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Use of Shaking Table for Proving Test of Piping and Equipment, and Selection of Input Motions

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Summary

Recently, the use of shaking tables for proving test of piping systems, equipment, active components and others in nuclear power plants and petro-chemical industries is rapidly expanding in Japan. This paper is dealing with the way of planning of such testings based on the author's experiences.

As he discussed in his previous papers [1][2], the purpose of a shaking test is devided into five or six. One of them is a proving test. The proving test is very important for engineers to obtain their confidence as well as for publics. However, in the engineering viewpoint, other testings are also important. The author tries to discuss the procedures and the design of testings in each categories, especially emphasizing in the relation of input motions and input level to the structural and functional reliability of these items.

This subject is based on the fields of the seismology, the mechanical vibration, the strength of materials as well as the system engineering. But the author intends to discuss this subject mainly in the view point of the response and strength of the items associated with the reliability problem. And he also tries to discuss on generating the fragility curve under seismic input conditions.

§1 Introduction and History

Since early 1960's we have been making various shaking tests for the aseismic design of nuclear power plants and petro-chemical industries. Most of such testings were done using shaking tables. In this period an unbalance-weight type table was mainly used. For the space industry in the United States, an electro-magnetic type was widely used, but it was very expensive and rare in Japan. Free-vibration-type was also used for a large size shaking table.

In 1970, a 500 ton hydro-electric shaking table was completed for National Disaster Prevention Center in Tsukuba-Science City. Such hydro-electric shaking tables were successfully used for various important projects, but they employed a displacement input-feedback control system. In 1971, an acceleration input-feedback control system had been developed, and one of newly developed tables was installed in our Field Station in Chiba. In 1981, a two-dimensional 1000 ton shaking table had been completed for NUclear Power Engineering Test Center in Tadotsu, Shikoku Island. This shaking table was built for the Proving Test Project of Nuclear Components. Various two and three-dimensional shaking tables have been completed for last two years as shown in Fig. 1. One of them, with the three face strong walls, was built in our Field Station as the third shaking table in that station.

Since 1983, tests for a one-fourth scale containment vessel model for PWR and 10 m diameter LNG storage tank model were made, and a full scale model of a primary coolant piping system with a pump model for BWR has been tested in Tadotsu.

The author organized a project of testings on various active-safety related components with electric utilities and heavy industries in Japan last four years. Through such experiences, the author would like to mention the significance of such testings in proving their integrity and functionality during and after the destructive earthquake. Especially, how to design the testing, including input motions, is a very difficult job. Such testings usually spend a lot of expenses both for manufacturing the model specimen and performing them.

§2 Concept of Testing in Relation to Design

The testing for this purpose is including a shaking test on a shaking table, which is sometimes called " Earthquake Simulator ", and a forced displacement test using hydraulic jacks. The purposes of such testings are devided into several ones as follows:

i) Analysis Confirming Test; Low level (ACL),

ii) Analysis Confirming Test; Design level (ACD),

iii) Function Proving Test (FP),

iv) Margin Check Test (MC),

v) Type Approval Test (TA).

These testings are deeply related to their design procedure as shown in Fig. 2. Those purposes are also considered to be as follows, that is;

i) the research on dynamic characteristics of structures,

ii) provings of a new computer program for dynamic response analysis of structure,

iii) the qualification of newly designed components.

The author discussed such subjects in the previous paper(1). One of the important problems for performing those testings is the selection of input wave forms. In this paper, the author tries to clear what kind of indices should be considered to identify various types of failure modes. And, he also discusses on the choice of waves from natural earthquakes, artificial time histories and pseudo-earthquakes, the significance of 2-D and 3-D waves, and some problems of wave generation technique from wide-range shape response spectrum which is employed in Japan and the U.S.. Various types of shaking tests of mechanical and electrical components have been performed. Also such tests were done for other industrial facilities and equipment in ordinary office and commercial buildings in Japan, even though their safety requirements are not so severe as for nuclear power plant components. All new products are tested on shaking table or at least by a shock input based on their specification in some fields, even though they are not general.

§3 Design of Input Motion for Testings

§3.1 Sinusoidal Input Motions

The author discussed the relation between testing and design in the previous papers(1)(2) and the Introduction of this paper. The design of input motions for such testings is deeply depending for their purpose. Even a sinusoidal input testing, how to decide the frequencies of excitation or how to sweep the frequency is very significant. One of the key specifications of sinusoidal input is to change its frequency under constant displacement amplitude or constant acceleration amplitude. Recently it is rather often that the increase of the amplitude in one frequency to another to made step by step, because of the use of a digital control device for the shaking Table. If the system which is tested has completely linear characteristics, the details of the design of testing are not sensitive to the result. The sweeping rate β or frequency step Δf is only significant to the result as a function of the damping ratio of the system. The optimal sweep rate has not been designated yet. Some references, for example, " Shock and Vibration Handbook "(3) shows how to change the response curve according to the sweep rate. The optimal sweep rate is the function of the critical damping ratio of the object and the criteria for allowable discrepancy between the theoretical resonance curve to a steady sinusoidal input test and that obtained by a sweep test. The formulation has not been made, the author believes. In the case of step by step method, the duration of the frequency Δf is also significant. But the definite way to determine the size of the step has not been well established.

If the system has some nonlinear characteristics, such as hardening or softening type spring, friction, gap and so on, the detail designs; the parameters of sweeping, direction; increasing or decreasing, and sweeping rate are significant to make clear its vibration characteristics. This is quite well-known fact as a theory, however, it is very often eliminated for the design of testing under some practical reasons. Some an extreme example is shown in Fig. 3.

The design, shape and size, of equipment is usually common to several nuclear power stations. Also the same type equipment are used in various locations in a plant, or in various sites. Therefore, the choice of input motions is very complicated to satisfy the design requirements, and if we want to cover the all possibilities where they will be installed. This will be discussed in next section.

§3.2 Widened Spectrum Input Motions To cover various possibilities of vibration characteristics of input motions, the Test Input Motion Spectrum is usually using very widened one (in Fig. 4(a)). Such a widely flatened response spectrum produces white noise type motions, if the phase restriction is not settled. Although to produce a realistic shock-type or transient-floor-response-type motions for such a TIMS, the phase restriction is considered as earthquake-dependent. However, the author consideres that this is correct to the ground motions of a natural earthquake, but those of floor responses are not strongly dependent to each input earthquake, if the system is lightly damped. It is more similar to ordinary transient response motions of a simple-freedom, two or three-degree-of-freedom, system. Therefore, he recommends the use of the adequate phase restriction obtained from some typical natural earthquake response or the theoretical transient damped vibration of its simplified model to some simple input.

The wave form obtained the B type spectrum in Fig. 4(b), that is, the widely flatened spectrum with a single sharp peak, is usually a sinusoidal wave plus some white noise type waves. If those for PWR and BWR are combined, it becomes as shown in Fig. 5. Such input motions have been often used for vibration test of a space craft(4), because to apply its back ground, noise-type vibration caused by turbulence flow of the vehicle. In our case, the circumstantence is much different, because the author discussed for a flattend test input motions, with a sharp peak. If some phase restriction of an impulsive type earthquake is applied to this spectrum, the waves which have a very strong feature will be obtained, that is, usually they contein a high peak motion with continuous pseudo-sinusoidal waves. Therefore, it is very difficult to produce such motions to fit a particular shaking table for testing, because of the limit of its performance. The pseudo-sinusoidal waves can be obtained as Rayleigh-type distribution random process, or narrow-banded white noise. It is rather easy to operate, if separate the single peak motion from continuous pseudo-sinusoidal type motion tests. In this case, the limitation of the number of specimen for separate test becomes a problem sometimes. The decision, a test using which input will be done at first, should be made under the consideration on the relation of the peak frequency to the distribution of eigen-frequencies of the testing object.

§3.3 Alternative Input Motions Instead of the use of natural earthquake records or ATH generated from the given TIMS, two ideas are coming to give an equivalent effect on a tested object. The first one is the wave form based on sinusoidal waves. The second one is the wave form based on random waves.

i) tuned n-continuous wave sinusoidal motions,
ii) tuned constant amplitude beating sinusoidal motions,
iii) tuned damped beating sinusoidal motions.

Some other wave forms may be introduced also. By tuning the frequency of the waves to an eigen-frequency of the object, the server test can be done.

The main features of such wave forms are almost same, that is, the maximum response level and its evolutional function. The time duration of input motions is controlable independently from the response level in the cases of ii) and iii). Simple beating waves consist of two components of sinusoidal waves, therefore, they can cover some uncertainty or fluctuation of the eigen-frequency of the object. Tuned three-wave sinusoidal motions are very often used for the testing of electric power apparatus in Japan. The response factor to this type of input is usually higher than those to natural earthquakes[5].

If the object has many distributed eigen-frequencies, then, two practical methods can be considered, that is, a sinusoidal sweep method or a random-wave based one. The sinusoidal sweep method can make clear the nonlinear characteristics of the object as mentioned before, but usually it is too much to emphasize them comparing to the response to natural earthquakes. The random-wave based one is more suitable. Wide-band random waves are useful to know the general response behavior, but it is rather difficult to generate them on a shaking table because of the high level of ZPA and the wide frequency range requirements. Applying a moving window type frequency filter, that is, the center frequency of the filter is swept, to white noise waves is an idea, but it is not used usually, because it takes rather long duration to keep the stationarity of the response and the fluctuation of the level is not so small. A mixed wave form, that is, a sinusoidal wave form, which is being swept, plus low level wide-band random waves can be used for this purpose. This method is widely used for space craft testings (3).

If the vibration characteristics of ground motions and supporting structure can be stated, the narrow-banded white noise can be used as a pseudo-earthquake. This technique has been widely used since Cal. Tech. group used it (6). Such narrow-banded random waves are easily obtained both by an analog device and a digital computer, and also to fit the theoretical mode for the analysis.

§4 Three-dimensional Motion Input

Three-dimensional input test including two-dimensional input test is necessary for a system whose nonlinear behavior is significant to its earthquake resistant performance. Some are the reguratory requirement in the U.S. (7).

Several phenomena observed in some previous earthquakes. One of the examples is a mulfunction of an edicurrent-disc-type over current relay (8). The author found that this mulfunction can be induced by two axial horizontal motions, whose phase relations are almost rectangular to each other. This is a rather special case, and the behavior of an object which is affected by the gravity force is more common for two axial, one horizontal and one vertical input motion test. Some codes like IEEE require to find the three principal axes of vibration of the object. For this test, we need to spacially rotate the object or distribute the three components as rotating the vector of the motions (Fig. 6, this figure shows a two component case, to understand the concept easily. After finding these three axes, three independent excitations, which are most effective independently to its three principal axis response, shall be simultaneously imposed. For such purpose, a device, to distribute three independent input signals into three axes stated in arbitrary directions relatively, is necessary. In other word, this device can give the controlled dependency to the motions in the three axes, one vertical, two horizontal axes those motions consist of three independent motions, of the shaking table.

§5 Evaluation of Damage Effect of Input Waves

The response spectrum and other expressions on vibration characteristics of input motions can give only an information on the peak value of the motions. The failure mode of an object can not be stated before the testing usually. On the other hand we should expect some damage accumulation type failure as well as an instant-loading type failure like a simple breakage or buckling. The spectrum type expression is only effective on the latter one, because it does not contain the information on the time duration of each earthquake. The author discussed on D-value to evaluate the damage accumulation(9). This D-value is similar to the Usage Factor defined in ASME Boiler and Pressure Code, Section III. The D-value is directly evaluated in relation to its failure limit without the consideration on the safety factor like the Usage Factor. Even though this D-value itself does not directly relate to the absolute damage effect of the input motions, because the local strain value is decided by the result of the stress evaluation including that of stress concentration factors. Therefore, the author defined more simple parameters, D_1 and D_2 as follows:

$$\tilde{D}_1 = \int_0^{T_l} [\ddot{x}\ (t)]^{\alpha}\ \alpha t \qquad (5.1),$$

$$\tilde{D}_2 = \int_0^{T_l} [x\ (t)]^{\alpha}\ \alpha t \qquad (5.2)$$

where T_l is the duration of the earthquake, $x(t)$ and $\ddot{x}(t)$ are the response of the tested object in displacement and acceleration repectively. The parameter α is the gradient of the damage accumulation S-N relation curve. Although a result of the author's study(10) shows that it takes 2.5 as shown in Fig. 7, here he employed α=2 for the simplicity of the analysis. It is considered that the nature of $\overline{D}_1$ is mainly related to the primary stress evaluation, and that of $\overline{D}_2$ is to the secondary stress induced by the displacement of the object. One example of the new type of spectra is shown in Fig. 8, and it is similar shape to the ordinary response spectra, but it is twice larger in ordinate as shown in Figs 8 and 9. And they are considered to be useful for evaluating the effect of input motions. By using them, the total damage accumulation through the testing procedure must be evaluated in advance for the safety of the testing object.

§6 Role of Environmental Conditions and Functional Operation of Objects

For the qualification test of various mechanical and electrical components, we meet the problem how to specify its environmental conditions and functional operation test during shaking states. Such tests are money-consuming, and troublesome one for engineers. Even though, it is very important and significant way to find their failure modes. One of the problems to test the object in the environment of their using condition is the economy. This relates to the selection of materials using for parts of the object. If test will be done in the real environment, we can not substitute of their materials to cheaper ones. Then this makes the object expensive. The author tries to mention some examples of the effects of environments briefly:

Temperature: Temperature usually does not have much effects on the testing result:

i) Strength and yielding condition of material do not change in the range of using temperature, unless in the range of applying high temperature criteria like ASME N-41 (11). Otherwise, test data can be compensated by the result of specimen testings.

ii) Brittle failure under NDTT may change the failure mode of the object. So low temperature testing to meet its actual environment is very significant.

iii) Effects on strength and other material properties from chemicals including water may be affected by its environment temperature. But it is not significant for a short term loading like earthquake load in general, except pre-deterioration problem like SCC of nuclear pipings.

iv) Some mechanical properties may change its vibration characteristics. One of typical examples is the damping ability of a dash pot.

Pressure: Pressure has more effect on the testing result than temperature:

i) Buckling condition of thin shell cylindrical vessel is a typical example. It changes as a function of internal pressure.

ii) Ratcheting effect is also very significant for the short term repeating load like earthquake load. Its criteria is almost one sixth of the limit of usual low cycle fatigue, if the internal pressure of ordinary design level exists (10).

iii) Change of the internal force induced by pressure is sometimes significant to the dynamic behavior of the object. One of the examples is a flat-sheet safety value. Because of internal operating pressure, the force acting between valve body and sheet becomes almost zero in operating state. Therefore, the valve body-stem system looses its damping divice obtained by a friction force between them. Another example is a cone sheet valve. At the moment when it completely closes, the vibration characteristics is suddenly changing.

Dynamic Operating Load: Usually this load is not so significant for their non-linear analysis. They can superpose this to ordinary vibration response. Sometimes dynamic force effect of rotating machine should be examined. Especially, the failure caused by touching a rotating part to a fixed portion as a result of response of the rotating part is significant for their safety.

Content: Water in a containment induces various type of dynamic load as well as static load condition.

i) Hydro-static pressure causes internal strain in a thin wall. As a result, the buckling criteria changes remarkably under some conditions.

ii) Sloshing induced by earthquake input gives significant reaction force on its containment as well as on its internal structures.

iii) Sloshing also induces cyclic change of temperature on the wall and dipped structure. It causes some thermal fatigue and ratcheting of its material.

Change of Configuration: By operating equipment, its configuration, for example, length of the stem changes, and it causes a kind of parametric change of the vibration system. In some case, it brings parametrically excited instability.

As the author described, the design of testing is related to not only its dynamic characteristics but also its function. The engineer must pay his attention much on the functionality of the object.

§7 Concluding Remarks

We have been done many qualification tests on electric and mechanical components for these ten years. Recent large project is " Active Component Test ", done by utilities and heavy industries under cooperation of researchers in several universities. This project was done on eleven items according to the philosophy described in this paper. Based on the results and findings, we are drafting the new guideline how to proof their functionality under and after the design basis earthquake by analysis and testing.

One of the seismic qualification testing projects is a series of testing done in Tadotsu by NUPEC. This project mainly supported by the Ministry of International Trade and Industry. The test on a 1/4 containment vessel for PWR was over, and a full scale primary coolant piping model has been tested. Other six mechanical component tests are planned by MITI, and some others by various organizations. This 1000 ton shaking table has a capability to find many new subjects and keys to improve the aseismic design of nuclear power plant [5], and also other industrial facilities.

The main portion of this paper was presented at KESWICK Conf. on " Third Vibration in Nuclear Plant " in 1982 in England. And the author rewrote it based on the new knowledge obtained through recent researches, and also through the discussions done in various occasion of the projects above-mentioned. He wants express his gratitude to the related people for their co-operation.

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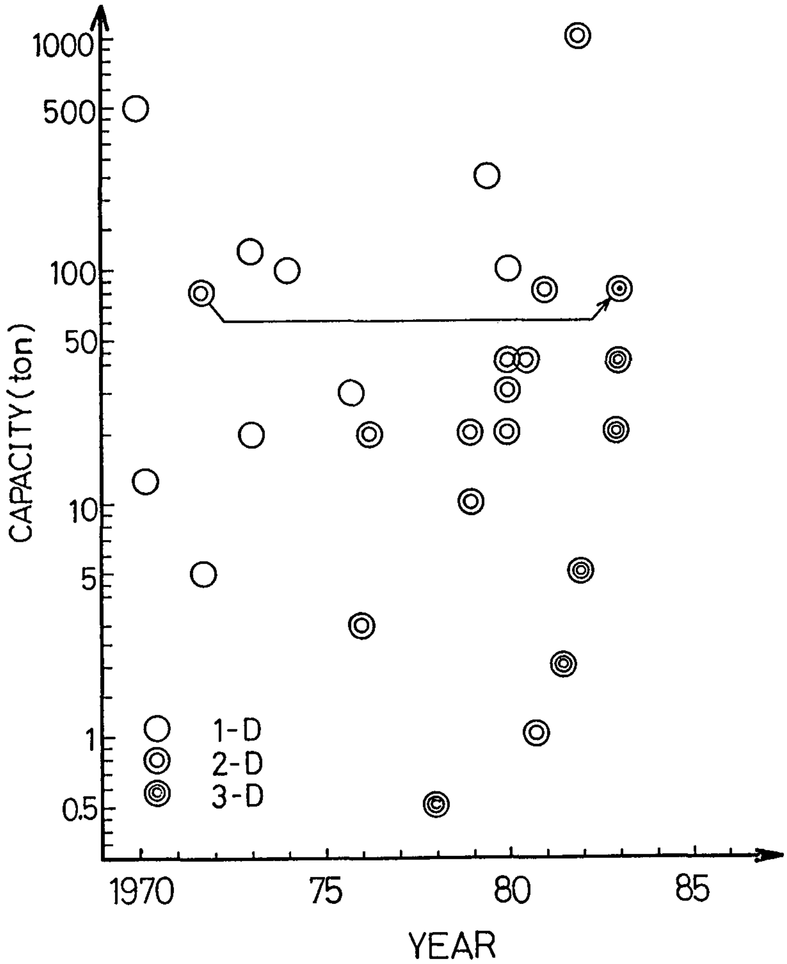

Fig. 1: The Capacity Development of Japanese Shaking Table in the Year: 3-D means a Tri-axial shaking table

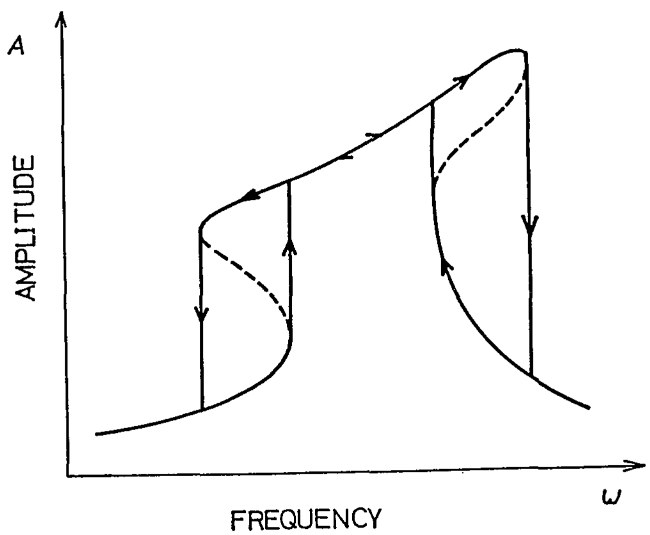

Fig. 3: Schematic Response Curve of Extreme Non-linear Model

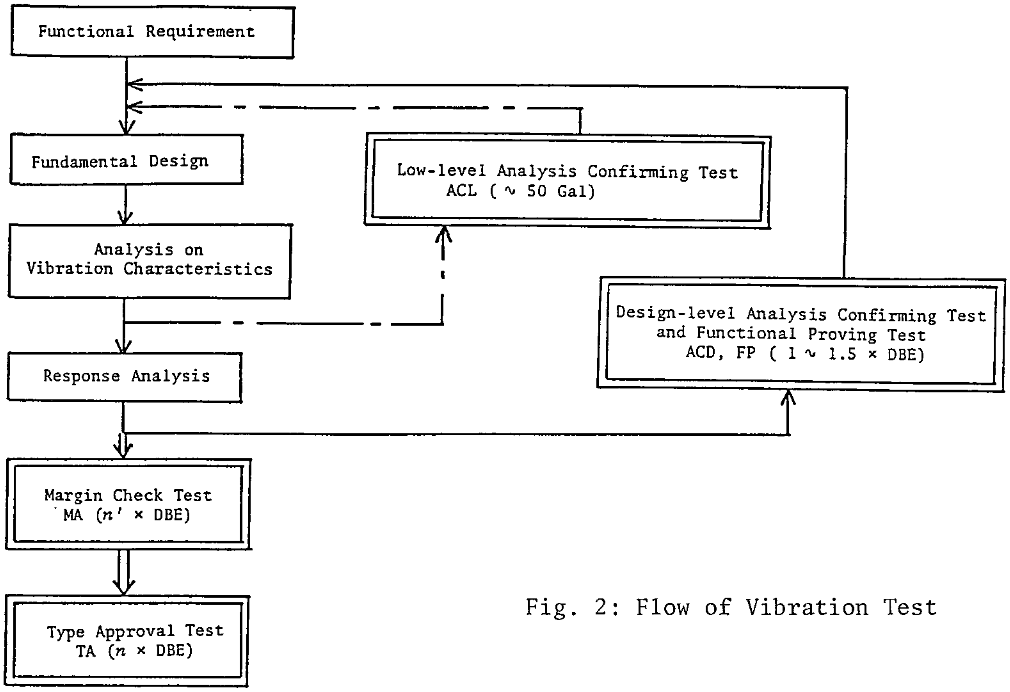

Fig. 2: Flow of Vibration Test

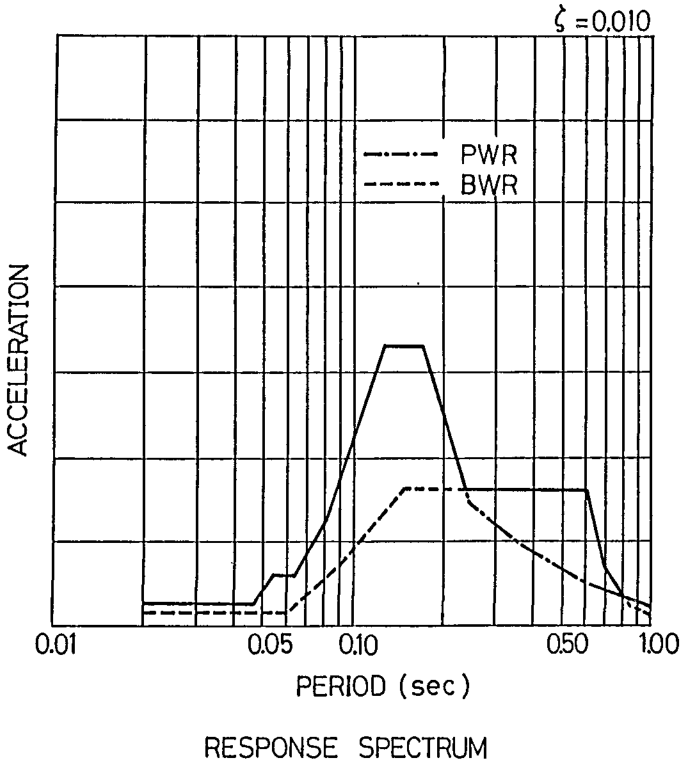

Fig. 5: Enveloped Design Response Spectrum for Component in PWR and BWR

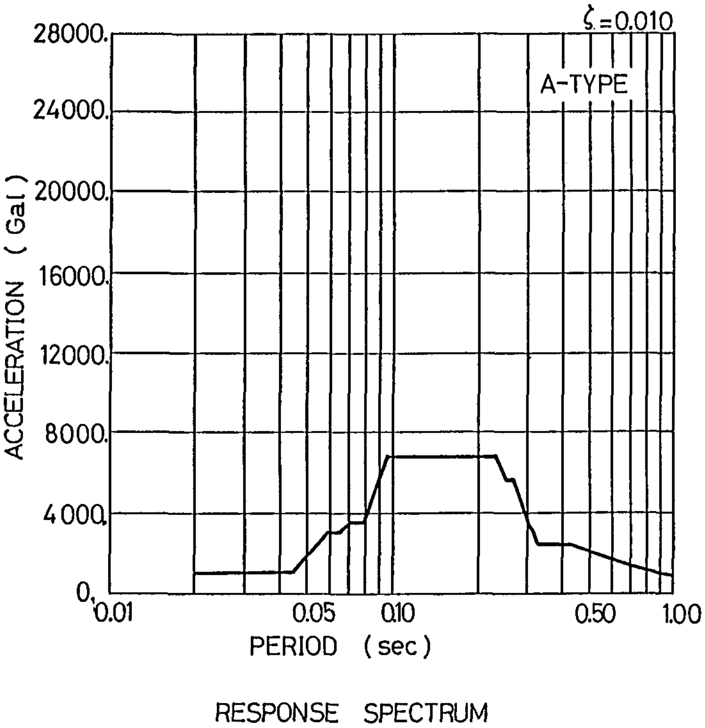

Fig. 4(a): Schematic Design Response Curve for Component: Type A, flat top type

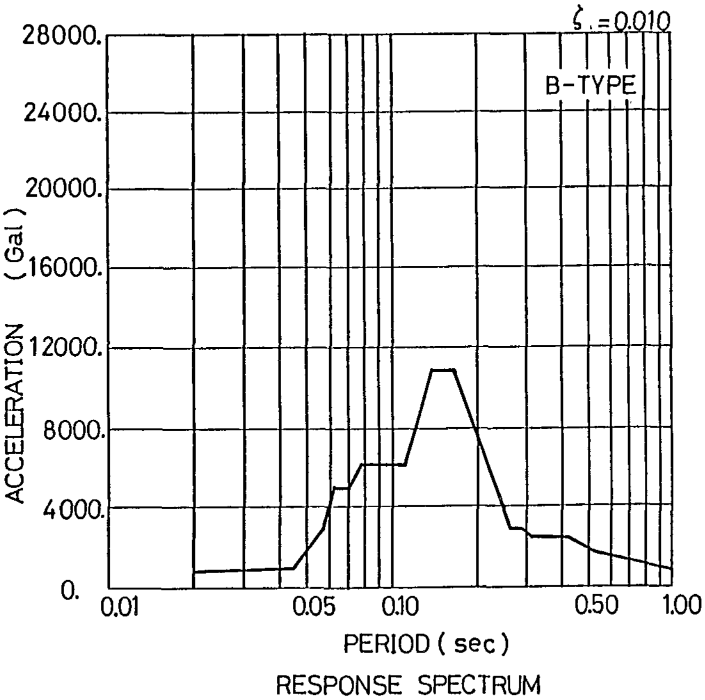

Fig. 4(b): Schematic Design Response Curve for Component: Type B, flat top type with a peak

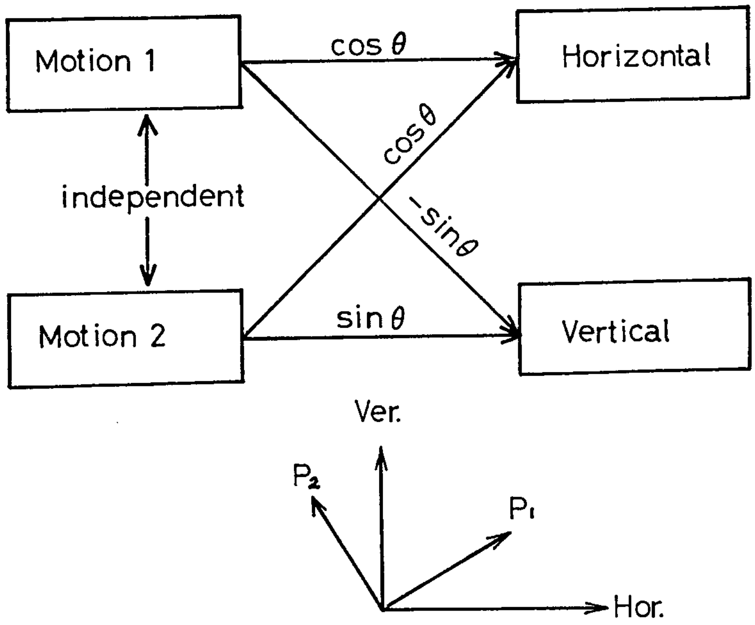

Fig. 6: Rotation of Principal Motion Axes

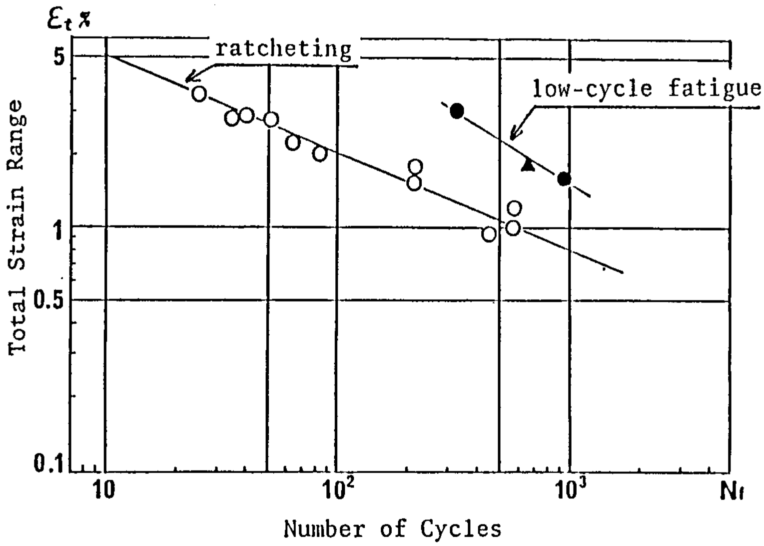

Fig. 7: S-N curve for Ratcheting of Nuclear Pipings under Cyclic-Load

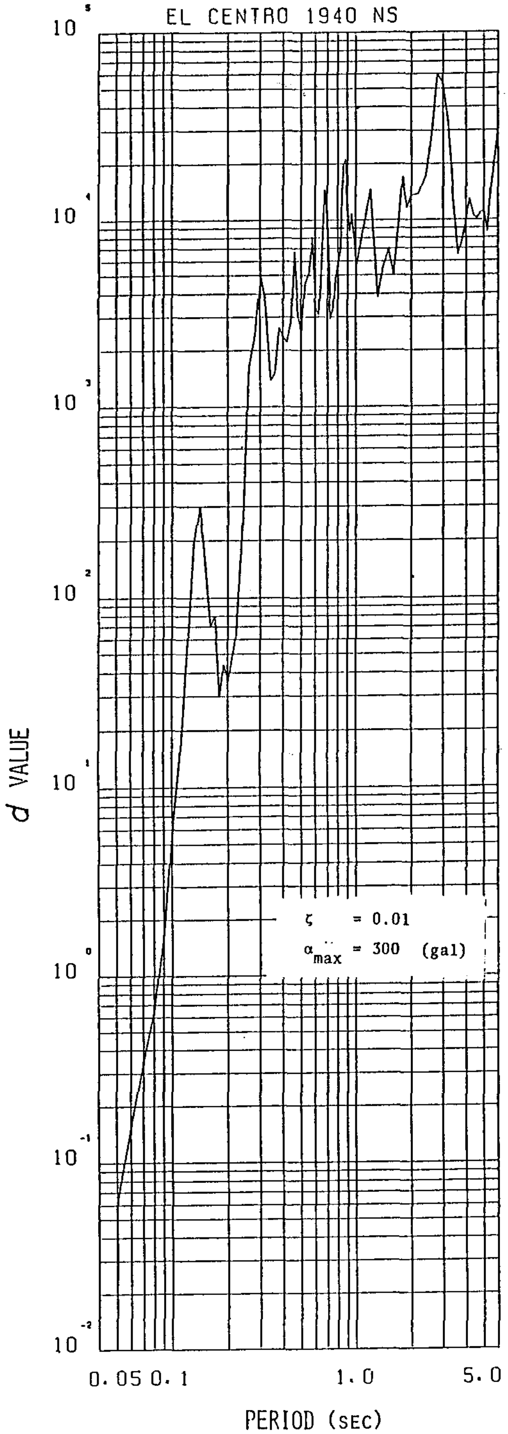

Fig. 8: Damage-factor, *d*, Response Curve

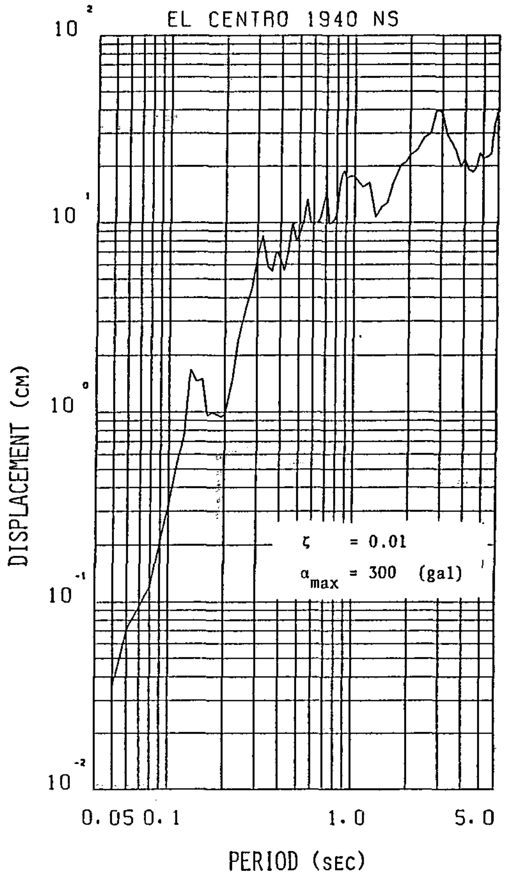

Fig. 9: Displacement Response S_d Curve

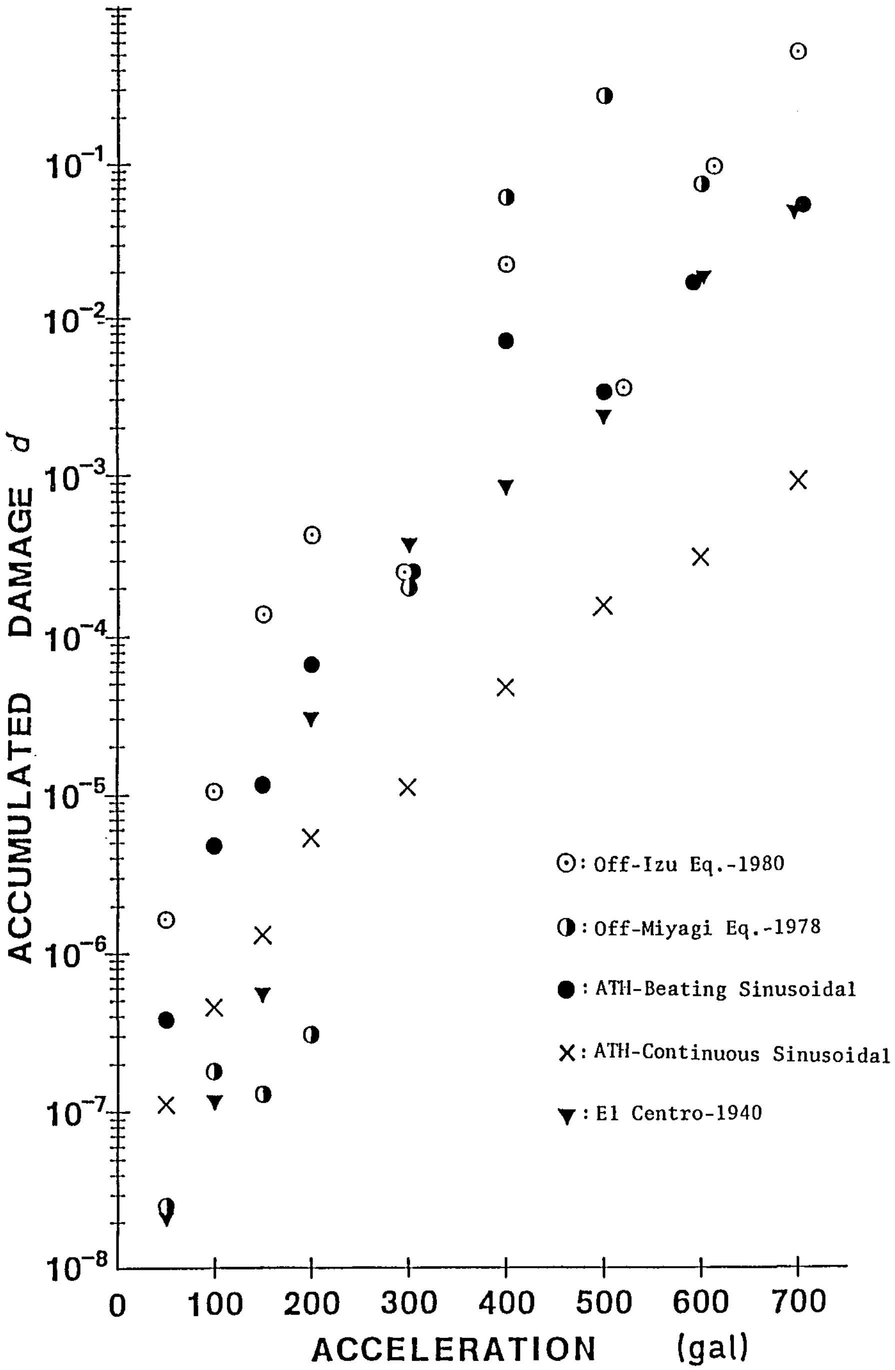

Fig. 10: Simulation Result of d-values to Natural Earthquakes and ATH using Non-linear Single-mass Model