Improving the Simulation Accuracy of the Substructure Approach for Soil-Structure Interaction Analysis Using a Refined Impedance Function

Abdelrahman Taha
Ph.D. Student, Depart. of Civil and Environmental Engineering, University of Nevada Reno, Reno NV, USA

Hamed Ebrahimian
Assistant Professor, Depart. of Civil and Environmental Engineering, University of Nevada Reno, Reno NV, USA

Ramin Motamed
Associate Professor, Depart. of Civil and Environmental Engineering, University of Nevada Reno, Reno NV, USA

ABSTRACT: The objective of this study is exploring the limitations of the substructure approach for soil-structure-interaction (SSI) analysis. The key assumption in the substructure approach is that the soil-structure system can be partitioned into two subsystems: the superstructure and the soil-foundation. The soil-foundation subsystem is then replaced by a set of springs and dashpots, i.e., the impedance function, representing soil-foundation flexibility and damping, respectively. To calculate the impedance function, the behavior of a massless rigid foundation resting on/embedded in the soil medium, i.e., the soil-foundation subsystem, is studied, where the different foundation vibration modes are considered separately. In the soil-structure system, however, the applied structural inertial forces on the foundation causes coupling between the foundation horizontal translational and rotational vibration modes. This creates a soil displacement field and wave field different from those observed when considering the foundation vibration modes separately. Since the presence of the superstructure is the reason for this coupling effect, the impedance function shall be developed considering the presence of the superstructure.

In this paper, we examine the validity of this proposed solution by means of a numerical study on a two-dimensional linear elastic frame structure resting on the surface of a linear elastic half-space. The refined impedance function for this system is estimated using a Bayesian model inversion technique. Subsequently, the seismic response of this system is analyzed using the direct approach (treated as the true response), the substructure approach developed using the traditional impedance function, and the substructure approach developed using the refined impedance function. The results show that the refined impedance function improves the simulation accuracy of the substructure approach and makes it capable of accurately reproducing the simulated response of the direct approach.

1. INTRODUCTION

Soil-structure interaction (SSI) analysis can be done using one of two approaches: the direct approach or the substructure approach (John P.Wolf, 1985; Kausel, 2010; Kramer, 1996; NIST, 2012). Despite its accuracy, the use of the direct approach is limited due to its computational cost and technical complexity. Alternatively, the substructure approach is more widely adopted in practice. In this approach, the soil-structure model domain is simplified by replacing the soil-foundation subdomain by a set of springs and dashpots, referred to as the impedance function, simulating soil-foundation flexibility and damping mechanisms, respectively.

Many impedance functions were developed in the literature using analytical or numerical methods, e.g., (Hryniewicz, 1981; Luco & Westmann, 1971, 1972; Seylabi et al., 2016; Wong & Luco, 1976, 1978). These impedance functions are commonly developed by studying the behavior of a massless rigid foundation resting on the surface of a soil domain or embedded within it (this impedance function is referred to as the traditional impedance function hereafter). In studying the massless foundation behavior, a set of forces with varying frequencies are applied separately on the foundation, and the corresponding foundation deformations are calculated. The complex-valued stiffness matrix of soil, i.e., the impedance function, is then computed. However, a recent study (Taha et al., 2022), conducted by the authors, showed that the substructure approach does not provide accurate results, compared to the direct approach, when using the traditional impedance function. It was argued that the reason for the poor performance of the traditional impedance function is neglecting the coupling between the horizontal translational and rotational foundation vibration modes in developing the impedance function. This coupling alters the soil-foundation subsystem behavior by changing the soil displacement field and wavefield in the vicinity of the fundamental frequency of the soil-structure system. To consider this coupling effect, the impedance function shall be developed considering the presence of the superstructure, wherein the aforementioned coupling effect is accounted for.

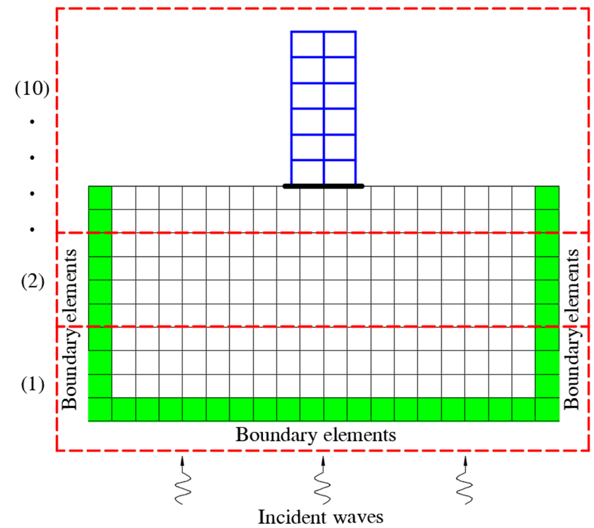
This paper investigates the validity of this argument through a numerical study of a two-dimensional (2D) linear elastic frame structure rested on the surface of a linear elastic, homogeneous soil domain. First, we develop a refined impedance function for this case-study building, which considers the presence of the superstructure. Then, we validate the refined impedance function by studying how the simulated responses of the substructure models, developed using the refined impedance function and the traditional impedance function, compare to the direct model response. In Section 2, the design and modeling details of the case-study building are presented. The model inversion framework is introduced in Section 3. It is then used in Section 4 to estimate the refined impedance function. The analyses results are shown in Section 5. Finally, the conclusions are summarized in Section 6.

2. CASE-STUDY BUILDING

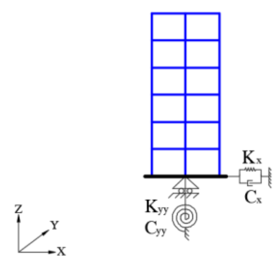
The case-study building is a 2D linear elastic structure with a rigid foundation resting on a linear elastic half-space in plain-strain setting and subjected to vertically propagating shear (SV-) waves. In this section, the design and modeling details of the building are explained for both the direct and substructure models. The finite element analysis framework OpenSees (McKenna, 2011) is used for the modeling and response simulation. In this case study, the structural and soil properties are selected to result in significant inertial SSI effects. In their work, Stewart et al. (Stewart et al., 1999) showed that the most important parameter controlling inertial interaction is the structure-to-soil stiffness ratio ($h/_{V_s T}$), where h is the building height, V_s is the soil shear wave velocity, and T is the fixed-base building period. It was shown that inertial interaction is generally significant if this ratio is more than 0.1.

The studied building is a ten-story, two-bay reinforced concrete frame structure with story height of 3m, bay length of 5m, and foundation width of 12m. The column and beam cross-sectional dimensions are 40cm × 90cm and 30cm×90cm, respectively. The concrete modulus of elasticity is assumed to be 30GPa. The structural mass is 200ton per floor. The fixed-base fundamental period is 1.34s. The soil domain is assumed to have a shear wave velocity of $150^{\mathrm{m}}/_{\mathrm{s}}$ and a Poisson's ratio of 0.25. The soil density is equal to $1.7^{\mathrm{ton}}/_{\mathrm{m}^3}$. Given the system properties, the ratio $h/_{V_s T}$ is found to be equal to 0.15. Hence, significant inertial SSI effects are expected. No damping is considered for either the structure or the soil domain; therefore, the only source of energy dissipation in the system is radiation damping.

The direct model is developed by explicitly modeling both the structural system and the supporting soil medium as shown in Figure 1(a). The response simulation of such large models is typically computationally expensive. To reduce the computational cost, the parallel analysis capabilities in OpenSees are utilized. For this purpose, the OpenSeesMP application is employed, which requires manual decomposition of the domain (McKenna, 2011). Figure 1(a) shows schematically the direct model division into 10 parts. The frame elements are modeled using *elasticBeamColumn* elements. The foundation is also modeled using *elasticBeamColumn* with large cross-sectional dimensions to satisfy the rigid foundation assumption. The soil domain is modeled using four-node *quad* elements with plane-strain formulation. The thickness of the quad elements is 1m, the in-plane element size is 1m×1m to ensure that the ratio between the element size and the minimum wavelength of the waves propagating in the soil domain is less than 1/12 (Lysmer & Kuhlemeyer, 1969). The soil domain's depth and width are 50m and 100m, respectively. Perfect bond between the foundation and soil surface is enforced using the *EqualDOF* constraints. To simulate a semi-infinite soil medium using a finite soil domain, proper boundary conditions should be defined to ensure that the outgoing waves at the soil domain boundaries do not reflect back into the soil domain. Several absorbing boundary conditions were developed in the literature, e.g., (Joyner, 1975; Kuhlemeyer & Lysmer, 1973; Kunar & Rodriguez - Ovejero, 1980; Lysmer & Kuhlemeyer, 1969; Nielsen, 2006; Seed & Lysmer, 1978; Zienkiewicz et al., 1989). In this study, we adopt the soil boundary element introduced in (Nielsen, 2006).



(a)



(b)

Figure 1: Schematic representation of (a) The direct model, and (b) The substructure model

The substructure model is created by replacing the soil domain with the impedance function. The traditional impedance function is adopted from Luco and Westmann's work (Luco & Westmann, 1972). This impedance function was developed for a rigid strip footing bonded to a homogeneous elastic half space, which is similar to this case study. Since the case-study building has a surface foundation and is subjected to SV-waves, the vertical impedance parameters (K_z and C_z) are neglected and replaced by a roller support as shown in Figure 1(b). Moreover, the coupling terms (K_{xy}, K_{yx}, C_{xy}, and C_{yx}) are neglected since their effects are relatively small and insignificant for surface foundation (Pais & Kausel, 1988).

Evaluating the impedance function requires calculating the fundamental frequency of the coupled soil-structure system. To calculate the fundamental frequency, the roof floor in the direct model is subjected to an impulse load, and the free-vibration response is recorded. The fundamental frequency of the system is found to be equal to 0.28Hz through calculation of the Fourier transform of the free-vibration response time history. To evaluate the impedance function, the dimensionless frequency parameter, i.e., $a_0 = {\omega b}/{V_s}$, has to be calculated first, where ω is the fundamental circular frequency, b is the foundation half-width, and V_s is the soil shear wave velocity. Given a frequency of 0.28Hz, a_0 is equal to 0.07 (i.e., $a0 = (2\pi \times 0.28) \times 6 /_{150}$= 0.07). The values of the traditional impedance function parameters corresponding to $a_0 = 0.07$ are obtained from the charts in (Luco & Westmann, 1972) and presented in Table 1.

3. MODEL INVERSION FRAMEWORK

In this section, we briefly introduce the Bayesian model inversion method used for estimating the refined impedance function. This method can be perceived as an optimization technique in which the objective is minimizing the discrepancy between the simulated response of the substructure approach and that of the direct approach. Given the probabilistic nature of this method, the uncertainty of the unknown model parameters are considered by modeling them as random variables with a Gaussian probability distribution function (PDF), which can be fully characterized using its mean and covariance. The model parameter uncertainty is then propagated into the model response using a sequential, window-based model updating approach. In this approach, the response/estimation time history is divided into successively overlapping estimation windows. In each window, the mean vector and covariance matrix of the model parameters are iteratively updated to maximize the posterior PDF of the unknown model parameter vector at its mean, i.e., the maximum *a posteriori* (MAP) estimate of the model parameter vector. The estimated mean vector and covariance matrix at the end of each estimation window are then transferred to the next window as prior information. For mathematical derivation details of this sequential Bayesian estimation method, the reader is referred to these references (Astroza et al., 2015; Ebrahimian et al., 2015, 2017, 2023; Ebrahimian, Astroza, et al., 2018; Ebrahimian, Kohler, et al., 2018; Ghahari et al., 2022; Simon, 2006; Simon & Simon, 2010).

4. REFINED IMPEDANCE FUNCTION

The refined impedance function is developed for the case-study soil-structure system considering the presence of the superstructure. In other words, the response of the direct model is simulated, and the impedance function is estimated so that the discrepancy between the direct model response and the substructure model response is minimized. Since the refined impedance function is intended to be used for time-domain SSI analysis and given the frequency dependence of the impedance function, the impedance function is estimated using the fundamental modal response of the direct model. This approach ensures tuning the estimated impedance function to the flexible-base fundamental frequency, which is a good approximation provided that the response of most civil structures is dominated by the fundamental vibration mode. The estimation process starts with defining a harmonic load with the flexible-base fundamental frequency, which is then applied at the foundation centroid in the direct model (this load is treated as the foundation input motion (FIM) in the substructure model). Then, the response of the direct model, along with the FIM, are jointly used within the Bayesian model inversion framework to estimate the impedance function parameters. The estimated refined impedance function parameters are presented in Table 1.

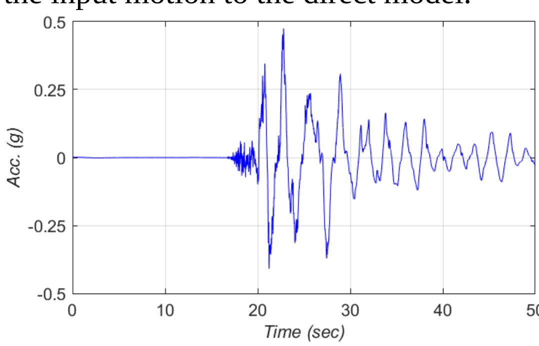
Table 1: Impedance function

Parameter	K_x (10^4)	K_{yy} (10^6)	C_x (10^4)	C_{yy} (10^5)
Units	*kN/m^2*	*kN/rad*	*kN.s/m^2*	*kN.s/rad*
Traditional impedance function	*3.83*	*3.12*	*1.05*	*0.71*
Refined impedance function	*3.11*	*3.04*	*0.62*	*0.98*

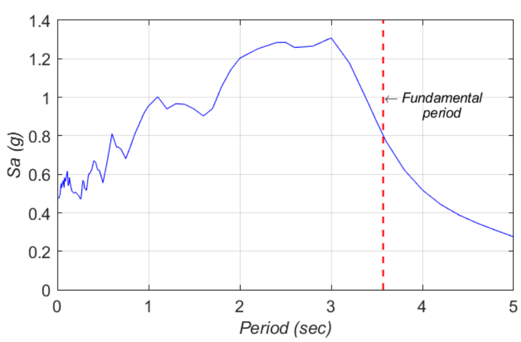
Comparing the traditional impedance function to the refined impedance function, we can observe a non-negligible difference between both the stiffness and viscosity parameters. This validates the argument made in Section 1 about the effect of coupling between the foundation vibration modes, which changes the soil displacement field and wavefield corresponding here to changes in the stiffness and viscosity parameters of the impedance function.

5. ANALYSIS RESULTS

In this section, the refined impedance function is validated by comparing its performance to that of the traditional impedance function developed by Luco and Westmann. To do this, the responses of three models of the case-study building, i.e., the direct model and two substructure models, developed using the refined impedance function and the traditional impedance function, are compared. The 2007 Chuetsu-oki earthquake record (Kariwa station – NS component) is used as the input motion to the direct model.



(a)



(b)

Figure 2: 2007 Chuetsu-oki earthquake (Kariwa station – NS component), (a) Acceleration time history, and (b) Acceleration response spectrum (5% damping)

To calculate the FIM of the substructure models, a site response analysis is carried out and the soil surface response is recorded. Since the incident seismic waves are SV-waves and given that the structural foundation is rested on the soil surface, no kinematic interaction will arise, and hence, the recorded surface motion from the site model is equivalent to the FIM (Kramer, 1996). Figure 2 shows the acceleration time history of this record and its acceleration response spectrum. Due to its insignificance, the first 10-sec time interval of this record is ignored.

Figure 3 shows the roof and middle-floor responses of the case-study building. It can be noticed that the fundamental frequency of the substructure model developed using the refined impedance function correlates almost perfectly with the direct model fundamental frequency, whereas Luco and Westmann's impedance function overestimates the fundamental frequency. This indicates that the refined impedance function provides a better simulation of soil flexibility. Moreover, the amplitude of the fundamental-frequency response of the substructure model developed using the refined impedance function better matches that of the direct model, which proves that the refined impedance function provides a better simulation of radiation damping. These two observations support our argument about the necessity of considering the presence of the superstructure in the development of the impedance function.

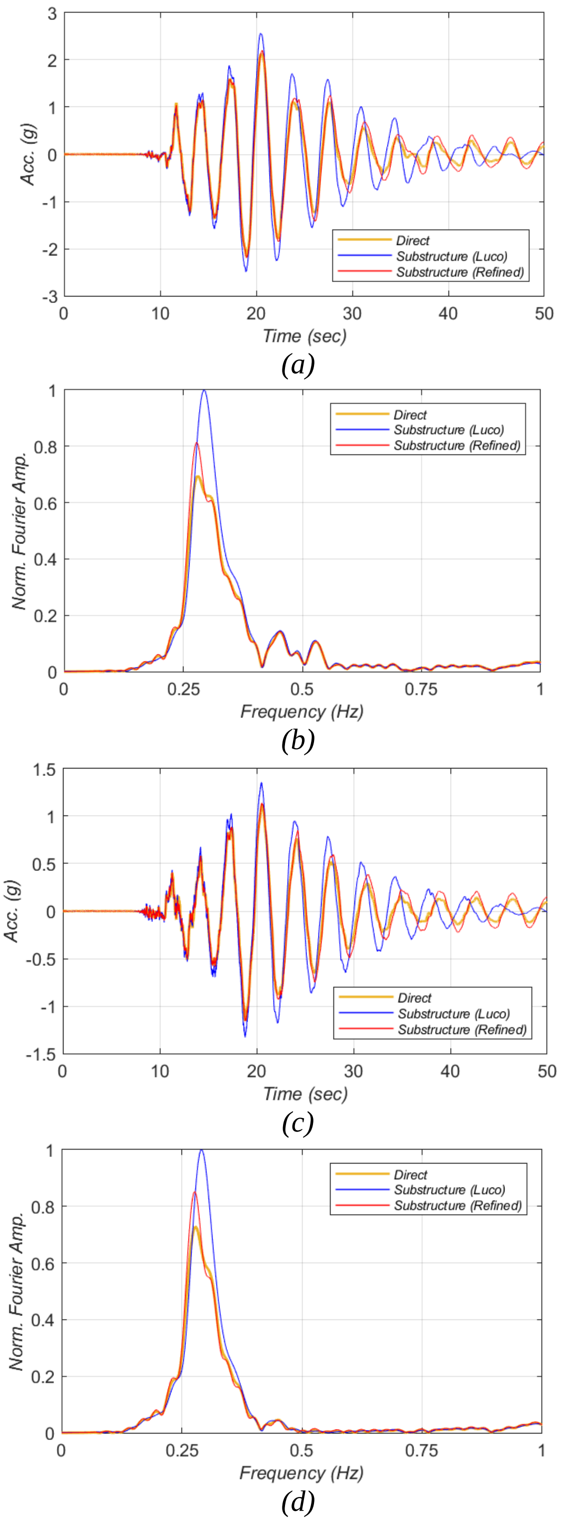


Figure 3: Absolute acceleration response, (a) Roof response, (b) Fourier transform of the roof response, (c) Middle-floor response, and (d) Fourier transform of the middle-floor response

6. CONCLUSIONS

This study highlighted one of the limitations of the substructure approach for SSI analysis and proposed a refined solution. Developing the impedance function by studying the behavior of a massless rigid foundation, where the foundation vibration modes are considered separately, was argued to be a limiting conviction in the substructure approach. Therefore, the impedance function shall be refined by considering the presence of the superstructure to account for the coupling between the foundation vibration modes. To validate this proposal, a numerical study was carried out on a 2D case-study building. The refined impedance function was estimated for the case-study building using a Bayesian model inversion technique. In this model inversion framework, the objective was minimizing the discrepancy between the fundamental modal response of the direct model and that of the substructure model, hence tuning the estimated impedance function to the flexible-base fundamental frequency. Then, a comparison between the responses of a direct model of the building and two substructure models, developed using the refined impedance function and the traditional impedance function, was conducted. The refined impedance function was shown to provide a better simulation of soil flexibility and radiation damping, hence improving the simulation accuracy of the substructure approach. These results suggest the need for generalizing the refined impedance function for the practical range of soil-structure systems.

7. ACKNOWLEDGMENTS

This material is based upon work supported by the U.S. Geological Survey under Grant No. (G20AP00115-01).

8. REFERENCES

Astroza, R., Ebrahimian, H., & Conte, J. P. (2015). Material parameter identification in distributed plasticity FE models of frame-type structures using nonlinear stochastic filtering. *Journal of Engineering Mechanics*, *141*(5), 4014149.

Ebrahimian, H., Astroza, R., & Conte, J. P. (2015).

Extended Kalman filter for material parameter estimation in nonlinear structural finite element models using direct differentiation method. *Earthquake Engineering & Structural Dynamics*, *44*(10), 1495–1522.

Ebrahimian, H., Astroza, R., Conte, J. P., & de Callafon, R. A. (2017). Nonlinear finite element model updating for damage identification of civil structures using batch Bayesian estimation. *Mechanical Systems and Signal Processing*, *84*, 194–222.

Ebrahimian, H., Astroza, R., Conte, J. P., & Papadimitriou, C. (2018). Bayesian optimal estimation for output-only nonlinear system and damage identification of civil structures. *Structural Control and Health Monitoring*, *25*(4), e2128.

Ebrahimian, H., Kohler, M., Massari, A., & Asimaki, D. (2018). Parametric estimation of dispersive viscoelastic layered media with application to structural health monitoring. *Soil Dynamics and Earthquake Engineering*, *105*, 204–223.

Ebrahimian, H., Taha, A., Ghahari, F., Asimaki, D., & Taciroglu, E. (2023). Estimation of Soil–Structure Model Parameters for the Millikan Library Building Using a Sequential Bayesian Finite Element Model Updating Technique. *Buildings*, *13*(1), 28.

Ghahari, F., Malekghaini, N., Ebrahimian, H., & Taciroglu, E. (2022). Bridge Digital Twinning Using an Output-Only Bayesian Model Updating Method and Recorded Seismic Measurements. *Sensors*, *22*(3), 1278.

Hryniewicz, Z. (1981). Dynamic response of a rigid strip on an elastic half-space. *Computer Methods in Applied Mechanics and Engineering*, *25*(3), 355–364.

John P.Wolf. (1985). *Dynamic Soil-Structure Interaction. Prentice-Hall international series in civil engineering and engineering mechanics*.

Joyner, W. B. (1975). A method for calculating nonlinear seismic response in two dimensions. *Bulletin of the Seismological Society of America*, *65*(5), 1337–1357.

Kausel, E. (2010). Early history of soil-structure interaction. *Soil Dynamics and Earthquake Engineering*, *30*(9), 822–832. https://doi.org/10.1016/j.soildyn.2009.11.001

Kramer, S. L. (1996). *Geotechnical earthquake engineering*. Pearson Education India.

Kuhlemeyer, R. L., & Lysmer, J. (1973). Finite element method accuracy for wave propagation problems. *Journal of the Soil Mechanics and Foundations Division*, *99*(5), 421–427.

Kunar, R. R., & Rodriguez-Ovejero, L. (1980). A model with non-reflecting boundaries for use in explicit soil—structure interaction analyses. *Earthquake Engineering & Structural Dynamics*, *8*(4), 361–374.

Luco, J. E., & Westmann, R. A. (1971). Dynamic response of circular footings. *Journal of the Engineering Mechanics Division*, *97*(5), 1381–1395.

Luco, J. E., & Westmann, R. A. (1972). *Dynamic response of a rigid footing bonded to an elastic half space*.

Lysmer, J., & Kuhlemeyer, R. L. (1969). Finite dynamic model for infinite media. *Journal of the Engineering Mechanics Division*, *95*(4), 859–877.

McKenna, F. (2011). OpenSees: A framework for earthquake engineering simulation. *Computing in Science and Engineering*, *13*(4), 58–66. https://doi.org/10.1109/MCSE.2011.66

Nielsen, A. H. (2006). Absorbing boundary conditions for seismic analysis in ABAQUS. *ABAQUS Users' Conference*, 359–376.

NIST. (2012). NIST GCR 12-917-21 Soil-Structure Soil-Structure Interaction for Building Structures. In *Soil-Structure Interaction for Building Structures* (Vol. 12).

Pais, A., & Kausel, E. (1988). Approximate formulas for dynamic stiffnesses of rigid foundations. *Soil Dynamics and Earthquake Engineering*, *7*(4), 213–227. https://doi.org/10.1016/S0267-7261(88)80005-8

Seed, H. B., & Lysmer, J. (1978). Soil-structure interaction analyses by finite elements—State of the art. *Nuclear Engineering and Design*, *46*(2), 349–365.

Seylabi, E. E., Jeong, C., & Taciroglu, E. (2016). On numerical computation of impedance functions for rigid soil-structure interfaces embedded in heterogeneous half-spaces. *Computers and Geotechnics*, *72*, 15–27.

Simon, D. (2006). *Optimal state estimation: Kalman, H infinity, and nonlinear approaches*. John Wiley & Sons.

Simon, D., & Simon, D. L. (2010). Constrained Kalman filtering via density function truncation for turbofan engine health estimation. *International Journal of Systems Science*, *41*(2), 159–171.

Stewart, J. P., Fenves, G. L., & Seed, R. B. (1999). Seismic soil-structure interaction in buildings. I: Analytical methods. *Journal of Geotechnical and Geoenvironmental Engineering*, *125*(1), 26–37.

Taha, A., Malekghaini, N., Ebrahimian, H., & Motamed, R. (2022). Time-Domain Analysis Approaches of Soil-Structure Interaction: A Comparative Study. *International Journal of Structural and Construction Engineering*, *16*(12), 341–347.

Wong, H. L., & Luco, J. E. (1976). Dynamic response of rigid foundations of arbitrary shape. *Earthquake Engineering & Structural Dynamics*, *4*(6), 579–587.

Wong, H. L., & Luco, J. E. (1978). Tables of Impedance Functions and Input Motions for Rectangular Foundations. In *Report - University of Southern California, Department of Civil Engineering* (Issues 78–15).

Zienkiewicz, O. C., Bicanic, N., & Shen, F. Q. (1989). Earthquake input definition and the trasmitting boundary conditions. In *Advances in computational nonlinear mechanics* (pp. 109–138). Springer.