ON ESTIMATED MODE OF FAILURES OF NUCLEAR POWER PLANTS BY POTENTIAL EARTHQUAKES

H. SHIBATA
Institute of Industrial Science, University of Tokyo, Minato, Tokyo, Japan

K. AKINO, H. KATO
Japan Atomic Power Co., Chiyoda, Tokyo, Japan

SUMMARY

This paper deals with estimated "mode of failures" of nuclear power plants which will be caused during violent earthquakes.

The group of the authors have been surveying the damages of industrial firms by several violent earthquakes since 1960. Some of them were already reported in English, but there they try to rearrange those in the view-point of "mode of failures" of buildings, equipment, vessels and pipings of nuclear power plants.

The authors categorize the mechanism of failures as follows: (i) damaged by acceleration shock, (ii) by pseudo-resonance in acceleration wave, (iii) by resonance in acceleration wave, (iv) by resonance in displacement wave, (v) by seismic force slower than the natural period of building, equipment and so on, (vi) by external force from attached pipings and so on, (vii) by forced deformation and (viii) by liquefaction of soil.

Also items of nuclear power plants are assorted as follows: (i) main building, (ii) auxiliary building, (iii) containment vessel, (iv) primary coolant system, (v) emergency cooling system, (vi) secondary coolant system, (vii) turbine, (viii) control rod system, (ix) safety shut down system, (x) refueling machine and crane, (xi) cooling pond, (xii) main power system, (xiii) emergency power supply, (xiv) control room instrumentation, (xv) air-conditioning system and stack, (xvi) underground pipings for cooling system, (xvii) auxiliary equipment and (xviii) auxiliary pipings.

The authors try to figure out the modes of failures of these items in a matrix form of these view-points.

They also examine them in anothers' view-point, that is, in "the classification of importance" of the items, and comments in relation to their aseismic design method. "Classification of importance" is the most important and basic concept in aseismic design of various kinds of plants, and has been employed for nuclear power plants in Japan and the United States since the beginning.

1. Introduction

When we start the aseismic design of a certain structure, we should know how and why it may break down. These "how and why" are the "mode and mechanism of failures" in the title of this paper.

Some of the authors, Shibata and Akino have been engaged in the aseismic design of nuclear facilities since 1957.(1) There was no experience to design equipment, pipings and other such complicated structures for earthquake resistant structures. At first they made vibration experiment of piping systems of conventional power plants. And as a second step, they made their precise survey on damages of industrial firms suffered to Niigata Earthquake in 1964.(2) Since these two jobs, we have been continuing our efforts to make surveys in Japan. The report presented by Shibata and others in the Session K 5 is one of such our efforts. The "mode of failures" can be clarified only through such efforts as an accumulation of data or experiences. On the other hand, the "mechanism of failure" is an essence of results obtained through theoretical studies and observations.

The principle of the aseismic design of nuclear facilities was already reported in the previous conference as a guideline(3) and other reports on individual studies.(4)(5)

2. Mechanism of Failure

As already mentioned, we should know how and why they broke down or may break down during a strong earthquake for their earthquake resistant design. To know the mechanism of failure, we have to think about earthquakes and the responses of structures to them in the sense of dynamics. Dynamic characteristics of earthquakes or ground motions are usually shown by Housner's Response (Fig. 1).

At first we have to discuss on this curve little bit. An acceleration response curve (Fig. 1-(a)) is used for regular types of design. And the second peak of period T_b is ignored in general. If we turns our eyes upon responses of long period structures (Fig. 1-(b)), that is, free surface of water in torus or cooling pond and so on, the second peak becomes more important.

The peak of T_b or the wave of displacement region is more dominated, when the magnitude of earthquake is bigger.

Fault has another possibility to give damages to a whole structure. Relative displacements of rock blocks of both side of a fault line may give hazardous effects to the structure which placed on the fault line. Method of relaxation of the effect of forced displacement to the structure, for example, to place cushioning layer, may be necessary to consider.

Liquefaction of ground has possibility to give damages to burried structures, like pipings, pond and so on. This phenomena are understood the combined force of sand grains in a ground layer containing water is lost and they loose their coupling by water film when they are subjected to repeating shear force. So necessary conditions of liquefaction are homogeneous fine sand to certain depth and high water level.

2.1 Failure caused by Acceleration Effect

A system which has its natural period far shorter than the dominant period of ground motion is subjected to the ground acceleration as a static force. And it may fail at the weakest point in the sense of static force balance. So low level structure or monolithic structure is usually designed by using static force caused by static acceleration. In a view point of dynamic design, if the natural periods of such structures are placed in the region of rigid structure, or of far shorter period than T_s , the static acceleration is equal to ground acceleration. If its natural period is near to T_a or to resonant condition, then we need to introduce an idea of amplification factor, as they are going to be refered in next section. But in the region lower than T_s , this amplification factor is rather low, so we can put it 1.0 or 1.2 independent of the natural period and other dynamic factors of structures.

Against very keen shock come from the source of earthquakes directly through hard rock layers, even a rigid structure behaves in other way. Structures which has enough ductility usually suffer no damage to such a earthquake but brittle structures, for example, porcelain equipment in an electric power system, may fail by the shock. In the case of San Fernando Earthquake porcelain cylindrical vessels of many air-blast type switch gears were ruptured.

Very massive structures, like electric power transformer or non-anchored storage tank, may slip in side way by the effect of horizontal acceleration.

2.2 Failure by Acceleration Resonance

A tower or a storage tank supported by several legs is represented by a single mass and single spring model. We usually call it as a seismic system. Such a system has an evident natural period. If its natural period is near to the dominant periods T_a and T_b of ground motions, the system may resonate to them. An amplification factor is functions of parameters of the system, natural period and critical damping ratio, and the wave form of ground motions. More dangerous case is whipping of appendage portion of two masses system. Especially where the mass of appendage is very smaller than that of main structure and its damping coefficient is low, the vibration energy of main structure may concentrate in appendage, and it may be damaged very seriously.

Failure of the system in resonant condition may occur mainly in spring portion, like legs, bracings, frames, skirt and so on. In some cases, attached equipment may fail by high acceleration of mounting point.

2.3 Failure by Relative Deformation and Resonance to Long Period Motion

Of course, all failures of a structure may be caused by excess strain, but the portion, which has relatively small cross section and is bridged on two separate major systems, may be enforced a large relative displacement by their responses. In this case the amount of the strain will be decided by the amount of relative displacement, not by the force. So there is the higher possibility to cause complete rupture in this case than the case of members subjected to dynamic force as a spring part of the seismic system.

If the system bridged between two sides of rock blocks on both sides of a fault, the situation is the same. Estimating the possibility of sliding a fault and the amount of sliding is extreemly difficult.

In the case of flexible structures which may resonate to the ground motion in a region near to the second peak of the period T_b (Fig. 1-(b)), response in displacement is usually more significant than response in acceleration. An example is the response of sloshing motion of water surface of cooling pond. In this case no portion is related to strain problem.

2.4 Failure by Liquefaction of Supporting Ground

The authors described the mechanism of liquefaction already. Although this phenomenon gives the most hazardous effect to plants built on fill ground, in a case of a nuclear power plant, fortunately, it is very seldom to build on ground of such a condition. But there may be a possibility for this phenomenon to occur in some places between the main building and water side, if there is fill ground. In such area, there may be water-intake and other facilities of the cooling water system, gas duct and filters of the off-gas system and some water storages and so on.

2.5 Topics on New-type Mechanisms of Failure --- Torsional Vibration and Others

Torsional vibration of structures during a strong earthquake is one of the important topics. The mechanisms causing torsional vibration are considered in three ways. One is that responded to torsional motion of ground. We can expect them in cases of strong earthquakes, and one of the authors recorded them in several times. Another type is that caused by unsymmetry of a structure responding to pure horizontal ground motion (3.2.2). The third one is that caused by the motion of content, that is the rotational movement of sloshing liquid in a cylindrical tank. In several earthquakes the authors observed torsional buckling of upper cylindrical part of oil storages.

The effect of shocks of vertical ground motion is not known. Response spectrum of vertical motion is usually flat and spreaded to shorter period region. The effect to reduce a frictional co-efficient of horizontal motion of massive and large scale structures is also not known.

3. Mode of Failure

3.1 The Meaning of Mode of Failure

To make the proper aseismic design, we should know the weak points of an object of design. By rearranging their weak points as the "mode of failures", we can establish the design procedures of various items of nuclear facilities. When we design a vessel, even though we calculate its stress distribution to the horizontal force precisely, if we omit the overturning moment to calculate the cross section of anchor bolts and decide it only by the effect of the shear force on them, it is said to be non-design against the earthquake.

It is easy to know the mode of failures of simple systems which are represented by a seismic system. But in a case of the system which has very complex shape like a containment vessel and torus system or piping systems for control rod driving of BWR type reactor, it is very difficult to know which are the weak points. But unless we know the weak points, we could not choose the points where we should check the strength of members or evaluate the strains.

3.2 Modes of Failure for Buildings and Structures

3.2.1 Reactor Building of PWR

One calles the reactor building of PWR is rather simple structure consisted of cylindrical concrete shielding wall or concrete containment vessel and mat foundation, and condition of stress distribution for the earthquake loading is easily analyzed. Should responded lateral force be large, vertical tension due to bending moment cancelling its gravitate compression will occur and considerable membrance and transverse shearing stresses due to lateral force will appear in lower portion of the circular wall, and much reinforcement should be arranged to withstand those stresses.

In the case of the cylindrical shell structure, oval mode vibration will be excited by earthquakes, but stresses occurred due to that mode are the secondary stresses and are less than the primary stresses mentioned above. Unless sufficient amount of reinforcements for the above stresses are provided, cracking of concrete would occur when very intense earthquake happens. In case of the structural formation is simple as the cylindrical wall, it is apprehended that a catastrophic failure of the structure may occur from growing cracking.

In the PWR reactor building, there is an internal concrete structure to support the reactor vessel, steam generator, pressure riser, piping, and so on, and a height of the internal structure is shorter comparing with its spread and so it is rigid. Responded acceleration for the internal structure will be less than the outside cylinder, but its structural formation in plane and in vertical sections is complicated and condition of stress distribution will be intricate. Therefore, careful consideration for the reinforcement at junctions, corners and edges of concrete members where stress concentrations are inevitable should be taken into their designs. If not, local collapsing may occur, and it will be significantly hazardous because the structure supports the primary cooling system of PWR.

3.2.2 Reactor Building of BWR

In many cases of BWR, the reactor building forms square or rectangule and consistes of three portions. In the first phase of their construction a biological shielding wall in which the steel containment structure, reactor vessel, its supporting pedestal, and so on are constructed. In the second an annex concrete structure is constructed outside the shielding wall in which control rod drive units, heat exchangers and other vital facilities, are installed. The third is a housing covering the operating floor, and that housing supports a large crane for handling of spent fuel cask. The outermost concrete walls and roof serve for the last containment barrier holding negative pressure in the building by its ventilation system.

The reactor building is a complexity as mentioned above, and the box-type outermost walls, biological shielding wall, other portion walls and floors construct a space frame as a whole to resist earthquake lateral forces. Making a model of the space frame together with its foundation to carry out the dynamic analysis involves doubtful problems including an interaction with soil. Anyhow calculated responded acceleration obtained from utilizing current analytical technique will be too intense at an area of high seismic zone, and seismic walls consisted of the above walls will be subjected to result large lateral forces. In a such severe case, shearing stresses in the seismic walls will exceed the allowable shearing stress of concrete, and shear reinforcement should be provided. As a nature of the reinforced concrete structure, shearing stress is critical for withstanding the strong earthquake, therefore, sufficient reinforcements for the shearing stresses in the walls of the reactor building are indispensable.

If center of rigidity and center of gravity of the building do not coincide with each other, torsional vibration will occur. Additional shearing stresses in the outermost walls, especially at their corners, will generate from the above eccentricity. So far as the torsional vibration, it is the most desirable to eliminate that vibration by making well-regulated wall layout.

3.2.3 Steel Containment Vessel

(1) PWR A form of the steel containment vessel of PWR is simple, a cylindrical wall and semi-spherical or ellipsoidal top and bottom shells construct one vessel. Generally, stresses in the vessel due to a nuclear accident are larger than those occurred by earthquakes in high seismic zones. If the vessel supports a large capacity crane at its top portion, however, stresses occurred by a strong earthquake are considerable at junction with the crane girder and at fixed portion of the vessel with foundation concrete, and, if required, special reinforcement should be provided.

As mentioned in 3.2.1, oval mode vibration of the vessel will occur, and by way of precaution stress calculation for the oval vibration may be needed.

(2) BWR The form of the steel containment vessel of BWR is not simple, and there are two types as Mark I and Mark II. In Mark I, the containment consists of two vessels, namely, one is a bulb vessel or dry well and the other is a torus or suppression pool, and vent pipes connect both vessels. In Mark II, the containment consists of two portions of one vessel, namely, upper portion is conical dry well and lower portion is cylindrical suppression pool, and diaphragm floor divids these two portions of a vessel. Mark II has not the vent pipes, but down comers connect both portions functionally.

At the top of the dry well of Mark I, and at the top and at an elevation of the diaphragm floor of Mark II, there are special devices by means of male and female mechanism to connect the vessel with concrete building. When an earthquake happens, a deformed concrete structure lean towards the steel vessel because rigidities of the vessel is larger than the concrete building. Natural frequencies due to elastic deformations are 10 to 30 Hz for the vessels and 3 to 8 Hz for the building. In the steel vessel, therefore, stresses due to the above leanings are larger than those due to responded accelerations or inertia forces, and the former stresses govern the design of the vessel in high seismic zone.

The torus vessel is generally supported by steel columns and diagonal bracings. In one case in Japan, the natural frequency of this supporting mechanism coincided with that of the reactor building, and its responded acceleration reached too large even though the vessel located under the ground surface. Hence, the above supporting mechanism was replaced by other mechanism which provides rigid lateral supports at the bottom of torus permitting vertical deformations of the vessel due to poured water and thermal expansion.

3.2.4 Auxiliary Building

In nuclear power plants, there are auxiliary buildings to install many equipment and facilities of A class in the aseismic design, therefore, the auxiliary buildings should be designed to A class. Height of the auxiliary building is shorter than the reactor building, and its responded acceleration is not so intense, but in many cases the form of the auxiliary building is irregular, for instance L-shape in plane, and torsional vibration will occur when earthquake happens.

3.2.5 Plan of Structural Conception

(1) Reasons for Failure of Concrete Structures

Many earthquake desasters illustrated us failures of the reinforced concrete buildings or structures, and they indicated what were sortcomings. Main buildings of the nuclear power plants must be constructed by reinforced concrete owing to radiation protection, and structural engineers concerned designing and constructing the buildings of nuclear power plants have to "Learn to be wise by the follies of others".

Failures or collapsing of the reinforced concrete structures happened from the following reasons that;

i) Not sound condition of supporting soil,

ii) Unsuitable foundation work or adoption of different foundation constructions underneath one structure

iii) Insufficient strength, especially for shear resistability,

iv) Insufficient ductility or less reinforcement,

v) Inadequate arrangement of reinforced bars,

vi) Connecting annex or appendage with main structure,

vii) Not well-regulated arrangement of structural frames and shear walls or unbalanced weight distribution,

viii) Collision of two buildings due to their deformations,

ix) And others.

(2) Plan of Structural Conception

In the planning of structural conception, an arrangement of equipment and facilities is taken the initiative and the planning have to be frequently pursued to meet the preferential arrangement. In consequence of that the plan of structural conception was made not following the above manner, therefore the reinforced concrete building or structure might be said to inhere in questionable defects from the view point of aseismic design. In order to avoid such inevitable implication with defects, the plan of structural conception should be advanced considering the following principles;

i) To reduce seismic force, to suppress sectional exciting vibration and to prevent torsional vibration;

a. To lower the center of gravity of the building,

b. To set the foundation sufficiently deep in ground,

c. To make the plan and elevation as simple as possible,

d. To do away with protruding sections, and

e. To made the center of rigidity coincide with center of gravity as much as possible.

ii) To preclude differential settlement and undesirable differential dynamic movements of structural blocks, it is necessary to unify the entire structure by connecting them with a monolithic foundation.

iii) To perform equivalent aseismic designs of equipment, piping, facilities, and so on as well as the building, these important items should be installed in the well-designed one building.

3.3 Mode of Failure for Equipment and Pipings

3.3.1 Reactor Vessel and Internals

In general the reactor vessel itself has no seismic problem, because it is very rigid structure of which design is mainly controlled by the mechanical duty as the high pressure boundary, in the case of a light water reactor.

However, for some reactor vessels mounted by the supporting cylinder, the supporting load, rigidity and strength of the cylinder should be checked with careful attention. The whole rigidity of that structure consisting both of the rigid reactor vessel and the comparatively flexible supporting cylinder will be decreased, and therefore, their response may increase so that the reactor internals will suffer the excessive seismic stress and strain. Especially the fuel assemblies and their supporting structure have the possibility of the structural failure. It is very difficult but an important problem to estimate the stress and strain of such a complicated structure existing in the liquid and having some non-linear characteristics, and it is also so how to evaluate the allowable limit of the responses.

To prevent the phenomena abovementioned, it is better to provide a horizontal supporting device such as the stabilizer or the radial keys at the top or middle point of the reactor vessel, to minimize its response.

3.3.2 Reactor Control Rods and Safety Shutdown System

It is the first thing to do to ensure the function for the safety shutdown of the reactor during a strong earthquake. For this purpose it is necessary for the control rods to be inserted smoothly into the core during the limited invervals.

This is a rather seldom case that the design criteria is governed by the displacement or deformation level rather than by the stress level. The functional loss of safety shutdown caused by the insufficient insertions of the control rods becomes very critical for the reactor system, prior to the structural failure of the control rods. In the aseismic design procedure of them, the most important problem is to set the simulation model for the dynamic response analysis of the flexible control rod and the fuel assembly in the coolant liquid.

3.3.3 Primary and Secondary Coolant System

The possible failure for the coolant pipings may take place at the nozzle end, the elbow and so on, on which the earthquake stress is apt to concentrate, and might cause the maximum credible accident.

Generally speaking, an inertia force by an earthquake produces the primary stress as a resultant of membrane, bending and torsional stresses. At the nozzle end and the elbow, the mode of failure may be mainly controlled by the bending and torsional stresses, as accompaning the large stress concentration factor. Another major stress on the coolant pipings is the secondary stress. To provide the anti-earthquake rigid support for limitting the primary stress caused by an earthquake, then the secondary stress will increase. So under some condition it is necessary to prepare a supporting device such as oil snubbers for reducing the earthquake stress without increasing thermal expansion stress.

3.3.4 Emergency Cooling System and Underground Piping

Vital structural component consisting of the final cooling system for the emergency cooling system is the burried underground pipings from the water intake structure to the emergency cooling heat exchanger.

The modes of failures for the underground pipings have various patterns as known from the recent strong earthquake experiences in Japan and the United States.

It is understood implicitly, that the behavior of the underground pipings under an earthquake has been affected directly by the ground movement such as the primary (longitudinal) wave which may give the axial strain or by the relative displacement of blocks on the both sides of a fault or of the ground and a structure.

Burried piping systems may float up when liquefaction occurs, and some parts adjacent to buildings and other structures may be broken. Storages and other massive structures may subside during a strong earthquake, if their foundation is loose.

To eliminate these modes of failures, the following aseismic countermeasures are to be taken into consideration, firstly to select the homogeneous and stable soil layer which does not cause liquefaction, secondly to ensure the flexibility and ductility of the pipe materials to accommodate enough earthquake ground movement, and thirdly to provide the flexible joint wherever the local different movement is expected. And a conduit is also effective to prevent the direct transmission of ground movement to the piping.

3.3.5 Emergency power supply system

The diesel generator has, in general, vibration isolators consisting of a spring and cussion between the generator base and concrete mat as mentioned in Section 2, these devices are a weak point to side force and also may cause the large acceleration response during a strong earthquake and may fall down.

Another, mode of the possible failure for the diesel generator during the potential earthquake may be brought by an impact loading between the generator base and the concrete mat. This type of load may cause the local shock damage to the generator base including the anchor and connecting bolts and the generator may loose their function as the dynamic safety equipment.

There are several ways to prevent the above troubles, such as preparing heavier reinforced concrete mat to support directly without isolators, or providing shock absorber or stopper on the isolators to minimize the response and to prevent side force effect.

Batteries may turn over and the fluid loss may loose their function. However, the aseismic design requirement can be easily attained by providing rigid support frame surrounding the train of the batteries.

3.3.6 Emergency Gas Treatment System and Stack

The main components of this system are an off-gas tank, an exhaust stack and the box shape and thin wall duct connecting the tank to the stack.

Failures of the off-gas tank may cause around the supporting legs and anchor bolts, because the tank shell structure is comparatively rigid. In the case of the aseismic design for this kind of the tank, it is necessary to pay careful attention to the strength of the supporting legs against the horizontal earthquake loading and to the anchor portion to resist the shear force.

The design of exhaust stack, even in high seismic zone like Japan, is mainly controlled by wind loading rather than the earthquake loading.

For the kind of structure of the duct we should take care to make rigid supporting frame structure including diagonal bracing members and tension rods.

3.3.7 Refuel Machine and Crane

The mode of failure for the refueling machine or the crane is the turning over of itself. Therefore they may give some damage to the top portion of the reactor.

To avoid such extensive accident, aseismic design of the crane girder and its supporting mechanism should be performed.

3.3.8 Auxiliary System and Component

There are many kinds of equipment, pipings and facilities in the reactor auxiliary system and the turbine auxiliary system and so on.

It is rather difficult to describe the mode of failures for the whole system. Then to describe on each component, that is heat exchanger, tank, piping, valve and pump. The concepts of design of each components might be found in the previous sections, so their details will appear at the authors' presentation and the following paper.

Only a thing which we should mentioned here is on legs and anchor bolts of a storage tank. Those are weak points to dynamic effect of sloshing liquid and lateral force. Their failures may cause loss of liquid by the rupture of pipings connected to the storage. Also casings of pump and valve are weak points against the external forces from pipings in such a case.

3.3.9 Turbine and its Pedestal

The turbine generator including the supporting concrete pedestal is very rigid structure in general, and therefore, no damage has been reported except minor damages. On the design the bearing capacity of its pedestal basement should be checked dynamically.

3.3.10 Main power System and Control Instrumentation

Recently many seismic damages were experienced as for the main transformer, the switch gear, the power-transmission line and so on in the main power system.

One of the modes of failures for these main power system may be caused by unstable condition of the bearing surface soil under a strong earthquake condition. And another may be caused by an impact load of earthquake of which source is near to the site. Some type of isolator is introduced recently in the United States.

As to the vital power and control transmission line in the building, their failures can be eliminated by using cable tray with dense seismic supports such as combination of vertical restraint and diagonal bracing.

The main control panel may turn over. This can be prevented by reinforcing the anchor portions and/or by tying up horizontally at the top of the panels.

The most important problem for the system from aseismic design point of view is probable existence of mulfunctions of the switches and relays during a strong earthquake.

4. Acknowledgement

As the authors mentioned in section 1, this paper is an essence of many surveys, studies and design experiences. So they owe much to the people in these fields in Japan, especially Drs. Kanai, Muto, Hisada and Fujii. They would like to express their deep gratitude to them.

And most of projects of field experiments and of development of their design procedures related to the aseismic design of nuclear facilities are supported by the Agency of Science and Technology.

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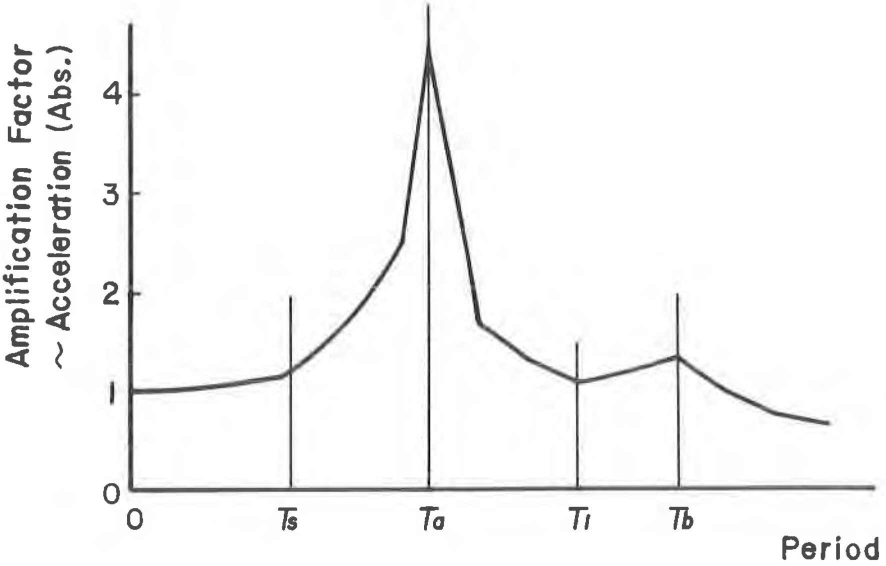

Fig. 1-(a) Schematic Diagram of Housner's Response Spectrum in Absolute Acceleration

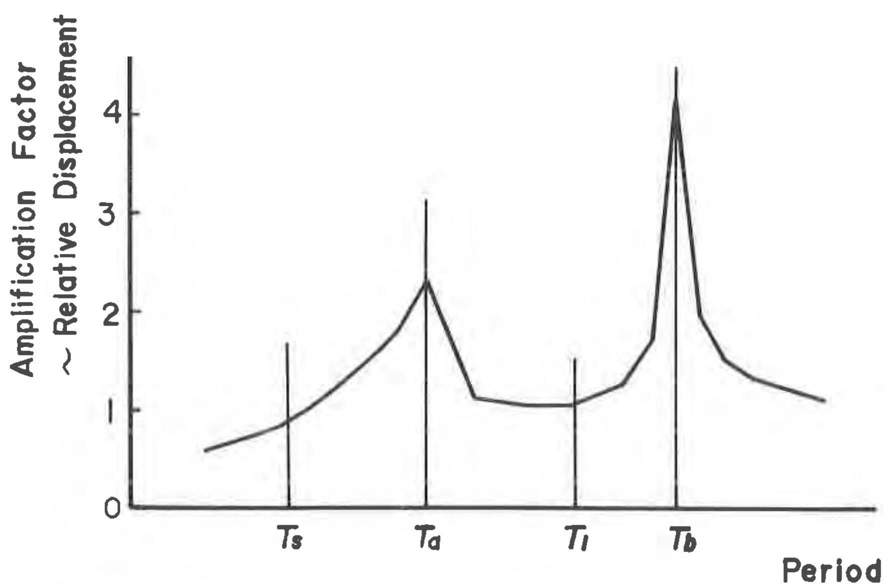

Fig. 1-(b) Schematic Diagram of Housner's Response Spectrum in Relative Displacement