Development of seismic damage estimation index for service lines with seismic resistant spring

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SUMMARY:
When a large scale earthquake occurs, many service lines, which connect electric power distribution equipment to electric power receiving buildings, such as residential homes or commercial buildings, to supply electric power, are simultaneously damaged due to the shaking and damage not only to the electric power equipment but also to the connected buildings. Therefore, in order to reduce the seismic damage of the service lines, the Tohoku Electric Power Company has applied a shock-absorbing spring as a seismic resistant device to the service lines. This paper proposes a seismic damage index to evaluate the seismic resistant capacity of service lines with and without the shock-absorbing spring. Based on the seismic damage record due to the 2007 Niigata-Ken Chuetsu-Oki earthquake, the seismic damage reducing degree of the shock-absorbing spring is discussed. As a result, it was clarified that if the shock-absorbing springs are installed in all service lines in a target area, the total amount of seismic damage to service lines in a target area decreased to 60%.

Keywords: Disaster Restoration, Earthquake, Damage Estimation, Service Lines, Shock-Absorbing Spring

1. INTRODUCTION

Since electric power distribution equipment has been installed on seismically vulnerable ground conditions and ambient surroundings in a wide range of electric power supply areas, when a large scale earthquake occurs, a lot of electric power distribution equipment including the pole, line, transformer and service line is simultaneously damaged. It usually takes a long time to find such damaged equipment by inspection after a seismic event. Therefore, highly accurate damage estimation technologies are desirable in order to support emergency restoration work of the seismic damaged electric power equipment.

Fig. 1.1 shows the percentage of damage modes associated with the electric power distribution equipment caused by the 2007 Niigata-Ken Chuetsu-Oki earthquake (Shumuta et al., 2011). The percentage of damaged service lines is the highest of all the damage modes. In order to reduce the seismic damage of service lines, the Tohoku Electric Power Company has applied a shock-absorbing spring as a seismic resistant device for the service lines. Photo 1.1 shows the shock-absorbing spring actually installed on a service line in an electric power service area of the Tohoku Electric Power Company.

Fig.1.2 shows the relationship between the measured seismic intensity and the damage rate of service lines caused by the 2007 Niigata-Ken Chuetsu-Oki earthquake. Fig.1.2 shows that the damage rate for the measured seismic intensity of 5.3 is the highest value for all the measured seismic intensities. In this case, it is assumed that some factors including soil condition other than the measured seismic intensity greatly influence the damage of service line. This result suggests that the seismic intensity does not necessarily have a high correlation with the damage rate of the service lines.

In order to accurately estimate the seismic damage of service lines, Takabatake et al., (2011) proposed a damage index for the service lines. However, because the existing damage index does not consider the existence of the shock-absorbing spring, it cannot evaluate the seismic damage reduction degree by the shock-absorbing spring. Therefore, this paper proposes a modified seismic damage index of service lines with and without the shock-absorbing spring. In order to verify the validity of the proposed model, the evaluation results by the proposed model are compared to those by a structural analysis based on the finite element method. In order to demonstrate the effect of the shock-absorbing spring, the proposed model is applied to an actual seismic damaged area due to the 2007 Niigata-Ken Chuetsu-Oki earthquake. In this case-study, the reasonable mechanical properties of the shock-absorbing spring used in the target seismic damaged area are discussed.

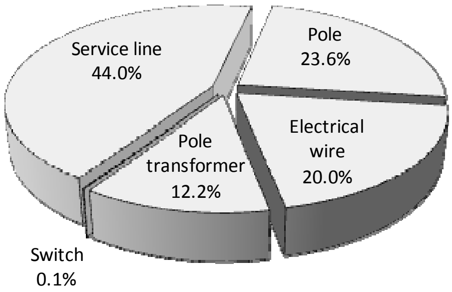


Figure 1.1 Percentage of damage modes associated with the electric power distribution equipment caused by the 2007 Niigata-Ken Chuetsu-Oki earthquake

Photo 1.1 Shock-absorbing spring

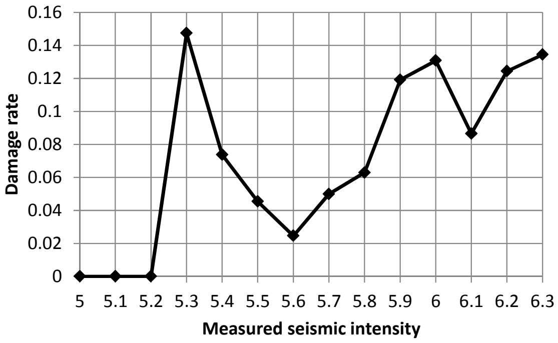
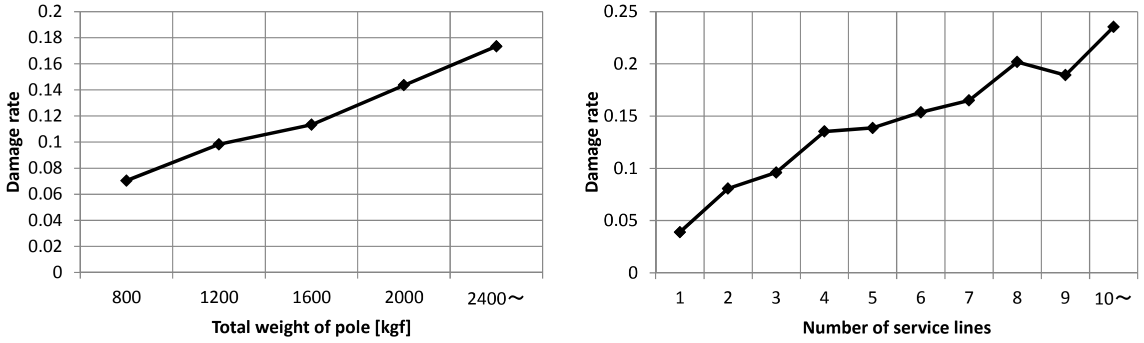


Figure 1.2 Relationship between the measured seismic intensity and the damage rate of the service lines caused by the 2007 Niigata-Ken Chuetsu-Oki earthquake

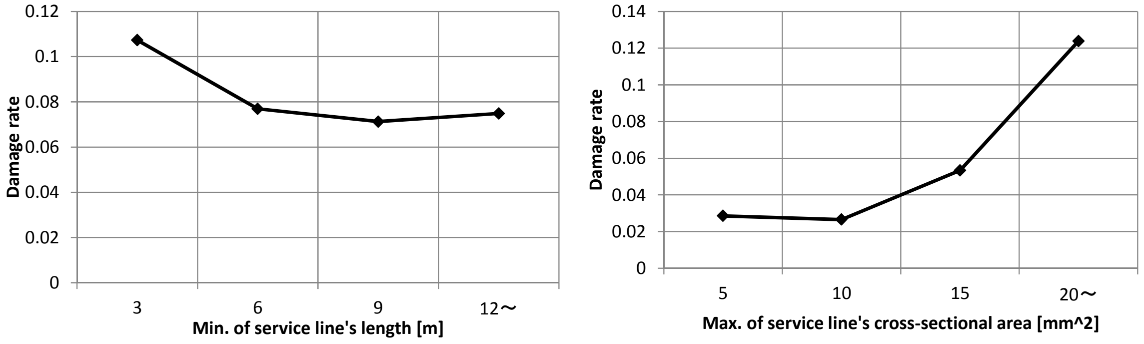
2. FORMULATON OF THE SEISMIC DAMAGE INDEX FOR SERVICE LINES WITH SHOCK-ABSORBING SPRING

2.1. Damage Characteristic of Service Lines and Basic Idea of the Proposed Model

As a proactive discussion, we investigated physical characteristics information of actually installed service line from an existing equipment database that Tohoku Electric Power Co. manages and selected high sensitivity physical characteristics against the damage rate of service line. For example, Fig. 2.1 shows the relationship between four physical characteristics of the distribution equipment and the damage rate of service lines caused by the 2007 Niigata-Ken Chuetsu-Oki earthquake. A typical seismic damage mode of the service lines is a torn loose from the electric power receiving buildings due to the large tension caused by an earthquake. Fig. 2.1(a) shows that the damage rate of the service line increases as the total weight of each pole including the pole, cables and transformers linearly increases. This result suggests that the total weight of the pole has a high correlation with the damage rate of the service line. Similarly, as shown in Figs. 2.1(b), (c) and (d), three other characteristics including the number of service lines, the shortest length of service lines on a pole, and the cross sectional area of the largest diameter service line installed on a pole also have a high correlation with the damage rate of the service line. These results suggest that these four characteristics become the dominant parameters to evaluate the seismic damage of service lines.



(a)The total weight of pole (b)The number of service lines



(c) The shortest length of service line (d) The cross-sectional area of the largest service line

Figure 2.1 Relationship between four physical characteristics and the damage rate of the service lines caused by the 2007 Niigata-Ken Chuetsu-Oki earthquake

2.2. Formulation of the Tension of the Service Line

In order to propose a seismic damage index, this study focused on the tension of the service line caused by a seismic event. The left picture of Fig.2.2 shows a typical installation of the service line, the shock-absorbing spring, the distribution plant, and the residential home. In order to evaluate the generation tension of the service line, the analytical conditions are assumed as follows based on a proactive analysis:

1. No effect from adjacent poles on the tension of a target service line.
2. The half weight on one span of a connected electric cable and the height of the installed electric cable are considered.
3. The weight and the installation height of the transformers are considered.
4. No effect from adjacent service lines installed on the same pole.

5. The installation position of the service line in an electric power receiving building does not change due to seismic force.

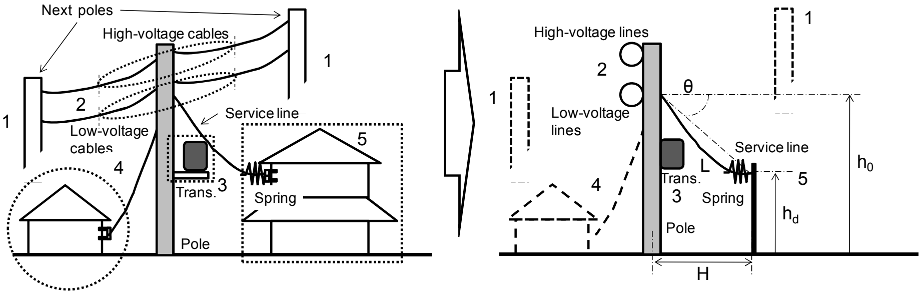


Figure 2.2 Analytical conditions

2.2.1 The equivalent seismic load to generate the tension on the service line

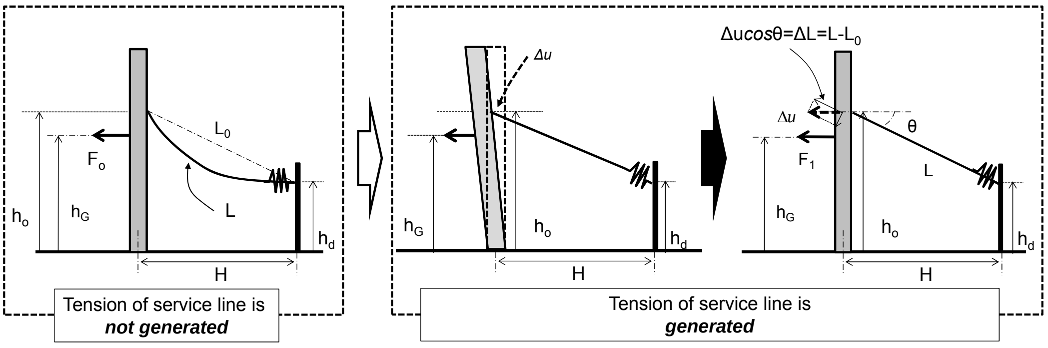


Figure 2.3 Conceptual figure for evaluating the tension of service line

As shown in Fig.2.3, it is assumed that the tension of each service line is not generated until the amount of the pole translation exceeds the sag degree of the service line. Note that the pole transformation is very low compared to the pole height. The seismic load to deform the pole F_1 is evaluated by

$$F_1 = \begin{cases} \dfrac{6E_pI_p\Delta u\cos\theta}{h_G^3\left(3\left(\frac{h_0}{h_G}\right)^2-\left(\frac{h_0}{h_G}\right)^3\right)} & for\ h_0 \geq h_G \\ \dfrac{6E_pI_p\Delta u\cos\theta}{h_G^3\left(3\left(\frac{h_0}{h_G}\right)-1\right)} & for\ h_0 < h_G \end{cases} \tag{2.1}$$

where h_0 is the installation height of service line at the pole, h_G is the height where the equivalent seismic load acts on, E_p is Young's module of the pole and I_p is the second moment of the area of the pole. The angle between the horizontal line and the line joining both sides of the service line θ is calculated by the horizontal distance between the pole and the electric power receiving buildings H and the installation height of the service line on the electric power receiving buildings h_d. The horizontal deformation displacement of the pole Δu caused by F_1, is evaluated by

$$\Delta ucos\theta = L - L_0 = \Delta L \tag{2.2}$$

where L is the length of the service line and L_0 is the distance between both sides of the service line after the pole deformed. The seismic load F to generate the tension of the service line is evaluated by

$$F = F_0 - F_1 = \begin{cases} F_0 - \frac{6E_pI_p\Delta u\cos\theta}{h_G^3\left(3\left(\frac{h_0}{h_G}\right)^2 - \left(\frac{h_0}{h_G}\right)^3\right)} & for\ h_0 \geq h_G \\ F_0 - \frac{6E_pI_p\Delta u\cos\theta}{h_G^3\left(3\left(\frac{h_0}{h_G}\right) - 1\right)} & for\ h_0 < h_G \end{cases} \tag{2.3}$$

where F_0 is the total seismic load evaluated as the total inertial force of the pole, cables and transformers.

2.2.2 Tension of each service line without the spring

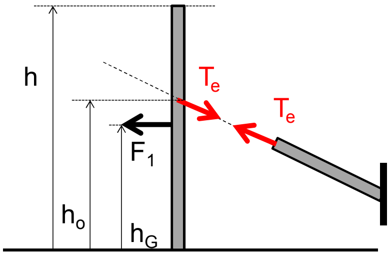


Figure 2.4 Statically-indeterminate problem for evaluating the tension of each service line

Fig. 2.4 shows statically-indeterminate problems for evaluating the tension of the service line. In this problem, the strain energy of the pole U_p and that of the service line U_s are evaluated by

$$U_p = \frac{1}{E_pI_p}\int_0^h \{M(x)\}^2 dx \tag{2.4}$$

$$U_s = \frac{L{T_e}^2}{2E_sA_s} \tag{2.5}$$

where $M(x)$ is the function for the bending moment of the pole, T_e is the tension of the service line, h is the height of the pole, E_s is Young's module of the service line and A_s is cross-sectional area of the service line.

The function for the bending moment of pole $M(x)$ is evaluated by

$$\begin{aligned} M(x) &= \begin{cases} (T_eh_0 - Fh_G) - (T_e - F)x & (0 \leq x \leq h_G) \\ T_eh_0 - T_ex & (h_G \leq x \leq h_0) \\ 0 & (h_0 \leq x \leq h) \end{cases} \quad for\ h_0 \geq h_G \\ M(x) &= \begin{cases} (T_eh_0 - Fh_G) - (T_e - F)x & (0 \leq x \leq h_0) \\ -Fh_G + Fx & (h_0 \leq x \leq h_G) \\ 0 & (h_G \leq x \leq h) \end{cases} \quad for\ h_0 < h_G \end{aligned} \tag{2.6}$$

Castigliano's principle of least work is expressed as

$$\frac{\partial U}{\partial T_e} = \frac{\partial(U_p + U_s)}{\partial T_e} = 0 \tag{2.7}$$

where U is the total of the strain energies. Base on equations (2.4) ~ (2.7), the tension of the service line without the spring is evaluated by

$$T_e = \begin{cases} \frac{\left(-h_0^3+3h_0^2 h_G\right) F E_s A_s \cos\theta}{2h_0^3 E_s A_s \cos^2\theta + 6LE_p I_p} & for\ h_0 \geq h_G \\ \frac{-\left(h_0^3-3h_0 h_G^2\right) F E_s A_s \cos\theta}{2\left\{h_0^3+(h_0-h_G)^3\right\} E_s A_s \cos^2\theta + 6LE_p I_p} & for\ h_0 < h_G \end{cases} \tag{2.8}$$

2.2.3 Tension of each service line with the spring

If the shock-absorbing spring is installed on a service line, the tension of the spring is equal to that of the service line with the spring. Thus, the strain energy of the spring U_{ss} is evaluated by

$$U_{ss} = \frac{{T_e}^2}{2k} \tag{2.9}$$

where k is the spring constant of the spring.

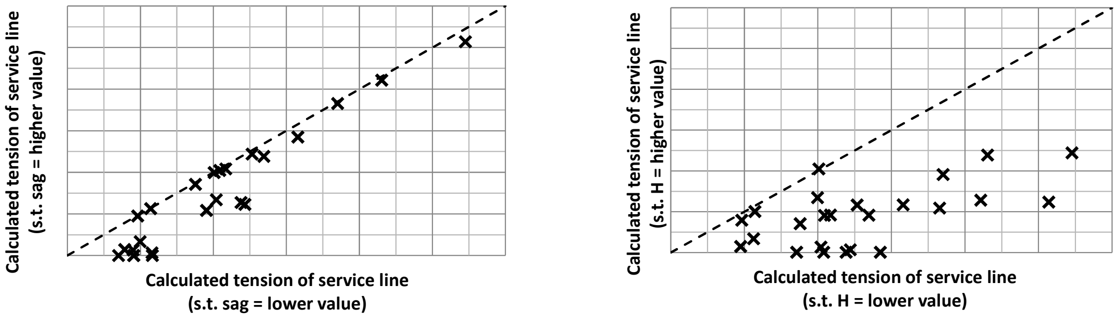
Base on Castigliano's principle of least work, the tension of service line with a spring is evaluated by

$$T_e = \begin{cases} \frac{\left(-h_0^3+3h_0^2 h_G\right) F E_s A_s \cos\theta}{2h_0^3 E_s A_s \cos^2\theta + 6LE_p I_p\left(1+\frac{E_s A_s}{k}\right)} & for\ h_0 \geq h_G \\ \frac{-\left(h_0^3-3h_0 h_G^2\right) F E_s A_s \cos\theta}{2\left\{h_0^3+(h_0-h_G)^3\right\} E_s A_s \cos^2\theta + 6LE_p I_p\left(1+\frac{E_s A_s}{k}\right)} & for\ h_0 < h_G \end{cases} \tag{2.10}$$

2.3. Formulation of a Proposed Seismic Damage Estimation Index for Service Lines

Table 2.1 Parameters for evaluating the seismic damage index for service lines

	NOTE	PARAMETER	DATABASE	SENSITIVITY
POLE	E_p	Young's module	OK	-
	I_p	Second moment of area	OK	-
	h	Height of pole	OK	-
SERVICE LINES	L	Length	OK	-
	E_S	Young's module	OK	-
	A_S	Area	OK	-
	h_d	Installation height of service line on building	NG	High
	h_0	Installation height of service line on pole	NG	Low
	H	Horizontal distance between building and pole	NG	High
	s	Sag ratio	NG	Low



(a)Sag ratio

(b) Horizontal distance between building and pole

Figure 2.5 Examples of sensitivity analysis

Table 2.1 shows the parameters for evaluating the tension of a service line. s is the sag ratio of a service line. s is needed to evaluate L_0. In the DATABASE column in Table 2.1, OK indicates a parameter whose physical characteristics information is obtained from the existing equipment database. On the other hand, NG indicates a parameter whose physical characteristics information is unknown.

In order to reasonably assume such unknown parameters, a sensitivity analysis between the tension of the service line and target unknown parameter values is performed based on Takabatake et al., (2011). The ranges of target unknown parameter in a sensitivity analysis are assumed based on the Japan Electric Technical Standards and Codes Committee (2007) and expert opinions. On the other hand, the known parameters including E_p, I_p, h, E_S and A_S are set based on the standard pole; a reinforced concrete pole with the commonly used height in Tohoku Electric Power Co. is assumed. Fig2.5 shows examples of sensitivity analysis result. Fig.2.5(a) shows the comparison of the tensions evaluated by lower sag ratio and by higher sag ratio. The horizontal and vertical axes show the tension of service line at sag ratios of lower value and higher value respectively. In this case, other parameters are fixed as same values. In addition the distance r from every plot point to the dashed line corresponding to the equal tension of the service line on the horizontal and vertical axes was calculated, and the mean value of r was found. This value is interpreted as a measure of the influence of parameter variation on the tension of the service line. In the case such as sag ratio shown in Fig.2.5(a), because the plot points lie near to the dashed line and the mean of r is small, the sensitivity is likely to be low. On the other hand, in Fig.2.5(b), the plot points are distant from the dashed line and he mean value of r is large. Hence the sensitivity of H is high. In the SENSITIVITY column in Table 2.1, High and Low indicate that the target unknown parameter has a high and low sensitivity to the tension of the service line, respectively. Table 2.1 shows that h_0 and s have low sensitivities to the tension. On the other hand, h_d and H have high sensitivities to the tension. Because the damage rate of a service line has a high correlation with the number of service lines installed on the same pole, the seismic damage index for the service lines T_G, is evaluated by

$$T_G = \frac{T_A}{\sum_{i=1}^{n} T_{ei}} \tag{2.11}$$

where T_A is the allowable tension of the service line, n is the number of service lines installed on the same pole and T_{ei} is the tension of service line i. Note that the average of n is three, maximum of n is 31 and n of more than 90% of poles is five or lower.

2.4. Damage Function of Service Line

Based on the seismic damage record due to the 2007 Niigata-Ken Chuetsu-Oki earthquake, the damage function of a service line with the proposed seismic damage index is evaluated using a log normal probability density function based on Shumuta et al.,(2011) as follows;

$$f(T_G) = \frac{DP}{TP} \cdot \frac{ln(T_G/\lambda_d,\xi_d)}{ln(T_G/\lambda_t,\xi_t)} \tag{2.12}$$

$$ln(T_G/\lambda_x\,,\xi_x) = \frac{1}{\sqrt{2\pi}\cdot\xi_x\cdot T_G} exp\left[-\frac{1}{2}\cdot\left(\frac{ln(T_G)-\lambda_x}{\xi_x}\right)^2\right] \tag{2.13}$$

where DP is the total number of actual poles with damaged service lines, TP is the total number of poles with the service lines, $ln(T_G/\lambda_d\,,\xi_d)$ is the log normal probability density function of the performance index (T_G) associated with poles with the damaged service lines, λ_d and ξ_d are the mean and standard deviation of $ln(T_G)$ associated with the damaged service lines, respectively, $ln(T_G/\lambda_t\,,\xi_t)$ is the log normal probability density function of the performance index (T_G) associated with poles with the service lines and λ_t and ξ_t are the mean and standard deviation of $ln(T_G)$ associated with the service lines, respectively.

3. VERIFICATION OF VALIDITY OF THE PROPOSED MODEL

3.1. Analysis Condition and Analysis Model for Structural Analysis

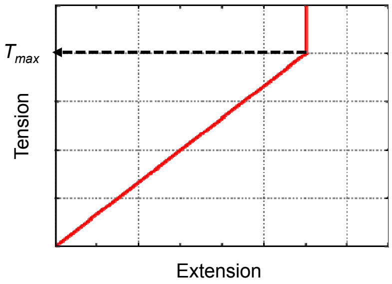


Figure 3.1 The restoring force characteristic of the spring

In order to verify the accuracy of the proposed model, the structural analysis results using the finite element method are compared to Equation (2.10). The target standard model shown in Fig.2.2 consists of a distribution pole, high-voltage cable, low-voltage cable, service line with the spring, and transformer. In this model, the pole is modeled as a beam element. The mechanical parameters of this pole such as the diameter, Young's module, height, etc., are assumed based on the standard pole. The cables are modeled as a mass element considering the half weight in one span of a connected electric cable and the installation height. The transformer is also modeled as a mass element considering the weight and the installation height. As for the service line, it is usually understood that the axial force of the service line is stronger than the force by the bending stress. Thus, this paper only focuses on the axial force. As a result, the service line is modeled as a truss element. The mechanical parameters of the service line such as diameter and Young's module are assumed based on the standard service line. The shock-absorbing spring is modeled as the non-linear spring element. Fig. 3.1 shows the assumed restoring force characteristic of the model spring. T_{max} is the elastic limit of the spring. The electric power receiving buildings are assumed to have no deformation displacement and are modeled as fixed points.

The dynamic response analysis in the time-domain is performed using the generic structural analysis code ABAQUS. One wave of a sinusoidal wave, whose frequency is equal to the natural frequency of the pole, is applied as an input seismic force. The damping constant is assumed to be 0.01 consulted Ref. Hatakeyama(1991).

3.2. Analysis Result

The reducing ratio of the tension of the service line is evaluated by

$$Reducing\ ratio = \frac{the\ tension\ of\ service\ line\ with\ spring}{the\ tension\ of\ service\ line\ without\ spring} \qquad (3.1)$$

Since the tension of the service line has a high sensitivity to the installation height of the service line on building h_d and horizontal distance between target building and pole H, the sensitivity analysis for the reducing ratio focuses on the change in the values of h_d and H. Table 3.1 shows the parameters for the structural analysis. Δh is the difference in the installation height of the service line h_d between both sides of the service line. In Table 3.1, "Small" or "Large" indicates the minimum or maximum value used in the sensitivity analysis referred to in section 2.3, respectively.

Table 3.2 shows a comparison of the reducing ratios evaluated by the structural analysis and by Equation (2.10). Table 3.2 shows that the reducing ratios by Equation (2.10) for every case tends to be overestimated, however, these values almost equal to those determined by the structural analysis. This result suggests that Equation (2.10) can reasonably evaluate the tension of a service line with a spring.

Table 3.1 Parameters for structural analysis

Case	1	2	3	4
H	Small	Large	Small	Large
$\Delta h(= h_0 - h_d)$	Small	Small	Large	Large

Table 3.2 Comparing the Reducing Ratio obtained by structural analysis to those by Eqn.(2.10)

Case	1	2	3	4
Structural Analysis	4.4%	16.2%	9.2%	28.2%
Eqn.(2.10)	4.9%	22.4%	10.0%	31.1%

4. ESTIMATION OF SESIMIC DAMAGE FOR SERVICE LINES WITH SHOCK-ABSORBING SPRING

4.1. Condition for Estimation of Seismic Damage

Table 4.1 Parameters for sensitivity analysis

Parameter		Number of Cases
k	Spring Constant	3 $(k_0, k_1 = 0.5k_0, k_2 = 2.0k_0)$
T_{max}	Elastic Limit	2 $(T_{max0}, T_{max1} = 2.0T_{max0})$

Based on the seismic damage record obtained after the 2007 Niigata-Ken Chuetsu-Oki earthquake, the numbers of poles with damaged service lines with having a shock-absorbing spring are estimated by Equation (2.12). In order to evaluate the seismic damage reducing degree of the shock-absorbing spring, the spring-damage ratio is defined as the estimated number with a spring divided by that without a spring. The shock-absorbing spring is installed in a service line in a target area at a constant ratio. This ratio is defined as the spring-installation ratio evaluated by the number of poles with the service lines and the spring divided by the total number of poles. T_e without and with a spring was evaluated by equations (2.8) and (2.10). If T_e with a spring evaluated by equation (2.10) exceeds T_{max}, T_e with a spring is also evaluated by equation (2.8). Table 4.1 shows the mechanical spring parameters of the spring constant and the elastic limit utilized in this simulation. In Table 4.1, k_0 and T_{max0} are the real spring values used by the Tohoku Electric Company.

4.2. Estimated Result

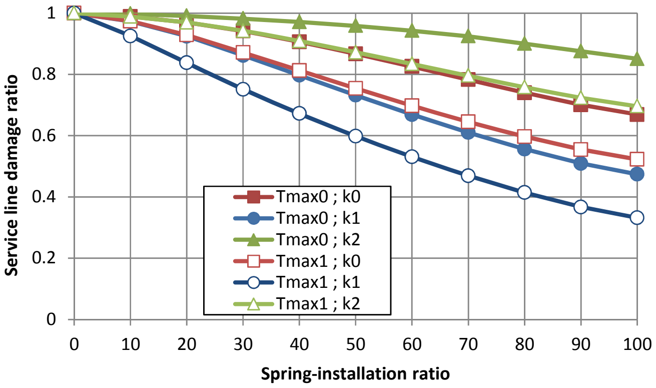


Figure 4.1 Relationship between the spring-installation ratio and the service line damage ratio

Fig. 4.1 shows the relationship between the spring-installation ratio and the service line damage ratio. Fig. 4.1 shows that the increase in the spring installation ratio, the increase in the spring constant k, and the increase in the elastic limit T_{max} cause a decrease in the service line damage ratio. It also shows that if the spring with T_{max1} (large elastic limit) and k_1 (small spring elastic constant) is installed in all service lines in the target area of this simulation, the number of poles with seismic damaged service lines decrease to 60% of that without the spring.

5. CONCLUSION

This paper proposed a seismic damage index for service lines having a shock-absorbing spring. The proposed index enables us to evaluate the tension reducing effects of the spring based on spring mechanical properties including the spring constant k. The tension evaluation result by the proposed model is compared to that from a structural analysis using the finite element method. As a result, it was clarified that the result of the proposed model roughly corresponds to the result of the structural analysis. As a case study, on the basis of the seismic damage record due to the 2007 Niigata-Ken Chuetsu-Oki earthquake, the sensitivity analysis for the mechanical properties of the shock absorbing spring including the spring elastic constant and the elastic limit was performed. As a result, it was clarified that a spring with the smaller spring elastic constant and larger elastic limit enabled us to more effectively reduce the seismic damage of service lines.

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