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All papers submitted to COBRA were subjected to a double-blind (peer review) refereeing process. Referees were drawn from an expert panel, representing respected academics from the construction and building research community. The conference organisers wish to extend their appreciation to the following members of the panel for their work, which is invaluable to the success of COBRA.

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Earthquake vulnerability of wastewater pumping stations in New Zealand

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1. Abstract

New Zealand is located in an earthquake prone part of the world where earthquakes are the most common natural hazard in New Zealand. Consequently, earthquake vulnerability especially in lifelines is of great concern of earthquake prone city councils. Wastewater systems as lifelines should be able to withstand earthquakes to have the minimum impact on public health and environmental pollution. Earthquake vulnerability of wastewater pumping stations in 3 earthquake prone cities in New Zealand was assessed in this research. The assessment revealed that the non-structural components are the most vulnerable parts in wastewater pumping stations. Structural vulnerability of wastewater pumping stations is notable and requires an immediate rehabilitation plan.

Keywords: earthquakes, vulnerability, wastewater pumping station

2. Introduction

The wastewater system is one of the public facilities in urban areas which have a direct impact on communities. The malfunction of which, affects a large number of people directly or indirectly. The wastewater systems in densely populated areas have been designated as a lifeline and therefore deserve particular attention due to their direct impact to community health.

The effect of earthquakes on wastewater systems both directly and indirectly influences human health and environment. Direct effects of earthquakes on wastewater systems are the damages which are caused directly due to ground shaking or ground movement. Direct damage can be defined as the immediate and onsite effect of an earthquake on different parts of a wastewater system (Heubach 2002). For instance, earthquake shaking or ground movement caused by earthquakes can cause damages in the structural or non structural component of wastewater pumping stations. In this research, only direct damages caused by earthquakes on wastewater pumping stations (WWPS) were taken into consideration and indirect damages were ignored.

Wastewater systems can be affected indirectly by earthquakes in a number of different ways. Tsunami waves flood wastewater system reticulation especially in wastewater systems which were built beside the sea shore. For instance a tsunami in Thailand flooded the wastewater system and caused system failures especially in wastewater treatment plants (Brix, Koottatep et al. 2007). Earthquake damage to other lifelines especially electricity and transportation networks can halt functions of wastewater pumping stations and treatment plants or hinder recovery processes. Earthquakes may also disturb the ocean or sea floor nearby the discharge point and pollute the sea (Morkoc, Tarzan et al. 2007).

Wastewater systems are often designed to transmit wastewater by gravity force, as the most reliable and economical way of conveying fluids. Economical issues and technical difficulties are the main barriers to using gravity force. Burying a pipeline to assist gravity flow costs more than constructing a wastewater pump station in terms of technical and environmental effects, especially in some soft soils. Due to these barriers, pumping stations are one of the main parts of each wastewater system. Pumping stations also are one of the main parts in the treatment plant and treated wastewater discharge stations. The main function of pumping stations in sewage reticulation is transmitting sewage to the upper level to carry by gravity. In some cases wastewater or treated wastewater is completely carried under pressure, which is powered by one or several pumping stations. The 18km pressure pipe in the Hutt City wastewater system is a good instance of the pressure system, which carries treated wastewater to the discharge point in Wellington harbour(Capacity-Co. 2008).

3. Earthquake effects on wastewater pumping stations

Earthquake effects on recently upgraded treatment plants during two main earthquakes in US and Taiwan show how the loss of power significantly affects wastewater systems, particularly pumping stations (Lund, Cornell et al. 1998; Schiff, Abrahamson et al. 2000). The 1999 Taiwan earthquake caused no damages in wastewater pumping stations, although power outage significantly affected wastewater systems in the industrial parks (Schiff, Abrahamson et al. 2000).

No damage was reported in the WWPSs in the affected regions by the 1994 Northridge earthquake (Schiff 1995). Moehle (1995) explained how 54 wastewater pumping stations stopped working due to the commercial power outage, although standby generators and sewer bypasses prevented sewage spilling (Moehle 1995). Power outage significantly affected wastewater pumping stations in the 1995 Kobe earthquake (NCEER 1995). The August 17, 1999 Marmara earthquake in Turkey is another example in which the wastewater treatment plants did not suffer any damage, although the power outage was the main concern (Scawthorn 2000).

During the 1987 Edgecombe earthquake in NZ, wastewater pumping stations with submersible pumps did not suffer damage (Pender 1987). The last notable earthquake in New Zealand (Gisborne) in 2007 caused minor damage to mechanical parts in some wastewater pumping stations (Rentoul 2008). The wastewater pumping stations continued working without major damages in the Ormond earthquake in 1993 (Read and Sritharan 1993).

The above case studies show that earthquakes caused minor damages to wastewater pumping stations. The main problem reported for pumping stations was power outage. In order to demonstrate the vulnerability of wastewater pumping stations to earthquakes in New Zealand, 3 earthquake prone cities in both North Island and South Island selected and earthquake vulnerability of 45 wastewater pumping stations were taken into account.

4. Wastewater pumping stations in New Zealand

Three earthquake-prone cities in New Zealand were selected to investigate their WWPSs vulnerability to earthquakes. Approximately, half of the wastewater pumping stations (WWPS) were visited and inspected in each city. WWPSs' vulnerability to earthquakes in each city was classified and investigated. Gisborne and Hutt City in the North Island and Blenheim in the South Island are three earthquake-prone regions, which were selected to investigate their WWPSs vulnerability. The following observations are the result of the site visiting, technical interviewing and data analysing which were done in 2008 by the authors.

Wastewater pumping stations can be classified by two different methods regarding to type of wells and the type of WWPSs structures. Regarding the first classification, New Zealand's wastewater pumping stations are classified into two main groups: drywell WWPTs and wet-well WWPSs. Pumps in dry well WWPTs are located in the separate underground structures, whereas in wet-well WWPSs submersible pumps are installed inside the reservoir. Usually wastewater pumping stations which were built before 1966 are drywell pumping stations. For instance, all 8 wastewater pumping stations built before 1966 are dry-well WWPSs in Gisborne (Gisborne District Council 2008). In terms of

WWPSs earthquake vulnerability WWPSs can be classified into two main groups: WWPSs with building and WWPSs without building.

Wastewater pumping stations in New Zealand usually comprise of two main types: structural component and non structural components. Structural components include above ground structure and under-ground structures. Above ground structures comprise of buildings of WWPSs mounted on top of the under-ground structures (usually in dry-well WWPSs) house all electronic equipment including control boards, telecommunication and data transferring devices. The WWPS building also is the access point to the dry well for maintenance.

Non structural components of WWPSs in New Zealand also can be divided into mechanical and electrical parts. Pumps, fitting, valves and pipes are main component of mechanical section and telecommunications, electrical boards, flow-meters and data transferring devices make electrical section of each WWPS. During the cities' development remote controlling and telecommunication devices were installed in WWPSs and mounted on the building walls in WWPSs with building or mounted in concrete pad beside the wet wells. All relevant data requires for WWPSs monitoring including wastewater level, working hours of each pump, discharge rate and security signal continuously records and transfers to control room. SCADA according to collected data controls the whole wastewater system.

5. Vulnerability of wastewater pumping stations in New Zealand

WWPSs comprise of different components in which failure of each component directly or indirectly affects the whole wastewater pumping stations functions. Vulnerability of wastewater pumping was divided into two categories including structural vulnerability and non structural vulnerability. Structural vulnerability comprise of vulnerability of WWPSs' buildings and non structural vulnerability cover vulnerability of mechanical and electrical component in WWPS. In this research underground structural vulnerability was not considered as a part of structural vulnerability.

5.1 WWPSs structural vulnerability

Buildings are one of the main parts of wastewater pumping stations especially for those wastewater pumping station constructed before 1980 and most of the dry-well wastewater pumping stations. This research showed that WWPSs with buildings comprise 87.5%, 70% and 33.3% of the assessed

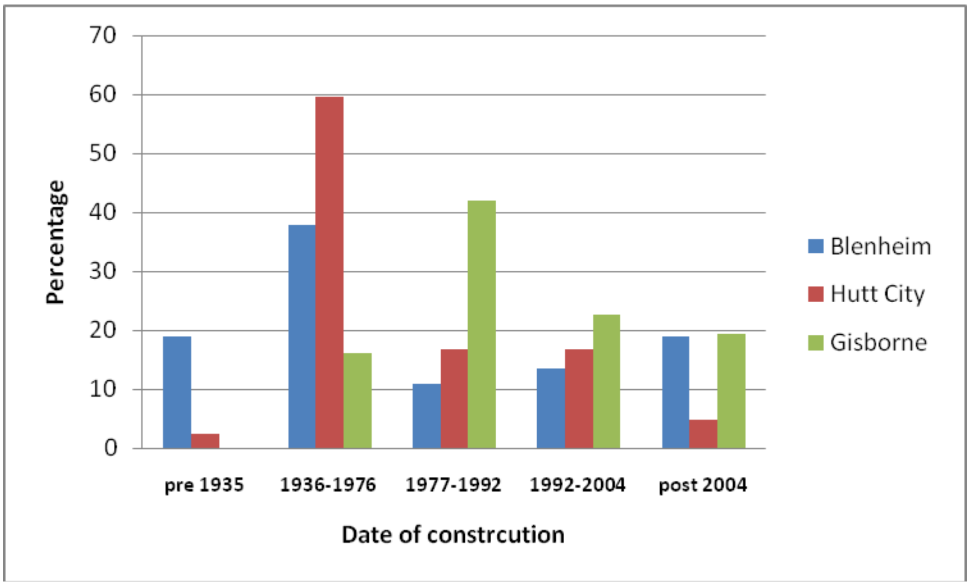
WWPSs in Hutt City, Gisborne and Blenheim respectively. Consequently, structural vulnerabilities in Hutt City and Gisborne were taken into consideration as structures were a significant part of their makeup.

WWPSs with a building will have all electronic, data transferring and telecommunication equipment installed inside the WWPSs buildings. Failure of any installed instrument inside the building makes the WWPS useless and failure of each WWPS directly affects whole wastewater reticulation system. In addition to this, the WWPS's building is the access point to the underground structure which includes pumps, valves and piping. Building collapse not only affects whole systems function but also hinders the repair process of affected WWPSs. Building vulnerability in the wastewater pumping stations was taken into account as a main susceptible factor.

In this research, various parameters were taken into consideration to demonstrate earthquake vulnerability of WWPSs' building. Building characteristics (such as age and type) and geotechnical characteristics (such as soil type, liquefaction susceptibility) were applied to reveal the WWPSs' building vulnerability to earthquakes (see (Building Act 2004 ; Standards New Zealand 2004; NZSEE 2006)). The latest earthquake vulnerability assessment of buildings in NZ has been applied to accurate initial assessment(NZSEE 2006). Building age is one of the main factors which shows a buildings vulnerability to earthquakes (NZSEE 2006). Various building codes have been developed in New Zealand to satisfy required standards during the urban area development. The first building code was established in 1935 and was renewed several times to decrease its deficiencies (Beattie and Thurston 2006). Beattie showed the first earthquake building code with sound engineering approach was established in 1976. Consequently, buildings built prior 1976 may have vulnerability to earthquakes.

Building age of each pumping station in three case study cities was extracted from the Hutt City and Blenheim GIS data bases as well as available data in Gisborne city council. Figure 1 illustrates WWPSs age among three earthquake-prone cities (Hutt City, Gisborne and Blenheim). As figure 1 shows the oldest WWPSs belong to Blenheim wastewater system, although a percentage of the new WWPSs also belongs to Blenheim. This shows the development of Blenheim city and replacing of aged WWPS's. About 60% of Hutt City wastewater pumping stations were built during 1935 and 1976, followed by 40% of Gisborne WWPSs. Finally, it should be summarized that in the three selected cities in New Zealand more than 40% of all wastewater pumping stations were built before 1976, which means at least 40% of wastewater pumping stations buildings should be accurately evaluated for earthquake vulnerability.

Figure1: Date of construction in three cities' wastewater pumping stations



Another factor which affects building vulnerability to earthquakes is material types used in building. For instance, masonry buildings are the most common building types in WWPSs, although some concrete buildings are also available in NZ's WWPSs. Roofs in the WWPSs' buildings usually are concrete slab, wood frame with ceramic tiles or steel frames with steel sheets on the top. The WWPSs' building height varies between 2 and 2.50 meters except main WWPSs with building height more than 3 meter. Another factor which affects vulnerability of wastewater pumping station buildings is the irregularity in the building plans. Most WWPSs' buildings in this study have almost regular plans (rectangular plan) but with different plan types. For Instance, Gisborne's WWPSs have different types of the plans compared with Blenheim and Hutt City WWPSs. Circular and hexagonal plans are common in the Gisborne's wastewater reticulation. The WWPSs' building except some trunk WWPSs in Hutt City and main WWPSs in two other cities have small area and building area in common WWPSs varies between 6 to 25 square meters. WWPSs in Gisborne and Hutt City have greater building area compared with Blenheim WWPSs. Recent field studies by the authors showed that superficial physical conditions of all assessed WWPSs were fine and no sign of deterioration or cracks in above ground structures was visually detectable. However, concrete deterioration in the wet well structures was seen in some WWPSs. Detailed tests and analysis should be done to show accurately the vulnerability of building structures.

Wastewater pumping stations' wells in New Zealand are usually made by precast concrete or cast in place concrete. However, in some cases the reservoir well is made by fibreglass tank. Early wastewater pumping stations were made by in place concrete. Concrete well deterioration was not obvious in the majority of cases at least above the reservoir water level. Further structural evaluation accompanied with some material tests are required to accurately evaluate underground ground structure vulnerability to ground shaking.

5.1.1. Initial assessment of Hutt City WWPS

The initial assessment procedure recommended by NZSEE (2006) was applied to disclose the Hutt City WWPSs' building vulnerability to earthquakes. NZSEE (2006) recommends if calculated percentage of the New Building Standard (%NBS) for each particular building be less than two thirds of the NBS then the building is vulnerable to earthquakes. Although the NZ Building Act (2004) declares if calculated %NBS be less than one third of the new building standard then the building is an earthquake prone building.

Geological characteristics of each WWPS in Hutt City including soil types were extracted from the Dellow and Dissen 1992((Dellow 1992) and (Van Dissen 1992). The Hutt City WWPSs GIS data base was applied to find location and age of each WWPS in the Hutt City wastewater system. Liquefaction vulnerability map of Hutt City also was applied to modify calculated %NBS in the initial assessment procedure (MWH 2005).

WWPSs structure assessment by the authors revealed that the WWPSs which were built during 1960-1964 are the most earthquake vulnerable WWPSs in the Hutt City wastewater system. All the WWPSs which were constructed between 1960 and 1964 are vulnerable to earthquakes by NZSEE (2006) and just one of them satisfies building act code 2004. All WWPSs were built before 1960 meet the NZ building act (2004) except one, although none of them satisfy NZSEE (2006). Construction of the WWPSs on the liquefiable soil during 1960-1964 is the main factor affected vulnerability of WWPSs in this period. Considering NZSEE (2006), 35 % of whole WWPSs in Hutt City should be rehabilitated structurally, while 15 % of whole WWPSs in Hutt City should be strengthened for earthquake according to building act (2004). This shows significant differences even between two NZ standards' references, which may deserve investment. Considering WWPSs as the necessary buildings may issue a great concern for any specific region. Consequently, the NZSEE 2006 recommendation seems more reliable and appropriate.

Construction dates in the Hutt City WWPSs which were applied for the above initial assessment reflected date of refurbishment for some pumping stations. Regarding to only refurbishment of mechanical and electrical equipment in the WWPSs in Hutt City, expected damages in the Hutt City WWPSs is more significant than the above initial assessment. In order to consider more accurate construction dates for the Hutt WWPSs, all WWPSs in Hutt City except trunk WWPSs were selected for the second initial assessment. The second initial assessment showed that 57% of all WWPSs which were built before 1957 are significantly vulnerable to earthquake. Considering the NZSEE (2006) recommendation for building vulnerability to earthquakes 17 WWPSs should be retrofitted out of the 22 WWPSs in the Hutt City wastewater reticulation. The second initial assessment showed building damages in the Hutt City WWPSs will significantly affect the whole wastewater system vulnerability if they do not retrofit or replace.

5.1.2. Initial assessment of Gisborne wastewater pumping stations

The WWPSs with a building in Gisborn similar to Hutt City comprise high percentage of the WWPSs. Recently constructed WWPSs do not have buildings and were extracted from data base for initial assessment. Wastewater reticulation in Gisborne was constructed some decades after the Hutt City wastewater reticulation. Consequently, expected damages in the Gisborne WWPSs after earthquakes are expected to be less than the Hutt City wastewater reticulation.

The NZSEE 2006 procedure was applied to show how vulnerable the Gisborne WWPSs can be. Gisborne city was divided into 4 municipal regions each of which includes two small municipal regions. Geological characteristics and earthquake vulnerability of each region were derived from the available resources. Regarding the location of each WWPS required parameters extracted from the available resources (Standards New Zealand 2004; Berryman, Marden et al. 2009; Zhao 2009; Bevin 2000). The two WWPSs which were built after 2004 were omitted and the vulnerability of the rest were assessed by the NZSEE (2006) initial assessment.

The initial earthquake vulnerability assessment in the Gisborne WWPSs showed 38% of the Gisborne WWPSs buildings do not satisfy NZSEE 2006 thresholds and should be retrofitted. Although, considering the New Zealand building act (2004) 17% of the WWPSs in Gisborne should be retrofitted with new building codes.

5.2 Non structural vulnerability of WWPS

Non structural vulnerability in the NZ's WWPSs was categorized into two main types including, vulnerability of electrical and electronic equipment as well as mechanical component vulnerability. Regional WWPSs transmit collected wastewater of each region to main collectors or trunk pipelines. These pumping stations usually house two pumps, two check valves, two control valves, flow-meter, pipes and fittings, control panels, data transmitting and telecommunication instruments. Alongside the mechanical and electrical instruments, each pumping station consists of a reservoir to collect and pump wastewater to the designated point. Under-ground structures in pumping stations usually consist of two wells (dry and wet wells) or one wet well. Wastewater discharges to the wet well and pumps to the designated point. Dry well in dry-well WWPSs houses fixed pumps, valves, pipes, fitting and access point. In the new pumping stations which usually are wet-well WWPSs, dry well was omitted and pumps were installed in wet well. Consequently, pumps and piping directly are installed in the wet well. Fixed pumps in dry-well WWPSs replace with submersible pumps in wet-well WWPSs and are directly installed in the wet-well.

Vulnerability of the electrical and electronic equipment in WWPSs should be taken into account as the monitoring and controlling devices, which control the system. This type of vulnerability is divided into two main groups of WWPSs: WWPSs with building and WWPSs without building. Wet-well WWPSs which electrical and electronic equipment is installed in the control panel outside the WWPSs' buildings are much less vulnerable to earthquakes compared with dry-well WWPSs. Wet-well WWPSs house all electrical and electronic equipment in a steel box mounted on the concrete pad near the underground structure, whereas electrical and electronics panels in dry-well WWPSs are simply mounted on the building walls without adequate fixing supporters. WWPSs with building cover about half of the WWPSs in all three cities and inadequate fixing of electrical and electronic equipments is the similarity in all of them. Even if building walls be able to stand earthquake shaking, toppling and falling of inadequately mounted equipment could cause whole failure in WWPSs during a strong earthquake.

Mechanical equipment, including pumps, piping and fittings are the main parts in each WWPS and their vulnerability can instantly affect whole system function. Earthquake vulnerability in mechanical parts is divided into the pumps vulnerability and the piping system vulnerability. Ground shaking effect of an earthquake can be controlled by vibration isolators in fixed pumps, which they did not be installed in all visited WWPSs in the three case study cities. Submersible pumps tolerate the earthquake affects better than the fixed pumps. Consequently, submersible pumps are less vulnerable in earthquakes (Heubach 2002; Rentoul 2008). Check and control valves, particularly heavy ones should be fixed properly to the basement of the underground structures in WWPSs. Steel strips and proper stands should be applied to fix valves and pipes in pumping stations. According to site visiting of WWPSs in New Zealand, many WWPSs did not have proper fixing for the mechanical parts. Almost all WWPSs built after 1992 are wet-well WWPSs, consequently they do not have structural vulnerability and non structural components are expected to stand earthquakes. According to the earthquake effects in wastewater systems in the previous earthquake scenarios, recently constructed WWPSs even those built as a dry-well WWPS should stand well during an earthquake.

Joints and fitting are usually the most vulnerable parts in the WWPSs piping system which even in the moderate earthquakes can be affected by earthquake shaking. For instance, the only problem reported in the WWPSs after the 2007 Gisborne earthquake was joints' leakages in a few WWPSs. Joints should tolerate shaking and displacement caused by earthquakes. In earthquake prone areas usually flexible joints installed to connect fittings, valves and pumps to pipes in order to tolerate shaking and displacement caused by earthquakes. Observations of WWPSs and some potable water pumping stations in the three earthquake prone cities in New Zealand revealed fixed joints are the predominant type of joints. Only in 2 main WWPSs flexible joints were used to cope with longitudinal pipe movement. This type of joint facilitates installation and maintenance in pumping stations.

Existence of deteriorated and fragile pipes in the under-ground structures of WWPSs is another sort of vulnerability, which resulted in less strength in earthquakes. Flowmeters have been installed in recently constructed or refurbished WWPSs to monitoring wastewater flow. In the WWPSs which were refurbished and a flowmeter installed usually fragile pipes replaced with more ductile pipes such as some WWPSs in Blenheim. The most popular pipe type, especially in the WWPSs built before 1992 is the cast iron pipe which compared with new pipe types is much more brittle and sensitive to shaking.

WWPSs in New Zealand also can be affected by indirect impacts of earthquakes. For instance WWPSs can be significantly affected by commercial power outage after earthquakes. Except few main WWPSs in all three case study cities which had emergency power generators most of the WWPSs in case of commercial power outage will not able to work.

6. Conclusion

Wastewater pumping stations in New Zealand can be affected directly and indirectly by earthquakes. Direct damage of earthquake on WWPSs in New Zealand comprises of the structural and none structural damages. The Structural damages in WWPSs with buildings in New Zealand are predominant because of their direct impact on none structural components including mechanical and electrical components. WWPSs which were built before 1976 are significantly vulnerable to earthquakes and should be retrofitted or replaced after more accurate analysis. Non structural earthquake vulnerability especially in dry-well WWPSs is also one of the predominant hazards in WWPSs. Power outage after earthquake is the main indirect damage of earthquakes on WWPSs because of unavailable onsite power generators as well as insufficient mobile power generators. In order to minimize vulnerabilities of the New Zealand's WWPSs to earthquakes in both direct and indirect earthquake damage the following recommendations should be taken into consideration. In terms of structural vulnerability WWPSs which were built before 1976 should be assessed accurately and their vulnerabilities to earthquake determined. In case of building vulnerabilities both building retrofitting and building replacement should be taken into consideration. Regarding to the corrosive environment in the underground structures of WWPSs earthquake vulnerability analysis with some material tests are required to show how vulnerable are underground structures of WWPSs especially those were built before 1976.

After making sure that the WWPSs buildings are able to stand earthquakes, earthquake stability of electrical boards which were mounted on the wall without sufficient supports should be taken into account. Electrical instruments should have sufficient supports to withstand earthquakes and also should not adversely be affected by other components failures in WWPSs. In terms of the mechanical vulnerability, at least in main WWPSs fixed rigid joints replace with earthquake resistant joints and deteriorated pipes replace with more flexible pipes. Earthquake resistance supports should be used to properly fix valves and pipes installed with improper and insufficient supports. Power generators and fuel tank with sufficient capacity should be provided for WWPSs in earthquake prone regions in order to overcome commercial power outage after earthquakes.

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