SEISMIC DESIGN CRITERIA FOR THE SYSTEM 80+ ADVANCED LIGHT WATER REACTOR

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ABSTRACT

This paper presents the development of seismic design criteria in support of design certification by the Nuclear Regulatory Commission (NRC) of the ABB-Combustion Engineering's System 80+ Standard Design. The design certification effort is sponsored by the U.S. Department of Energy (DOE). The development of the design criteria included: (a) development of the seismic control motion, (b) development of generic soil profiles for anticipated sites, (c) generation of in-structure response spectra and design loads for structures and equipment through soil-structure interaction (SSI) analyses, and (d) acceptance criteria for future construction sites.

INTRODUCTION

The ABB Combustion Engineering System 80+ Standard Design is a standardized design based on proven technology to give the certainty and confidence for a safe, reliable and economical energy option. It has evolved from a proven ABB Combustion Engineering standard design, the System 80, and it has been expanded to encompass the complete plant. The System 80+ is described in the licensing document CESSAR-DC [1]. The design is currently being reviewed by the NRC under the new Standardization Rule 10CFR52 and is expected to be certified and licensed as a standard design for use in U.S. nuclear plants.

The seismic design of the System 80+ structures and equipment is based on design criteria that are described in this paper. An overview of the criteria related to the basic seismic parameters and methodologies is presented, i.e, the earthquake ground motion, the soil profiles, the seismic analysis methodology, and the site acceptance criteria.

DESCRIPTION OF THE SYSTEM 80+ POWER GENERATION COMPLEX

The System 80+ Power Generation Complex (PGC) consists of the Reactor Building (RB), Control Building, Fuel Building, CVCS/Maintenance Area and Diesel Generator Areas (Figure 1). The Power Generation Complex is founded on a common embedded basemat.

The RB is located in the center of the PGC and is founded on a ten foot concrete basemat. All PGC structures are embedded 52 ft. in the soil. For reference purposes, the bottom of the basemat is located at elevation +40 ft. Ground elevation is at +91 ft. 9 in.

The RB is a reinforced concrete structure which is 220 ft. in diameter (at basemat elevation) and 52 ft. embedded in the soil. The embedment depth is a standard feature of the System 80+ RB design. The RB consists of three primary substructures: the Internal Structure (IS) , which houses the Reactor Vessel; the Steel Containment Vessel (SCV); and the Shield Building (SB). The SB is monolithically connected to the IS at elevation +115 ft. Above elevation +115 ft. it is free-standing and is not connected to any other substructure. The lower part of the SCV is embedded in the concrete walls of the IS. Above elevation +91 ft. it is also free standing similar to the SB.

EARTHQUAKE GROUND MOTION

The earthquake ground motion of the System 80+ Standard Design was developed to represent the ground motion at a rock outcrop. A Safe Shutdown Earthquake (SSE) excitation of 0.30 g and an Operating Basis Earthquake (OBE) of 0.10 g horizontal peak ground accelerations at rock outcrop were utilized. The smooth spectrum representing the control motion in the free field at a rock outcrop was developed based on spectral shapes for earthquake ground motions considered appropriate for Eastern North America and those on NUREG-0098 [2]. The selected horizontal smooth spectrum and the other spectra considered in developing this spectrum are shown in Figure 2. The spectral ordinates were kept equal to those obtained using NUREG-0098 for frequencies lower than about 4 Hz. For higher frequencies, the selected ordinates are significantly greater than those obtained using the NUREG-0098. The shape estimated for Eastern North America influenced this adjustment to these values and the use of the smooth spectrum selected for the System 80+ seismic design criteria.

The two horizontal components were considered to have identical spectra and the vertical was considered to be equal to 2/3 of the horizontal spectrum at all frequencies. For the seismic analyses, statistically independent synthetic time histories were generated for each component. The spectrum corresponding to each synthetic time history conservatively envelops the selected smooth spectrum.

The same spectral shape and time histories (normalized to 0.1 g) were used for the OBE analyses.

SOIL PROFILES

A standard plant design must be based on a sequence of analyses that cover a broad range of sites that the plant might be built on. Each site has unique seismic response characteristics. Therefore, the investigation and selection of multiple generic sites should account for the likelihood of resonance between the building structures and the site soil strata. The sites selected for the SSI analyses have free-field amplifications that cover a broad range of frequencies with which fundamental structural frequencies may coincide. Hence, the envelope of the results provide the maximum seismic response to the SSE and OBE rock outcrop motions when the RB is founded on soil sites that are bounded by the selected soil profiles.

Generic soil sites were selected by first choosing four generic site categories [3].

These categories were chosen to represent appropriate total thickness of soil overlying bedrock. The four categories are shown schematically in Figure 3. Site Category A consists of 52 feet of soil overlying bedrock. The soils in Category B extend to a depth of 100 feet and those in Categories C and D extend to depths of 200 and 300 feet, respectively.

One case was elected for Category A and one case for Category D; these were designated Case A-1 and Case D-1. Four cases were initially selected for site Category B; these were designated Cases B-1, B-2, B-3 and B-4. Three cases were initially selected for site Category C; these were designated Cases C-1, C-2 and C-3. Upon examination of the results of the response analyses for these cases, three additional cases were added. The additional cases were designated Cases B-1.5, B-3.5 and C-1.5. The latter cases were selected to properly and conservatively cover the response at frequencies that did not seem to be adequately covered by the other analysis cases. The variations with maximum shear wave velocities with depth assigned for each case are summarized in Figure 3. The shear wave velocity distribution with depth was selected to provide a reasonably wide range and also to provide significant contrast in velocities at certain depths for a selected number of cases.

STRUCTURAL MODEL OF THE POWER GENERATION COMPLEX

The modeling approach that was used for the RB structural model consists of developing 3-D finite element models (FEM) of the IS and the SB and, based on the FEM models, develop equivalent 3-D lumped parameter stick models. The stick models were then used in the SSI analyses. This approach was used for the IS and the SB. Furthermore, for the IS, two stick models were created: one for horizontal analyses and one for vertical analyses. The only difference between these models is the location of the center of rigidity at each floor, which is different when lateral loads or vertical loads are applied. Because of its slenderness, the SCV has significant "membrane-type" action when it vibrates, and it was explicitly modeled with shell elements. The Nuclear Steam Supply System (NSSS) model consists of an assembly of beam elements and lumped masses and is connected to the IS. The development of the 3-D FEM for the IS and SB and the procedure used to develop equivalent stick model properties is described in [4].

The final configuration of the adjacent structures was not completed at the time of the SSI analyses of the RB. However, in order to capture secondary effects from structure-to-structure interaction between the RB and its adjacent annex buildings, in the SSI analyses, the annex structures were modeled using approximate two-node/single element lumped parameter models. Mass and stiffness properties for these models were selected based on past experience with similar structures [5].

The RB model was constructed by connecting the stick models of the IS, the SB, the NSSS and the FEM of the SCV, as shown in Figure 4. The IS and SB stick models are essentially co-axial (except for floor eccentricities in the IS). Since the IS and the SB are monolithically constructed, the stick models of these structures were connected with a rigid link at elevation +115 ft. The SCV was also connected to the IS with rigid links at elevation +91 ft. The NSSS model was connected to the IS at several elevations using appropriate links whose properties depended on the flexibility of the connection. Also shown in Figure 4 are the stick models of the adjacent annex structures, which were not connected to each other or the RB.

For the purpose of generating floor spectra, the foundation of the RB and the foundation of the adjacent structures were modeled as rigid.

SEISMIC ANALYSES

Two different types of analysis methodologies were used for the seismic analyses. For the fixed-base cases, modal superposition time history analyses were performed using the rock outcrop motions as control motions. For the SSI cases, the methodology of the computer code SASSI [3] was used, which includes effects from soil-structure interaction and structure-to-structure interaction from adjacent buildings. These methodologies are discussed in more detail below.

Fixed-Base Analysis

The fixed-base analyses (SSE and OBE) were performed using computer program EDSGAP (a SAP derivative). A modal superposition time history approach was used in the analyses. All modes up to 78 Hz were included, with corresponding cumulative mass participation of 99% in the horizontal directions and 91% in the vertical direction. The base node (Elevation +50 ft.) of the RB's IS was fixed in all six degrees-of-freedom (three translational and three rotational).

The acceleration time histories applied at the base of the RB correspond to the rock outcrop motions. Simultaneous application of the three time histories was performed. Each time history contained 6000 acceleration values at a time step of 0.005 sec. The time history analyses were carried out at a time step of 0.0025 sec.

Response acceleration time histories at selected nodes were calculated as the algebraic sum of the individual response time histories due to input in each direction.

Soil-Structure Interaction Analysis

For the RB SSI analyses, the methodology of the computer program SASSI was used. SASSI (System for Analysis of Soil-Structure Interaction, [6]) is the most versatile tool currently available for SSI industry practice. The SASSI program uses a general substructuring method, which is formulated in the frequency domain using the complex response method and the finite element technique. In a substructuring method, the soil strata and halfspace are analyzed first, in the frequency domain, and the impedance and scattering properties at the soil-structure interface are established. Subsequently, these properties are used as boundary conditions in a dynamic analysis of the structure with a loading that depends on the free-field motions.

According to the SASSI formulation, the solution of the SSI problem reduces to three steps:

- Solution of the site response problem to determine the free-field motions within the embedded part of the structure.
- Solution of the impedance and scattering problem.
- Solution of the structural problem. This involves forming the complex stiffness matrices and load vector and solving the equations of motion for the final displacements.

The site model consisted of horizontal soil layers overlying a rigid base. All material properties were visco-elastic. The stiffness properties of each layer consisted of shear modulus and Poisson's ratio. The damping properties of each layer consisted of material damping ratios associated with shear waves (S-waves) and compression waves (P-waves). Stiffness and damping were compatible with the strains induced in the soil by the earthquake excitation. In the horizontal analyses, the seismic excitation was in the form of vertically propagating S-waves. In the vertical analyses, the seimic excitation was in the form of vertically propagating P-waves. The control motion was specified at the free-field ground surface and included the site amplification effects for each particular site. The results of the solution of the site response problem were used to obtain the frequency-dependent impedance and scattering functions .

Because of the size and shape of the RB foundation, an axisymmetric approach was used to obtain the foundation impedances and scattering matrices. This was accomplished using the axisymmetric analysis capabilities of SASSI.

The stiffness and mass matrices for the axisymmetric soil-foundation system were first produced using an axisymmetric 4-node solid finite element mesh, as shown in Figure 4. The model consisted of axisymmetric solid elements with appropriate material properties connected to semi-infinite layered zones which were represented by axisymmetric transmitting boundaries. Depth of soil to bedrock varied according to the case analyzed.

The stiffness and mass information were used to generate the impedance matrix and the scattering properties corresponding to P-wave in vertical direction, S-wave in one horizontal direction, and S-wave in the orthogonal horizontal direction. Since the foundations were rigid, the impedances and scattering properties were computed corresponding to 6 degrees-of-freedom (DOFs): two horizontal translations, one vertical translation, two rocking rotations, and one torsional rotation. The scattering matrix was a complex matrix accounting for the variation in motion due to the embedment, size and shape of the foundation, and the properties of the soil layers.

The solution of the combined system (soil, foundation and superstructures) were subsequently performed to generate frequency-dependent transfer functions for every node in the superstructure models.

The transfer functions were subsequently multiplied by the Fourier Transform of the control motion (in this case the free-field surface motion) to obtain the Fourier Transforms of the response acceleration time histories of all nodal points. Using an Inverse Fourier Transform technique, response acceleration time histories were obtained in the time domain.

The time histories of the input control motions and the output (response) consisted of 4096 acceleration values at a time step of 0.005 sec.

Analysis Cases

The SSI analyses were performed for both SSE and OBE. For the SSE, SSI analyses were performed using nine generic soil profiles out of the twelve generic sites developed for the System 80+. Those nine profiles were: B-1, B-1.5, B-2, B-3.5, B-4, C-1, C-1.5, C-2 and C-3. By inspecting the soil response results, it was found that the remaining three generic soil cases (A-1, B-3 and D-1) were enveloped by the nine cases selected for the SSI analyses, and they were not analyzed. To expedite the generation of OBE design spectra, two SSI analyses and a fixed-base analysis were performed and based on the ratio of the structural response between the three OBE analyses and the corresponding SSE analyses, generic scaling factors are derived to scale all SSE in-structure response spectra and develop OBE spectra. The OBE SSI cases were selected based on the critical SSE results.

All analyses were three-dimensional with input excitation provided in three directions simultaneously. The generic soil sites differed from each other with respect to soil properties and depth of soil over bedrock. As shown in Figure 3, the selected cases for SSI analysis included five cases with depth of soil to bedrock of 100 ft. and four cases with soil depth to bedrock of 200 ft. The embedment depth of the RB was the same (52 ft.) in all cases.

The response acceleration time histories from the fixed-base and SSI analyses were used to compute in-structure response spectra for 2 and 5% damping. For design purposes, the response spectra were broadened by ±15% and smoothened, according to Reg. Guide 1.122.

ACCEPTANCE CRITERIA

Acceptance criteria for future construction sites were established. The acceptance criteria aim at minimizing additional analysis tasks required in order to demonstrate the adequacy of a selected site. The acceptance criteria were divided in two categories: those related to the seimic rock outcrop motion, and those that are related to the soil characteristics. The fundamental acceptance citerion for the ground motion is that the potential construction site for the System 80+ should be related to a site-specific rock outcrop spectrum that is enveloped by the spectrum in Figure 2 at all frequencies. The fundamental criterion for the soil profile of the potential site is that the soil properties should be bounded by the lower bound soil properties considered in the analyses described herein.

REFERENCES

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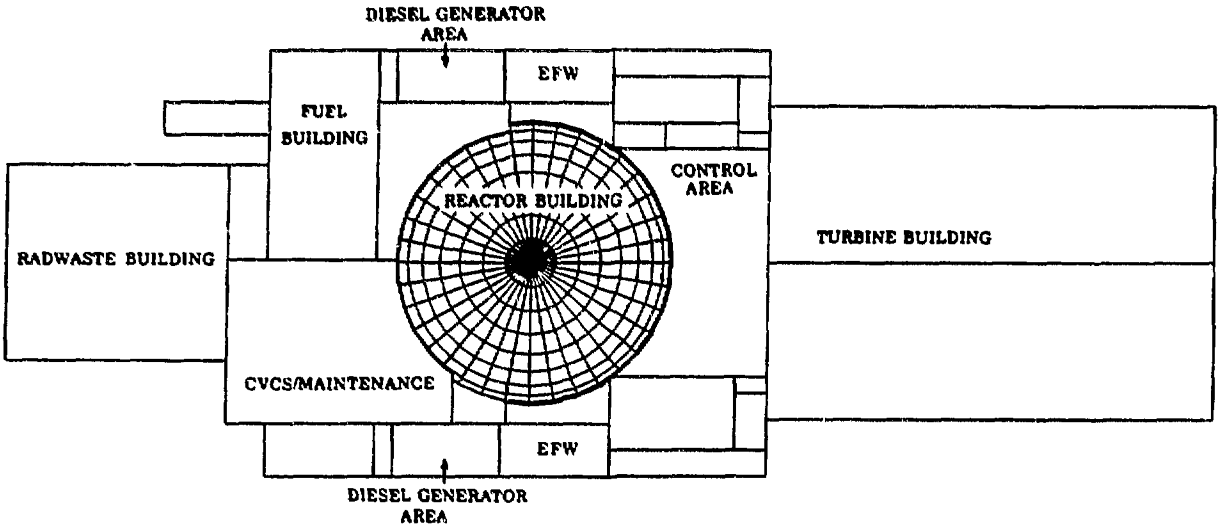
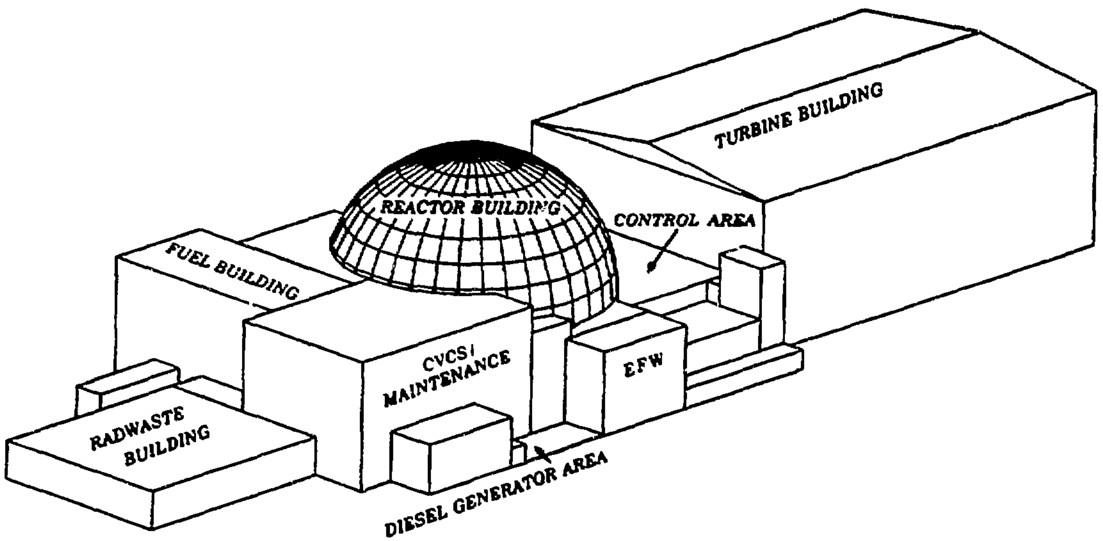


(a) Plan View



(b) Isometric

Figure 1 - Schematic of the System 80+ Standard Design

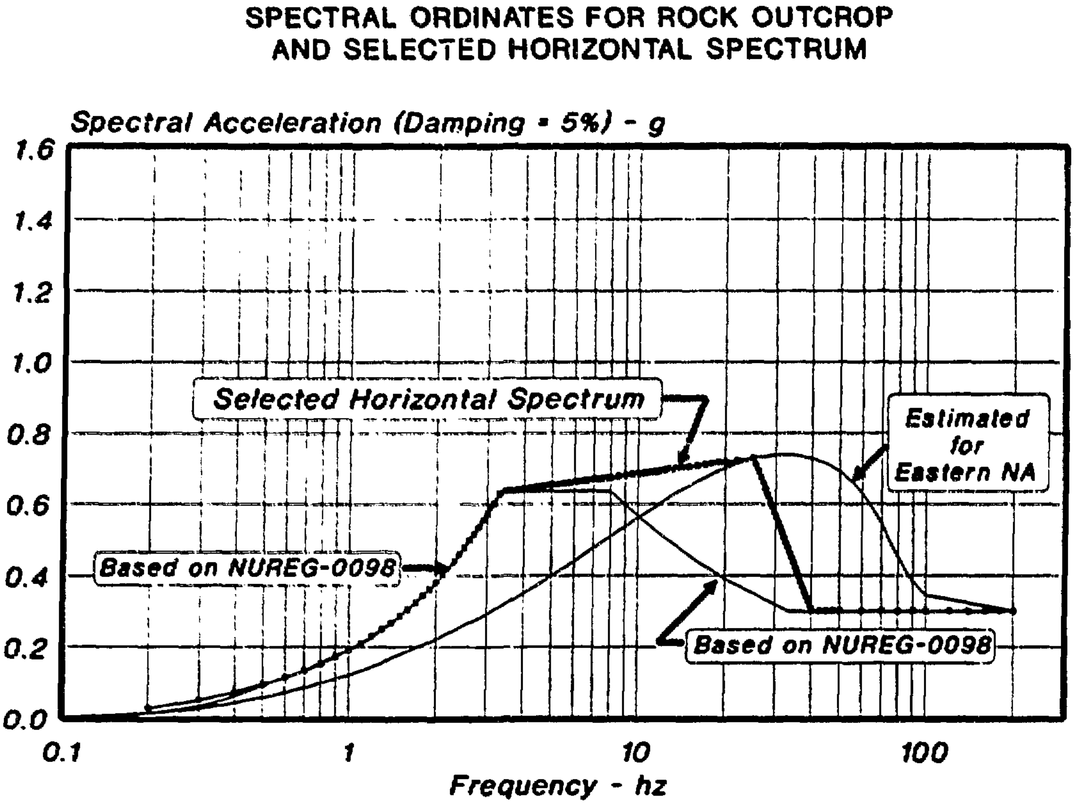


Figure 2 - Selected Design Response Spectrum at Rock Outcrop

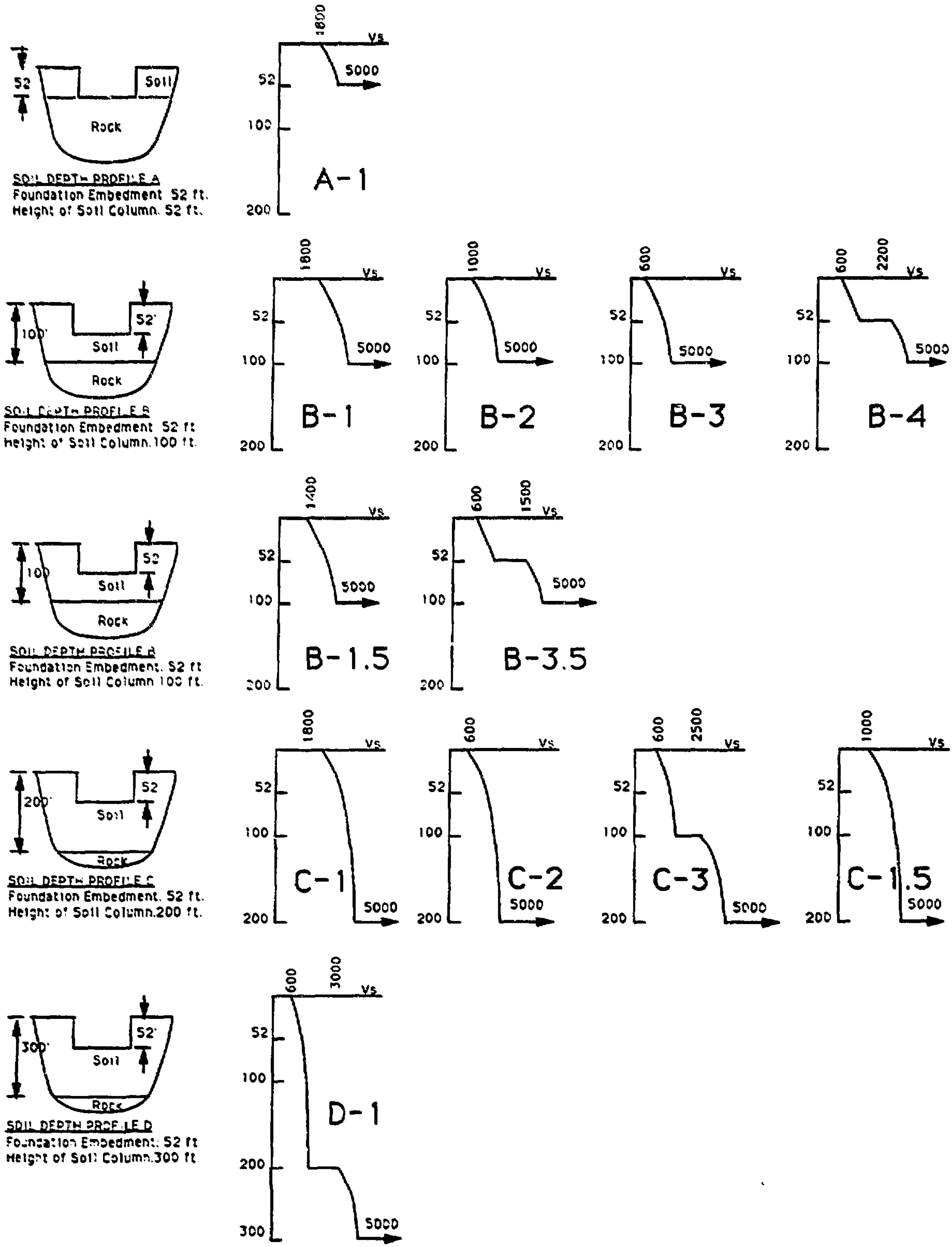


Figure 3 - Generic Soil Profiles for Soil and SSI Analysis

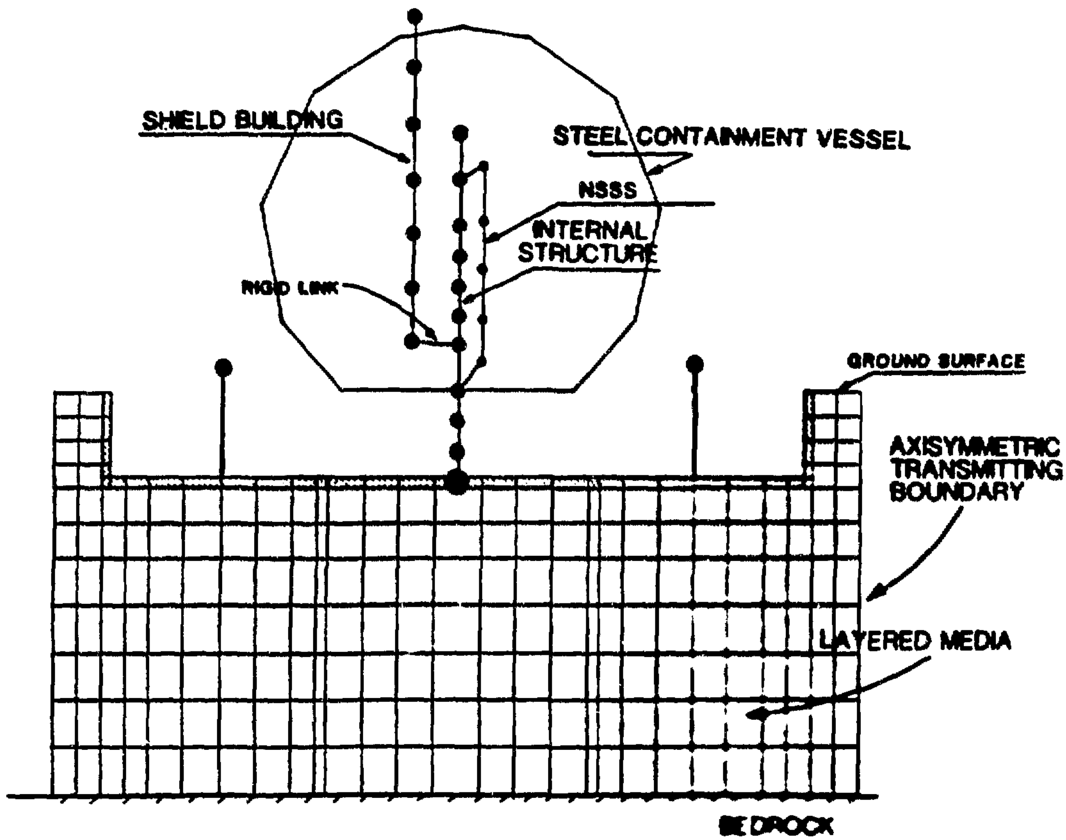


Figure 4 - Schematic Representation of the Combined Structural Model of the Power Generation Complex Used in the Reactor Building Analysis