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THE PROBABILISTIC METHOD OF EARTHQUAKE DAMAGE PREDICTION FOR FLOOR-SUPPORTED EQUIPMENT

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Abstract:

On the basis of the analysis for earthquake damage of industrial equipment, a two level's standard of equpment damage is proposed in the paper. Taking the random feature of earthquake action and structural resistance into consideration, the earthquake damage prediction method for floor-supported industrial equipment is put forward. An example is given to show the validity of proposed method.

Keywords:

Industrial equipment; Earthquake damage; Probability prediction; Floor response spectrum.

INTRODUCTION

In the violence earthquake, not only a vast amount of the civil engineering but also the equipment in these structures will be destroyed. The destroy of some petrochemical equipment can even lead to several kinds of dangerous secondary disasters, such as fire, leaking of poisonous gases and explosion. All these secondary disasters will cause enormous loss. The results of statistics have revealed that one third of the earthquake loss is directly from to the damage of equipment. For a modern industrial enterprise, ability of disaster resistance is closely associated with equipment. The recovery time between earthquake occurrence and producing ability regained is also closely related to the status of equipment. Therefore, the equipment earthquake damage prediction cannot be ignored but necessary. For the more, the equipment damage is not only related to the characteristics of earthquake itself but also the interaction between equipment and supporting structure. The earthquake damage prediction for equipment can never be done without the relationship analysis of structure and equipment. On the basis of analyzing on earthquake damage, the probabilistic earthquake damage prediction method is put forward with the random character of earthquake action and structure's parameters taken into consideration.

EARTHQUAKE DAMAGE REGULARITY OF INDUSTRIAL EQUIPMENT

Industrial equipment is attached to supporting structure's floors in many kinds of forms. For example, in petrol chemical enterprise, the majority supporting structures are hollow reinforced concrete frames because of the request of industrial art. The equipment is usually laid on upper part of the support building, attach to the floor in the form of bolt, hinge and pedestal, and support bracket. On the other hand, in instrument enterprise, because of the light in weightiness, the equipment is usually laid on the floors without any attachment. Nevertheless, the main forms of equipment attached to floors can be summarized in three kinds: (a) Laid on floor without any attachment (LWA); (b). Attached to the floor in forms of bolts and hinges(BAH); (c). Attached to the floor by means of support bracket(SBT).

Earthquake case study reveals that there are mainly two aspects of equipment damage in an earthquake: the equipment smashed by building collapse; the equipment destroyed by earthquake action itself. In the later case, it is usually shown in the situation of connection failure or damage of bracket. This kind of situation can be exemplified by Tangshan earthquake, taken place in China in 1976. In the earthquake, a number of industrial equipment were damaged, especially, an air separating tower whose capacity is 6000 cube meters per hour was destroyed. It was attached to the floor by 12 bolts whose diameters were 12 mm. In the earthquake, 9 of them were cut off by shear force. The equipment damage caused by earthquake action itself is mainly discussed in this paper.

PROBABILISTIC HORIZONTAL EARTHQUAKE COEFFICIENT

The intensity, location and occurrence time are all random for earthquake. In practice, the random of earthquake action is expressed in the horizontal earthquake influence coefficient. This probability model is as follows

$$F_x(x) = \exp[-(\frac{\alpha x_0}{x})^k] \tag{1}$$

Here x is horizontal earthquake influence coefficient; x_0 is horizontal earthquake influence coefficient corresponding to basic earthquake intensity; α is a factor related to design durability. When the durability is 50 years, α=0.385; K is a shape factor, K=2.35.

According to above model, the mean value and variation of x are respectfully:

$$m_x = \alpha x_0 \Gamma(1-\frac{1}{k}) \tag{2}$$

$$V_x = \sqrt{\frac{\Gamma(1-\frac{2}{k})}{\Gamma^2(1-\frac{1}{k})} - 1} \tag{3}$$

$$\sigma_x = m_x V_x \tag{4}$$

EARTHQUAKE ACTION ON EQUIPMENT

The supporting structure can be taken as the prime-system, and the equipment the subsystem. For the brevity of analysis, the prime-system and the subsystem can all be assumed as shear model in earthquake deformation. Then the Bottom-Shear method can be used to calculate the earthquake action imposed on the equipment attached to floor. The single mass model is used for isolated or single equipment and lumped multi-mass model is used for superposed equipment.

The earthquake action on equipment is determined as following:

$$F_{ei} = IK_i\beta_i W_i \tag{5}$$

Where I is an adjusting coefficient depending on the equipment pattern; K_i is the influence factor associated with the acceleration of floor; β is the dynamic amplify factor for equipment on floor; W_i is equipment's weight.

For isolated equipment, formula (5) is used for calculating earthquake action on equipment directly. However, for superposed equipment, the earthquake action at each part should be distributed further by following expression:

$$F_{el} = \frac{m_l h_l}{\sum_j m_j h_j} F_{ei} \tag{6}$$

Where m is equipment weight; F_{el} is the standard value of earthquake action on each mass point; h_j is the height of mass j to floor in which equipment is attached.

<u>Calculation of the Floor Equivalent Acceleration Influence Factor</u>

The horizontal shear force action on each floor caused by earthquake action is:

$$F_i = \frac{G_i H_i}{\sum_j G_j H_j} F_{ek} \tag{7}$$

$$F_{ek} = \alpha_1 G \tag{8}$$

Where α_1 is the horizontal earthquake influence factor corresponding to the period of the structure-equipment composite system. G is the total system weight; F_i is the standard value of earthquake action on each mass point; G_i is the nominal weight value on mass i. Hi is the height of mass i to ground.

Then the floor equivalent acceleration influence factor is:

$$K_i = \frac{F_i}{G_i} \tag{9}$$

Here, the equivalent floor acceleration is just the input acceleration for floor supported equipment.

<u>The Dynamic Amplify Factor for Equipment vs. Floor</u>

In earthquake, there is complicated interactions between structure and equipment. On the basis of the results from a model test, the interaction will cause the change of frequency spectrum of composite system (Li , <u>et al</u>, 1995). When earthquake response analysis is carried out, the dynamic interaction has to be taken into consideration. According to a number of analysis and statistics, the dynamic amplify factor for equipment versus floor can be determined as following (Su <u>et al</u>, 1990) :

$$\beta_i = \begin{cases} c + [1 - (\frac{T_e}{T_s})^d]^{-1} & \frac{T_e}{T_s} \le a \\ \beta_{\max} & a \le T_e / T_s \le b \\ [(\frac{T_e}{T_s})^d - 1]^{-1} & \frac{T_e}{T_s} \ge b \end{cases} \tag{10}$$

Here T_e is the fundamental period of the equipment; T_s is the fundamental period of the structure;

$$a = (1 - \frac{1}{\beta_{\max} - c})^{1/d} \tag{11}$$

$$b = (1 + \frac{1}{\beta_{\max}})^{1/d} \tag{12}$$

other parameters can be adopted as Table-1; In the table, ξ is the equipment damping ratio.

Table-1 Parameters value

ξ	0.1	0.05	0.02	0.01	0.005
$\beta_{\max}$	4.0	6.5	10.0	12.5	15.0
c	0.1	0.3	0.4	0.6	0.8
d	1.7	1.5	1.3	1.1	1.0

Because the equipment mass is great, the feedback factor R is chosen to express the influence of equipment on supporting system. Table-2 gives the value of R in differently situation.

Table-2 Feedback influence factor

Me/Ms	1/2	1/10	1/50	1/100	1/500
R	0.37	0.51	0.76	0.9	1.0

Where M_e is the equipment mass; M_s is the mass of floor to which the equipment attached.

EARTHQUAKE DAMAGE PREDICTION METHOD OF EQUIPMENT

In the above section, the earthquake action is taken as a deterministic action. However, earthquake is a random disaster phenomenon, when does it occur, where is the epicenter, how about its intensity, all these problems are uncertain. Because of the random character of supported structure system and the random character of equipment's mass, size and material intensity, the earthquake damage of industrial equipment in a future earthquake disaster is difficult to be quantitatively analyzed. In the following part, considering the uncertainty of earthquake and structure, a probability prediction model for earthquake damage of equipment is further studied. For application, the failure or damage in link element between equipment and floor is taken as prime damage model. In order to describe the influence of link element damage of equipment, the earthquake damages of equipment are divided into two levels, undamaged level and serious damaged level. The earthquake damage standards corresponding to each level are described as follows:

1. Undamaged level: The link element is undamaged, concrete or masonry support has not been evidently

cracked, equipment needn't repairing to be used again.

2. Serious damage level: The foundation bolts have been elongated or failed in shear or pulled out. The equipment cannot be used or must be heavy repaired.

To analysis the earthquake damages of equipment by probabilistic method, the strain or stress S in link element resulted from earthquake influence and the resistance R are taken as the prime variables of performance function. Then the performance function of link element is as following

$$z=f(R,S)=R-S \quad (13)$$

The strain or stress in link element can be described as

$$S_i = C_l F_{ei} \quad (14)$$

Where C_l is relation coefficient between Fei and S_i..

Considering the random character of earthquake input, the mean and variance of earthquake action are

$$\mu_{si} = C_L \gamma_i m_x \quad (15)$$
$$\sigma_{si}^2 = C_L^2 \gamma_i^2 \sigma_x^2 \quad (16)$$

Where

$$\gamma_i = \frac{GH_i}{\sum_j G_j H_j} I \beta_i W_i \alpha_1 \quad (17)$$

The mean and standard of the link element resistance can be obtained from statistical results of material experiments. For different link model, the resistance has different meaning, for example, the resistance of LWA equipment is slipping resistant ability and overturning resistant ability, for BAH equipment, they are shear strength and bent strength of equipment in earthquake action. In this paper, ultimate stress R_l and ultimate strain R_2 are chosen as resistance parameters corresponding to above two damage levels. Then, the limit state function equipment for undamaged level is

$$Z_1 = R_1 - S = 0 \quad (18)$$

The critical sate function of equipment for serious damaged level is

$$Z_2 = R_2 - S = 0 \quad (19)$$

If $Z_1 > 0$, the equipment is undamaged; if $Z_2 < 0$, the equipment is serious damaged. According to probabilistic distribution of S and R, Z submits normal distribution, then the distribution density function of Z is:

$$f(z) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(z-\mu)^2}{2\sigma^2}} \quad (20)$$

Where, μ and σ are mean and standard deviation of Z respectively.

$$\mu = \mu_R - \mu_S \quad (21)$$

$$\sigma = \sqrt{\sigma_R^2 + \sigma_S^2} \tag{22}$$

The distribution function of random variables Z is

$$F(z) = \frac{1}{2\pi}\int_{-\infty}^{\frac{z-\mu}{\sigma}} e^{-\frac{1}{2}x^2} dx = \Phi(\frac{z-\mu}{\sigma}) \tag{23}$$

Where, $x = \frac{z-\mu}{\sigma}$, $\Phi(\bullet)$ is distribution function of standard normal distribution.

Using this function, the probability of undamaged of equipment is:

$$P_{s_1} = P(z_1 > 0) = \Phi(\frac{\mu_{R_1} - \mu_S}{\sqrt{\sigma_{R_1}^2 + \sigma_S^2}}) \tag{24}$$

And the probability of equipment to be serious damaged is

$$P_{f_2} = P(z_2 < 0) = 1 - \Phi(\frac{\mu_{R_{21}} - \mu_S}{\sqrt{\sigma_{R_2}^2 + \sigma_S^2}}) \tag{25}$$

EXAMPLE

The proposed method has been used to predict equipment earthquake damage in some factory in China. One equipment is chosen here as an example to show the validity of proposed method. The structure of supporting equipment is a three story frame structure and the equipment is a horizontal one laid on the second floor. The measured nature frequency of the equipment is $0.1053s$ and the nature frequency of structure is $0.78s$. Other parameters of the structure and equipment are listed in Table 3 Table 4.

Table-3 Structure and equipment parameters

No. Floor	STRUCTURE		EQUIPMENT	
	M(kg)	H(m)	M(kg)	H(m)
1	160500	6		
2	152800	12	39500	1.6
3	85600	17		

Table-4 Earthquake Damage Prediction Results

Earthquake Intensity	7	8	9
Undamaged P_s	0.9999	0.9930	0.8212
Serious damaged P_f	0.0	0.0006	0.0800

CONCLUSION

This paper suggests a seismic reliability analysis and earthquake damage prediction method for floor supported equipment. This method considers the random character of earthquake action. The applied results for some floor supported industrial equipment have proved the efficiency of the suggested method. The suggested method provides a basement for the earthquake damage prediction of floor supported industrial equipment or the analysis of seismic reliability assessment of industrial system.

REFERENCES

Gao Xiaowang, Bao Aibin(1985). Probabilistic model and its parameters for seismic load, *Earthquake Engineering & Engineering Vibration*, 5, 13-22.

Huang Xingli(1990). *Reliability design of engineering structure*, Communications Publishing House of China.

Li Jie, Chen Hwai and Sun Zengsou(1995). An experimental investigation of dynamic feedback in structure-equipment system, *Journal of Southeast University,* 11, 551-555.

Sun Zengshou ,Chen Huai et al(1994). Earthquake damage prediction of equipment using probabilistic method, *World Information on Earthquake Engineering* No. 3, 45-50.

Su Jingyu et al(1990). Practical calculating method for seismic force of floor-supported equipment, *Earthquake Engineering & Engineering Vibration*, 10, 65-72.