The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

Soil structure interaction effects for strip foundations and layered soil

J.P. Pruiksma
TNO Structural Dynamics, Delft, The Netherlands

F. Besseling
Witteveen+Bos, Deventer, The Netherlands

ABSTRACT: Formula in seismic design codes and guidelines that cover inertial soil-structure interaction (SSI) effects are mainly developed for rigid circular or rectangular plate footings and homogeneous soil conditions. Analytical formula define period elongation and SSI damping based on foundation dimensions and soil stiffness. Corrections have been proposed for layered soils by a few researchers, based on the principle of depth averaging of stiffness. Residential buildings in the gas production induced seismicity region in Groningen (The Netherlands) typically have strip footing foundations and are built on relatively soft soils. It was questioned if the available analytical SSI formula apply to such buildings. For this reason a numerical FEM analysis study was performed investigating the behavior of such foundations. Period elongation effects were defined based on free vibration responses. SSI effects on spectral demand have been established based on time history analysis calculation of the acceleration and relative displacement demands. The interesting results of the study indicate ranges of conditions for which relative period elongation and increase of damping are significantly different compared to what would be predicted based on the existing code based formula for plate foundations.

1 INTRODUCTION

In the Groningen area, the gas production induced seismicity region in the north of The Netherlands, soil-structure interaction (SSI) effects are expected to be significant due to the abundance of very soft soils in the shallow subsurface. For the development of the Dutch code for seismic design, the NPR 9998 (2017), the implementation of the inertial soil-structure interaction in international codes has been investigated. Analytical formulae for inertial soil-structure interaction in international codes such as FEMA 440 (2005), ASCE-7-10 (2010), ASCE/SEI 41-13 (2014), and ASCE/SEI 41-17 (2017) are developed for rigid footings on a homogeneous linear elastic half space. These design formulae depend on relations for translational and rotational soil springs and dashpots, which can be traced back to two sources: Veletsos & Nair (1975) for rigid circular plate footings and Pais & Kausel (1988) for embedded rectangular plate footings. The period elongation in all codes is determined by combining the soil springs with the stiffness and equivalent height of the structure using the relation often credited to Veletsos & Meek (1974). SSI soil radiation damping is determined using approximate relations by Veletsos & Nair (1975) for circular footings and by Wolf (1985) for general rigid footings.

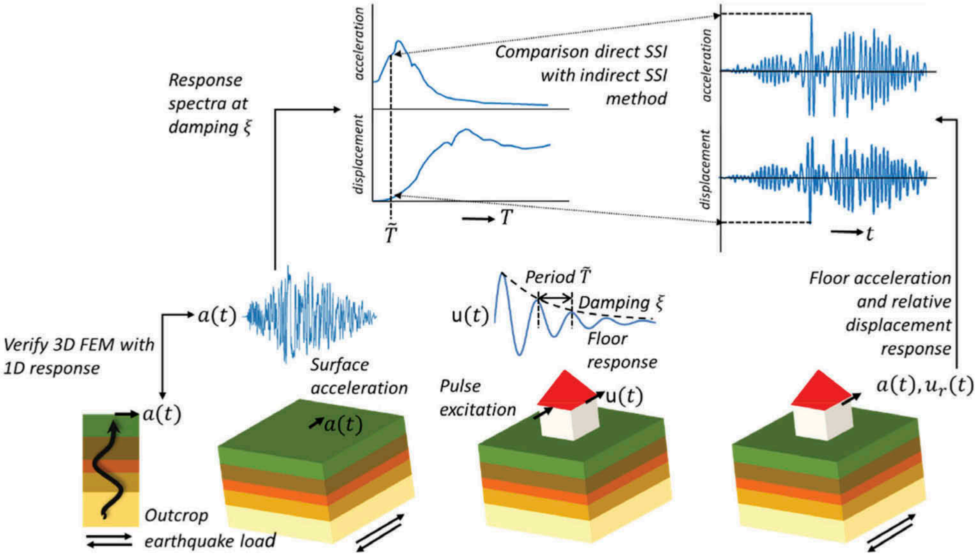
The shallow subsurface in the Groningen area is characterized by soft clays and peats deposited on stiffer sand layers. This raises the question to what extent the period elongation and damping formula for inertial SSI in international codes can be applied. In addition, residential buildings are often build on strip foundations that may not be assumed to behave as a rigid plate. The literature on these topics is scarce. NIST (2012) gives a guideline to compute average half space properties from layered soil data which are then used in the relations for rectangular foundations on a homogeneous half space. Other than this guideline, general SSI equations for buildings on stratified soil are not found. For individual building structures on stratified soils some case studies are available but neither the soil type, nor building type are common to the Groningen area.

In this paper fully coupled 3D finite element (FEM) models are used to address this question from a numerical point of view. Three different soil profiles are investigated representative of profiles commonly found in the Groningen area as well as a fourth fully homogeneous soil profile for benchmarking purposes with international codes. A rigid foundation as well as a two-strip foundation is investigated. Free vibration simulations are used to determine the period elongation and damping. Subsequently the models are subjected to earthquake loads to compare the fully coupled earthquake simulations with the response spectrum method. Two finite element packages were used for the simulations: Abaqus FEA and PLAXIS 3D. This enabled cross-benchmarking to avoid software package dependence of the results.

Simulations have been limited to linear elastic material behavior for both structure and soil to keep the focus on soil stratification and footing type while keeping other parameters as close to the SSI provisions found in international earthquake design codes.

2 COMPUTATIONAL METHOD

Figure 1 illustrates the work that has been carried out. Different soil profiles have been modelled of which 1D site response simulations (Figure 1a) have been used to verify the site response with the 3D soil block (Figure 1b). The free surface acceleration from the site response is used to compute acceleration and relative displacement response spectra which are evaluated at the damping and period computed from free vibration simulations (Figure 1c) where a structure is placed on a soil block, excited and left to freely vibrate. The resulting damping and period elongation is compared with analytical formulae. The same building structure and soil block are then used in earthquake simulations using the input records already used in the site response simulations (Figure 1d). The peak acceleration response of the floor of the building structure and the peak relative displacement response are compared with the response spectrum method.



a) 1D site response (DEEPSOIL)

b) 3D FEM site response

c) 3D FEM Free vibration response

d) 3D FEM earthquake simulation

Figure 1. Map of the performed work.

2.1 *Selected soil profiles and 3D soil-block modeling*

Three soil profiles have been selected near Amsweer, Ten Post and Slochteren. Figure 2 shows the schematization derived from available SCPT data. These profiles cover a range of soils found in the Groningen region. The Slochteren profile being a stiffer sandy profile is more representative of the south eastern part of the Groningen area. The Amsweer and Ten Post profiles have soft soil top layers more representative of the central area of Groningen. These two profiles do contain organic material and have been selected specifically to check the influence impedance contrasts on the soil radiation damping. Below the depth of 30 m half space properties are assumed of 300 m/s shear wave velocity and a density of 20 kN/m^3. As a benchmark case a soil homogeneous half space profile is used with a unit weight of 16.7 kN/m^3 and a shear wave velocity of 100 m/s. This profile serves to check SSI results with analytical formulae from literature.

The soil profiles are modelled in 3D in Abaqus FEA and PLAXIS 3D. Figure 3 shows the geometry. In Abaqus FEA explicit time integration was used and the soil block has an extent of 100 m x 100 m in horizontal direction and is 35 m deep. The model uses 8 node hexahedral elements of which the vertical size is about 0.5 m in the top layers ensuring a 50 Hz resolution at 4 nodes per wavelength for shear waves. Horizontally elements are about 1 m near the structure and coarser towards the edge of the model. In PLAXIS 3D implicit time integration is used. The model size is 75 m x 75 m horizontally and 35 m deep. The elements used are 10 node tetrahedrons with about 1 m spacing between nodes near the structure and coarser towards the edges.

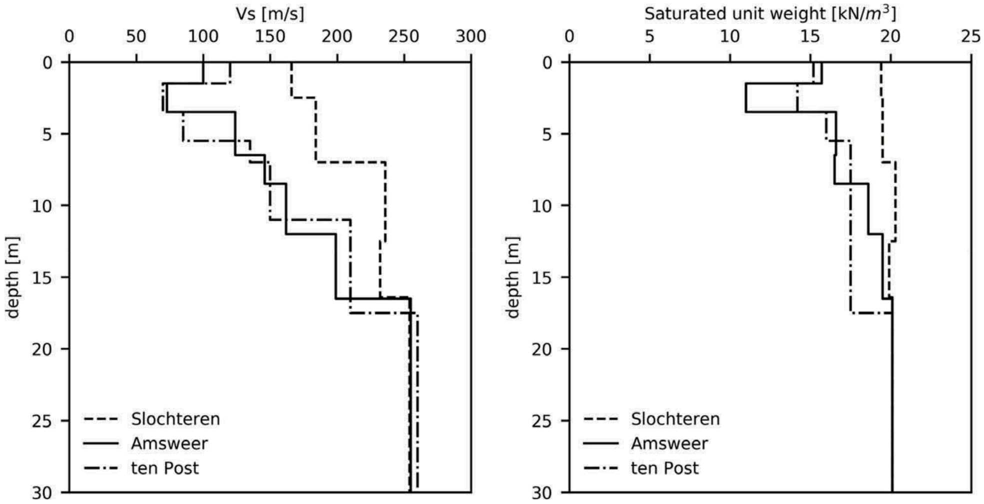


Figure 2. Soil shear wave velocity and unit weight profiles.

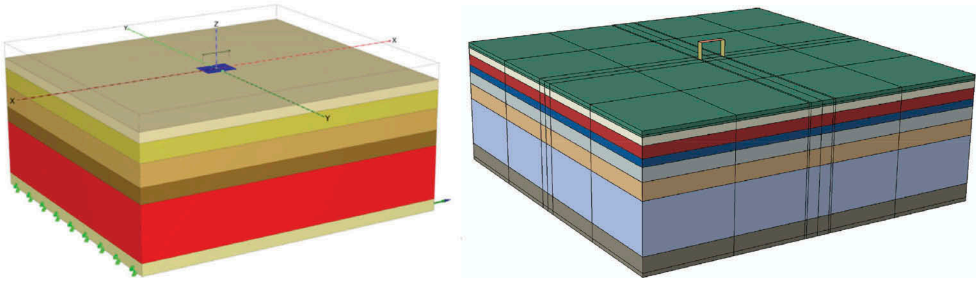


Figure 3. Soil blocks used in PLAXIS 3D (left) and Abaqus FEA (right)

The soil material model is linear elastic and the parameters for the soil profiles are derived from Figure 2 using a Poisson's ratio of 0.3. The soil has been given a small viscous material damping of 1% at 10 Hz to reduce any spurious high frequency oscillations.

As boundary conditions, the PLAXIS model uses absorbing boundaries at the bottom and sides. The Abaqus FEA model uses absorbing boundaries at the bottom and sides during the free vibration simulations. For the earthquake simulations, an absorbing boundary has been used at the bottom and for the sides of the model nodes on opposite sides are tied in the degree of freedom perpendicular to the plane.

2.2 *Model of the building structure*

Figure 4 shows the building structure that was used in the simulations. For a representative house in the Groningen area (Figure 4a) the equivalent mass m_{eff}, height h_{eff} and stiffness k are derived using relations from Chopra (1980). These are the properties for stick models used in international codes (Figure 4b). The actual finite element model used in the simulations in this paper is modelled as closely to the stick model as possible while at the same time allowing a two-strip foundation (Figure 4c and d). This is done to allow a good comparison of SSI behavior between analytical formulae and fully coupled FEM simulations. The building properties are listed in Table 1.

The PLAXIS 3D model (Figure 4d) uses a portal frame made up of beams, while the Abaqus FEA model uses shell elements (Figure 4c). Both models are used either on a rigid foundation or a strip foundation. The rigid foundation is modelled in Abaqus FEA by tying the bottom of the structure to the surface elements of the soil spanning the foundation area. In PLAXIS 3D, a stiff plate element on the foundation area is used to accomplish this. For the strip foundation two strips of 0.6 m width and length $2B$ are used with a depth of 1 m. These are modelled as rigids in Abaqus FEA and with a very stiff material in PLAXIS 3D. The effect of the coupling between the strips has been investigated as a function of the stiffness of the coupling, see Figure 4d.

To center the building structure on the two strips the distance between the legs of the portal frame is 7.4 m. The height of the building structure is the equivalent height h_{eff} and total mass of the structure is m_{eff} which is distributed such that 95% is in the floor and 5% in the legs. The floor is modelled as a rigid in Abaqus FEA and is very stiff in PLAXIS 3D. The stiffness of the legs is tuned such that the fixed base period of the structure is $T = 0.15s$. The structure is given an equivalent viscous damping of 5% at the frequency corresponding to the fixed base period of 0.15 s using Rayleigh beta damping in both FEM packages. Fixed base free vibration simulations have been carried out to verify the fixed base period and 5% damping.

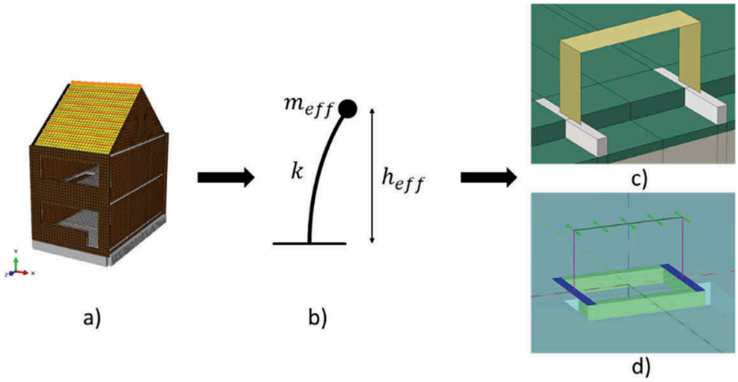


Figure 4. Building models: a) 3D FEM model used to derive b) schematization for analytical formulae, c)/d) extension of schematization to present study to allow strip footings (shown) as well as rigid foundation in Abaqus FEA c) and PLAXIS 3D d).

Table 1. Building parameters used in the analyses.

Building parameter	value
Total building mass	102600 kg
Effective mass m_{eff}	63000 kg
Effective height h_{eff}	4.8 m
Structural period T	0.15 s
Structural stiffness k	110.5 MN/m
Foundation length $2L$	8 m
Foundation width $2B$	6 m
Inherent (viscous) damping ratio ζ_0	5%

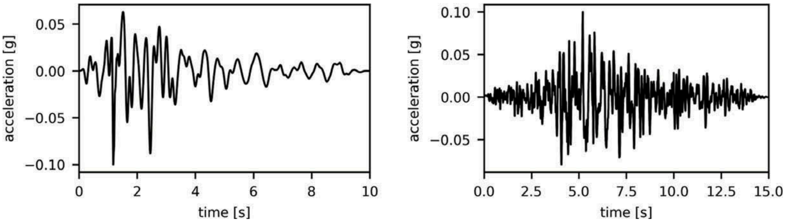


Figure 5. Selected records for the simulations.

2.3 *Selection of ground motion records*

Two records have been selected from those made available for site response in the NPR 9998 (2015), see Figure 5. These records are matched to the outcrop spectrum at 30 m depth and can be used for site response. Out of the 11 available records, two records are chosen that differ most in terms of duration to have enough variation for the goal of the present study in terms of the SSI effect.

3 FREE VIBRATION SIMULATION RESULTS

For each of the four soil profiles, the structure is excited and left to freely vibrate. The floor displacement has been used to determine the period and damping. This has been done for both the rigid and strip foundation case. The simulation results between PLAXIS 3D and Abaqus FEA are in such a close agreement that no distinction is made in the presentation of the results.

Figure 6 shows the free vibration result for the building structure on rigid foundation for the Amsweer soil profile. The analytical solution of a SDOF system, $u = Ae^{-\omega\zeta t}\sin(\omega_d t)$ is fitted through the 3D finite element results, with $\omega_d = \omega_0\sqrt{1-\zeta^2}$ the damped natural frequency of the structure/soil system. Both the total damping ζ as well as the elongated period $\tilde{T} = 2\pi/\omega_d$ is then determined. This procedure is followed for all soil profiles and both rigid and strip foundation. The SDOF fit is excellent in all cases and the results are presented in Tables 2 and 3.

For the rigid foundation, SSI equations from NIST (2012) are applied. Equation 1, originally derived by Veletsos & Meek (1974), is used to compute the period lengthening:

$$\tilde{T} = T\sqrt{1 + \frac{k}{k_x} + \frac{kh^2}{k_{yy}}} \tag{1}$$

With k the structural stiffness and $h = h_{eff}$ the effective height from Table 1. k_x and k_{yy} are the translational and rotational soil spring stiffnesses under the foundation. These are computed using the formulae from the NIST (2012) tables 2.2a and 2.3a. These formulae are for foundations on a homogeneous half space and were originally derived by Pais & Kausel

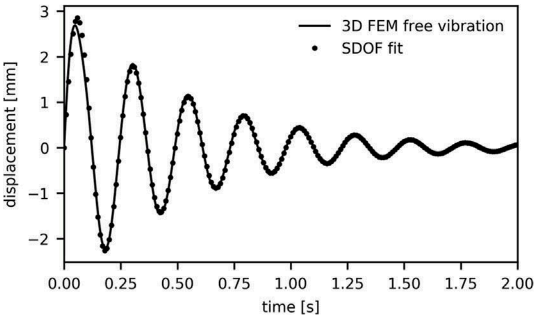


Figure 6. Floor displacement in free vibration for the rigid foundation on the Amsweer soil profile.

Table 2. Rigid foundation period and damping 3D FEM compared with NIST (2012).

Soil profile	period [s]		total damping [%]	
	3DFEM	NIST	3DFEM	NIST
Homogeneous	0.215	0.213	13.8	13.5
Slochteren	0.17	0.17	6.0	6.9
Amsweer	0.244	0.241	7.4	16.9
Ten Post	0.237	0.239	7.6	16.3

Table 3. Strip foundation period and total damping for the 3D FEM simulations.

Soil profile	period [s]	total damping [%]
Homogeneous	0.265	7.0
Slochteren	0.199	3.8
Amsweer	0.286	4.5
Ten Post	0.268	5.5

(1988) and Gazetas & Stokoe (1991). They need as input the foundation dimensions, embedment (which is set to zero here) and the soil shear modulus and Poisson's ratio. These soil parameters are computed from the shear wave velocity profiles in Figure 2 using depth averaging as recommended by NIST (2012) equation 2-18. The SSI system damping is then calculated using Equation 2 which is by Wolf (1985).

$$\beta = \frac{1}{\left(\frac{\tilde{T}}{T_x}\right)^2}\beta_x + \frac{1}{\left(\frac{\tilde{T}}{T_{yy}}\right)^2}\beta_{yy} + \frac{\zeta_0}{\left(\frac{\tilde{T}}{T}\right)^3}, T_x = 2\pi\sqrt{\frac{m}{k_x}}, T_{yy} = 2\pi\sqrt{\frac{mh^2}{k_{yy}}} \tag{2}$$

Here $m = m_{eff}$ is the effective structural mass from Table 1 and β_x and β_{yy} are the translational and rotational soil dashpot values under the foundation. These are likewise calculated with the formula in the aforementioned tables 2.2a and 2.3a from NIST (2012). The power 2 in the denominator of the 2nd term in Equation 2 is recommended by NIST (2012) and the power 3 in the denominator of the 3rd term is used because the structural damping is chosen linear viscous. It is noted that the period elongation and damping in Equation 1 and Equation 2 depend on frequency. As such an iterative scheme is used to compute the values.

Table 2 shows that the period elongation for the rigid foundation is computed very accurately by the depth averaging procedure in NIST (2012) for all soil profiles. The damping for the homogeneous soil profile from the NIST analytical formulae is in close agreement with the 3D FEM result giving confidence in the followed FEM procedure. For the stratified soft soil profiles the damping in the 3D FEM simulations is significantly lower than the analytical formulae. This is due to the reflection of energy from the stiffer layers back to the surface.

For the strip foundation as expected the period elongation is larger than for rigid foundation, while the damping is smaller due to the smaller strips imparting less energy to the soil.

4 FULLY COUPLED SIMULATION RESULTS

The selected earthquake ground motions have been applied as outcrop at 30 m depth of all the soil profiles. Simulations without building structure were run first and the results are in close agreement to those of 1D site response using Deepsoil, Hashash et al (2015). Subsequently, earthquake simulations with structure were performed. Figures 7, 8 and 9 show a selection of results for the homogeneous and Amsweer soil profiles. The 5% acceleration and displacement response spectra are shown with a marker at the fixed base period of the structure. The response spectra computed at the damping resulting from the free vibration simulations are shown as well with a marker corresponding to peak floor response in the earthquake simulations at the elongated period found in the free vibration simulations. For the displacement spectra the response has been divided by the square of the period lengthening to compensate for the base compliance effect, that part of the relative displacement is the relative displacement of the foundation and the free field motion, see Wolf (1985). Relative displacement is computed from the 3D FEM simulations by subtracting foundation translational displacement and effective height times foundation rotation from the floor displacement. For the strip foundation the relative displacement is not computed and only floor acceleration is shown.

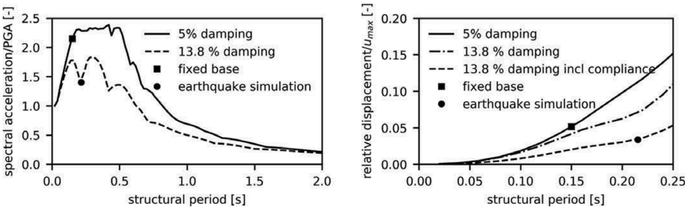


Figure 7. Homogeneous soil profile earthquake simulation results for the rigid foundation.

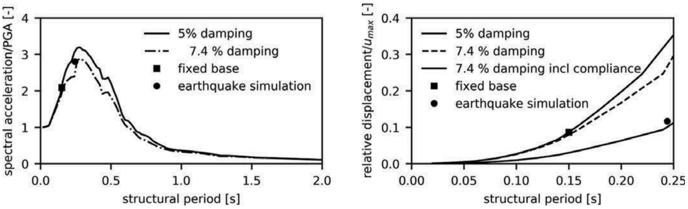


Figure 8. Amsweer soil profile earthquake simulation results for the rigid foundation.

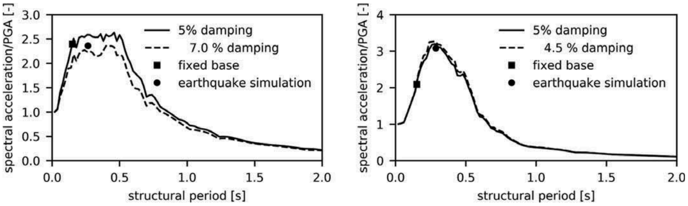


Figure 9. Earthquake simulation results for the strip foundation. Homogeneous soil profile (left), Amsweer soil profile (right).

The results show that the earthquake simulations are in close agreement with the response spectrum method using the 3D FEM free vibration period and damping, both for the rigid and strip foundation. This confirms that damping values for stratified soil, in particular the soft profiles, are indeed lower than found using analytical formulae.

5 CONCLUSIONS

Soil radiation damping and period lengthening have been computed for a building structure with a rigid and strip foundation on different soils. The results have been compared favorably to fully coupled earthquake simulations. For a rigid foundation on homogeneous soil the obtained results are in full agreement with analytical SSI formulae in literature. For rigid foundations on layered soils the period lengthening can be estimated accurately using analytical formulae with averaging soil properties over the foundation influence depth. However, for the considered soil profiles consisting of layered soft soils on a sand deposit, soil radiation damping is overestimated by analytical formulae compared to the detailed simulations in the present study. Because the shear wave velocity increases with depth, wave energy radiated from the structure is reflected back to the structure by the stiffer layers effectively reducing radiation damping. The effect is less pronounced for the stiffer sandy soil profiles because the variation of shear wave velocity with depth is much less.

For a building structure on two foundation strips, the period lengthening is larger and the soil radiation damping is smaller than for the building on a rigid foundation. For a foundation comprising a grid of rigidly coupled strip footings, the SSI behavior is close to the response of a rigid plate footing. The simulation results indicate that the extent to which a grid of strip footings prevents rotation of the individual strips is the primary factor that determines if soil damping of rigid footings can be approached.

REFERENCES

ASCE-7-10. 2010. Minimum Design Loads for Buildings and Other Structures. Reston, Virginia: American Society of Civil Engineers.

ASCE/SEI 41-13. 2014. Seismic evaluation and retrofit of existing buildings. Reston, Virginia: American Society of Civil Engineers.

ASCE/SEI 41-17. 2017 Seismic Evaluation and Retrofit of Existing Buildings, Reston, Virginia: American Society of Civil Engineers.

Chopra, A.K. 1980. Dynamics of structures. Earthquake engineering research institute

FEMA 440. 2005. Improvement of nonlinear static seismic analysis procedures. Redwood city, California: Applied Technology Council.

Gazetas, G. & Sokoe, K.H. 1991. Free vibration of embedded foundations: Theory versus experiment. Journal of Geotechnical Engineering 117(9): 1382-1401

Hashash, Y.M.A. & Musgrove, M. & Groholski, D.R. & Phillips, C.A. & Park, D. 2015. Deepsoil 6.0, User manual.

NIST. 2012 Soil-structure interaction for building structures. Redwood city, California: NEHRP Consultants Joint Venture.

NPR 9998. 2015. Assessment of buildings in case of erection, reconstruction and disapproval – Basic rules for seismic actions: induced earthquakes. Delft, The Netherlands: Koninklijk Nederlands Normalisatie-instituut (NEN)

NPR 9998. 2017. Assessment of buildings in case of erection, reconstruction and disapproval – Basic rules for seismic actions: induced earthquakes. Delft, The Netherlands: Koninklijk Nederlands Normalisatie-instituut (NEN)

Pais, A. & Kausel, E. 1988. Approximate formulas for dynamic stiffnesses of rigid foundations. *Soil Dynamics and Earthquake Engineering* 7(4): 213-227

Veletsos, A.S. & Meek, J.W. 1974. Dynamic behavior of building-foundation systems. *Earthquake engineering and structural dynamics* 3(2): 121-138

Veletsos, A.S. & Nair, V.V. 1975. Seismic interaction of structures on hysteretic foundations. *Journal of Structural Engineering* 101: 109-129

Wolf, J.P. 1985. Dynamic soil-structure interaction. Prentice-Hall