Seismic Vulnerability of Substation with interaction of structure and electrical equipments

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SUMMARY
According to an actual substation project, a three-dimensional dynamic analysis model involving the interaction of equipments-structure equipments is established. The natural vibration period of the substation with interaction of equipments-structure is compared to that of non-interaction. The results are shown that the disadvantage effect of equipments couldn't be ignored. Moreover, 100 practical earthquake records with different epicentral distances and magnitudes are chosen to analysis the seismic response of substation, the maximum inter-story drift angle is selected as seismic demand parameter, and the seismic vulnerability curves of substation are obtained in the end. With the increasing of the peak ground acceleration of the earthquake waves, the failure probability of the four destruction levels, namely mild damage, moderate damage, severely damaged and collapsed, are coinstantaneous increasing. The seismic vulnerability curves can be used for assessing the seismic performance level of substations and offering help to increase seismic capacity during the disaster.

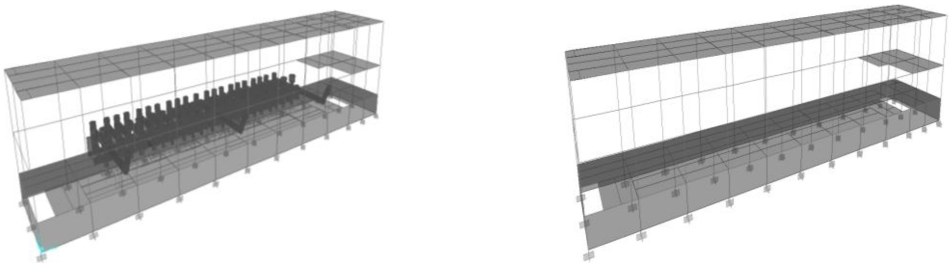
Keywords: substation; interaction; inter-story drift angle; seismic vulnerability curve

1. INTRODUCTION

Substations are critical components of the electric power system. Once substations are destroyed by earthquakes, it will not only cause serious disasters and heavy economic losses, but also slow the progress of relief work. More seriously, it will even cause the entire power system out of running. During the past several earthquakes, such as Kobe, Japan Earthquake in 1995, and Wenchuan, China Earthquake in 2008, the lifeline system including substation was significantly damaged, which resulted in the difficulty of the earthquake relief. With the rapid development of the national economy, substations are constructed with expanding speed and scale, so more attentions are paid to dynamic and seismic performances of substations under earthquake response. Previously, the seismic precautionary criterion of the substation is generally low and there were not enough attentions. Given the important role of substations to the national economy and earthquake relief, the study of seismic vulnerability of the substation nowadays is an urgent task. The analysis of the seismic vulnerability of substations has significant value, because we can use it to assess seismic damages of structures and take corresponding relief measures to control economic losses within our expectation. Presently the researches about the seismic performance of substations have entered into maturity stage and some achievements have been gotten involving the interaction between structure and equipments. However, the study of seismic vulnerability of substations is still in its initial stage and the references concerning with the interaction between structure and electrical equipments are very few. For this reason, the research will be taken to concentrates on this field in this paper.

2. FINITE ELEMENT MODELING AND MODAL ANALYSIS

There are some remarkable characteristics of substations different from the general buildings, such as the complex style of the main structure, the large sectional size of members, the oversize and multiform styles of the electric equipments and so on. Therefore, the seismic performance of the main structure and electric equipments should be noticed at the same time during earthquake. In practice, according to the seismic design code, the engineers only focus on the main structures and regard the electric equipments just as equivalent uniform load when they deal with the seismic design of substations. Actually, the interaction of structure-electric equipments is significant and complex. If the interaction of them is ignored, the reaction of buildings caused by earthquake would not be reflected correctly, the design parameters would be inaccurate and the conclusions would be incorrect. In this paper, the typical 3D finite element model of substation is established involving the interaction between the structure and electric equipments. The seismic dynamic and vulnerability analyses of the substations are performed. The main structure is modeled as concrete frame structure, among which slabs are modeled by thin shell elements, beams and columns are modeled by beam elements. The electric equipments are modeled by 3D shell and solid elements, which are fixed rigidly on the main structure along with the Z axis direction. The model of the substation involving the interaction is shown in Figure1, named as model A. To compare with it, another model is built up without the interaction, named as model B.



(a) Involving interaction (b) Non-interaction

Figure 1. Finite element model of substation

Based on the former study by the authors, the dynamic performance of substation is affected by the following factors, such as the structural type, the mass ratio of electric equipments to the main structure (shorted as mass ratio), the diversity layout style of the electric equipments and so on. By lots of investigation, it can be learned that the mass ratios almost range from 5% to 20%. Among this, 5%, 10%, 15%, 20% are chosen as typically mass ratios in this paper. Electric equipments are set in first floor or second floor, and there are totally 8 kinds of cases. The modal analysis is studied when the mass ratio and layout of electric equipments are chosen as analysis parameters. The relationship of mass ratios and the first natural vibration period is shown in Figure 2.

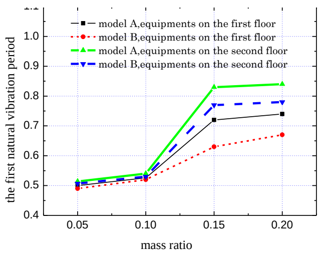


Figure 2. The first natural vibration period of structure

As shown in Figure 2, with the increasing of the mass ratios, the first natural vibration period of the substation involving the interaction is significantly differ from the corresponding value without the interaction, when the mass ratio is above 10%, the gap between two target values becomes larger. Therefore, the general structure design method of substations is not reasonable without considering the interaction. In order to ensure the safety of the design result, it should be taken high attention to the fact that the dynamic performance of the substations shows significant change when the mass ratio is above 10%. If not, the results will be more insecurity.

3. SEISMIC VULNERABILITY OF SUBSTATION

At the beginning, the earthquake demand parameters such as inter story displacement angle and the spectrum displacement has been calculated to analysis seismic vulnerability of the substation. The seismic response of the structure is related to the randomicity of ground motions and the structure itself. For this reason, 100 seismic real records with different focal mechanism, epicentral distance and site condition etc. selected from the database of Pacific Earthquake Engineering Research Center (PEER) are regarded as ground motion input, whose peak ground acceleration (PGA) ranges from 0.004g to 0.99g, the epicental distance ranges from 5.4 km to 89.2km.

3.1. The Earthquake Demand Parameters of Substations

The earthquake demand of structure or member is the minimum ability to maintain the safety and serviceability of buildings, which also is the maximum response of the structure caused by the earthquake action. The values of inter-story displacement angle can reflect the damage reason and the performance of the structure after the response get into nonlinear stage. Besides that, the concept of it is acceptable and commonly used, so the inter-story displacement angle of the main structure is selected as the earthquake demand parameter in this paper. The level of damage of the main structure are divided in four types, which are termed as basic well, slight damage, moderate damage, severe damage and collapse. The dividing point values among these four types reflect the seismic performance levels of substations. According to the former research, it is ruled the relationship of inter-story displacement angle and damage levels are shown in Table 1. The seismic performance levels are defined as termed safety operation, local outage, large area outage and out of operation.

Table 3.1. Relationship of Damage Grade of Structure and Inter-story Displacement Angle

Damage level	Basic well	slight damage	moderate damage	severe damage	collapse
inter-story displacement angle/θ	<1/600	1/600-1/300	1/300-1/150	1/150-1/60	>1/60
performance levels	safety	local outage		large area outage	out of operation

Based on the 100 real earthquake records, 3D finite element software SAP2000 is used to analyze nonlinear time history response of substation, from which receives the inter-story displacement angle. By the analysis, it is concluded that the values of Ln(θ) and Ln(PGA) are in agreement with linear relationship shown as Eqn. 3.1.

$$\ln(\theta) = n\ln(PGA) + m \tag{3.1}$$

Where θ is inter-story displacement angle, PGA is the peak ground acceleration, m and n are constants. As mentioned above in modal analysis, electric equipments affect the dynamic performance of structure significantly when the mass ratio is above 10%. Due to limited space, it is representatively shown the results of the earthquake response as the following when the mass ratio is 15%. Earthquake demand model of the substation is shown in Figure 3, in terms of Eqn. 3.1. As shown in Figure 3, the massive discrete points obtained from different conditions denote the relationship between ln(θ) and ln(PGA) and the straight line is the regressed earthquake demand model. The points and lines match to each other very well in Figure 3.

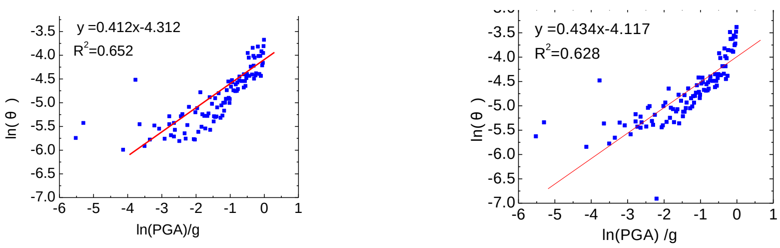


Figure 3. Earthquake Demand Model of Substation

3.2 The Seismic Vulnerability Curve of Substations

The probability function of earthquake response is used to analysis seismic vulnerability of structure. In other words, the function can reflect seismic performance of structures in the view of probability. When a certain earthquake has happened, the earthquake response of structure θ_d reaches or surpasses a previously specified structure ability θ_c, which the corresponding value at that state is the conditional exceeding probability Pf as shown in

$$P_f = P(Z<1) = P(\theta_c/\theta_d<1) \tag{3.2}$$

Where the random variable Z represents the ratio of structure's ability level to earthquake response value, $Z=\theta_c/\theta_d$. When both θ_c and θ_d are in conformity to logarithmic normal distribution, the function can be shown as $Z=\ln(\theta_c/\theta_d)$. The exceeding probability of the structure is expressed as Eqn. 3.3.

$$p_f = \phi(-\frac{\mu_z}{\sigma_z}) = \phi(\frac{\ln\mu_{\theta_d}-\ln\mu_{\theta_c}}{\sqrt{\sigma_{\theta c}{}^2+\sigma_{\theta d}{}^2}}) \tag{3.3}$$

Where $\mu_{\theta c}$ is structure mean value and $\sigma_{\theta c}$ represents logarithmic standard deviation of the inter-story displacement angles. $\mu_{\theta d}$ and $\sigma_{\theta d}$ represent the earthquake response mean value and the logarithmic standard deviation of the inter-story displacement angle respectively.

After Eqn. 3.1 is taken into Eqn. 3.3, the relationship between exceeding probability and *PGA* can be calculated by Eqn. 3.4.

$$p_f(PGA) = \phi\left\{\frac{\ln\left[e^m(PGA)^n/\mu_{\theta_c}\right]}{\sqrt{\sigma_{\theta c}{}^2+\sigma_{\theta d}{}^2}}\right\} \tag{3.4}$$

Whereφ (•)is the normal distribution function shown as Eqn. 3.5.

$$\phi(x) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x}\exp\left(-\frac{t^2}{2}\right)dt \tag{3.5}$$

Based on the earthquake demand model, the exceeding probability in different conditions can be calculated by Eqn. 3.4. Then *PGA* is used as independent variable to acquire the seismic vulnerability curve, which is drawn in Figure 4. The horizontal axis denotes *PGA* and the vertical axis denotes the exceeding probability.

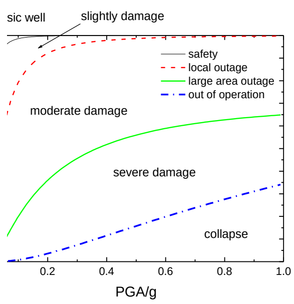


Figure 4. Seismic Vulnerability Curves

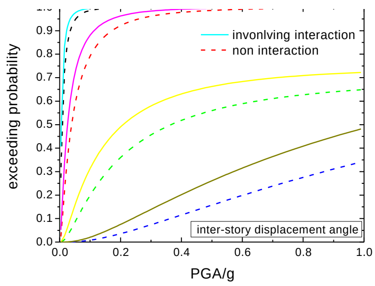


Figure 5. Comparison of Curves

As shown in Figure 4, with the increase of *PGA*, the exceeding probabilities corresponding to the damage conditions increase gradually, that is to say, the substation becomes more vulnerable. When

PGA is below 0.1g, the exceeding probability corresponding to the stage of safety operation and local outage increase sharply, and the value approximately reaches to 1.0. Because the upper limit of the slight damage is local outage, which is a manageable situation; Along with the further increase of the value of *PGA*, the seismic vulnerability curves increase gently, the peak exceeding probabilities are obviously less than 1.0, which means the probabilities of the stage of moderate damage and severe damage increase smoothly by the increase of the seismic acceleration. The vulnerability curves comparison of involving interaction and non interaction based on the quantificational indexes of inter story displacement angles is shown in Figure 5. As shown in Figure 5, if interaction is considered, the exceeding probability of performance level of structure will become larger than that of non interaction, especially in the condition of large area outage and out of operation, the effect is more significant. All these indicate that electric equipments obviously affect the earthquake response of the main structure, which is remarkable under strong earthquake. In order to ensure the safety and reliability of substation, the seismic design of substations located in high intensity areas should take the adverse impacts of the electric equipments into account and ensure the safety of substation.

3. CONCLUTION

In this paper, the model of the substation is established involving the interaction of electric equipments and main structure. The dynamic characteristics of the substation is analyzed which is learned that the natural vibration period are enlarged by electric equipments. Therefore, the interaction of electric equipments and structure could not be ignored. It is put forward damage stage and corresponding seismic performance ability by using inter-story displacement angle as the earthquake demand parameter, earthquake demand model is built up and the seismic vulnerability curve is obtained finally. From above, it can be learned that if the PGA and mass ratio are known, the seismic vulnerability curve can be used to assess the seismic vulnerability level of the substations, which also supply some theoretical references for earthquake prediction, strengthening and post-earthquake assessment. Due to the limited space, it is just chosen PGA as ground motion parameter to obtain seismic vulnerability curve of substations in this paper. If the spectra acceleration spectrum or displacement spectrum are chosen as parameters to analysis the seismic vulnerability, the results would be more applicative and meaningful. The authors would take further researches in these aspects.

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