CONSISTENT SITE-RESPONSE/ SOIL-STRUCTURE INTERACTION ANALYSIS AND EVALUATION

1 Background

The subject of development of site-specific, performance-based design motion and its application for soil-structure interaction (SSI) analysis has been discussed in several regulatory guides, standard review plans, and other standards, including RG 1.208, SRP 2.5.2, SRP 3.7.1, SRP 3.7.2, ASCE 4-98, and ASCE 43-05. More recently, the Interim Staff Guidance (DC/COL-ISG-1, May 2008) describes the use of various site-specific ground motions for structural analysis and evaluation. In this paper, the industry interpretation of the guides and the agreement on the details of the development and application of the ground motion for SSI analysis reached during the NRC-NEI meeting on September 25 and 26, 2008 are presented. The emphasis of this document is on development of the site-response motion consistent with its application to SSI analysis and evaluation.

In this paper, first the definitions of the types of ground motions required for seismic design are presented. Following the definition, the use of the ground motion for evaluation of the certified design motion applicability to the site is discussed. Next, the application of the ground motion for site-specific SSI analysis is presented. Finally, consideration of the minimum requirement of input motion for SSI analysis is discussed.

As discussed during the NRC meeting on September 25 and 26, 2008, the Staff plans to propose an alternate approach for the development of input motion for SSI analysis. It was agreed that either the proposed approach presented in this paper or the forthcoming alternate approach can be used.

It should be noted that the discussion of consideration of geometry of the backfill in the development of the ground motion is outside the scope of this paper. It is assumed the soil profile is comprised of in-situ soil layers or the lateral extent of the backfill is so large that backfill can be modeled as a soil layer in the free-field analysis.

2 Seismic Motion and SSI Input Parameters

2.1 CSDRS

Certified Seismic Design Response Spectra (CSDRS) - Site-independent seismic design response spectra that have been approved under Subpart B of 10 CFR Part 52 as the seismic design response spectra for an approved certified standard design NPP.

CSDRS are used in SSI analysis of the standard plants. Typically, CSDRS are used as a surface motion for SSI analysis of the structures.

2.2 FIRS

Foundation Input Response Spectra (FIRS) – This is the site-specific motion developed at the foundation elevation of the structure in the free field.

The foundation elevation is the most appropriate location to develop FIRS, which in turn is used to develop SSI input motion. Specifying the seismic input at any other location can lead to unrealistic response spectra at the foundation level (either seriously unconservative or unrealistically high). Development of the FIRS should be consistent with its application for SSI input motion development.

FIRS is a site specific performance-based design motion. Various soil amplification methods in NUREG/CR 6728 can be used to develop FIRS. For example in Method 2A of NUREG/CR 6728, the probabilistic seismic hazard analysis (PSHA) is performed and, for sites in Central and Eastern United States (CEUS), the uniform hazard spectra at the horizon with the shear wave velocity of 9200 ft/sec at the mean annual probability of exceedance (MAPE) of 10-4 and 10-5 are obtained. The rock motions are amplified in the soil column representing the site. To consider variation and uncertainties in dynamic soil properties, the properties are randomized and a suite of typically 60 randomized soil profiles are generated for soil amplification analysis. Soil amplification analysis is performed and the response motion at the horizon of interest is obtained as the median response motion at the two levels of the input motion (10-4 and 10-5 MAPE). A frequency-dependent design factor is computed using the uniform hazard soil motions. The design factor is applied to the soil response motion at the MAPE of 10-4 and the design response spectrum (DRS) is developed. Once the horizontal DRS is obtained, the vertical DRS is developed using the appropriate V/H ratios for the site. The details of development of performance-based motion are presented in NUREG/CR 6728.

In summary, FIRS is a site-specific, performance-based design response spectrum with both horizontal and vertical components at the foundation level of the structure in the free field and includes the design factors.

In this paper, FIRS defines the motion that is developed following the process described above. Depending on the project and number of Category I structures in the facility, more than one FIRS may be required for the site. Also, depending on the application of FIRS for development of SSI input motion, FIRS may be computed as surface motion of a truncated soil column or as outcrop motion at the foundation level as defined in the Section 2.4.

2.3 Performance-Based Surface Response Spectra (PBSRS)

Performance-Based Surface Response Spectra (PBSRS) follows the same computation steps as performed to develop FIRS except that the soil column surface response defined in Section 2.5 is used. The vertical component of PBSRS is obtained using applicable V/H ratio.

2.4 SSI Input Motion and Soil Profiles

As stated in Section 2.2, FIRS is a performance-based motion and, in effect, is a probabilistic motion. The SSI analysis is currently a deterministic analysis and is performed with a minimum of three soil profiles. Input motion developed for SSI analysis typically consists of 3-component acceleration time histories (two horizontal and one vertical component). FIRS are used to develop SSI input motion. Development of SSI input motion from FIRS is discussed in Section 3.2.

For the deterministic SSI analysis, typically three soil profiles are used. The soil profiles used in the SSI analysis should be consistent with the soil profiles used for generation of FIRS and its subsequent use to develop the SSI input motion.

From the set of soil profiles used in the soil amplification analysis to develop the FIRS, a companion set of strain-compatible soil shear wave velocity and damping profiles are obtained. From this set, the median and one standard deviation of the soil velocity and damping for each soil layer are computed. The best estimate, the lower, and the upper bound soil profiles for SSI analysis are obtained from the median profiles plus/minus one standard deviation maintaining the minimum variation of 1.5 x G_{best} and G_{best} / 1.5 to define the range as required in SRP 3.7.2, where the term “best” denotes the best estimate or median properties. The P-wave velocity profiles are obtained from the corresponding shear wave velocity profiles using the soil Poisson’s ratio of each layer. For the soil layers below the ground water table, the minimum P-wave velocity of 5000 ft/sec should be maintained. For SSI analysis, P-wave damping may be set to be equal to S-wave damping for all soil layers.

In this paper, the three soil profiles defined above are referred to as the SSI soil profiles.

2.5 Soil Column Response - Surface and Outcrop Motion

Depending on the application of FIRS, FIRS may be a surface motion or an outcrop motion as defined below.

The soil column analysis is typically performed using the one-dimensional wave propagation programs such as SHAKE. The solution to the one-dimensional wave propagation shows that, for each frequency of analysis, the motion in each layer can be decomposed into one incoming and one reflected component. In layered profiles such as the one shown in Figure 2.1, the incoming and reflected components for layer “m”, defined as Em and Fm, are functions of the corresponding components of the layer next to it. Following the trend layer by layer, it becomes clear that the incoming component of motion in each soil layer is a function of the properties of the layers above it. In the formulation of the SHAKE family of programs, the "outcrop" motion for each layer is defined as two times the incoming component of the motion in that layer. Consequently, SHAKE "outcrop" motion is a motion that, in effect, is a function of the soil layers above and below that layer. The outcrop motion with this definition is different from the surface motion of the same column with the upper soil layers removed. The latter soil column with top soil layers removed has also been referred to as "geologic outcrop" which in, effect, is a surface response motion of a truncated soil column.

In this paper, the outcrop motion definition used in the program SHAKE is adopted. The Soil Column Outcrop Response is labeled as SCOR. The Soil Column Surface Response is labeled as SCSR. If the soil column is reduced in height by removing some of soil layers at the top of the soil column, the Truncated Soil Column Surface Response is labeled as TSCSR. At the ground surface level, SCSR and SCOR are the same.

Depending on application of FIRS, FIRS may be computed as SCSR, TSCSR, or as SCOR as described in Section 3.

G_m shear modulus of layer m
ρ_m mass density of layer m
ω circular frequency, cps

$$k^2 = \frac{\rho\omega^2}{G + i\omega\eta} = \frac{\rho\omega^2}{G^*}$$

$$\alpha_m = \frac{k_m G_m}{k_{m+1} G_{m+1}} = \sqrt{\frac{\rho_m G_m^*}{\rho_{m+1} G_{m+1}^*}}$$

$$E_{m+1} = \frac{1}{2} E_m (1+\alpha_m) e^{ik_m h_m} + \frac{1}{2} F_m (1-\alpha_m) e^{-ik_m h_m}$$

$$F_{m+1} = \frac{1}{2} E_m (1-\alpha_m) e^{ik_m h_m} + \frac{1}{2} F_m (1+\alpha_m) e^{-ik_m h_m}$$

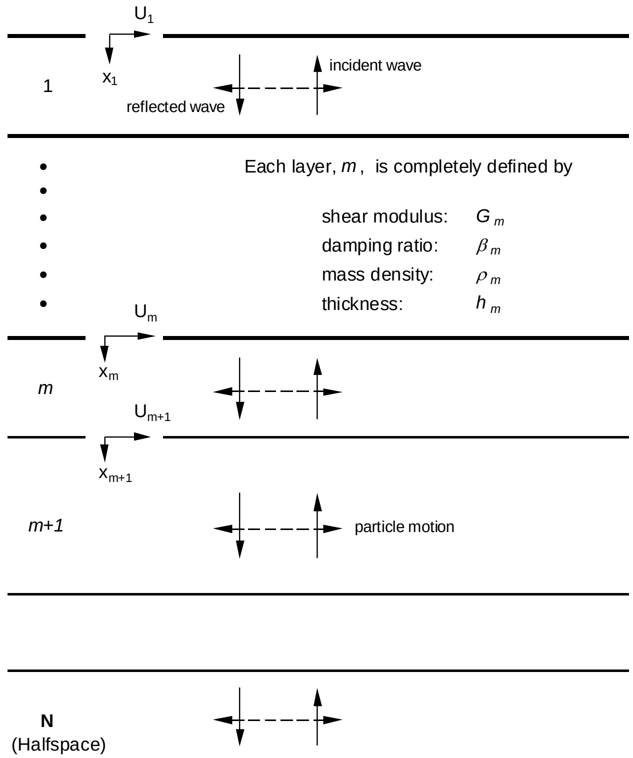


Figure 2-1 One-Dimensional Wave Propagation in Layered System

3 FIRS Application

FIRS has three basic applications as described below.

3.1 Comparison of FIRS with CSDRS to Determine Certified Design Motion Applicability

3.1.1 Surface Structures

If the certified design is a surface founded structure, the SSI analysis for the design has been performed with an SSI model with no embedment. This condition is illustrated in Figure 3-1. For the evaluation of the applicability of the design to the site, the FIRS should be computed as the soil column surface response (SCSR). For this case, FIRS is same as PBSRS defined in Section 2.3. The horizontal and vertical FIRS are compared with the corresponding CSDRS and the decision on the need for site-specific SSI analysis is made.

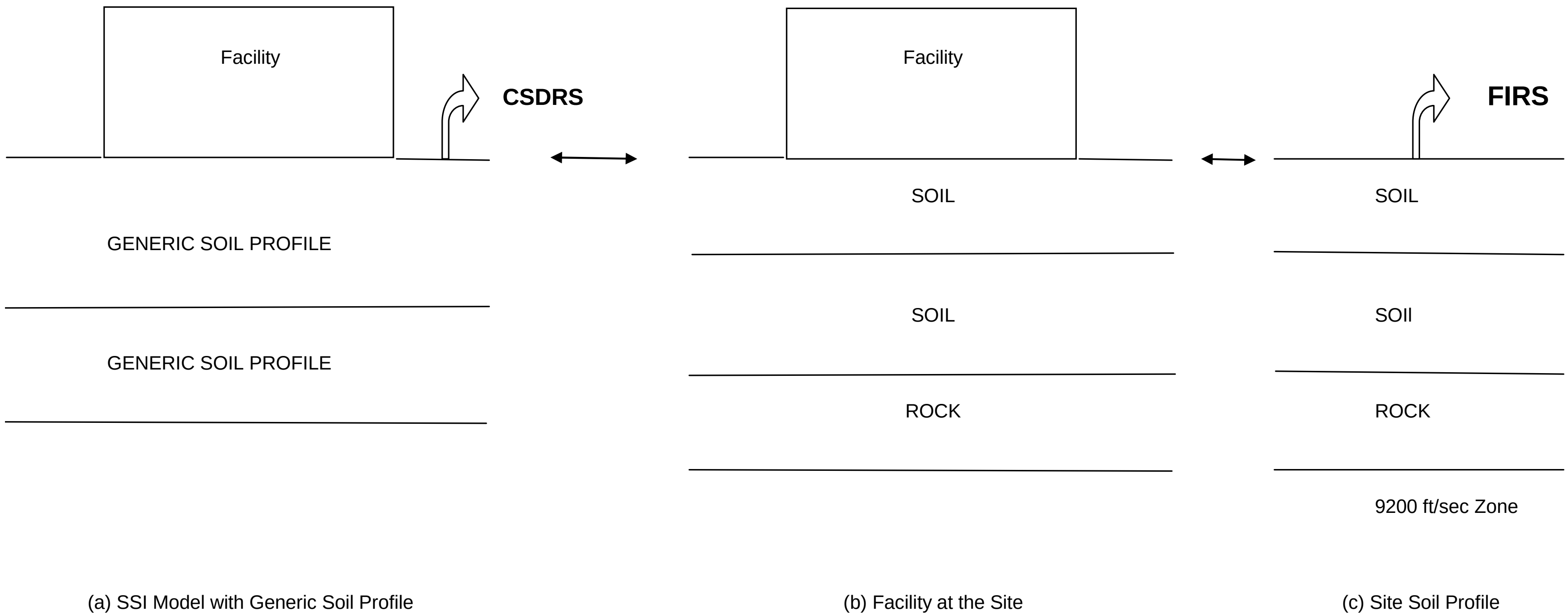


Figure 3-1 Comparison of CSDRS with FIRS for Surface Structures

3.1.2 Embedded Structures Analyzed as Surface Structures in the Certified Design

Some structures in certified design have been analyzed as surface structures with no embedment. The embedment has been ignored since the certified design is based on numerous soil profiles that cover a wide range of site conditions. However, the structure is an embedded structure as shown in Figure 3-2. For these structures the FIRS should be computed as the surface response motion of a truncated soil column (TSCR) and compared with the CSDRS.

For computation of FIRS as TSCR, the truncated soil column should include the effect of soil layers above the foundation depth on the nonlinear soil properties of the soil layers below in terms of both the confining pressure and the soil column frequency of the soil layers above the truncated depth. One direct approach to include these effects in the analysis is to perform the soil column analysis for the full soil column with no truncation and develop the set of strain-compatible soil velocity and damping profiles. Once the strain-compatible soil profiles are obtained, remove the soil layers corresponding to the embedment depth of the structure (soil-E in Figure 3-2) and perform the second round of soil column analysis with the truncated soil columns with no further iteration on soil properties. Once the response motions at the truncated surface are obtained (TSCR), the FIRS are developed using the procedure described in Section 2.2. The FIRS in the horizontal and vertical directions are compared with the CSDRS in the respective directions and the decision on the need for site-specific SSI analysis is made.

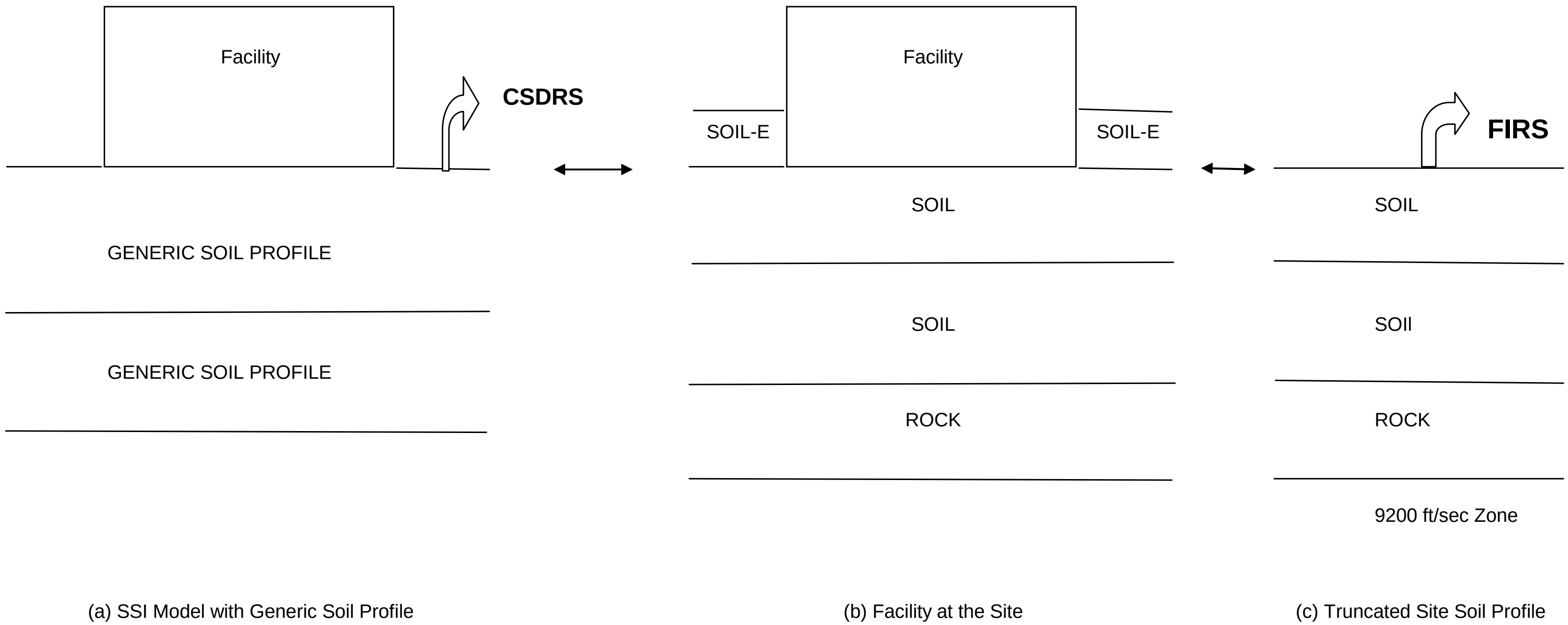


Figure 3-2 Comparison of CSDRS with FIRS for Embedded Structures Analyzed as Surface Structures in Certified Design

3.1.3 Embedded Structures Analyzed as Embedded Structures in the Certified Design

In the certified design, the structures have been modeled and analyzed as embedded structures as shown in Figure 3-3. It is assumed that CSDRS is used as surface motion in the certified design.

For this structure, first the CSDRS-based foundation spectra should be developed. This is the soil column outcrop response (SCOR) at the depth of the foundation in the soil column. The generic design soil profiles used in the certified design of the structure and the input CSDRS should be used in the soil column de-convolution analysis to develop the CSDRS-based foundation motion. The envelope of the CSDRS-based foundation spectra for all the generic soil profiles is computed and used for comparison with the site specific FIRS. De-convolution analysis is repeated to develop the CSDRS-based foundation spectra in the vertical direction.

For the computation of FIRS, the soil column analysis using the full height soil column is performed and the soil column outcrop response (SCOR) at the depth of the foundation is used to develop the FIRS. The vertical motion should be obtained from the applicable V/H ratio.

In this evaluation, both the FIRS and CSDRS-based motion are defined as outcrop motions. The site-specific FIRS is compared with the CSDRS-based foundation spectra to decide if a site-specific SSI analysis is needed or not.

If, in the certified design, CSDRS is used as outcrop motion in the free field at the foundation level of the structure, the CSDRS-based foundation motion is the same as the CSDRS. For this evaluation, CSDRS can be compared with the FIRS computed as outcrop (SCOR) motion for design applicability evaluation.

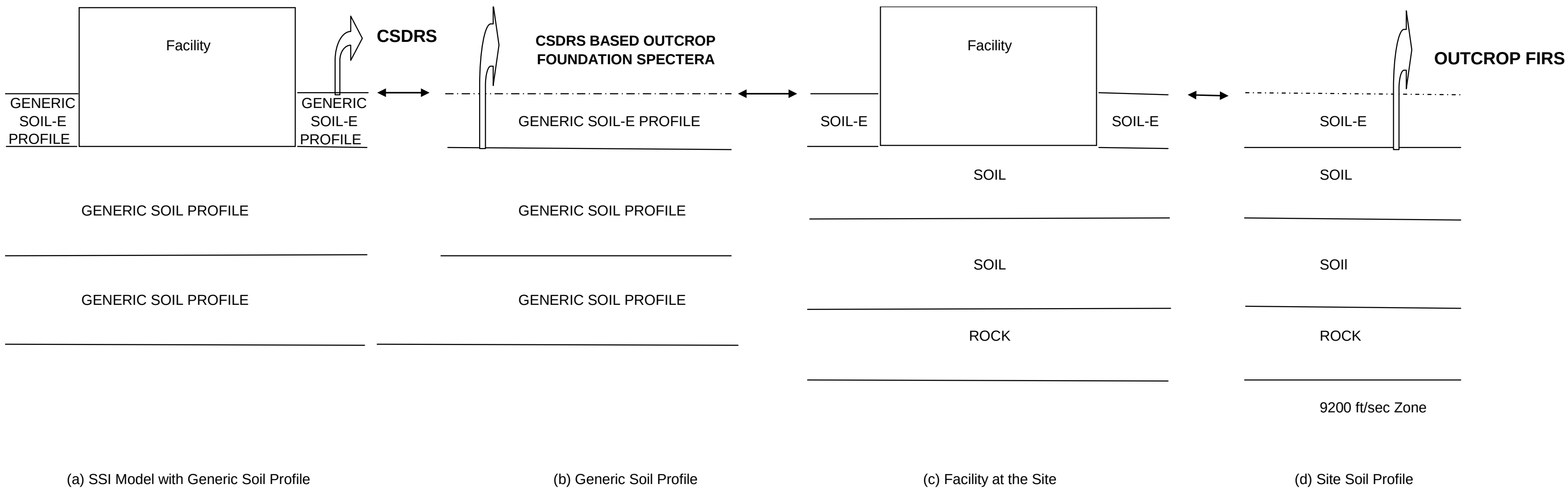


Figure 3-3 Comparison of CSDRS with FIRS for Embedded Structures Analyzed as Embedded Structures in Certified Design

3.2 Using FIRS to Develop Input Motion for Site-Specific SSI Analysis

Once the decision is made to perform site-specific SSI analysis, the SSI input motion and the soil profiles for SSI analysis should be developed. The SSI soil profiles and input motion should be consistent with the soil profiles and the motion used for development of the FIRS.

3.2.1 Site-Specific SSI Analysis of Surface Structures

For surface structures with the foundation essentially at the ground surface, FIRS should be developed using the soil column with its full height, and the soil column surface response (SCSR) will be used to develop the FIRS. Vertical FIRS will be developed using the applicable V/H ratio. In this case, FIRS and PBSRS are the same. The horizontal and vertical FIRS can be used for SSI analysis. This is shown in Figure 3-4. For SSI analysis that requires acceleration time history for input (e.g., SASSI2000), FIRS-compatible acceleration time histories should be developed and used as input following the requirements of the time history generation.

The three soil profiles for SSI analysis are obtained from the set of strain-compatible soil profiles as described in Section 2.4.

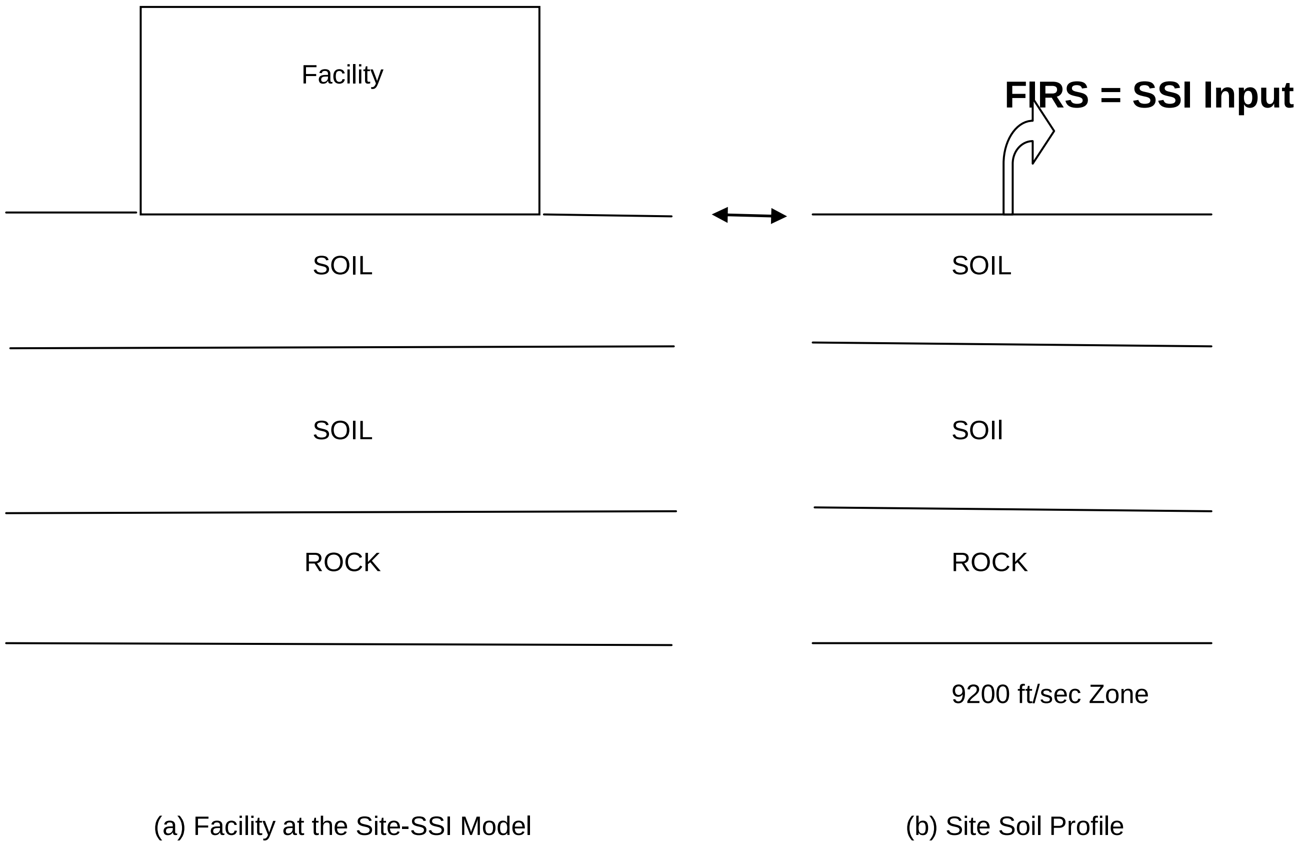


Figure 3-4 Development of FIRS and SSI Input Motion for Analysis of Surface Structures

3.2.2 SSI Analysis of Embedded Structures Modeled as Surface Structures

If the structure has shallow embedment and is modeled as a surface structure, the FIRS should be developed from the truncated soil column surface response (TSCR). As described previously, the soil column analysis is performed using the full soil column in order to obtain the strain-compatible soil properties. The soil columns with the strain-compatible soil properties are truncated by the removing the top layer (layer E in Figure 3-5) and soil amplification is repeated without any further iteration on soil properties. The truncated soil column response is used to develop FIRS. The input motion for SSI analysis is the same as FIRS. The soil columns for SSI analysis are obtained from the set of soil columns used for the generation of the FIRS as described in Section 2.4.

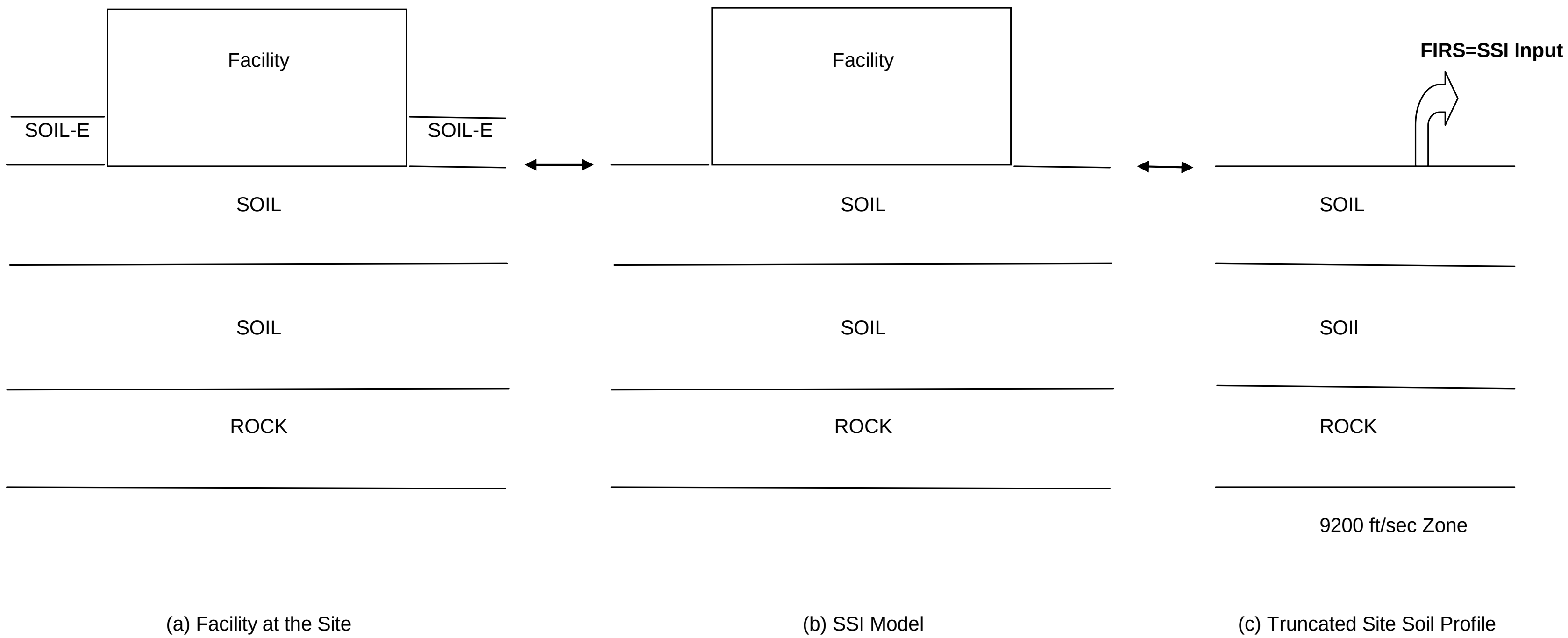


Figure 3-5 Development of FIRS and SSI Input Motion for Analysis of Structures with Shallow Embedment Modeled as Surface Structures

3.2.3 SSI Analysis of Embedded Structures Including Embedment

Development of FIRS and input motion for SSI analysis for embedded structures is a multi-step process as defined below. The model is shown in Figure 3-6. The steps are as follows:

1. Using the soil column (full height), two response spectra are developed. At the ground surface, the soil column surface response (SCSR) is obtained and used to develop the performance-based surface spectra (PBSRS) as defined in Section 2.3. From the same soil column analysis, the FIRS at the foundation depth is obtained using the soil column outcrop response (SCOR) at the foundation depth.

2. From the set of strain-compatible soil profiles obtained from generation of the FIRS, the three soil profiles for SSI analysis are developed using the procedure described in Section 2.4.

3. Using the SSI soil profiles, the outcrop FIRS is used as input at the depth of the foundation level as “outcrop input” motion in the soil column convolution analysis and the three soil column responses are obtained at the surface of the soil column. The envelope of the three response spectra at the ground surface should be compared with the PBSRS developed at the ground surface in Step 1. If the PBSRS is less than the envelope of the three spectra, the outcrop FIRS can be used to develop SSI input motion. Time histories are generated to match the outcrop FIRS following the requirements for the time history generation. The time histories can be used as outcrop input in the three SSI soil columns at the foundation level. For the SSI methods that do not permit outcrop input motion such as SASSI2000, soil column analysis will be performed (using the three SSI soil columns with no further iteration on soil properties) and the outcrop time histories as input to develop the in-column time histories for SSI analysis. Alternatively, the response time histories of the three soil columns at the ground surface can be used for SSI analysis. The surface time histories are fully consistent with the in-column time histories.

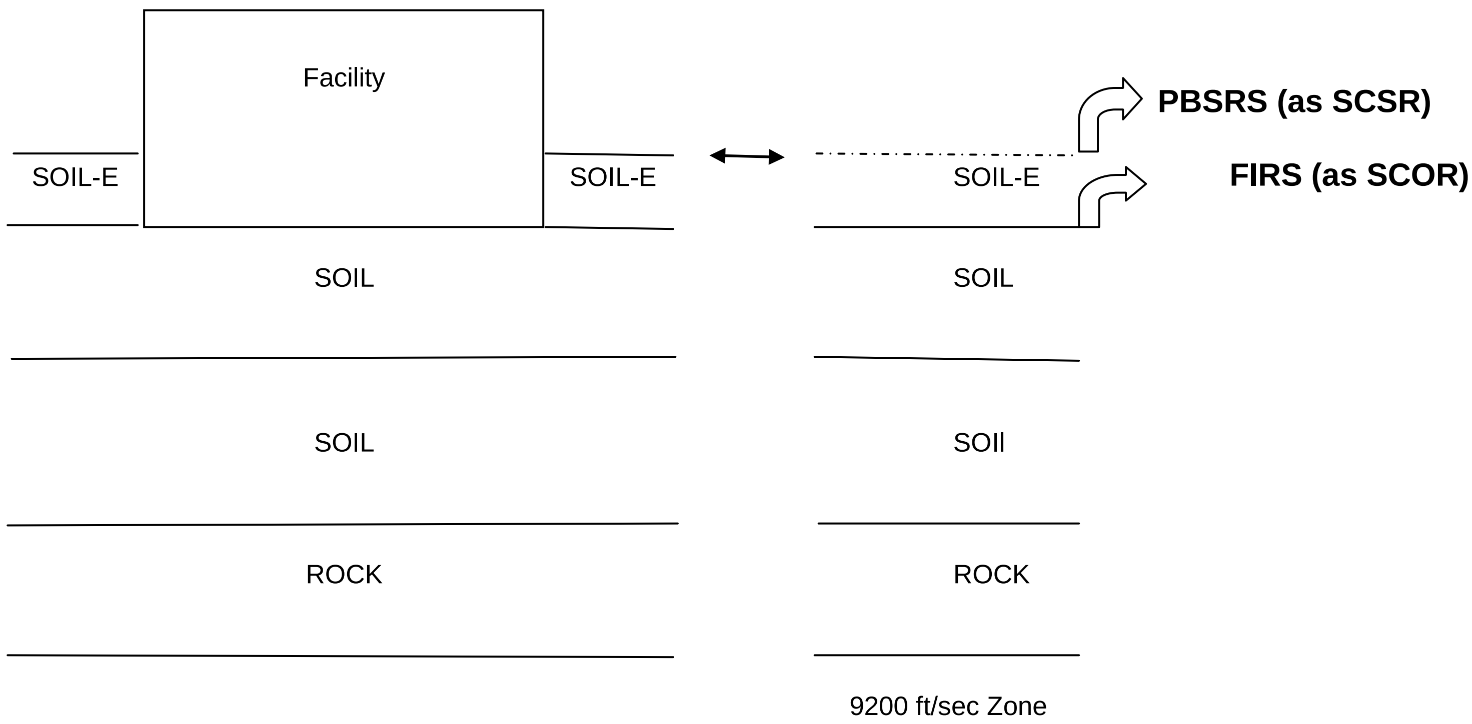
4. The same steps as outlined in Step 3 will be performed for the vertical motion. The envelope of the vertical response of three SSI soil columns at the surface should be compared with the surface vertical PBSRS developed in Step 1. If the surface vertical PBSRS is less than the envelope of three soil column responses, the outcrop FIRS at the foundation horizon can be used to generate time histories for SSI analysis. Similarly, the in-column time histories can be developed from analysis of the three SSI soil columns using the P-wave velocity profiles developed for SSI analysis.

5. If the envelope of the three SSI soil-column responses at the ground surface level, either in the horizontal or the vertical directions, is less than the corresponding

PBSRS at the ground surface computed in Step 1, the SSI input motion must be developed as follows.

- Develop time histories to match the outcrop FIRS from SCOR as discussed above.
- Use the outcrop time histories and the three SSI soil columns to generate the in-column time histories. Modify the in-column time histories for the upper bound, mean, or lower bound soil profiles, or all the in-column time histories so that the resulting surface response from the modified in-column time histories envelops the PBSRS. The modified time histories can be used for SSI analysis as in-column motion with the control point defined as within motion at the foundation level. Alternatively, the surface time histories associated with the in-column time histories of the three soil profiles may be modified and used for SSI analysis with the control point defined at the ground surface for SSI analysis.

  Instead of modifying the time histories, another acceptable approach is to select additional soil columns (in addition to the three soil columns already developed for SSI analysis) from the set of soil columns used to generate the FIRS (as SCOR). For this option and using all the selected soil columns for SSI analysis, it should be demonstrated that envelop of the surface response spectra using the outcrop FIRS (as SCOR) as input motion will exceed the surface PBSRS computed in Step 1. This check needs to be made for both horizontal and vertical motions. Once the check is made, the same set of soil columns must be used for SSI analysis. Development of the in-column time histories for SSI analysis follows the same steps described above.



(a) Facility at the Site-SSI Model (b) Site Soil Profile

Figure 3-6 Development of FIRS and SSI Input Motion for Analysis of Structures with Embedment

3.3 Checking SSI Input Motion for the Minimum Requirement

As described in SRP 3.7.1, the horizontal input motion for SSI analysis should not be less than the suitable broad band spectrum scaled to 0.1g. For all certified designs typically designed to a broad band spectrum scaled to 0.30g, this check is not necessary. For site-specific SSI analysis of Category I structures not covered by the certified design, the minimum requirement must be satisfied. For this evaluation, the FIRS used as the basis to develop the SSI input must be compared with the minimum motion. The FIRS are either the outcrop FIRS (SCOR) or the surface FIRS depending on the SSI analysis as described in Section 3.2. If the FIRS does not envelop the minimum spectra, the envelope of the FIRS and the minimum spectra should be used to develop the SSI input motion. Alternatively SSI analysis should be performed twice using the site-specific FIRS and the minimum spectra separately and enveloping the SSI responses. The three SSI soil profiles obtained from the generation of FIRS can be used for the SSI analysis.

The check for the minimum requirement is only for the horizontal motion. For vertical analysis, appropriate V/H ratios should be used to develop vertical motion.

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