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AN IDEA OF A SEISMIC CAPACITY LIMIT EVALUATION-TYPE DESIGN OF EQUIPMENT AND PIPING SYSTEMS

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§1. Introduction

The author once discussed on a new approach of the earthquake resistant design method of nuclear power plants in SMiRT-5. This method is the inverse method compare to the ordinary design method. Based on a standard design of a plant, if the earthquake resistant capacity of a standardized plant can be evaluated, then the construction site, which is adequate to this particularly designed plant, can be mapped. This paper deals with the new development of this approach for re-evaluation of existing plants, such as VVERs and other light water reactor plants.

§2. Concept

In one(1) of the previous papers, the author refered to this design method as the "critical limit force method", and developed into a critical seismic coefficient method and a critical floor response curve method. These three are based on a concept, that is, the capacity of structure can be evaluated based on its structural design configuration. The term "capacity limit" may be almost same as this "critical limit". The concept of "capacity limit" is rather easy to be understood by engineers, but it is difficult to define it exactly. As the author discussed in another previous paper(2) on the evaluation of design codes and guidelines. At that time, he assumed an earthquake which he subjectively judged the severest earthquake in general, according to his experience. The maximum PGZA at the basement was assumed to be 0.7 G, but it is too subjective judgement to evaluate them. As shown in Table 1, there are several key values, that is, design basis earthquakes (DBE), subjective anticipated maximum earthquake (SAME), seismologically expected maximum earthquake (SEME), probabilistically expected maximum earthquake (PEME), as an input for the design. On the other hand, "capacity limit" may be categolized as, that based on seismic allowable stress for Plant condition III(C): (CLE), and that based on its elasto-plastic capacity limit, that is for Plant condition IV(D): (CLP). And the limit for practically and actually failing to keep its function: (CLF), may be added. Where P.C. III or VI is Japanese nomination and P.C. C or D is ASME's nomination.

The author discussed in Ref.[1] is DBE-CLE evaluation, and in Ref.[2] is a SAME-type evaluation of existing codes. And SEISMIT-HV, which will be described in detail in Chapter 4, is DBE-CLE type design code for a high-pressure gas facilities in Japan. These several years Japanese utility group have been working for SEME-CLF evaluation(3).

§3. Evaluation of Structural Capacity

Japanese Building Code requires two steps of design analysis for ordinary conventional buildings and structures. The first step is the static seismic coefficient design with allowable stress to short-term loading, that is DBE-CLE. And the second step is its capacity evaluation in elasto-plastic region against 1.0 G as the assumed maximum earthquake motion through Japan as a kind of SAME above.

As an extending of this concept, the Japanese utility group have been working to evaluate the margin of equipment and piping systems designed by the current design practice in Japan. The result has not been reported, but the concept(3) is as follows: the margin is the ratio of the seismic safety limit to an actual response. And they defined as

$$M = \frac{\text{real seismic safety limit}}{\text{actual response}}$$

$$= \frac{\text{response in design analysis}}{\text{actual response}} \times \frac{\text{allowable limit for design}}{\text{response in design analysis}}$$

$$\times \frac{\text{real seismic safety limit}}{\text{allowable limit for design}} = M_1 \times M_2 \times M_3 \qquad (1)$$

If we try to interprete these three margins, M_1 is the margin for the response analysis, that is, related to the practices how to decide the design response spectrum, how to generate the design time history and how to design the floor response spectrum. Then M_2 is the ordinary margin in structural design, and M_3 is a safety margin of allowable limit like allowable stress. In design procedure, we evaluate M_2 only, and it is deterministic conceptual value. The margins M_1 and M_3 are values obtained by comparing the design values to real values, and stochastically distributed.

According to the practice in Japan, S_2 earthquake is the upper bound earthquake and the probability of occurence of a stronger earthquake exceeding this level is very low(4), therefore, most of stochastic effect on M_1 is coming from the design of response spectrum. For M_3, we need evaluate its fragility curve for the precise value, however, they considered as the ratio of the yielding stress to the computed stress under the design basis seismic condition with the design basis damping coefficients. This value is usually under-estimated than the value obtained through its fragility curve, if it exists. When we try to improve existing power plants, it is difficult to use the seismic failure probability for the target value which will be obtained by the design modification, but we can evaluate a value of margins as above mentioned.

§4. Critical Limit Design

This design procedure was planed for standardized plants at the beginning. The author had been working for standardizing light water reactor plants in 1970s, and also worked for the anti-earthquake design code for high-pressure gas facilities known as MITI Notice #515, and the computer program SEISMIT-HV was developed. Through these works, the concept of critical limit design practice became clear for the author, and he tried to discuss about its concept. The SEISMIT-HV computes the table on the relation of factor of importance to the seismice zones where that a particular designed horizontal liquid tank can be constructed under the restriction of the MITI Notic # 515. In this case, the critical limit is shown by the table. Even the cases, which the author discussed in Ref.[1], were similar to this, the relation was more complicated, because of the complexity of stress analysis in Fig.1. If the stress condition of the element is simple like a tension bolt, the relation can be expressed in Figs.2 and 3. However, if their stress condition is two axial or three axial one, it becomes a curve in plain or a surface in a space like Fig.4. As the author discussed on a piping system in the previous paper(1), three components of moment forms an allowable external force (moment) vector surface. The shape of this surface is not similar for Class I piping and Class IV piping, for example, because the stress criteria of these two classes are different. For a structural member, the stress criteria like

$$\sigma_c \,/\, \sigma_{ac} + \tau \,/\, \tau_a \quad < \quad 1 \qquad (2)$$

is used often. In this case their critical limit in σ_c-τ plain is a straight line, but, for a piping, the stress criterion for the combinination of bending moment and torsional moment forms a circle or an ellipse.

To combine these two criteria: load and capacity limit, we have to calculate the remaining allowable stress for external loadings, and estimate the strength, or intensity, against the external load to induce this amount of the stress.

For example, we assume a tower-type vessel which can be expressed by a single-degree-of-freedom system or several-degrees-of-freedom system. Such a system has one or several eigen-frequencies, and, those peaks are observed in the allowable limit curve as shown in Fig.2 or Fig.3. If we consider only an allowable seismic coefficient $\overline{K_r}$, its curve is a straight line, however, the allowable limit curve has several notches correspond to its eigen frequencies. The earthquake motions at the mounting floor are indicated by a reference response spectrum of the supporting structure as shown in Fig.2. It should be noticed that this spectrum is different from the floor response spectrum. The reason to compares these two lines is for the simplisity of analysis is as follows. An allowable limit curve belongs to mechanical components, and its most critical case is that for a sinusoidal input case, and we can usually set a reduction factor from that curve as shown by a chain line in Fig.3. And response spectra of each floor of supporting structure can be obtained through only one analysis when the design of the supporting structure is fixed.

If the allowable limit curve is fixed like ALRS (allowable limit response curve) in Fig.2, we can find the marginal distance γ as the minimum distance between these two curves. The allowable seismic coefficient curve (ALRS in Fig.2) itself decides allowable critical stresses of structural elements, for example, anchor bolts. The value $\overline{K_r}$ decides the allowable overturning moment of the structure, and then their tensile stress, if we considered only overturning moment. The allowable critical stress of the anchor bolt is defined, then the allowable seismic coefficient $\overline{K_r}$ can be defined inversely, if the size of anchor bolts has been fixed. Therefore, the allowable limit (ALRS) curve is defined from its structural design and allowable critical stress. Allowable critical stress is usually decided according to the choice of the designer.

The margine distance γ, which we difine as the distance from the allowable limit curve (ALRS) to the reference input floor motion, is zero, then the allowable stress is distributed to the seismic induced one for 100% in a case of anchor bolts, that means, allowable critical stress is equal to allowable stress. If there is other kinds of normal stresses, like those induced by its internal pessuse, its weight and so on, the allowable seismic coefficient is decreased to the remaing portion. Anyway, if $\gamma \neq 0$, it means that there is still allowance to decrease the size of anchor bolts, for example.

When the author made the survey(1) how the designer chose the ratio of the allowable critical stress to the allowable stress, it was less than 50% on the pressure boundary in 1970s, but now it becomes higher, and in the case of anchor bolts, almost 100%.

Back to the combination of stress components like tensile stress and shear stress of an anchor bolt, it is difficult to start from the seismic allowable stress to the margin distance γ, because the ratio of two stress components is not unique in general. As for the practice of design, we can fix the ratio for some components, but it is unusual. Therefore, only the way is to assume the adequate margin destance γ, for example, the margin ratio is 80%, and solve $\overline{K_r}$ then tries to share it to two components. In this case, two values as allowable tension force P and allowable shearing force N on an each bolt, for allowable over-turning moment M and shear force F of the structure. And those relations can be described in a two-dimensional plane, or 3-D space as shown in Fig.4.

§5. Reevaluation of Existing Structure

Now, it is almost clear how to apply this method to existing structures. We collect the informations on the configuration of a structure, the dynamic characteristics of the supporting structure and the design basis ground motions. Then we can obtain the design flow like Fig.1.

According to the author's experience, anchor bolts are critical in most of process plants. And the shearing force N is usually supported by other devices like a shear plate or key, then the method which the author described in the previous chapter, and we can obtain their margins distance γ easily. If $\gamma > 0$, the structural design of an existing plant has no problem. The selection of the level of allowable critical stress is one of the points for discussion. The seismic allowable stress is usually for the Plant Condition III(C), but for the reevaluation, it may be higher than elastic limit like the Plant Condition IV(D). In the case of petro-chemical industries in Japan, some local governments employed this criteria. The other approach is to evaluate the absovable energy of an element by its seismic response. Professor Housner refered to this practice in Ref.[5], and now this method has been used for buildings already as a paractical form. It can be allowed higher loading, but the author doesn't discuss this approach in this paper.

The reevalution of Class I piping is another significant subject for the reevaluation of plants. Fortunately, most of critical points are the anchoring devices, and the way of evaluating is not much difference to the case of anchor bolts which the author discussed above.

However, we also find some critical points on piping itself, for example, elbow, tee and point near to valve. Sometimes the primary stress is critical, but in other case the secondary stress is critical. In principle, the way of three component stress can be employed. Criteria $P_L + P_b < 1.5S_m$ or $(P_L + P_b + Q)_E < 3S_m$ in Japanese Practice. These components obtained by combining several components of seismic induced forces and moments as in Fig.1, and they are numerical function of the seismic response of the piping system. Starting from one design basis earthquake, seismic input and through those seismic response forces and moments, then reached into one value like $P_L + P_b$. It is rather difficult to calculate inversely a unique design basis earthquake level from the bottom in Fig.1. Through backward calculation, we will obtain several levels of design basis earthquake as a solution, and the lowest level is the allowable design basis earthquake. Of course, the results of recalculation from this DBE, like $P_L + P_b$, is lower than the original given value. If we wish, we could compensate the actual allowable design basis earthquake by using the reculculated value for a linear piping system. Also, we start from an adquate assumed level of the earthquake, and calculate a value, then can compensate the level of the allowable design basis earthquake based on an allowable critical stress. The author has not impliment these practice.

Another choice is to modify the design of the system, for example, the distribution of supporting devices. Most of cases, we have already the design basis earthquake newly defined. Therefore, the lowest allowable level of DBE obtained by above practice will exceed the new required value, it would be no problem. If not, it is better to modify the design itself, because the margin of the original design as awhole usually not so high in such a case.

§6. Checking the General Design Criteria

As the author frequently mentioned, to ensure the safety of equipment and piping systems during destructive earthquakes, detailed parts of structures are significant. One of them is quality of welding. Very often, we observe very poor welding for strengthening anchoring devices for them. To melt together both metal parts is very significant, but it is difficult to do so in general, because of its position, difference of heat capacity of both parts, quality of welding engineers working for such miscellaneous jobs and so on.

§7. Concluding Remarks and Acknowledgement

The author has experienced the walkdown survey and drawing checks of nuclear power plants as well as petro-chemical industries. It is very difficult to make a systematic survey in the field. On main items, we usually list up them in advance and to evaluate them before starting the survey, but on their details only the sense of experts is effective to do so. The author once tried to develop a system to examine the quality of aseismic designs of piping systems in the field as well as on the drawings(6), and it has been applied for the reevaluation of petro-chemical industries in Kanagawa-pref. for these several years, and the final report for those through the nation was now completed. He feels the necessity to improve it for nuclear power plants to avoid excess radiation exposure of experts who make walkdown survey in the operated plant.

The author has been working in technical committees of aseismic design of petro-chemical industries for long years as well as for NPP. And also he has been working in the member of the mission of IAEA for existing plants. Through both experiences, he obtained some idea. This paper is a part of that.

He greatly appreciates the help of members of these committees and the mission, especially, Dr.Gürpinar and Mr.Godoy, IAEA.

§8. Reference

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Table 1 Levels of Input Ground Motions and Earthquakes

DBEII	Design Basis Earthquake II--S_2 (Upper Bound Eq.)	↑ High
SEME	Seismologically Expected Maximum Eq.	
SAME	Subjectively Anticipated Maximum Eq.	
PEME	Probabilistically Expected Maximum Eq.	
DBEI	Design Basis Earthquake I--S_1 (Historical Maximum Eq.)	↓ Low
DBEO	Design Basis Earthquake 0--S_0 (Operation Eq.)	

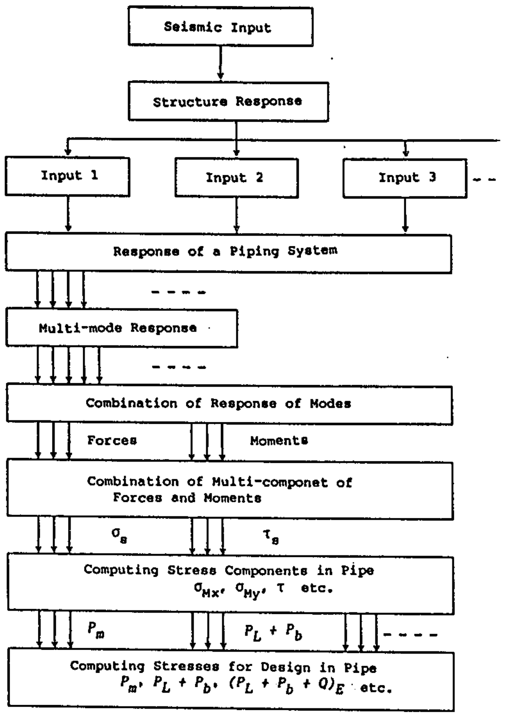

Fig.1 Flow of Seismic Stress Analysis

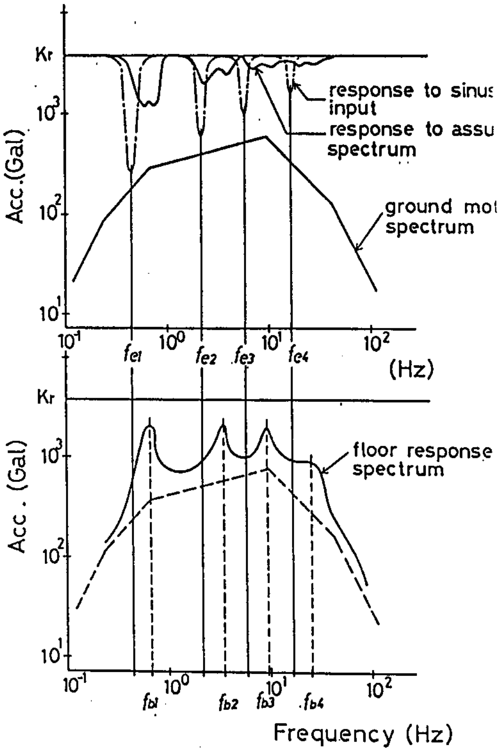

Fig.3 Schematic Figures on the Relation of Allowable Limit Spectrum to Reference Floor Motion Spectrum

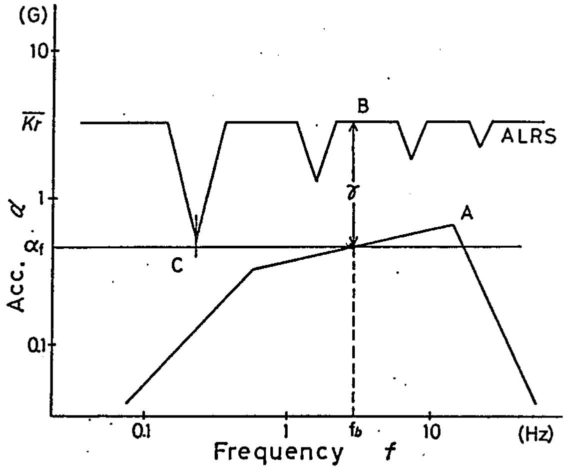

Fig.2 Conceptual Relation of Allowable Limit Response Spectrum (ALRS) or Allowable Seismic Coefficient to Reference Floor Motion Spectrum

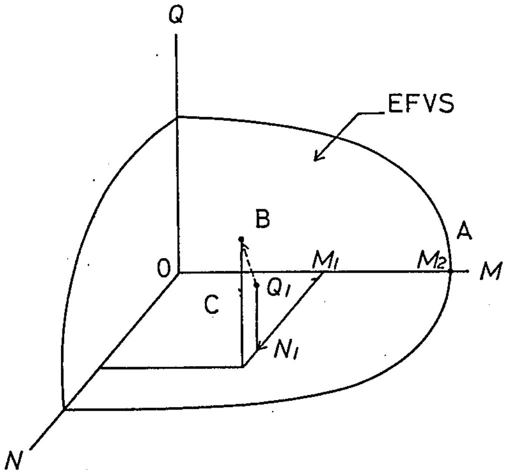

Fig.4 Concept of Allowable External Force Vector Surface, EFVS