SEISMIC DESIGN CONSIDERATIONS FOR NUCLEAR FUEL CYCLE FACILITIES

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Abstract

During the last few decades, there have been considerable advances in the field of a seismic design of nuclear structures and components housed inside a Nuclear power Plant (NPP). The seismic design and qualification of theses systems and components are carried out through the use of well proven and established theoretical as well as experimental means. Many of the related research works pertaining to these methods are available in the published literature, codes, guides etc. Contrary to this, there is very little information available with regards to the seismic design aspects of the nuclear fuel cycle facilities. This is probably on account of the little importance attached to these facilities from the point of view of seismic loading. In reality, some of these facilities handle a large inventory of radioactive materials and, therefore, these facilities must survive during a seismic event without giving rise to any sort of undue radiological risk to the plant personnel and the public at large. Presented herein in this paper are the seismic design considerations which are adopted for the design of nuclear fuel cycle facilities in India.

1. INTRODUCTION

The term Nuclear Fuel Cycle Facilities essentially refers to those facilities meant for fuel fabrication, spent fuel storage, fuel reprocessing and the waste management. The primary objective of earthquake resistant design of these facilities is to prevent any such damage to the structures and equipment that could lead to significant exposures to plant personnel or members of the public. Invariably, the need for the earthquake resistant design of these facilities depends on the probability of seismic events and on the consequences of such events if no earthquake resistant design features were applied. Therefore, seismic issues are given due attention right from the stage of site selection for these facilities. The civil structures which house the various systems, components and piping for such facilities are usually massive in nature. This is because mostly the dimensions of various walls of the structures are based on radiation shielding considerations. Seismic design of these structures along with the various components and piping is normally carried out for an earthquake potential which is consistent with the consequences of their failure and their intended design life. A brief account of the various design features provided in the design of these facilities to cater for the seismic loading is given in this paper.

2. VARIOUS DESIGN SAFETY FEATURES

The design features relevant to the nuclear fuel cycle facilities are mostly governed by the various process features to which they are supposed to cater for. Whereas during the planning of conventional chemical engineering installations, emphasis is laid on the planning of processing equipment, during the planning of installations for the nuclear fuel cycle facilities, it is also necessary and equally important to consider simultaneously the planning for processing equipment, the maintenance strategy and the building design. This is due to the fact that once these facilities start operating, it is difficult to attend to any kind of modification or repair works on the plant systems and components on account of high radiation fields.

The buildings housing these facilities are of increased importance because they serve the purpose of protective function. They serve as shielding against the radiations emanating from the various processes and also act as protective barriers to guard against the external events such as the occurrence of an earthquake. The building structures for these facilities are normally complicated structures which have to cater for the various requirements from the process side. Amongst these requirements, the consideration of criteria for the maintenance of the process equipment in order to achieve a high plant availability and reduced radiation exposure during repair and maintenance works plays a major role. In addition, the layout of process equipment in accordance with the process-technical and radioactivity-aspects also leads to a complicated design of the civil structure. The component layout is invariably carried out in such a way that the components which are subjected to mechanical wear or to ageing when exposed to the radioactive environment are disposed at the front end of the buildings so that the components can be replaced under remote control with the help of suitable manipulators.

3. SAFETY AND SEISMIC CLASSIFICATION

3.1. Fuel reprocessing facilities

The fuel reprocessing facilities involve various chemical processes for the seperation of desired elements from the spent fuel received from a reactor. The fuel is normally kept in the spent fuel storage bay for a definite period of time before it is taken for reprocessing. The information on design codes, standards and the other associated literature related to such facilities is scanty in nature. As such, no single document contains comprehensive guidelines for the safety and seismic classification of these facilities. In order to arrive at a rational design basis for these facilities, the authors have tried to compare these facilities with a reactor system based on the available information in the literature. The reprocessing process has certain important features, described below, which determine the safety and seismic classification of the various systems and components:

(1) In a nuclear reactor system, the large source of stored energy requires that the safety systems controls respond rapidly to maintain safe conditions during all the operational states and also during all the abnormal events. There being no such large source of stored energy in nuclear fuel reprocessing facilities, the safety system design can take advantage of the relatively longer time periods generally required for the development of conditions hazardous to the safety of plant personnel and public.

(2) The fuel reprocessing plants do not have the high temperatures and pressures that are associated with the power reactors. Mostly, the process conditions are such that the pressure is close to atmospheric and the temperature hardly reaches around 100^0C. In a power reactor, most of the radioactive materials are encapsulated in the fuel assemblies and most of the activity in the fuel is due to short-lived radionuclides. However, in case of fuel reprocessing plants the activity due to these short-lived radionuclides is absent because of their decay in the spent fuel storage bay before the fuel is transferred for reprocessing. The radioactive materials are released from the fuel matrix during the chemical processing of the spent fuel.

(3) The reprocessing plants are designed to cater for the reprocessing needs from multiple number of reactors. However, the amount of fuel handled at one particular time of the processing may not be as large as in a reactor system and thus, the associated radiation risk with a reprocessing facility would be much smaller as compared to a reactor system.

(4) The fuel reprocessing plants are designed with multiple confinement barriers for the prevention of any unwanted spread of radioactive materials. This, thus, helps in containing the radioactivity even if there is a failure of mechanical system or components. Also, the material handled or processed is retained, contained and confined within known bounds in a reprocessing facility for the reasons of accountability and also to minimise the spread of radioactive contamination.

(5) The design of various components and systems assumes a great importance in case of fuel reprocessing plants in terms of their shape and size so as to avoid the formation of any critical mass at any stage. This needs to be ensured even in case of unanticipated failure of the systems or components. Therefore, integrity of various systems and components assumes a greater significance in this regard.

(6) These facilities shall be designed for all the natural phenomena and postulated accidents as stipulated in 10 CFR 50 Appendix A — Criteria 2 and 4 excluding those accidents which are pertinent to nuclear reactors only [1]. The criterion 2 is regarding design bases for protection against natural phenomena such as earthquakes, wind loading etc. whereas criterion 4 is related to the enviornmental and dynamic effects design bases [2].

(7) The chemical corrosion and erosion conditions encountered in these processes tend to be extremely severe, placing a great emphasis on design for the containment integrity.

The above features are peculiar to these facilities. Based on these, it is recommended that the fuel reprocessing facilities shall be classified as Safety Class-4 facilities and that the design of various structures, systems and components pertaining to these facilities shall be performed using ASME B & PV Code, Section VIII. This is because fuel reprocessing is a chemical process and does not involve any sort of nuclear reaction as in case of a reactor system and, therefore, it does not require the components to be classified as Safety Class-1, 2 or 3 since none of the components in a reprocessing plant perform the safety functions which are pertinent to these safety classes. Use of Safety Class-4 for their design is consistent with the requirement of safety function 'n' for this class of systems and components which is as given below:

- For components performing safety function 'n' , safety class-4 is assigned such that if they failed, would not result in the exposure of public or site personnel in excess of the prescribed limits.

This is achieved in case of these facilities by the use of multiple barriers to prevent the spread of radioactivity. This is also in conformance with the opinion expressed in ANSI N46.2.11-1977, wherein it is mentioned that the ASME Section III design rules for Safety Class-1,2 and 3 components are applicable to nuclear reactor systems and do not directly apply to chemical plants such as the reprocessing facilities [3]. As such even the provisions of ASME B & PV Code, Section VIII are also not applicable for the low pressure and temperature conditions encountered in a fuel reprocessing plant. This is because the provisions of ASME Code Section VIII are not mandatory for such low pressure and temperature conditions. However, as a minimum, for meeting the requirements of sound engineering design, fabrication and inspection, the use of ASME code is recommended. The design of various systems and components is carried out for a set of artificial pressure and temperature conditions along with the other loadings so that the provisions of the code will apply for their design. This is because the main considerations in the design are equipment operability and long-term integrity which are duly met by proper material selection and the use of large corrosion allowances consistent with the service. As far as the civil structures which house these facilities are concerned, the design is performed using the same standards as applicable to a nuclear reactor system. This is due to the fact that the civil structures form the ultimate barrier which helps in preventing and containing the radioactivity.

As far as the seismic classification of these facilities is concerned, because of the hazards associated with these facilities, it is necessary to categorise them as the high hazard facilities where the confinement of contents and public and environment protection are of paramount importance [4]. The performance goal for High Hazard facilities is to provide a very high degree of confidence that the hazardous materials are confined both during and after the occurrence of a natural phenomenon such as a seismic event. Maintaining the confinement of hazardous materials requires that the damage be limited within the confinement barriers. The High Hazard facilities handle substantial quantities of radioactive materials in the forms which may permit wide spread dispersion. Facilities in this category represent hazards with potential long term and wide spread effects and, hence, they are designed for the maximum potential earthquake for that site. This is on account of the reason that for the High Hazard facilities, a reasonable performance goal is an annual probability of exceedance of around 10^{-5} of damage beyond which hazardous material confinement is impaired. This performance goal approaches, at least for earthquake considerations, the performance goal for seismic induced core damage associated with the nuclear reactors. Therefore, it has been the practice to design the High Hazard facilities such as the fuel reprocessing facilities for the Safe Shutdown Earthquake (SSE).

3.2. Fuel fabrication facilities

The fuel fabrication facilities basically include the various processes which are required for the fabrication of fuel sub-assemblies which are used for the nuclear reactors. The facilities which usually handle the normal uranium oxide fuel or the natural uranium do not pose much of a safety concern as the amount of activity handled is very small. These facilities are, therefore, designed using ASME Code Section VIII or the other similar relevant codes and standards. For their design to cater for the seismic loading in India, use of normal building code such as IS-1893:1984 is made wherein a higher value of Importance Factor is usually adopted for defining the design basis earthquake motion. Other facilities which are meant for the fabrication of either enriched uranium or plutonium, need a greater level of safety as compared to the natural uranium fabrication facilities. These facilities shall have multiple barriers for the prevention of spread of radioactivity and shall be designed using procedures similar to those given in ASME Code Section VIII. However, their seismic design shall be carried out using the earthquake of the level of Safe Shutdown Earthquake (SSE). These facilities also fall under the category of High Hazard facilities because the spread of powdered fuel in these facilities is quite dangerous for both the public as well as the plant personnel. However, the fuel enrichment facilities which handle relatively smaller amounts of radioactive materials with less consequences are categorised as Medium Hazard Facilities. Such facilities are designed for an earthquake of the level of Operating Basis Earthquake (OBE). The annual hazard exceedance probability for such medium hazard facilities is of the order of 10^{-3}.

3.3. Spent fuel storage facilities

The irradiated fuel after coming out of the power reactors is normally stored in spent fuel storage bays. This is done to reduce the decay heat and activity levels in the fuel before it can be sent for reprocessing or disposed off. Spent fuel storage facilities usually contain a pool of water under which the spent fuel is stored in the spent fuel storage racks. The water in the spent fuel pool is continuously circulated through a system consisting of the associated piping, pumps, valves and heat exchangers. The spent fuel storage facility in a nuclear power plant or in a fuel reprocessing facility is classified as a Safety Class-3 facility because this safety class incorporates all the safety functions associated with maintaining sub-criticality of the fuel stored outside the reactor coolant system and with the removal of decay heat from irradiated fuel stored outside the reactor coolant system. As far as their seismic design is concerned, these facilities are designed for an earthquake of the level of SSE [5,6]. The Project Design Safety Committee (PDSC) in India recommends similar guidelines for the design of these facilities.

However, the design rules for the independent spent fuel storage installations are somewhat different. The salient features which are peculiar to these installations are as follows:

(1) Such facilities are independent of both a nuclear power plant and a reprocessing facility and, therefore, the consequent risk associated with these facilities is much less.
(2) The storage of spent fuel in these installations is a low hazard potential activity. This is because very little of the radioactivity present is available in a dispersible form and there is no mechanism present to cause the release of radioactive materials in significant quantities from the installation.
(3) A risk study performed for these facilities utilising the conceptual design approach, site selection criteria, various design basis events etc. indicates that the radiological risk associated with these installations is 2 to 3 orders of magnitude lower than that of a nuclear power plant [7,8].
(4) The independent spent fuel storage installations are designed to resist an earthquake which has a mean recurrence interval of 500 years or in other words, the probability of occurrence for the design basis seismic event is taken as 2×10^{-3} per year.

These features are introduced in their design by performing their design using the standards similar to ASME Code Section VIII. The seismic design for these installations is carried out for an OBE level of earthquake.

3.4. Nuclear waste management facilities

The nuclear waste generated in reactor systems is usually handled by the liquid radioactive waste processing system which is generally attached with the nuclear reactor. This system is not a safety system nor does it contain the components that need to be safety class. The activity levels in these systems are much lower than that in a spent fuel storage bay or in a reprocessing plant. This system is, therefore, classified as a Safety Class-4 system with its design intent being met by performing the design in accordance with the provisions of ASME Code Section VIII or other similar relevant standards. The seismic design of various components and piping is performed for the OBE level of earthquake. The building housing these systems too is designed to cater for the OBE loading [9].

The nuclear waste generated from a reactor system as well as from a fuel reprocessing plant is stored in huge waste storage tanks in a Waste Tanks Farm (WTF). The WTF usually has multiple number of waste tanks which cater for the various types of wastes generated depending on their activity levels. Since the WTF is a store house of huge quantities of radioactive materials, it is classified as a Safety Class-3 system. This is because in performing the safety function 'n', the amount of radioactivity spread in the event of failure of such a system may lead to the radiation dose in excess of the prescribed limits [10].The civil structures housing these tanks are designed using the guidelines similar to a nuclear reactor system. This is because these structures are the ultimate barriers which contain the radioactivity and, thus, help in preventing the spread of radioactivity in the event of any failure on the process side. Similarly, for seismic design also, they are required to maintain their structural integrity in case of the maximum potential earthquake at the site; i.e. SSE. This requirement too comes from the large amount of the activity handled in these structures.

4. SEISMIC DESIGN METHODOLOGY

Currently, very few published guidelines are available regarding the seismic design of nuclear fuel cycle facilities. As compared to this, there is plenty of information available for the design of nuclear power plant components for seismic loading. At present, the designer is rather forced to adopt some of the conservative design and analytical techniques (meant for the design of reactor components and structures) for performing the seismic design of nuclear fuel cycle facilities. However, specific guidelines are needed to specify the methods of design and analysis for such facilities to ensure safe design of various critical systems and structures against the potential seismic hazards. It is worth mentioning here that there are many uncertainties associated with the earthquake response of real structures and systems. Much engineering judgement and experience is required to obtain meaningful results. This, therefore, many a time calls for a conservative seismic design for the critical systems and structures for these facilities. Hence the design of these items is carried out in such a manner that they remain functional even during and after the occurrence of a strong earthquake with very little or no structural damage The discussion here is restricted to the design of such critical equipment, systems and structures whose failure during a seismic event could result in a radioactive hazard to the public.

The nuclear fuel cycle facilities are generally designed with multiple confinement barriers for the control of radioactive materials. The structures, systems and components in these facilities are classified according to their function and the degree of integrity required for the plant safety in the following manner:

- seismic category I structures, systems and components are those whose failure could cause uncontrolled release of radioactive materials or those whose operation is required to effect and maintain a safe plant shutdown. Systems and equipment in this category are designed, constructed and inspected to withstand all the postulated loadings without loss of function. These are designed for the SSE loading.

- seismic category II structures and systems are those whose failure would not result in an uncontrolled release of radioactive materials and whose function is not required to effect and maintain a safe plant shutdown. These are invariably designed for OBE loading or any other appropriate level of seismic loading in few cases, which is consistent with the requirement of the structures and the systems.

- All the other systems and structures which are not covered above, are designed as codal structures and systems using the provisions of IS-1893:1984 which gives guidelines for the earthquake resistant design of industrial buildings.

For example, the control room of a fuel reprocessing facility is designed to be a seismic category I structure which is isolated from the process systems by remote instrument systems so that no transfer of radioactive materials into the control room can occur.

4.1. Design of civil structures

The civil structures in nuclear fuel cycle facilities may be either above the ground or below the ground. For example, most of the fuel fabrication facilities are housed in above ground structures, whereas the fuel reprocessing plant and the WTF are examples of below the ground structures. Seismic design of civil structures is performed using the latest available tools and techniques so as to ensure their containment function under all the postulated loading conditions. Analysis of civil structures is usually carried out using the finite element method (FEM) using the softwares such as COSMOS/M, NISA, ABAQUS etc. for the seismic category I and II structures. Soil-structure interaction is given due considerations while analysing the structures for earthquake loading. This is accomplished mostly through the use of frequency independent soil springs and dashpots in the analysis. It is mostly observed that the soil-structure interaction effects are quite predominant for these structures because of their stiff nature (as compared to the normal civil structures) wherein the structural stiffness becomes comparable to the soil or rock stiffness and thereby alters the dynamic characteristics of the structure. Seismic design of the structures is mostly carried out using the Response Spectrum Method (RSM). Time history analysis of these structures is also required for generating the Floor Time Histories (FTHs) which are required for the computation of Floor Response Spectra (FRS). These FRS are then used for the design of various systems, components and piping which get their support motions from the respective floor locations.

In the analysis of buildings having frame type of structures, use of lumped mass beam models is quite common wherein the masses are lumped at appropriate levels in the model which is consistent with the mass distribution in the real structure. The stiffness of the structure in these models is modelled with beam elements that reflect both the bending and the shear stiffness of the real structure. For the other complicated structures which have shear walls and frames, use of plate / shell elements is made with a lumped mass formulation. For both the kinds of models, FE mesh refinement is decided in such a way that all the modes up to 33 Hz are excited with a reasonable accuracy. This is very important in the case of these structures which generally have high mass participation in higher modes only because of the stiff nature of structures which are used for housing these facilities. Moreover, the model should be able to predict high frequencies correctly also because most of the equipment and piping systems lie in the high frequency zone of the applicable FRS. Design of all the critical structures is carried out using the same standards as those used for the design of civil structures for the nuclear plant.

4.2. Seismic design of systems and components

Design of various systems and components pertaining to these facilities for earthquake loading is performed by considering the seismic load in the faulted condition of design. The primary objective here is to maintain the structural integrity and the functional requirement for the safe plant shutdown under all the operational states. The structural integrity of various components is normally assessed by either an equivalent static method or the dynamic methods such as the time history method (THM) or response spectrum method (RSM). Seismic loading on the equipment is usually determined by analysing either a coupled building-equipment system or by conducting two separate analyses, one on the building structure and the other one on the equipment. If the mass and/or stiffness properties of the equipment are such that it could affect the overall building response or if the equipment is supported at multiple locations so as to affect the building response, then a coupled dynamic analysis is required. The criterion used to judge this interaction effect is as stipulated in USNRC SRP 3.7.2 [11].

The coupled analysis would require only one set of dynamic response calculations. However, the mathematical model required would be more complex. It may require many more degrees of freedom in order to include both the equipment and the support structure. This complex and larger model is necessary to capture accurately the response of the equipment. Such a model would not only require much more computer effort for its solution, but would also increase the likelihood of introducing errors in its solution by way of ill-conditioned mass and stiffness matrices. As compared to this, performing separate analyses on the building structure and the equipment is generally more practical. Although two sets of response calculations are required, the models are much more manageable and result in the use of much less manpower and computer time. The building analysis provides the seismic loading to the equipment in the form of FTH or FRS. Subsequently, the designer has the flexibility of performing either an equivalent static or dynamic analysis.

Analysis using the equivalent static method is normally carried out for the simple equipment which have predominantly higher mass excitation in their first fundamental mode of vibration or for the rigid equipment. In this method, the equipment is subjected to a static load equal to 1.5 times the acceleration corresponding to its first fundamental frequency which is obtained from the applicable FRS for the requisite damping value. In case the frequency of the equipment is not available, then the equivalent static analysis is performed using the static load equal to 1.5 times the acceleration corresponding to the peak in the applicable FRS. This analysis is performed separately for each direction of vibration and then the resulting response is combined using the method of Square Root of Sum of Squares (SRSS). However, the equivalent static method results in undesirable conservatism in many cases.

Amongst the dynamic methods of analysis, use of RSM is preferred over the use of THM on account of its simplicity, less time consumption and conservatism. In addition, the design of equipment using FRS caters to a number of earthquake time histories as compared to the use of an FTH which represents the floor motion for only a single earthquake. The FRS and FTH are peak broadened and smoothened before their use in design, to cater for the various uncertainties associated with the analysis such as the variation in material and soil properties, uncertainties in frequency calculations etc.[12]. While using RSM for the seismic design, the modal responses are combined using the 10 percent grouping method and the spatial responses are combined in an SRSS manner [13]. The inertial response of equipment is evaluated using the dynamic analysis only up to the modes which have their frequencies below the ZPA frequency in the applicable FRS. Subsequently, a missing mass correction is applied in an equivalent static manner for the mass which has not participated upto the floor ZPA frequency. Use of THM is made only in cases where non-linear effects are required to be modelled.

For the equipment which are supported at multiple locations, the seismic response is composed of two parts, namely the inertial response and the response due to Seismic Anchor Movement (SAM). The inertial response is usually found out either by using an envelope spectrum approach or by using the different motions at various support locations in the form of FRS or FTH. The envelope spectrum approach uses a spectrum which envelopes the spectra at various support locations. This approach results in a conservative prediction of seismic response in most of the cases except in few cases where the equipment is extending beyond its supports such as in case of an overhanging equipment. In such cases, the use of multiple response spectrum technique is recommended. The SAM response is computed in an equivalent static manner and it is combined with the inertial response in an absolute manner.

5. DESIGN OF A TYPICAL WASTE TANK FARM

There are various layouts for the Waste Tank Farm designs. A typical WTF unit houses four stainless steel tanks in a single rectangular concrete vault. The vault in turn sits on a massive raft. The entire structure is an underground structure located at a rocky site with a seismic potential of 0.2 g acceleration during an SSE event (Fig. 1). The tanks storing the waste are cylindrical vertical tanks with flat top and bottom heads with suitable stiffening arrangements. The dimensions of civil structure are decided based on radiation shielding considerations. The concrete vault is capped by a heavy top slab at the top. This top slab has a corridor upto a certain height for the movement of materials etc. The entire civil structures has been designed using ACI-349 standard, whereas the tanks are designed as per the provisions of ASME Code Section III Sub-section ND which is meant for the design of Safety Class-3 components.

The pressure inside the tanks is kept under sub-atmospheric conditions so as to avoid the leakage of radioactivity to the environment. The maximum vacuum for which the tanks have been designed is 6895 N/m^2 (1.0 psi). The waste in these tanks is continuously cooled by the

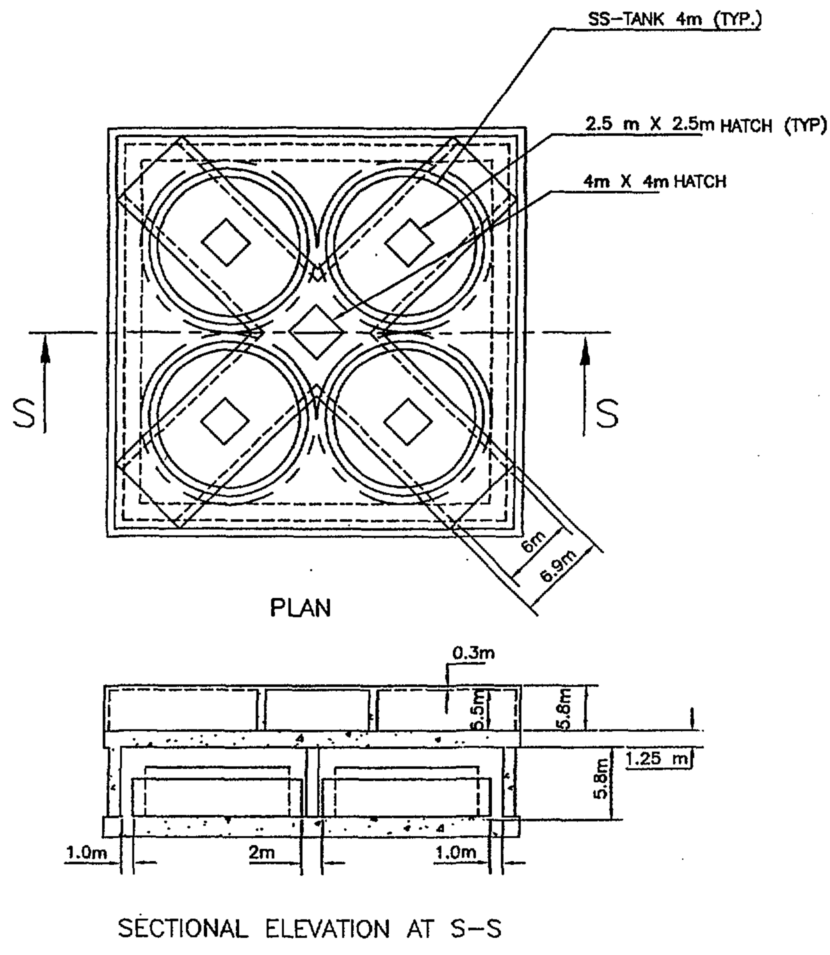


FIG. 1. Details of a typical WTF structure.

water flowing through the cooling coils which are present inside the tanks. The adequacy of the thickness of these tanks has been checked for both internal as well as external pressure as per the provisions of ASME Code Section III, Subsection ND since they are classified as Safety Class-3 components. The forces arising out of hydrodynamic effects during a seismic event have been evaluated as per the procedure given in the ASCE 4-86 standard [14]. The tank wall has been checked for the buckling under the combined effect of external pressure and the axial compressive loading due to the weight and earthquake loads as per the provisions of ASME Code Case N-284. In addition to this, separate stability checks have been performed to safeguard the tanks against the elephant foot buckling and the diamond buckling.

The concrete vault housing these tanks has been analysed for various postulated loadings using its finite element model (Fig. 2). This model is composed of plate/shell elements. The soil has been modelled in the form of frequency independent soil springs and dashpots at the base and the sides. Seismic response has been evaluated using the RSM wherein the modal responses have been combined using the 10 percent grouping method and the spatial responses have been combined using the SRSS method. The structure has been analysed for the first thirty modes of vibration upto 33 HZ. Figs. 3 and 4 respectively show the mode shapes for the first two modes of vibration. Similarly, the response due to the other loadings has also been computed. Design of the structure has been then carried out as per the provisions of ACI-349 standard.

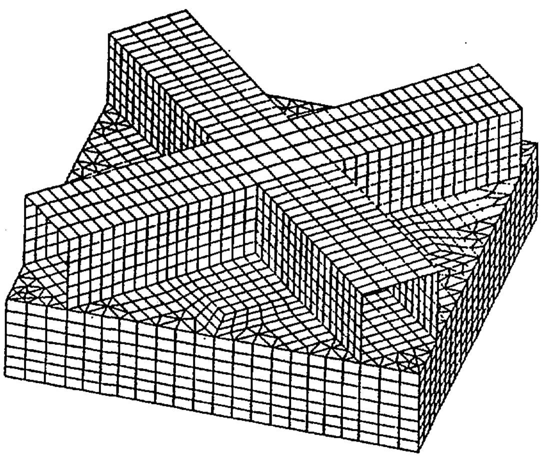


FIG. 2. FEM model of civil structure.

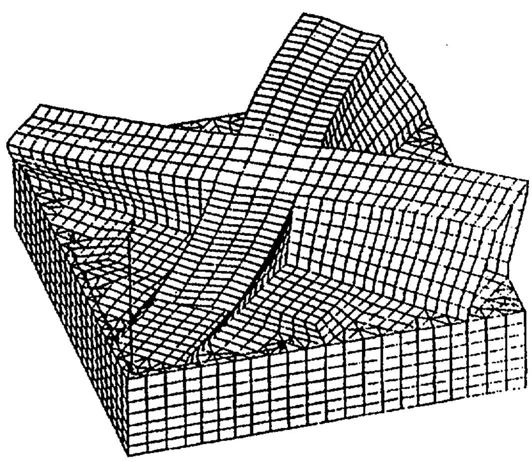
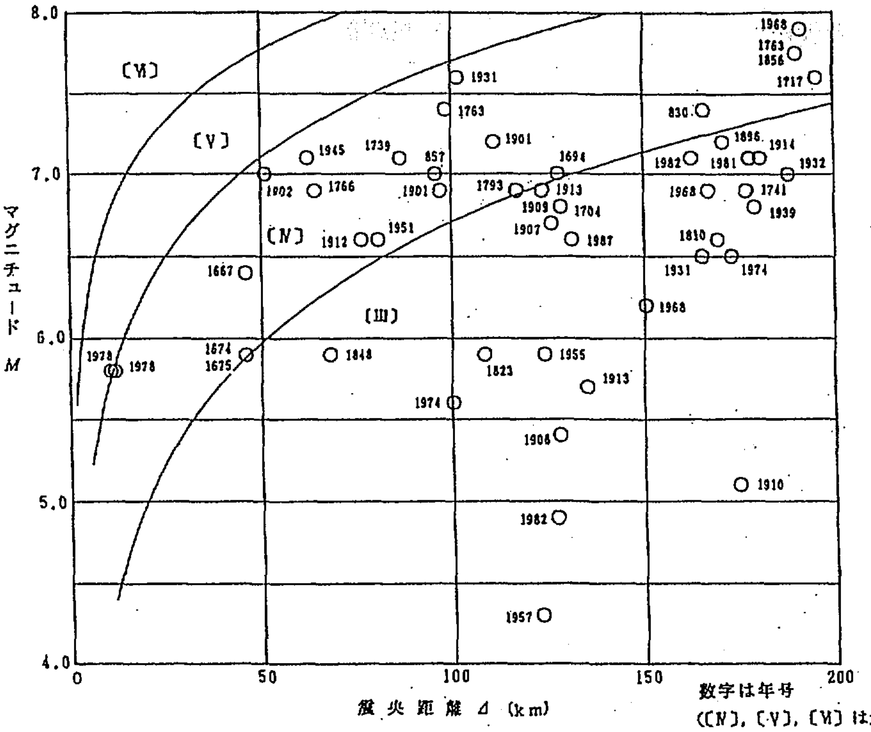


FIG. 3. First mode vibration of WTF structure (f = 11 Hz).



	年 月 日 地名または 地 震 名	基盤速度 (kine)
主な被害地震	1978. 5.16 青森県東岸	4.58
	1902. 1.30 三戸地方	4:30
	1978. 5.16 青森県東岸	4.22
	1945. 2.10 八戸北東沖	3.77
	1931. 3. 9 青森県南東方沖	3.75
	1968. 5.16 十勝沖地震	2.20

FIG. 4. Second mode vibration of WTF structure (f = 13 Hz).

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