SUMMARY OF THE HISTORICAL DEVELOPMENT OF SEISMIC DESIGN OF NUCLEAR POWER PLANTS IN JAPAN AND THE U.S.

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ABSTRACT

Over the past 50 years seismic design of nuclear power plants in Japan and the U.S. have undergone very significant changes in the three activities associated with design:

- Quantification of Seismic Load and other Applicable Loads and Specification of their Load Combinations to be considered in design
- Analysis Methods and Procedures necessary to convert input earthquake motions and loads normally expressed in the form of acceleration to resultant seismic dynamic or equivalent static forces, moments or stresses, fms in structures, systems and components, SSC
- Codes or standards acceptance criteria used to evaluate resultant forces, moments or stresses, fms in nuclear safety SSC to determine design adequacy.

These applications to the historical development of Nuclear Power Plant, NPP designs in Japan and U.S. are summarized.

INTRODUCTION

It is essential that it be understood while national codes and standards provide to a very large measure the earthquake resistant design necessary to assure life safety, they do not provide an earthquake “proof” design nor do they assure continued safe operation of a facility. Earthquake resistant design for nuclear power plants is generally significantly more rigorous than for other types of power plants and are meant to reduce the probability of failure of an NPP to shut down safely due to a design basis earthquake effects on the plant to an expectation roughly equivalent of one’s house being hit by a destructive meteorite.

Today, as at the time of their inception, both the Japanese and the United States seismic building codes used in the design of conventional structures are still based primarily on the equivalent static forces developed from seismic accelerations applied to the mass of the structure. The applicable seismic acceleration is a function of the seismic zoning of the site and its local foundation media. In current designs the loads on building structural members for all applicable loads including seismic are based on either allowable stresses which are typically taken as 2/3 yield stress for S_1 and OBE level earthquakes or the ultimate strength of the member or section based on it reaching yield stress for Japanese S_2 and U.S. SSE earthquakes which is based on the yield strength of the structural steel or reinforcing bar of the member. Since 2006 there has been a new larger S_s earthquake defined in Japan and more recently in the U.S. a Beyond Design Basis Earthquake 1.67 times SSE acceleration.⁽¹⁾ In the Japanese Nuclear Safety Commission Guide 1-DS-1.02⁽²⁾ an acceptance criteria is defined for the S_s earthquake, but as of yet no equivalent acceptance criteria guide prepared by the U.S. Nuclear Regulatory Commission appears to have been developed for the U.S. Beyond Design Basis Earthquake effects.

Current design in both countries of steel high pressure retaining components and distribution systems is based on working stress design and for the load combinations that include the most severe earthquake inertia load is based on twice the elastically computed yield stress. Design of nuclear power plants follows both a load and resistance criteria a great deal more stringent and rigorous than that used for conventional structures, systems and component designs as discussed herein.

In Japan and in the United States the seismic design modeling requirements for NPP structures, systems and components, SSC have proceeded along parallel paths where in the beginning in both countries the seismic load criteria were first based on static uni-mode and direction lateral loads defined in the National Building Codes of the time and gradually became dynamic, multi-mode and multi-directional in nature by considering dynamic ground and in-structure response spectra as modal analysis input. More recently dynamic two and three dimension finite

element modeling of structures, systems and components in a 3 dimensional space have become available for design of individual sections or members.

The acceptance criteria for buildings was first based on allowable stress procedures and currently considers strength design procedures where limiting member or section forces or moments are used to define capacity, and factored load equations are used to define demand which is required to be less than capacity (i.e. a demand to capacity ratio less than 1.0). The design of mechanical and components generally still consider allowable stresses as the basis for design acceptance.

It is interesting to note this increase in complexity of design in both Japan and the U.S. is also mirrored in the development of the seismic text of their National Building Codes. For example, in 1967 in the U.S. (at the beginning of the first NPP construction era) the seismic design, Section 2314 of the Uniform Building Code, UBC⁽³⁾ consisted of 8 pages of text and one seismic zone map for the U.S. By 2010 the ASCE 7-10 Standard⁽⁴⁾ which includes the technical design requirements successor to the UBC had grown to 12 chapters and 179 pages of text and figures.

Impact of Recent Strong Motion Damaging Earthquake in Japan

Starting in 2006 as a result of the unexpected intensity (recorded accelerations) of the Kobe-1995 earthquake in southern Japan and other earthquakes in west central Japan a new S_s level earthquake has been used to evaluate Japanese NPP Safety Class A and A_s structures, systems and components. Recently, for several NPP in Japan, the original S_2 and S_1 level of earthquake acceleration have been exceeded. With the exception of the tsunami flooding resulting from the simultaneous rupture of at least 3 fault zones which caused station blackout which in turn caused severe damage to and release of radiation from the Fukushima Daiichi NPP site, all NPP nuclear safety related structures, systems and components have resulted in no failure to perform their required safety function. This is true even though the recorded peak seismic acceleration have exceeded by a factor of two or more their original design basis seismic acceleration values. With the exception of tsunami design this indicates that the design criteria used in Japan to resist seismic loads is capable of resisting seismic loads well above their design basis.

The damaging tsunami was the result of the occurrence of three larger than moment magnitude M_m 8 earthquakes all occurring within a three minute time period for a combined Magnitude 9. Such an event was considered incredible, but the potential similar occurrences will require a careful reevaluation for future and existing nuclear power plant sites in the future.

Seismic Design Classification and Load Definition in Japan and the U.S.

The first consideration of seismic design of NPP in Japan began with the planned importation of a gas cooled English reactor design in 1957. This was followed by the importation of the first light-water cooled Boiling Water Reactor, BWR NPP by the Tokyo Electric Power Co., TEPCO, Tsuruga and Fukushima Unit No. 1 and Pressurized Water Reactor, PWR by Kansai Electric Co., Mihama Unit No. 1.

By 1970⁽⁵⁾ in Japan, until 2006 there was specified a two earthquake dynamic ground motion S_1 and S_2 , where the S_2 earthquake motion was 1.5 times the S_1 and there were four Seismic Safety Classes of SSC defined as A_s , A, B and C with different seismic input accelerations defined for design of the four safety/seismic classes of SSC with A_s and A being dynamic in nature and B and C being static. The earthquakes and safety classification used are summarized in Table 1. In Tables 2 and 3 is a listing of the specific seismic loading criteria defined for Japanese NPP in design before 1973. More recently, as a result of the Kobe earthquake in 1995 an S_s earthquake with a pga up to 1.0g has been specified with an energy based acceptance criteria as shown in Figure 1.⁽¹⁾

In the U.S. in 1973 the equivalent to the S_2 earthquake in Japan was defined, with the publication of the NRC's Regulatory Guide 1.60⁽⁶⁾ and was named the Safe Shutdown Earthquake, SSE and a lesser earthquake typically taken as $\frac{1}{2}$ the SSE was named the Operational Basis Earthquake, OBE. Since the beginning of the nuclear era, those SSC at a NPP related to reactor safety was designated Seismic Category 1. In the current R.G. 1.208⁽⁷⁾ a site earthquake is probabilistically defined at a mean 10^{-4} probability of exceedence. A coefficient is applied to the site earthquake which is determined as a function of the slope of the seismic hazard curve between 10^{-4} and 10^{-5} per year probability of exceedence to define a Design Basis Earthquake to be used in design of plant Seismic Category I in-structure systems and components.

The U.S. NRC defined a Beyond Design Basis Earthquake⁽¹⁾ as 1.67 times the Safe Shutdown Earthquake, but without prescribing the acceptance criteria to be used in evaluating this earthquake. Elastic energy absorption factors, F_u have been published by the ASCE⁽⁸⁾ which define various inelastic behavior or Limit States representing

recommended deformation capacities of various structural and mechanical components beyond their elastic behavior states as shown in Table 4, which are comparable to the inelastic deformation strains defined in Figure 2.

Table 1 Typical Historical Levels of NPP Design Basis Earthquakes in Japan

Design Basis Earthquake	Design Basis Seismic Coefficient (Static) Times Gravity	Dynamic ZPGA ⁽¹⁾ Gal	Applicable to Safety Class SSC
S ₂ (margin check upper bound)	0.9	240 Typically ⁽²⁾ 270 to 600	A _s
S ₁ (design basis historical max.)	0.6	180 to 400	A
S ₀ (operational) once per 2~10 years	----	50~60	All
S _B	0.3	(=1/2 S ₁)	B
S _C	0.2	(=1/3 S ₁)	C

(1) ZPGA* is "Dynamic Design Basis Peak Acceleration"

(2) Depending on the plant site region historical earthquake intensity

(3) 1 Gal. equals 980 cm/sec² acceleration or approximately 1.0g where g is the acceleration of gravity

Table 2 Japanese NPP Aseismic Design Data for NPP Before 1973^(1,2)

Name of Site	Location	Seismic Data (pga)			
		A	B	C	D
Onagawa	Miyagi	0.48	0.24	250	375
Fukushima – Site No. 1	Fukushima	0.48	0.24	180	270
Hamaoka	Shizuoka	0.48	0.24	300	450
Mihama	Fukai	0.48	0.24	300	450
Takahama	Fukai	0.48	0.24	270	405
Shimane	Shimane	0.48	0.24	200	300
Tokai	Ibaragi	0.48	0.24	--	--
Tsuruga	Fukai	0.48	0.24	250	375
Genkai	Saga	0.48	0.24	150	225
Fugen Atr	Fuki	0.48	0.24	250	375

Notations:

A. Design seismic coefficient static horizontal, g (C_o x 3 x 0.8)

B. Design seismic coefficient static vertical, g (C_o x 1.5 x 0.8)

C. Design seismic coefficient dynamic horizontal, gal., S₁

D. Design seismic coefficient dynamic horizontal, gal., S₂

C_o Seismic coefficient; for most of the cases C_o = 0.20

⁽¹⁾ Personal communication between K. Muto and D.S. Mehta, P.T. Kuo and A.A. Vizzi, November 1972.

(2) In 2006 a new higher seismic evaluation/design requirement was specified.

Table 3 Typical U.S. NPP Seismic Design Data for NPP Before 1973

Name of Plant	Location	Seismic Data (pga)		
		A	B	C
Diablo Canyon ⁽¹⁾	California	0.4	0.2	0.67
San Onofre, Unit 2	California	0.67	0.33	0.67
Trojan	Oregon	0.25	0.15	0.67
D.C. Cook	Michigan	0.20	0.10	0.67
Davis Besse	Ohio	0.15	0.08	0.67
Indian Point	New York	0.15	0.10	0.67
Duwane Arnold	Iowa	0.12	0.06	0.80
Turkey Point	Florida	0.15	0.05	0.67
St. Lucie	Florida	0.10	0.05	0.67

Notations:

A = SSE Dynamic PGA

B = OBE Dynamic PGA

C = Ratio of Vertical to Horizontal PGA

(1) Later changed to 0.67g and 0.33g

- Stress must be below allowable stress
- Deformation must be below allowable deformation
- Shear strain must be below allowable strain for S_s

Figure1 Ductile Strain Limits

Table 4 Inelastic Energy Absorption Factor for Buildings, Components and Distribution Systems, F_{μ}			
Limit State	F_{μ}^*		
	Limit State A	Limit State B	Limit State C
A. BUILDING STRUCTURES			
Reinforced concrete shear wall, in plane:			
Bending controlled walls, $\frac{h_w}{w} \geq 2.0$	2.25	2.0	1.75
$6\sqrt{f_c} < f_v$	2.5	2.25	1.75
$f_v < 3\sqrt{f_c}$	2.0	1.75	1.5
Shear controlled walls, $\frac{h_w}{w} < 2.0$			
Roof slabs, floor slabs, beams and walls reinforced concrete			
($15 \leq h$)	2.5	2.25	2.0
($1 h \leq 10$)	2.25	2.0	2.0
Columns	1.0	1.0	1.0
B. EQUIPMENT			
Vessel, Heat Exchanger, Coolers, Chillers	1.50	1.25	1.15
Tanks (vertical)	1.25	1.25	1.15
Tanks (horizontal)	1.50	1.25	1.15
Pumps, Fans, Valves, Dampers	1.50	1.25	1.15
Filters ¹	2.00	1.50	1.25
Electrical Boards, Racks, Cabinets	2.00	1.50	1.15
C. DISTRIBUTION SYSTEMS			
Butt joined groove welded pipe ¹	1.75	1.50	1.25
Socket welded pipe ¹	1.50	1.25	1.15
Threaded pipe ¹	1.25	1.15	1.00
Conduit ¹	1.50	1.35	1.25
Instrument tubing ¹	1.50	1.35	1.25
Cable trays ¹	1.50	1.35	1.25
HVAC duct ¹	1.50	1.25	1.15
Equipment supports ¹	2.00	1.50	1.25
<p>General Notes:</p> <p>f_c=Concrete compressive strength</p> <p>f_v=Average concrete shear stress, which is equal to shear divided by the shear area</p> <p>h_w=Height of the entire shear wall or segment of the shear wall considered</p> <p>h=Beam depth</p> <p>w=Length of shear wall or segment of shear wall considered in direction of shear force</p> <p>σ_y = specified minimum yield stress</p> <p>σ_u = specified minimum ultimate stress</p> <p>σ_n = specified allowable stress</p> <p>Specific Notes:</p> <p>¹ The components and systems designed to ASME B&PVC Section III Code have allowable stresses approximately two times that of ASME B.31, AISC and SMACNA Codes.</p>

Figure 2 Typical Load-Deformation Curve and Limit States

Differences Between Japan and U.S. Seismic Loading Criteria

In the U.S. until recently the applicable seismic input motion (i.e. ground motion response spectra) has usually been defined at the free-field ground surface independent as to whether or not the structural support media is rock or soil. In Japan the NPP safety related reactor containment structures have been founded on rock or what is defined as rock like media. In the U.S. both soil and rock foundation media have been used. When soil was used a soil structure Interaction analysis was required.

Other significant difference between Japanese and U.S. practice was in Japan where until recently vertical seismic motion used in design was defined as a static constant while in the U.S. it has been defined by means of vertical ground response spectra. It should also be noted that since the 1990's there appears to be a basic difference between how seismic peak ground acceleration at a site used in NPP seismic design are defined. In Japan, and in most of Western Europe, it appears to be defined by the largest earthquake in the seismotectonic province or region during recorded history being moved to be adjacent to the site or otherwise identified on potentially active fault(s) which would control site seismic accelerations in order to define the earthquake design basis ground motion. There is also a basic difference in the application of the S_1 and S_2 , and the OBE and SSE earthquake levels between Japan and the U.S. In the U.S. there is only one safety/seismic category defined applicable to reactor safety SSC; Seismic Category I and both the SSE and OBE were applied to Seismic Category I SSC with the OBE peak ground acceleration, pga typically being half of the pga of the SSE. In Japan, either the S_2 (Safety Class A_s SSC or S_1 (Safety Class A SSC) were applied, but not both to the same structure, system or component, SSC.

ANALYSIS METHODS AND MODELING PROCEDURES

In both countries the following analytical methods for seismic design were developed more or less in the following chronological order.

- Equivalent static seismic lateral loads were determined on the basis of the fundamental frequency of the structure and an assumed ground response spectra taken from the literature based on the review of the earthquake response spectra recorded for limited number of strong motion earthquake (i.e. Housner spectra).
- Seismic lateral loads on systems and components located on the grade level of the supporting building structure used the same input ground acceleration response spectra for the distribution system or component, but with damping value applicable to the particular distribution system or component being evaluated.
- A dynamic stick model of a building was developed with a single degree of freedom defined for each mass point in the direction of the earthquake with mass points typically representing a floor of the building. These models were typically limited to no more than about 3 to 5 mass points.¹
- The equivalent static lateral seismic loads on distribution systems at elevation above the ground floor used the same ground response spectra modified as a function of the increased floor acceleration replacing the p_{ga} .
- While commercial computer programs became available about 1967 to analyze dynamic multi-degrees of freedom systems, which could be used to generate in-structure or floor response spectra applicable to systems and components at various heights in the building structure, it was not until the early 1980's that computer programs became available for direct generation of floor or in-structure response spectra based on their dynamic characteristics and the ground response spectra. Prior to that time actual earthquake time histories or simulated earthquake time histories whose response spectra enveloped the design basis earthquake ground response spectra were used to generate floor or in-structure response spectra.
- By 1985 it began to be recognized in the U.S. that for unsymmetrical buildings the applied motion in one orthogonal direction could cause response motion in a different orthogonal direction due to coupling in the structure which resulted in the use of 3 dimensional finite element models.
- The initial modeling of building structures in both countries was to assume a rigid building foundation. Soil structure interaction for Seismic Category I building structures was started in the U.S. in the late 1960's by use of a one-dimensional translational and rotational springs representing the building foundation stiffnesses as a function of its foundation soil shear wave velocity and soil density and the use of experimentally determined levels of radiation damping in the foundation. Since the 1990's finite element modeling of the foundation media, coupled with the building finite element model, has been used in computer programs such as SASSI or more generalized finite element programs such as ANSYS.

ACCEPTANCE CRITERIA

The seismic design acceptance criteria include limitations on both Japan and the U.S. allowable forces, moments and stresses, f_m s which have generally been defined by the different engineering disciplines. The Civil Engineering discipline designs building and other similar type of structures. The Mechanical Engineering disciplines designs pressure retaining components, cranes and transportation systems. The Electrical Engineering discipline designs electrical power, instrumentation and control I&C devices and components. Seismic design of Civil and Mechanical SSC are typically determined by stress analysis. Seismic design adequacy of electrical power, instrumentation and control devices and components is normally determined by shake table tests or a combination of tests of devices and analysis of the component or structure which supports electrical devices using either envelope seismic time history input for either proof or fragility type testing. In proof type testing the device or component is tested up to a prescribed limiting response spectral shape and acceleration. In fragility testing the device or component is tested up to initial malfunction or failure of the device or component.

CONCLUSIONS

Seismic design requirements in both Japan and the U.S. have had a significant effect on safety related NPP design.

¹ In 1962 it typically took approximately 160 engineering manhours to determine the dynamic response of a 5 mass/model dynamic degree of freedom system using an \$800 mechanical calculator capable of adding, subtracting, multiplying and dividing equivalent to a \$3 electronic calculator of today.

In the area of building design it has lead to shorter and widened building layouts associated with a nuclear island with some increase in reinforcing steel in predominately reinforced concrete structures used to carry in-plane seismic shear and overturning seismic loads. It also has lead to a significant increase in the engineering effort required to analyze and design such structures. For safety related buildings a low height to base aspect ratio is required to reduce the potential for uplift which in addition to changing the loading pattern on the base mat would begin to change the response frequency of the structure; hence, its seismic loads.

It is in mechanical and electrical distribution system analysis and design where seismic requirements appear to have their greatest impact. Lateral supports required to carry seismic loads are typically spaced every 2 to 4 times deadweight support spacing as a function of design basis seismic acceleration in U.S. NPP and 1 to 2 times deadweight support spans in Japan due to typically larger earthquake intensity and lower specified design basis damping values. In elevated temperature distribution systems many such supports are required to be active in nature where they move when subjected to thermal loads yet lock up when subjected to suddenly applied seismic loads.

For electrical and instrumentation and control devices and components it is usually necessary to provide seismic qualification by dynamic earthquake simulated shake table testing which adds a significant cost to such devices or components.

The seismic analytical and testing methods associated with seismic design have required the continuous development of more and more sophisticated and rigorous qualification procedures, as well as a significant increase in the perceived level of applicable seismic loading over the past 50 years. It is hoped that the seismic design requirements applied to NPP has finally reached an acceptable level of maturity and major changes in methodology and procedures may finally have stabilized in order to allow nuclear power to continue to be a major economical resource for generation of electrical energy.

REFERENCES

- [1] Interim Staff Guidance, DC/COL-ISG-20, "Probability Risk Assessment-Based Seismic Margin for New Reactors," U.S. Nuclear Regulatory Commission, 2010.
- [2] NSCRG: 1-DS-1.02 Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities," (Japan) Nuclear Safety Commission, September 2006
- [3] UBC 1967, Uniform Building Code 1967 edition, Vol. 1, International Conference of Building Officials.
- [4] ASCE 7-10, "Minimum Design Loads for Buildings and Other Structures," American Society of Civil Engineers, 2010.
- [5] JEAG 4601-1970, "Technical Guidelines for Aseismic Design of Nuclear Power Plants," Japan Electrical Association, Japan.
- [6] U.S. NRC Regulatory Guide 1.60, "Design response Spectra for Seismic design of Nuclear Power Plants," U.S. Nuclear Regulatory Commission, 1973.
- [7] U.S. NRC Regulatory Guide 1.208, "A Performance Based Approach to Define the Site Specific Earthquake Ground Motion," U.S. Nuclear Regulatory Commission, March 2007.
- [8] ASCE Std. 43-05, "Seismic Design Criteria for Structures, Systems and Components in Nuclear Facilities," American Society of Civil Engineers.