Earthquake damage in wastewater systems and post-earthquake repair methods; limitation and practice

M. R. Zare[1,] S. Wilkinson[2], R. Potangaroa[3]

1. PhD candidate, University of Auckland, Auckland, New Zealand, Email: mzar004@aucklanduni.ac.nz

2. Associate Professor, University of Auckland, Auckland, New Zealand, Email: s.wilkinson@auckland.ac.nz

3. Associate professor, UNITECH, Auckland, New Zealand, rpotangaroa@unitec.ac.nz

Keyword: seismic, damage, wastewater system, sewer repair

Abstract:

The 2010 earthquakes in Christchurch caused significant damage to the wastewater reticulation of Christchurch city and the Waimakariri district. The 2010 Darfield earthquake caused severe damage to each components of the Christchurch wastewater system i.e. treatment plant, pumping stations and pipelines, however, the wastewater pipeline network in Christchurch was severely damaged compared with two other components. Various methods of repair can be applied for post-earthquake restoration of damaged wastewater reticulation. Open-cut and trenchless methods, as two broad types of repair methods, can be applied to repair defects in wastewater pipelines. In spite of the notable advantage of trenchless techniques in normal rehabilitation and repair plans, application of some trenchless methods after an earthquake cannot add more advantages compared with open-cut methods in some urban areas.

Christchurch wastewater system

Christchurch is the largest city in the South Island, and also is the second largest city in New Zealand. Christchurch City is located in the east of the South Island, and the territorial authority area is bounded by the Pacific Ocean, and the estuary of the Avon and Heathcote rivers in the east. The Christchurch wastewater reticulation system collects and treats the wastewater created by 150,000 households. The Christchurch wastewater system comprises treatment plants, pumping stations and wastewater reticulation. The main wastewater treatment plant in Broomly, plus 5 other small treatment plants treat collect the wastewater. Wastewater is collected and transferred by 1,600km of sewer mains and 950 km of laterals in Christchurch city (CCC 2005). Furthermore, 91 wastewater pumping stations continuously transfer collected wastewater to the wastewater treatment plants (CHC 2010).

The Christchurch wastewater reticulation comprises of 30 types of pipes, although only some types of pipes are predominant in the Christchurch wastewater system. The wastewater pipelines in the Christchurch wastewater system can be mainly divided into concrete, earthenware, UPVC and asbestos pipes, each of which comprises 32.9%, 20.1%, 17.5% and

9.6 % of the total length of sewers in Christchurch, respectively. Wastewater pipe diameters vary from 65mm to 2000mm in the Christchurch wastewater reticulation. The 150mm pipes are the predominant type of pipes in the Christchurch wastewater reticulation that comprise 56.2 % of the length of the wastewater reticulation.

The 2010 Darfield earthquake effects on the Christchurch wastewater system

Christchurch city was affected by the magnitude 7.1 earthquake on 4 September, 2010. The epicentre of the earthquake was near Darfield town, 40 km west of Christchurch city. The 2010 Christchurch earthquake caused damage in each component of wastewater reticulations in Christchurch city and Waimakariri district including treatment plants, pumping stations and pipe networks. The wastewater system in Christchurch was severely affected compared with other infrastructures (Gordon 2010). The Darfield earthquake effects on the Christchurch wastewater system can be divided into direct and indirect effects. Direct effects of the earthquake on the Christchurch wastewater system can be classified into failure of the sanitary network in some residential and business areas and also damage to sewers, manholes, pumping stations, treatment plants, roads, and pavements. On the other hand, public health issues, tap water pollution, stream pollution, underground water pollution, soil pollution and increasing treatment costs are indirect effects of the wastewater system failure. In this paper only direct damages from the Darfield earthquake on each component of the Christchurch wastewater system will be briefly discussed.

The Darfield earthquake damage to the Christchurch wastewater treatment plant

The Christchurch WWTP (also called the Bromley WWTP) is located about 6.5 km east of the Christchurch CBD in Bromley and south of Bexley region. The oxidation ponds in the Christchurch WWTP are the tertiary, and the final, treatment process which prepare the treated effluent to be safely discharged into the estuary of the Avon River and Heathcote River. After passing through the clarifiers and ponds 1, 2A and 2B, the treated effluent is transferred into the Pond 3 via the underground concrete pipes (the left photo in Figure 1). Dyers Road along State Highway 74 passes through the oxidation pond area in the Bromley WWTP, and works as a stop bank. The bypass concrete pipeline is constructed between the effluent pumping stations, located after the clarifiers, and the Pond 4. The bypass pipeline directly transfers extra effluent to Pond 4 without passing through the previous ponds.

Figure 1: Christchurch wastewater treatment plant ponds location and damage (Google map)

Significant earthquake induced damage in the Bromley WWTP can be divided into damage to the ponds, connection pipelines and pipeline inside the pond area. The 2010 earthquake significantly affected the pipes installed within the pond area; especially the connecting pipes between Ponds 2 and 3, and also the bypass pipeline in Pond 1. The earthquake severely damaged the under-road 900 mm concrete pipes which connect the treatment ponds on both sides of the State Highway between Pond 2 and Pond 3. Joint separations and pipe crushing in joints and body were the main types of damage in the pipes underneath of State highway 74. The pipes failure created some significant sink holes in the main road and forced Highway 74 to be closed for two weeks. Failure of the bypass pipeline is another significant pipe failure in the pond area. The joint separation and misalignment (horizontally and vertically) were the main types of failure in the concrete bypass pipes.

Further significant damage caused by the 2010 earthquake to the Christchurch WWTP was pond damage. After the earthquake, some stop banks slumped to the ponds or outside the ponds, and caused severe cracks in some particular regions including State Highway 74, stop bank between the ponds 3 and 6, stop bank shared by the ponds 4 and 5 and stop bank between the Pond 1 and 2. The earthquake induced damage between Ponds 3 and 6 and also damage in ponds 4 and 5 were serious because of the significant difference in water levels in both sides of the shared stop banks. The right photo in Figure 1 shows the main damaged regions (lines 1 and 2) and also installed sheet piles which were installed to protect the severely damaged stop bank (line 3). After the earthquake, in order to decrease risk of dike failure and also protect of the downstream ponds, first, the water level in the Ponds 3 and 4 was decreased, and then two series of sheet piles of 250 and 170 meter in length were installed in the shared dikes 3-6 and 4-5, respectively. Some minor cracks were also seen near the recently constructed pumping stations underneath Pond 6 and also stop banks of Pond 2. On top of the direct damage in the ponds, power outage after the 2010 Darfield earthquake affected the wastewater treatment plant. For instance, on the second day after the earthquake, the Christchurch WWTP came to service again (Gordon 2010).

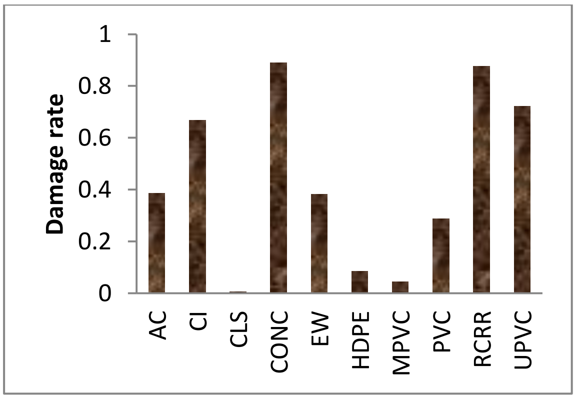
The Darfield earthquake damage to the Christchurch wastewater pumping stations

The Christchurch wastewater system comprises 123 wastewater pumping stations (WWPS) which house 239 pumps (Christchurch City Council 2010). According to the Christchurch GIS database, 39 % of all the WWPSs in Christchurch had been built before 1976, and 15.4 % have been built after 2004. The WWPSs in Christchurch were affected in two ways by the 4 September 2010 earthquake, i.e. complete failures due to failure of underground structure and temporary failures because of power outage. Approximately 90 % of all WWPSs in Christchurch suffered temporary failures, and only few pumping stations failed completely. The power outage after the 2010 Darfield earthquake affected the rest of the WWPSs, except 10 % which had emergency power generators. At least two WWPSs were uplifted and failed near the Avon River in Christchurch. Inspection of the damaged WWPSs indicated that the severity of damage in the WWPSs, especially in underground structures, increased as the distance from their location to the riverside decreased. Soil liquefaction was the main cause of damage in WWPSs near the riversides.

The Darfield earthquake effects on the Christchurch wastewater reticulation

The 4 September, 2010 Darfield earthquake caused significant damage to the Christchurch wastewater pipelines. In the context of the sewer damage in the Christchurch wastewater reticulation, 1273 repair points were reported to the Christchurch city council by 20 October 2010 (about 7 weeks after the earthquake). The Darfield earthquake caused severe damage to almost every type of pipe including the main and connection pipes in terms of pipe material, pipe diameter, pipe depth and pipe age. The most damaged pipes in the Christchurch wastewater network in terms of the pipe material are the reinforced concrete with rubber ring joint (RCRR), the unplasticized poly vinyl chloride (UPVC), the earthen ware (EW), the concrete (CONC) and the asbestos (AC) pipes shown in the left graph on Figure 2. Damage rate is defined as number of defects in unit length of pipelines. The GIS data base of the damaged wastewater reticulation is used to calculate damage rate. Damage rate in each type of pipes is calculated by total length of each type of pipes in terms of material, diameters, pipe age and etc. divided by number of defects in that particular type of pipe. Damage rates in concrete and reinforced concrete pipes are significant and the damage rate is approximately about 0.9 per unit length of each type of pipe. High damage rate in concrete pipes shows the pipes were probably affected by corrosion in the Christchurch wastewater reticulation. If the damage rate in each pipe diameter is observed, the 150 and 225mm diameter pipes show the highest damage rate in the Christchurch wastewater reticulation with damage rates of 1.3 and 0.42, respectively.

GIS data base in Christchurch shows approximately 69% of the Christchurch wastewater reticulation has been developed since 1950, that 31% of the sewers in Christchurch had been installed before 1950. Furthermore, about 46 % of the sewers in Christchurch were installed more than 50 years ago. Comparison of the earthquake damage in sewers installed in different decades shows sewers built between 1960 and 1970 were reported to suffer the maximum amount of damage after the earthquake, however, the maximum damage rate belongs to sewers installed between 1940 and 1950. The right graph in Figure 2 indicates that the Christchurch sewers constructed between 1920-1930, 1950- 1970 and 1980-1990 suffered severe damages after the 2010 Darfield earthquake.



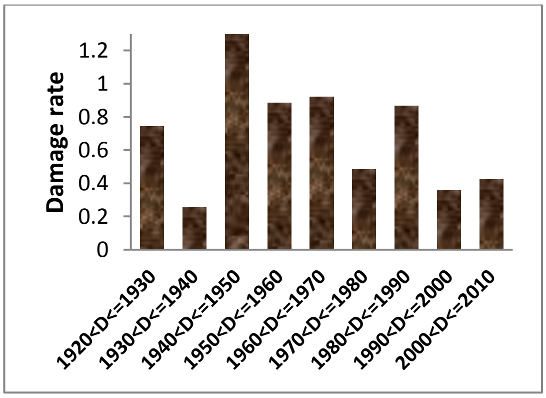


Figure 2: Distribution of damage in the Christchurch WW network

Repair methods in restoration of damaged wastewater pipelines after the earthquake

The restoration process of damaged wastewater pipelines after an earthquake can be divided into the following three stages: emergent investigation and countermeasures, temporary investigation and recovery, and formal investigation and restoration as the final stage (Tsan-Hui 2001). In this paper damage detection and common repair methods as two main steps of restoration plan are taken into consideration. Detecting earthquake induced damage is the initial and critical step for restoration of wastewater pipelines network. Detecting earthquake induced damage in wastewater reticulation comprises two main steps i.e. on ground inspection and underground inspection. Above ground inspection comprises all activities used to detect damages without application of any instrument. For instance, damage in wastewater pipelines can be detected indirectly by visual inspection such as damage on road pavement on top of wastewater pipelines, uplift or settlement of manholes or alongside of buried pipelines, water invasion, wastewater collecting in manhole and overflowing wastewater from manholes.

Visual inspection in wastewater pipelines can only be used to directly detect a very small portion of earthquake induced damage. As a result, underground inspection inside wastewater pipelines is essential to detect all earthquake induced damage and also type of defects in pipes. There are various types of sewer inspection method to overcome the deficiency of different methods, although close circuit camera (CCTV) is broadly applied to detect damage in buried pipelines. CCTV inspection is based on accessibility, as a result when a camera cannot pass through the pipes or part of pipeline, it will not able to be used. For instance, in heavily damaged pipelines or blocked pipes, where the wheeled platform cannot be moved, this method cannot be applied. On the other hand, accuracy of the CCTV inspection method is based on the systems inherent restriction and offline defect recognition. For instance, lighting system, accuracy of the CCTV camera and acquired images, in some situations such as under the effluent, are inherent system restrictions. Human error in the defect analysing process is another problem in the CCTV inspection method. CCTV inspection methods are usually slow and expensive methods, especially when the system is used for inspection of pipelines with many defects because in each defect the operator must stop, assess and record the condition (Duran, Althoefer et al. 2002). Regardless of some deficiency of the CCTV inspection method, this method was the major type of underground inspection in sewers after the 2010 Darfield earthquake.

Wastewater pipelines restoration methods can be divided into two main methods i.e. open-cut and trenchless methods. In open-cut methods, after excavation of a trench, the damaged pipe will be exposed and then the repair, replacement or rehabilitation process will be performed. The excavated soil will be replaced with the designed backfill material accompanied by appropriate compaction, after repair completion. It should be noted that cost of backfilling, compacting, reinstatement of the ground and pavement in some cases can be 70 % of the project costs.

Open-cut methods have been applied all around the world for installing new pipes and also repairing and rehabilitating damaged pipes. Soil excavation is the initial and main operation in open-cut methods, and depending on underground conditions, different excavation methods can be applied. Trench excavations in open-cut methods can be categorised as excavation below and above the groundwater level.

Excavation nearby other buried infrastructures is one of the main problems in open-cut methods, other than the technical difficulty of excavation, especially in regions with high ground water level and in densely populated urban areas. Before excavation, especially in urban areas, the nearby buried infrastructure and pipe characteristics should be derived from available utilities map. In cases where there is no available map, or available maps are not accurate enough for the excavation operation, detection equipment should be used to detect any buried infrastructures such as water and gas pipe, power cables, communication cables, etc.

Applying open-cut methods in regions with a high level of groundwater and loose soil is much more difficult and expensive than open-cut methods in dry and stable soil. Many cities in New Zealand are located in the vicinity of sea or river basins. As a result, trench excavation is done in usually soft soil with very high groundwater levels in these regions. Accordingly, open-cut methods used for excavation below the groundwater level are quite popular in New Zealand. Two common methods are usually used for under groundwater excavation in New Zealand. In the first method sheet piles are used to confine and stabilize repair sites, in the second method adjustable steel boxes are used to stabilize repair sites. The significant and most costly parts of excavation in earthquake affected areas with loose sand and a high groundwater level are drainage and stabilization of the excavated trench. Drainage rods are mainly used for dewatering of trenches located in regions with low ground water level in New Zealand.

The second category of wastewater pipelines repair and rehabilitation methods are based on trenchless techniques. Unlike conventional open-cut methods, trenchless based rehabilitation and repair methods do not need excavation of the surrounding soil for rehabilitation and repair of damaged buried pipes. However, some trenchless methods require access pits that should be excavated in particular places for installation of the required machineries. Application of conventional open-cut methods in urban areas, especially in populated areas, can cause significant effects on nearby residential and business regions. For instance, increasing route and time is a common issue in the rehabilitation or repair process of buried pipes in urban areas.

The number of heavy vehicles and machineries used in open-cut methods is larger than in trenchless methods, and application of heavy vehicles and machineries produces significant noise and dust pollution in excavation areas. Excavation in open-cut methods is generally complicated and time consuming because of the high density of other buried facilities on top or in vicinity of wastewater pipelines, including power, telephone, data lines and private television cables as well as water and gas pipelines. Excavation in regions with several underground facilities is not only expensive and time consuming but can also damage or interrupt other facility operations. In terms of safety, the working environment is much safer than in open-cut methods because significantly less excavation and open areas are required in trenchless methods. Removing spoil and damage to the pavement are other disadvantages of open-cut methods, in addition to high costs. For instance, in some open-cut projects, backfilling, compaction and reinstatement of the ground and the pavement makes 70% of the project costs, and life expectancy of the pavement after excavation decreases by up to 60% (Najafi 2005). Finally, in terms of aesthetics, trenchless technology is preferable to open-cut methods, particularly in tourist attraction areas.

Advantage and disadvantages of trenchless techniques in sewer rehabilitation after an earthquake

Application of each trenchless method not only has its own restrictions in terms of technical feasibilities but it can also be affected by seismic induced conditions which restrict application of some trenchless methods. Earthquakes can damage almost each type of wastewater pipeline in different ways. Different types of earthquake induced damage can directly affect selection of trenchless methods used in wastewater pipe repair and pipe rehabilitation. Earthquake induced defects in wastewater pipelines can be divided into direct and indirect damage. Direct damage in wastewater pipelines is defined as earthquake damage in body or joints of pipes in main or connection lines and indirect damage can be defined as damage to other components of the wastewater system, which indirectly affects the wastewater pipe function. For instance, seismic damage to connection points of wastewater pipelines to pumping stations, manholes and treatment plant cause different types of seismic damage. Indirect damage in wastewater pipelines cause restriction to use of trenchless methods after an earthquake.

Less excavation and minimum damage to the pavement and adjacent facilities are significant advantages of trenchless methods compared with conventional open-cut methods. In case of a strong earthquake, street and road pavements can be ruptured and severely damaged. As a result, when pavements are damaged by an earthquake, application of trenchless methods does not make a significant advantage compared with open-cut methods, in terms of reduced damage to pavement. Less disturbance of the traffic flow and less pollution are advantages of trenchless methods in normal condition, which, again, in regions severely affected by an earthquake, cannot be considered as advantages of trenchless methods.

The repair time in open-cut methods is usually less than in trenchless methods, especially for pipes buried in low depths. Consequently, after an earthquake, open-cut methods are more attractive compared with trenchless methods in term of repair time. Furthermore, there are some restrictions in the application of trenchless methods when the available equipment and machineries cannot satisfy the required needs. Trenchless equipment is usually expensive, and designed for specific application in a particular trenchless method. Furthermore, trenchless equipment for a particular method cannot be used for other trenchless methods, in contrast with popular construction machineries which can be used in all common open-cut methods.

This research notices that earthquake induced damage in buried pipes can be divided in two groups, i.e. damage only in the pipe body or joint without causing any change in pipe alignment and elevation, and damage causing change in the pipe alignment and elevation. In the first group, buried pipes are affected by earthquake forces such as compression, tension and torsion, but the pipe alignment and the pipe elevation in the affected points did not change. In the second group of earthquake induced damage, earthquake forces disturb the pipe alignment and the pipe elevation beside some damage in body of pipes. Both open-cut and trenchless techniques can be applied to repair the first type of damage, but, open-cut method can be the only applicable method in the second type of damage, especially when elevations in both sides severely change after an earthquake. Open-cut methods can also be the best method of repair in indirect damages caused by an earthquake such as damage occurred in connection of manholes or pumping stations to main pipelines or connections.

Conclusion:

Each component of a wastewater reticulation system can be severely damaged in earthquake prone zones. Earthquakes can directly and indirectly damage each component of wastewater reticulation and also affect communities unfavourably. In spite of the fact that buildings and mechanical equipment of wastewater treatment plants can tolerate seismic forces, other components of the treatment plant can suffer damage severely and affect the function of an undamaged treatment plant. Furthermore, failure of other infrastructure facilities, especially the power network, can adversely affect the function of a WWTP or WWPS. WWPSs not only can be severely affected by power outage but they can also completely fail, especially when located in loose sand soil with high groundwater table (such as riversides).

Wastewater pipelines can be severely affected by seismic forces according to type and location of wastewater pipelines. Concrete based pipes installed in the Christchurch wastewater reticulation were severely damaged after an earthquake mostly because of liquefaction (permanent ground displacement) and also wave propagation effects. This fact shows that rehabilitation or replacement of concrete based sewers with much more flexible pipes and adequate joint types should be one of the first priorities for wastewater rehabilitation of populated cities located in earthquake prone zones. On the other hand, the cost of repair and restoration can be significantly more than repair cost of seismic damage in other infrastructures such as water pipelines. Furthermore, intensive post-earthquake inspection is required to detect all sort of damage in wastewater pipelines within earthquake affected zones. Post-earthquake inspection should comprise various methods to detect all type of earthquake induced defects in wastewater pipelines. In spite of several advantages of trenchless techniques compared with open-cut methods in normal repair of wastewater pipelines, application of some trenchless methods can be restricted for post-earthquake restoration of damaged pipes especially in initial phase of repair.

Acknowledgment:

Christchurch City Council, Waimakariri District Council, GNS and Becca are gratefully acknowledged due to their supports during site visiting after the 2010 and 2011 earthquakes in Christchurch and also their provided data.

References:

CCC (2005). Water & Sanitary services assessment. Christchurch, Christchurch city council.

CHC. (2010). "Wastewater collection." from http://www.ccc.govt.nz/homeliving/wastewater/wastewatercollection/index.aspx.

Christchurch City Council. (2010). "Facts and figures ", from http://www.ccc.govt.nz/homeliving/wastewater/wastewatercollection/factsandfigures.aspx.

Duran, O., K. Althoefer, et al. (2002). "State of the art in sensor technologies for sewer inspection." IEEE Sensors Journal **2**(2): 73-81.

Gordon, M. (2010). Canterbury earthquake 4 September 2010 lifelines coordination and infrastructure recovery. Christchurch, lifelines Co-ordinator.

Najafi, M. (2005). Trenchless technology, pipeline and utility design, construction and renewal, McGrow-Hill.

Tsan-Hui, H. (2001). "Guideline and procedure for post earthquake safety evaluation and retrofitting of underground lifeline system." Earthquake Engineering and Engineering Seismology **3**(1): 8.