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SEISMIC ESTIMATION STUDY OF RATIO OF DAMAGE TO TELECOMMUNICATION CONDUITS DURING PAST EARTHQUAKES

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ABSTRACT

Like other lifeline facilities, telecommunication pipelines suffered damage from past earthquakes in Japan. Telecommunication pipelines contain cables for networking. It will cause network breakdown as a result of the damage of these pipelines. This study is focused on the vulnerability of telecommunication pipelines, and discusses ratios of seismic damage by analyzing conduit inspection data gathered after the 1995 Great Hanshin Earthquake, 2004 Chuetsu Earthquake, and 2007 Chuetsu Offshore Earthquake. A model for determining ratio of damage using the variables peak ground acceleration (*PGA*) and peak ground velocity (*PGV*) is discussed. Different conduit attributes such as type of conduit, length, and topography are used to analyze damage tendencies. A mathematical method that introduces dummy variables is used to compare the vulnerability and analyze the interaction between different attributes during earthquakes. The results of this analysis will be used as a basis for estimating the seismic damage pipelines are liable to sustain, and for selecting the most vulnerable conduits when implementing countermeasures.

Keywords: Seismic Assessment; Telecommunication Conduit; Damage Estimation

1. INTRODUCTION

Lifeline facilities, such as telecommunication, gas, and water supply pipelines were widely installed during Japan’s period of rapid economic growth. The aging of these facilities is becoming a serious problem. Specifically, conduits used in these pipelines that were built with old specifications are considered to be especially vulnerable to earthquake damage. Nippon Telegraph and Telephone Corporation (NTT), maintains an approximately 620,000 km long conduit system nationwide for cables that makes up a telecommunication network. Conduit maintenance is one of the most critical issues for NTT because about 80% of the conduits were installed before 1985 with old -specifications that are not earthquake-resistant. During past earthquakes, some buried conduits were damaged, requiring very costly conduit replacements. Determining a way to efficiently and effectively implement countermeasures against seismic activity to a vast quantity of these underground conduits is a significant task.

Previous studies have used numerous methods to assess the ratio of seismic damage in underground conduits. For instance, Isoyama et al. (1998) discussed the ratio of damage in water supply conduits in the 1995 Great Hanshin Earthquake using regression analysis of *PGA* data. They also proposed a model for determining the ratio of damage on the basis of the conditions of different types of conduits, conduit diameters, and topographies. Maruyama and Yamazaki (2009) discussed the ratio of damage

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from several earthquakes by using *PGV* data. Kougo et al. (2016) studied the damage sustained by gas conduits using a 50-m-mesh geographic information system that contained gas conduit and topography information; they also proposed a damage prediction model using the ground motion data.

For underground telecommunication conduits, Yamazaki et al. (2012) studied the characteristics of damage from the 2011 Great East Japan Earthquake, and concluded that damage tends to occur at seismic intensities of upper-5, and increase rapidly around seismic intensities of upper-6. Shoji et al. (2016) studied the damage that underground telecommunication conduits sustained from the same earthquake by analyzing the ratio of damage for different types of conduit, lengths, and topographies. They then proposed a mathematical method to assess the seismic vulnerability of conduits. They demonstrated that the insertion-type joint conduit was more capable of withstanding earthquakes resistant to seismic damage than other types, while conduits buried in alluvial plains and landfill sites were more vulnerable.

Building on these past studies, this study discusses the ratios of seismic damage by analyzing the data of conduit inspections gathered following three strong inland earthquakes: the 1995 Great Hanshin Earthquake, 2004 Chuetsu Earthquake, and 2007 Chuetsu Offshore Earthquake. We discuss a model for determining ratios of damage using the variables *PGA* and *PGV*. Damage tendencies are analyzed with different types of conduit, lengths, and topographies. We also use a mathematical method that incorporates a dummy variable in order to compare the vulnerability of different conduit attributes.

2. COMPOSITION OF DATA

2.1 Overview

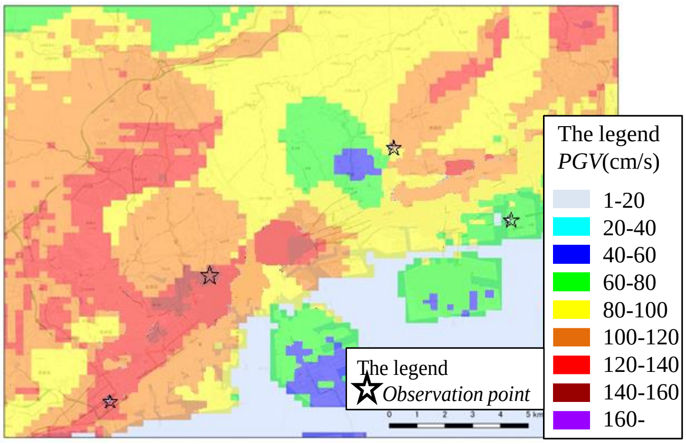
This study examines the underground conduits of telecommunication pipelines. The conduits have been grouped into spans between every two manholes. The inspection data was collected by NTT after the above mentioned earthquakes, including information on the conduits' damage situation (that is, whether or not it was damaged). The overall damage caused by the earthquakes is given in Table 1. In the Great Hanshin Earthquake, 928 spans of conduits were damaged out of a total number of 4447 spans. In the Chuetsu Earthquake, there were 2235 spans in total, of which 58 were damaged. In the Chuetsu Offshore Earthquake, 102 out of a total of 910 spans were damaged. According to this data, the ratios of damage of the Great Hanshin Earthquake, Chuetsu Earthquake, and Chuetsu Offshore Earthquake were 0.21, 0.03, and 0.11, respectively. The inspection data of the Great Hanshin Earthquake was collected mainly in areas that experienced large seismic intensity, so its damage ratio is higher than that of the other two earthquakes.

Table 1. Overall damage situation of each earthquake

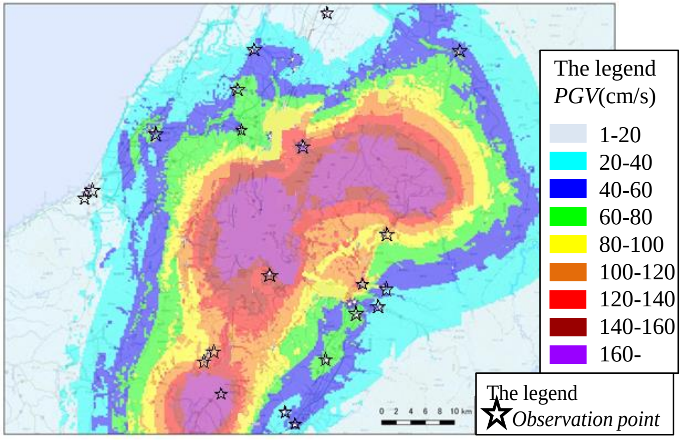
	Great Hanshin Earthquake	**Chuetsu Earthquake**	**Chuetsu Offshore Earthquake**
Damaged (spans)	928	58	102
Not Damaged (spans)	3519	2177	808
Ratio of Damage	0.21	0.03	0.11

2.2 Ground Motion Data

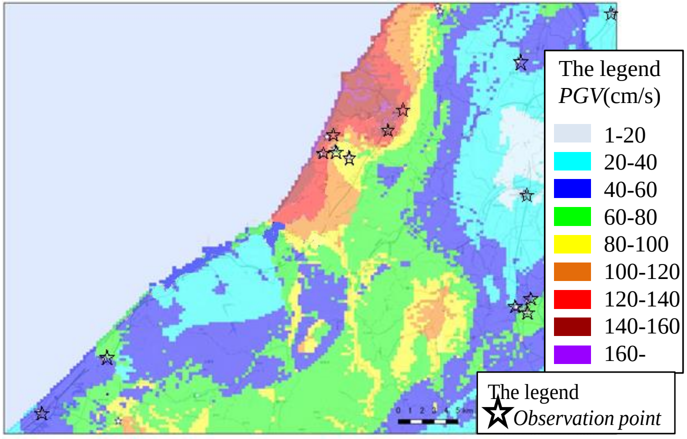
The ground motion data *PGA* (shown in Figure 1) and *PGV* (shown in Figure 2) of these three earthquakes were calculated using the Kriging method introduced by Suetomi et al. (2017) on the basis of observation data gathered from each observation point. First, the average velocity of *AVS30* (the average of the shear wave velocity profile for the first 30 meters) was used with the hazard map developed by the Japan Seismic Hazard Information Station (J-SHIS) (2009) to calculate the earthquake amplification of the surface ground and then calculate the *PGA* and *PGV* of each observation point of the engineering bedrock. The ground motion data *PGA* and *PGV* of every 250-m-mesh was calculated using the attenuation relation function introduced by Kataoka et al. (2006) and the Kriging method. The ground motion data of each conduit used in this study was taken from the mesh in which the center of each conduit span was located.



a) Great Hanshin Earthquake

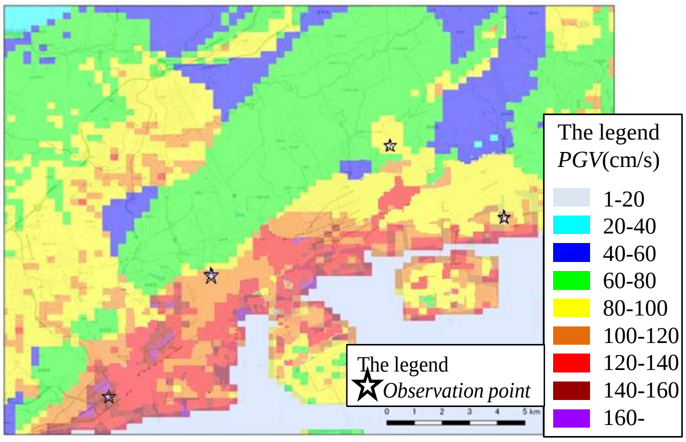


b) Chuetsu Earthquake

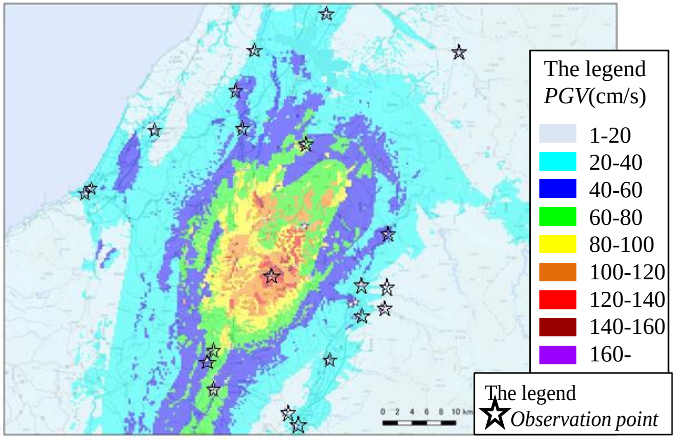


c) Chuetsu Offshore Earthquake

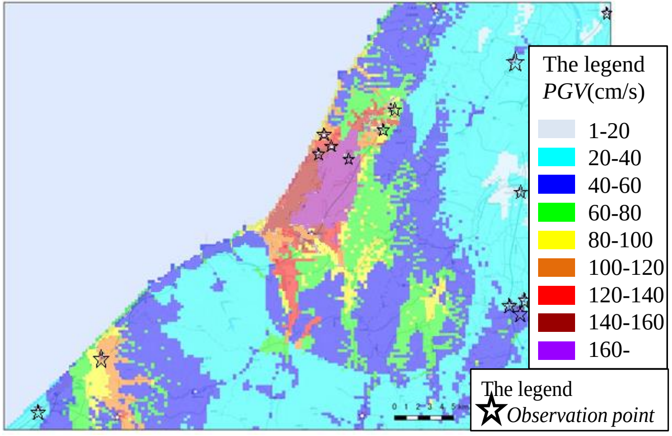
Figure 1. Calculated *PGA* distribution



a) Great Hanshin Earthquake



b) Chuetsu Earthquake



c) Chuetsu Offshore Earthquake

Figure 2. Calculated *PGV* distribution

2.3 Conduit Attributes

Information on the attributes of the conduits (type of conduit, year of construction, length, and the ground topography) are stored in NTT facility maintenance data base. We discuss damage tendencies on the basis of these attributes.

2.3.1 Type of Conduit

The types of conduit discussed in this study are listed in Figure 3. They are: the cast iron pipe (I-type), asphalt covered steel pipe (SA-type), polyethylene coated steel pipe (PS-type), rigid polyvinyl chloride pipe (V-type), insertion-joint steel pipe (PLPS-type), and insertion-joint vinyl pipe (PV-type). The year of construction of each type is also given in Figure 3. I-type is the oldest type, while the two insertion joint conduit types (PLPS-type and PV-type) are considered to have new-specifications.

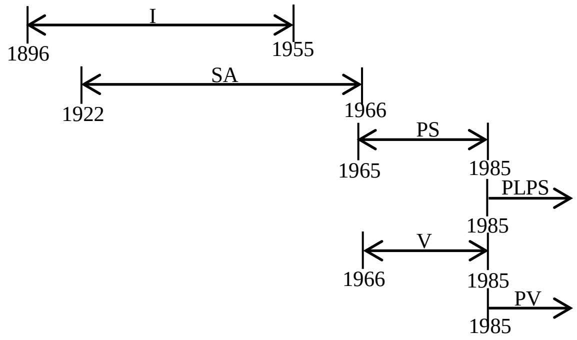


Figure 3. Conduit types with year of construction.

2.3.2 Length

The length discussed in this study is the straight distance between every two manholes. As the length increases, the conduit is considered to be more physically affected by ground motion, and has a higher likelihood of sustaining damage. Therefore, the lengths are analyzed at 50-m intervals to determine the effect of different conduit lengths.

2.3.3 Topography

The topography used in this study is based on a 250-m-mesh J-SHIS (2009) map. The topography of each span is the same as that of the mesh in which the center of the span is located. The topographies discussed in this study are classified into six types according to J-SHIS's micro-topography classification as given in Table 2: mountains, hills, gravel terraces, loam terraces, alluvial plains, and landfill sites. The liquefaction zones are not considered in this study.

Table 2. Topography classification

Classification	**J-SHIS micro-topography**
Mountains	Mountain, Mountain footslope, Volcano, Volcanic footslope
Hills	Hill, Volcanic hill
Gravel terraces	Gravelly terrace
Loam terraces	Terraces covered with volcanic ashsoil
Alluvial plains	Valley bottom lowland, Alluvial fan, Natural levee, Back marsh, Abandoned river channels, Delta and coastal lowland, Marine sand and gravel bars, Sand dune, Lowland between coastal dunes and/or bars, Rock shore and rockreef, Dry river bed, River bed, Water body
Landfill sites	Reclaimed land, Filled land

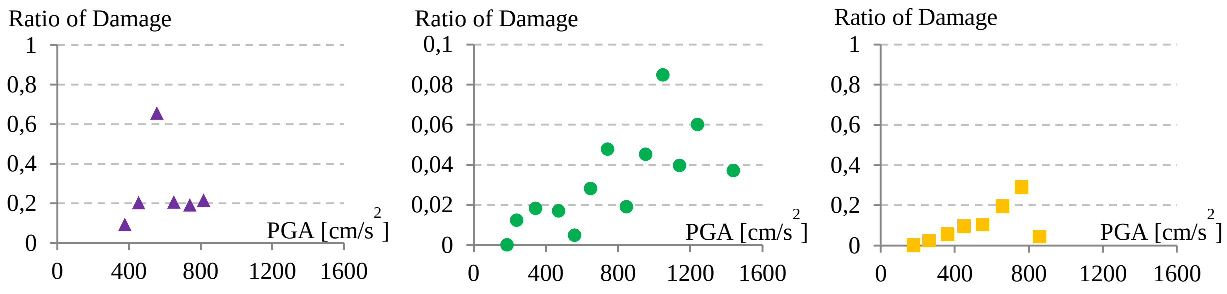
3. DAMAGE CHARACTERISTICS OF DIFFERENT EARTHQUAKES

This chapter discusses the damage situation and characteristics on the basis of the ground motion data and conduit attribute data that were introduced in chapter 2. We discuss spans made up of a conduits that can be classified into the six types shown in Figure 3; spans with other types of conduit are not included in this study.

3.1 Damage Characteristics by Earthquake Intensity

The damage sustained by the underground conduits during the earthquakes is discussed using ground motion data as indices of the strength of the earthquakes. The original data is used without being classified into different types of conduit, lengths, or topographies.

Figure 4 shows the relationship between *PGA* and the ratio of damage. The points are the average damage ratio per 100 cm/s^2. The tendency evident from the results of the three earthquakes is that damage generally starts when *PGA* equals 300 to 400 cm/s^2. In the Great Hanshin Earthquake, the distribution range of *PGA* is narrow and the number of data is limited, so it is difficult to determine a trend for this earthquake. In the Chuetsu Earthquake, the damage ratio tends to increase as *PGA* increases. In the Chuetsu Offshore Earthquake, the damage ratio tends to increase until *PGA* reaches 800 cm/s^2; it then becomes lower at 900 cm/s^2. Since there is no further data, it is also difficult to determine a trend for the Chuetsu Offshore Earthquake.



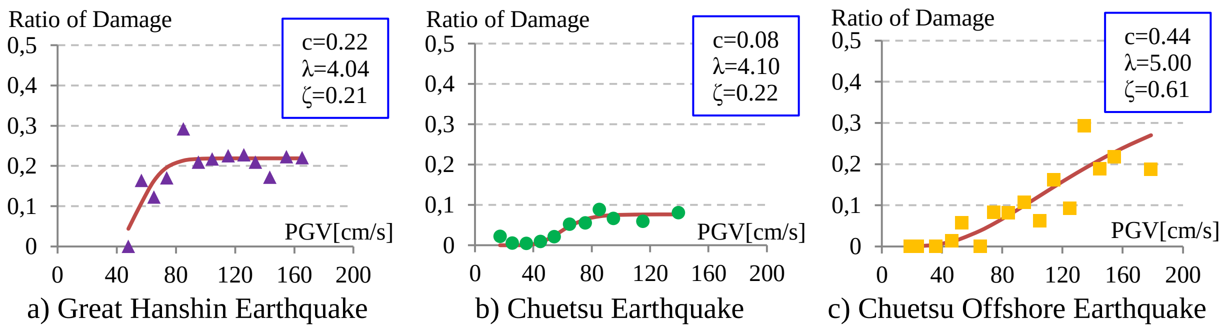
a) Great Hanshin Earthquake b) Chuetsu Earthquake c) Chuetsu Offshore Earthquake

Figure 4. Relationship between the ratio of damage and *PGA*.

Figure 5 shows the relationship between *PGV* and the ratio of damage. The points are the average ratio of damage per 10 cm/s, and the lines are the predicted curve of the ratio of damage. Based on the function proposed by Maruyama et al. (2009), the prediction model of these three earthquakes is defined as Equation 1, where Φ is the cumulative function of the standard normal distribution. Equation 2 is the objective function, where R is the average ratio of damage, and w is the weight, which in this case is the number of spans. The constants C, λ, and ζ can be calculated by minimizing the objective function ε (*PGV*). A model for calculating the ratio of damage was determined for each earthquake. Using these models, it is possible to show that damage starts to occur when *PGV* equals about 40 cm/s. For the Great Hanshin Earthquake and Chuetsu Earthquake, the trends become flat when *PGV* equals about 80 cm/s, but the Chuetsu Offshore Earthquake did not show such a trend.

$$R^*(PGV) = C \cdot \Phi\left(\frac{lnPGV - \lambda}{\zeta}\right) \tag{1}$$

$$\varepsilon(PGV) = \sum (R - R^*(PGV))^2 \cdot w \tag{2}$$



a) Great Hanshin Earthquake b) Chuetsu Earthquake c) Chuetsu Offshore Earthquake

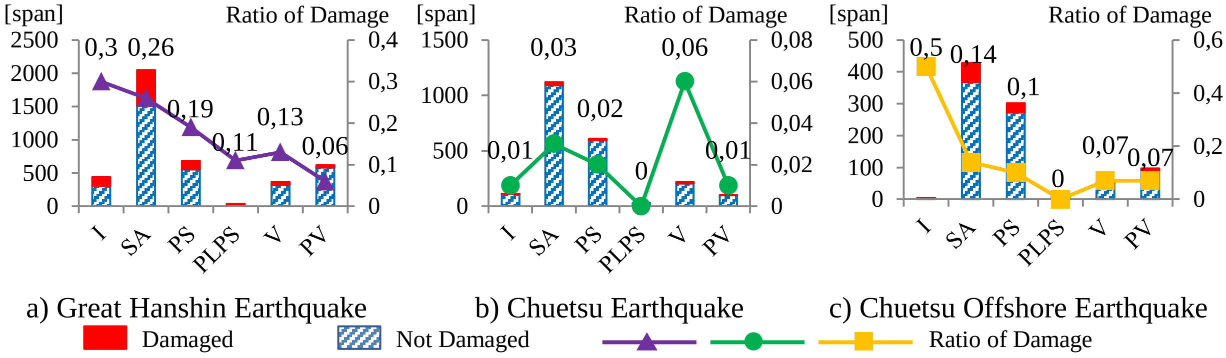
Figure 5. Relationship between the ratio of damage and *PGV*.

On the basis of these findings, the sufficient number of data, and the commonality of the ratios of damage between earthquakes, we consider *PGV* to be more effective than *PGA* for building prediction models for ratio of damage in the analysis of underground telecommunication conduits.

3.2 Damage Characteristics by Conduit Attributes

The damage characteristics of underground conduits differ between different conduit attributes. This study used the type of conduit, length, and topography to analyze damage trends. The bar graphs below show the damage situation. The blue bars are the number of spans with un-damaged conduits, red bars are the number of spans with damaged conduits, and points are the ratios of damage.

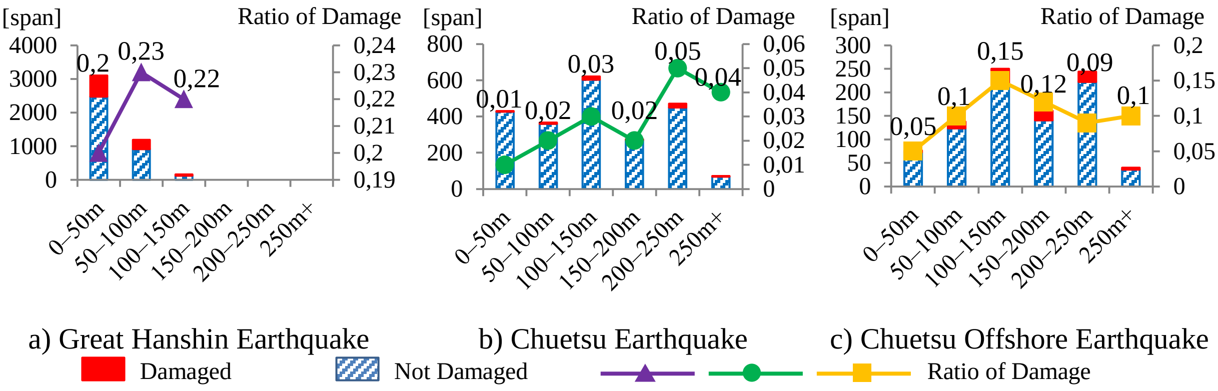
Figure 6 shows the damage situation of each type of conduit in these three earthquakes. SA-type and PS-type conduits are present in great number among the conduits, and as Figure 6 shows, these two types also sustain more damage than the other types. I-type, SA-type, PS-type and V-type tend to have high ratios of damage, and PLPS-type and PV-type tends to have low ratios of damage. The insertion joint has an expansion and contraction mechanism, so the insertion-joint type conduits (PLPS-type and PV-type) are less likely to suffer damage than the other conduit types. I-type conduits, which were buried earlier than other types, tend to have a higher ratio of corrosion damage than the other steel conduits, so I-type tends to have a high ratio of damage than SA-type and PS-type.



a) Great Hanshin Earthquake b) Chuetsu Earthquake c) Chuetsu Offshore Earthquake

Figure 6. Damage situation regarding conduit type.

Figure 7 shows the damage situation of conduits with different lengths. The conduits in Kobe (the location of the Great Hanshin Earthquake) were built in a city area that these conduits are generally short, so there are few conduits that are 100 m or longer. In the Great Hanshin Earthquake, conduits less than 50 m long were heavily damaged; in the Chuetsu Earthquake and Chuetsu Offshore Earthquake, however, conduits longer than 100 m sustained heavy damaged. The ratios of damage for the three earthquakes tend to be higher as the length of the conduits increases. However, the increase in the ratios is moderate.

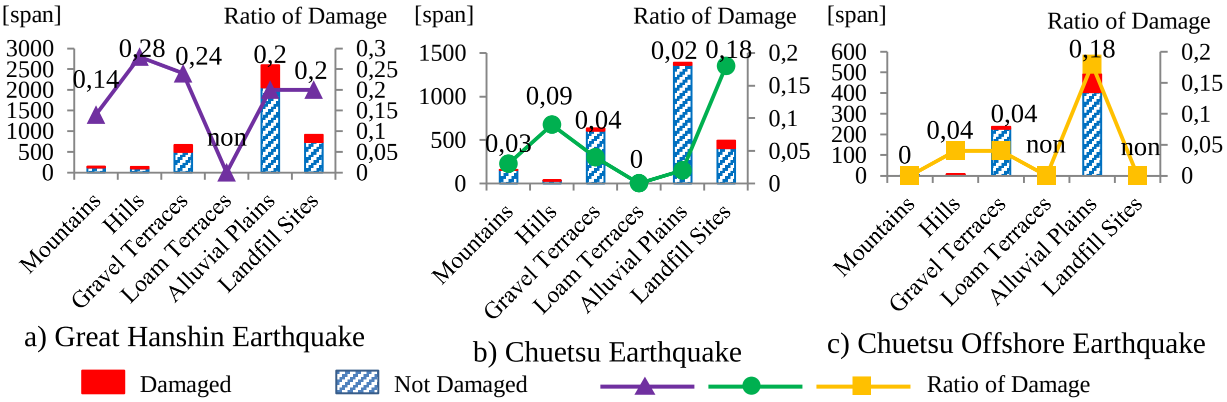


a) Great Hanshin Earthquake b) Chuetsu Earthquake c) Chuetsu Offshore Earthquake

🟥 Damaged ▨ Not Damaged Ratio of Damage

Figure 7. Damage situation of conduit regarding span lengths.

Figure 8 shows the damage situation of conduits in different topographies. Spans located in alluvial plains had the highest number of damaged conduits in all three earthquakes. The damage caused by the three earthquakes has a common trend: the ratio of damage for conduits in mountains is low, and the ratio is high in hills, gravel terraces and alluvial plains. Disregarding the lower number of landfill sites affected by the Chuetsu Earthquake, the overall ratio of damage in this type of topography is also high. In general, the ratio of damage for conduits tends to be higher in soft grounds. The damage ratio in hills and gravel terraces is usually considered to be low. But as mentioned above and shown in Figure 8, the damage ratio in these topographies are relatively low. One reason of this difference is estimated to be the existence of developed land in these areas. The influence of developed land to conduit damages are planned to be studied.



a) Great Hanshin Earthquake b) Chuetsu Earthquake c) Chuetsu Offshore Earthquake

🟥 Damaged ▨ Not Damaged Ratio of Damage

Figure 8. Damage situation of conduits regarding topographies.

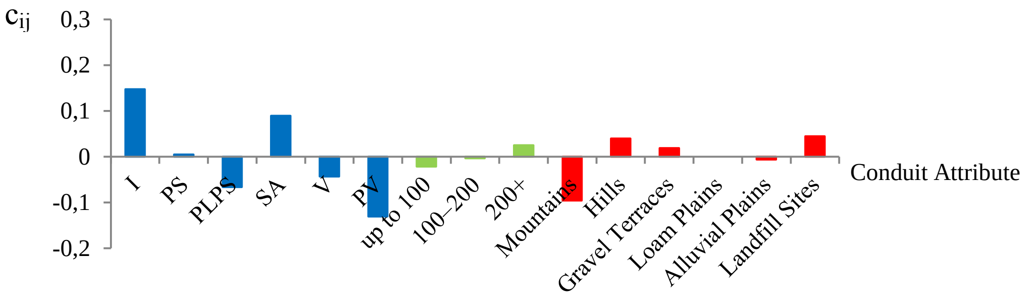
4. VULNERABILITY ANALYSIS USING CORRECTION COEFFICIENT

This chapter introduces a mathematical method with dummy variables to analyze the vulnerability of different conduit attributes. Building on previous study by Shoji et al. (2016), this method is based on the quantification theory (Type I). The correction coefficient can be calculated using a regression equation of the ratio of damage. For λ denoting a combination of different types of conduit, lengths, and topographies, let R_λ be the actual ratio of damage of each combination, and let R_λ^* be the regression model defined as shown in Equation 3. Here, N^i is the number of items i, $x_{ij\lambda}$ is a dummy variable, and c_0 is one constant item. The number of spans w_λ of each combination is introduced as weight. c_{ij} is the correction coefficient that gives the vulnerability of each attribute and can be calculated by minimizing the objective function ε shown in Equation 4. When the value of c_{ij} is positive, it means that the conduits with this attribute are more likely to sustain damage.

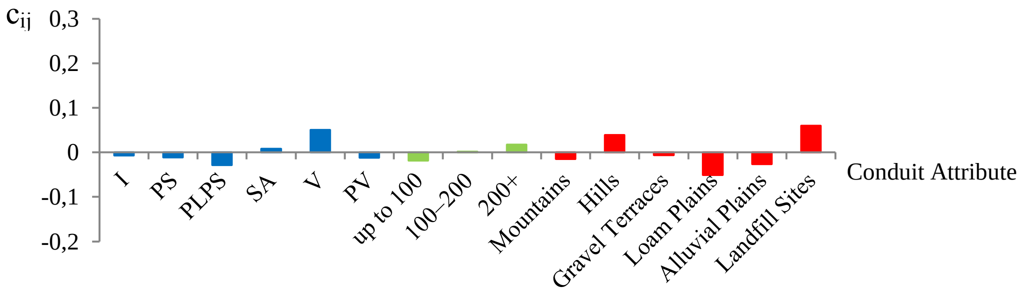
$$R_\lambda^* = \sum_{i=1}^{N^i} \sum_{j=1}^{N^{ji}} c_{ij}\, x_{ij\lambda} + c_0 \tag{3}$$

$$\varepsilon = \sum_{\lambda=1}^{N^\lambda} (R_\lambda - R_\lambda^*)^2 w_\lambda \tag{4}$$

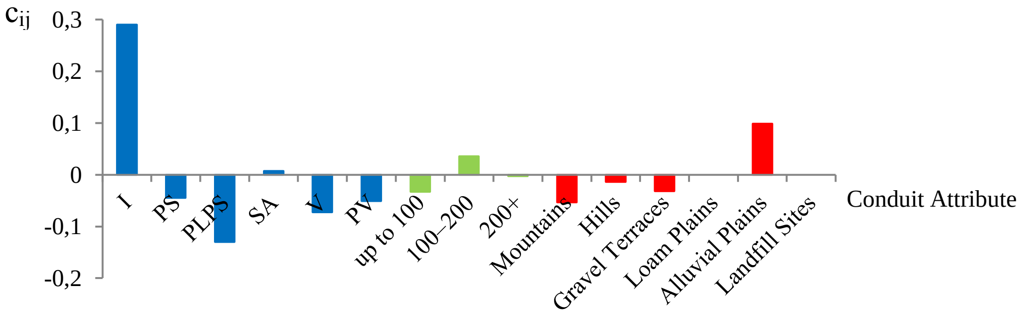
The c_{ij} results are shown in Figure 9. Calculating with the above equations, the PLPS-type and PV-type conduits have a negative c_{ij}, which means that these types of conduits have stronger seismic resistance than others. As the data in Figure 9 shows, conduits longer than 100 m are more likely to be vulnerable. As for topography, the c_{ij} of mountains are negative in all three earthquakes, which means that conduits buried in mountains are less likely to sustain damage, whereas the c_{ij} of landfill sites are positive in the earthquakes that had sufficient data for calculation, which shows that conduits buried in landfill sites are more likely to be damaged.



a) Great Hanshin Earthquake



b) Chuetsu Earthquake



c) Chuetsu Offshore Earthquake

Figure 9. c_{ij} of each conduit attribute.

5. CONCLUSIONS

This study discussed the damage situation of telecommunication pipelines after the 1995 Great Hanshin Earthquake, 2004 Chuetsu Earthquake, and 2007 Chuetsu Offshore Earthquake. We proposed *PGV* as more effective than *PGA* in models for calculating ratio of damage in telecommunication conduits. The damage tendencies of different conduit attributes were also analyzed, with the conclusion that insertion-joint conduits are more resistant to earthquake damage than other types of conduit, longer conduits are more likely to sustain damage, and conduits buried in mountains are less likely to sustain damage than conduits buried in other types of ground.

We also used a mathematical method that incorporated the correction coefficient to analyze the vulnerability of different conduit attributes. The PLPS-type and PV-type conduits were found to be more resistant to earthquake damage than the other types of conduit, conduits longer than 100 m were found to be more likely to sustain damage, and without considering the permanent ground deformation in landfill sites, mountains were found to be a relatively safe ground type, while landfill sites were more vulnerable than other types of ground.

The findings from this study will be used when implementing seismic countermeasures to decide which conduits are more vulnerable and should have countermeasures implemented first. More studies are required to discuss the influence of permanent ground deformation in landfill sites, and determine how to make models to calculate ratios of damage and how to analyze the effects of interactions between type of conduit, length, and topography, especially for inland earthquakes. The data gathered from the 2016 Kumamoto Earthquake will be added in future analysis. A rationale for selecting vulnerable underground conduits that should be prioritized for countermeasure installment will be proposed in future work. We consider that the methods used in telecommunication conduit studies can also be applied to studies of other underground lifeline facilities.

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