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A SEISMIC DAMAGE EVALUATION METHOD FOR WATER SUPPLY PIPELINES BASED ON SPATIAL GRADINENT OF PGA

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ABSTRACT

Conventional seismic damage estimations for water supply pipelines are primary based on ground motion index at the site, such as peak ground acceleration (PGA), velocity (PGV) and seismic intensity (SI). However, underground line structures suffer damage that is mainly induced by the strain of the ground and therefore are likely to be vulnerable to sharp spatial changes in the ground motion. In this study, we propose a new method for evaluating the seismic damage of underground water supply pipelines based on the spatial gradient of the PGV. We investigated the spatial distribution of the damage caused to water pipelines during the Niigata-ken Chuetsu earthquake on October 10, 2004 (Moment magnitude scale (Mw) of 6.6) and the Kobe earthquake on January 17, 1995 (Mw6.9) and compared the surveyed damage with the PGV distribution as well as with the gradients of the PGV calculated around the damage areas. Our results show that the distribution of damage to underground water supply pipelines exhibits a greater correlation with the gradients of the PGV than with the PGV itself. Thus, the gradient of the PGV is a useful index for preparing initial-screening hazard maps of underground facilities.

Damage Estimation; Seismic Design; PGV Gradient: Underground Water Pipeline; Conventional Approach

1. INTRODUCTION

Large earthquakes invariably induce the damage to lifeline facilities such as roads and gas and water pipelines as well as the life risk of the residents. The damage to roads isolates the affected regions, while the failure of gas and water supply pipelines further distresses the earthquake victims. In Japan, the 1995 Kobe earthquake (Moment magnitude scale (Mw) of 6.9) took the lives of thousands of people and hundreds of people have died due to the stress caused by the severe conditions of life (Hyogo Prefecture 2016). Therefore, most of all seismic codes of various lifeline structures were revised as well as those of bridges and buildings. The governments and lifeline suppliers gradually had been reinforcing the infrastructures regarding to the revised codes. However, the 2004 Niigata-ken Chuetsu earthquake (Mw 6.6) induced extensive damage to lifeline facilities such as roads and the water supply pipeline (WSP) in the Niigata prefecture. These earthquakes highlighted the importance of developing appropriate seismic assessment and damage prediction methods for lifeline facilities.
Conventional seismic evaluation methods for lifeline facilities are typically based on some type of a ground motion index. Jeon and O'Rourke (2005) studied the relationship between pipeline damage and the peak ground acceleration (PGA), the PGV, and the spectrum intensity corresponding to the 1994 Northridge earthquake, and found a strong correlation between the pipeline repair rate (for earthquake-induced pipeline damage), the pipe material used, and the PGV. Further, the American Lifelines Alliance (2005) has reported two simple methods for assessing transient ground movement: one is a chart method for water pipelines based on parameters such as the PGA, the PGV, and the permanent ground displacement and does not involve any mathematical calculations, while the another

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is an equivalent static method based on the ground strain, which is calculated using the PGV and the propagation speed of the seismic wave. Most self-governing bodies, lifeline facility companies, and government agencies in Japan use the PGA, PGV, seismic intensity, and degree of liquefaction or intensity as measured by instruments to predict the damage to lifeline facilities. For instance, G&E Engineering Systems Inc. (2005) has summarized the various damage assessment methods used for water pipelines according to their intended function and the pipe material used, based on the transient ground movement (i.e., the PGA and PGV) and the permanent ground displacement induced by landslides and liquefaction. The Tokyo Prefecture Office and the Japan Water Works Association have adopted methods based on the PGV for designing seismically sound WSPs. A large number of Japanese self-governing bodies use modified methods based on a technique that uses the PGA values (Kubo et al. 1975) obtained from damage assessment studies performed during the 1995 Kobe earthquake for predicting the seismic damage caused to water supply and sewer pipelines. Gas supply companies evaluate the damage that could be caused to gas pipeline networks by future earthquakes based on the PGV and spectrum intensity values. Indian Authority (2007) has reported a seismic design method for buried pipelines based on the axial ground strain calculated using the PGV for transient ground movements. Kuwata et al. (2009) determined the trend in the pipe repair rate for high-level ground motion through a numerical analysis while using the PGV. Using the PGV and the other above-mentioned measures has a number of advantages, in that they allow for real-time observations during earthquakes and can be used for quick damage predictions. However, a pipeline that is underground is more likely to be affected by strong local variations in the ground motion instead of the absolute values of the peak ground motion. To address this problem, O'Rourke et al. (2004) showed that the ground strain can be calculated using the PGV, the apparent wave velocity, and the predominant period of the seismic wave. The Eurocode (2006) also has a simple method for calculating the ground strain caused by the transient ground motion based on the Newmark method while using a sinusoidal wave and the apparent wave velocity (1967). However, it is difficult to estimate the apparent wave velocities or the predominant period of the seismic waves for future earthquakes. Paolucci and Smerzini (2008) introduced a method for calculating the in-plane strain tensor at the ground surface based on previous observations made using dense seismic arrays. This method might be useful for evaluating the strain distribution for well-recorded previous earthquakes but might not be appropriate for producing hazard maps for lifeline facilities in the case of future earthquakes. As mentioned above, the ground strain is considered a useful index for predicting the damage that will be incurred by underground pipelines. In fact, the major failure mode during the Kobe and Chuetsu earthquakes was reported to be cast-iron pipes falling off at the joints (Ballantyne 2010, Survey team on water supply utilities damages due to the Niigata-ken Chuetsu earthquake 2005). This type of failure is mainly caused by axial-ground-strain-induced tensile forces. (A bending failure is induced by a shear strain.) From this viewpoint, the change in the peak ground displacement (PGD), namely, the PGD gradient, would be a more suitable index for predicting damage to WSPs, since this index has the same unit as that of strain. However, it is difficult to calculate the PGD due to transient ground movements. This is because the amplification factor of the displacement is usually not known with as much accuracy as those of the PGA and PGV. In this paper, we propose a method based on the PGV gradient for evaluating the seismic damage of WSPs. In the rest of the document, we will present an outline of the method and its application in estimating the damage caused to WSPs by the 2004 Chuetsu and 1995 Kobe earthquakes. We will show that the PGV gradient is a better predictor of damage to WSP systems than is the PGV, which is the index used currently.

2. METHOD

2.1 Strong Motion Estimation

We used the following PGV distributions simulated using multi-asperity source models and three dimensional basin structures. Pulido and Matsuoka (2006) calculated the seismic bedrock strong motions during the Chuetsu earthquake using a hybrid method that combined wave propagation within a one-dimensional crustal model at low frequencies and a semi-stochastic modeling approach at high frequencies, and estimated the PGV values with the identified amplification factors. Matsushima and

Kawase (2009) estimated the ground motions at the upper layer corresponded to an S-wave velocity of 350 m/s during the Kobe earthquake, based on a three-dimensional finite difference method using the rupture model consisted of five rectangular strong-motion-generation areas. We calculated the PGV at the ground surface for a mesh with a size of 250 m by multiplying the simulated strong ground motions by amplification factors (Fujimoto and Midorikawa 2006).
In order to estimate the differential ground motions that could be a potential source of damage to water supply pipeline during an earthquake, we calculated the gradients of the PGV (G) along the geographical coordinates based on the simulated PGV values for a dense and uniform grid mesh as follows;

$$G = \left| \frac{\partial PGV_{xy}}{\partial x} \boldsymbol{i} + \frac{\partial PGV_{xy}}{\partial y} \boldsymbol{j} \right| \tag{1}$$

where PGV_{xy} is the peak ground velocity in the x, y grid, and ***i*** and ***j*** are the unit vectors along the east and north directions.
We calculated the PGV and PGV gradient values at the center of every grid cell of 250 m where WSP damage had been observed previously.

2.2 Damage to Water Supply Pipelines

A survey of the damage sustained by WSPs during the Chuetsu earthquake revealed that the Nagaoka and Ojiya cities water system suffered damage at 329 and 95 locations, respectively. While during the Kobe earthquake, the WSP damage locations are defined as the point-wise repair locations and the number of locations amounted to 1,367 in Kobe city. Where the damage to WSP contains the ones presumed to be caused by earthquake-induced liquefaction and landslide.
In order to estimate the extent of WSP damage, we determined the WSP repair and damage rates within the three cities. We defined the WSP damage rate (WDR %), as follows;

$$WDR = \frac{Nw}{Lw} \tag{2}$$

where Nw is the number of damaged WSPs (count) and Lw is the WSP length (in km). We estimated the relationship between the WDR and the simulated PGV and PGV gradient values. For all the analyses involving the PGV and PGV gradient, the WDR was calculated for PGV or PGV gradient values averaged for a WSP length of 50 km. Specifically, we prepared a dataset of the number of WSPs damaged, the pipeline length, the PGV and PGV gradient per mesh. This dataset was sorted by the WDR values and PGV or PGV gradient, and the PGV and PGV gradient were calculated as an average for every 50 km.

3. RELATIONSHIP BETWEEN STRONG MOTION AND DAMAGE TO WATER SUPPLY PIPELINES

3.1 The Chuetsu Earthquake

3.1.1 Peak Ground Velocity (PGV)

Figure 1 shows the points where the WSPs were damaged during the Chuetsu earthquake overlapping with the simulated PGV values. It can be seen from the figure that the WSP damage points are located along a narrow region with a width of 5 km and oriented along the NNE-SSW direction. It can also be seen that most of the points are not concentrated around the highest simulated PGV values in the region, which are mostly higher than 80 cm/s. The WSP damage points are mainly concentrated in the areas with PGV values lower than 60 cm/s and 80 cm/s in the cases of Nagaoka and Ojiya cities, respectively. The previous results suggested that the damage to the WSPs was not highly correlated to the PGV values.

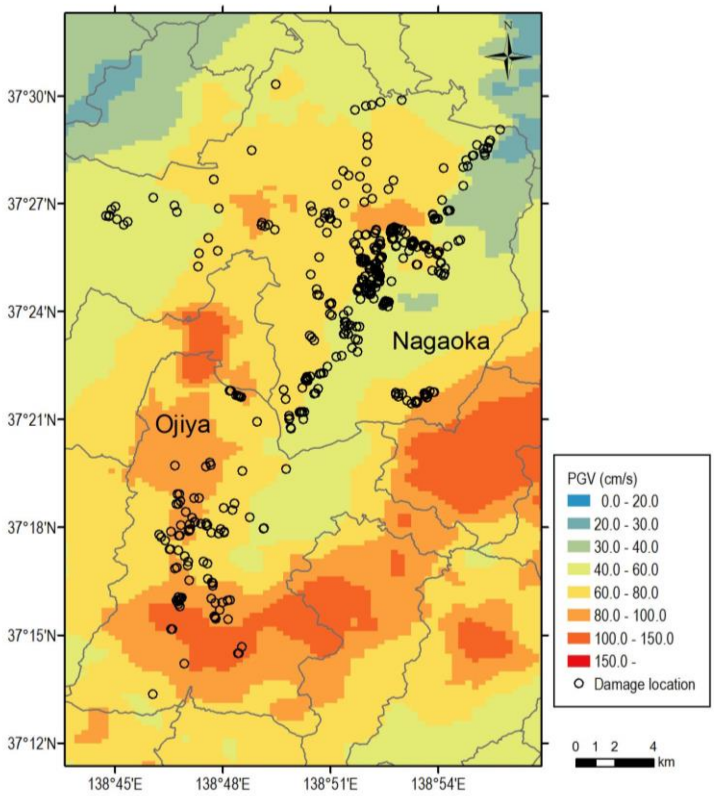

Figure 1. Simulated PGV distribution and locations of WSP damage points. (Chuetsu earthquake)

On the other hand, we noticed that the WSP damage points align perfectly along a region in which the PGV values change rapidly from 40 cm/s to 80 cm/s. This change in the PGV begins at the boundary between two dissimilar geomorphological units, namely, the mountainous region to the east of Nagaoka city and the alluvial fans to the west of the city. The previous observations strongly suggested that the damage to the WSPs might have originated from the large spatial variations in the ground motion and were not related to the actual magnitude of the motion. These variations can be explained on the basis of pronounced spatial changes in the site amplifications arising from dissimilarities in the geomorphologies, which were incorporated in the ground motion simulations.
Figure 2 shows the relationship between the WDR and the simulated PGV values.

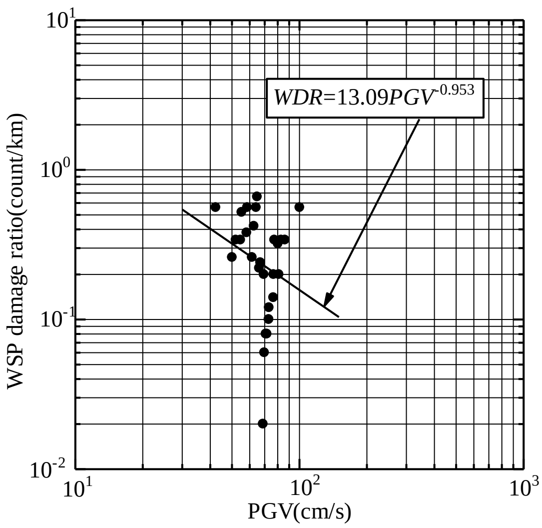

Figure 2. Relationship between the WDR and PGV values. (Chuetsu earthquake)

It can be seen from Figure 2 that the correlation between the simulated PGV and WDR values is very poor (correlation coefficient R = 0.22). These results together with the observations shown in Figure 1 strongly suggest that the WSP damage is not highly correlated to the PGV. An inspection of the above-mentioned database also indicated that most of the WSP systems in Nagaoka and Ojiya cities experienced PGV values between 50 cm/s and 90 cm/s. The plotted dataset for this study was calculated using the weighted means method. Therefore, the regression lines corresponding to the different WSP lengths should have been approximately coincident.

3.1.2 Peak Ground Velocity Gradient (PGV Gradient)

Figure 3 shows the points of damage to the WSPs on a map of the simulated PGV gradients within the Chuetsu region. This figure suggests that there is a higher correlation between WSP damage and the PGV gradients. It can be seen that most of the points of damage to the WSPs align perfectly along stripes with high PGV gradients; the exception is a cluster of damage points enclosed by a red ellipse in Figure 3. This cluster actually corresponds to an area damaged by landslides. The observed good agreement between the extent of WSP damage and the PGV gradients may be explained by the fact that lifeline structures such as water and gas pipelines suffer damage because of the axial or shear strain of the ground along the length; this strain is likely generated by out-of-phase ground vibrations along the structure.

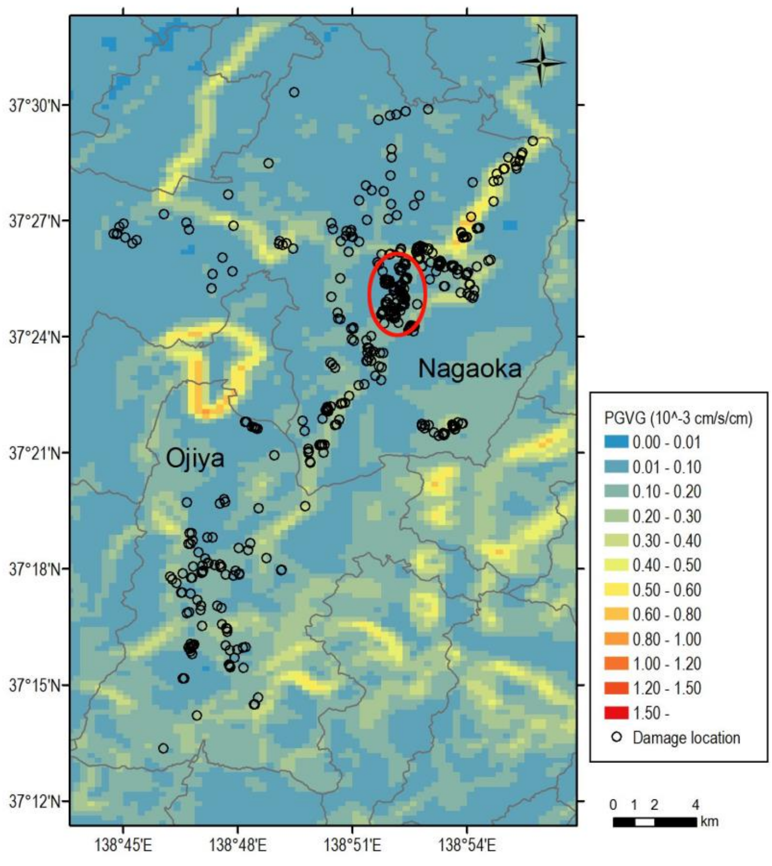

Figure 3. Simulated PGV gradient distribution and locations of WSP damage points. (Chuetsu earthquake) The region enclosed by a red ellipse, which is a landslide-affected area.

Figure 4 shows the relationship between the WDR and the PGV gradients. It can be seen from Figure 4 that there is good agreement between the PGV gradients and the WSP damage rate (correlation coefficient R = 0.62). A comparison of Figure 2 and Figure 4 shows clearly that the WDR exhibits a significantly higher correlation with the PGV gradients than with the PGV values.

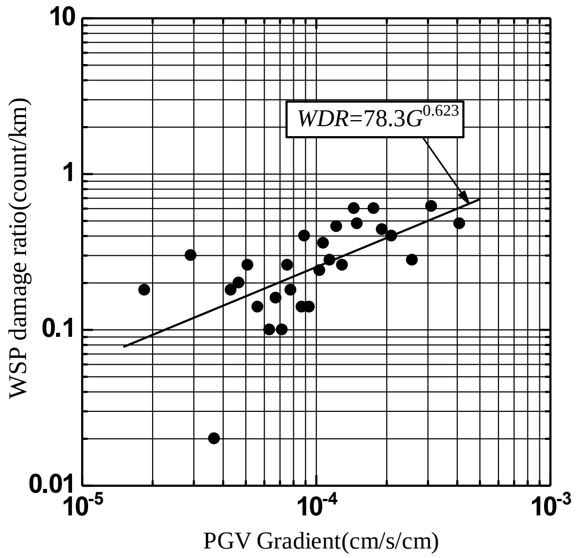

Figure 4. Relationship between the WDR and PGV gradient values. (Chuetsu earthquake)

3.2 The Kobe Earthquake

3.2.1 Peak Ground Velocity (PGV)

In this section, we examine the relationship between WSP damage and strong ground motion during the 1995 Kobe earthquake. The damage to WSPs was digitized in the vector format using paper-based maps. Figures 5 shows the PGV distribution and the locations of WSP damage points. The WSP damage points are defined as the point-wise repair locations.

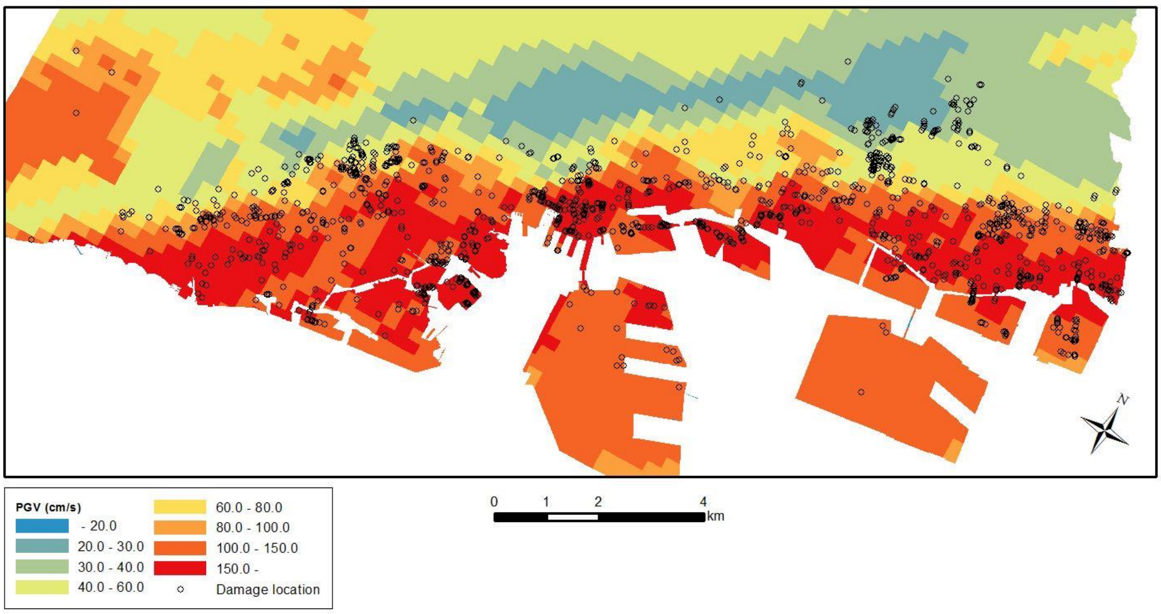

Figure 5. PGV distribution and locations of WSP damage points in Kobe city. (Kobe earthquake)

It can be seen from Figure 5 that approximately half of the WSP damage points coincide with an area with a PGV value greater than 100 cm/s. However, the other half of the WSP damage points are located on a mountain side and in areas with comparatively smaller PGV values.

Figure 6 shows the relationship between the WDR and the simulated PGV values for the Kobe and

Chuetsu earthquakes. For all the analyses involving the PGV, the WDR was calculated for the PGV values averaged for a WSP length of approximately 50 km. The figure presents three water supply pipeline vulnerability relations: The first (orange) is the fragility curve proposed by Maruyama and Yamazaki (2009) based on the damage data during the 2007 Noto-Hanto and the 2007 Niigate-ken Chuetsu-oki earthquakes, as well as the Kobe and the Chuetsu earthquakes. The second (light blue) is the damage predictive relation without liquefaction information, a relation commonly used in Japan. It represents the standard damage rate curve calculated using the damage data of the Kobe earthquake by Isoyama et al. (1998), by obtaining the products of the parameters and the coefficient factors of pipe material, diameter, and so on. The third (blue) is the curve obtained by multiplying the standard damage rate and the coefficient factor of DIP (= 0.3). Herein, DIP was generally used pertaining to the Kobe and Chuetsu regions.
It can be seen from the Figure 6 that the correlation between the simulated PGV values and the WDR is better (correlation coefficient R = 0.47) than that of only the Chuetsu earthquake. Furthermore, the correlation coefficient between the simulated PGV values and the WDR for only the Kobe earthquake was 0.79.

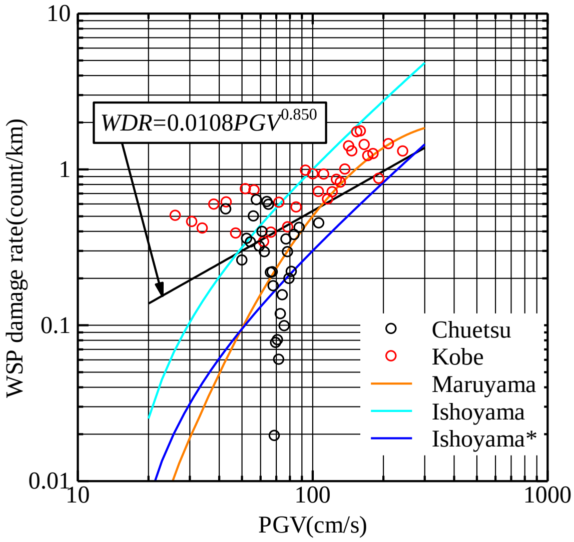

Figure 6. Relationship between the WDR and PGV values. (Kobe and Chuetsu earthquakes)

The WDR values for the Kobe earthquake were higher than the ones corresponding to the equivalent PGV range for the Chuetsu earthquake. This difference between the Kobe and Chuetsu earthquakes can be explained by the fact that the degree of liquefaction-induced damage to WSPs during the Kobe earthquake was much larger than that during the Chuetsu earthquake. This was because liquefaction at a site is strongly correlated to the seismic characteristics at the site, such as the PGV value and the seismic intensity.

3.2.2 Peak Ground Velocity Gradient (PGV Gradient)

Figures 7 shows the PGV gradient distribution and the locations of WSP damage points.
It can be seen from the figure that the distribution of the PGV gradient exhibits a high correlation with the damage points, especially on the eastern side of the map, with the WSP damage points being concentrated in the area with a PGV gradient greater than 0.40×10^{-3} cm/s/cm. However, there are a few regions where the WSP damage points do not overlap with the PGV gradient distribution. For example, in the Uzugamoridai and Sumiyoshiyamate areas, which are located within the red ellipse in Figure 7, a large number of landslides or tensile cracks were observed around places of residence, while in the middle of Port Island severe damage due to liquefaction had occurred. The landslides and liquefaction at these spots were caused by strong ground motion; however, the damage was not related to a change in the motion.
Figure 8 shows the relationship between the WDR and the simulated PGV gradients.

It can be seen from the figure that the correlation between the WDR and the PGV gradients (correlation coefficient R = 0.83) is even better than that between the WDR and the PGV values for the Kobe earthquake. Further, this trend is similar to the one observed in case of the Chuetsu earthquake. The data corresponding to the Kobe earthquake confirm the relationship between the WDR and the PGV gradient for a large range of gradient values, with the trend being the same as that in the case of the Chuetsu earthquake. This result indicated that the ground strain increases around the boundary between two dissimilar geomorphological regions with a marked difference in their Vs30 values, owing to which the damage to WSPs is concentrated around the boundary. Therefore, we proposed the equation relating the PGV gradient (G, in cm/s/cm) and the WDR (in count/km) for as a WSP damage rate estimator for future scenario earthquakes:

$$WDR = 46.0G^{0.550} \quad (3)$$

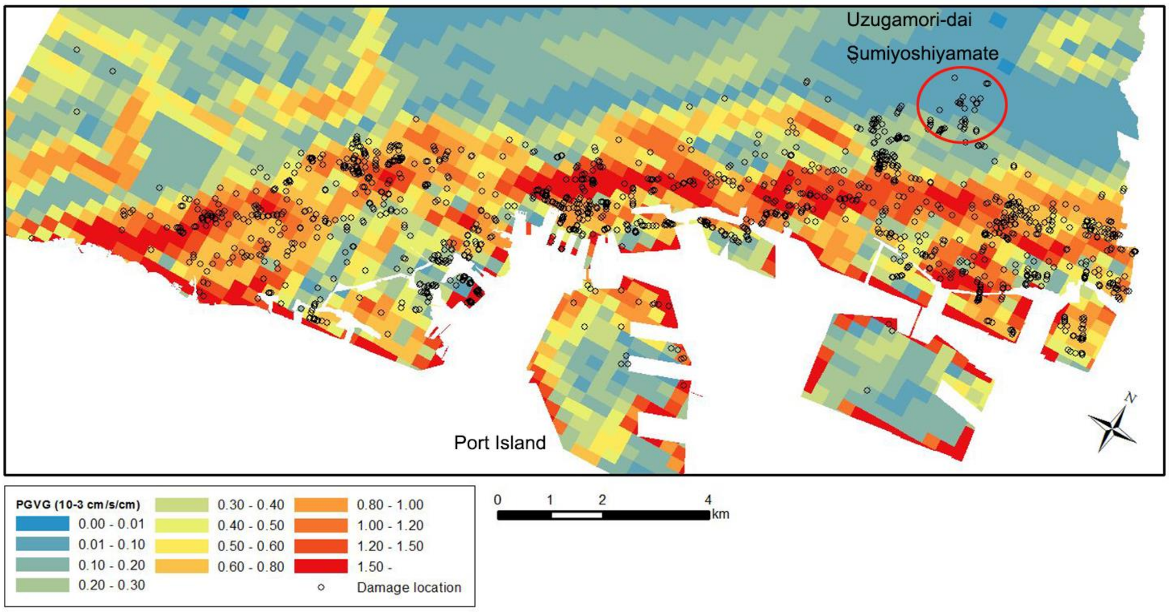

Figure 7. PGV gradient distribution and locations of WSP damage points. (Kobe earthquake)

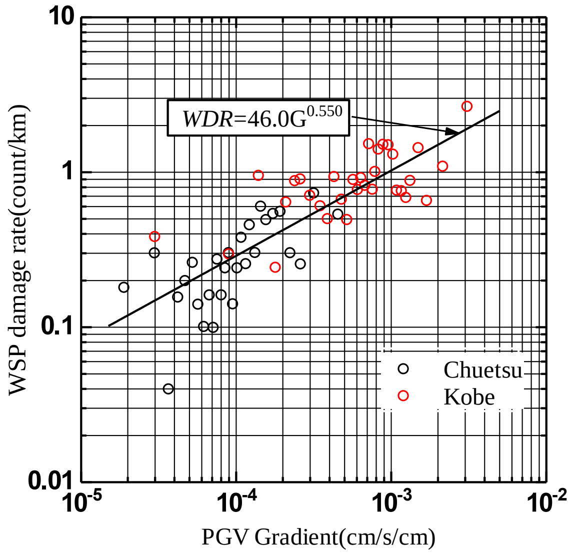

Figure 8. Relationship between the WDR and the simulated PGV gradients. (Chuetsu and Kobe earthquakes)

Herein, the lowest threshold of PGV gradient can be 1.5X10^{-5} cm/s/cm for equation (3) on the safe side. Because, from the original data of damage to the WSPs and the PGV gradient without averaging for WSP length of about 50km, no damage to the WSPs occurred under PGV gradient of 1.2X10^{-5} cm/s/cm in the Chuetsu and Kobe cases. From Figures 3 and 7, we can observe that no damage points are located in meshes under the PGV gradient of 1.0X10^{-5} cm/s/cm.

4. DISCUSSION AND CONCLUSIONS

We developed a new method to estimate the damage incurred by WSPs owing to earthquakes, based on the peak ground velocity gradients (PGV gradients), which were obtained from simulated PGV values that incorporated the site amplifications (every 250 m). We surveyed the damage to WSPs in Ojiya and Nagaoka cities in the Niigata prefecture during the 2004 Chuetsu earthquake and analyzed the distribution of the damage points based on the simulated PGV and PGV gradient values. Our results indicate that the majority of the points of damage to WSPs are located along stripes of lands with high PGV gradient values. These gradients are associated with rapid changes in the PGV at the boundary between two dissimilar geomorphologic units, namely, the mountainous region to the east of Nagaoka city and the alluvial fans to the west of the city. Further, the results show that there is a statistically significant correlation between the WSP damage and the PGV gradients. A possible explanation for this strong correlation is that the damage incurred by underground structures such as water and gas pipelines is due to a severe axial or shear strain of the ground surrounding the structures, which is generated by the differential motions of the ground. We also examined the applicability of the proposed method in understanding the characteristics of damage to WSPs in Kobe city during the 1995 earthquake in the city. For this earthquake, the location of the WSP damage points do not always correspond to the areas with large PGV values, in contrast to the case for Nagaoka and Ojiya cities during the Chuetsu earthquake. On the other hand, the areas with PGV gradients values higher than 0.4X10^{-3} cm/s/cm showed a high degree of correlation with the WSP damage; the exception were the areas that experienced widespread landslides or tensile cracks in the soil. The results of the statistical analyses of the Chuetsu and Kobe earthquakes demonstrate that the PGV gradient is correlated to a greater degree to the WSP damage rate than is the PGV. Further, the results show that the wide range of the WSP damage data corresponding to the two earthquakes can be explained based on a common linear empirical relationship with the PGV gradients.

Based on the above-mentioned analyses of the Chuetsu and the Kobe earthquakes, we derived an empirical relationship to predict the WSP damage rate from earthquakes based on the PGV gradients. The proposed method is not applicable in the case of regions that experience widespread liquefaction or landslides during earthquakes. We are aware that highly detailed estimates of WSP damage from earthquakes may require information regarding the material used for the pipelines as well as their intended function, in addition to the effects of the permanent ground displacement induced by the landslides and liquefaction. However, we consider that the proposed method is suitable for obtaining an initial estimate of WSP damage because of scenario earthquakes for large regions.

5. ACKNOWLEDGMENTS

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