Civil Engineering and Architecture 11(2): 1083-1090, 2023 http://www.hrpub.org
DOI: 10.13189/cea.2023.110239

Nonlinear Dynamic Study of Soil and Structural Interference Issues

Larah R. Abdulwahed[1,*], **Aymen R. Mohammed**[2]

[1]Middle Technical University, Technical Institute of Baquba, Iraq
[2]Middle Technical University, Engineering Technical College Baghdad, Iraq

Received August 8, 2022; Revised November 14, 2022; Accepted December 22, 2022

Cite This Paper in the Following Citation Styles

(a): *[1] Larah R. Abdulwahed, Aymen R. Mohammed , "Nonlinear Dynamic Study of Soil and Structural Interference Issues," Civil Engineering and Architecture, Vol. 11, No. 2, pp. 1083 - 1090, 2023. DOI: 10.13189/cea.2023.110239.*

(b): *Larah R. Abdulwahed, Aymen R. Mohammed (2023). Nonlinear Dynamic Study of Soil and Structural Interference Issues. Civil Engineering and Architecture, 11(2), 1083 - 1090. DOI: 10.13189/cea.2023.110239.*

Abstract The connection of the soil with the building was already extensively studied on the supposition of the soil's basic and structural uniformity. Nonetheless, during intermediate or powerful earthquakes, the maximum shearing stress can readily exceed the elastic modulus of the properties of the soil. When considering soil-structure connection, nonlinear processes may modify soil rigidity at the building's foundation and hence power dispersion into the soil. As a result, disregarding the nonlinear properties of the dynamic soil-structure interface (DSSI) may result in incorrect dynamic loading estimates. The purpose of this research is to incorporate a completely nonlinear parametric framework for soils into a mathematical notation and examine the impact of soil nonlinearity on dynamic soil building interactions. Furthermore, several problems are defined, for instance the impact of restricting strain on the shear strength of the soil, the preliminary static configuration, and interface components at the soil-structure interface, and so on. Throughout this study, a basic absorbing layer approach that relies on a Rayleigh/Caughey dampening concept, which is frequently accessible in current code, was used. Computational Component software is shown as well. The stability criteria of wave dispersion difficulties are investigated, and it is demonstrated that the linear and nonlinear performance vary dramatically when coping with numerical propagation. This research is separated into two sections. In the first section, a soil column is simulated. There is a development of computational and semi-analytical approaches for describing the one-dimensional linear and nonlinear dynamic soil reactions to a predefined movement. Because the linear formula is simpler to comprehend and explain, it is achieved initially. In addition, it is utilized to determine the amount to which nonlinearity affects soil characteristics. In nonlinear assessment, the strain-dependent shear strength and dampening proportion are employed. Such input variables are crucial for completing a ground response assessment. For the formulations of strain-dependent mechanical properties and dampening in this work, hyperbolic soil model-constructed curves are utilized.

Keywords Nonlinear Dynamic Study, Structural Interference Issues, Dynamic Soil Building Interactions, Dynamic Soil-Structure Interface (DSSI)

1. Introduction

Because most buildings depend directly or indirectly on the ground, analyzing the reaction of structural components while incorporating soil-structure interactions are currently a topic of significant importance in structural dynamics. The investigation of the soil-structure interaction when the building is exposed to seismic events is a subject of special concern in this field. Earthquake occurrences are among the most complicated dynamic forces encountered in civil engineering systems. The significance of studying such a topic in light of the influence of soil structure is related to the soil's natural ability to modify its characteristics as a consequence of frequency components. The study of geometry nonlinearity in buildings has also been an essential problem in structural analysis, particularly for structures like framing, bridges, and trusses [1].

Nonlinear processes accompanying soil-structure interface (nonlinear reaction in the soil and detachment of the structure from the soil) are potent seismic power drains. The capability of such occurrences to inhibit tidal energy from entering buildings must be examined and measured so that their passive absorption potential may be incorporated into the construction, taking benefit of the occurrences that are almost always occurring throughout significant ground-shaking seismic occurrences [2].

The soil-structure contact of prolonged constructions (tunnels, bridges, dams) is also exceptionally susceptible to the asymmetrical movements and rotations of particular supports (as seen before during differential settlement, earth vibrations, flow collapse, and lack of ultimate load) [3]. Future studies should attempt to measure all of these variable excitations and build designing methods that compensate for their influence. The consequences of complicated earth processes associated with intense earth shaking of marginal soil layers on the dynamic behavior of concrete institutions are a significant area of study that may have implications for future modifications of the seismic design code.

This research is separated into two sections. In the first section, a soil column is simulated. There is a development of computational and semi-analytical approaches for describing the one-dimensional linear and nonlinear dynamic soil reactions to a predefined movement. Because the linear formula is simpler to comprehend and explain, it is achieved initially. In addition, it is utilized to determine the amount to which nonlinearity affects soil characteristics. In nonlinear assessment, the strain-dependent shear strength and dampening proportion are employed. Such input variables are crucial for completing a ground response assessment. For the formulations of strain-dependent mechanical properties and dampening in this work, hyperbolic soil model-constructed curves are utilized.

2. Objective of the Study

This study aims to create a generic approach for addressing the whole non-linear DSSI issue.

This approach requires:

- the design of an accurate estimation framework that truthfully accounts for the physical manifestations experienced, including the wave proliferation and the non-linear attitudes of both the structural elements and the soil, in addition to the soil-foundation interaction issue;
- the recognition of a series of appropriate methods explaining the seismic activity, the soil, and the building's vibrant responses;
- the implementation of the acceptable simulation analysis and the set of indicators;
- the incorporation of non-linear DSSI impacts into an earthquake risk evaluation

3. Literature Review

In recent years, a considerable body of work has concentrated on soil-structure interaction (SSI), which has arisen as an important issue incorporating the dynamically linked behavior of building, foundation, and soil. Stewart et al. [4,5] provided simpler theoretical formulas that could be employed to anticipate inertial interplay, and they also discovered that in numerous circumstances, whereas kinematic interrelations on ground movement at the base of buildings may be comparatively little, inertial significant interactions on structural behavior to this foundation movement can be considerable.

Kim and Stewart [6] offered suggestions for adjusting free-field displacements to approximate foundation slab movements to be utilized in response to assessments of structures with shallow basements after examining kinematic interplay and consequently changes among foundation-level and free-field ground movement. SSI is not necessarily advantageous in the construction of a structure unlike popular belief to the contrary. In particular, significant publications on the topic show that, in particular earthquake and soil settings, an elevation in the natural frequencies of a relatively flexible framework owing to SSI may result in a negative influence on earthquake forces [7,8].

In the context of nonlinear soil reaction, inertial interaction is typically modelled using soil-foundation macro-elements, which already have been demonstrated to be a viable method for SSI assessment. SSI macro-element designs can be especially helpful not only because they recognize nonlinear characteristics and therefore avert the emergence (happening with a weakened modelling exertion) of potential bias in seismic hazard evaluation studies, notably when ground movement intensity thresholds are substantial, but also since of that kind designs are significantly more computationally effective than 3D finite element (FE) soil-block designs.

The computing expense of either makes them especially infeasible for vulnerability functional development, which requires dozens of nonlinear dynamic studies [9]. The fundamental objective of this work is thus to investigate and, if possible, establish the validity of these macro-element systems. The macro-element framework by Correia and Paolucci [10], as instated in SeismoStruct [11], was validated by comparing the institutional feedback and near-field soil-footing behavior of two comparable single (SDOF) structures, the latter becoming premised on the macro-element and on a 3D nonlinear soil-block framework indicating a layered soil, lately established by [12].

Kinematic and inertial contacts are understood to exist concurrently and should so be modeled as functioning in concert. Underneath the soil linearity hypothesis, it is theoretically and computationally feasible to describe SSI employing the foundation technique, which permits breaking kinematic and inertial contact into separate sub-steps and assessing their cumulative influence utilizing the collocation method [13,14]. To compensate for soil nonlinearities, nevertheless, the only practical solution is the direct one-step method, which can concurrently compensate for inertial and kinematic coupling and whose execution is feasible using a soil-block model.

FE soil-block studies are used to compensate for (linear or nonlinear) SSI in existing research. Numerous earlier investigations, which are of importance for the present study, evaluated the impacts of SSI on architectural reaction by contrasting alternative simulations that include soil-structure interaction with the standard fixed-base example. Pitilakis et al. [15] modeled SSI using a 2D FE soil-block model to recover the vulnerability curves of reinforced cement (RC) constructions. They determined that SSI impacts may severely impair the durability of buildings established on soft soils. Karapetrou et al. [16] and Mitropoulou et al. [17] used a 2D soil-block model to illustrate how SSI affects high-rise RC construction effectiveness.

Fathi et al. [18] utilised a 3D nonlinear soil-block model to measure the effect of SSI on the out-of-plane behavior of wall-type unreinforced masonry. They found that I SSI frequently enhances dispersion requirement and reduces velocity requirement, and (ii) soil nonlinearity increases the system's period and moves the out-of-plane acceleration response out of the resonance area. Bolisetti et al. [3] noted the importance of soil nonlinearity in SSI for nuclear earthquake vulnerability. A nonlinear time-domain SSI assessment using a 3D FE soil-block model in LS-DYNA was contrasted with an equivalent-linear assessment utilizing the SASSI frequency-domain code [19]; it was discovered that ignoring soil nonlinearity may result in an illiberal prediction of the superstructure's response and earthquake hazard. Since these studies show, 3D nonlinear soil-block modeling is the most developed alternative for SSI.

In early study, Cavalieri et al. [12] evaluated the stability of the created soil-block model by performing cross-checks and cross-modelling validation employing STRATA's equivalent-linear approach as a standard. To ensure the correctness of the produced soil-block model, it was chosen to expand the cross-modeling validation using DEEPSOIL as a standard. This supplementary validation helps with the following macro-element validation [20].

4. Soil Structure Interactions

In recent centuries, soil structure interactions, a significant topic in earthquake engineering, has received global interest. Soil-structure interactions include wave propagation in a linked system: on-soil buildings. It began in the late 19th century, evolved and matured gradually in the following decades and the first half of the 20th century, and progressed rapidly in the second half due to the needs of the nuclear power and offshore industries, the debut of powerful computers and simulation tools such as finite elements, and the need to improve seismic safety. Dynamic soil–structure interaction effects may be calculated analytically. Due to interference of structural reactions via the soil, the soil-structure issue becomes a multi-structure cross-interaction problem. Ishihara [21] showed that dilatational (compressional) waves create virtually pure isotropic stress in saturated soils.

Soil–structure interaction (SSI) refers to multi-structure dynamic interaction via soil-ground. Soil–structure interaction was initially identified by Luco and Westmann [22]. Dynamic cross interaction (DCI) is another term for nuclear power plant (NPP). Because prior research only considered structures on soil sans superstructures, SSSI was sometimes called foundation–soil–foundation interaction (FSFI). SSI analyzes the impact of neighboring buildings on others via subsurface interaction during dynamic stresses. Dynamic disturbances may be externally imposed stresses or seismic waves [23]. External loads or earthquakes may cause dynamic disruptions. SSI combines soil and structural mechanics, soil and structural dynamics, earthquake engineering, geophysics and geomechanics, material science, computational and numerical approaches, and other fields. SSI has been successfully studied using multiple conceptual methodologies and experimental deployments. This study reviews soil-structure interaction investigations, including background [22], principles [24,25], previous [7,8,15] and current studies [9-11], and the future research direction.

An undrained cyclic simple shearing experiment may simulate the seismic response of saturated soil exposed to one-dimensional shear waves (Figure 1-a). The loop's area indicates the energy wasted throughout a cycle, which may be measured quantitatively by a damping ratio:

$$\xi_g = \frac{\Delta E}{4\pi E}$$

Figure 1-c indicates that cyclic shearing stress intensity decreases secant shearing strength. This connection may be expressed by a 'backbone curve' linking residual stress points under different strain amplitudes. Especially at fixed shearing maximum stress, the residual stress flattens with rising periods n, as seen in Figure 1-d. Raising the frequency of rotations on saturated soils leads to a deteriorated backbone curve.

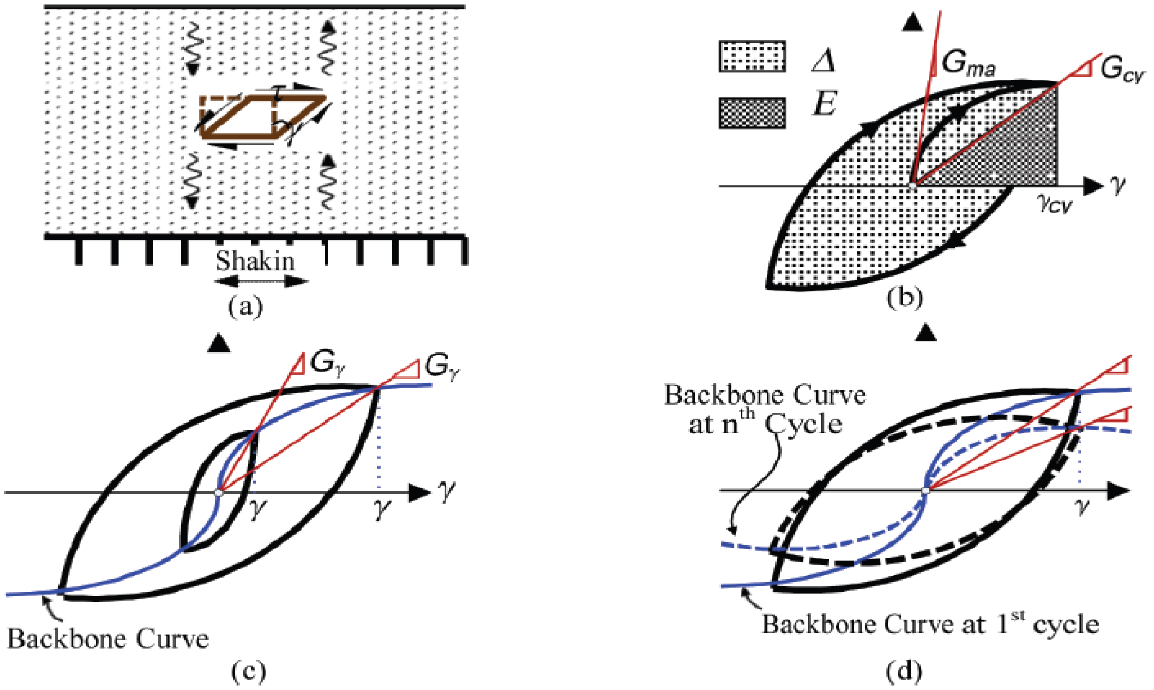

Figure 1. The cyclic behavior of (a) a soil component at a shearing wave-exposed location, which is characterized by (b) a magnetization influenced by (c) cyclic stress magnitude and (d) frequency of cycles [24]

5. Validation of the 3D Numerical Simulation of Soil Blocks

The created soil-block 3D mathematical analysis, performed in OpenSees, is confirmed by contrasting its findings to those acquired in DEEPSOIL, a software instrument that provides credible nonlinear soil reaction estimations. Stewart and Kwok [25] revealed that DEEPSOIL's nonlinear analysis findings accord well with those from DMOD 2 [26], TESS [27], and SUMDES [28]. Bolisetti et al. [29] observed that DEEPSOIL and LS-DYNA produce comparable nonlinear forecasts of surface excitations, while using distinct persistence criteria, whereas SHAKE2000's frequency-domain corresponding linearised deviates for moderate to severe shear stresses.

For comparable linear and nonlinear assessments, you can choose between the General Quadratic/Hyperbolic model (GQ/H) [30], the pressure-dependent Altered Kondner Zelasko design (MKZ) [26], and the material with a hyperbolic backbone curve proposed by Yee et al [31]. For each of these soil types, the Masing [32] and non-Masing [33] unloading/reloading procedures may be used. This study investigated three kinds of substance (GQ/H, MKZ) and both forms of hysteretic unloading/reloading composition (Masing and non-Masing rules), for an overall of six nonlinear pairings [31].

In DEEPSOIL, unlike other ground response assessment applications like as STRATA, the seismic data can only be supplied as an accelerated record at the half-space level, with no option to specify "escarpment" or "inside" movement. In the second scenario, shear wave speed, specific gravity, and damping proportion (not utilized in time-domain analysis) must be provided.

Time-domain analysis may use computational viscosity dampening. DEEPSOIL offers three frequency-dependent Rayleigh dampening formulas: one mode/frequency (simple), two modes/frequencies (full), and four modes/frequencies (extended). When complete Rayleigh dampening is chosen, the application recommends two management frequency bands: the soil deposit's basic resonance and 5 times it. The frequency-independent approach, advocated by the project's creators and used in all studies in this study, addresses most of Rayleigh damping's restrictions thus significantly boosting processing time. For small-strain dampening, the dynamic response cannot be supplied, regardless frequency-dependent or independent [34].

6. Impact of Elastic and Nonlinear DSSI on the Earthquake Requirements of SDOF Buildings

Several studies have examined the effect of the contact of the soil with a superstructure on its dynamic characteristics, presuming the linearity of both the superstructure and the soil base. For flexible networks, Jennings and Bielak [35], Veletsos and Meek [36], and Veletsos and Nair [37] provided the first investigations for soil-structure interaction processes. In these studies, the impacts of the inertial DSSI are described using an analogous SDOF to characterize sustainment flexibility and basis resonance. The influence of the elastic soil is accounted for by altering the basic time of the frame structure. The foundation dampening related with radiation and soil substance dampening is addressed by establishing an efficient dampening of the superstructure-foundation systems as the total of a component corresponding to the building's fluid flow and a corresponding viscous basis dampening.

Numerous scholars [38-40] have exhaustively examined the growth of the fundamental period and the additional foundation dampening. This substitution oscillator strategy is appropriate, however, only for flexible superstructure-foundation complexes. This is a fundamental restriction for seismic design, which deliberately accepts inelastic superstructure performance. Notwithstanding the the elastic innate presumption, this method has indeed been incorporated into a number of seismic analysis clauses [41-43], employing free-field response spectra mixed with efficient principles of both, basic duration and comparable viscous damping, such as elastic DSSI.

The impact of DSSI may vary among elastic and inelastic structures in concept. Consequently, the present interaction requirements based on elastic reaction investigations are not directly relevant to the earthquake engineering of ordinary structures, which are anticipated to flex much over the demand threshold during strong earthquakes [44]. In accordance with the essays of Veletsos [38], the bending of the superstructure may be understood as a generalized improvement in the comparative elasticity among the superstructure and the soil, which reduces the impacts of DSSI. Regrettably, little research has been conducted on the impacts of the DSSI on producing superstructure technologies.

Priestley and Parck [45] did theoretical research on elastoplastic concrete structure and discovered that underlying stiffness affects the system's ductility capability. Latest study utilizing the substitution oscillator approach [12,44,46] aimed to clarify the influence of the DSSI on the maximal necessary ductility. Likewise, Ghannad and Jahankhah [47] employ the substitution oscillator technique to investigate the influence of DSSI on the lowering parameters of elastoplastic SDOFs' intensity. These research has identified situations in which the DSSI has a significant influence on the flexibility requirements of buildings.

In the aforementioned experiments, the soil substitute spring and dashpots are chosen based on frequency-independent simplifications of the alternatives available for the dynamic reactance of strict concrete foundations on elastic soil samples, utilizing Cone designs or a sequence of linear wells and dashpots connected to the base framework. The numerical quantities of the soil replenishment spring and dashpot rely on the undrained shear strength regardless of the technique used. The majority of these scientists employ deteriorated shear wave speed measurements in their models because shear propagation velocity diminishes as the soil shear tension rises. The findings of experiments indicate that the threshold of linear-elastic properties of the soil is very low.

Typically, this shear strain limit is surpassed during movements that cause damage to superstructures. However, the self-weight of the superstructure enhances the soil constriction beneath the ground, hence decreasing the local hysteretic power loss. In fact, more soil power loss occurs in less constrained areas. Therefore, the only adjustment of the shear wave speed beneath the basis does not seem to be an acceptable method for incorporating nonlinear soil characteristics [48].

7. Conclusion and Recommendations

7.1. Conclusions

Based on the analysis undertaken in this research, the inclusion of non-linear DSSI phenomena often lowers seismic response or architectural destruction. This decrease is primarily attributable to two effects: radiative dampening and hysteretic dampening resulting from nonlinear soil behavior. The two-step method utilized as a standard during this whole paper disregards radiation dampening rather incorporates nonlinear soil characteristics to adjust the functional movement given to the superstructure. Nonetheless, both impacts occur concurrently throughout the loading condition, and it is very challenging to differentiate the role of each factor in lowering seismic response. Furthermore, the beneficial movement imparted to the superstructure does not match the free field reaction owing to geometrical and mechanical interactions in addition to the local alteration of soil response, particularly owing to the additional constriction caused by the mass of the superstructure. Numerous attempts were undertaken with little effectiveness to extrapolate the results. For this objective, a number of strong-motion intensity measurements, progressive collapse indicators, and energy disposal markers have been developed and researched. However, findings are often inconsistent, making generalization exceedingly difficult.

Our study strongly demonstrates the significance of controlling for nonlinear properties of the soil. In this instance, the majority of non-linear DSSI impacts are advantageous in terms of reducing the maximal seismic structural requirement. Nonetheless, based on the kind of building, the input movement, and the soil texture qualities, the non-linear DSSI might raise or reduce the projected structural failure. In addition, there is an economic need to consider the alteration impacts caused by nonlinear soil behavior. To achieve broader main findings for various structural and soil types, additional research in this area is required.

7.2. Recommendations

- It is essential to build a comprehensive database of strong-motion data for key metropolitan centres in seismically prone parts, as well as to record the local soil and geological characteristics of the location. These data are crucial for all areas of earthquake engineering study and applications, and they should be made accessible to the research community through websites.
- The integration of different techniques for computer models of free-field strong ground motion is of the utmost relevance if "on demand" fake time periods are to be generated for different locations.
- In earthquake-prone areas, it is vital to create and deploy protection solutions for certain kinds of buildings. In the future, it is envisaged that the cost of safety systems and the installation of innovation would become financially sustainable to the point where they may be applied routinely in big groups of traditional structural systems.
- The overall purpose is a high degree of seismic security for the building design and the accessibility of affordable coverage.

REFERENCES

[1] Paullo, M. L., Goncalves, P. B., Silveira, R. A., & Silva, A. R, "Nonlinear dynamics analysis of frame structures under seismic excitation considering soil-structure interaction and elasto-plastic soil behavior," In 11th International Conference on Vibration Problem, Lisbon, Portugal, Sept., 2013, pp. 9-12.

[2] Pecker, A., & Chatzigogos, C. T, "Nonlinear soil structure interaction: impact on the seismic response of structures," In Earthquake engineering in Europe, Springer, Dordrecht, 2010, pp. 79-103.

[3] Bolisetti, C., Whittaker, A. S., & Coleman, J. L, "Linear and nonlinear soil-structure interaction analysis of buildings and safety-related nuclear structures," Soil Dynamics and Earthquake Engineering, vol. 107, pp. 218-233, 2018. https://doi.org/10.1016/j.soildyn.2018.01.026

[4] Stewart, J. P., Fenves, G. L., & Seed, R. B, "Seismic soil-structure interaction in buildings. I: Analytical aspects," Journal of Geotechnical and Geoenvironmental Engineering, vol. 125, no. 1, pp. 26-37, 1999a. https://escholarship.org/uc/item/9t09660m

[5] Stewart, J. P., Seed, R. B., & Fenves, G. L, "Seismic soil-structure interaction in buildings. II: Empirical findings," Journal of Geotechnical and Geoenvironmental Engineering, vol. 125, no. 1, pp. 38-48, 1999b. https://escholarship.org/uc/item/7qp9w0tb

[6] Kim, S., & Stewart, J. P, "Kinematic soil-structure interaction from strong motion recordings," Journal of Geotechnical and Geoenvironmental Engineering, vol. 129, no. 4, pp. 323-335, 2003. https://doi.org/10.1061/(ASCE)1090-0241(2003)129:4(323)

[7] Mylonakis, G., & Gazetas, G, "Seismic soil-structure interaction: beneficial or detrimental?" Journal of earthquake engineering, vol. 4, no. 3, pp. 277-301, 2000. https://doi.org/10.1080/13632460009350372

[8] Gazetas, G. and Mylonakis, G, "Soil-structure interaction effects on elastic and inelastic structures," In Fourth International Conference on Recent Adavances in Geotechnical Earthquake Engineering and Soil Dynamics. Symposium in Honor of Professor W.D. Liam Finn. San Diego, California, 2001

[9] Cavalieri, F., Correia, A. A., Crowley, H., & Pinho, R, "Dynamic soil-structure interaction models for fragility characterisation of buildings with shallow foundations," Soil Dynamics and Earthquake Engineering, vol. 132, pp. 106004, 2020. https://doi.org/10.1016/j.soildyn.2019.106004

[10] Correia, A. A., Paolucci, R, "A 3D coupled nonlinear shallow foundation macro-element for seismic soil-structure interaction analysis," Earthquake Engineering and Structural Dynamics, submitted for publication, 2021

[11] Seismosoft, "SeismoStruct 2021 – a computer program for static and dynamic nonlinear analysis of framed structures," 2021, available at: http://www.seismosoft.com. Accessed from 17 Jan 2022

[12] Cavalieri, F., Correia, A. A., & Pinho, R, "Variations between foundation-level recordings and free-field earthquake ground motions: numerical study at soft-soil sites," Soil Dynamics and Earthquake Engineering, vol. 141, pp. 106511, 2021. https://doi.org/10.1016/j.soildyn.2020.106511

[13] Kramer, S. L, "Geotechnical earthquake engineering," Pearson Education India, 1996

[14] Mylonakis, G., Nikolaou, S., & Gazetas, G, "Footings under seismic loading: Analysis and design issues with emphasis on bridge foundations," Soil Dynamics and Earthquake Engineering, vol. 26, no. 9, pp. 824-853, 2006. https://doi.org/10.1016/j.soildyn.2005.12.005

[15] Pitilakis, K. D., Karapetrou, S. T., & Fotopoulou, S. D, "Consideration of aging and SSI effects on seismic vulnerability assessment of RC buildings," Bulletin of Earthquake engineering, vol. 12, no. 4, pp. 1755-1776, 2014. https://doi.org/10.1007/s10518-013-9575-8

[16] Karapetrou, S. T., Fotopoulou, S. D., & Pitilakis, K. D, "Seismic vulnerability assessment of high-rise non-ductile RC buildings considering soil–structure interaction effects," Soil Dynamics and Earthquake Engineering, vol. 73, pp. 42-57, 2015. https://doi.org/10.1016/j.soildyn.2015.02.016

[17] Mitropoulou, C. C., Kostopanagiotis, C., Kopanos, M., Ioakim, D., & Lagaros, N. D, "Influence of soil–structure interaction on fragility assessment of building structures," In Structures, Elsevier, vol. 6, pp. 85-98, 2016, May. https://doi.org/10.1016/j.istruc.2016.02.005

[18] Fathi, A., Sadeghi, A., Emami Azadi, M. R., & Hoveidae, N, "Assessing the soil-structure interaction effects by direct method on the out-of-plane behavior of masonry structures (case study: Arge-Tabriz)," Bulletin of Earthquake Engineering, vol. 18, no. 14, pp. 6429-6443, 2020.

https://doi.org/10.1007/s10518-020-00933-w

[19] Ostadan, F., & Ghiocel, D. M, "SASSI2000: A System for Analysis of Soil Structure Interaction-User's Manual," University of California, Berkeley, California, 2006.

[20] Hashash, Y. M. A., Musgrove, M. I., Harmon, J. A., Groholski, D. R., Phillips, C. A., & Park, D, "DEEPSOIL 7.0, User Manual". Urbana, IL, Board of Trustees of University of Illinois at Urbana-Champaign, 2016. Erişim adresi: http://deepsoil. cee. illinois. Edu/Files/DEEPSOIL_User_Manual_v6. pdf.

[21] Ishihara, K, "Soil Behaviour in Earthquake Geotechnics," Clarendon Press, 1996, pp. 338.

[22] Luco, J. E. and Westmann, R. A, "Dynamic response of circular footings," Journal of the Engineering Mechanics Division, 1972.

[23] Pecker, A. (Ed.), "Advanced earthquake engineering analysis," Springer Science & Business Media, vol. 494, 2008.

[24] Safi, M., & Mohammadi, N, "Models Used for Seismic SSI Problems: A Review," International Institute of Earthquake Engineering and Seismology (IIEES), 2019.

[25] Stewart, J. P., & Kwok, A. O, "Nonlinear seismic ground response analysis: Code usage protocols and verification against vertical array data," Geotechnical Earthquake Engineering and Soil Dynamics IV, 2008. https://escholarship.org/uc/item/7db3d49z

[26] Matasovic, N., & Vucetic, M, "CYCLIC CHARACTERIZATION OF LIQUEFIABLE SANDS. DISCUSSION AND CLOSURE," Journal of Geotechnical Engineering, vol. 121, no. 1, 1995.

[27] Pyke, R. M, "TESS: A computer program for nonlinear ground response analyses," TAGA engineering systems and software, Lafayette, California, 2000.

[28] Li, X. S., Wang, Z. L., & Shen, C. K, "SUMDES: A nonlinear procedure for response analysis of horizontally-layered sites subjected to multi-directional earthquake loading," Department of Civil Engineering, University of California, Davis, 1992.

[29] Bolisetti, C., Whittaker, A. S., Mason, H. B., Almufti, I., & Willford, M, "Equivalent linear and nonlinear site response analysis for design and risk assessment of safety-related nuclear structures," Nuclear Engineering and Design, vol. 275, pp. 107-121, 2014. https://doi.org/10.1016/j.nucengdes.2014.04.033

[30] Groholski, D. R., Hashash, Y. M., Kim, B., Musgrove, M., Harmon, J., & Stewart, J. P, "Simplified model for small-strain nonlinearity and strength in 1D seismic site response analysis," Journal of Geotechnical and Geoenvironmental Engineering, vol. 142, no. 9, pp. 04016042, 2016. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001496

[31] Yee, E., Stewart, J. P., & Tokimatsu, K, "Elastic and large-strain nonlinear seismic site response from analysis of vertical array recordings," Journal of Geotechnical and Geoenvironmental Engineering, vol. 139, no. 10, pp. 1789-1801, 2013. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000900

[32] Beuckelaers, W. J. A. P., Houlsby, G. T., & Burd, H. J, "A comparison of the series and parallel Masing-Iwan model in 2D," In Numerical Methods in Geotechnical Engineering IX (pp. 173-178, 2018). CRC Press.

[33] Numanoglu, O. A., Musgrove, M., Harmon, J. A., & Hashash, Y. M, "Generalized non-Masing hysteresis model for cyclic loading," Journal of Geotechnical and Geoenvironmental Engineering, vol. 144, no. 1, pp. 06017015, 2018. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001816

[34] Cavalieri, F., Correia, A. A., & Pinho, R, "Comparative nonlinear soil-structure interaction analyses using macro-element and soil-block modelling approaches," Bulletin of Earthquake Engineering, vol. 20, pp. 3295–3328, 2022. https://doi.org/10.1007/s10518-022-01379-y

[35] Jennings, P. and Bielak, J, "Dynamics of building-soil interaction," Bulletion of the Seismological Society of America, vol. 63, no. 1, pp. 9–48, 1973. https://doi.org/10.1785/BSSA0630010009

[36] Veletsos, A. and Meek, J, "Dynamic behavior of building-foundation systems," Earthquake Engineering and Structural Mechanics, vol. 3, pp. 121–138, 1974. https://doi.org/10.1002/eqe.4290030203

[37] Veletsos, A. and Nair, V, "Seismic interaction of structures on hysteretic foundations," Journal of the Structural DIVISION (ASCE), vol. 101, pp. 109–129, 1975. https://doi.org/10.1061/JSDEAG.0003962

[38] Veletsos, A, "Structural and Geotechnical Mechanics, chapter Dynamic of structure-foundation systems," pp. 333–361, 1977. Prentice-Hall, Englewood Cliffs, NJ.

[39] Wolf, J, ″Dynamic Soil-Structure Interaction," Prentice Hall, Englewood Cliffs, New Jersey, 1985.

[40] Avil´es, J. and P´erez-Rocha, L, "Evaluation of interaction effects on the system period and the system damping due to foundation embedment and layer depth," Soil Dynamics and Earthquake Engineering, vol. 15, pp. 11–21. 1996. https://doi.org/10.1016/0267-7261(95)00035-6

[41] ATC 40, "Seismic evaluation and retrofit of concrete buildings," Report atc, Applied Technology Council, 1996.

[42] FEMA 356, "Prestandard and commentary for the seismic rehabilitation of buildings," Report fema, Federal Emergency Management Agency, 2000.

[43] FEMA 450, "NEHRP recommended provisions for seismic regulations for new buildings and other structures," Provisions. Commentary. Report fema, Federal Emergency Management Agency, 2003.

[44] Avil´es, J. and P´erez-Rocha, L, "Soil-structure interaction in yieding systems," Earthquake Engineering and Structrual Dynamics, vol. 32, pp. 1749–1771, 2003. https://doi.org/10.1002/eqe.300

[45] Priestley, M. and Parck, R, "Strength and ductility of concrete bridges columns under seismic loading," ACI Structural JOURNAL, vol. 84, no. 1, pp. 61–76, 1987.

[46] Rodriguez, M. and Montes, R, "Seismic response and damage analysis of building supported on flexible soils," Earthquake Engineering and Structural Dynamics, vol. 29, pp. 647–665, 2000. https://doi.org/10.1002/(SICI)1096-9845(200005)29:5%3C647::AID-EQE929%3E3.0.CO;2-A

[47] Ghannad, M. and Jahankhah, H, "Site-dependent strength reduction factors for soil-structure systems," Soil Dynamics and Earthquake Engineering, vol. 27, pp. 99–110, 2007. https://doi.org/10.1016/j.soildyn.2006.06.002

[48] Robert, E. S, "Dynamic nonlinear soil-structure interaction (Doctoral dissertation, Ecole Centrale Paris), 2009.