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Numerical investigation on dynamic response of a steel lattice tower under various seismic events

Tomasz Falborski[1], Natalia Lasowicz[2]

Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Gdańsk, Poland

E-mail: [1]tomfalbo@pg.edu.pl (corresponding author)

Abstract. The present paper presents the results of the numerical study designed to investigate the soil-structure flexibility effects on modal parameters (i.e. fundamental frequencies) and time-history analysis response (represented by the top relative displacements) of a 46.8 m high steel lattice tower subjected to a number of ground motions including also one mining tremor. In addition to the fixed-base condition, three different soil types (i.e. dense soil, stiff soil, and soft soil) were considered in this investigation. Site conditions were characterized by their average effective profile velocities, Poisson's ratios, and finally mass densities. Soil-foundation flexibility was introduced using the spring-based approach, utilizing foundation springs and dashpots. The first step was to investigate the influence of different base conditions on modal parameters of the steel lattice tower. In the final part of the current study time-history analysis was performed using different two-component ground motion records (in two horizontal, mutually perpendicular directions). The results obtained indicate that modal parameters and dynamic response of the structure may be considerably affected by the soil-structure interaction effects. Therefore, the present paper confirms the necessity of utilizing soil-flexibility into numerical research.

Keywords: steel lattice tower, dynamic analysis, earthquake excitations, soil-structure interaction effects.

Introduction

There are many different types of structures that need to remain either intact or least operational immediately after a disaster such as a strong earthquake shaking. Serviceability of facilities like hospitals, fire and police stations or telecommunication centres are fundamental in case of an emergency situation. Moreover, power plants and transmission towers which provide electricity, as well as telecommunication masts which ensure signals for cell phones are also recognized to be strategic structures whose safety and reliability are issues of particular importance in many seismically-active regions of the world (see, for example, Behrouz, Soheil, Arash, & Masoud, 2016; Sato & Ishikawa, 2012).

Dynamic response of a structure may be modified by a number of different factors (see, for example, Falborski & Jankowski, 2017, Falborski, Sołtysik, & Jankowski, 2018). The most common contributors, however, are incorporation of additional bracing systems in steel structures (see, for example, Lasowicz & Falborski, 2018a), utilizing active or passive structural control devices (see, for example, Naderpour, Naji, Burkacki, & Jankowski, 2019; Lasowicz, Falborski, & Jankowski, 2018a; Lasowicz, Kwiecień, & Jankowski, 2018b; Falborski & Jankowski 2018a, 2018b, 2012; Lasowicz & Jankowski, 2016, 2017), possible pounding between the adjacent buildings (see, for example, Miari, Choong, & Jankowski, 2019; Sołtysik, Falborski, & Jankowski, 2017, 2016), and finally soil-structure interaction effects (see, for example, Lasowicz & Falborski, 2018b; Gazetas, 1991; Wolf, 1985). Neglecting either one of these aspects may significantly alter the dynamic response, and eventually result in incorrect interpretation of the actual structural behaviour due to strong dynamic excitations (see, for example, Mylonakis & Gazetas, 2000; Wong, Trifunac, & Luco, 1988; Stewart & Fenves, 1998).

Motivated by these aspects, the present study was designed to numerically investigate the soil-structure flexibility effects on modal parameters and time-history response of a 46.8 m high steel lattice telecommunication tower subjected (to a number of strong ground motions, including one mining tremor serving as an example of so-called human-induced seismicity (see, for example, Zembaty, 2004). Different soil conditions were characterized by their average effective profile velocities, mass densities and Poisson's ratios. Soil flexibility was introduced using the spring-based approach, utilizing foundation springs and dashpots, as it is the most frequently adopted approach to capture the interaction between the structure and the underlying soil (see, for example, Harden & Hutchinson, 2009; Mylonakis, Nikolaou, & Gazetas, 2006; Stewart, Kim, Bielak, Dobry, & Power, 2003; Stewart, Fenves, & Seed, 1999a, 1999b; Pais & Kausel, 1988).

Numerical model and soil flexibility

Finite element (FE) model of the analyzed structure as well as the whole numerical investigation of its response to a number of various ground motions were conducted using the educational version of Autodesk Robot Structural Analysis Professional (ARSAP) 2019, which is counted among the most popular civil engineering software programs in Poland.

The telecommunication tower considered in this research is a 46.8 m high steel lattice structure resting on a circular concrete mat foundation. The structure consists of thirteen 3.60 m high segments, most of which gradually narrow upward. The three-dimensional FE model of the tower consists of 162 beam elements, whereas the mat foundation was modelled with standard 4-node shell elements available in ARSAP. In order to incorporate the weight of the equipment and other heavy components, additional masses were added at the upper parts of the tower model. Eventually, the total mass of the analyzed structure is approximately 20 tons. Two different views of the numerical model along with the key dimension and global coordinate system XYZ are presented in Figure 1.

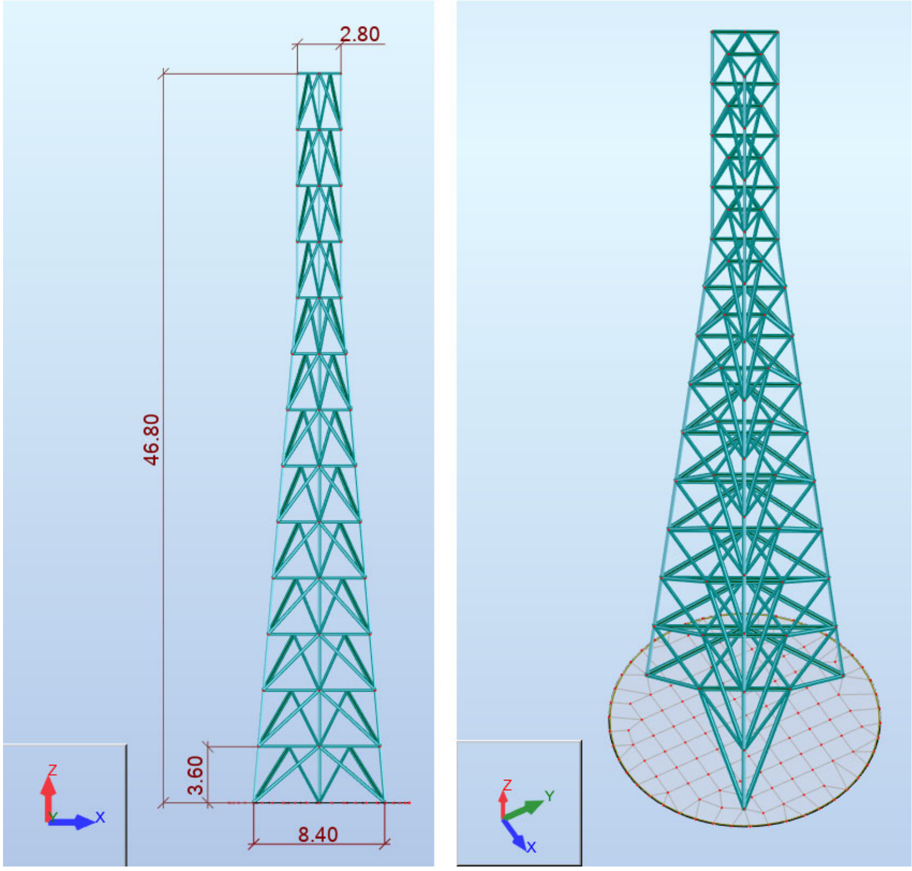

Figure 1. FE model of the steel lattice tower

In addition to the fixed-base condition, three different soil types (i.e. dense soil, stiff soil, and soft soil) were considered in the present study. Site characteristics were briefly represented by the average effective profile velocities, Poisson's ratios, and finally mass densities as introduced in Table 1. In accordance to the current engineering practice these values were employed in order to estimate key parameters for the foundation springs and dashpots, which were than distributed under the mat foundation.

Table 1. Characteristics of different soil types

Soil type	Shear wave velocity (m/s)	Poisson's ratio (-)	Mass density (kN/m^3)
Dense soil	450	0.40	20
Stiff soil	300	0.35	18
Soft soil	150	0.30	16

Modal analysis

The next step was to perform modal analysis in order to examine the soil flexibility effects on natural frequencies of the steel lattice tower considered in the present study. Two fundamental modes of vibration for the fixed-base structure are shown in Figure 2. The next step was to perform modal analysis in order to examine the soil flexibility effects on natural frequencies of the steel lattice tower considered in the present study. Results for different base conditions are graphically presented in Figure 3.

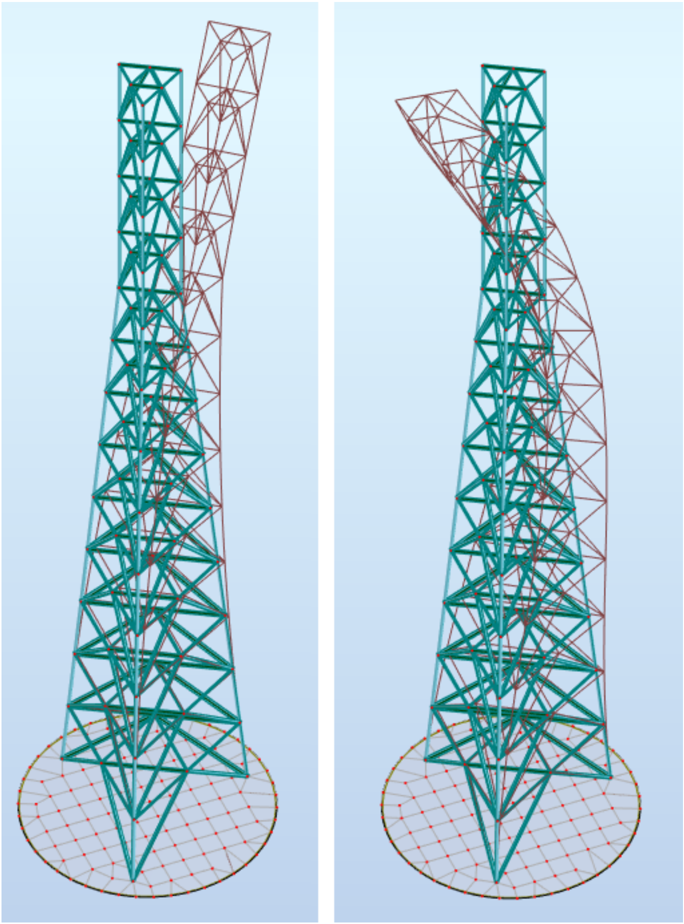

Figure 2. Two fundamental modes of vibration of the steel lattice tower

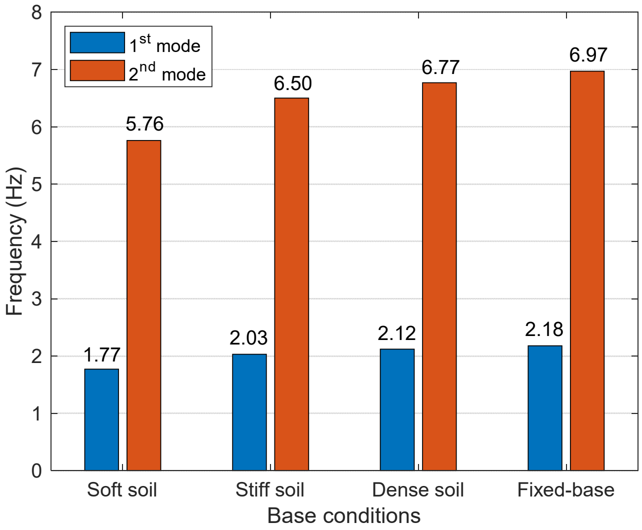

Figure 3. Natural frequencies of the structure for different base conditions

Dynamic analysis

In the final part of the present investigation dynamic transient analysis was conducted. The FE model of the steel lattice tower with different base conditions was subjected to a number of dynamic excitations including two earthquakes and one mining tremor which is as an example of the human-induced seismicity occurring frequently in the mining regions of Poland. Each of these ground motions was represented in the numerical investigation by two horizontal (mutually perpendicular) components. The list of the ground motions considered in the present study along with the peak ground acceleration values in both directions are presented in Table 2 (global Y and X directions are shown in Figure 1). In order to conduct time-history analysis Newmark's average acceleration method was employed (Newmark 1959). The damping ratio for the steel structure was assumed as 0.02 (i.e. 2% which is a typical value for steel and metal structures). Peak lateral displacements are summarized in Table 3. Examples of computed time-history records, in both Y and X global directions, for the El Centro earthquake of 1940, and Polkowice mining tremor of 2002 are presented in Figures 4–7.

Table 2. List of ground motions considered in the study

Ground motion (year)	Station	Peak Ground Acceleration Y direction	Peak Ground Acceleration X direction
El Centro earthquake (May 18, 1940)	Imperial Valley	3.069 m/s^2 = 0.313 g	2.107 m/s^2 = 0.215 g
Athens earthquake (Sept. 7, 1999)	Sepolia	3.201 m/s^2 = 0.326 g	3.045 m/s^2 = 0.31 g
Polkowice mining tremor (Feb. 20, 2002)	Polkowice	1.615 m/s^2 = 0.165 g	0.955 m/s^2 = 0.097 g

Table 3. Dynamic transient analysis results

Base conditions	Peak relative computed displacement (cm)					
	El Centro earthquake		Athens earthquake		Polkowice mining tremor	
	Y direction	X direction	Y direction	X direction	Y direction	X direction
Soft soil	8.6	6.1	6.2	5.5	1.7	1.0
Stiff soil	10.7	7.3	7.0	6.1	1.9	1.2
Dense soil	11.5	8.6	7.2	6.3	2.4	1.4
Fixed-base	13.1	11.1	7.7	6.9	3.6	2.2

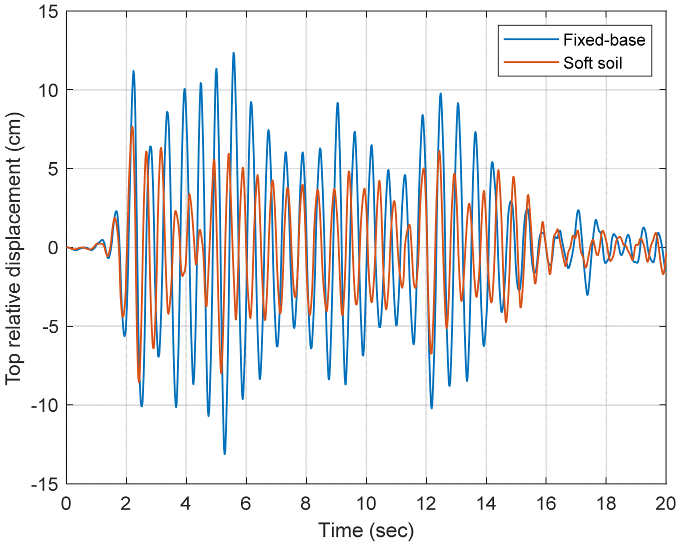

Figure 4. Time-displacement history for the El Centro earthquake (Y direction)

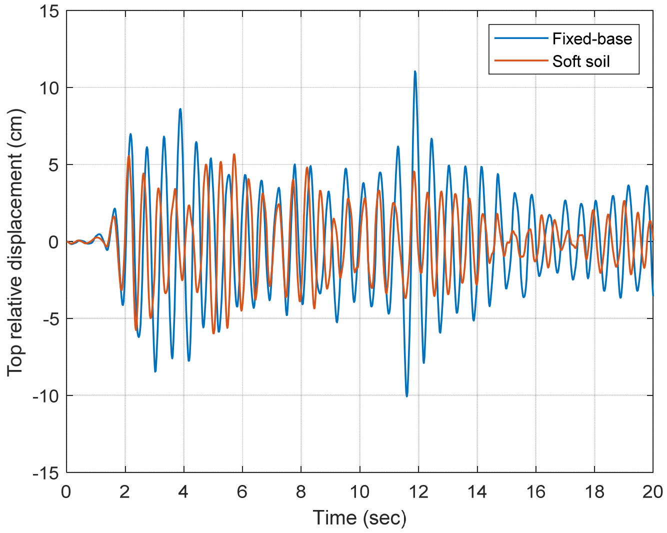

Figure 5. Time-displacement history for the El Centro earthquake (X direction)

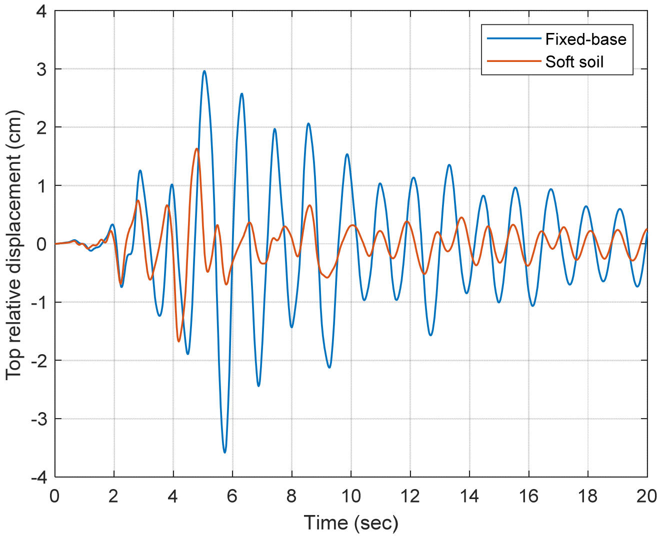

Figure 6. Time-displacement history for the Polkowice mining tremor (Y direction)

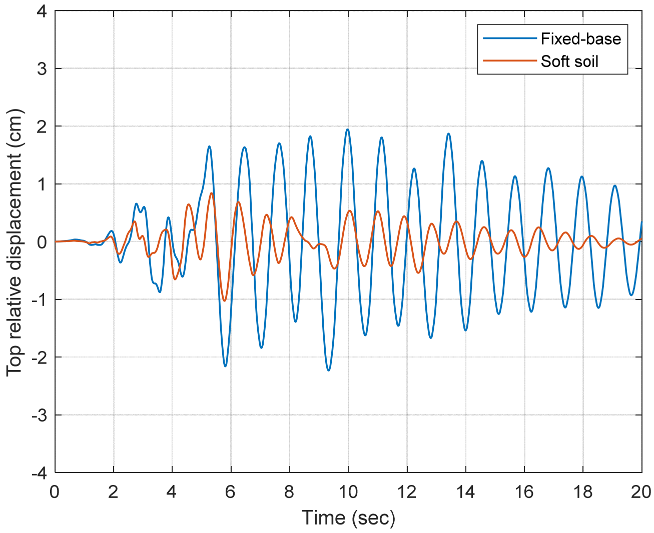

Figure 7. Time-displacement history for the Polkowice mining tremor (X direction)

Conclusions

In the present paper the soil-structure flexibility effects on modal parameters and time-history analysis response of a 46.8 m high steel lattice telecommunication tower under different dynamic excitations were numerically investigated. Soil conditions were characterized by their average effective profile velocities, mass densities and Poisson's ratios. In order to capture the interaction between the structure the underlying soil in the numerical study the spring-based approach was adopted.

Inspection of Figure 3 shows that the soil-structure interaction affects modal parameters of the steel lattice tower. When compared to the fixed-base condition, the frequencies corresponding to the 1st and the 2nd mode of vibration of the structure resting on a soft soil were decreased by 19% (from 2.18 to 1.77 Hz) and 18% (from 6.97 to 5.76 Hz), respectively.

Table 3 along with Figures 4–7 demonstrates that soil flexibility strongly modifies the time-history analysis results. Again, when compared to the fixed base conditions, the peak lateral displacements computed for the structure resting on the soft soil, for Y and X directions, respectively, were decreased by 35% and 45% for the El Centro earthquake, 19% and 20% for the Athens earthquake, and finally 52% and 54% for the Polkowice mining tremor.

The results of this investigation clearly demonstrate the importance of soil-structure flexibility as it may considerably modify modal characteristics as well as the dynamic response of a structure.

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