Update of ASCE Standard 4 “Seismic Analysis of Safety-Related Nuclear Structures and Commentary”

Short, Steve[a], Orhan Gürbüz[b], and Mike Salmon[c], Farhang Ostadan[d]

[a]*Simpson, Gumpertz and Heger, Newport Beach, California, USA, e-mail: sashort@sgh.com*
[b]*Bechtel Corp., Huntington Beach, CA, USA, e-mail: ogurbuz@bechtel.com*
[c]*LANS, LLC., Los Alamos, New Mexico, USA, e-mail: salmon@lanl.gov*
[d]*Bechtel Corp., San Francisco, CA USA, e-mail: ostadan@bechtel.com*

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1 ABSTRACT

The American Society of Civil Engineers Standard 4 (ASCE 4) has been the main guidance document for the seismic analysis of the nuclear safety-related facilities and other critical or important facilities in USA for more than two decades. The Standard was last revised in 1998. This standard was developed mainly for the U.S. Department of Energy non-reactor nuclear facilities. A working group of the ASCE Dynamic Analysis of Nuclear Structures (DANS) Standards Committee undertook a task in 2005 to update the standard to implement recent developments in seismic analysis of these facilities. Recently, a resurgence of the nuclear power industry has made it even more important to have up-to-date seismic analysis provisions.

ASCE 4 is a companion document to ASCE Standard 43 (ASCE/SEI 43), “Seismic Design Criteria for Structures, Systems and Components in Nuclear Facilities.” ASCE Standard 43 has been used as a reference document by several utilities in submittal of combined license applications (COLAs) for New Reactors.

The working group responsible for this revision is part of the ASCE DANS committee. Its members are drawn from the industry, academia and governmental organizations, thus encompassing the potential users of the standard in different groups. It is expected that the revised document will be available in 2009.

The revised standard will reflect the state-of-the-art approaches for determining seismic demands on nuclear safety-related structures, systems and components. This document is expected to become the definitive source for seismic analysis in the nuclear industry and resolve many outstanding controversial issues.

2 INTRODUCTION

Major ASCE 4 updates are summarized in this paper. The standard is now composed of seven Chapters, appendices, and related commentary. The entire standard has undergone a major editorial change in order to implement the new developments in seismic analysis and design, make it more user-friendly; commentaries are provided right after the provisions for each section or subsection for the convenience of the user.

This standard is applicable to the analysis of safety-related structures, systems and components (SSCs) of nuclear facilities. The SSCs addressed include above and below ground structures, above ground or elevated tanks, buried piping, all distribution systems and base-isolation. Provisions of this standard may also be applied to other structures and components at the discretion of the analyst.

3 SEISMIC ANALYSIS AND PERFORMANCE-BASED DESIGN/EVALUATION

Chapter 1 was expanded to highlight the “target performance goal” approach and support performance-based seismic design. Performance based seismic design criteria have been implemented for Department of Energy Facilities for many years. Only recently, has the nuclear power industry employed such criteria. Note that these provisions provide many levels of criteria in a graded approach that can be implemented based on the hazards and importance of the facilities. As a result, these criteria are especially valuable for nuclear facilities such as fuel processing facilities where potential hazards are significant but much less than those associated with nuclear power plants. Such criteria have not existed in the past and these other nuclear facilities have not been designed in a consistent manner.

ASCE 4 is intended to be consistent with ASCE/SEI 43, *Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities*. ASCE/SEI 43 is aimed at achieving specified target performance goal annual frequencies. The target performance goals are expressed as annual frequency of exceeding unacceptable behaviour for structures, systems, and components being designed. For the definition of "unacceptable behaviour" a graded approach of ASCE/SEI 43 is followed: from elastic behaviour, Limit State D, to non-collapse, Limit State A. To achieve these target performance goals, ASCE/SEI 43 specifies that the seismic demand and structural capacity evaluations have sufficient conservatism to achieve both of the following:

- Less than about a 1% probability of unacceptable performance for the Design Basis Earthquake Ground Motion, and:
- Less than about a 10% probability of unacceptable performance for a ground motion equal to 150% of the Design Basis Earthquake Ground Motion.

Commentary to ASCE/SEI 43 shows that the above performance goals will be met if the demand and capacity calculations are carried out to achieve the following:

- Demand is determined at about 80% chance of not being exceeded for the specified input response spectrum.
- Design capacity is calculated at about 98% exceedance probability.

The ASCE 4 provisions for determining seismic demand include sufficient conservatism that, when combined with the seismic design provisions in ASCE/SEI 43, the probabilistic target performance goals are achieved. Hence, when probabilistic seismic analyses are performed, the demand used for seismic design should be selected at the 80% non-exceedance level. For deterministic seismic analyses, the conservatism is contained in the following areas:

- The spectra of time-histories used in analysis envelop the design response spectra, thus introducing some level of conservatism
- For soil-structure interaction, three cases are analyzed using a range of dynamic soil properties and the results of the three cases are enveloped.
- For in-structure response spectra, the peaks are broadened.
- In modeling, small structural members and non-structural elements are ignored, thus maximizing the calculated responses in the modeled elements.
- For structural damping, generally conservative values are specified.
- Demand is generally determined using conservative approaches such response spectrum or equivalent static methods.

It is the judgment of ASCE Dynamics Committee Working Group that following the analysis criteria given in this standard will result in a demand that has at least 80% chance of not being exceeded. Thus, it is concluded that the use ASCE/SEI 4 and 43, together, will achieve the performance goals set in ASCE/SEI 43. At this time, many probabilistic seismic analyses have or are being performed. Once the results of these analyses become widely available, they can be used as a measure to assess whether the ASCE 4 deterministic seismic provisions are achieving sufficient conservatism. Thus, it is possible that the ASCE 4 seismic provisions for analyses may have to be modified in the future such that they are sufficiently conservative.

4 SPECIFICATION OF INPUT GROUND MOTION

Chapter 2 brings in the latest developments in seismic ground motions and the various input ground motion definitions which have come to use in recent years. Guidelines for utilizing the output from a probabilistic seismic hazard analysis to establish the input to a seismic soil-structure interaction analysis are presented.

Seismic input ground motions shall be specified in terms of smoothed Performance-Goal Based Design Spectra (DRS) derived from mean uniform hazard response spectra (UHRS) in accordance with Section 2.2 of ASCE/SEI 43-05. These spectra shall be defined for motions in the horizontal and vertical directions. A single set or an ensemble of acceleration time histories matching or enveloping the design response spectra may be used in seismic response analyses.

The design response spectra shall be specified as free-field outcrop motions. For sites where thin, relatively soft layers overlay stiffer competent materials, the spectra and corresponding motions may be specified as outcrop motions at the elevation of the top of competent material.

The outcrop motions at any depth may be defined as either free-surface motions (computed as a geologic outcrop with no soil layers above) or as an outcrop motion including the effect of down-coming waves from layers above the outcrop depth (full column outcrop). In either case, the outcrop motion must be fully probabilistic and consistent with both the best-estimate and variability of the properties of the full soil column. The transfer of the outcrop motions from one level to another must consider effects from the full soil column down to the depth of the uniform halfspace. Transfer of the outcrop motions from one level to another shall be performed in accordance with the criteria specified in Section 2.3 of ASCE/SEI 43-05.

Foundation Input Response Spectra (FIRS) shall be used to develop the input motion for SSI analyses of structures. These FIRS shall be site-specific ground response spectra characterized by horizontal and vertical spectra computed at the foundation level of the structure as free-field outcrop motion using performance-based procedures in accordance with ASCE 43-05. The soil/rock column used for computation of FIRS shall be consistent with the free-field SSI model of the structure, as well as being consistent with the best estimate and variability of the strain dependent soil properties associated with the DRS.

5 MODAL RESPONSE COMBINATION

Chapter 4 of the updated ASCE 4 provides a significant expansion on the subject of modal response combination. Modal response shall be combined in a manner that accounts for the relative phasing between modes. Low-frequency modes are out of phase with each other (periodic), high frequency modes are in phase with each other (rigid), and modes in between are in transition phasing as shown in Figure 1. The standard provides methods for modal combination methods in each region to obtain accurate total responses.

Combination of out-of-phase (Periodic or Low Frequency) modal responses for the I^{th} component of motion is calculated using the following double sum equation:

$$R_I = \pm\sqrt{\sum_i \sum_j \varepsilon_{ij} R_{Ii} R_{Ij}} \tag{1}$$

where:

R_I	=	the response for the I^{th} component of motion
R_{Ii}, R_{Ij}	=	the signed modal response of interest in the $i^{th}\left(j^{th}\right)$ mode
ε_{ij}	=	modal correlation coefficients

If the frequencies of all modes are sufficiently separated, it is acceptable to combine out-of-phase modal responses using the SRSS method. In this approach, ε_{ij} is equal to 1.0 when i is equal to j and equal to 0.0 when i is not equal to j. If there are closely spaced modes (i.e., not sufficiently separated as discussed above), it is permissible to use either of the following two approaches for modal combination for which equations for ε_{ij} are given in the standard:

- Modified Rosenblueth's Correlation Coefficient
- Der Kiureghian's Correlation Coefficient (Complete Quadratic Combination or CQC)

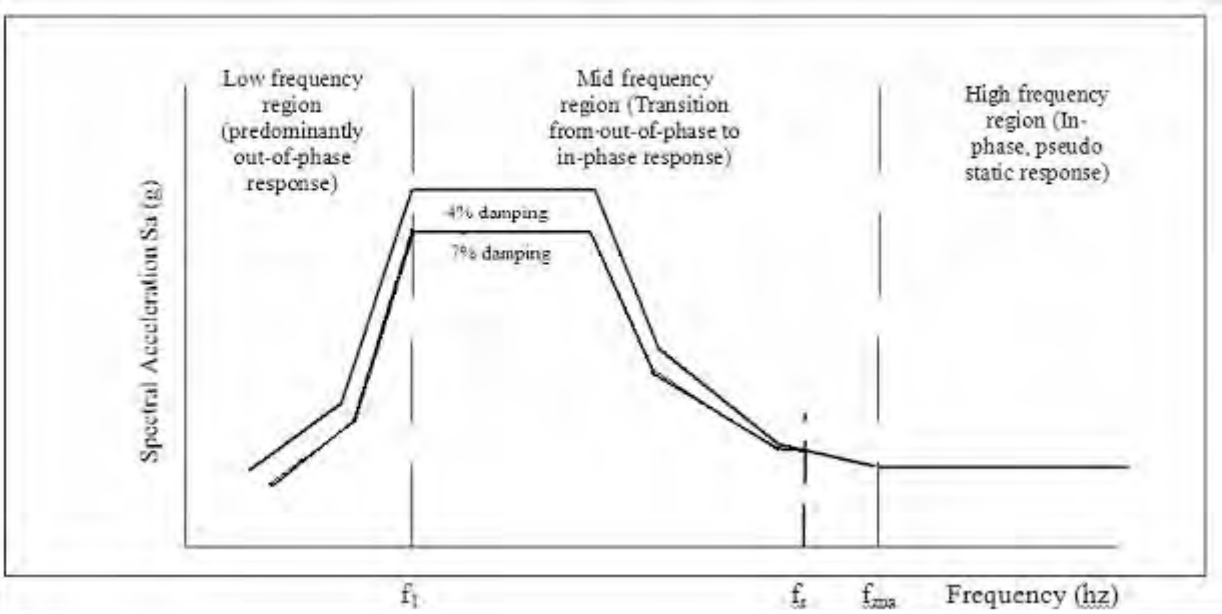

Figure 1. Modal Phasing and the Ground Response Spectrum

Combination of Rigid (In-Phase or High-Frequency) Modal Responses in the high-frequency region (greater than rigid frequency, f_r, as shown in Figure 1), is by algebraic sum:

$$R_{Ir} = \sum_{i=1}^{n} R_{Iri} \tag{2}$$

where:

R_{Ir}	=	the combined response of the I^{th} component of motion
R_{Iri}	=	the response of the I^{th} component of motion for mode i
f_r	=	the rigid frequency

The rigid frequency can be identified as the frequency at which response spectra curves for different damping ratios converge. Note that f_r can be less than f_{zpa}, the ZPA frequency.

In the transition region between frequencies f_1 and f_r, the modal responses consist of both periodic and rigid components. For these, it is permissible to use either of the following two approaches for modal combination:

- Gupta Method (called General Modal Combination or GMC in some computer codes)
- Lindley-Yow Method

Both of these methods are implemented through the use of a rigid response coefficient, α_i, that is defined in the standard for each method. Note that the frequency at the beginning of rigid response, f_2 (f_r in Figure 1) has been modified from that published in many references. Also note that in the previous standard, the rigid frequency was not different from the ZPA frequency as it is in the current standard. As a reasonable approximation, the previous edition of the standard permitted a jump in the value of α_i from 0 to 1 at a frequency of 1/2 f_r. This approximation is no longer permitted in the current standard. Recent work at Brookhaven National Laboratory indicated that periodic response is very strong close to the rigid frequency (Morante et. al. 1999).

6 EQUIVALENT STATIC AND MULTI-STEP ANALYSIS METHODS

The little guidance given in ASCE 4-98 on the equivalent static method of analysis for seismic loads has been expanded into comprehensive provisions. In addition, a new subsection entitled “Multi-Step Analysis Methods” has been added to capture the state-of-the-art analysis procedures currently practiced for the analysis of large facilities.

In the static equivalent method, the base shear for analysis of a structure or a component is defined in terms of spectral acceleration and dynamic amplification. The latter parameter was applied in the past to all situations as a constant multiplier of 1.5; the new provisions make distinctions for the cases depending on the point of application of the load and number of supports. Thus, unnecessary conservatism has been eliminated to a large extent.

In the multi-step approach, a dynamic analysis of the structure is first carried out to determine the response parameters of importance. This step is necessary especially for the complex facilities where dynamic analysis of a detailed model may not be feasible. Thus, a relatively simplified model can be used in the dynamic analysis, with sufficient detail to capture the seismic parameters of interest, such as accelerations, displacements and base shear. These parameters are then applied statically as input, to a more detailed model of the structure or component to determine the maximum response parameters for design.

The second step analysis may also be a dynamic analysis for a segment of the structure or a component, using the dynamic responses obtained at the attachment points to the overall structure. Guidance is provided to achieve an acceptable and accurate response calculation that will capture the important response parameters for design.

Limitations for both the static equivalent and the multi-step methods are defined to help the analyst make the right decisions regarding seismic analysis. Although many of these provisions are new, they are derived from the current practice, including some regulatory review experience, to assure that the resulting design meets the target performance goals.

7 SOIL-STRUCTURE INTERACTION

A significant change to ASCE 4 is the explicit consideration of seismic wave incoherence combined with soil-structure interaction seismic analyses (Short et. al. 2006 and Ostadan et. al. 2005b). The assumption of vertically propagating plane shear and compressional waves when performing SSI analysis is generally conservative in terms of predicting in-structure responses. However, seismic wave incoherency effects may be considered. The incoherency effects reduce the foundation translational motions and increase the rotational motions. The differences are larger at high frequencies and with larger foundation dimensions. Coherency models that represent spatial variation effects as a function of frequency and separation distance and SSI formulations that implement such coherency models require adequate justification. The coherency function for hard rock sites that has been approved for use in design/evaluation of nuclear power plants by the U.S. Nuclear Regulatory Commission is provided in the Commentary (Abrahamson, 2007).

The evaluation of seismic wave incoherence in SSI analyses pointed out that SSI effects may be very significant even at relatively stiff site conditions. For stiff site conditions characterized by shear wave velocities less than 8,000 ft/sec, but greater than 3,500 ft/sec, subjected to free-field seismic input motion characterized by high frequency amplification, i.e., greater than 10 Hz, a fixed-base analysis may be very conservative in the high frequency range, but unconservative in the low frequency range as shown in Figure 2 (Johnson et. al 2007). The structure whose response is shown in Figure 2 is a simplified model of a nuclear island, supported on rock with varying shear wave velocity from about 3,000 ft/sec near the surface increasing to over 6,000 ft/sec at depth, and subjected to a high frequency free-field input motion with significant peaks at about 25 Hz. The figure shows that SSI effects are significant - reducing the response in the high frequency range.

The assumption of a fixed-base condition needs to be carefully evaluated when considering high frequency input motions to typical nuclear power plant structures. SSI produces rotations of the foundation that are not possible in the fixed base condition.

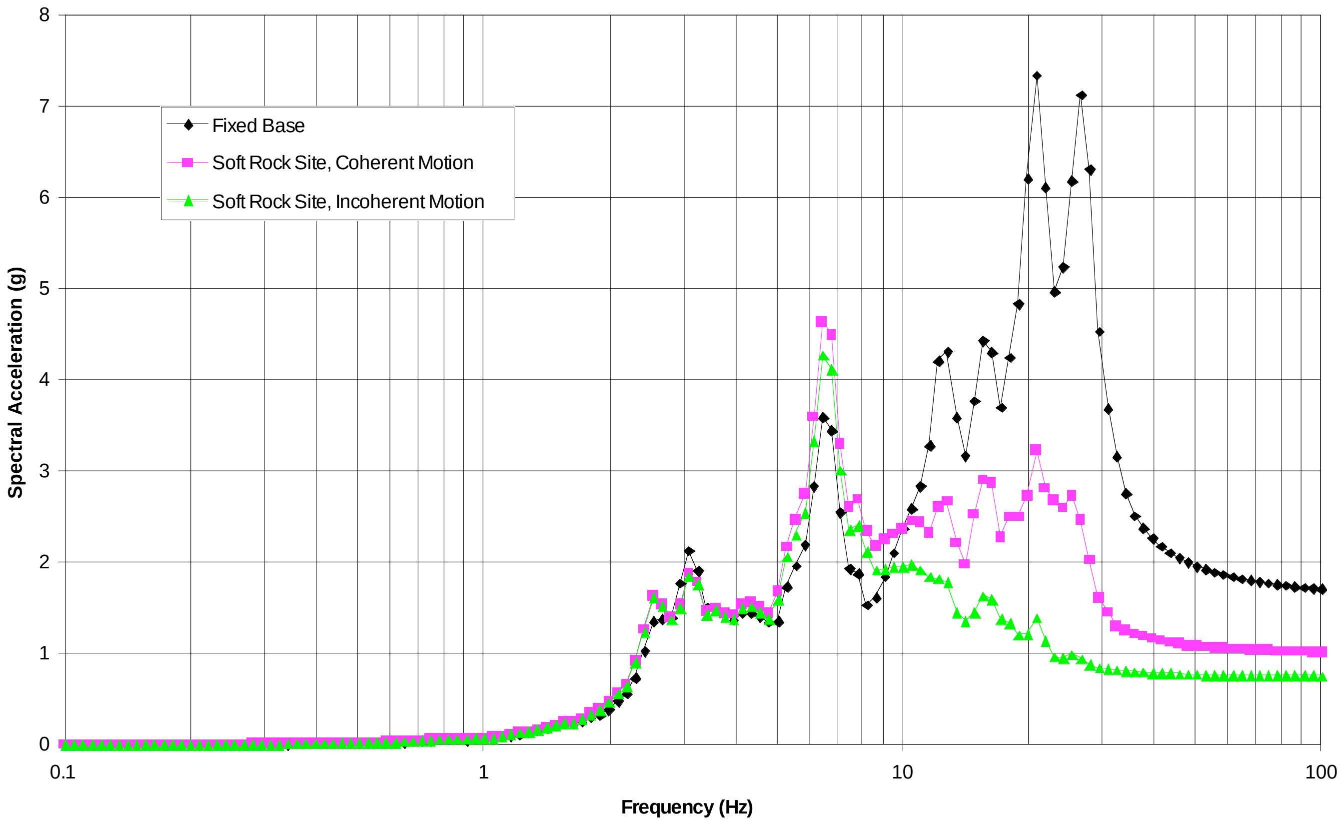

Figure 2. Top of Shield Building Response, Horizontal Direction – Fixed-Base, SSI for Coherent Input Motion, SSI for Incoherent Input Motion

Additional provisions for SSI in the update of ASCE 4 include:

- The direct method and the sub-structuring methods including widely used computer programs SASSI and CLASSI are described and use of hybrid method for special application are discussed.

- Use of random vibration theory and probabilistic SSI analysis is encouraged.

- Use of strain-compatible soil properties generated from probabilistic site response analysis (for development of the design motion) for application to SSI analysis is described and the minimum variation of soil properties for SSI analysis are specified.

- Development of input motion for SSI analysis consistent with its development and its application to the SSI model is described. The new standard specifically asks for the control point to be specified at the foundation level of the structure in the free-field.

- For SSI analysis, the same soil material damping may be used for horizontal and vertical excitations for soil layers above the ground water table. For submerged soil layers a reduction in P-wave damping is recommended.

- Poisson's ratio, ν, is defined from measurements of low strain S- and P-wave velocities measured in situ in accordance with the theory of elasticity for isotropic behaviour. Poisson’s ratios developed from the geotechnical characterization of dynamic soil properties shall be maintained for seismic SSI analysis, except for saturated soil layers for which the compressional wave velocity of saturated soil shall be maintained as a minimum.

8 DYNAMIC PRESSURE ON BASEMENT WALLS

ASCE 4-98 provided two approaches for determination of the dynamic pressures behind walls below soil. The first method is called the “Wood’s Method” and is considered applicable to walls where significant lateral movement is prohibited by the geometry of the structure. The second method, “Mononobe-Okabe,” is considered applicable to retaining walls where significant lateral displacement may occur. Both of these methods are retained in the new revision.

It is known that the Wood’s Method is conservative. An alternative approach, “Ostadan’s Method,” has been added to more accurately determine the dynamic incremental pressures behind the walls of structures with large footprints (Ostadan 2005a and Ostadan et. al. 1998). In this approach, a soil column analysis is performed to obtain the response motion at the depth corresponding to the base of the wall in the free-field. Using the soil mass and the free-field accelerations, the maximum soil pressure is obtained. Vertical distribution of the dynamic pressure is then calculated using a polynomial which was developed after a comprehensive study.

Alternatively, dynamic soil pressure may be computed directly from soil-structure interaction analysis using a computer code such as SASSI. In this approach, soil elements are placed strategically behind the walls and the stresses in these elements are monitored. The maximum soil pressures are then the normal stresses computed for these elements.

Thus, the analyst is provided with a number of approaches that could determine the dynamic incremental pressures with varying degree of accuracy and conservatism.

9 SLIDING AND ROCKING OF UNANCHORED COMPONENTS AND BUILDINGS

ASCE 4-98 did not address the sliding and rocking of unanchored rigid bodies. For this reason, sliding and rocking topic was added to ASCE 43-05 in its initial issue. This addition to ASCE 43-05 was considered as temporary; both sliding and rocking are analytical topics that rightfully belong in the revised ASCE 4. Thus, the sliding and rocking subject is now added to ASCE 4-09 and it will be removed from ASCE 43 during its next revision.

The new section in ASCE 4 updates and expands the methodology included in ASCE 43. The standard allows a static, conservatively biased evaluation for both sliding and rocking and requires 10% higher resistance than the demand. If this criterion is met, it is concluded that sliding will not take place and that the rigid body will not tip over about its edge. Then, no further calculation is necessary.

If the static stability cannot be demonstrated, then both sliding distance and rocking angle must be calculated, using either approximate methods or time-history analyses. If approximate methods are used, the resulting displacement and rocking should be increased by a factor of 1.5 and the component or structure should be designed for the increased displacement or rocking. The standard provides approximate methods of sliding and rocking calculations. Special provisions are provided for rocking of cylindrical components; for these cases only 10% of the instability angle is considered as allowable. Tests have shown that cylindrical components tend to roll around its edge if the angle of uplift becomes appreciable. Hence, a large factor of safety is applied. For non-circular footprint, 75% of the instability angle is considered allowable. Thus, in high seismic zones, it would be prudent to provide a square footprint for the cylindrical components.

If nonlinear analysis is preferred, the standard requires use of 5 time-history analyses, calculation of the mean values and assuring that the design can accommodate 150% of the calculated sliding distance and rocking angles. Alternatively, 16 time-history analysis can be performed and the 80% non-exceedance level of displacement and rocking angle are established for design.

For buildings, special provisions are provided. Static stability can be calculated using one of the following equations:

$$V_R = C + N*\mu \geq 1.1 V_{BS}\text{, or,} \tag{3a}$$

$$V_R = N*\mu + P_u \geq 1.1\, V_{BS} \tag{3b}$$

where V_R is the sliding resistance, C is the effective cohesion force, N is the normal force, μ is the coefficient of friction, P_u is the at rest resistance (passive resistance can be permitted if all the implications are addressed) and V_{BS} is the base shear.

In rocking evaluation of the buildings, only compression is assumed to exist between the structure and the soil. The structure is assumed to rotate about an axis through the point of zero compression. The maximum uplift of the building is then calculated using simple geometry. The designer must assure that the resulting displacements will not adversely affect any building umbilicals.

10 SEISMIC CONSIDERATIONS FOR DISTRIBUTION SYSTEMS

The section on raceways in ASCE 4-98 has been expanded to include all distribution systems, including piping, raceways, tubing, ductwork, and their supports. Seismic analysis and design of distribution systems may require operability (Limit State D), leak-tightness (Limit State C or B), or structural integrity (Limit State B or A). The Limit States are defined in ASCE 43-05. The analytical procedures included in the standard can be used with any Limit State, together with the acceptance criteria that can be found in the applicable code or standard.

Both elevated temperature (i.e., differential temperatures greater than 100^0F during operation cycles) and cold piping are addressed. For high temperature piping either static equivalent or dynamic (both response spectrum and time history) analyses are permitted. Piping supports can be excluded from the analytical models so long as the dominant frequencies of the piping system are less than the frequency at peak spectral acceleration.

For cold piping, in addition to the analytical approach, "Design by Rule" or "Load Coefficient Method" approaches are in use. These more simplified approaches are included in a non-mandatory appendix because of some regulatory questions regarding their use in nuclear applications.

For both piping, the standard provides guidance on support spacing and fundamental frequencies as a function of support spacing.

Similar to piping, seismic analysis of the ductwork can be carried out using static or dynamic approaches. The standard provides guidance on elastic stability and provisions for stiffeners so as to preclude buckling failure of the system.

Raceway systems may also be analyzed using static or dynamic methods. However, determination of the dynamic properties of the raceway systems is rather difficult; available experimental data should be used both in modelling these systems and interpreting the analyses results.

The standard addresses both unbraced and braced systems. Guidance is provided in determining the spacing of transverse and longitudinal support spacing. Guidance is also provided on the modelling of raceway systems for seismic analysis and in determining the stiffness properties of the members.

The Non-Mandatory Appendix B describes the Load Coefficient and Design by Rule methods for the design of cold piping. The Load Coefficient method uses reduced allowable stresses in conjunction with single span analysis to determine the support spacing. Then the same spacing may be used for similar piping. In the Design by Rule method, piping is divided into several groups with specific support spacing. The maximum spectral accelerations are specified for each group. The system is installed using the support spacing criteria and no additional analysis is required. This system may be used for 6" or smaller diameter piping. When this method is used, it would be prudent to perform a seismic walkdown of the facility to ensure no unacceptable seismic interaction can take place. Example problems are included in this appendix to help the user.

11 SEISMIC ISOLATION FOR STRUCTURES IN NUCLEAR FACILITIES

The standard addresses specific requirements and techniques for dynamic response evaluation of seismic isolated structures. The focus of this section is on structures isolated at their base, although seismic-isolated subsystems, portions of a structure, may also be modelled and analyzed using similar techniques.

Some of the main requirements of the standard are:

- Nonlinear Analysis: Seismic-isolated structures shall be analyzed using nonlinear time-history analysis methods where the isolation system is modelled with its non-linear properties and all other structural elements maybe modelled with their elastic properties if it is anticipated that they will remain elastic during seismic excitation.

- Design Review: An Independent Peer Review of the isolation system design, analysis and related test programs shall be performed by a team that includes professionals experienced in seismic analysis methods and the theory and application of seismic isolation.
- Multiple Dynamic Analyses: A minimum of five nonlinear dynamic analyses of isolated-structure response shall be performed. The response quantity of interest for the isolator support system and the superstructure shall be based on the envelope of the five nonlinear analyses results.
- In-Structure Response Spectra: ISRS shall be developed as envelop of the responses from the multiple nonlinear analyses, without additional peak broadening.
- Minimum Separation: Minimum separation between the isolated structures (including the basemat) and surrounding retaining walls or other fixed obstructions shall not be less than the 1.25 times the total maximum displacement capacity of the isolator system.
- Access Requirements: Provisions for inspection, replacement and long term testing of the isolation system shall be provided. A minimum of two isolators shall be loaded under similar compressive stresses to the installed isolators and located under the isolated base slab. They shall be tested every five years in accordance with an approved in-service inspection plan
- Qualification Testing: For nuclear applications, it is mandatory to perform qualification testing on isolator systems to develop average and variances of stiffness and damping properties.

The committee hopes that inclusion of the detailed base isolation provisions in the standard will provide the impetus for application of the base isolation system to nuclear plants.

12 CONCLUSIONS

ASCE 4-09 will bring about many advances to the seismic analysis process of the safety-related SSCs. The improvements include:

- The potential for uniform margin of safety in the nuclear facilities by relating the analysis and design to specific target performance levels,
- Explicit performance goals for both demand and capacity calculations,
- Comprehensive analytical procedures by addressing all seismic analysis issues in sufficient detail,
- Expanding the modelling provisions to help the analyst in defining the mathematical model needed for a specific analysis goal,
- Definition of acceptable seismic analysis procedures, including static equivalent methods, multi-step approaches and dynamic analysis,
- Detailed guidance on sliding and rocking analysis of structures and components,
- Acceptable performance criteria for analysis of isolated structures that may lead to wider acceptance of the nuclear energy option.

The revised ASCE 4 should provide adequate guidance in seismic analysis of various safety-related SSCs, leading to a more consistent analysis approach, hence more consistent designs, as a function of the intended use of the facility. It is hoped that the US nuclear authorities will adopt this document in its entirety, thus supporting the uniformity of safety goals achieved by the use of the document.

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