Bulk water supply – Impacts of a Wellington Fault Earthquake

Jim Cousins, Nick Perrin, Graeme Hancox, Biljana Lukovic, Andrew King & Warwick Smith

GNS Science, Avalon, Lower Hutt, New Zealand.

Alastair McCarthy & Tony Shaw

Greater Wellington Regional Council, Wellington, New Zealand.

ABSTRACT: Urban Wellington Region is uniquely vulnerable to large earthquakes. Not only is it bisected by large active faults but it is extremely isolated, with all supplies being transported along a small number of lifelines. All are vulnerable to earthquake damage. The potential for total loss of water and food supplies is real and could render large areas uninhabitable for weeks to months.

Greater Wellington Regional Council is evaluating new sources of potable water for the four cities of the Wellington Region. One important consideration is security of supply following major earthquakes near Wellington, in particular an earthquake involving rupture of the Wellington Fault because current bulk-supply pipelines cross the fault at several places.

We describe the pipeline damage expected from a Wellington Fault Earthquake and estimate the times needed for restoration of the bulk supply to main delivery points throughout the region. Priority is given to Wellington City because of its high population and lack of access to alternative supplies. One key finding is that the shortest time needed to get a limited supply back into Wellington is five to eight weeks. A second is that constructing a new supply dam west of the Wellington Fault could lower the restoration time by about one third, to three to five weeks. Even the lowered times are too long and it is clear that alternative solutions must be found.

1 INTRODUCTION

Greater Wellington Regional Council (GW) manages the bulk supply of potable water for the cities of Upper Hutt, Hutt, Porirua and Wellington. One important consideration is security of supply following major earthquakes near Wellington, in particular an earthquake involving rupture of the Wellington Fault because current bulk-supply pipelines cross the fault at several places (Figure 1). The potential economic and social consequences of protracted loss of water supply to urban Wellington Region are extremely severe, therefore GW wished to have estimates of the time needed to restore bulk water supply to the two main termination points in Wellington City, at Karori and Thorndon.

Our approach was to overlay the bulk supply network with maps of geological hazards including landsliding, liquefaction, soft-soil amplification and faulting, prepared specifically for this study. This allowed fault crossings, potential landslides and areas of liquefaction ground damage to be accurately mapped in relation to the pipelines. We then applied the shaking field expected from a Wellington Fault earthquake and, using fragility functions that took into account the properties of the pipes and the effects of the geological hazards, estimated the numbers and locations of breaks and leaks. This was done semi-probabilistically.

Failure rates were estimated for four sources, the existing Kaitoke, Wainuiomata, and Hutt Artesian systems, and a proposed new Whakatikei system. A critical comparison was the time to restore bulk supply to Wellington from the proposed Whakatikei source compared with the existing Kaitoke source. Because the Whakatikei source was on the western side of the fault there was only one fault
crossing between it and eastern Wellington, compared with three for the Kaitoke system and two for the Wainuiomata and Hutt Artesian systems.

The isolation of central and eastern Wellington (areas to the right of the Wellington Fault in Figure 1) is stark. There are no significant sources of vital supplies within the zone, including water, food, power or fuel. All have to be imported through the steep hill country that surrounds the City.

![Figure 1. Wellington area bulk water supply system showing water sources (yellow stars) (Wainuiomata, Kaitoke, Hutt Artesian, proposed Whakatikei), bulk mains (dotted black lines), places where the bulk mains cross the Wellington Fault (purple circles) (Te Marua, Silverstream, Petone, Thorndon, Karori), main supply points for eastern Wellington City (blue triangles) (Thorndon, Karori), and the Wellington Fault (red line). Two of the main cities of the region are labelled, Hutt City, occupies the valley containing the Hutt Artesian water source, and Upper Hutt lies between Silverstream and Te Marua.]

2 SEISMIC HAZARD

Only a worst-case scenario was considered, i.e. a magnitude 7.6 earthquake generated by rupture of the Wellington Fault. Shaking from the earthquake was estimated using the MMI (Modified Mercalli Intensity) attenuation model of Dowrick and Rhoades (2005). An intensity of MM10 was estimated over most of Wellington and Hutt Cities, and MM9 over much of the remaining urban area.

3 GEOLOGICAL HAZARDS

Ground type varies along the pipeline routes, and includes weak rock (with landslide hazard in some places), compact river gravels, and soft soils (with liquefaction hazard in some places). The entire pipeline route, including to the proposed Whakatikei source, was flown by helicopter and extensively photographed. The aerial photos and video, Google Earth images, Google Street View (in many cases), and in-house databases, were used to assess geological hazards along the pipeline routes. This was done to establish locations with a potential for fault rupture, liquefaction-induced lateral spreading and subsidence, or landsliding, which could damage or rupture the pipelines. Then followed a process of establishing a “risk rating” for the potential effects of the identified geological hazards, as follows:

- Low – No perceived geological hazards.
- Moderate – Minor hazard from landslides on to buried pipeline; small (<5-10 m) slope collapses of ground in which pipe is buried.
• High – Significant hazard from major (>10 m) long slope failure collapse; or major liquefaction lateral spreading and subsidence. Specific note was taken of places where landslide under-failure was expected.

• Extreme – Almost certain likelihood of rupture (e.g. all the Wellington Fault crossings and a few landslide and lateral spread areas).

Finally, the resulting hazard ratings were mapped and overlaid on the pipelines so that each pipe segment could be allocated a risk rating.

4 PIPE DAMAGE MODEL

4.1 Data

Reports of damage to water-supply pipelines in eleven major earthquakes were scanned for useful information, as were three major reviews of the topic (ALA 2001, 2005, Rojahn and Sharpe 1985). A great deal of anecdotal / descriptive information was found, but despite the quantity of words and data the topic was fraught with incomplete and often inconsistent data, apparent high variability, and models with inadequate support. Reports were found for complete water supply systems that had experienced shaking levels comparable to those expected from a Wellington Fault earthquake in five historical earthquakes, viz. Hawke’s Bay (New Zealand) 1931, Kobe (Japan) 1995, ChiChi (Taiwan) 1999, Kocaelli (Turkey) 1999, and Bhuj (India) 2001. In all cases, there was severe damage to water distribution systems, but bulk-supply pipelines and related structures (dams, weirs, artesian wells, pump stations and treatment plants) appeared to have performed much better.

Figure 2 summarises the available data and expert assessments. The general trends within the cloud of points are (a) damage increases with shaking intensity, (b) increases greatly when ground damage (liquefaction or landsliding) is present, (c) decreases with increasing pipe diameter, and (d) depends on pipe material, jointing method and diameter. Large diameter (≥ 400mm) steel pipelines with welded joints appeared to be the most robust, and small diameter cast-iron pipelines with old couplings (more than c. 50 years) the most fragile.

![Figure 2](image-url)

Figure 2. Historical data (ALA 2001, 2005) and expert panel assessments (Rojahn and Sharpe 1985 – ATC-13) on damage to buried water-supply pipelines affected by earthquake shaking. The two ATC-13 points plotted at 0.0001 represent zero expected repairs per km.
4.2 Model

The method adopted was to estimate the repair rate for a base case of large-diameter, modern, welded-steel pipeline, buried in ground that had negligible potential for liquefaction or landslide failure, and then to allow for other situations with a series of multiplying factors. With this in mind, the expression for estimating the repair rate, $RR$, for any situation become

$$RR = F1 \times F2 \times F3 \times F4 \times F5 \times RR_{GS}$$

(1)

where $RR_{GS}$ was the base repair rate (for ground shaking alone), and $F1$ to $F5$ were factors to allow for pipe material, coupling age, pipe size, landslide hazard, and liquefaction hazard. They were assumed to be 1.0 unless specified otherwise in Table 1.

Table 1: Relative fragility factors. The factor value is 1 for all conditions not specified here.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Name</th>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Pipe Material Factor</td>
<td>Cast-Iron</td>
<td>2</td>
</tr>
<tr>
<td>F2</td>
<td>Coupling Age Factor</td>
<td>Couplings more than 50 years old</td>
<td>2</td>
</tr>
<tr>
<td>F3</td>
<td>Size Factor</td>
<td>Diameter &lt; 400 mm</td>
<td>4</td>
</tr>
<tr>
<td>F4</td>
<td>Landslide Hazard Factor</td>
<td>Moderate Hazard</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Hazard</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extreme Hazard</td>
<td>27</td>
</tr>
<tr>
<td>F5</td>
<td>Liquefaction Hazard Factor</td>
<td>Moderate Hazard</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Hazard</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extreme Hazard</td>
<td>27</td>
</tr>
</tbody>
</table>

The formula for the base-case repair rate was

$$RR_{GS} = A \times 10^{(B/(MMI-C))}$$

(2)

where MMI was the shaking intensity and $A$, $B$ and $C$ were fitted constants. It was a completely empirical model, chosen so as to give a plausible match to the available data, as illustrated in Figure 3 for base-case and worst-case (cast-iron pipes, old couplings, in ground of extreme risk rating) situations.

4.3 Immediate Repair

Pipe failure can range from minor leakage at a distorted coupling to complete annular rupture, and depends strongly on the pipe material and the jointing method (Shi 2006). Of considerable importance are assertions by Shi, based on observations, that (a) the only failure mechanism for welded steel pipeline is compressive buckling in the bell section of the bell and spigot joint, and (b) only 20% of such failures proceed to tearing or splitting of the wall, and hence leakage. We have assumed that in the immediate aftermath of a major earthquake only actual leaks will need to be repaired for restoration of survival-level supply, and hence have reduced the repair rate for welded steel pipelines to one-fifth of the nominal rate.

4.4 Fault Breaks

Places where the pipelines cross the Wellington Fault are well known. Complete failure of the pipeline is expected at each crossing point.
Figure 3. Examples of the pipe failure model compared with data and expert assessments. “Large Diameter” means 400mm or more.

4.5 Computation Detail

Brief details of the computation sequence are as follows:

- Estimate the average MMI at the centroid of each pipe segment. Allow for uncertainty in the MMI model (using random selection from distributions about mean parameters), and allow for soft soil amplification / rock de-amplification. (Pipe segmentation was based on changes in either pipe attributes or geological conditions, with a maximum segment length of 100 m being imposed.)

- Estimate the repair rate, in repairs per km, using Equations 1 and 2. Multiply the repair rate by the segment length to give the repair rate specific to the segment.

- Treat the segment repair rate as a probability of failure for the segment, generate a random number in range 0 to 1, and when the random number is less than the probability of failure assume that the segment has failed.

- Allow for fault damage. The failure probability is assumed to be 1 wherever the Wellington Fault crosses a pipeline, and the failure type is complete rupture. Ensure that there is no double counting of failure, i.e. a pipe segment ruptured by the fault is not also damaged by ground shaking and associated effects (landsliding etc.).

- Accumulate the numbers of failures.

- Repeat the above procedure 10,000 times so that natural variability can be described.

- Carry out sensitivity studies for critical parameters.
5 REPAIR TIME MODEL

Repair times were based on expert opinion of experienced GW staff. Tasks covered included:

- Assembly of repair crews, initial inspection and planning, assembly of plant and materials;
- Repair of ruptures at fault crossings (preparatory work has already been done at the Kaitoke and Karori sites so that restoration of emergency flow is expected to take c. 5 days for each, repairs at the other locations are expected to take 8 to 18 days); and,
- Pressurise pipe, locate leaks, de-pressurise, repair leaks, re-pressurise, repeat as necessary.

Given sufficient manpower, repairs at fault crossings were to some degree carried out in parallel with repairs to pipelines. Repair of the pipelines, however, had to be sequential from water treatment plants to reservoirs.

Given that Hutt, Upper Hutt, and to some degree Porirua, had alternative supplies of water (from rivers and streams), priority was given to the Kaitoke to Karori system. Restoration of the Hutt Artesian to Thorndon system had second priority, and Wainuiomata to intersection with the Hutt–Thorndon line third priority.

In a second scenario the Kaitoke source was replaced with the proposed Whakatikei source as the priority one restoration task. In both scenarios, restoration of supply to Porirua was undertaken once water was available at the point where the Porirua main branched from the Kaitoke-Karori main.

6 RESULTS

Table 2 compares the estimated numbers of failures for each of the four main source-to-termination routes for the Wellington Area bulk supply network. The failures are those that have to be repaired (i.e. are leaks), and the heading “Shaking” includes failures due directly to ground shaking and those from shaking-induced ground damage. The raw numbers suggest that the main advantage of the proposed Whakatikei source is in reducing the numbers of fault ruptures.

Repair times derived from the numbers of repairs, Table 3, indicate that replacing the Kaitoke source with a source at Whakatikei results in a 15 to 20-day reduction in the time needed to restore water to Karori, and small reductions for the Thorndon supply point. The Karori reduction occurs primarily because there are two fewer fault ruptures to be mended, and the Thorndon reductions because staff can be allocated sooner to that phase of the restoration.

<table>
<thead>
<tr>
<th>System</th>
<th>Shaking</th>
<th>Fault Rupture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaitoke – Karori</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Whakatikei – Karori</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Wainuiomata – Thorndon</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Hutt Artesian – Thorndon</td>
<td>7 (max)</td>
<td>2</td>
</tr>
</tbody>
</table>

It must be borne in mind that two potential failures of the Kaitoke system have not been included in the modelling. One is failure of a “Flume Bridge” which carries water from the Kaitoke intake across the Hutt River in a steep-sided gorge. Although the Flume Bridge has been strengthened against earthquake shaking its survival is not guaranteed. If it does fail the repair time could be substantial, and additional to the time needed to repair the other breaks in the Kaitoke – Karori pipeline. The other is failure of a highway bridge across the Hutt River at Silverstream. The pipeline is attached to the bridge piers, but is located partly beneath the deck, and so is likely to be ruptured if any of the several
spans were to drop. Once again, repair could be complex and lengthy.

Table 3. Estimated times to restore a limited bulk water supply to Wellington City, in days from the earthquake, without and with the proposed Whakatikei source.

<table>
<thead>
<tr>
<th>System</th>
<th>Current Sources</th>
<th>Whakatikei Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaitoke – Karori</td>
<td>35 – 55</td>
<td>–</td>
</tr>
<tr>
<td>Whakatikei – Karori</td>
<td>–</td>
<td>20 – 35</td>
</tr>
<tr>
<td>Wainuiomata – Thorndon</td>
<td>60 – 80</td>
<td>55 – 75</td>
</tr>
<tr>
<td>Hutt Artesian – Thorndon</td>
<td>60 – 80</td>
<td>55 – 75</td>
</tr>
</tbody>
</table>

6.1 Sensitivity Studies

A few sensitivity studies were conducted, mainly to check that the results were not unduly sensitive to some of the mean parameters selected. Note that only the numbers of failures were of interest here, because the fault breaks remained the same in all cases. The cases investigated were as follows:

- Location of epicentre (base case: epicentre at the centre of fault, variations: epicentre moved 6 km to the northeast (along the fault) so as to increase the shaking intensity over the northern source zones and then 6 km to the southwest). The northeast shift of the epicentre made no significant changes to the numbers of failures, and the southwest change lowered the numbers of failures by one or two.

- Earthquake magnitude (base case: 7.6, variations 7.3 and 7.9). Increasing the magnitude by 0.3 increased the numbers of failures by about two for each system, and reducing the magnitude by 0.3 lowered the numbers by about two.

- Proportion of welded steel failures needing immediate repair (base case: 20%, variations 50% and 100%). Increasing the proportion from 20 to 100% increased the numbers of failures by two – four for the systems supplying Karori, and by 12 – 13 for the systems supplying Thorndon. This difference arises because the Karori routes are dominated by jointed pipelines, whereas the Thorndon route is dominated by welded steel pipeline.

The first two cases seem unlikely to have a great impact on the restoration times of Table 3, and the third, which results in significantly increased restoration times for the Thorndon termination point, simply serves to reinforce the importance of the pipelines to the Karori terminus.

7 DISCUSSION

The original motivation for the water restoration project (Cousins et al 2009) was to provide input to a study of the potential economic benefits of a new regional water source at Whakatikei (Sanderson and Norman, 2009). A more important outcome, however, may be to provide input to the ongoing debate about how best to prepare for a large earthquake in the vicinity of Wellington. In 1991 the belief was that “recovery of a basic water service for priority use would take two days following a major earthquake event. … To restore a 50% service would take two weeks … .” (CAE 1991), and current Ministry of Civil Defence and Emergency Management advice to Wellington area residents is to store “Water (3 litres per person, per day, for up to 3 days or more)” (MCDEM, 2007). Such advice now seems totally inadequate. A recent unpublished background paper (Brunsdon, 2002) indicates (a) a higher recommended minimum daily usage of about 15 litres per person per day, (b) that reservoirs around Wellington City might retain 8 – 18 days of water at that usage rate, (c) that restoration of the Kaitoke to Karori bulk system could take about 23 days, thus (d) leaving a 5 – 15-day deficit between the end of the stored water and the restoration of emergency supply.

Anther important point that the restoration times are for provision or a survival-level of water to
specified delivery points throughout the city. People will have to collect their water from those points. Extrapolating from work on the Hutt City distribution network (Zhao et al, 2008) would indicate that a further 6-12 months might be required for full restoration of reticulated water to households.

The current results (Table 3) suggest that there would be an approximate 30-day water deficit if supply from Kaitoke is required, or about 15 days for the proposed Whakatikei source. Neither are tenable, because water is essential for life. Clearly new thinking is required about ways to provide water to Wellington area people post large earthquakes.

8 ACKNOWLEDGEMENTS

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