

EQUIPMENT-STRUCTURE INTERACTION OF HEAVY EQUIPMENT ON CONTAINMENT INTERNAL STRUCTURE

Andrew C. Appelbaum¹, Vamshi Krishna Gudipati², Cameron B. Sanford³, Frederic F. Grant⁴, Benny J. Ratnagar⁵

¹ Consulting Engineer, Simpson Gumpertz & Heger Inc., Newport Beach, CA, USA (acappelbaum@sgh.com)

² Consulting Engineer, Simpson Gumpertz & Heger Inc., Newport Beach, CA, USA (vgudipati@sgh.com)

³ Senior Consulting Engineer, Simpson Gumpertz & Heger Inc., Newport Beach, CA, USA (cbsanford@sgh.com)

⁴ Principal, Simpson Gumpertz & Heger Inc., Newport Beach, CA, USA (ffgrant@sgh.com)

⁵ Principal Engineer, Southern Nuclear, Birmingham, AL, USA (bjratnag@southernco.com)

ABSTRACT

Historically, practitioners have commonly neglected the dynamic interaction between a primary (structure) and secondary (equipment) system when evaluating the seismic demands on equipment and other subcomponents attached to a structure. However, this dynamic coupling is increasingly recognized as an important consideration in seismic response and fragility analysis of some components and has generally become referred to as equipment-structure interaction (ESI). Potential significance of ESI can be assessed by comparing the equipment mass and frequency to the mass and frequency of the structural mode dominating in-structure motion at the point of equipment attachment to the structure. The significance of ESI increases as equipment-to-structure frequency ratios approach unity and for increasing equipment-to-structure mass ratios.

A case study is presented from a recent seismic fragility analysis where ESI was found to be significant. The subject component is an approximately 310-kN air cooling unit (ACU) located at the top of steel framing inside a containment building. The original in-structure response spectra (ISRS) at the ACU location, which neglect ESI, exhibit sharply amplified peak horizontal response coinciding with the ACU fundamental horizontal frequency, resulting in high seismic demands on the ACU. The original ISRS were computed using a detailed three-dimensional finite element model of the containment structure and accounted for soil-structure interaction (SSI). The ISRS were generated treating the dynamic response of the ACU as decoupled from the structure seismic response and no ACU mass was included in the structure model.

Electric Power Research Institute (EPRI) 3002010666 (2017) provides a simplified approach for estimating the effects of ESI based on the results of a parametric study of coupled dynamic systems. The EPRI parametric study accounted for uncertainty in the system parameters and calculated generic response reduction as median factors and associated logarithmic standard deviations suitable for application to fragility analysis. The study assumed perfect tuning between the structure mode and equipment frequency (i.e., frequency ratio of unity) and aligned them at the peak spectral acceleration of the seismic input motion. EPRI 3002010666 presents reduction factors as a function of equipment-to-structure mass and damping ratios. The perfect tuning assumption means these reduction factors should be applied to ISRS peaks.

EPRI 3002010666 (2017) results suggest that the median ACU ISRS can be reduced by over 50% to account for ESI. Dynamic properties of the ACU and containment internal structure were reviewed for consistency with the EPRI 3002010666 studies. Most parameters are consistent, but differences were identified in the ground motion and structure modal characteristics. Therefore, a study was performed to confirm the reasonableness of the EPRI generic factor. This confirmatory study used response spectrum analysis to roughly estimate the response reduction due to ESI that should be expected and found it to be reasonably consistent with the peak reduction factor determined from EPRI 3002010666.

For certain equipment-structure systems, this response spectrum analysis approach may be an effective tool for efficiently determining ESI effects. Further development should investigate how this approach may be appropriately extended to calculate median ESI ISRS reduction factors and associated logarithmic standard deviations.

EQUIPMENT STRUCTURE INTERACTION BACKGROUND

As explained in Section 6.4.3.2 of EPRI 3002012994 (2018), response spectra developed for seismic fragility analysis of equipment at nuclear power plants are typically calculated using a series of zero-mass single-degree-of-freedom (SDOF) oscillators at specific frequencies. This approximation is appropriate for equipment that has essentially zero mass relative to the modal mass of the structural mode that dominates the in-structure response at the equipment's mounting location. When the equipment-to-structure modal mass ratio is about 5% or greater, coupling effects can significantly reduce the spectral acceleration input to the equipment. Coupling effects and seismic demand reduction typically become more significant as the ratio of the equipment frequency to the structural mode frequency approaches unity.

Several methods to account for ESI have been developed. Lim and Chouw (2015) and Appelbaum et al. (2017) summarize some available approaches to quantifying ESI. In general, current approaches to ESI are resource-intensive, and, as a result, their application is generally reserved for situations where simplified analysis approaches are insufficient to demonstrate compliance with seismic performance objectives. Some of the approaches require extensive, specialized calculations that are not easily implemented. A more straightforward approach, which Lim and Chouw (2015) refer to as the "combined system modelling" method is to explicitly include a representation of the equipment in the structural model used for the seismic response analysis. Although conceptually simple, this approach may become impractical in applications where many seismic fragilities are developed as part of a seismic probabilistic risk assessment (SPRA). To quantify variability in the ESI analysis, the analyst might have to repeat the seismic response analysis multiple times, which becomes especially impractical when response analysis includes SSI.

To simplify application of ESI in SPRAs, EPRI 3002010666 (2017) developed generic response reduction factors that, while not universally applicable, are useful across a broad range of ESI scenarios.

CASE STUDY INTRODUCTION

Simpson Gumpertz & Heger Inc. (SGH) performed seismic fragility analysis of an ACU located within a containment building (CNTM) using the Separation of Variables approach described in EPRI 3002012994 (2018). The ACU is composed of an approximately 3.9 m by 3.9 m by 5.1 m (155 in. by 155 in. by 200 in. tall), steel-framed box structure that integrates several cooling coils and a top-mounted fan. The ACU weighs approximately 310 kN (70 kips), and it is mounted on top of a concentrically braced, steel-framed platform at the top of the containment internal structure. Steel bolts anchor the base of the ACU directly to the platform's steel beams.

Due to its relatively high centre of mass and tall aspect ratio, the ACU seismic capacity is governed by tensile demands on the anchorage from overturning induced by lateral seismic demands. The horizontal ISRS at the ACU location are shown in Figure 1. These ISRS were computed by others from seismic response analyses that accounted for soil-structure interaction (SSI). The SSI analyses incorporated a finite element model that explicitly models the CNTM steel framing but does not model the ACU structural properties (i.e., neither ACU mass nor stiffness were modelled). Therefore, the SSI model and resulting ISRS do not account for dynamic interaction between the ACU and steel platform: the seismic response analysis neglected ESI.

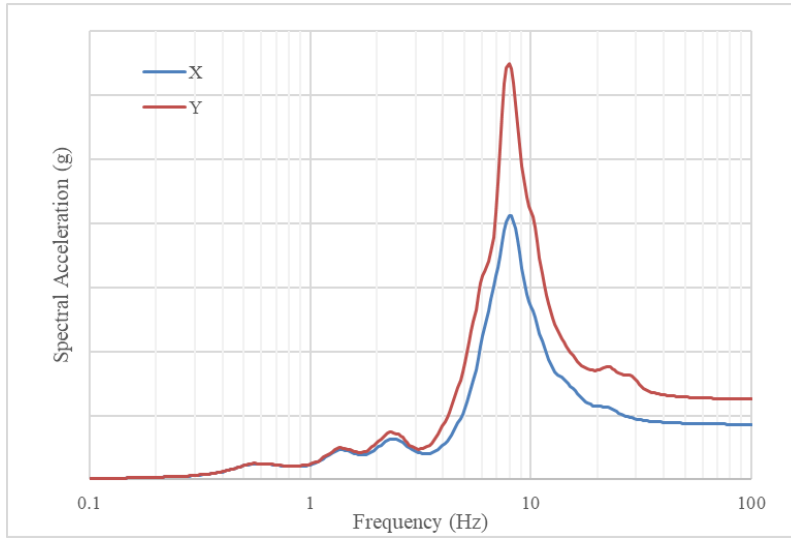


Figure 1. Horizontal ISRS Demands at the ACU Location (Neglecting ESI)

A seismic qualification report for the ACU identified a fundamental horizontal frequency of approximately 7.6 Hz, which nearly aligns with the peak frequency of the Y-direction ISRS. The CNTM structural model modal analysis indicates a mode at 7.7 Hz characterized by localized ACU platform response that drives the governing horizontal direction ISRS peak. The mode shape for this locally dominant structural mode is shown in Figure 2.

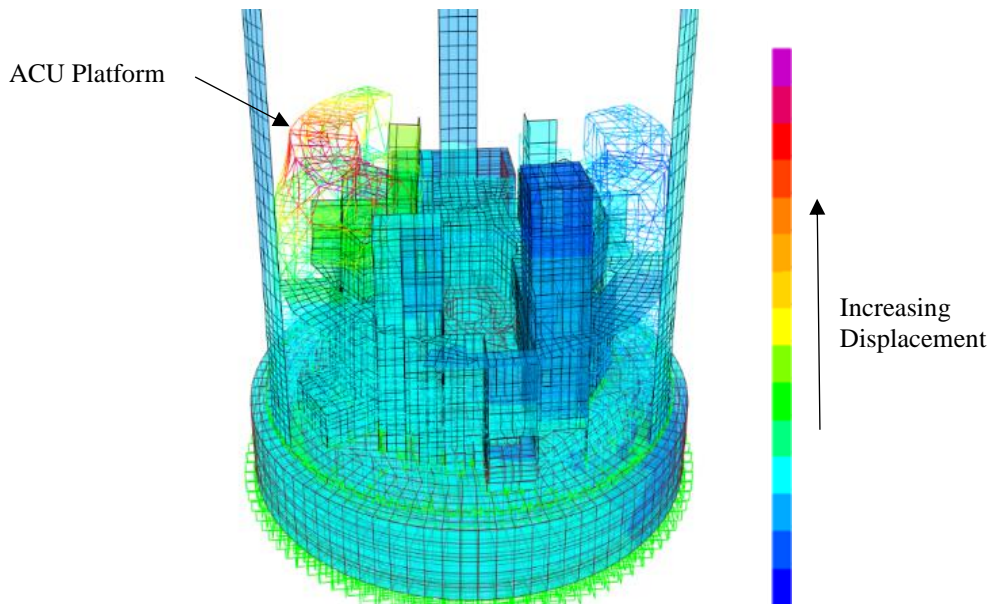


Figure 2. ACU Support Platform Local Mode Displaced Shape.
(Contours indicate Y-direction displacement)

Based on the heavy ACU weight relative to the steel platform and the alignment of the ACU natural frequency with the steel platform local mode frequency, we identified that ESI could be important. We refined the ACU fragility to account for ESI using the median ESI response reduction factors and associated logarithmic standard deviations developed in EPRI 3002010666 (2017).

APPLICATION OF EPRI GENERIC RESPONSE REDUCTION FACTORS FOR ESI

EPRI 3002010666 (2017) provides a simplified approach for estimating the effects of ESI. Generic values of ISRS reduction factors are developed therein based on a statistical analysis of the dynamic response of representative, 5-degree of freedom (5-DOF) structural systems. Guidance on seismic fragility analysis in EPRI 3002012994 (2018) considers these reduction factors to be conservative for more complex systems, but they are only applicable to coupled equipment-structure systems meeting a specific range of criteria. That is, the equipment-structure system should be verified to fall within the parameter envelope considered in EPRI 3002010666.

The EPRI 3002010666 (2017) ISRS reduction factors are based on parametric study results for simplified equipment-structure systems. The parametric study investigated the equipment damping ratio and equipment-to-floor mass ratio as the primary independent variables. For each combination of damping ratio and mass ratio, EPRI developed a median reduction factor and associated logarithmic standard deviation by Monte Carlo simulation, accounting for uncertainty in equipment-to-structure frequency ratio, equipment-to-floor mass ratio, and equipment damping. For the ACU damping ratio of 5% and equipment-to-floor mass ratio of 15%, Table 4-17 of EPRI 3002010666 (2017) yields a median ISRS peak reduction factor of 0.435 with an associated logarithmic standard deviation of 0.08.

For the ACU fragility refinement, we reviewed several parameters of the ACU and CNTM to establish whether the generic EPRI ESI reduction factors are applicable to the ACUs. The ACU parameters listed in Table 1 fell within the parameter envelope of the EPRI study. The two subsequent subsections describe characteristics of the present case study that did not obviously align with the EPRI parametric study.

Table 1: Comparison of ACU Parameters with EPRI Study Envelope

Parameter description	EPRI 3002010666 Parameter Envelope	ACU
Equipment -to-floor mass ratio	5% - 25%	15%
Equipment damping	2% - 7%	5%
Structure damping	5%	5%
Equipment-to-structure frequency ratio	1.0	0.99
Response analysis model	Decoupled, no equipment mass included in model	Decoupled, no ACU mass included in model

Ground Motion Characteristics

EPRI 3002010666 (2017) conducted seismic response analyses of coupled ESI systems using six different single-component ground motion time histories as seismic input. Of the six ground motions, five were classified “high frequency” (HF), with amplified response above about 20 Hz, and peak response in the range of 30 Hz to 60 Hz, depending on the specific ground motion. The sixth ground motion was classified as “low frequency” (LF), with amplified response below about 10 Hz, and peaks at about 2 Hz and 4 Hz. EPRI 3002010666 (2017) developed the generic ESI response reduction factors from the HF motion results, and did not consider the LF motion results.

In the present case study, the uniform hazard response spectrum (UHRS) has an amplified response between approximately 6 Hz and 20 Hz, and peak response at approximately 10 Hz. This spectral shape does not clearly align with either the HF or LF ground motion classifications considered in the EPRI parametric study. Furthermore, the 5-DOF structure and SDOF equipment models in the EPRI 3002010666 (2017) parametric study were tuned to the frequency at the spectral acceleration peak of the input ground

motions. The shared ACU and platform frequency is in the amplified region of the UHRS, but they are not perfectly tuned to the peak ground motion spectral acceleration, as was the case for the systems in the EPRI parametric study.

Considering that the EPRI study found greater response reductions in the HF ground motion analyses than in the LF analyses, we judged that the ground motion spectral shape is potentially a significant deviation from the EPRI study that warranted further investigation. We confirmed the reasonableness of the EPRI generic factors for the ACU by conducting a coupled analysis that used the site-specific seismic ground motion.

Structure Complexity

The structure analysed in EPRI 3002010666 (2017) is a 5-DOF series system with uniform mass and stiffness distribution. The CNTM is much more complex, with multiple series and parallel systems, as well as nonuniform mass and stiffness distribution. We judged this discrepancy to warrant further investigation, and we confirmed the reasonableness of the EPRI generic factors for the ACU by conducting a coupled analysis that used the plant-specific detailed CNTM finite element model.

ACU-SPECIFIC STUDY OF EQUIPMENT-STRUCTURE INTERACTION

As discussed above, the site-specific ground motion characteristics and plant-specific structure complexity differed from the equipment-structure systems studied by EPRI 3002010666 (2017). We conducted analyses that used site-specific seismic demands and the detailed CNTM finite element model, comparing results from two coupled system models to confirm the reasonableness of the ACU ESI ISRS reduction factor obtained from EPRI 3002010666 (2017). The analyses leveraged response spectrum analysis with fixed-base models and SSI-modified foundation response to reduce the level of effort involved in conducting a coupled analysis.

We created two stick model representations of the ACU and incorporated them into the CNTM FEM to develop the Case 1 and Case 2 coupled models schematically illustrated in Figure 3.

Case 1: The model includes a cantilever stick tuned to the ACU natural frequency of 7.6 Hz in both orthogonal horizontal directions. The ACU first-mode mass was lumped at the top of the stick. The cantilever height was matched to the ACU centre-of-mass.

Case 2: The model includes a cantilever stick with nearly zero mass (approximately 1% of the ACU mass) and tuned to the ACU natural frequency of 7.6 Hz. This model is analogous to one of the massless SDOF oscillators among the series of oscillators used to compute ISRS by the traditional floor response spectrum analysis approach.

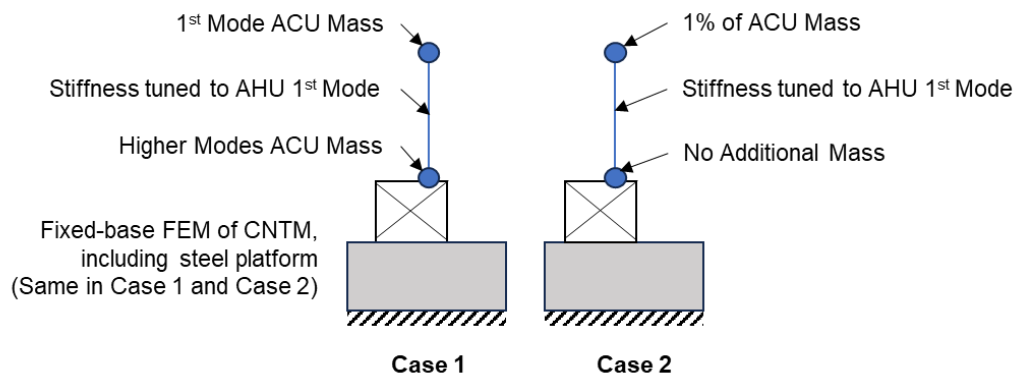


Figure 3. Fixed-Base Coupled Equipment-Structure Models

We added the Case 1 and Case 2 stick models to separate copies of the fixed-base CNTM finite element model. The stick models were added at the location of the ACU and attached to the steel platform framing with rigid frame elements connecting the base of the stick to the approximate ACU anchorage locations. The Case 1 model had the first mode mass of the ACU concentrated at the top of the ACU stick, and the higher modal mass of the ACU assigned at the bottom of the stick (i.e., rigidly affixed to the platform). The higher-mode mass was not assigned to the platform in the Case 2 model. The Case 1 model is a coupled system model that accounts for ESI between the CNTM and the ACU. ESI is negligible in the Case 2 model due to the lack of significant mass assigned to the ACU stick.

We conducted response spectrum analyses with the fixed-base, Case 1 and 2 models. We applied median ISRS from the CNTM base mat (calculated by the CNTM SSI analyses) as the seismic demand input to the response spectrum analyses. This approach neglects the rocking and torsional foundation demand inputs, but we judged the translational component alone was sufficient to reasonably estimate ACU demand reduction due to ESI.

Using fixed-base response spectrum analyses eliminated the need to repeat the SSI analyses and greatly reduced computational time and effort. In addition, response spectrum analysis allows for direct extraction of equipment seismic demand parameters without the intermediate step of extracting in-structure time histories and computing ISRS. Accelerations were compared at the top node of the Case 1 and Case 2 ACU sticks in the models. Since Y-direction demand governed the anchorage fragility, we compared accelerations for this governing direction.

The response reduction observed in Case 1 relative to Case 2 was 0.29, whereas the generic median factor was 0.435 from EPRI 3002010666 (2017). The rough magnitude of de-amplification from this ACU-specific study confirms the reasonableness of the EPRI generic reduction factor, despite the site ground motion characteristics and CNTM complexity not aligning with the EPRI parametric study. However, the ACU-specific value is a simplified approximation that does not account for randomness or uncertainty in the coupled dynamic interaction and it should not be considered a median-centred result. The response spectrum analyses modelled the ACU and platform frequencies as approximately aligned (i.e., frequency ratio of unity), which is likely a best-case scenario for response reduction due to ESI. If we considered a probabilistic distribution of frequency ratios, most ratios would result in less demand reduction, and we would expect the median ACU demand to be higher than calculated in our ACU-specific study. Therefore, although the response-spectrum analysis results suggest lower ACU demands than the generic EPRI factor, this should not be interpreted as conservatism in the application of the generic factor to the ACU fragility analysis.

CONCLUSIONS

This case study presents a situation where we found ESI to significantly reduce the seismic demands on a platform-mounted ACU at a nuclear power plant. ESI is significant for the ACU because of its relatively large mass and alignment of the ACU frequency with the local mode of the steel platform upon which the ACU is mounted. For seismic fragility analysis of the ACU, we applied a generic response reduction factor from EPRI 3002010666 (2017). We conducted a study that confirmed the reasonableness of the generic factor, despite some discrepancies between the site-specific seismic demand and plant-specific structure relative to the parameter envelope considered in the EPRI study.

To efficiently confirm the reasonableness of the generic response reduction factor, we used an approach that leveraged fixed-base response spectrum analysis of coupled equipment-structure models. The approach could be further developed into a generalized, practical, and efficient method to quantify ESI that may be preferable to other methods currently available. Future development of the approach for application to seismic fragility analysis should focus on validating it against other ESI methods and developing the methodology to calculate median-centred response and associated logarithmic standard deviations due to

randomness and uncertainty. Depending on the application, some possible advantages and disadvantages of the response spectrum ESI approach are listed in Table 22.

Table 2: Response Spectrum ESI Quantification Method Advantages and Disadvantages

Advantages	Disadvantages
<ul style="list-style-type: none"> • Improved efficiency relative to other ESI methods. • Does not require rerunning SSI analyses. • Adaptable to more- or less-detailed models of the structure and equipment . • Can account for ESI with multiple pieces of equipment. • Applicable equipment demands can be computed directly from the coupled model. 	<ul style="list-style-type: none"> • Does not generate ESI-modified ISRS for evaluations of nearby equipment (although responses could be obtained by the selective insertion of SDOF oscillators at nearby locations). • The soil-structure-equipment response could conceivably be different for some systems than when the SSI and ESI components of the system are decoupled. • Quantifying variability may require repeating analysis with additional models. • Methodology to estimate median-centred response needs to be developed.

NOMENCLATURE

ACU	Air Cooling Unit
ASCE	American Society of Civil Engineers
CNTM	Containment
EPRI	Electric Power Research Institute
ESI	Equipment-Structure Interaction
ISRS	In-Structure Response Spectra
SDOF	Single-Degree of Freedom
SGH	Simpson Gumpertz & Heger Inc.

REFERENCES

- Appelbaum, A.C., Samuelson-Sanford, C.B., Kennedy, R.P., Hardy G.S., Grant, F.F., & Drake, R.S. (2017). “Coupled Vertical Dynamic Response of Equipment Mounted on Diaphragms,” *Transactions, SMiRT-24 Division V*, Busan, Korea.
- Electric Power Research Institute 3002010666. (2017). *Coupled Analysis of Primary-Secondary System to Generate Floor Response Spectra (Quantifying Reduction Factors for Coupled In-Structure Response Spectra Amplitudes)*. Palo Alto, California, USA.
- Electric Power Research Institute 3002012994. (2018). *Seismic Fragility and Seismic Margin Guidance for Seismic Probabilistic Risk Assessments*. Palo Alto, California, USA.
- Lim, E. and Chouw, N. (2015). “Review of Approaches for Analysing Secondary Structures in Earthquakes and Evaluation of Floor Response Spectrum Approach,” *International Journal of Protective Structure*, Vol. 6, No. 2, 237-261.