Restoration of earthquake damaged water distribution systems

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ABSTRACT: This paper reports progress made to date of a research project that investigates the post-earthquake functioning of communities. Our research programme is aimed at minimising post-earthquake disruption and we suggest that the greatest trauma for the survivors in the epicentral area will be due to loss of water, loss of shelter, loss of services and loss of employment caused by damage to structure and infrastructure.

Experience shows that damage to infrastructure can have far-reaching consequences. Loss of potable water, for example, was a major reason for the evacuation of a third of the population from Napier, NZ in 1931. On Rokko Island, Kobe, 1995, there was minimal damage to the mostly high-rise housing blocks but the entire 30,000 population had to be evacuated because the water supply was lost.

Using models for the seismic behaviour of buried pipes and other components, we evaluate the impacts of various sizes of earthquakes on the functioning of a water supply network and the effort and time for various restoration strategies. In this way, we test strategies for reducing the post-earthquake restoration time. A GIS (Geographical Information System) environment is used for the study area, near Wellington, NZ, representing a typical urban water supply system. The methodology to model seismic hazard on a water network could be adapted to hazards other than earthquake and lifelines other than water.

1 INTRODUCTION

Earthquake risk is of concern in New Zealand, especially for the Wellington region. A major earthquake on the Wellington fault could result in considerable direct damage to buildings, business interruption and many deaths and casualties. This is despite the fact that New Zealand is amongst the world leaders in earthquake resistant construction. While inadequate buildings may be the main cause of casualties in earthquakes, damage to infrastructure and loss of functionality can significantly disrupt normal economic and social activity.

We currently have a research project which investigates the post-earthquake functioning of communities. Our research programme is aimed at minimizing post-earthquake disruption. While hundreds of casualties will undoubtedly cause great distress, we suggest that the greatest trauma for the 300,000 or so survivors in the epicentral area of a Wellington Fault earthquake will be due to loss of shelter, loss of water, loss of services and loss of employment caused by damage to structure and infrastructure. Those losses and their restoration are our focus. The part of this project which is of interest to the water industry is presented in this paper.

2 BACKGROUND

There have been many examples of cities damaged by earthquakes where there has been severe
disruption to the water distribution systems. These include San Francisco (1906), Tokyo (1923), Napier (1931), Loma Prieta (1989), Northridge (1994) and Kobe (1995). Visits by investigators to Northridge (Norton et al., 1994) and Kobe (Park et al., 1995, Brunsdon et al., 1995) present reports with relevance for New Zealand conditions.

The impact of loss of functionality of a water system can be great. One use of the water supply is for fire fighting and there are several cases of cities where fire has followed an earthquake causing further damage. Water is also essential for life functions and we cannot live long where it is not available in sufficient quantities. Loss of potable water, for example, was a major reason for the evacuation of a third of the population from Napier in 1931. On Rokko Island, Kobe in 1995, there was minimal damage to the mostly high-rise housing blocks but the entire 30,000 population had to be evacuated because the water supply was lost.

Aspects of the functioning of a water supply have been considered by the Wellington Earthquake Lifelines Group (Brunsdon, 1993). This considered the damage level to the network rather than the detailed recovery process and the time needed to repair it. A Phoenix Civil Defence exercise in New Zealand identified the ability to deliver potable water to the disaster area as one of the three most important critical system weaknesses of our current earthquake response plan. There is talk of a "60-day gap" between the exhaustion of stored water in Wellington after a Wellington fault earthquake and the restoration of even a sustenance supply. Very large numbers of people would need to be evacuated if this is the case.

Rapid recovery of basic water supply function to as many people as possible is desirable. With damaged and leaking pipes this is a problem, because until the bulk supply is functioning, what little water stored in local reservoirs is precious, and needs to be preserved. Automatic shut off valves are becoming common at reservoir outlets. The duration of this loss of service is a critical determinant of the economic and social disruption. Quantitative models of the post-earthquake restoration process, therefore, are important in evaluating the total losses caused by an earthquake. The objective of this study is to develop and demonstrate a model of the post-earthquake water distribution system restoration process.

The model simulates the initial physical damage caused to the pipe network and with an understanding of the repair and recovery operations needed, simulates individual tasks to provide estimates of time and cost to achieve the restoration of the system. Using the model, we can evaluate the impacts of various sizes of earthquake on the functioning of a water supply network and the effort and time for various restoration strategies. Our aim is to model the performance of a damaged infrastructure network, and then to use the model to test ways of reducing the post-earthquake restoration time.

A large volume of data is needed for the computations in the simulation. A digital computer is essential to perform this and because of the spatial nature of a water distribution network, a Geographic Information System (GIS) is best suited to manage the data.

We use an area in the Wellington region for the case studies primarily because seismic risk there is greater than anywhere else in New Zealand (Davenport, 1998). The methodology used for the Wellington area will, however, be applicable anywhere in New Zealand. While the models are for a seismic hazard and a water distribution network, the methodology could be adapted to other hazards and other lifelines.

3 SEISMIC HAZARD

Natural hazards are the physical phenomenon associated with events of nature which may produce adverse effects on human activities. Earthquake events are basically the fracture of brittle rock when it is under stress. The stress is due to strain of deformation movement within the Earth's crust and this tends to be more concentrated at the boundaries of tectonic plates. The principal physical manifestation of the earthquake is the shock wave that travels away from the rupture zone and is felt as shaking of the ground. It may also cause other effects. The widespread ground shaking causes strains within the soil mass and accelerations of objects above the surface which may damage pipes, buildings and other items.
The ground shaking may also cause ground movement due to liquefaction, lateral spreading, landslide and fault offset resulting in permanent ground deformation (PGD). This would generally be localized.

Liquefaction is a phenomenon which occurs in loose, saturated, granular soils when subjected to long duration, strong shaking. Silts and sands tend to compact and settle under such conditions. If these soils are saturated, as they compact and settle, they displace pore water which is forced upwards. Increased pore water pressure causes two effects. First, it quickly creates a condition where the bearing pressure of the soils is temporarily reduced. Second, if the generated pressures become large enough, material can be ejected from the ground to form characteristic sand boils on the surface. The displaced material, in turn, causes further settlement of the site.

Lateral spreading is a phenomenon which can accompany liquefaction. Many sites have layers of liquefiable materials located some distance below the ground surface. If the site has a significant slope, or is adjacent to an open cut such as a depressed stream bed or road, liquefaction can cause the upper soil layers to flow down the slope or towards the cut. Lateral spreading can be highly disruptive of buried structures and pipelines, as well as structures supported on the site.

The liquefaction hazard along a specific pipeline route is evaluated with site-specific analyses as liquefaction usually occurs in certain types of soil. The liquefaction analysis should provide an estimate of the probability that a specific site will liquefy and, if it does, the amount of permanent ground deformation expected at the site. Ground movement can be either vertical (settlement) or horizontal (lateral spread) or a combination of the two. Severe pipe breaks can occur in areas of liquefaction-induced lateral spreading. The orientation of the pipeline relative to the ground movement can affect the amount of damage.

Landslides are permanent deformation of the soil mass, producing localized, severe damage to buried pipe. More landslides will occur if the earthquake occurs during the wet season. Landslide hazards encompass several distinct types: deep-seated landslides, debris flows and avalanche/rock falls. These different types can affect water distribution systems in different ways. Buried pipelines are mostly affected by deep-seated rotational and translational landslides, while debris flow and avalanches mostly affect above-surface items such as tanks and buildings. While some landslides may be small and displace the soil by a small amount, others can be very large, displacing the soil by a large distance, and cause damage to many pipes in an area. As with liquefaction, a landslide hazard analysis should provide an estimate of the probability that a specific site will move and, if it does, the amount of permanent ground deformation expected at the site.

Surface displacement can occur when an earthquake fault rupture reaches the ground surface. This is a consideration when there are known faults in the area. Models are available to estimate the amount of surface displacement, usually the maximum somewhere along the fault. Fault offset will vary along the fault from zero to the maximum. Damage to pipes can be severe when crossing surface ruptured faults. Some pipe types may be better able to withstand the displacement.

3.1 Hazard Measures

As with volcanic eruptions, floods and droughts, earthquakes also occur randomly. They can only be observed directly as they happen, or be inferred from evidence remaining afterwards. Analysis of historical measurements of earthquakes and their effects is therefore vitally important.

Ground shaking is measured by earthquake recorders present and functioning when the earthquake occurs. These provide time history records of the transient ground movement and from that can be derived the peak ground acceleration (PGA), peak ground velocity (PGV), or response spectra (RS) at the site of the recording instrument. Generally the horizontal component of motion is more relevant. The vertical component is often not critical for structures that usually resist gravity loads. The ground movement due to liquefaction, lateral spreading, landslide and fault offset is best quantified by the amount of permanent ground deformation (PGD).

While it is desirable to have a physical measurement of ground shaking and ground displacement, there are limited numbers of earthquake recording instruments out in the field, so the recordings from them are only available at widely spread locations. Also before the advent of recording instruments,
the only information available was descriptive observations of the damage sustained which were used to
determine a felt intensity measure. The most commonly used felt intensity scale used around the
world and in New Zealand is the Modified Mercalli Intensity (MMI) as described by Dowrick (1996).

Seismic hazard levels at locations near the earthquake source are typically higher than the hazard at
locations more distant, but uncertainty in ground motions and local soil conditions can change this
trend. As a water distribution system may cover a considerable area, at different parts of the system
there can be a wide variation of shaking effects during an earthquake. The variation of hazard level
with location is expressed by an attenuation model. Such models have been developed for New
Zealand considering parameters including earthquake source magnitude, depth, mechanism type, and
site ground conditions. Given an earthquake source and its parameters, and a site location, attenuation
models can be used to estimate the felt intensity (MMI) or ground shaking parameters (PGA, PGV,
and RS). These provide the mean motions together with an estimate of the variability.

As a measure of hazard, for above ground items (such as buildings) PGA and RS are commonly used,
while for below ground items (such as pipelines) PGV is used. If detailed spatial distributions of these
are not available, a felt intensity measure, such as MMI, would be appropriate as this is based on
observed damage. In the case study presented, MMI is used as the hazard measure.

3.2 Hazard Models

The two broad approaches used for seismic hazard modelling are the deterministic and probabilistic
methods. The probabilistic method considers all possible seismic sources and then estimates the
individual annual probability that each source could cause a certain level of effect at a specific
location. These individual probabilities are aggregated to estimate the total annual probability of
occurrence of that level of impact at that location. The process is repeated for each level of effect and
for each location that is of interest. The results are often specified as the inverse i.e a hazard level for a
given annual probability of occurrence. This is also often expressed as a return period, typically in the
range of 50 to 2500 years.

The result is a consistent measure of the seismic hazard at individual locations, and is used, for
example in the loading code to provide a uniform measure of hazard. The seismic hazard will vary
with location and when comparing the seismic hazard levels at two locations for the same return
period, it should be noted that these levels of hazard are not likely to occur at both locations
simultaneously.

In contrast, the deterministic method utilizes a scenario earthquake and estimates the impact of this at
many locations. The scenario earthquake may be one related to a specific seismic source, such as a
known fault. In this case, for two different locations, the seismic hazard levels are consistent in that
they would occur simultaneously. To avoid sensitivity of the performance of a system to a single
chosen earthquake, several different scenario events could be selected.

The scenario approach seems more suitable to gauge the overall seismic impact on a geographically
spread out water distribution system. For a single location or compact system, the probabilistic method
would be more appropriate.

For the Wellington region, it is found that the Wellington Fault dominates the seismic hazard for
return periods greater than 400 years. It the case study, the scenario approach is used, although the
methodology would allow either approach.

4 WATER DISTRIBUTION NETWORK INVENTORY

Data about the components of the water distribution network is a key requirement of the modelling
process. For a water distribution network, the components modelled in this study are the pipes to
convey the flow, the valves to control the flow, the fire hydrants to access the water and the tanks or
reservoirs to store and supply the water.

Distribution pipe refers to buried pipe which carries water to customers and fire hydrants. There can
be a large amount of this pipe spread over a large area and it is not a trivial task to collect the data. Also there can also be a wide variety of pipe materials, sizes and ground conditions. The interaction of the pipes in the network can be complex. The location and characteristics of all such components should be captured and a Geographic Information System (GIS) is a good tool to achieve this. The use of a GIS for input and output of data allows rapid visualization of the network.

The information needed for seismic evaluation of water distribution pipe includes the pipe material, type of jointing system, size, age and condition, ground conditions, type of bedding or encasement, depth of burial and leak history.

Some of these attributes will yield some extra information on the pipeline's vulnerability but may not be available for all cases. For example, the material used to construct the pipelines might not be known with certainty unless original pipeline construction drawings are available. Since pipeline performance is likely to be a function of the material used in construction, use of the model might assume "average" quality construction and a vulnerability representative of "average" quality materials when these are not otherwise known. If a rough description of the inventory is collected, then only a rough estimate of the performance of how the water system will perform in an earthquake will be possible. The uncertainty in the analysis results will increase, but this may be satisfactory if the model is only trying to estimate a rough "first-cut" type of evaluation.

Service connections to customers have been ignored at this stage as they are generally small. Also, as they can be numerous, it can require much effort to collect the data. Other components such as pumps, also found in water distribution systems, have yet to be included in the models.

Collection of the inventory data will most likely be the most time consuming activity of the modelling process. For the case study, a preliminary GIS database for Lower Hutt has been utilized. This has been augmented with assumed data when fine detail is not known in the first instance. The intention is to get an overview.

5 SEISMIC VULNERABILITY

Knowing the hazard level and the nature of the components subjected to this hazard, we want to estimate how they respond to that hazard and what damage they might suffer. This will provide a starting point for modelling the restoration process. It will be appreciated that different components respond in different ways to the same level of hazard and also that one type of component can respond in different ways to different levels of hazard.

A damage function for buried pipe is usually expressed as a repair rate, as a function of ground shaking or ground failure (permanent ground deformation). Development of damage functions is primarily based on empirical evidence from data collected after an earthquake; what length of buried pipe experienced what level of hazard; and how many pipes were damaged (broken or leaking) at that level of hazard. This empirical evidence is tempered with engineering judgment and sometimes by analytical formulations.

Much of the early empirical evidence relating to water distribution networks is for cast iron pipe, the most prevalent material in use in cities damaged in earthquakes (Eidinger et al., 2001). More recent earthquakes have given damage data for more modern pipe materials, including asbestos cement, ductile iron and welded steel pipe (Jeon & O'Rourke, 2005). Other parameters relevant to pipe damage are pipe size, age and condition, ground conditions, and bedding type. A complete empirical database for all pipe materials under all levels of shaking does not yet exist, so there remains some uncertainty.

Most empirical evidence shows pipe fragility in terms of repair rate per unit length of pipe exposed to the hazard. A pipe repair can be either due to a complete fracture of the pipe, a leak in the pipe or damage to an appurtenance of the pipe. In any case, the damage requires a repair in the field. Repair records and reports are commonly produced but may be sketchy on details. The main objective of the field crew is to restore water as rapidly as possible and, understandably, documenting damage is of secondary importance.
It would be useful to know the degree of damage to assess the priority for a repair. For purposes of system-wide hydraulic analysis, it would be useful to differentiate whether the repair was a "small leak" or a "major failure." A small pipe leak allows continued system operation and thus has relatively low repair priority, while a major failure of a pipe requires the local system to be shut down and no water can flow. This would merit a higher repair priority.

Vulnerability functions relate overall pipe damage measures to intensity descriptions. Two separate mechanisms that cause pipe damage are considered and require different intensity measures. These are seismic ground shaking (or wave passage) and earthquake induced ground failure (permanent ground displacement).

Wave passage effects are transient vibratory soil deformations caused by seismic waves generated during an earthquake. Wave passage effects cover a wide geographic area and affect pipes in all types of soil. Strains are induced in buried pipe because of restraint within the soil mass. In theory, for vertically propagating shear waves, peak ground strain is directly proportional to peak ground velocity (PGV) and thus PGV is a natural intensity measure for this.

Ground failure effects are permanent soil movements caused by such phenomena as liquefaction, landslides and fault movements. These ground movements tend to be fairly localized in a geographical area and potential zones can be identified a priori by the specific geotechnical conditions. Ground failure can be very damaging to buried pipe because potentially large, localized deformations can cause pipe segments embedded within the soil to fracture or pull out of place. Permanent ground displacement (PGD) is commonly used here as the intensity measure.

The modelling process requires that a vulnerability function be assigned to each component in the distribution system. For the case study, the hazard intensity measure used is MMI and thus an appropriate vulnerability function is of the form proposed by Cousins (2004), based on Californian experience as given by ATC-13 (Rojahn & Sharpe, 1985) and adapted for New Zealand conditions. This gives the expected repair rate per kilometre for several pipe vulnerability classes, several ground classes and an intensity measure of MMI. The model could utilize other vulnerability and intensity measures.

6 SIMULATION OF DAMAGE SCENARIOS AND RESTORATION

The basic goal of the modelling approach is to assess the functionality of a lifeline system versus time as the restoration proceeds. It is desirable for a restoration model to:

- Model the real-life restoration process explicitly.
- Include strategy decisions so their effects on the speed of restoration can be assessed. Possible decisions might involve the number of repair crews, spare parts and materials inventory, priority rules, and mitigation measures.
- Represent the uncertainty in the restoration process.
- Require only available data.

The methodology used here is a discrete simulation approach which utilizes a "queue" system for tasks to be performed and a set of "servers" to carry out the tasks as resources become available. The model first estimates the initial physical damage state of the water distribution network and then proceeds with tasks determined by a restoration strategy. This requires that the damage state of the network can be updated as the restoration proceeds.

An initial damage state is generated for the simulation. This uses the assessed hazard level at the location of each component pipe, and assigns damage to the individual pipes on a probabilistic basis using the vulnerability function and the network properties. By using a probabilistic distribution of damage, when the simulation is run again, a different initial damage state will be produced. It is not suggested that the scenarios are predictions of what will happen but they are predictions of what might happen. This procedure allows for uncertainty in the initial damage state.
Simulation of the restoration tasks proceeds after the earthquake event. The restoration involves an initial inspection and damage assessment. Any damaged pipes that are located are scheduled for repair by adding them to a queue of repair work.

As water is required before pipes can be checked for leaks, inspection can only proceed from a storage reservoir as a supply point and follow along currently functioning pipes. A point may be reached that further inspections cannot proceed until a repair is affected and water made available for flow and pressure testing. In such cases, the repair of the pipe break blocking further inspection may be given higher priority. Other reasons for high priority repairs are that the damaged pipe is critical for large sections of the network and there is a benefit in doing this repair ahead of others. The model attaches an "importance" parameter to each pipe to gauge what priority any repair to it should have.

The queue of repair work is serviced by repair crews. As a repair crew becomes available for work, they take the next item of repair work on the queue. This could be one classed as high priority. Time to travel to the sites can be simulated as well as additional delays due to damage to roads and bridges. Specific repairs may be delayed because specialist repair crews, plant or materials are not available.

The discrete simulation technique recognizes the real-world operations to be performed. It is important that all necessary work tasks are considered and appropriate costs and times are allowed for each task. The outcome is to simulate the time and cost to perform each repair. These are tracked, in time and space as the restoration proceeds, to generate a simulated history of the system being restored indicating how the functionality of the water distribution system changes with time.

### 7 DISCUSSION

To plan and manage the restoration of any damaged system, an understanding of what damage has occurred is needed. It is important to remember that we will not know precisely what damage occurs until the earthquake happens. When carrying out the simulation process, the initial damaged state is just one scenario out of many that are possible. The simulation process will allow the time and costs for restoration of that damage state to be assessed.

With this simulation method, the results of the restoration process depend not only on the current damage state, but also on the available inspection and repair resources. Hence the effects of resource constraints can be considered. Simulation will allow prior assessment of how best to respond with different strategies. One possible decision is how many repair crews to utilize. If there are too few, the restoration process will take a long time to complete, while if there are too many, there may be times when some are waiting for inspections to identify damaged pipes. Simulation will allow such questions to be addressed. The spare parts and material inventory to hold, or have accessible nearby, could also be assessed. By using the simulation to identify critical sections of the pipe network, higher priority can be assigned to these areas for both inspection and repair. The results of these decision studies can be incorporated in response plans.

Multiple scenarios allow the assessment of the most vulnerable areas by giving a statistical overview of damage patterns. Individual pipes more likely to impact system reliability can be identified and mitigation measures, such as upgrade of a pipeline, planned. The simulation process will allow a "before" and "after" assessment of the mitigation work. This can result in achieving a more robust and resilient water distribution system which in turn will reduce the restoration time after an earthquake.

The development of the simulation model is an on-going project requiring further development. Currently the basic damage and network simulation processes are functioning with some real-world data available to calibrate and test the model. More specific results and conclusions derived will be presented at a later date.

### 8 CONCLUSIONS

Earthquake damage to water distribution systems can be very disruptive with the loss of functionality having significant impact on normal economic and social activity. Rapid restoration after an earthquake is desirable.
The simulation model proposed can provide estimates of the time and cost to restore the functionality of the water distribution network. In turn, this information can be used to estimate the economic and social impact of the earthquake and help assess the resilience of the water distribution system.

In addition, by explicitly representing the tasks performed during restoration, the model can be used to help identify ways to improve processes after earthquakes. Sensitivity analyses can be conducted to explore the relative effect of the decision variables on the restoration curve. This can be done without the pressures of having to learn what to do during a real event with limited information and under adverse conditions. The system operator can experiment with the model and try out the effects of doing things in a different way without the consequences of wrong decisions during a real event.

While the simulation based model of post-earthquake restoration of a water distribution network has been described, the approach is generally applicable to modelling the post-disaster restoration process for other lifeline systems and other hazards. This is because of the explicit representation of the decision variables and the ability to follow the work sequences in space and time. Interaction effects of several lifeline systems, such as water networks and road networks, could also be modelled.

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REFERENCES:


