Predictions on the seismic response of monumental towers on soft soil

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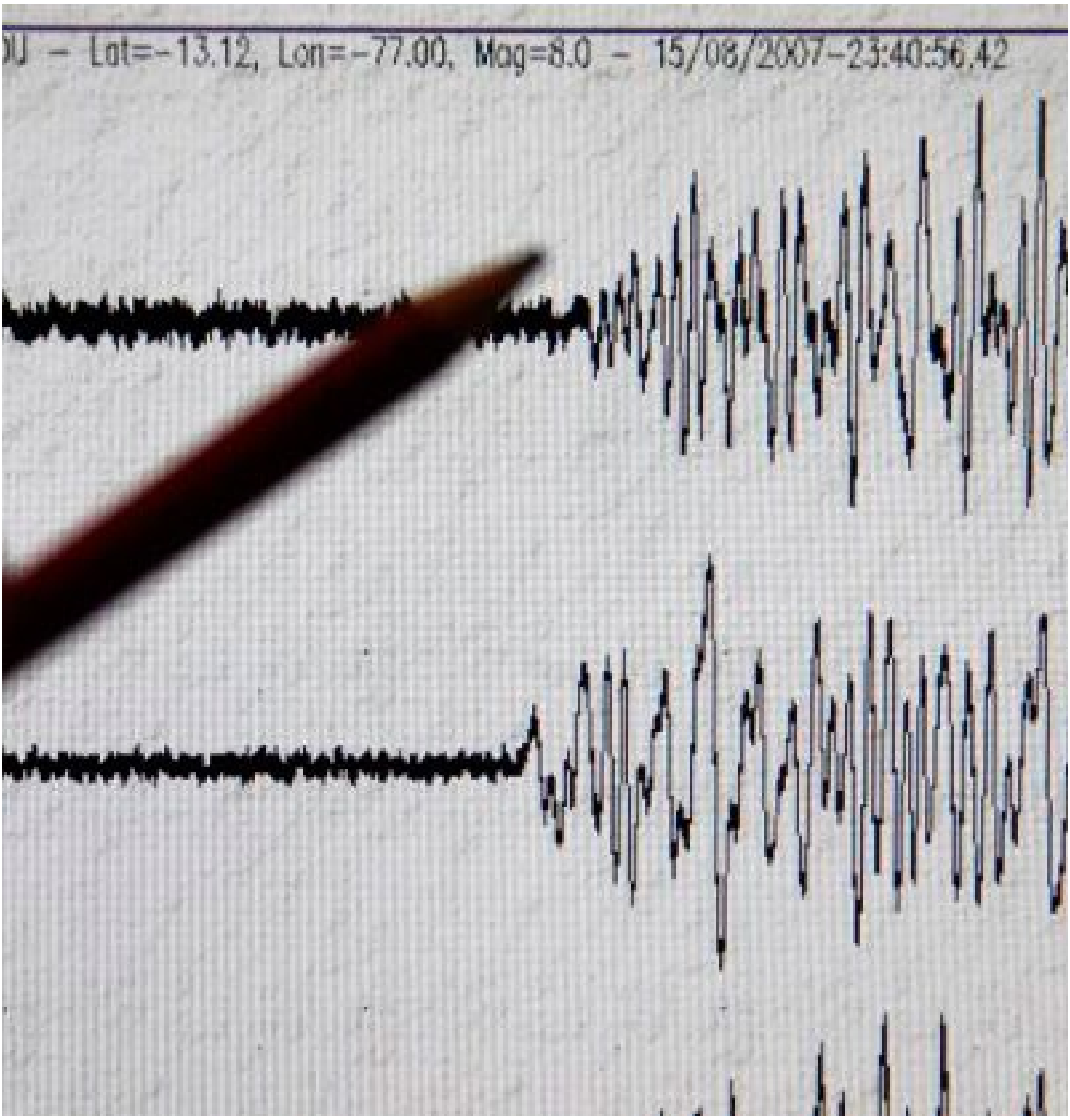
Abstract

After the damages to the cultural heritage caused by the most recent earthquakes, the protection of ancient buildings is an urgent and relevant theme in Europe, especially in the Mediterranean countries, characterized by high seismic hazard. The fine tuning of the seismic protection requires analyses on refined models in order to catch the dynamic behaviour of the soil–foundation– structure system in a lifelike way. Neglecting soil structure interaction effects, in fact, may be conservative or not, depending on the structural pattern and the nature of the subsoil. Focusing on the historical towers, the most symbolic building among monuments, a method is here proposed for preliminary predictions on the variation of natural period and damping ratio due to the dynamic interaction between soil and structure. The simplified approach is then applied to three cases of monumental towers on soft soil, located in three European cities, characterized by high seismic hazard.



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1. EUROPEAN SEISMIC HAZARD

The European Seismic Hazard map, reported in Figure 1, has been realized in the framework of the European project SHARE, http://www.share-eu.org, (Woessner et al., 2015). The map illustrates the peak ground acceleration (PGA) on a rigid rock outcrop, corresponding to a return period of 475 years (i.e. probability of exceedance equal to 10% in 50 years). According to the map, the highest level of the seismic hazard is estimated along the North Anatolian Fault Zone, reaching value of PGA>0.75g in the Aegean and in the Marmara Sea. Similar hazard values characterize Iceland along the plate boundary of the Mid-Atlantic ridge transform faults. PGA>0.50g correspond to the Appennines in Italy and the Cephalonia fault zone from the Western Greece until Albania. The Balkan and Mediterranean countries such as Italy, Turkey, Eastern Greece, Bulgaria and Romania show significant level of seismic hazard, reaching PGA>0.35 g. Relevant hazard with PGA around 0.25 g, characterizes Brussels in Belgium, Lisbon in Portugal and some areas near Budapest in Hungary and along the Pyrenees mountain.

Earthquakes may impact on the European society and strongly affect the lives of European citizens, as occurred in the 1999 in Izmit (Turkey), when a strong earthquake of local magnitude M_L 7.6 killed 17 000 people. More recently in Italy a 5.9 magnitude shock in L'Aquila (2009) killed more than 300 people and destroyed part of the historical centre. The last European earthquake occurred in 2012 in Emilia (Italy) when, due to a 5.8 magnitude event, 5000 people were displaced and a lot of industrial buildings damaged, causing severe economic losses.

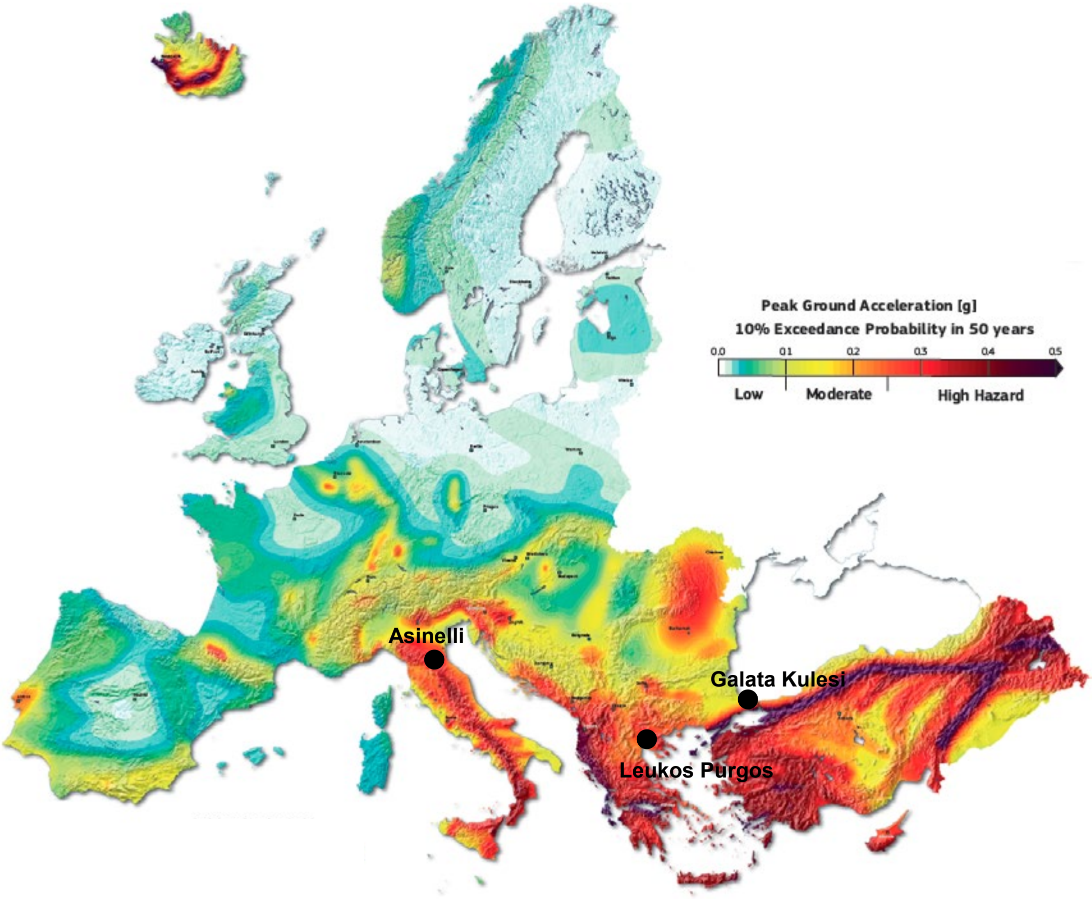

Figure 1: European Seismic Hazard Map (http://www.share-eu.org).

2. MONUMENTAL TOWERS AND SEISMIC HAZARD

Towers are important expressions of monumental heritage in Europe, especially in Italy which boasts the largest cultural heritage of the world. Civic or bell towers, lighthouses, dovecotes, dungeons, watchtowers and clock towers are generally identified as towers, due to their common monolithic shape with a small base, but their function is very different. The height and the consequent structural texture generally depend on building function and are sometimes related to building age, type of materials and social-economical context of the area (de Silva et al., 2015).

Civic and bell towers are generally very tall, especially after the 17th century Catholic Reformation. Lighthouses and watchtowers along the coast are usually squat and high just enough that nothing could obstruct the view from and to the sea. Clock towers and dovecotes are rather tall, depending on the importance of the municipality and of the house they belong to, respectively. Different heights may be found also among structures with the same function, such as dungeons. Before the XV century, the military technique, based on the safety of the fortresses, reckon on tall dungeons from which stones, arrows and boiling oil were thrown against the enemies. In the 15th century, with the spread of gunpowder, rather tall structures became an easier target and most of the forts were rebuilt shorter and larger.

Depending on the slenderness ratio, H/B, of the height, H, to the base width, B, of the structure, towers can be distinguished in:

- very slender towers, H/B>6: civic and bell towers;
- slender towers, 3<H/B<6: clock towers, dovecotes and dungeons before the 15th century;
- squat towers, H/B<3: dungeons built after the 15th century, lighthouses and watch towers.

Due to their high seismic vulnerability and exposure, sometimes combined with a really hazardous location, the monumental towers are more affected by seismic risk than common buildings. The seismic structural damage of squat towers may be strongly affected by shear mechanisms; on the other hand, for many tall towers the most recent strong-motion earthquakes occurred in Italy caused collapse or severe damages due to large structural deformations related to flexural (Figures 2a) or even torsional vibration modes.

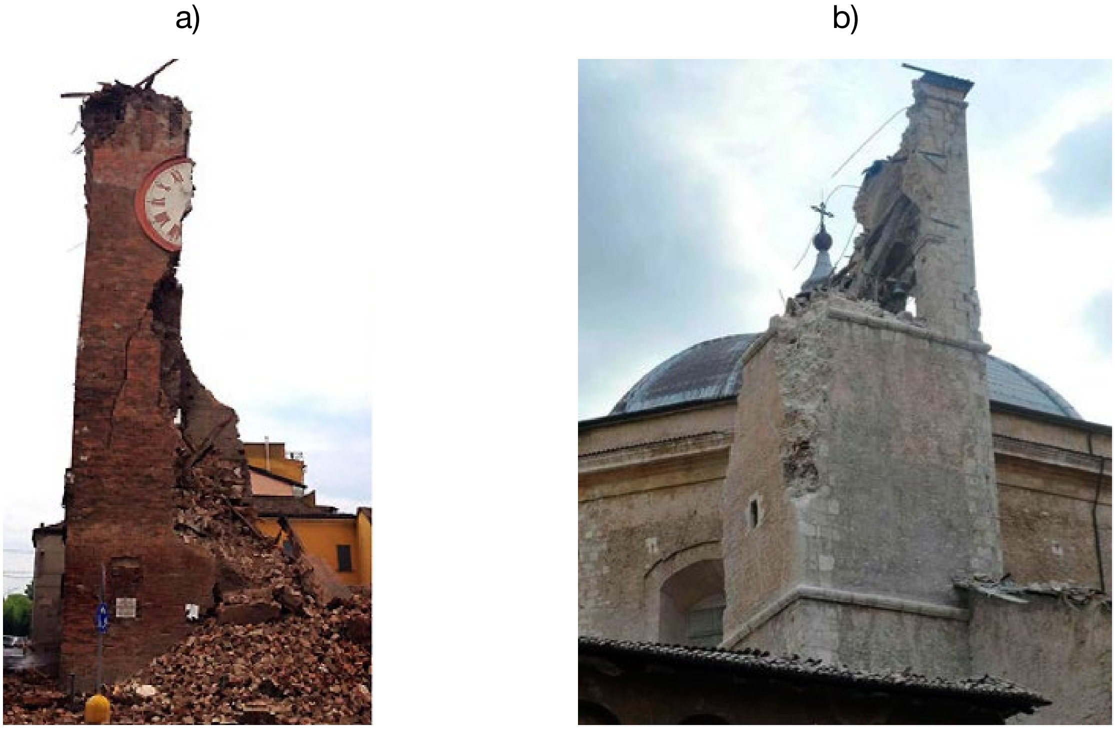
a) b)

Figure 2: (a) Finale d'Emilia clock tower destroyed by the Emilia earthquake (2012, M_L =5.8) and (b) San Bernardino bell tower, damaged by L'Aquila earthquake (2009, M_L =5.9).

With increasing height, the reduction in section may, indeed, promote the inception of secondary vibration modes, causing damage to the empty part of the structure; for example, the bell cell (Figure 2b) is often a very vulnerable element due both to its architectonic configuration and its location on the top subjected to amplified acceleration.

The symbolic role played by most of the tower increases their exposure and the emergency in their seismic protection, as highlighted by the changes in the Italian skyline, after the numerous damages to the towers caused by the Emilia earthquake. Even though out from the European borders, the collapse of the Dharahara tower (Figure 3) recognized by UNESCO in Katmandu, due to the Nepal earthquake in April 2015 (magnitude 7.8), is equally serious.

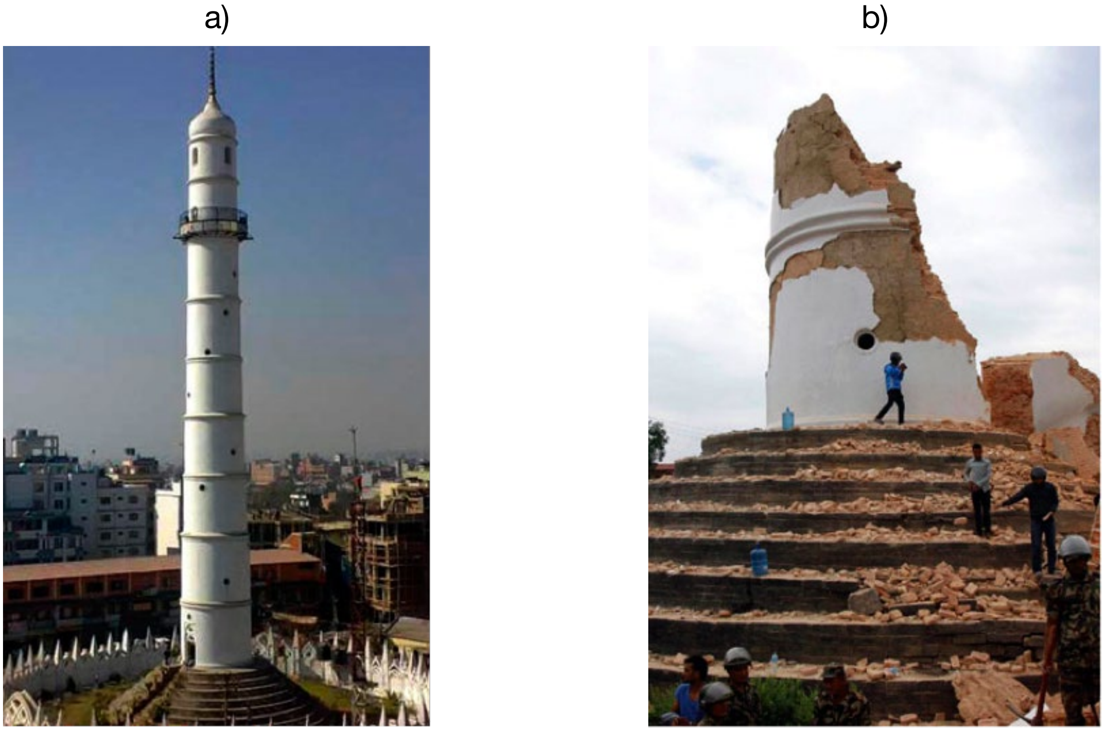

Figure 3: Dahara tower in Katmandu, before (a) and after (b) the Nepal earthquake (April 2015, ML=7.8).

3. SEISMIC SOIL-TOWER INTERACTION

Due to their seismic vulnerability and exposure, sometimes combined with a really hazardous location, monuments are more affected by seismic risk than common buildings. The higher structural performances, required in order to preserve monuments by earthquakes, may imply strong mitigation interventions, which bring down their artistic value. Thus, catching the dynamic behavior of the system in a realistic way becomes important to realize seismic protections which represent a compromise between safe fruition and conservation of the historical heritage.

The dynamic behavior of a real building may be affected by the interaction among soil, foundation and structure, usually neglected in the conventional design. Neglecting soil-structure interaction effects may be conservative or not, depending on the structural pattern and the nature of the subsoil. It is widely shown that, if the subsoil is softer with respect to the structure, the fundamental period of the soil - structure system increases and part of the seismic energy is radiated through the subsoil, so the flexural displacement and the related structural damping are reduced (Veletsos and Meek, 1974). Although the structural motion is reduced with respect to the oundation, the absolute overall structural displacement is increased due to subsoil deformability.

The consequences may be dangerous for several historical towers of Italian cultural heritage, since tall buildings can suffer excessive structural displacements under strong-motion earthquakes; on the other hand, the conventional fixed-base predictions can yield inadequate interpretations of the actual behavior.

In order to study the interaction effects, the structure can be assimilated to a single degree of freedom (SDOF) oscillator (Figure 4), with mass m, height H and flexural stiffness k. The dynamic response is therefore characterized by the fixed-base period, T_0, and damping ratio, ξ. Soil deformability is modeled through a combination of springs and dashpots with stiffness k_u , k_θ, and damping c_u, c_θ, for the translational and the rotational degrees of freedom, respectively (Gazetas, 1991).

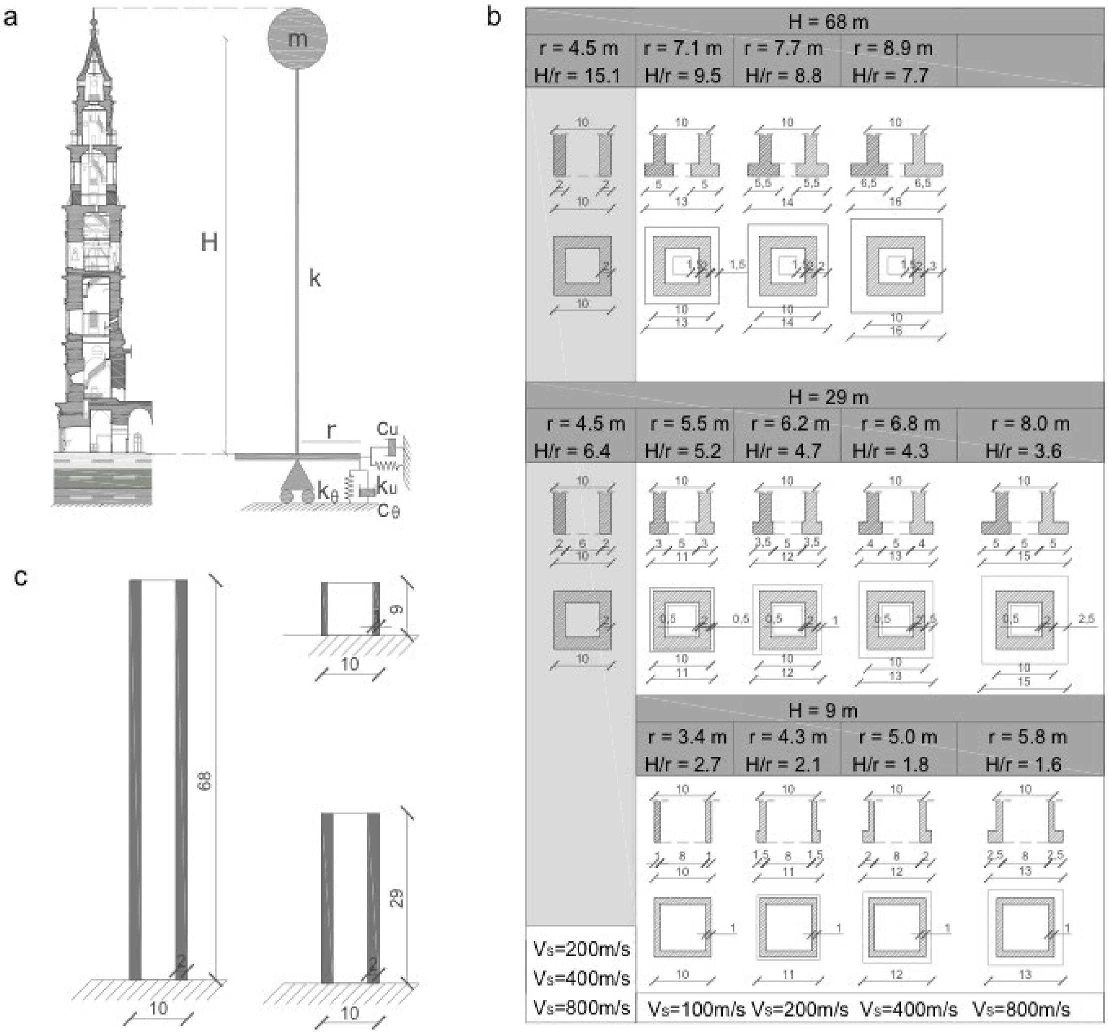

Figure 4: Single degree of freedom on springs, equivalent to the soil-foundation-stuctural system (a); combinations of structural slenderness and soil properties for the parametric analyses (b); structural models (c).

The simplified approach proposed by Veletsos and Meek (1974) has been applied in this study to different cases of hypothetical prismatic towers on springs, in order to calculate the modified period T^* and damping ratio ξ^*. The schemes, reported in Figure 4b and c, have been defined by realistic combinations of structural slenderness and soil properties (de Silva et al., 2014). Three masonry towers, respectively 9 m, 29 m and 68 m tall, resting on soft to stiff soil (200 m/s < V_S < 800 m/s) have been analyzed, varying the width of the foundations from 10 m to 16 m. The unit weight of the structure has been set equal to 11 kN/m^3, which is a typical value for a soft rock masonry.

Some representative results are reported in Figures 5a-b, showing respectively the soil-structure period T^* and the damping ratio ξ^*, normalized to the fixed base values, plotted versus the soil-tower stiffness ratio, σ, evaluated on the basis of the shear wave velocity of the subsoil (Figure 5c).

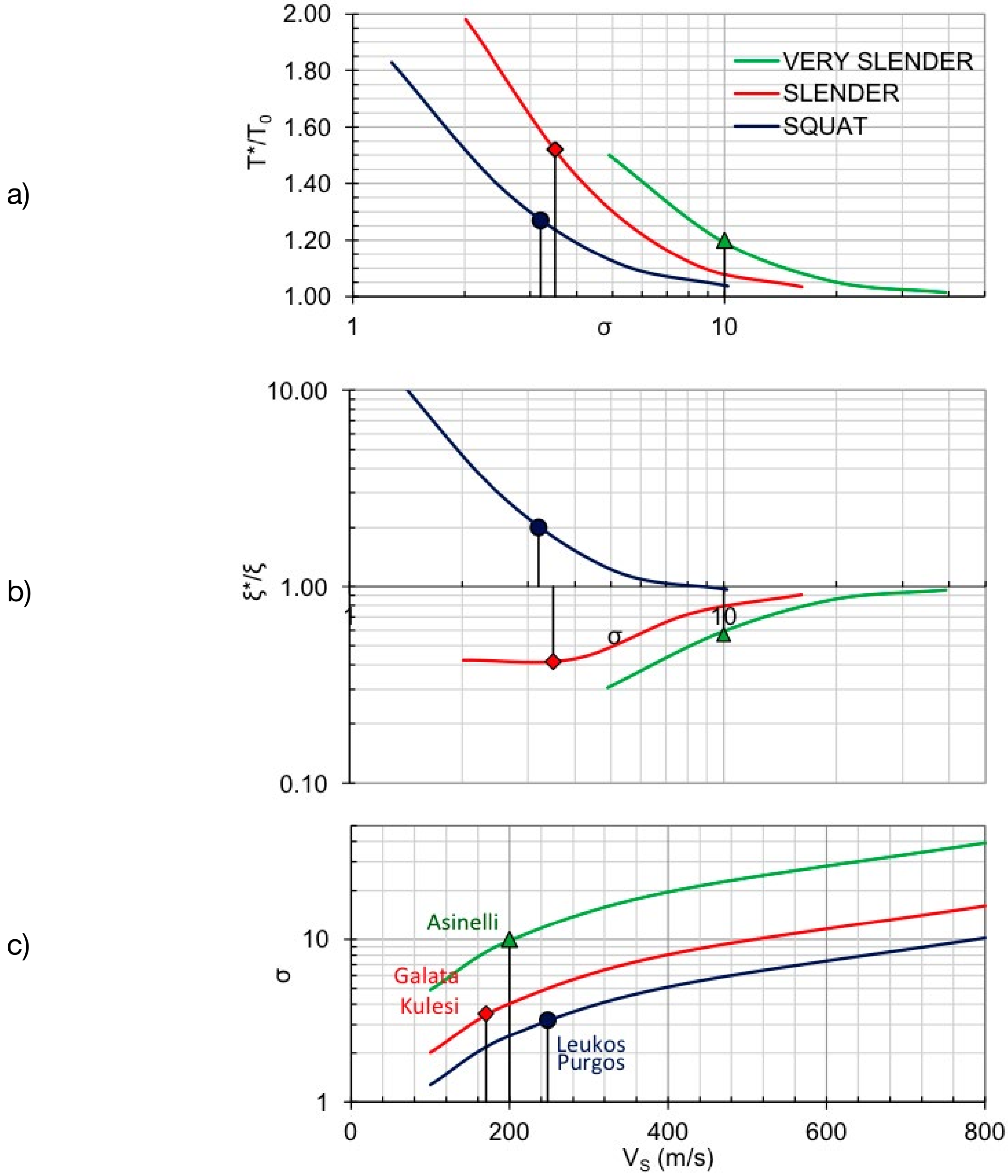

Figure 5: Variation with the stiffness ratio, σ, of the structural period (a) and damping ratio (b), both normalized to the fixed base value; dependency of σ on the shear wave velocity VS (c).

The plots are drawn for three slenderness ratios, corresponding to very slender, slender and squat structure (§ 2). As expected, whatever the slenderness ratio, the modified period T^* is higher than the fixed-base period T_0. The equivalent damping ratio ξ^* is lower than ξ for slender or very slender towers, while it is higher for squat structures due to the contribution of the radiation damping; the effects decay as the parameter σ increases, i.e. increasing soil stiffness. The deviation from the fixed-base solution is significant (i.e. T^*/T_0 and ξ^*/ξ are different from unity in Figures 5a-b) for very slender structures on deformable soils (σ<20, i.e. V_S<400m/s), for slender towers on soft to stiff soils (σ<15, i.e. V_S<600m/s) and for squat towers even on stiff soils (σ<10, i.e. V_S<800m/s).

4. APPLICATION OF THE PROPOSED METHOD TO SOME EUROPEAN TOWER

The three cases of the squat Leukos Purgos (Figure 6a) in Thessaloniki (Greece), the slender Galata Kulesi (Figure 6b) in Istanbul (Turkey) and the very slender Asinelli tower (Figure 6c) in Bologna (Italy) are here

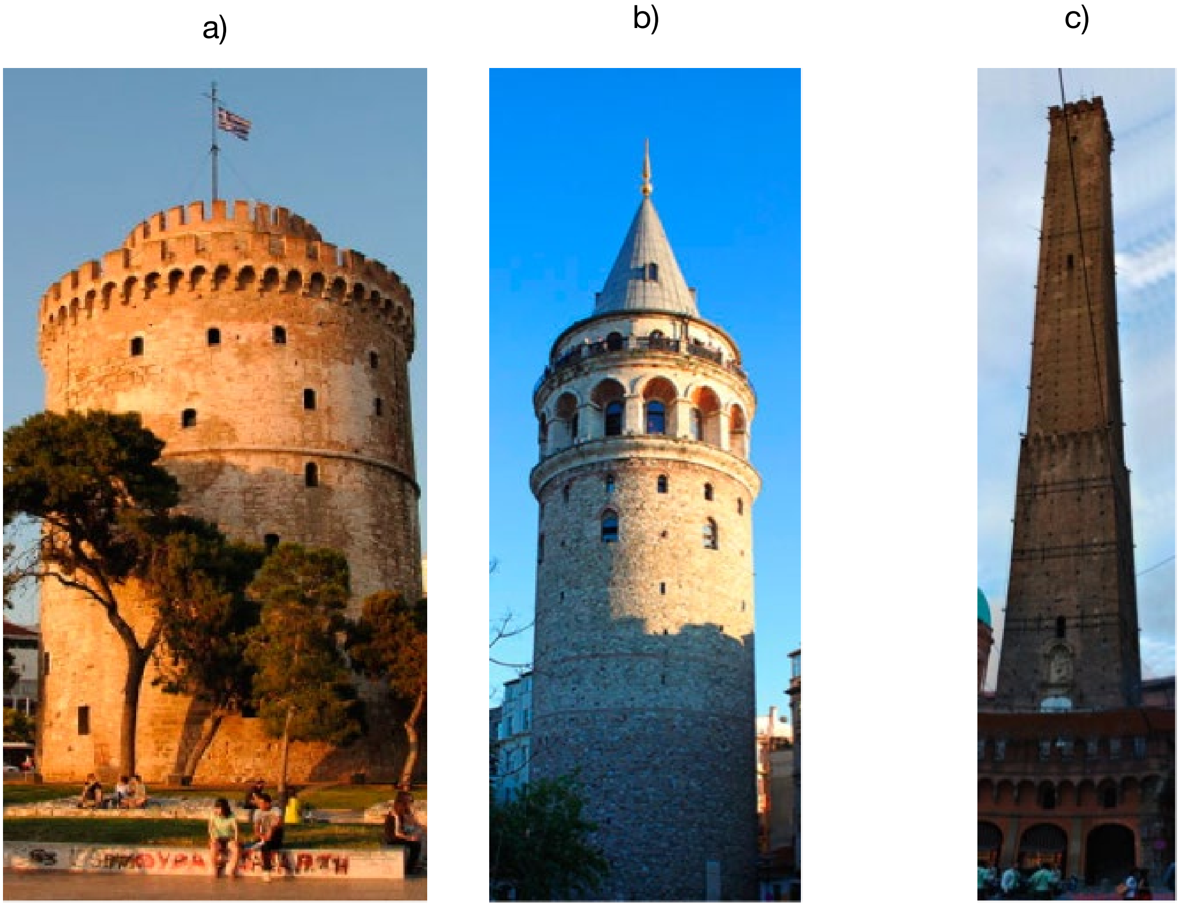

Figure 6: Leukos Purgos in Thessaloniki, Greece (a); Galata Kulesi in Istanbul, Turkey (b); Asinelli tower in Bologna, Italy (c).

considered, as illustrative examples of towers located in high seismic hazardous places.

The Leukos Purgos in Thessaloniki (Greece) was a watch tower of the city wall, completed in 1535. Converted in a prison in the last two centuries, today the tower hosts the historical museum of the city. The tower is 33 m tall and 22 m wide (H/B = 1.3), laying on clayey sand covered by filling materials (Anastasiadis et al., 2010). To quickly evaluate the effect of soil-structure interaction, the graphs in Figure 5 may be adopted, assuming the depth of the soil volume involved in the dynamic soil structure interaction equal to the half wide of the tower. For squat tower and a shear wave velocity V_S = 248 m/s, resulting from the mean value in the first 12 m of the measured V_S profile (Anastasiadis et al., 2010), Figure 5c provides a value of σ=3.2 to which an equivalent period T^*=1.27T_0 (Figure 5a) and an increased equivalent damping ratio ξ^*=2ξ (Figure 5b) are associated (circular symbol in Figure 5).

Built in 1348 by the Genoese settlers on a fractured sandstone formation, the Galata Kulesi in Istanbul (Turkey) is 66.9 m tall and about 16.5 m wide (H/B=4.0). Built as a part of a fortress, it became a watch tower in the XVIII century and today is the most panoramic place of the city. Considering a value of V_S = 175 m/s, compatible with the mechanical properties measured in the same formation, during the design of the Northen Marmaramotorway Odayeri, the corresponding value of σ is 3.5. On the curve corresponding to a slender structure, for σ = 3.5, an increased equivalent period T^*=1.52T_0 and a decreased equivalent damping ratio ξ^*=0.42ξ are associated (rhomboidal symbol in Figure 5).

Built since 1110 to 1684, the Asinelli tower is 97 m tall and 8.15 m wide (H/B=12), laying on loose sand and soft silty clay. By assuming V_S = 200 m/s , the parameter σ = 10 is obtained, to which an increased equivalent period T^*=1.20T_0

and a decreased equivalent damping ratio $\xi^*=0.57\xi$ are associated (triangular symbol in Figure 5).

As shown by the above examples, the dynamic response of the towers may be really different accounting or neglecting their interaction with the subsoil.

CONCLUSION

The fine tuning of the seismic protection of monuments requires accurate analyses, possibly accounting for the dynamic interaction between soil, foundation and structure. Focusing on the monumental towers, a simplified approach has been proposed for preliminary estimations of the equivalent period, T*, and the damping coefficient, ξ*, of the whole soil-structure system approximated with an equivalent oscillator. As expected, the period T* increases with respect to the fixed-base value. The damping ratio ξ* decreases for slender or very slender towers, while increases for squat structures due to the radiation damping. The proposed approach may be useful for the preliminary design of the intervention on monuments against earthquakes, to predict the importance of the interaction effects. The damages caused by recent European earthquakes to the cultural heritage highlight the emergency in protecting monumental towers and buildings from the seismic extreme events, to let them watch over the safety of the related population in the future as they did in the past.

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