



THE ANTI-CATASTROPHE SEISMIC DESIGN CONCEPT FOR 'PERIPHERAL' LIFELINE SYSTEMS

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Abstract

The seismic design against Level 2 earthquakes (JSCE 2016) of the peripheral systems for water and energy, both above and below ground remains problematic. While countermeasures, such as allocating hubs and seismic retrofitting of specific facilities are being prioritised, peripheral lifeline systems remain vulnerable.

In Honda et al.'s (2017) discussion of the anti-catastrophe concept for seismic design, they observed that seismic damage to infrastructure could shift discontinuously from a normal to a severe level, defined hereinafter as 'the next phase of infrastructure damage dislocation'. When a large earthquake occurs, it may not be realistically possible to completely prevent damage to the peripheral lifeline system, but measures to suppress a shift in mode from normal to extremely severe are necessary and effective.

In this paper, a representative example of damage to a peripheral lifeline system involving buried pipes for water distribution and sewerage, and power distribution equipment was identified and discussed in relation to 1) the damage in the 2011 Tohoku Earthquake; 2) whether the damage corresponds to the next phase of infrastructure dislocation according to Honda et al.'s (2017) anti-catastrophe framework; and 3) the reduction of the 'big uncertainty of the impact' of the next level of infrastructure dislocation.

Keywords: anti-catastrophe, next phase, lifeline, peripheral lifeline system, seismic disaster, resilience



1. Introduction

Lifeline systems support critical social and economic activities. However, their scope is enormous, and they may not always be properly maintained. It is important to consider the resilience of these systems during disasters and during the post-disaster reconstruction period. In the 2000s, the Department of Homeland Security in the U.S.A (2003) developed a national strategy for critical infrastructure protection [1], and government bodies and utility companies in Japan also developed infrastructure disaster prevention measures at this time [2].

The seismic design of bridges has been more advanced than that of other infrastructure elements [3][4], and countermeasures against landslide disasters are issues, but more recently the seismic performance of road networks has improved. The seismic design against Level 2 earthquakes [5] of the peripheral system of water and energy, both above and below ground (hereinafter, 'the peripheral lifeline system'), remains problematic. While countermeasures, such as allocating hubs and seismic retrofitting of specific facilities are being prioritised, peripheral lifeline systems remain vulnerable. Rather, social needs and interests have shifted to such issues and are becoming more important as issues to be addressed.

In terms of damage to the peripheral lifeline system, the impact may be sporadic if damage is limited, but widespread damage may have a significant negative effect on social and economic functions. Recent disasters frequently involved water outages, gas-supply disruption and electrical power failures.

In Honda et al.'s (2017) discussion of the anti-catastrophe concept for seismic design [6], they observed that seismic damage to infrastructure could shift discontinuously from a normal to a severe level, defined hereinafter as 'the next phase of infrastructure damage dislocation'. When a large earthquake occurs, it may not be realistically possible to completely prevent damage to the peripheral lifeline system, but measures to suppress a shift in mode from normal to severe are necessary and effective.

In this paper, a representative example of damage to a peripheral lifeline system involving buried pipes for water distribution and sewerage, and power distribution equipment was identified and discussed in relation to 1) the damage in the 2011 Tohoku Earthquake; 2) whether the damage corresponds or not to the next phase of infrastructure dislocation according to Honda et al.'s (2017) anti-catastrophe framework [6]; and 3) the reduction of the 'big uncertainty of the impact' of the next level of infrastructure dislocation.

2. Review of the issues in lifeline earthquake disaster mitigation research

In Japan, after the 1978 Miyagiken-Oki earthquake, the turning point in lifeline earthquake disaster mitigation research was undoubtedly the damage to lifelines caused by the 1995 Kobe earthquake. Water, sewage, electricity, gas and telecommunications lifelines all suffered severe damage due to strong ground movement and deformation, resulting in water outages, power failures, gas-supply and telecommunications disruption as well as transportation disruption. This disruption continued for a long time. Takada and Miyajima's research group (2001) [7] investigated damage to the peripheral lifeline system, particularly buried pipe damage introduced to prolong recovery period, and Nojima and Kameda (1995) [8] built a systematic model to estimate the post-seismic functionality of lifelines taking into account physical and functional damage. In addition, Nojima consistently addressed the issue of functional impairment based on real data. Since 2000, following the considerable social and economic losses incurred as a result of the Kobe earthquake, and following the example set by the US government, the Cabinet Office of the Japanese government has been leading the way in preparing damage limitation measures against the anticipated Tokyo earthquake [9] and the anticipated Nankai Trough giant earthquake tsunami as a national security priority. This process was accelerated after the 2004 Indian Ocean tsunami disaster, but the anti-catastrophe concept in relation to infrastructure and lifelines on began to be systematically discussed with urgency after the 2011 Tohoku Earthquake. The melt-down of the core at the Fukushima nuclear power station [10] is considered to be the point at which the anti-catastrophe concept began to be systematically incorporated into the design of critical infrastructure in Japan.

As described above, there have been many events where urban lifelines have been damaged, and there is an abundant amount of research clarifying how these lifelines are damaged, how consequent functional



damage occurs, and how the damage can be modelled theoretically. On the other hand, there has been insufficient research into seismic damage to lifelines that has produced quantitative thresholds that might indicate the next phase of infrastructure dislocation according to the anti-catastrophe concept. In addition, although the disruption of top-level infrastructure systems, and associated functional disruption, was experienced during the Fukushima Daiichi nuclear power plant accident caused by the 2011 Tohoku Earthquake, there has been little discussion about the next phase of dislocation involving peripheral lifeline systems such as water and sewage pipes, and electricity distribution facilities.

Therefore, in the subsequent two chapters, the seismic intensity values and damage ratios that establish the threshold for the next, more serious, phase in the dislocation of peripheral lifelines are discussed. The discussion is informed by analyses of data on damage to water and sewage pipes and electricity distribution facilities caused by the combined effect of strong ground motion and liquefaction in the 2011 Tohoku earthquake by Naba et al. (2012) [11], Shoji et al. (2012) [12], and Tsukiji and Shoji (2013) [13]. These analyses defined the vulnerability of peripheral lifelines that is expressed by the relationship between the damage rate/damage probability and seismic intensity of earthquakes.

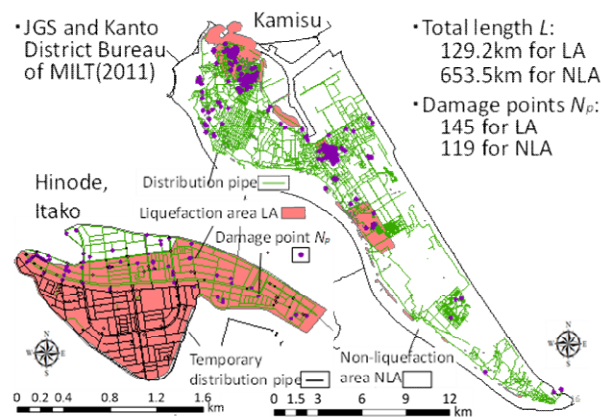


Fig. 1 – Physical and spatial damage to the water distribution networks managed by these water utilities in Kamisu City, Ibaraki Prefecture and the Hinode area, Itako City, in the 2011 Tohoku earthquake

3. Water and sewage pipelines

Based on the data focusing on water distribution pipe damage in Kamisu City, Ibaraki Prefecture and the Hinode area, Itako City, in the 2011 Tohoku earthquake, Figure 1 shows the physical and spatial damage to the water distribution networks managed by these water utilities. In the case of Kamisu City, the network is distributed over an area covering 30 km north–south by 30 km east–west, and for the Hinode district of Itako City, the area covered measures 2 km north–south by 3 km east–west. It was found that the combined action of strong ground motion and liquefaction caused widespread damage to these networks. The estimated maximum peak ground velocity PGV in this area was 20–60 cm/s, which is not a level that can usually cause damage, such as breakage of water pipes or disconnection of joints, when only the maximum seismic ground motion value is considered. The serious damage was caused by ground deformation, or liquefaction. In Kamisu City, the damage was concentrated in a few areas: Horiwari, Fukashiba and Chitte. In Itako City, the Hinode area on the south side suffered comprehensive network damage. A liquefaction countermeasure project using the groundwater lowering method to reduce the risk of the recurrence of liquefaction by lowering the groundwater level from about 2.5–3.0 m in the Horiwari area of Kamisu City and the Hinode area of Itako City has been implemented. Liquefaction measures that target a broad area are very difficult because they are labour intensive and alternative reconstruction method is inherently limited. Verification of the efficacy of the groundwater lowering method has been a long-term project, lasting some nine years since the Tohoku Earthquake disaster.

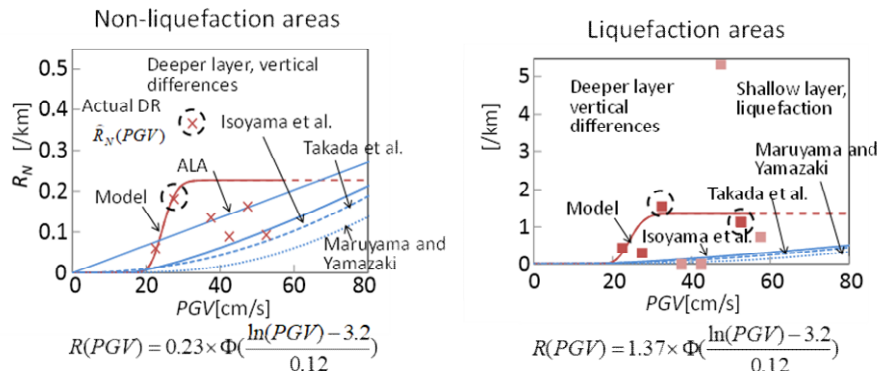


Fig. 2 – The relationships between the spatially estimated maximum ground velocity PGV and the damage rate defined as locations/km for water distribution pipes

Figure 2 shows the relationship between the spatially estimated maximum ground velocity PGV and the damage rate defined as locations/km. In addition, a typical damage function named the fragility curve was introduced by the American Lifelines Alliance (ALA) (2001) [14], Isoyama et al. (1998) [15], Takada et al. (2001) [7], and Maruyama and Yamazaki (2010) [16]. The ALA damage function relies mainly on the data analysis of damage to buried water supply pipes in the United States, e.g., during the 1994 Northridge earthquake. Both damage functions by Isoyama et al. (1998) and Takada et al. (2001) were derived from data on damage following the 1995 Kobe earthquake. Later, Maruyama and Yamazaki analysed the data on damage following the 2004 Niigata-ken Chuetsu earthquake. Any damage functions depicted by blue lines also, although believed to large variations because of the damage data, the damage rate shows the average trend against the PGV of the overall data, gradually increasing as the PGV increases despite the fact that the magnitude of damage ratio is different in both the non-liquefied areas and the liquefied areas.

The important point from Figure 2 is that degree of the damage to the peripheral lifelines goes beyond the assumption made under the previous damage function by over $PGV = 20$ cm/s, at which degree of the damage becomes rapidly serious as the threshold. When a model is constructed based on these damage rate data, it becomes a step function of the red line. Based on this model assuming the averaged recurrence rate of the damage points in water distribution pipes network as be followed by Poisson process and anticipating the number of damage points in the targeted water distribution network, it means that the spatial area that causes severe damage points will be widened at a stretch. In the field of seismic geotechnical engineering, physical mechanisms such as liquefaction damage in the relatively low and moderate amplitude of $PGV = 20\text{--}60$ cm/s over a long duration of even several minutes are becoming apparent. It can be said that models and damage assumptions based on damage rate data implicitly reflect such physical mechanisms.

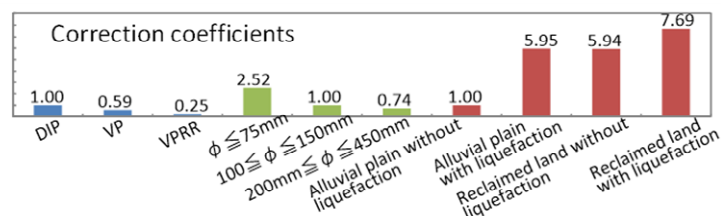


Fig. 3 – The relationships among the damage rate data of water distribution pipes from the perspective of pipe type, pipe diameter, and microtopography buried in

In addition, as shown in Figure 3, ‘liquefaction’ under the condition that the ‘alluvial’ exhibits higher spatial correlation. If the occurrence of each point of damage is independent, it is very rare that the damage occurs all at once over a wide range, but if there is a correlation, it is necessary to treat it as a sufficiently feasible event. When the number of damage points in the peripheral lifelines increase rapidly, 1) the function of the network, that is, the system reliability, is rapidly reduced, and 2) the human and physical needs



following the restoration work rapidly increase in the target areas, which might prolong the recovery and reconstruction period and widen the negative social and economic effects. Figure 4 indicates the spatial distribution of the elongated recovery periods from water outages in Kamisu City after the event on March 11, 2011. The recovery periods in the Horiwari, Fukashiba and Chitte areas in Kamisu City are elongated in correlation with the spread of the damage points in these areas as shown in Figure 1. In other words, it shows how the level of damage to the water and sewerage system transitions to the next phase of the peripheral lifeline system dislocation, that is, both the physical damage as well as its social and economic impact rapidly worsens.

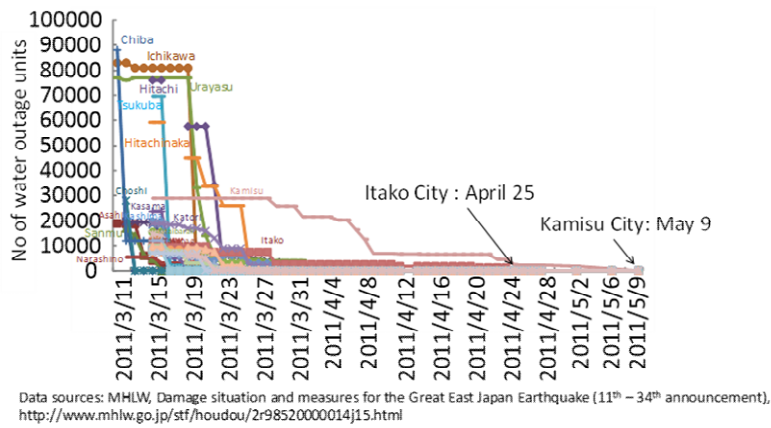


Fig. 4 – Spatial distribution of the elongated recovery periods from water outages after the event on March 11, 2011

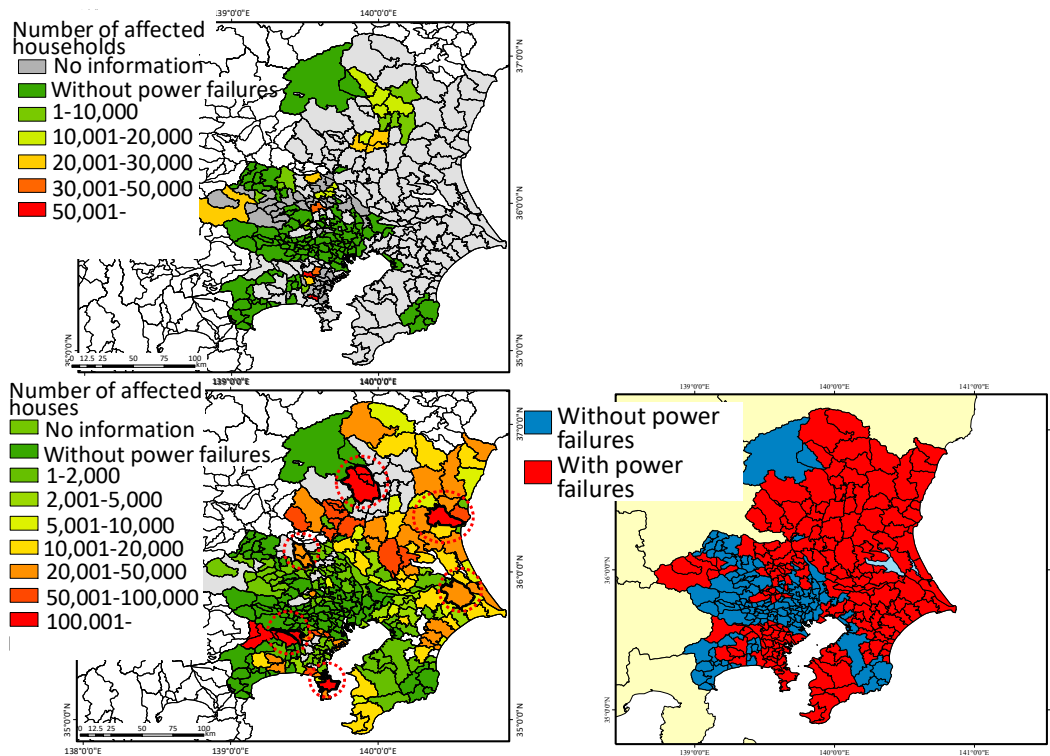


Fig. 5 – Power failures distribution caused by the 2011 Tohoku Earthquake disaster



4. Power distribution facilities

Disruption to the power supply network due to the physical damage to electrical power facilities by the 2011 Tohoku Earthquake disaster [12] caused an extreme power failure across 315 municipalities supplied by TEPCO as shown in Figure 5.

In the following section, the network performance of the peripheral lifelines during a catastrophic event is analysed from a phenomenological viewpoint by measuring power failure data. Based on power failure data from 315 municipalities, the relative frequency of the number of municipalities in which a power failure occurred in a unit class of instrumental seismic intensity IJ by an algorithm from the Japan Meteorological Agency (JMA) [17], as be the occurrence rate of a power failure, was computed as shown in Figure 6. Further, for each municipality classified as belonging to IJ class, the power failure rate was defined by dividing the number of failed power units by the number of units supplied. The two dimensional histogram showing the IJ class and the power failure rate can be seen in Figure 7. From Figure 6, for less than or equal to be $IJ = 5.1$ the power failure rates are about less than 60%, whereas the power failure rates grow rapidly from $IJ = 5.2$ to $IJ = 5.5$; over $IJ = 5.6$ the power failure rates become 100%. The same tendency can be seen in Figure 7, and it is clear that when $IJ = 4.8$ or more, the number of municipalities whose power failure rate exceeds 0.6 sharply increases.

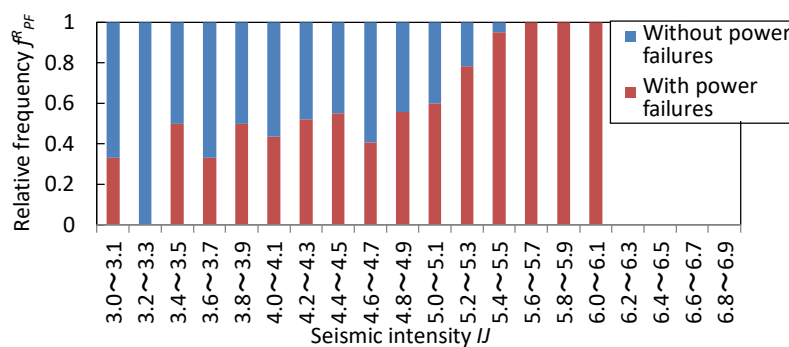


Fig. 6 – The relative frequency of the number of municipalities in which a power failure occurred in a unit class of instrumental seismic intensity IJ by an algorithm from the Japan Meteorological Agency (JMA)

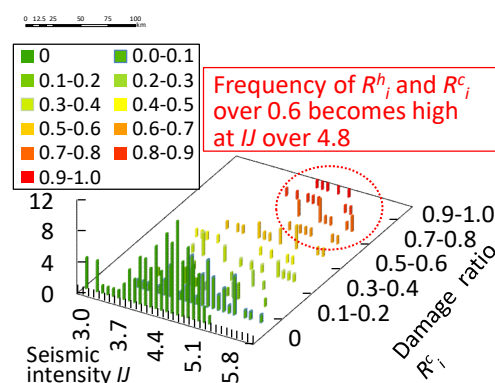


Fig. 7 – The two dimensional histogram showing the JMA IJ class and the power failure rate

Based on these findings, the trend in the recovery period for the municipalities affected by a power failure is discussed, which indicates the essence of the network performance resilience for the peripheral lifelines. Figure 8 shows the relationship between the JMA IJ and the restoration period (unit: day) for the municipalities where the power failure occurred, as in Figure 5. Figure 9 also shows the spatial distribution of the restoration period following the power failures. In Figure 8, it can be seen that municipalities with restoration periods of five days or more begin to appear around $IJ = 5.0$, and the restoration periods suddenly



increase stepwise. This is because in addition to the damage to the power plants, transmission lines and substations, the amount of damage caused by liquefaction of the distribution facilities managed by the Ibaraki and Chiba branch offices became extremely large. The network performance impacts on recovery efforts through the quantitatively widespread damage to peripheral lifelines as well as through the disruption caused by damage to one key infrastructure element like a power plant. In this next phase event, the threshold value of the instrumental seismic intensity IJ , at which the liquefaction damage to the distribution facilities suddenly became serious and the dislocation to the next phase occurred, can be considered to be around $IJ = 5.0$.

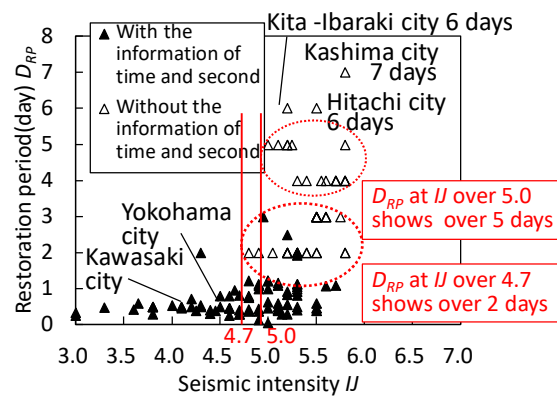


Fig. 8 – The relationship between the JMA IJ and the restoration period (unit: day) for the municipalities where the power failure occurred

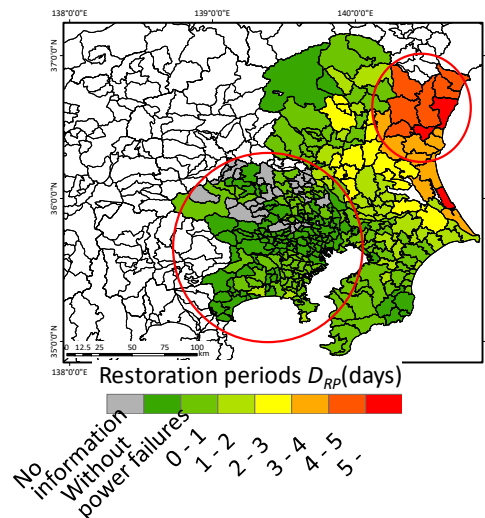


Fig. 9 – The spatial distribution of the restoration period following the power failures

5. Conclusions

In this paper, a representative example of damage to a peripheral lifeline system involving buried pipes for water distribution and sewerage, and power distribution equipment was identified and discussed in relation to 1) the damage in the 2011 Tohoku Earthquake; 2) whether the damage corresponds or not to the next phase of infrastructure dislocation according to Honda et al.'s (2017) anti-catastrophe framework; and 3) the reduction of the 'big uncertainty of the impact' of the next level of infrastructure dislocation.

From these discussions it was found that degree of the damage to the peripheral lifeline systems goes beyond the assumption made under the previous damage measures by over $PGV = 20$ cm/s or around the



JMA instrumental seismic intensity $IJ = 5.0$, at which degree of the damage becomes rapidly serious as the threshold to the next phase of infrastructure performance of the systems. It means that the spatial area that causes severe damage will be widened at a stretch and also shows how the level of damage to the system transitions to the next phase of the peripheral lifeline system dislocation, that is, both the physical damage as well as its social and economic impact rapidly worsens.

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