010 pre-Q model, minimum pressure at the property boundary is noted as around 27m (meter) for the combined water supply network (7 major pressure zones). In the hill suburbs minimum pressure for water supply drops to around 23m. Maximum pressure at the property boundary is found as around 80 meter.

In case of 2011 post-Q model, minimum pressure at the property boundary is around 16m for the combined water supply network (7 key pressure zones). In the hill suburbs minimum pressure for water supply drops to around 14m in some areas. Maximum pressure at the property boundary is found as around 67m.

6. 2. 2. Fire-flow Availability Building footprints, sprinkler systems and hydrant locations were assessed as part of this investigation. New Zealand's firefighting water supplies code of practice has been used to

TABLE 1. Water model development method (2010 pre-quake model vs. 2011 post-quake model)

	Model	Description
Elevation	Pre-Q	Extracted from 2008/09 LiDAR (light detection and ranging) and network survey files and imported into hydraulic modelling software package.
	Post-Q	Extracted from 2011 LiDAR (light detection and ranging) and network survey files and imported into hydraulic modelling software package.
Nodes Valve, Pipe etc.	Pre-Q	Imported into Infoworks WS water modelling software from pre-earthquake water network GIS files. Around 130, 000 pipes, total length of around 3150 km added into the model. Pipe roughness data were automatically calculated in the modelling tool (Infoworks WS) based on pipe material, construction year and site inspection data.
	Post-Q	Imported into Infoworks WS water modelling software from pre-earthquake water network GIS files. Further water network adjustments were done based on network survey documents of 2011. (pipe closure, valve closure, site inspection and survey data etc).
Reservo irs	Pre-Q	89 reservoirs had been imported into the water network model from pre-earthquake GIS files.
	Post-Q	Same as 2010 pre-earthquake model. Further adjustments were done to deactivate 2 reservoirs and reduced level of service for another 12 service reservoirs.
Pumps	Pre-Q	A total of 214 pumps (69 submersible, 145 surface) were imported into the water network model from the CCC pre-earthquake GIS layers. Pumps were modeled based on operational set up in the actual network (operator controlled, pressure controlled or controlled by reservoir level). The CCC asset register provided design pump flow, head and appropriate pump curves.
	Post-Q	Same as 2010 pre-earthquake model. Further adjustments were done in the 2011 post-earthquake model to deactivate 3 pump stations and reduced capacity for another 11 pump stations due to earthquake damage.
Water Demand	Pre-Q	Customer points and water demand data have been imported into the model from the pre-quake 2009 CCC GIS file and SCADA documents. Appropriate water demand profiles for residential consumption (L/property/day), commercial consumption (L/s) and leakage (L/s) were developed and added into the model. These were calculated using flow and pressure data and SCADA files.
	Post-Q	Water consumption data were imported into model from the post-earthquake 2011 CCC GIS file and SCADA documents.
Water Zones	Pre-Q	Seven large pressure zones are replicated in the model using appropriate control valves. The pressure zones are shown in Figure 1.
	Post-Q	Though in the pre-quake model there are seven key pressure zones, in post-quake model, this had been subdivided into a number of smaller zones. In reality, the number of new pressure zones varied time to time based on emergency response measures.
Oper ation	Pre-Q	Data imported into the model from CCC pre-earthquake asset registers and operational data files
	Post-Q	Data imported into the model from CCC 2011 post-earthquake asset registers and operational emergency data files.
Model Calibration	Pre-Q	The 2010 pre-quake water supply model was calibrated to a peak summer day of 2009 [11]. Leakage data were taken from a winter day in August 2009.
	Post-Q	The 2011 post-quake water supply model was at first calibrated to a peak summer day of 2009. Further input parameter adjustments were done to replicate post-earthquake water demand and control information [11]. Leakage data were taken from a winter day in August 2011.

understand where the network fails to meet the specification [12]. A number of random fire-flow simulations were done. The 2010 pre-earthquake network has a number of areas where it fails to meet New Zealand fire-flow specification. Earthquake made the situation worse. The non-complying area (where it fails to meet New Zealand fire-flow specification) had increased by around 45% in the post-earthquake network.

6. 2. 3. Reliability and Security of Supply The reduced level of operation of different pump station sites due to the earthquakes caused around 15% loss of capacity to pump water around the city. A number of random simulations were run to assess the reliability and security of the network (pump failure, trunk pipe shut off, reservoir failure, multiple asset failures etc.). 35 scenarios were modelled and assessed to test reliability and security of supply.

Category 1: Three or more asset failures (10 scenarios)
Category 2: Two asset failures (10 scenarios)
Category 3: One asset failure (15 scenarios)

In the post-earthquake network, reliability and security of supply became a big issue and out of 35 scenarios, the network failed in 27 scenarios (ten category1, eight category 2 and nine category 3) as it was unable to provide adequate pressure (>20m) at the property boundary. The Pre-earthquake network was able to perform well for 24 emergency shut off scenarios (five category 1, six category 2 and thirteen category 3) . The remaining 11 extreme emergency scenarios involved multiple asset failures and even the pre-earthquake network was unable to cope with these extreme asset failure scenarios.

6. 2. 4. Water Leakage Water leakage (minimum night-time flow) had increased significantly due to the earthquakes in Christchurch. Earthquake damage of the water supply network was assessed by comparing pre-earthquake leakage information with the post-earthquake leakage data. 260 L/connection/day water leakage was estimated for the pre-earthquake network whereas water leakage increases to 366 L/connection/day in the post-earthquake 2011 network. (as per model inputs and simulation results). Data were extracted from CCC's (Christchurch City Council) SCADA (Supervisory Control and Data Acquisition) for winter periods (eight weeks starting from 12 June) pre-earthquake (before 4 September 2010 earthquake) versus post-earthquake (after 13 June 2011 earthquake). All the control data (pump station operation, reservoir operation, water meter data) were added in hydraulic models and simulations were run for winter periods. Pre and post-earthquake minimum night-time flows (MNF) were compared for the combined Christchurch water network and outlined in Figure 6.

As shown in Figure 6, leakage levels had increased by around 40% across the city, based on the comparisons of the MNF data. There was a sudden increase in minimum night-time flow just after the earthquake on 13 June 2011. The MNF data then stabilised and a 40% increase in leakage flow was notified. Earthquake damage such as pipe breakage and cracks caused increase in water leakage rates. As part of Christchurch's water supply recovery programme, millions of dollars have been spent repairing and rebuilding the network in different areas. Around 400 km pipelines were rebuilt and/or repaired, a number of new pump stations were built in the eastern part of the city, all the major reservoirs and wells were repaired and/or rebuilt.

Minimum night-time flow (during winter) in the 2017 water supply network has been compared with the pre-earthquake minimum night-time flow during winter (using hydraulic model simulation results and SCADA data). As shown in Figure 6, system leakage in the network has returned to the pre-earthquake level. The study is a key indication of the success of the repair and rebuilds work done in Christchurch where the water leakage has returned to the pre-earthquake level.

6. 2. 5. Customer Complaints Pre-earthquake customer complaints related to water supply network is compared with the 2017 post-earthquake (post-rebuild) customer complaints. It is interesting to note that the water quality related complaints have increased notably (22%) in the post-earthquake post-rebuild network. Further investigation confirmed the complaints were mainly related to high nitrate levels specially in zone 1 and 5. Upstream livestocks and industry discharge can be the reason behind high nitrate levels. No further investigation was done to confirm this. Pipe burst and water leakage complaints have increased by around 5% in the 2017 post-quake network. It can be attributed to ongoing earthquake aftershocks in the Canterbury region. Customer complaints related to low water pressure has returned back to the pre-earthquake level.

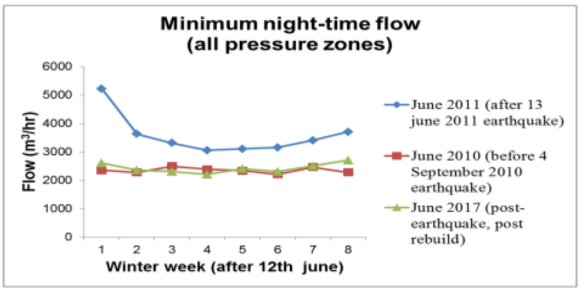

Figure 6. Minimum night-time flow in the water network pre-quake (2009), post-quake (2011), and post-rebuild (2017) networks

7. CONCLUSIONS

The overall impact of earthquakes on Christchurch's water supply network included the loss of wells and pump stations and a significant increase in leakage (around 40%) due to pipe breakage and cracks. Asbestos cement pipes were found to be the most vulnerable pipe material in the face of ground movement whereas flexible pipe materials – such as PVC and PE – performed well. Hydraulic modelling assessments of pre and post-earthquake water network showed that the post-earthquake water network performed with reduced pumping capacity and level of service (low pressure, reliability etc.) deteriorated in different parts of the network. A multi-million dollar repair and rebuild work is helping to return the level of service of the network to the pre-earthquake level. Water leakage of the 2017 water-supply network is found similar to the pre-earthquake level. Customer complaints related to water supply network service have also become stable in 2017 and it is estimated to be similar to pre-earthquake level with some minor exceptions.

8. ACKNOWLEDGEMENTS

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چکیده

این مقاله خلاصه تاثیر زمین لرزه های عمده ۲۰۱۰-۲۰۱۱ را در شبکه آبرسانی کریستچرچ و اقدامات بهبودی را اعمال می کند، چه کار می‌کند، چه چیزی کار نمی‌کند و چرا. تعدادی از مسائل مربوط به ماهیت باز شبکه تامین آب کریستچرچ در طی زلزله شناسایی شد. در حین واکنش اضطراری پس از زلزله، به دلیل خرابی های متعدد دارایی، مدیریت مناطق بزرگ فشار آب را دشوار می‌نماید. عملکرد زلزله پس از زلزله، شبکهٔ آبرسانی پس از بازسازی سال ۲۰۱۷ با شبکه تامین آب قبل از زلزله برای بررسی موفقیت برنامه بازسازی پس از زلزله مقایسه گردید. کارهای تعمیر و بازسازی چند میلیون دلاری به بازگشت سطح خدمات شبکه به سطح قبل از زلزله کمک کرد و نشت آب شبکه آبرسانی ۲۰۱۷ مشابه سطح پیش از زلزله بود. مدل هیدرولیکی برای پاسخ فوری زلزله فوری، تحقیقاتی که در مورد سناریوها و ارزیابی آسیب زلزله صورت گرفته است، استفاده شد. مدل‌های هیدرولیکی برای شبکه آبرسانی قبل و بعد از زمین لرزه کریستچرچ ساخته شد. عملکرد مدل های هیدرولیکی پیش از و پس از زلزله مقایسه شد و نتایج نیز در این مقاله گزارش شده است. مدل‌سازی هیدرولیکی به عنوان ابزار بسیار قدرتمندی بود که می‌توانست برای ارزیابی تاثیر زلزله بر روی یک شبکه تامین آب و برنامه‌های جایگزین در واکنش اضطراری استفاده گردد.

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