Uncertainty in Earthquake Engineering in Relation to Critical Facilities

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Abstract

This paper deals with "uncertainty" in a narrow sense. The author understands that "uncertainty" is the lack of knowledge on an event, such as an earthquake, a human behavior and so on. Therefore, if we would be able to establish its physical model, it will be no more uncertain in a narrow sense. However, because of rare chance to observe it, some natural events should be remained with "uncertainty".

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1. Introduction

Once the author made a comment on "Uncertainty". He mentioned the following terms; Randomness, Subjective Probability, Fuzzy Characteristics and Vagueness and Ignorance. He had been understood that "uncertainty" is lack of knowledge and it came from ignorance on mechanism or, at least, behavior on natural event, human behavior, social activity and so on, because they are so huge for observing and to establish its model. However, except some natural events which are difficult to be observed because of their rare occurrence, we could reduce the uncertainty, if we try to understand them well. For modeling a particular event, we often introduce the very stochastic model like a normal distribution or log-normal distribution. It is adequate in almost case, because of the central limiting theorem. However, some of them can be established only by a combination of two or three models which can be clearly described according to their physical models.

The author had a surprise, when he found that "uncertainty" in the wide sense included randomness. If it includes random process, we could introduce various types of models. Even though, the author limits the definition of "uncertainty" as he described, then he will discuss on his experience how to reduce uncertainty of an earthquake event which is significant for Seismic PSA of nuclear power plants. he will discuss on his experience how to reduce uncertainty of an earthquake event which is significant for Seismic PSA of nuclear power plants.

2. Way of Understanding Uncertainty

The author understood that "uncertainty" was "degree of unknown" as most of persons who are working in the area of the PSA study. The Probabilistic Safety Assessment is employed for assessing the probability of a core damage and its consequence of a nuclear power plant induced by an internal event or an external event. As one of external events, an earthquake is significant for the results of its assessment on a nuclear power plant whose site is located in a high seismicity region as Japan and western U.S.A. In the eastern U.S.A., the probability of occurrence of a destructive earthquake like New Madrid earthquake-1811 is not so high as that of series of destructive earthquakes in the western earthquakes which has been occurring every one to two hundred years at a particular place. And the historical record of North-American Continent is not so long compare to the return period of the destructive earthquake in the eastern U.S.A. So we don't know its return period in the sense of the stochastics based on our knowledge.

That will have been "unknown factor" to estimate the probability of occurrence of a destructive earthquake in the area of New Madrid from which in 50 km radius there are five states, that is, Illinois, Kentucky, Tennessee, Arkansas and Missouri, unless next earthquake would occur in this area 1,000 or 10,000 years later. Of course, if we will obtain some new knowledges on techtonics in that area or on traces of previous fault movements by field survey, we could estimate the value of the return period in that area. In such a case, this uncertainty can be decreased by other types of knowledge obtain by seismological surveys than the knowledge obtained by historical records. We defined the normalized standard deviation, that is, the variation of its return period as β_U. This β_U means the degree of our knowledge. This uncertainty range is different from the fluctuation of the return period. The return period itself is also fluctuated as shown in Fig. 1 as an example. This example of the distributions of return periods or simple cyclic periods of main shocks is those had occurred in Sagami-trench in the south of Tokyo including the famous Kwanto earthquake-1923. Its mean cyclic period is 66.4 years and they fluctuated as its standard deviation is 23% of the mean. We defined β_R in such a way. This part of the variation comes from the random nature of the phenomenon.

When the author talked with a specialist of PSA about the conference, he responded me the following way: If we can model on an uncertainty, it is no more uncertainty. This concept on "uncertainty" is very common to PSA analysts.

The opposite position to this may be expressed by a book titled "Convex Models of Uncertainty in Applied Mechanics" by Ben-Haim and Elishakoff[1]. In this book, they assumed that the upper bound of dynamic behaviors of a system to a certain input can be expressed. In some sense, it is a deterministic approach. Drenik innovated his excellent approach. He described his approach at the 2nd Joint

U.S.-Japan Seminar on "Applied Stochastics"[2] in 1968 as a non-stochastic paper presented at the stochastic meeting. This method leads the input time history, which was introduced so as to give the worst response to the structure. If we know the dynamic characteristics of a structure, we can estimate the worst response by using this input time history. This deterministic approach covers all uncertainty of input motions, but they may be an extremely large margin in the engineering sense. The previous method by Ben-Haim and Elishakoff is based on the central limiting theorem again. This theorem is very convenient for engineering purpose, and any technical procedure will be lead to a simple mathematical one, even a system has some non-linear characteristics. And this leads to the concept of β_U as described before. But under some assumptions, the concept of an upper bound of the response of a system would be introduced, again there is a possibility to over estimate.

3. Typical Modelings of Uncertainty

The author recognizes that there are several ways to understand uncertainties.

i) Random phenomenon whose behavior can be completely described,

ii) Random phenomenon whose behavior has not been completely observed.

iii) Deterministic phenomenon whose behavior has not been completely observed.

iv) Deterministic phenomenon whose behavior has been known well in principle, but we have never experienced.

v) Phenomenon whose behavior is understood to be known, but there is a possibility that we don't know some new facts.

vi) There are some unknown factors, but these factors will be clarified by ordinary engineering efforts.

vii) There are some unknown factors, and some of them will not have been solved, because the probability of occurrence is not so high, so there is no chance to understand the phenomenon as the general one.

viii) The phenomenon itself is difficult to be understood based on our knowledge.

For the PSA study, theoretically, we should know every things in stochastical sense, but phenomenon itself is random. This is idealistic model. However, there may be unknown factors because of "Lack of knowledge" on the phenomenon. To overcome this for PSA study, we have to study on the phenomenon harder by experiments and the theoretical study, and simulations. However two factors, that is, human factors and natural events disturb the behavior of the model. Human factor has its effect through all process of establishing the structural response as well as a seismic load induced by earthquakes. The author has been trying to clarify both uncertainties through his studies. In this paper, he describes on the seismic response problems of equipment and piping systems of industrial plants.

4. Response Fluctuation of Structures

The uncertainty of the seismic response factor of such structures is one of key factors governs the result of Seismic PSA study on nuclear power plants. Those values are significantly large in the Seismic PSA study. It comes from the lack of our knowledge on "earthquake".

Back to 1967, the author tried to get records of ground motions in high frequency range up to 30 Hz. He constructed a model structure of a plant complex model with a piping system, vessels, frame structures and a rigid reinforced concrete structure to compare their responses in the Chiba Field Station, Institute of Industrial Science, University of Tokyo[3]. The location of this is the north-east corner of Tokyo Bay 50 km east of Tokyo, and in the area between two major nests of seismic sources in Kwanto district. We can expect to feel two or three earthquakes in every month.

At almost the same time, the author and Shimizu[4] tried to simulate the response of low damping piping systems bridged on two isolated buildings by an analog computer. For the input, they used 100 pseudo-earthquake motions obtained from a random noise oscillator. They found unexpected large fluctuation of its response. Then they tried to evaluate this fluctuation based on the random vibration theory originated from Rice. On the other hand, he obtained approximately forty analyzable records in 1971 and 72, and they found that most of the records at the model plant, expressed by a response factor, had a smooth distribution like a normal distribution. However, several records were larger than the $2 \times 3\sigma$ range. The response of a hung tank was carefully examined, and several year later, it recorded the maximum response factor of 67 against the mean was 15 and the standard deviation was around 5. This means that the maximum response factor reached to 10σ range, and it is unfeasible in the ordinary stochastic sense. And they found that the distribution of the response factors is combination of two distributions, by examine their time histories in the sense of dynamic analysis. A distribution in a lower value side fits to that based on the random vibration theory. The details of this were described in two author's papers[3][5].

Later, Okamura pointed out that such an abnormally high response factor came from the assumption of a normal distribution, and if we assume a log-normal distribution, it was not so strange as shown in Fig. 2[6]. Although this idea seemed to bring the discussion to the end, the author once noticed that wave forms of ground motions in the case of showing high response factors were pseudo-sinusoidal waves or beating sinusoidal wave against more white noise type waves in other cases.

Since 1971, the author obtained 271 data on the hung tank. We had several earthquakes exceeding 100 gal in this period. The average peak input ground motion (so-called ZPGA) of these 271 records is 7.25 gal.

5. Elimination of Unknown Factor

The distribution of these data is shown in Fig. 3. Even we assume that this is either a normal distribution or log-normal distribution, they don't pass the testing by the risk 0.1%. In Table 1, notation α is the risk to mis-reject a certain distribution assumption. Usually we use α=5% or 1%, and the criteria 0.1% and lower, expressed * mark in this table is unusually low. The value of α^2 indicated in the table is a value from χ^2, therefore, those values are greater than α=5% or 1%, this means to pass the ordinary testing.

The second row of Table 1 show the same type testing on 235 data which were obtained from 271 data by eliminating abnormally high response data, as discussed in Ref.[5]. From these 235 data their distribution can be said to be log-normal distribution with the mean 13.2 and the standard deviation $\times$ (1.46/0.68). Based on the fact above, the author tries to analyze the data of every two years in the same way. These results are also shown in Table 1 and Fig. 4. The upper part of the figure shows the result of the mean and standard deviation, and lower part the result of testing. Most of data which don't fit to these two distributions came from the records from 1972 to 1975 and number of records in these years in obviously larger than other years. The maximum response factor $\lambda=67$ was observed in 1974. The degree of fitting to the normal distribution is better than that to log-normal distribution from 1976 to 1983 and it was observed as opposite from 1983 to 1986.

From the histograms, the tendency that the distribution is skewed towards the higher response factor in most of cases, and the results are shown in Table 1 also. These values are fluctuated also. However, the skewness of the 235 data without abnormally high response ones is only 0.007, that is almost no skew.

Another example of analyses is how the response factors are depending on their source. Depending source characters, the author divided the source area to the several regions as shown in Fig. 5. Area 1 is the nearest to the station, and earthquakes which occurred in Area 3 have a tendency of a slow earth- quake. The result of the same type analysis is shown in Table 2. Even numbers of earthquakes in each regions in the period of 1971 to 1990 are quite different, fitting is very well for the earthquakes in Area 3, and the skewness is also low. Abnormally high response factor, that is, pseudo-sinusoidal wave type and beating sinusoidal wave type earthquakes only come from Area 1 and Area 2. The result shows that the mean response factors and the standard deviations of earthquakes come from Area 1 and Area 2 are almost same values, even the numbers of these data are different, but from Area 3, which is a slow earthquake region, those distribution is almost normal.

6. Deviation from Ordinary Stochastic Model

It is obvious that the uncertainty of response factor can be reduced by adding the knowledge on wave forms of input ground motions as the author discussed in the previous sections. The results on earthquakes from Area 1 and Area 2, we can reduce such uncertainties by establishing the model of source mechanisms of earthquakes, that leads to wave form of an individual earthquake. On the other hand, the fluctuation of the response factors from Area 3 may be not reduced anymore from the result.

Most of data analysis in the stochastic sense, we simply assume a certain distribution without analyzing the physical characteristics of the phenomena. If these are several factors which are not known, the distribution may be treated as a normal distribution by the central limiting theorem. However, in some cases, which the author described, the deviation from that is extremely large, and it is only the way to reduce such an uncertainty to examine its physical characteristics, and to separate it from the stochastic model. For modeling the "uncertainty" in wide sense, we need such a type of study. If it is beyond our capacity for surveying, it should stay in an uncertainty, or obtains the knowledge by a system like an expert system, or guess it by using fuzzy technique to cover its unknown part.

7. Concluding Remarks

The author has been working for anti-earthquake design of nuclear power plants and other critical facilities. To establish their safety feature, we are asked to reduce the uncertainty on a seismic event and a structure response to it as well as possible. The subject which the author discussed in this paper is one of those efforts, and it is solved by a combination of a stochastic model and a deterministic physical model.

However, through these process, we are facing another problem, that is chaos. "Chaos" caused from a deterministic process with initial conditions, but obtained process itself is quite random. And this is caused by a nonlinear behavior of model. "Failure" treated in the earthquake engineering is one of examples of such non-linear phenomenon. Also, our final target of the seismic design is to reduce the catastrophic state of the plant as a consequence induced by an earthquake, such as a core meltdown in a nuclear power plant. To reach the state, there are many contributions by human operators and external phenomena. Those, especially the human factor, have extremely non-linear and deeply related to bring chaotic state as a final result. It is not clear for the author that the ordinary stochastic approach is applicable to such a case.

8. Acknowledgment

The data and analysis described in Sections 4 and 5 have been done by Mr. T. Shigeta, Research Assistant and Mr. H. Komine, Technical Assistant of Plant Engineering Laboratory, operated by the author. Especially, Mr. Shigeta's daily effort to observe the response of chemical engineering complex for last twenty years is great. The paper to describe the details on this study will be prepared in the near future by them and the author. The author greatly appreciate their cooperation to this paper.

9. Reference

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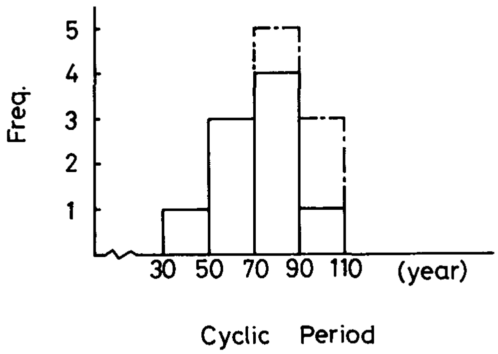

Fig.1 An Example of Distribution of Cyclic (Return) Period of Destructive Earthquakes from a Particular Nest --- Kwanto Earthquakes in Japan.

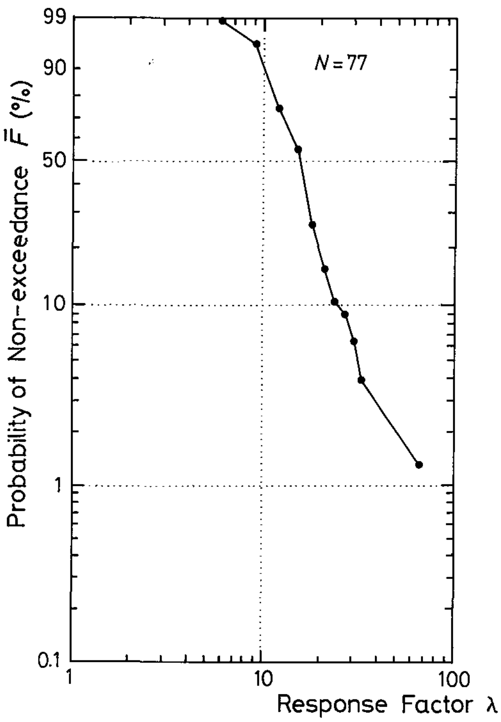

Fig.2 Probability of Non-exceedance Curve of Response Factor of Hanged Tank Observed in Chiba F.S. (Ref.[6]).

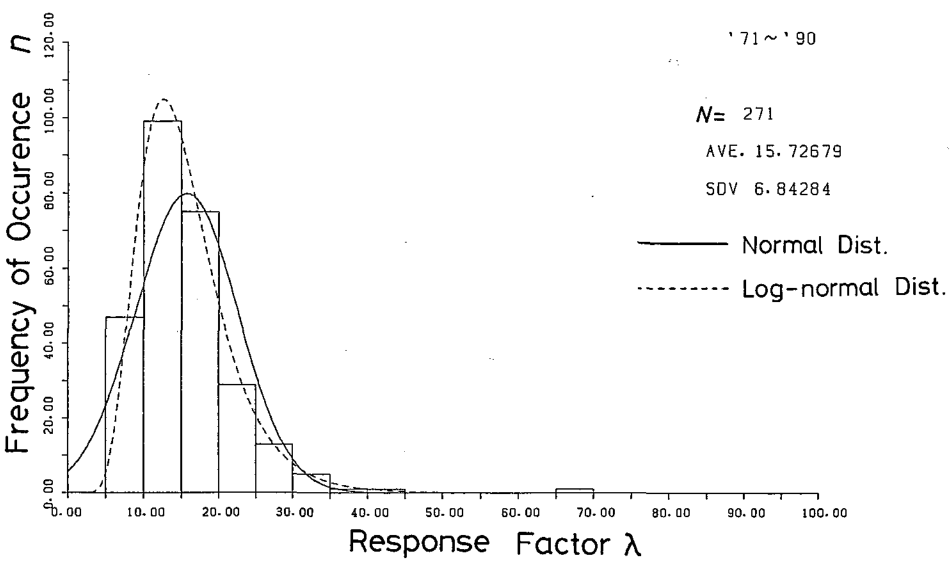

Fig.3 Distribution of Response Factor of Hanged Tank Observed in Chiba F.S. 1971 to '90.

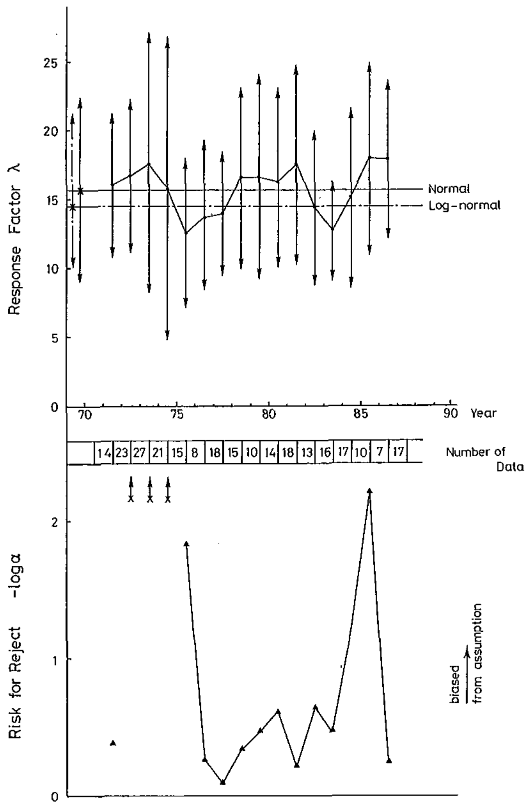

Fig. 4
Annual Change of Stochastic Values of Response Factor of Hanged Tank in Chiba F.S.

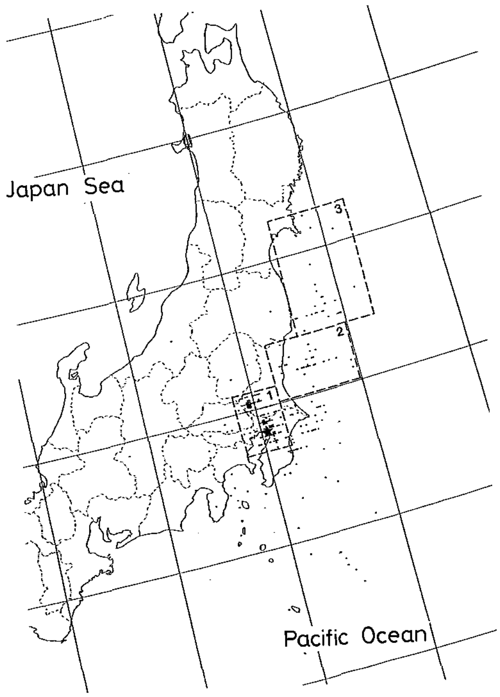

Fig. 5
Epi-center Distribution and Areas 1, 2 and 3, and the Position of Chiba F.S.

Table 1 Stochastmic Values of Response Factor of Hanged Tank in Chiba F.S. from 1971 to '87.

Risk for rejection α is obtained by re-reading from a graph in a hand book, therefore, not so accumulate. The value of α is usually chosen 0.05 or 0.01 for testing. Mark * is shown the value of α is less than 0.001, that is almost sure to reject the assumption of a normal distribution.

Year	Number of Data N	Average Response Factor λ	Standard dev. σ	χ^2	Degree of Freedom	Risk for Rejecting Assumption α	Skewness	Average Acc. (gal)
'71～'90	271	15.73	6.83	96.496	5	*	1.3883	7.256
'71～'72	37	15.92	5.30	6.844	7	0.425	0.2545	3.266
'72～'73	50	16.62	5.69	47.898	10	*	1.7108	4.779
'73～'74	47	17.55	9.63	45.071	10	*	1.8492	6.266
'74～'75	35	15.76	10.94	34.622	9	*	1.3420	8.519
'75～'76	23	12.45	5.50	17.737	7	0.015	1.7238	9.435
'76～'77	26	13.73	5.73	5.119	6	0.545	0.1967	8.989
'77～'78	33	13.93	4.57	2.258	5	0.815	0.0167	8.894
'78～'79	25	16.64	6.62	7.776	8	0.455	0.2734	7.104
'79～'80	24	16.64	7.29	9.213	8	0.335	0.3317	10.917
'80～'81	31	16.25	6.94	9.247	7	0.245	0.2581	8.940
'81～'82	30	17.46	7.33	5.344	7	0.620	0.0067	5.954
'82～'83	29	14.39	5.60	9.469	7	0.225	0.5411	9.527
'83～'84	33	12.70	3.72	6.864	6	0.345	0.0736	8.978
'84～'85	27	15.12	6.47	15.613	10	0.060	0.7250	7.552
'85～'86	17	18.00	7.16	20.261	8	0.006	0.2344	6.560
'86～'87	24	17.91	5.80	7.625	9	0.570	0.0001	8.185

Table 2 Variation of Stochastmic Values according to Epi-center Areas.

Year & Area	Number of Data N	Average Response Factor λ	Standard dev. σ	χ^2	Degree of Freedom	Risk for Rejecting Assumption α	Skewness	Average Acc. (gal)
Area 1 '71～'90	104	15.81	7.09	42.773	10	*	0.7926	8.635
Area 2 '71～'89	28	15.58	7.17	17.271	4	0.0042	0.547	7.297
Area 3 '71～'87	19	15.73	3.99	0.904	4	0.930	0.0173	6.081