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COUPLED APPROACH TO SSI USING TIME DOMAIN AND FREQUENCY DOMAIN TECHNIQUES – AN EXAMPLE

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***Abstract**: The advances in computer hardware and the software capabilities are ever increasing the domain of physics and engineering simulations. However, the non-linear time domain SSI analyses are still rarely seen outside of research projects as they are expensive, require increased awareness and judgement from the analyst, and are somehow seen as exotic from utilities and regulators. In this paper we present a practical approach for two-stage SSI and SSSI analyses of safety-related structures at sites with complex stratigraphy.*

In the first stage the impedance functions of a rigid massless foundation are obtained using ACS SASSI and are used for sensitivity analysis of the soil-foundation response to establish a representative best estimate soil profile from a suite of candidates. In the second stage a full 3-D model of the soil and the structures including material non-linearity and gapping/sliding is developed in PLAXIS 3D. The analysis is based upon Section 5 of ASCE 4-16 together with supporting information from other sections of this standard. The direct method described in Section 5 of ASCE 4-16 is used for analysing the combined soil-structure system in a single step, without invoking superposition for the structure or the soil separately.

The PLAXIS soil domain properties are calibrated against 1-D site response analysis results and the boundary conditions are simulated using the free field boundary elements. A comparison of the results of the time domain analysis is presented against the output of a full 3-D analysis in the frequency domain using ACS SASSI. It is show that these advanced software's can handle soil non-linearity and gaping and provide results in realistic time frames.

Introduction

Soil-Structure-Interaction (SSI) analysis of nuclear structures is generally performed using frequency-domain codes such as SASSI. These linear analysis codes, when used in accordance with relevant good practice such as the one presented in ASCE 4-16 (ASCE, 2016) and ASCE 43-05 (ASCE, 2005), generally lead to appropriate seismic response calculation for low to moderate amplitude earthquake shaking (Coleman et al. 2015). However, these codes cannot address gapping, sliding and other non-linear effects that may result from intense earthquake shaking that is expected at many sites of nuclear facilities for design basis and beyond design basis shaking. Nonlinear analysis is required to capture these effects and to generate appropriate in-structure response spectra.

This paper presents a comprehensive study of SSI for two buildings subjected to earthquake ground motions in three directions. A comparison of the results of the time domain analysis is presented against the output of a full 3-D analysis in the frequency domain using ACS SASSI. It is shown that these advanced software's can handle soil non-linearity and gaping and provide results in realistic time frames.

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Analysis methodology

The direct method analysis is based upon Section 5 of ASCE 4-16 together with supporting information from other sections of this standard. The direct method described in Section 5 of ASCE 4-16 is used for analysing the combined soil-structure system in a single step, without invoking superposition of structure and soil separately. The direct method will solve the SSI problem in the time domain. Essentially, this analysis can capture nonlinear behaviour during larger earthquakes which could include gapping and sliding and material non-linearity. The framework of the analysis is shown in Figure 1. These key modelling steps are discussed below:

- The structural models are based on the drawings and the structural models adequately represent the distribution of mass and stiffness of the structure and retain the dominant frequencies, related mode shapes, and participation factors.
- Soil properties (strength, stiffness, variation of damping with strain) are derived from the site-specific Geotechnical information. Upper and Lower Bound variations will be performed based on the high-strain shear modulus of soil.
- Each of the soil layers is modelled by using small strain stiffness, damping curve variation with strain, stiffness variation with strain. These properties will be derived by using the information provided in the Geotechnical reports.
- The soil foundation surface will be modelled using interface elements that have zero strength in tension and necessary resistance against frictional behaviour. The choice of the interface element will depend on the gapping expected at the interface.
- Transmitting boundary conditions will be applied at the base and the side boundaries of the SSI model. These boundaries will simulate the behaviour of the infinite soil domain.
- The analysis shall be based upon the UHS (Uniform Hazard Spectra) spectra provided by the Client.
- The three components of ground motions will be applied at the base of the soil domain as rock outcrop motion.
- As required by ASCE4-16, the analysis shall be based upon the use of 5 independent sets of time histories, with the resulting accelerations averaged for providing floor level spectra.

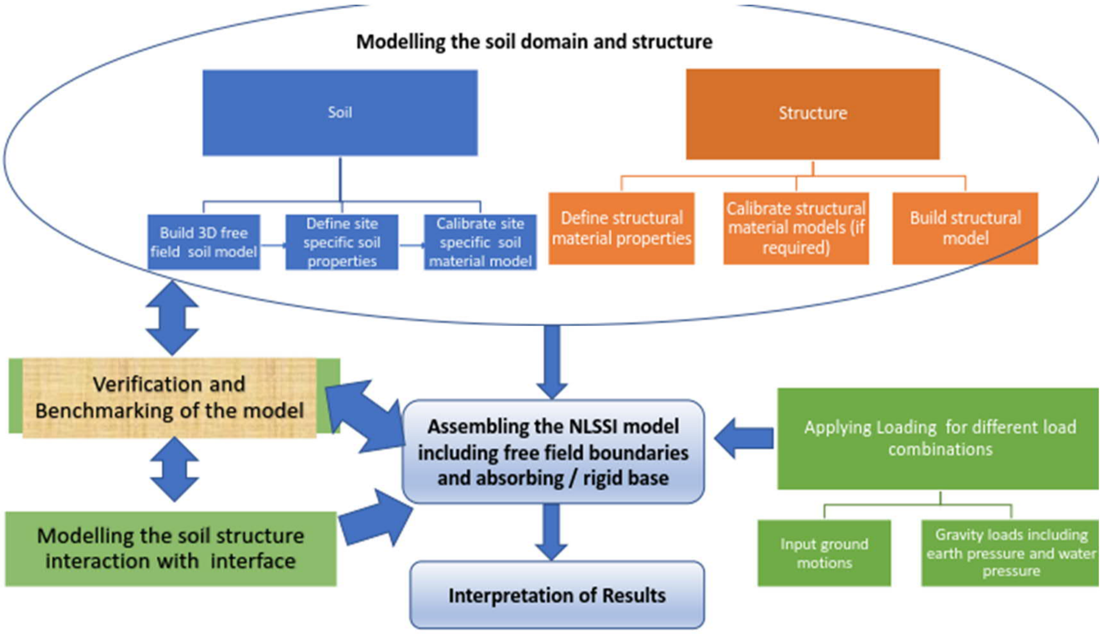

Figure 1. Proposed methodology for SSI analysis

SSI modelling

Structural modelling

Finite element models (FEMs) of two buildings were developed to assess their structural response under design-basis seismic events. The FE models were developed and validated using two software codes – SAP2000 and PLAXIS 3D. SAP2000 is a widely used 3D finite element software for static and dynamic analysis of structures. PLAXIS 3D is a finite element package for three-dimensional deformation and stability analysis in geotechnical engineering.

The first building is a two-storey building with a plan dimension 86.25m by 81.05m along East-West and North-South directions, respectively. The building is supported by a raft foundation which is 1400 mm thick. The second building is an E-shaped 3-storey reinforced concrete framed structure which is 80.20 m long by 49.15 m wide along North-South and East-West sides, respectively. The approach for modelling various structural elements of buildings in PLAXIS 3D and SAP2000 is shown in Table 1.

Component	**PLAXIS 3D**	**SAP2000**
Walls, floors and roofs	6-noded Triangular PLATE element	3/4-noded SHELL element
Deep roof beams	6-noded Triangular PLATE element	3/4-noded SHELL element
Columns	3-noded BEAM element	2-noded FRAME elements
Soil below foundation slabs	10-noded tetrahedral VOLUME element (with pore fluid degree of freedom)	Fixed base conditions

Table 1. Modelling of Elements for Buildings 1 and 2

Free vibration analyses were performed for both models in PLAXIS 3D assuming fixed base, to check their natural frequency against modal analyses of the SAP2000 models. At this stage, the two buildings were kept in two separate PLAXIS models to simplify the process of geometry modelling, assignment of section properties, loads and mesh generation. Comparison of fundamental horizontal frequencies between SAP2000 and PLAXIS 3D structural models for fixed base condition is shown in Table 2.

PLAXIS 3D performs the free vibration analysis via direct integration in time-domain whereas SAP2000 performs undamped modal analysis in the frequency domain. In the time-domain, closely-spaced response modes are lumped together compared to a frequency-domain solution. The natural frequencies of the structures in PLAXIS 3D is interpreted from the power spectral density of the displacement time histories. Reasonable agreement is observed in the predicted natural frequencies for both buildings given the different analysis techniques. In the full 3D SSSI model 4% structural damping was used as suggested in ASCE4-16 as qualification input for subsystem is required.

Software	**Building 1**	**Building 2**
SAP2000	7.49Hz	5.02Hz
PLAXIS 3D	7.92Hz	5.93Hz

Table 2. Comparison of fundamental frequencies between SAP2000 and PLAXIS 3D

Available Geotechnical Information

The encountered stratigraphy at the site is summarised as:

- Made ground was encountered from ground level to between 0.8m and 1.4mBGL (below ground level).
- Silchester gravels were extend from the base of the Made ground to between 4.3 and 5.4mBGL. It generally comprises sandy, clayey gravel although some flint cobbles were identified.
- Bagshot Beds are underlying the Silchester Gravel to between 5.5m and 10.7mBGL.
- The gradational boundary between the Bagshot Beds and the London Clay is termed the “Transitional Zone”.
- London Clay is consistently present across the site and below the Transitional Zone and is generally a stiff clay, becoming very stiff with depth, containing sand and gravel horizons (hard bands) and infrequent organic pockets and shelly fragments.

- The thickness of the London Clay has been inferred at ~83m.
- Beneath the London Clay there is an 8m thick layer of Lambeth Group.
- The bedrock consists of chalk and is assumed to start at depth around 105m.

The general site stratigraphy and basic soil parameters is shown in Table 3.

Soil layer	**Top elevation (mAOD)**	**Top depth (m)**	**Unit weight (kN/m^3)**	**Plasticity Index PI (%)**
Silchester gravels	103.5	0	20.5	
Bagshot Beds	99.6	3.9	20.5	25
Transition Zone	95.0	8.5	20.0	20
London Clay	90.0	13.5	20.5	25
Lambeth Group	8.0	95.5	21.0	25
Chalk	-2.0	105.5	21.0	-

Table 3. Adopted soil stratigraphy and parameters

Site profiles

Due to the variability of the ground conditions and lack of site-specific information four proposed site profiles were developed:

- P1 – Having transition zones without hard bands/sand layers
- P2 – Having Transition Zone with presence of hard bands/sand layers
- P3 – No transition zone and no hard bands/sand layers
- P4 – No Transition Zone with presence of hard bands/sand layers.

The assumed distributions of the small-strain shear wave velocity are shown in Figure 2.

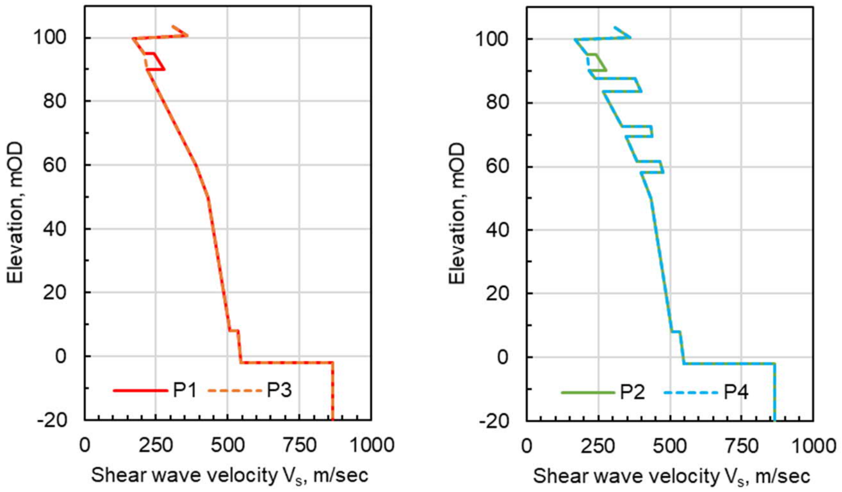

Figure 2. Shear wave velocity distribution at the four proposed sites

Selection of representative Site Profile

Appropriate selection of representative site profiles is the cornerstone for any SSI analysis of safety-related nuclear structures or other critical infrastructure. For the case described in the current paper the process was not straightforward as there was insufficient knowledge of the site stratigraphy and dynamic soil properties were inferred from two adjacent sites. These two sites are generally very similar, but differences in the soil strata, especially changes in stiffness, were expected to influence the results from the SSI analysis.

A sensitivity study was performed to: 1) support the selection of a representative best estimate (BE) site profile for the full 3D SSSI (structure-soil-structure interaction) model of the two buildings, 2) to demonstrate the limited influence of the differences on the soil-structure response, and 3) to justify an appropriate depth of the lower bound of the explicitly modelled soil allowing for correct modelling of wave propagation and minimum size of the full 3D PLAXIS model.

A series of analytical foundation impedance functions for the larger Building 1 was developed using ACS SASSI assuming the different soil profiles P1 to P4. The frequency-dependent foundation impedance functions were then used as boundary conditions for frequency-domain analysis of a rigid superstructure having the mass property of Building 1 using SAP2000. The results show that the differences in the assumptions for the soil profiles have small effect on the response foundation response and cost-efficient approach using a single representative profile could be implemented.

The frequency-dependent foundation impedance functions (FIFs) were calculated by integrating the soil impedance functions for each interaction node for rigid translations and rotations of the foundation. Figure 3 shows the real part (stiffness) of the calculated FIFs for horizontal translation and rocking. Although for all four suggested profiles the static stiffness is similar, the FIFs are deviating significantly above ~4Hz.

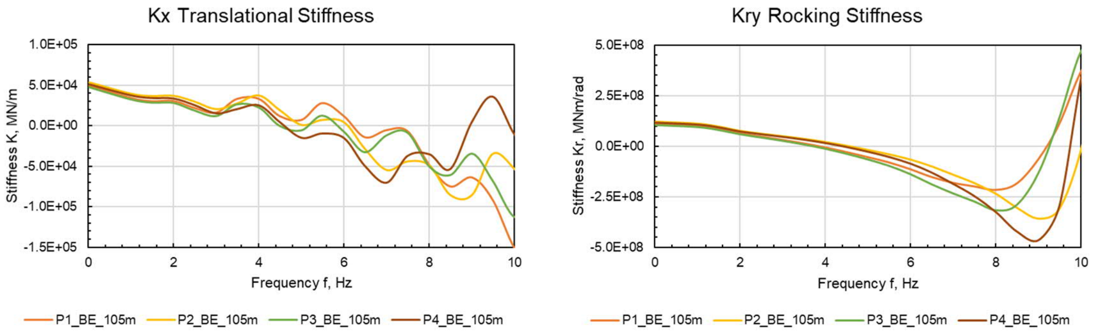

Figure 3. P1 to P4 comparison - Translational stiffness (left) and Rocking stiffness (right)

Figure 4 shows results from the sensitivity analysis, performed in SAP2000. The amplitude displacements due to soil response only (rigid superstructure) for the four proposed site profiles are shown on the left. Despite the significant difference in the shape and values of the calculated FIFs, the effect on the response due to soil compliance is less pronounced. Profile P1 was selected as representative for the site based on the geotechnical considerations and the demonstrated response: it produces response slightly higher than the median of the four profiles.

Based on the comparison of amplitude response for site profiles with different depths, the lower bound of the full 3D PLAXIS model was established as the bottom of the London Clay strata at -95.5mBGL, slightly more than one foundation length of Building 1. The depth of the full soil model is much smaller than the recommended in ASCE 4-16 (~170m) and allows for efficient model size and computational time.

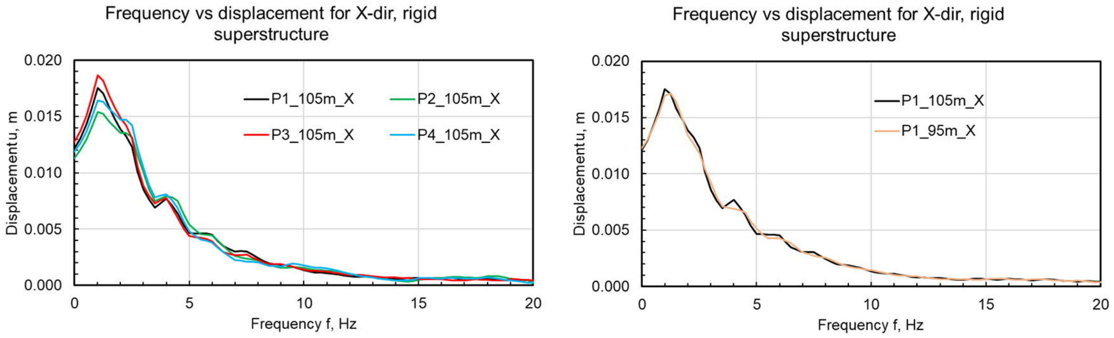

Figure 4. Sensitivity study results – comparison of different site profiles (left) and different profile depths (right)

Combined model for SSSI analysis

The FE models developed for the two buildings were combined with the soil model for the preferred profile P1 (Figure 5) into a fully coupled SSSI model. For the 3D SSI of buildings 1 and 2 in a combined FE model, it is assumed that the ground floor of buildings are at the same elevation. After the modal verification both the structural models were imported into a single PLAXIS file. The lateral gap between the West wall of building 1 and East wall of building 2 is about 3.3m.

The soil was modelled below the foundation level of buildings without considering any embedment of either building. The mesh density was kept very fine below the footprint of the buildings and around the corners of the soil model. To optimise the number of soil solid elements and run time, non-reflecting boundary conditions ("compliant base" BC for the bottom of the model and "free-field" BC) were modelled in PLAXIS 3D. They allowed the lateral boundaries to be modelled 90m (one foundation length) away from the nearest (parallel) edge of the buildings.

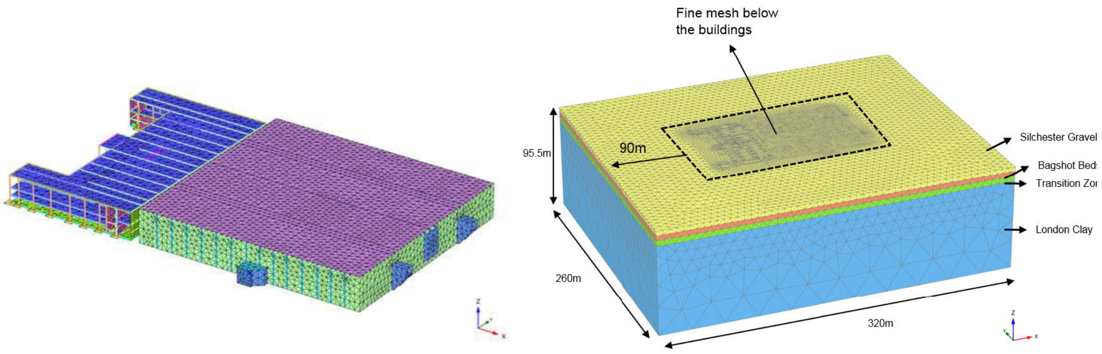

Figure 5. PLAXIS 3D model for the Combined SSSI

Hardening soil small (HS$_{\text{small}}$) strain soil model

The PLAXIS "HSs$_{\text{mall}}$", is a well-regarded effective-stress based soil model for modelling the decay of stiffness with increasing strain in the soil skeleton, based on the Hardin-Drnevich relationship. The HS$_{\text{smal}}$l model is suitable for 3D cyclic dynamic analyses, as the soil model tracks for strain reversals in three principal deviatoric strains directions, like Simpson's brick model. The HSsmall model also considers the stress-dependency of soil stiffness as power-law function so it allows for effective modelling of the gradual increase of stiffness in deep soil deposits, such as the London Clay at the site in question.

An example of stiffness degradation curve for London Clay modelled with HS$_{\text{small}}$ is shown in Figure 6. The "dashed" line is the Darendeli & Stokoe (2001) curve for calculated using the effective confining stress and the PI% of the clay that is used as reference. The "solid line" is the HSsmall stiffness degradation curve calibrated in PLAXIS 3D. All the modulus degradation curves and damping curves for different soil layers were calibrated in this manner for the 3D analysis.

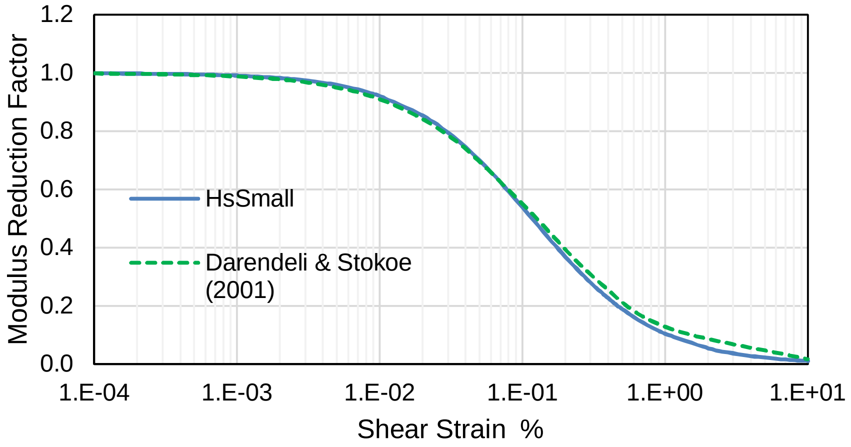

Figure 6. Example of Modulus reduction curves for London Clay – HSsmall calibrated against the Darendeli & Stokoe median curve

Validation

A careful process of calibration and validation was performed in transferring the information from the 1D PLAXIS model to the 3D PLAXIS model. Briefly, this included the following:

- Benchmarking of fixed base structural model developed using SAP 2000 with the SSI model to check for fundamental frequency and expected seismic path;
- Calibration of soil models based on geo-seismic data.;
- Verification of soil domain model. This was performed by matching the response of free field model without the structure with equivalent linear site response codes (DEEPSOIL) at low levels of ground input motion;
- Validating the free field response of PLAXIS 3D Combined SSSI model;
- Calibration of structural models. Significant non-linear response of the structures was not expected, so linear elastic structural modal was used.

The free-field site response of a soil column modelled in PLAXIS was validated against spectra obtained at the soil surface (assumed at foundation depth) from site response analysis in DEEPSOIL. All 15 (10 horizontal and 5 vertical) input motions were analysed in PLAXIS and average surface spectra were obtained for both horizontal and vertical directions.

Figure 7 shows the comparison of average of surface spectra between DEEPSOIL and PLAXIS soil column analyses for soil profile P1 with best estimate ground parameters. Reasonable match is obtained between the different constitutive models in DEEPSOIL (Darendeli & Stokoe equivalent elastic) and PLAXIS 3D (HS_{small}) for horizontal ground motions.

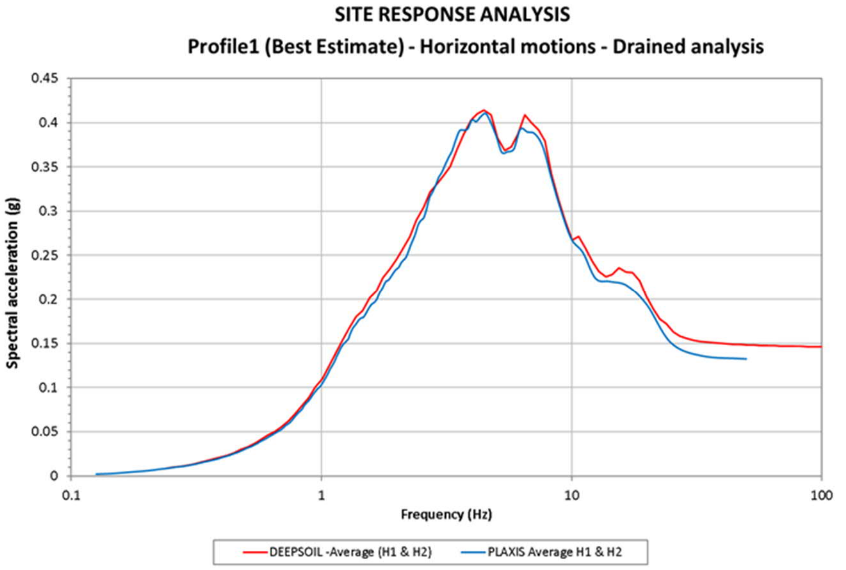

Figure 7. Comparison of surface spectra from DEEPSOIL and PLAXIS soil column

Baseline Analysis Results

A total of 30 baseline analyses were performed for the Combined SSSI model for three ground stiffness profiles (best estimate BE, lower bound LB, and upper bound UB) and five sets of input ground motions. For each combination of soil stiffness and ground motion set two analyses were run – one in horizontal (motions in X and y directions), and one in vertical direction. The groundwater table for the baseline analyses was considered at the bottom of Silchester Gravels. Some of the key results are presented below.

Figure 8 plots results for a single output point, at the corner of Floor 1 slab in Building 1. On the left are the 5% damped SRS from 5 input motions with the averaged SRS plotted with solid black line. On the right is a plot of the normalized standard error (the standard error of the mean divided by the mean) for the SRS at the same location in Building 1. As the NSE is less than 8% along the frequency range of interest, it was judged that averaging the minimum number of ground motions recommended in ASCE4-16 (five sets) is appropriate.

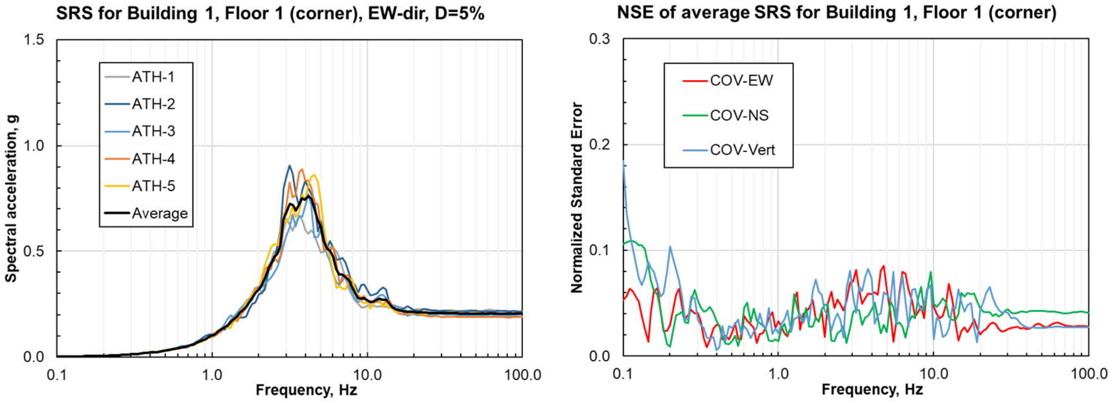

Figure 8. Response of single output point: SRS from five input motions (left), NSE of the average SRS along the frequency range

To facilitate the qualification of equipment the response output from multiple points was enveloped for representative locations in the two buildings, eg Ground floor (GF), Floor 1 (F1), Roof (RF). Enveloped SRS for BE soil conditions and 5% damping for Floor 1 of Building 1 are plotted in Figure 9. On the left are the three SRS for F1 in EW, NS and Vertical directions and on the right are the SRS in EW directions along the building height. The soil-structure response in the horizontal direction is dominated by the soil with very similar peak spectral accelerations and frequency content of the EW and NS spectra. The increase of horizontal response along the building height is rather small, because in the fundamental horizontal the building is moving as a rigid body. In the vertical direction there is significant increase of the response compared to the input. This was understood as an effect of a combination of few factors: 1) dominating structural response (with lower damping values); 2) reduced radiation damping in the soil due to impedance contrast; 3) matching of fundamental vertical frequencies of the floors with the peak frequency of the input vertical response spectra. From the analysis results it was judged that SSSI between the two buildings and the ground is limited, but however increases the torsional response of the irregular Building 2.

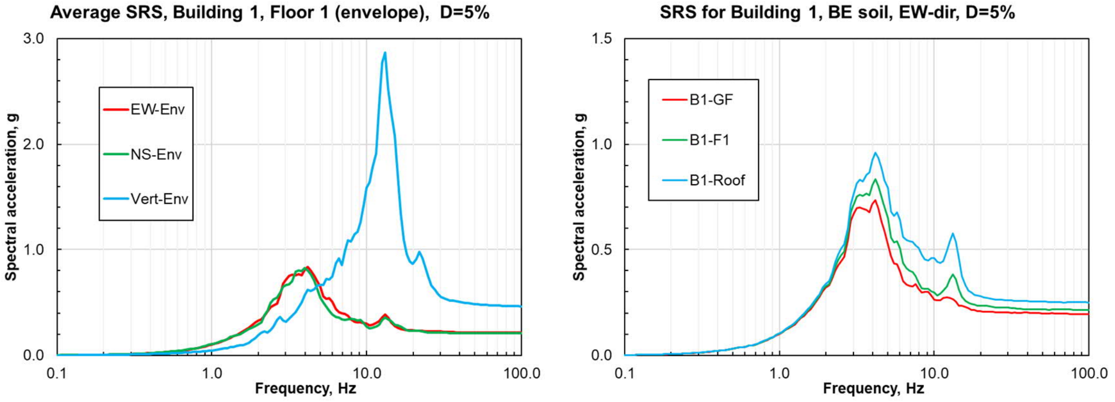

Figure 9. Envelope response for Building 1, BE soils: SRS for three directions at F1 (left), development of horizontal SRS along the building height (right)

As the calculated SRS were required for equipment qualification, the ASCE4-16 procedure for developing “design SRS” was applied. The enveloped SRS for multiple output points for BE, LB and UB soils were smoothed, and the narrow band peaks were clipped by 15%. After the clipping the SRS for the three soil conditions were broadened (±15% for BE soil, +15% for LB soil, and -15% for UB soil) and then enveloped to produce the design SRS. Enveloped SRS for 5% damping for the three soil conditions and design SRS for Floor 1 of Building 1 are shown in Figure 10. As expected the upper bound soil conditions produce the highest peak spectral accelerations as for this case the peak response frequencies are closer to the peak frequencies of the seismic input and the total damping of the soil-structure system is reduced.

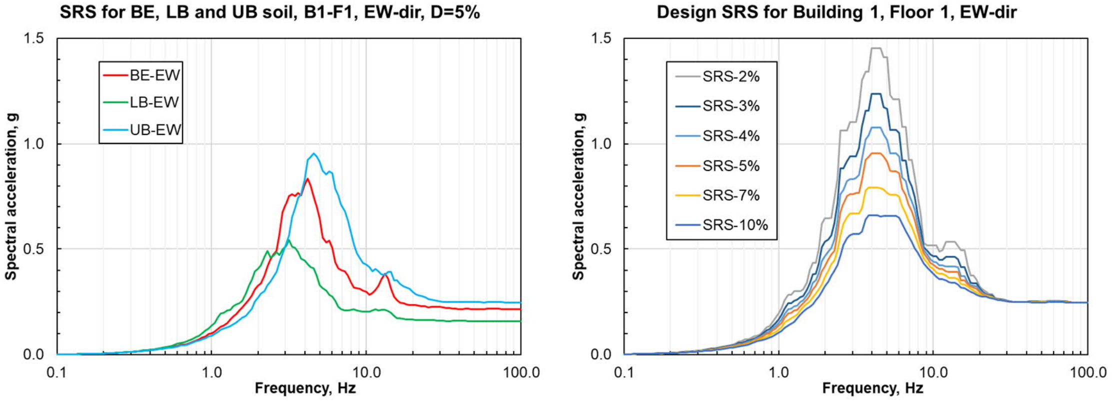

Figure 10. Envelope response for Building 1, UB, BE and LB soils: SRS for BE, LB and UB at F1 (left) in EW direction, development of horizontal SRS for different damping level.

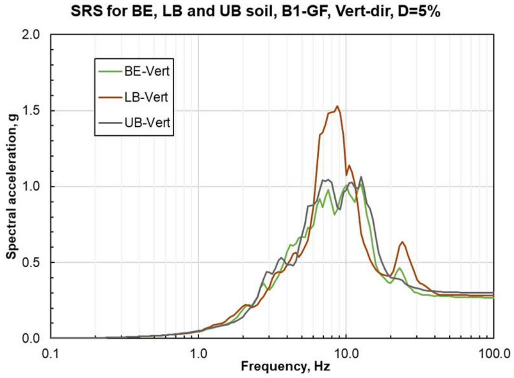

Figure 11. SRS response for Building 1, BE soil, Vertical direction

Figure 11 show contours of vertical acceleration in the ground slab of Building 1 for LB, BE and UB soil stiffness profiles. Groundwater table for all these analyses is at the bottom of Silchester Gravels. The impedance (based on compression wave velocity) between the unsaturated Silchester Gravels and saturated soil below it increases as the soil stiffness decreases. When the impedance increases, compression waves travelling downwards tend to be reflected more into the Silchester Gravels layer. It could be observed that due to the combined effect of softer stiffness (flexible soil below foundation) and higher impedance (wave propagation effects), ground slab of Building 1 might experience higher spectral accelerations with LB soil stiffness than in BE and UB soil stiffness profiles. As the soil stiffness increases and wave reflection effect decreases, the spectra for ground slab for BE and UB reduces and tend to be quite similar.

The soil and soil-structure interface modelling assumptions such as linear elastic vs inelastic soil, fixed vs sliding interface may influence noticeably the SSI analysis results (Bolisetti, 2014). To check the influence of sophisticated soil and interface modelling versus traditional modelling approaches, the response of Building 1 from the full 3D model was compared to the response from standalone SSI analysis in ACS SASSI. In the ACS SASSI analysis, the soil is modelled as linear elastic with strain-compatible properties taken from the DEEPSOIL site response analysis. The basemat is welded to the soil, as the ACS SASSI linear approach does not allow for sliding and gapping. A comparison of SRS for the corner of Floor 1 (Building 1) for BE soil conditions for one of the input motion sets is shown in Figure 12. The results from the two analysis are very similar with PLAXIS producing slightly higher peak spectral accelerations. Due to relatively low input ground motion intensity (horizontal PGA~0.15g) the non-linearities in the soil and the soil-structure interface do not have significant combined effects and are assumed to neutralise each other.

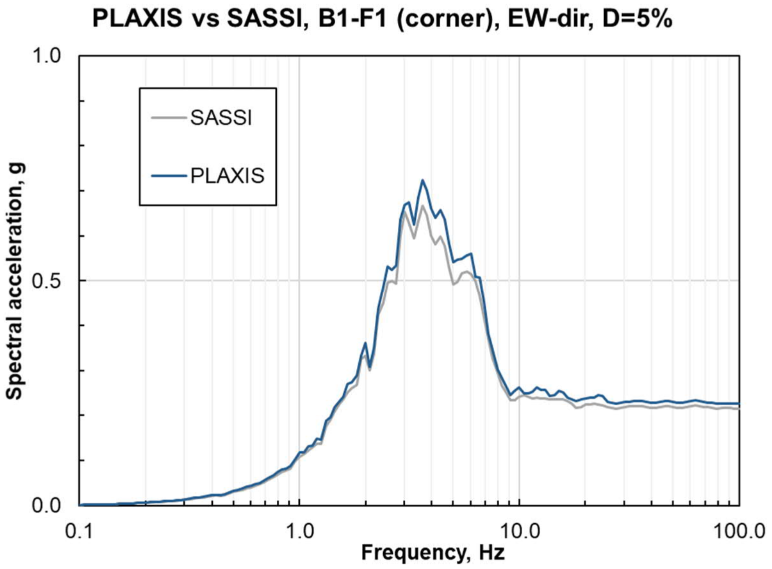

Figure 12. Comparison of response for Building B1(corner) for SASSI and PLAXIS

Conclusions

A sophisticated SSSI analysis was performed on two large buildings located on a site with complex stratigraphy and stiffness variation with depth. Representative Best estimated site profile was selected from four proposed profiles based on geotechnical and soil-structure response considerations. Site response analyses (deconvolutions and convolutions) were used to establish the appropriate site-specific seismic input from Uniform hazard spectra developed for generic site conditions. The response of the structural and soil models in PLAXIS 3D were independently validated against simpler SAP2000 and DEEPSOIL models. The results of the full coupled 3D SSSI PLAXIS analysis were compared and verified against standalone SSI analysis of Building 1 performed in ACS SASSI.

The results of the performed SSSI analysis show dominant influence of the relatively soft site profile on the horizontal soil-structure response: significant period elongation, reduction of the peak spectral accelerations and almost rigid body movement of the building. The vertical response, especially the mid-floor vibrations is dominated by the structure and amplified due to matching of vertical floor frequencies with the peak region of the input response spectra.

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