INNOVATIVE SEISMIC ANALYSIS SOLUTIONS APPLIED ON THE GENERATION MPOWER PROJECT

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ABSTRACT

Generation mPower LLC is a joint company formed by Babcock & Wilcox Company and Bechtel Power Corporation to design, license, and build the next generation of nuclear power plants based on small modular reactor technology. The Generation mPower (GmP) design is expected to be qualified at many viable sites in the continental United States. The seismic analysis for nuclear facilities is very specific to the site where the project is located, as the soil parameters and anticipated seismic input motions are different in each geographical location. For generic design, consideration must be given to a range of soil properties representative of many viable sites. In addition, the input motion for generic design must be robust enough to address the variable nature of seismic conditions throughout the continental United States. The process of selecting the soil parameters and seismic motions for generic design will be discussed in this paper.

One distinguishing feature of the B&W mPower™ Nuclear Island (NI) is the almost fully-embedded structure. The design incorporates a below grade containment and spent fuel pool, which reduces the consequences of aircraft impact or natural phenomena.

The embedded nature introduces significant challenges to the seismic Soil-Structure Interaction (SSI) analysis of the structure, such as: (a) an increase of the analysis solution time due to the large area of soil-structure interface and (b) the lack of available benchmark results for the analysis of deeply embedded structures. Therefore, the complexities associated with the SSI analysis are significantly greater than those faced in the current state of practice. Hence, several innovative techniques are implemented for the SSI analysis of the NI. These innovative SSI techniques are discussed in this paper.

CONSIDERTION OF POSSIBLE SITE CONDITIONS FOR GENERIC DESIGN

A goal of the generic design is to use a range of soil parameters that will produce a design that is robust enough to be seismically qualified for many viable sites in the continental United States. The GmP generic design will include a wide range of realistic soil profiles, representative of soil conditions at current and planned nuclear power plant sites. In order to accomplish this task, data is collected from a number of sources, including public Design Control Documents (DCDs), Combined Operating License Applications (COLAs), and reports from government facilities with nuclear safety-related structures.

The following soil parameters—required for the ground response analysis and subsequent SSI analysis—were collected: shear wave velocity, dynamic shear modulus and damping, unit weight, Poisson's ratio, and groundwater level.

The soil characteristic that typically has the most influence on seismic response is shear wave velocity. This soil parameter represents the stiffness of the soil in response to seismic motion, and is a good basis for estimating the seismic response of the soil. Hence it is important to analyze a range of shear wave velocities (i.e., soil stiffness values) to generate a generic design. The shear wave velocity profiles from several DCDs, COLAs and government facilities were used to determine a realistic range of soil shear wave velocity profiles. Figure 1 is a sample composite plot of such shear wave velocity profiles.

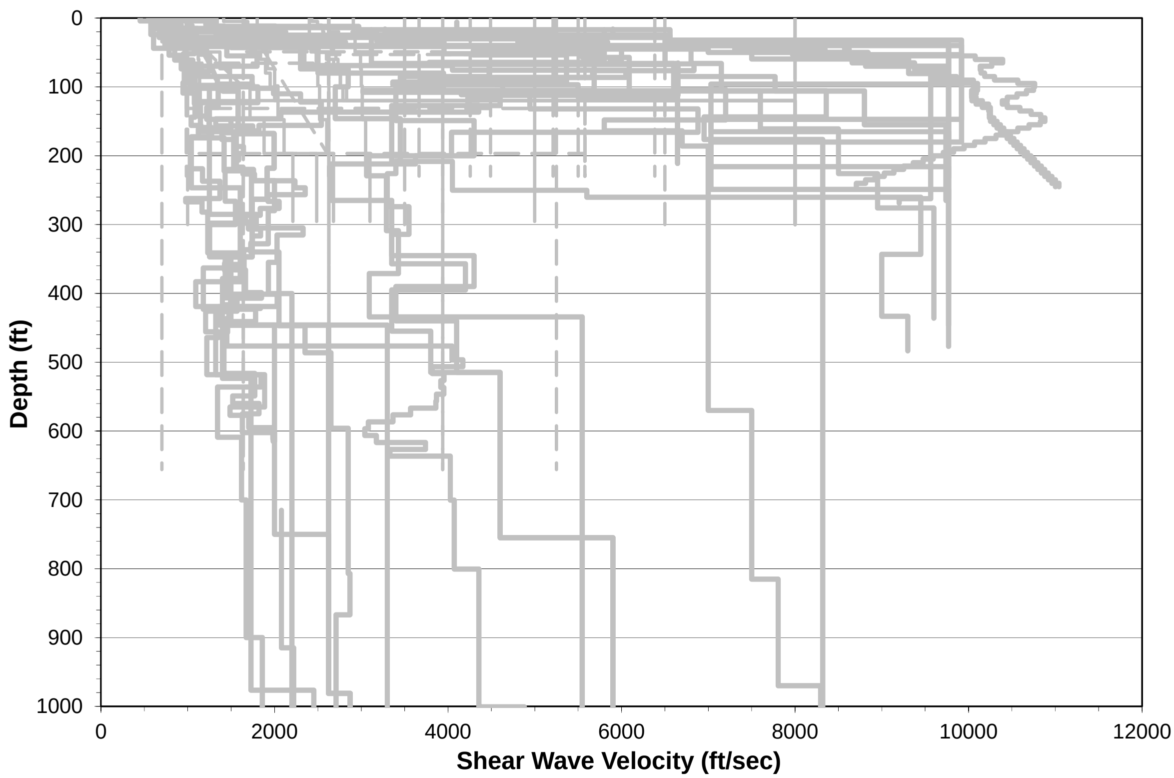

Figure 1. Shear Wave Velocity Composite.

The GmP soil profiles or soil models for generic design are primarily based on soil data collected at sites where COLAs have recently been submitted (i.e., over the last decade) to the United States Nuclear Regulatory Commission (NRC).

Through this process of compiling existing data, a range of soil parameters was selected as inputs to the seismic design. These selected soil input parameters will produce a plant that may be qualified at many sites in the continental United States.

DEVELOPMENT OF CERTIFIED SEISMIC DESIGN RESPONSE SPECTRA

The Certified Seismic Design Response Spectra (CSDRS) is the seismic input motion that the plant will be designed to as submitted in the Design Certification Application (DCA). For the GmP Project, the goal in developing the CSDRS is to cover a wide range of seismic hazards so that the qualification of the plant is achievable for many sites in the continental United States.

The CSDRS for the GmP design is defined at the foundation level. Note that all the safety-related systems are contained within the deeply embedded Reactor Service Building (RSB), founded at a depth of about 140 ft., and the adjacent embedded annex, founded at a depth of about 70ft. (see Figure 2). The RSB and embedded annex together make up the Nuclear Island (NI). Defining the CSDRS at the foundation eliminates the need to de-convolve a surface CSDRS to the foundation level as is typically done (see Figure 3). For qualification of a site, the CSDRS defined at the foundation level is readily compared to the site-specific Foundation Input Response Spectra (FIRS).

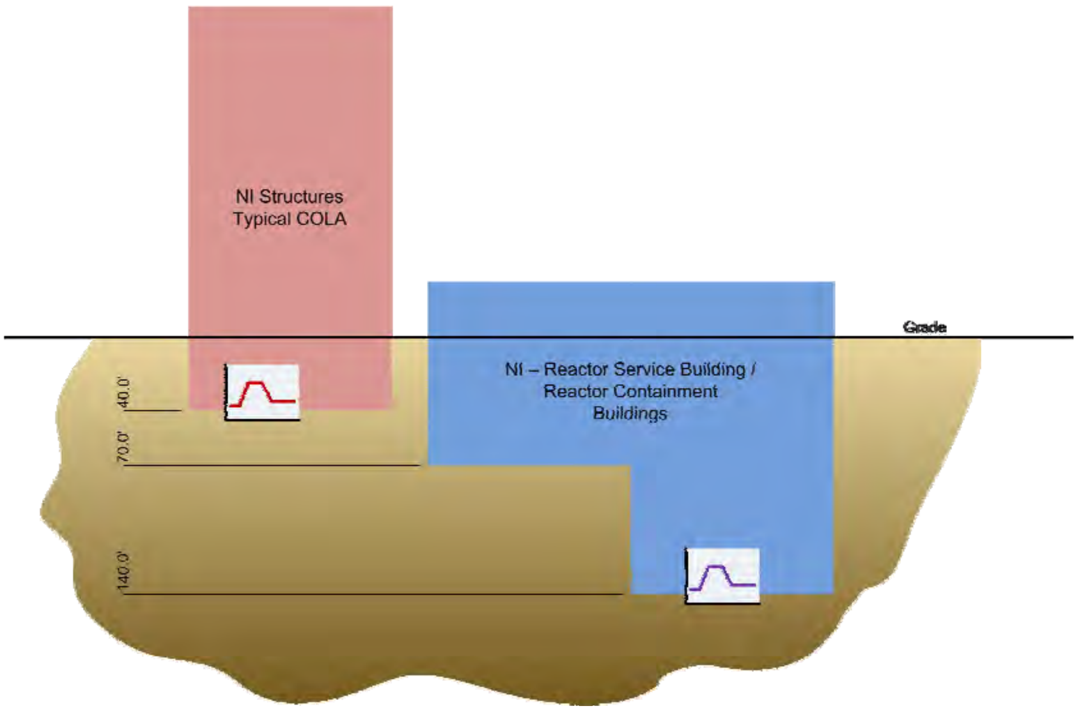

Figure 2. Comparison of Embedment Depth.

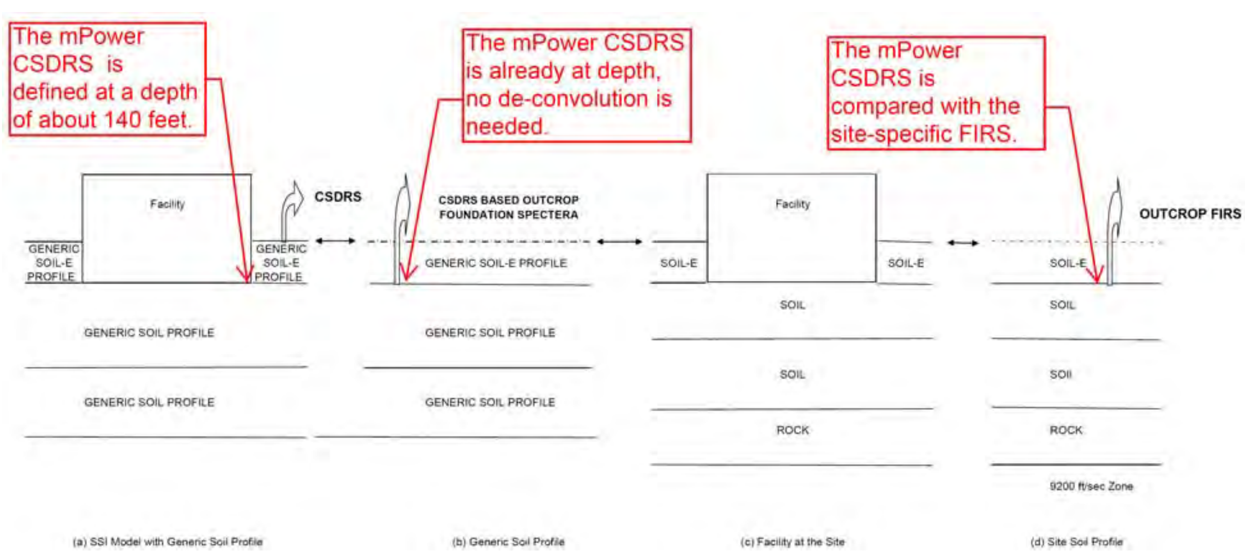

Figure 3. Comparison of CSDRS with FIRS – Nuclear Energy Institute (2009).

Since seismic ground motion characteristic of the Western United States (WUS) and the Central and Eastern United States (CEUS) differ in their frequency content, the decision was made to have two CSDRS with frequency content appropriate for these two regions. Using two CSDRS with appropriate frequency content more closely considers the regional earthquake motions and produces more realistic design responses.

The development of the CSDRS involved collection of the input response spectra associated with the soil data from existing DCDs and COLAs. In addition to the DCD and COLA input response spectra, other historical data—that was used for seismic design of currently operating nuclear facilities—was also gathered.

The collection of input response spectra served as a useful frame of reference in selection of the CSDRS for the GmP design. However, this collection of input response spectra represents ground surface response. The FIRS that were gathered from COLAs are applicable to structures with relatively shallow embedment. Typical power containment buildings are embedded about 40 ft. while the GmP RSB is embedded approximately 140 ft. (see Figure 2). Therefore, typical FIRS are not appropriate for direct comparison with the GmP CSDRS. Development of CSDRS for the deeply embedded RSB required additional analysis as described next.

In order to develop CSDRS that would facilitate qualification of the RSB at current COLA sites, proposed CSDRS were convolved from a depth of 140 ft. through select COLA soil profiles to a depth of 40 ft. (see Figure 4). The spectra at the 40 ft. depth were then compared with FIRS obtained from the COLAs. Proposed CSDRS at 140 ft. depth were then adjusted iteratively until the response spectra at the 40 ft. depth would be comparable to the COLA FIRS.

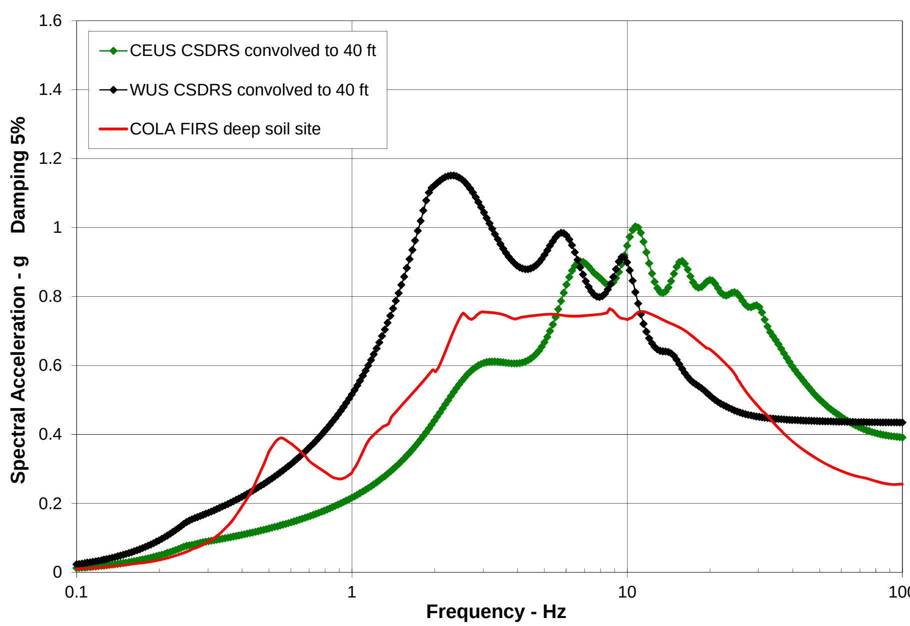

Figure 4. Comparison of CSDRS Convolved to Depth of 40 ft. with a Selected COLA FIRS.

Numerous sets of existing input response spectra data were collected and iteratively compiled to produce two final CSDRS. The CSDRS consider the WUS and CEUS historical earthquake characteristic response frequency content. The choice of two CSDRS, as opposed to a single broad spectrum, is more realistic and is expected to better represent demand on the structure and reduce design conservatism.

NRC guidance documents RG 1.60 (NRC, 1973) and NUREG/CR-6728 (McGuire et al., 2001) influenced the selection of ordinates for both the WUS and CEUS CSDRS. The vertical CSDRS is based on horizontal CSDRS and vertical to horizontal (V/H) ratios appropriate for either the WUS or CEUS (see Figure 5). In addition to the NRC guidance documents, V/H from COLAs for both rock and non-rock sites influenced selection of V/H ratios. The final WUS and CEUS V/H ratios used for the GmP CSDRS exceed 1.0 for higher frequencies. It's noted that V/H ratios in NRC guidance documents, and in the literature, are based on empirical data recorded at ground surface or numerical modeling also at the ground surface. The GmP Project has applied these surface V/H ratios, but additional research would be useful in confirming their applicability to a deeply embedded structure. It's possible that the surface V/H ratios are conservative.

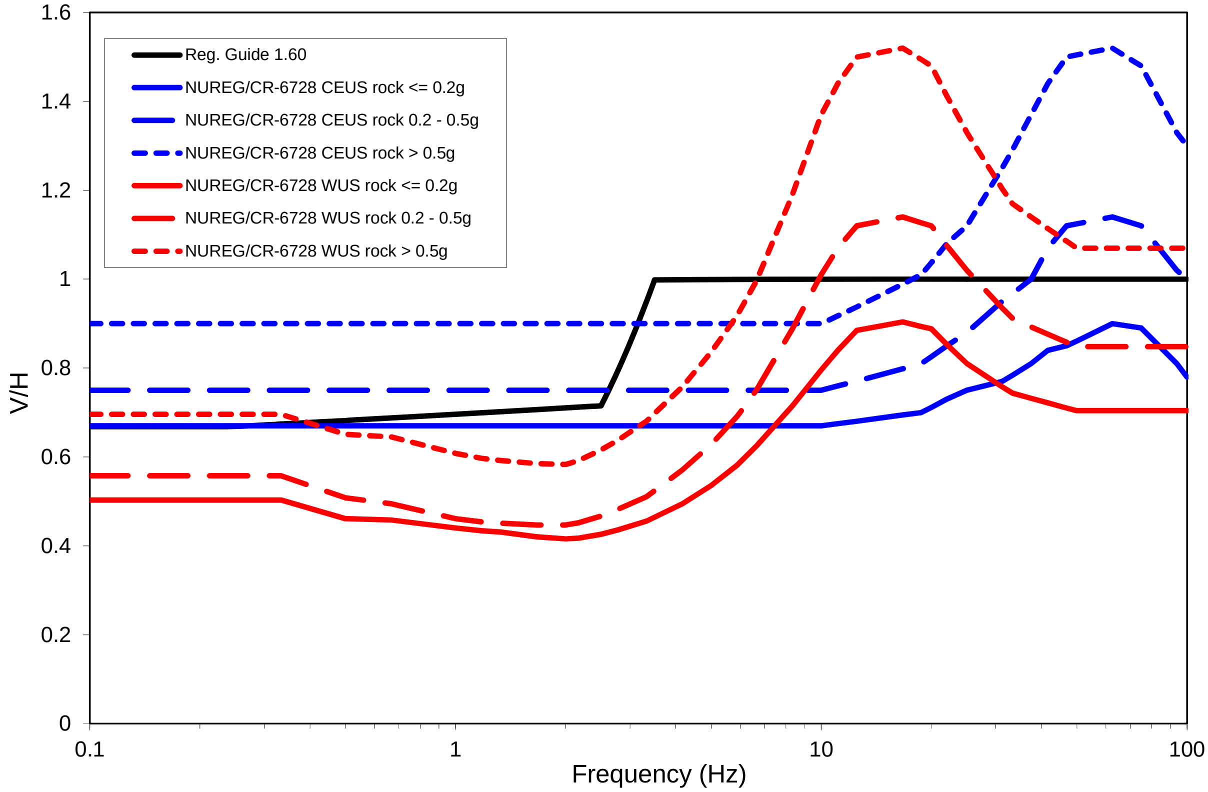

Figure 5. V/H Ratios from Reg. Guide 1.60 (NRC, 1973) and NUREG/CR-6728 (McGuire et al., 2001).

VALIDATING DEEP SOIL-STRUCTURE INTERACTION ANALYSIS

The GmP design represents a "first of a kind" SSI analysis problem. In particular, the embedment depth of the structure (i.e., deeper than 130 ft.) greatly increases the computational effort required to solve the SSI problem. The main challenges include: (a) the inversion of large dynamic flexibility matrices and (b) verification of the numerical accuracy of the calculations. Therefore, two innovative approaches were implemented to validate the application of SSI solution methods and the enhancements to Bechtel's version of SASSI2010: a global level validation/comparison and a local level validation/comparison.

Global Level Comparison

The global level comparison is performed using a simplified model, assuming two lines of symmetry. The model is representative of the global response of the RSB and has an embedment depth and footprint that envelope those planned for the RSB structure. A uniform 2,500 fps shear wave velocity soil profile was used for the global level comparison with a rigid halfspace imposed at a depth of 100 ft. below the foundation level. The geometry for the SAP2000 model, including soil elements, is shown in

Figure 6. SASSI 2010 (Ostadan and Deng, 2011) analysis results for the simplified global model were independently verified using SAP2000 (Computers & Structures Inc., 2000). The SAP2000 and SASSI2010 results are comparable as discussed by Anderson et al., (2013).

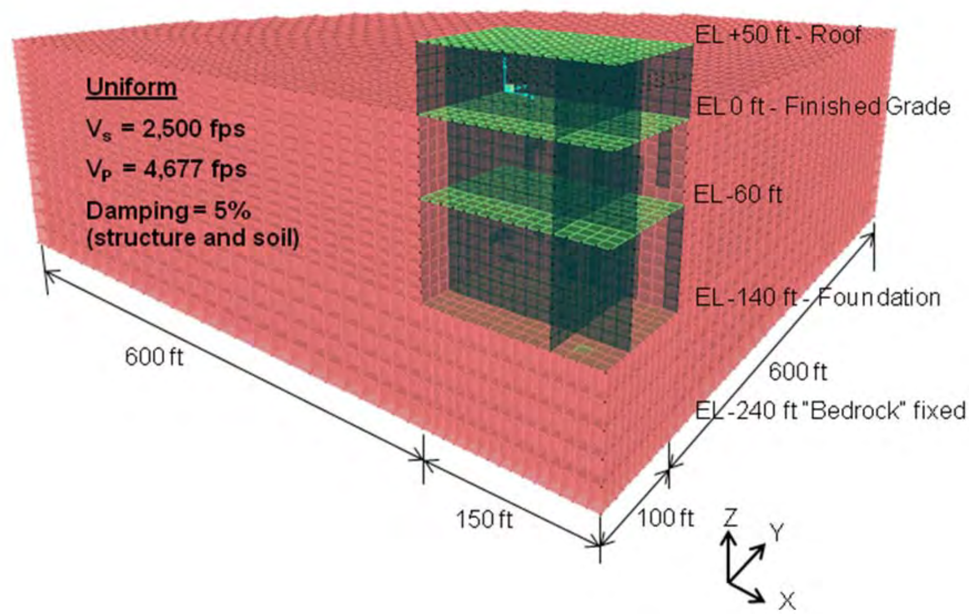

Figure 6. Model Geometry used for Global Validation.

Local Level Comparison

The local level comparison is performed using a more refined model, representing the entire NI, assuming one line of symmetry. The local level model, shown in Figure 7, is adequate to capture all local structural element responses of the NI. Analysis is completed using SASSI2010, with a soil case emulating a fixed boundary condition, and compared with ANSYS (ANSYS, 2009) harmonic analysis, using a fixed boundary condition. Results from the SASSI2010 and ANSYS analyses are compared for several locations throughout the structure. The ANSYS and SASSI2010 results are comparable as discussed by Coronado et al., (2013).

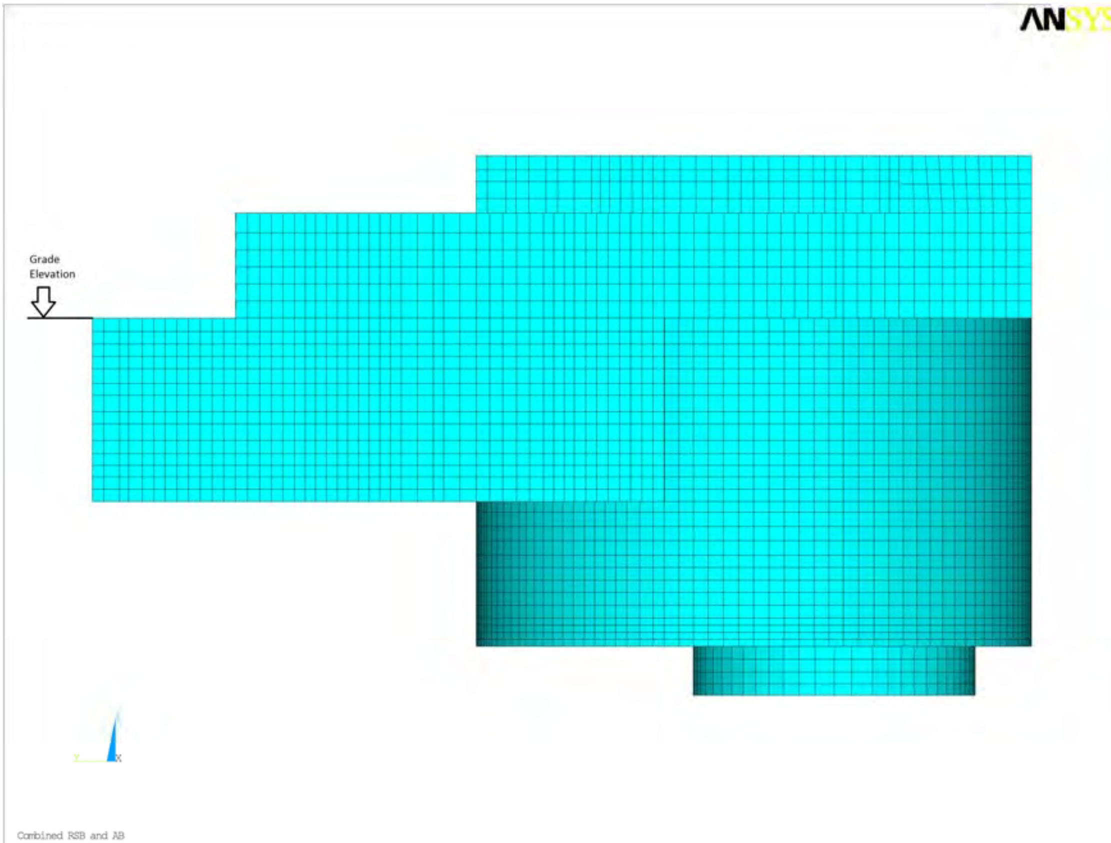

Figure 7. Local Level Model – Elevation View.

The comparisons with SAP2000 representation of the soil model to the equivalent SASSI2010 solution (global comparison) and ANSYS harmonic analysis (local comparison) serve as an independent verification of the solution algorithm and the application to a deeply embedded and complex SSI analysis problem.

CONCLUSION

The process used to select a range of soil profiles and seismic input motions for the generic design of the B&W mPower plant is presented in this paper. Innovative techniques were applied to develop CSDRS that will produce a design that is qualified for a wide range of ground conditions expected at reasonable site locations in the continental United States. The techniques used account embedment depth unprecedented for nuclear power plants.

The deeply embedded design of the NI structure challenges the state-of-the-art with regard to SSI analysis. This degree of deep embedment introduces a "first of a kind" level of complexity to the SSI analysis required for seismic design. Innovative approaches have been employed to validate the SSI techniques planned for the final seismic analysis.

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