Chapter

Impact of Tunnels and Underground Spaces on the Seismic Response of Overlying Structures

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Abstract

Depending on the circumstances, the design and construction of tunnels and underground spaces may be very challenging. In the case of an underground project located at a relatively shallow depth in an urban area, the design and construction will probably be more demanding since there is a potential interaction between the underground project and the overlying pre-existing structure(s) that are founded at the ground surface, such as buildings, bridges, etc. This interaction is generally related to the (usually differential) settlements at the ground surface due to the excavation and the consequent distress of the overlying structures. Nevertheless, in areas that are characterized by seismicity, this interaction may be more complicated, since, apart from the aforementioned static interaction, various phenomena of soil dynamics and dynamic interaction may take place, dominating thus the seismic excitation, response, and distress of the overlying structure(s). The current chapter deals with this interesting topic of geotechnical earthquake engineering. After a literature review, some indicative numerical analyses have been performed in order to determine the impact of the main parameters involved. Although the problem is generally complex and multi-parametrical, the numerical results are indicative of the dynamic interaction between the underground project, the ground, and the overlying structure(s).

Keywords: tunnel, underground space, seismic response, dynamic interaction

1. Introduction

Undoubtedly, during the last decades, a significant progress has been made in the design and construction of underground projects worldwide. Apart from the construction of underground spaces for various purposes (e.g., environmental, military, etc.), the most important underground projects are long tunnels which usually comprise important elements of highways and railways. In urban areas and especially in big cities, the increase in population and the need for fast transportation means have led to the development of metropolitan railways (i.e., subways), and therefore, there has been a large increase in the number and size of underground structures (i.e., metro stations and tunnels). Depending on the local site conditions, in an urban area, one of the main issues during the construction of a tunnel at a relatively shallow depth is the potential (static) interaction between the tunnel and a pre-existing overlying structure at the ground surface, such as a building or a bridge. It is evident that the development of (usually differential) settlements at the ground surface will probably distress any pre-existing structure.

Nevertheless, in areas that are characterized by seismicity, the construction of a tunnel under a pre-existing structure may have an impact, not only on the seismic excitation of the structure but on its seismic (i.e., dynamic) response as well. In geotechnical (earthquake) engineering, the term "local site conditions" is usually used to describe the prevailing topographical and geotechnical conditions. In the case of the existence of an underground project at a relatively shallow depth, the local site conditions include the underground project as well. As shown in **Figure 1**, in the case of a structure founded at the ground surface and subjected to a seismic excitation, there exist four general cases of local site conditions: (a) a structure founded on rock without a tunnel, (b) a structure founded on rock with a tunnel underneath, (c) a structure founded on soil layers without a tunnel, and (d) a structure founded on soil layers with a tunnel underneath.

Additionally, it is generally acknowledged that underground structures suffer less from earthquakes than buildings on the ground surface. Nevertheless, earthquakes in Kobe (1995), Chi-Chi (1999), and Duzce (1999) (see [1–5]) have caused extensive failures in tunnels (and buried pipelines), reviving the interest in the associated analysis and design methods.

The current chapter attempts to shed some light on the seismic (i.e., dynamic) behavior of underground projects and mainly on their impact on the overlying structures. **Figure 2** shows a sketch of the problem under consideration. An underground project (i.e., a circular tunnel) is constructed within a soil layer. A structure is founded on the surface of the soil layer, at a relatively short distance from the underground project. For the sake of simplicity, the structure is considered to be a single-degree-of-freedom system (i.e., a concentrated mass on a single beam). The soil layer and the two structures are subjected to seismic loading, i.e., an acceleration time history applied at the base of the soil layer. Therefore, the dynamic

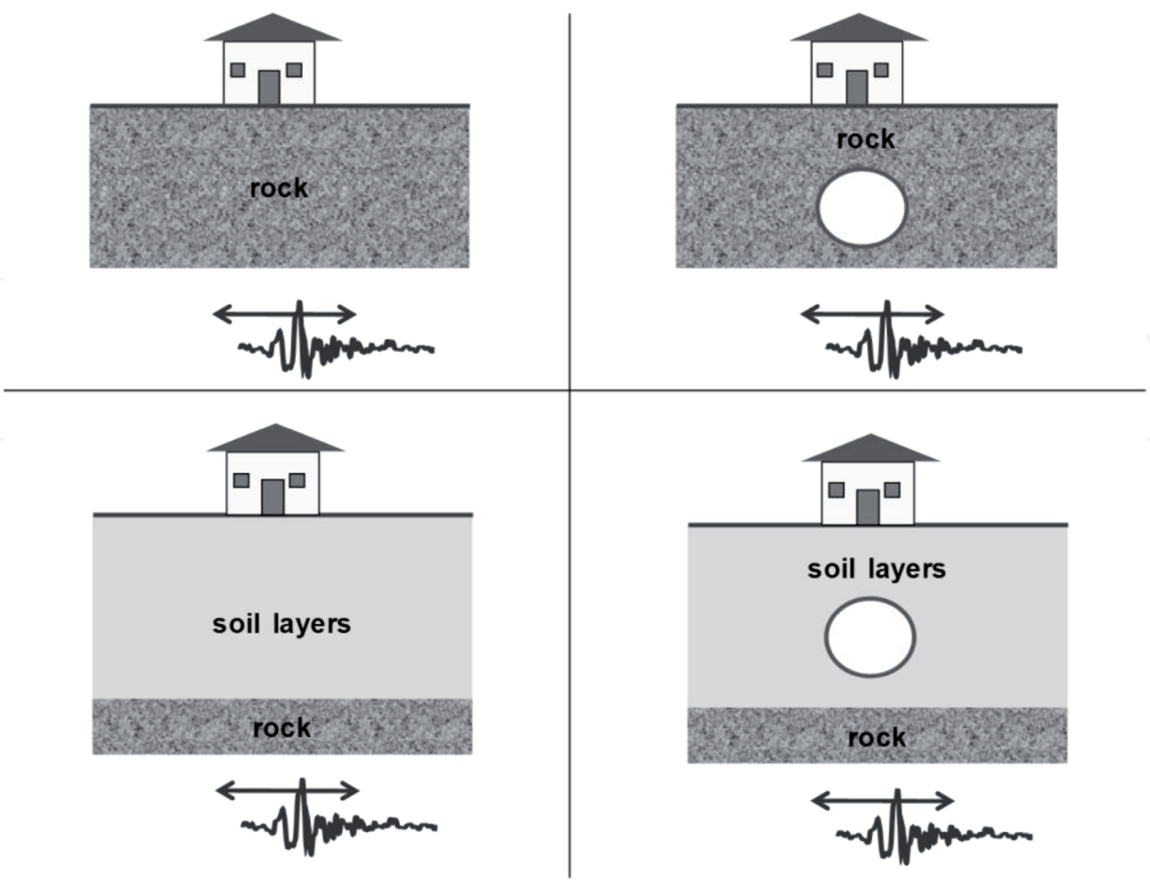

Figure 1.
Sketch showing the four potential cases of "local site conditions" of a structure founded at the ground surface and subjected to a seismic excitation.

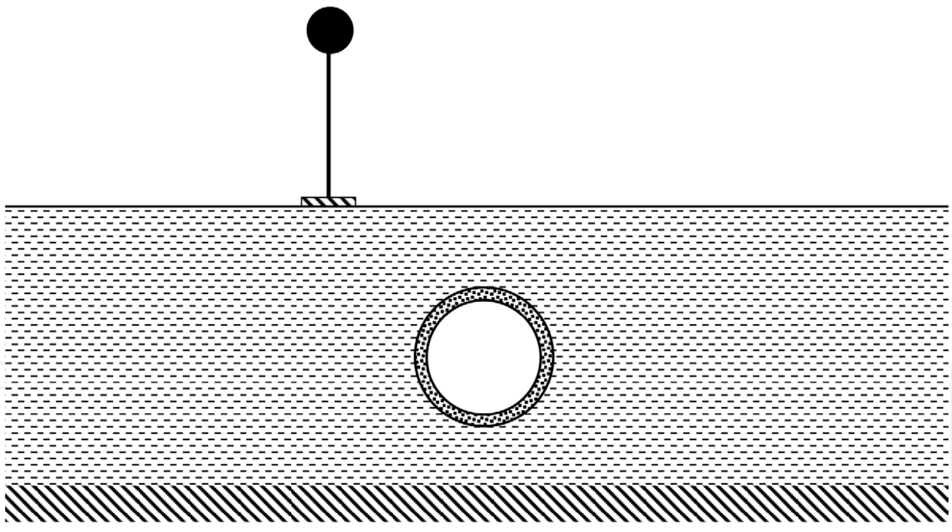

Figure 2.
Sketch of the problem under consideration: a simple structure founded on a soil layer is overlying a tunnel. The soil layer and the two structures (i.e., tunnel and simple structure) are subjected to an acceleration time history being applied at the base of the soil layer.

interaction between the underground project, the soil, and the overlying structure is investigated, while emphasis is given to the impact of the underground project on the dynamic response of the overlying structure.

The next sections are involved with various topics of the problem under examination. More specifically, a literature review on the impact of underground structures on the characteristics of the seismic motion at the ground surface is described in Section 2. The aim of the literature review is to identify the most important parameters of the problem. This section also includes some indicative numerical results related to the distribution of accelerations on the ground surface in the presence of an underground circular lined tunnel. Finally, Section 3 is devoted to the dynamic soil-structure interaction phenomena and the seismic response of structures overlying circular tunnels. Although the literature on this issue is relatively limited, various parameters are considered, and useful conclusions are drawn. In this section the numerical simulations also include the overlying structures. The results are indicative of the complexity of the dynamic interaction between the tunnel, the ground, and the structure.

2. Impact on the seismic motion at the ground surface

One of the first studies on the impact of underground projects on the seismic motion was the study of Lee and Trifunac [6]. In their work, Lee and Trifunac analyzed the scattering and refraction of SH shear waves due to a circular tunnel in a homogeneous elastic half-space using an analytical solution.

The main parameters that determine the response at the ground surface are (a) the angle of incidence and the frequency content of the seismic waves, (b) the distance from the vertical axis of the tunnel, and (c) the tunnel depth.

During the last four decades, various researchers have studied similar problems. More specifically, many researchers have examined analytically the impact of a circular underground structure on the surface ground motion, while few researchers have examined the problem numerically using mainly the finite element method. In addition, some researchers have verified their analytical results with numerical simulations or vice versa. Finally, very few attempts have been made in order to simulate experimentally the seismic response of underground structures. For more details the reader may refer to [7–20].

The evaluation of the aforementioned publications shows that the impact of underground projects on the seismic motion at the ground surface consists of the following:

- The horizontal seismic motion may be increased or decreased along the ground surface (compared with the corresponding seismic motion observed without the underground project).

- A "shadow zone" is created over the underground project. This phenomenon consists of a reduction of the seismic motion right above the tunnel and an increase at the two corners of the shadow zone.

- The seismic response at the ground surface is further complicated by the appearance of a parasitic vertical component of seismic motion, which may be substantial, especially at the two corners of the shadow zone.

- There is a specific range of frequencies (or periods) in which the seismic motion is increased. That range depends on the characteristics of the underground project and the eigenfrequencies (or eigen-periods) of the ground. Ground response for excitations with wavelengths larger than the tunnel diameter is not affected by the presence of the tunnel.

Figure 3 shows the four numerical models that have initially been examined in order to indicatively demonstrate the potential impact of a tunnel on the seismic motion at the ground surface. Model 1 is actually a rigid rock, while Model 2 is a rigid rock with a lined tunnel. On the other hand, Model 3 consists of a soil layer

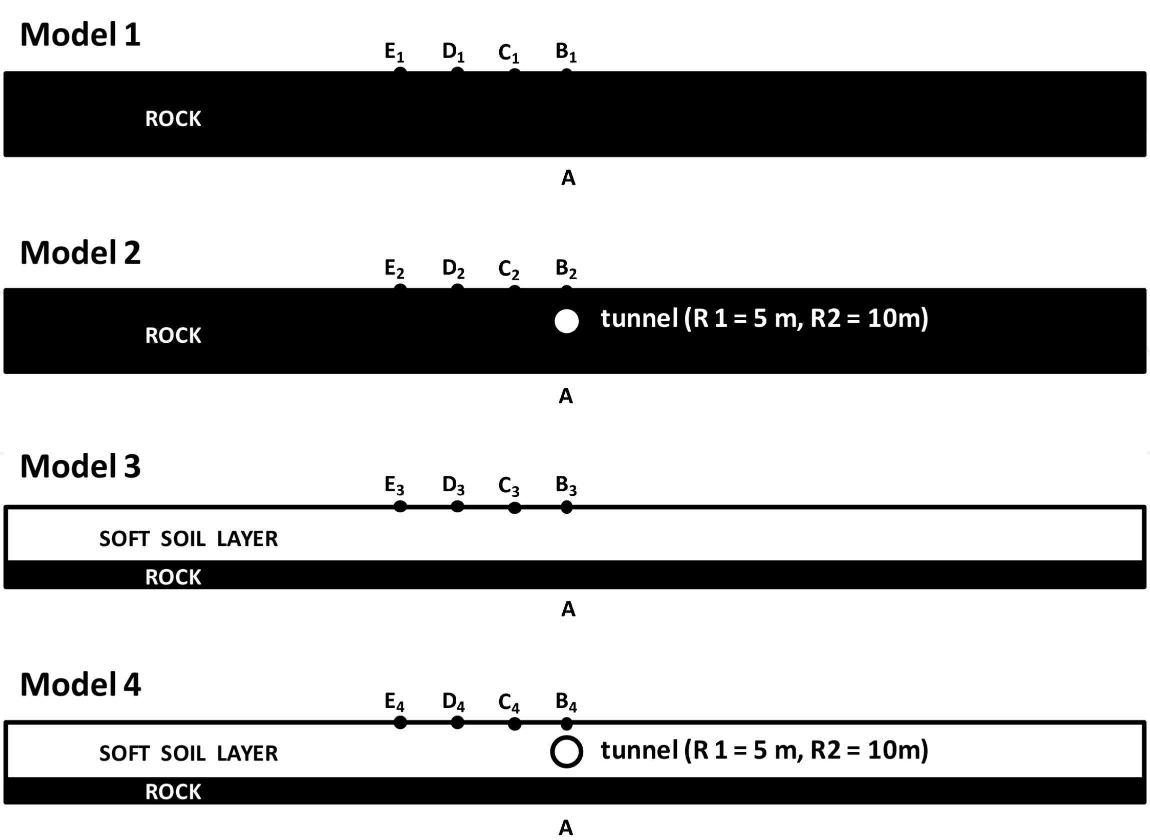

Figure 3.
The four examined numerical models showing the points of interest at the base and at the ground surface. Model 1 is a rigid rock, Model 2 is a rigid rock including a tunnel, and Model 3 is a soft soil layer on rock, while Model 4 is the same model with a tunnel. Point A is located at the base, while the points Bi, Ci, Di, and Ei (with i = 1 to 4) are at the ground surface.

with a height, H, of 25 m, overlying a rigid rock (i.e., one-dimensional model). The soil layer is characterized by a shear-wave velocity, V_S, equal to 200 m/s. Model 4 is the same model including also the aforementioned lined tunnel. Two cases of tunnel radius, R, have been examined: $R1$ = 5 m and $R2$ = 10 m.

All numerical analyses have been performed with PLAXIS2D which is a commercial finite element program capable to perform dynamic ground response analyses in the time domain. Special transmitting boundaries have been applied at the two vertical boundaries of both models in order to avoid unrealistic trapping of the seismic waves.

The four models have been horizontally excited by three acceleration time histories. As shown in **Figure 4**, the first is a sinusoidal motion with frequency f_o = 2 Hz, the second is a simple Ricker wavelet of central frequency f_o = 2 Hz (characterized by a wide range of frequencies up to $3fo$ = 6 Hz), while the third is a real accelerogram that has been recorded during the 1990 Upland earthquake, in California, with a peak ground acceleration (PGA) of the order of 0.15 g. All excitations have intentionally been scaled to low values of peak acceleration (i.e., 0.01 g) in order to keep the behavior of the geomaterials in the elastic range.

According to the wave propagation theory, the first eigenfrequency of Model 3 (i.e., a single soil layer) is equal to $f_1 = V_S/(4H)$ = 2 Hz, while its maximum theoretical response at resonance is $2/(\pi\xi_s)$, where ξ_s is the material damping. Therefore, the sinusoidal motion with frequency f_o = 2 Hz has been used in order to verify the numerical simulations with the corresponding analytical solutions. If we suppose that the material damping of soil, ξ_s, is 5%, the amplification factor, AF, is 12.7.

Figures 5–11 show some indicative numerical results.

More specifically, **Figure 5** shows the dynamic response of Model 3 in the case of sinusoidal excitation. As it was expected, resonance phenomena are evident at the ground surface. As aforementioned, the peak ground base acceleration is only 0.01 g, while the peak ground surface acceleration has been amplified almost 12 times. The discrepancy between the AF from the analytical solution and the corresponding AF from the numerical modeling is attributed mainly to some deficiencies of the numerical modeling, such as the Rayleigh-type material damping, the size of the finite elements, and/or the rather medium accuracy of the vertical transmitting boundaries.

Figure 6 shows the dynamic response of Model 3 in the case of Ricker excitation and in the case of the record from Upland earthquake. In the case of Ricker excitation, the peak ground surface acceleration is almost 0.02 g, while the duration of the ground motion has been substantially increased from 1 second to almost 5 s. In the case of the recorded acceleration from the Upland earthquake, the ground acceleration has been amplified almost 2.5 times since the peak ground surface acceleration is almost 0.025 g.

As it was expected, in the case of Model 1, Model 2, and Model 3, there are no differences of the dynamic response at the ground surface. Model 1 and Model 2 are rigid, while Model 3 is characterized by one-dimensional conditions. **Figure 8** and **Figure 9** show the calculated time histories of horizontal acceleration at various locations at the ground surface in the case of Model 4 with the small tunnel ($R1$ = 5 m) and in the case of Model 4 with the big tunnel ($R2$ = 10 m), respectively. It is evident that the existence of the small tunnel has actually no impact on the variation of the response at the ground surface, a phenomenon that can be attributed to the fact that the size of the tunnel is relatively small compared to the examined wavelengths. On the contrary, in the case of the big tunnel, there is an impact, although it is rather minor. More specifically, the acceleration levels are lower right above the tunnel (i.e., a "shadow zone" has been created), while few meters away (at point C4) the acceleration is locally increased. Similar are the results shown in **Figure 10** where the seismic responses of the points at the ground surface are being compared in the case of Upland excitation.

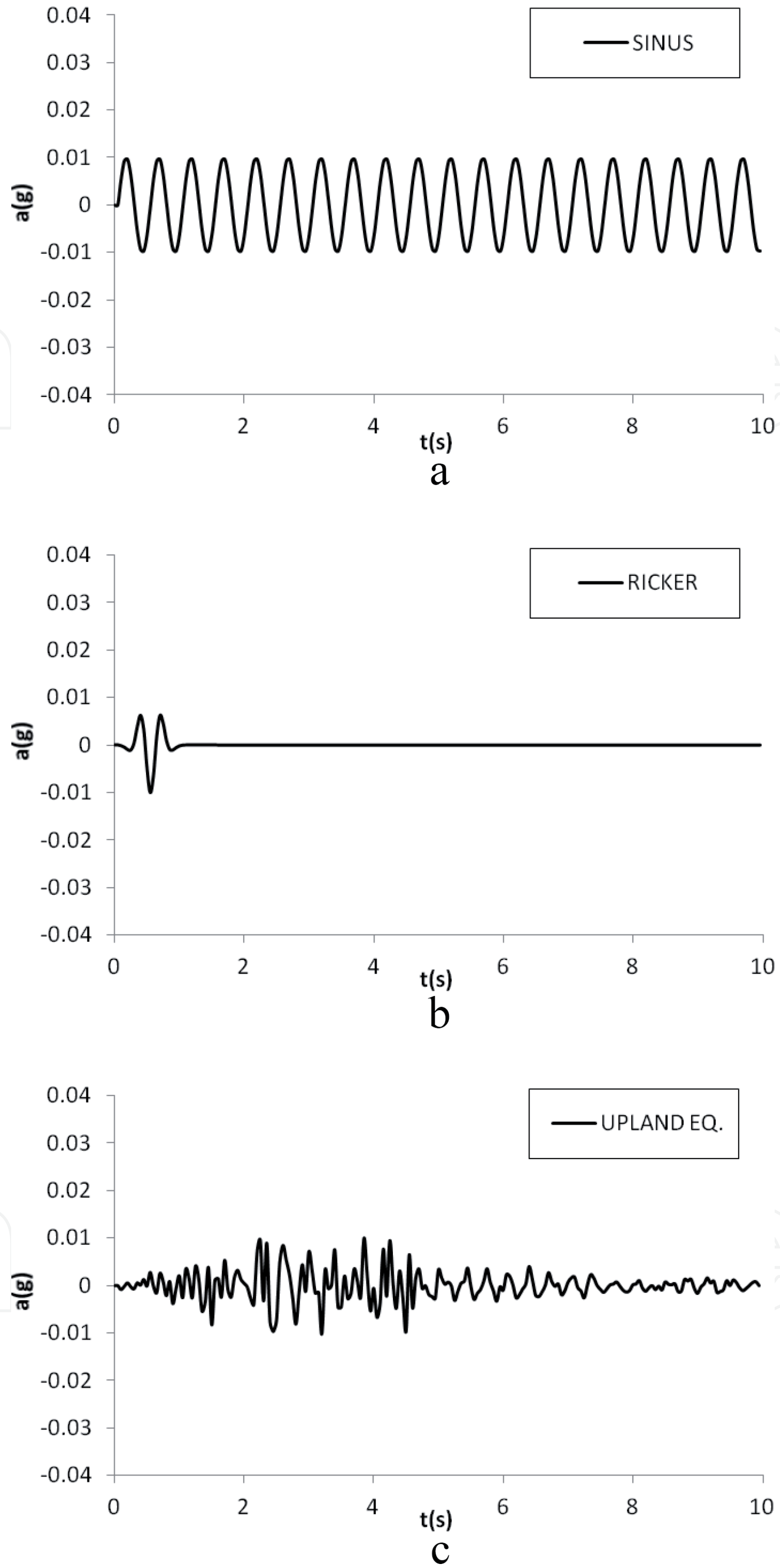

Figure 4.
The three acceleration time histories that have been used as seismic excitations (all scaled to 0.01 g): (a) a sinusoidal excitation, (b) a Ricker pulse, and (c) the record from the Upland earthquake.

As aforementioned, another phenomenon that may take place due to the presence of a tunnel is the development of parasitic vertical accelerations. Since the seismic excitation in all numerical analyses was only horizontal (i.e., S waves), no

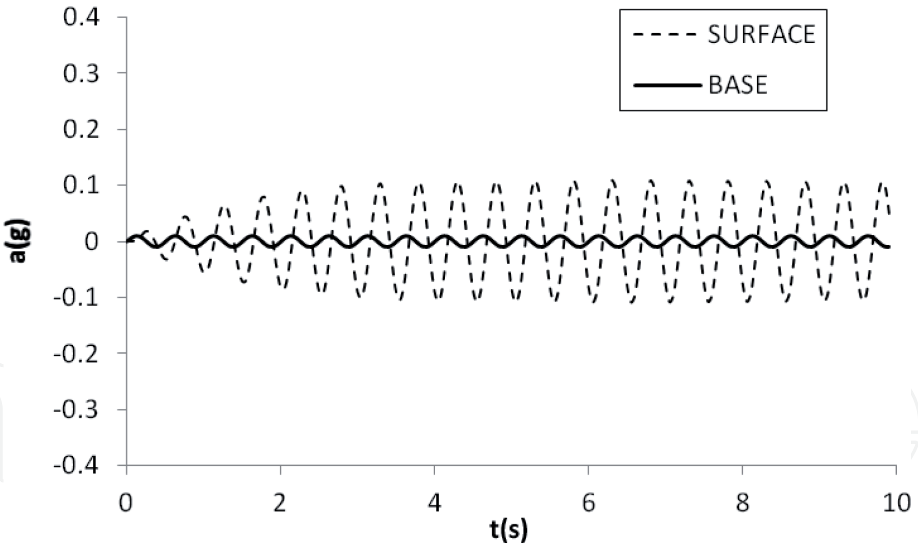

Figure 5.
The dynamic response of Model 3 subjected to the sinusoidal excitation.

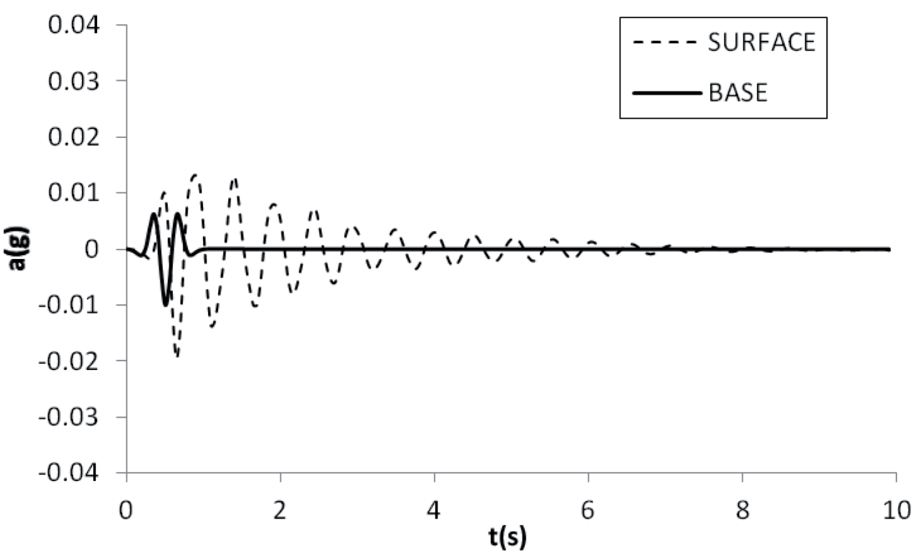

Figure 6.
The dynamic response of Model 3 subjected to the Ricker excitation.

vertical ground motion is expected. This is reasonable for Model 1 and Model 2 that are rigid and for Model 3 that is one-dimensional. Nevertheless, the points at the surface of Model 4 exhibit this vertical parasitic acceleration. **Figure 11** shows the vertical acceleration at various locations along the ground surface in the case of the big tunnel and the Upland excitation. It is noted that the maximum vertical acceleration is observed at point C4 where its value is almost 30% of the corresponding peak ground surface acceleration (i.e., 0.03 g) and in parallel comparable to the peak ground base acceleration (i.e., 0.01 g).

Judging from the numerical results of this rather limited parametric study, it becomes evident that the existence of the tunnel alters the acceleration pattern along the ground surface. The "shadow zone" right above the tunnel and the vertical parasitic seismic motion are rather obvious.

In any case, it has to be emphasized that the interaction between the soil, the structure, and the tunnel is a problem with several parameters, and therefore, in any other case the patterns of horizontal and vertical acceleration at the ground surface may be completely different.

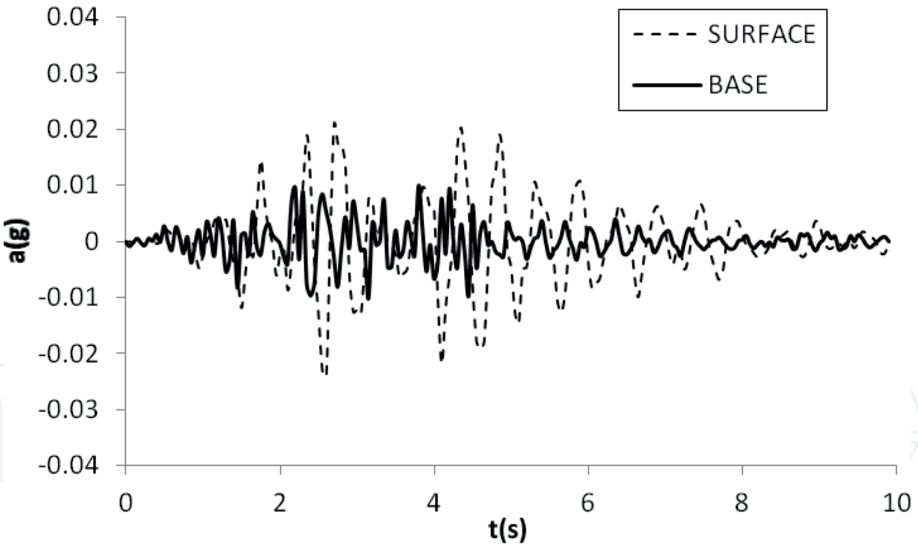

Figure 7.
The dynamic response of Model 3 subjected to the Upland excitation.

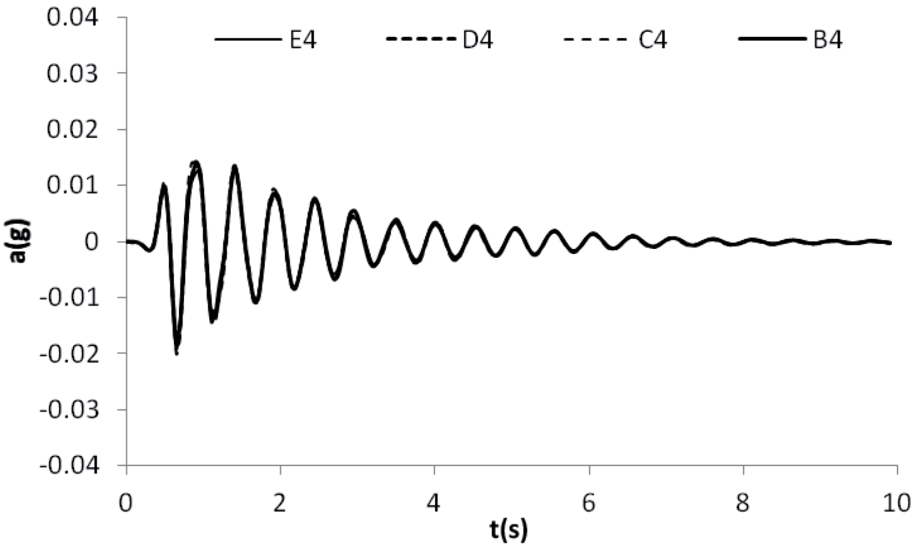

Figure 8.
The dynamic response of Model 4 with the small tunnel (R1 = 5 m) subjected to the Ricker excitation.

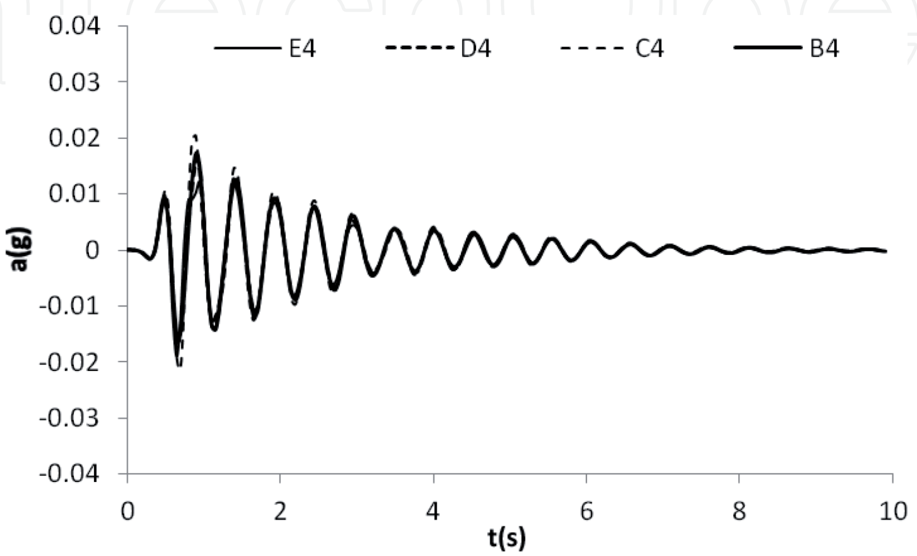

Figure 9.
The dynamic response of Model 4 with the big tunnel (R2 = 10 m) subjected to the Ricker excitation.

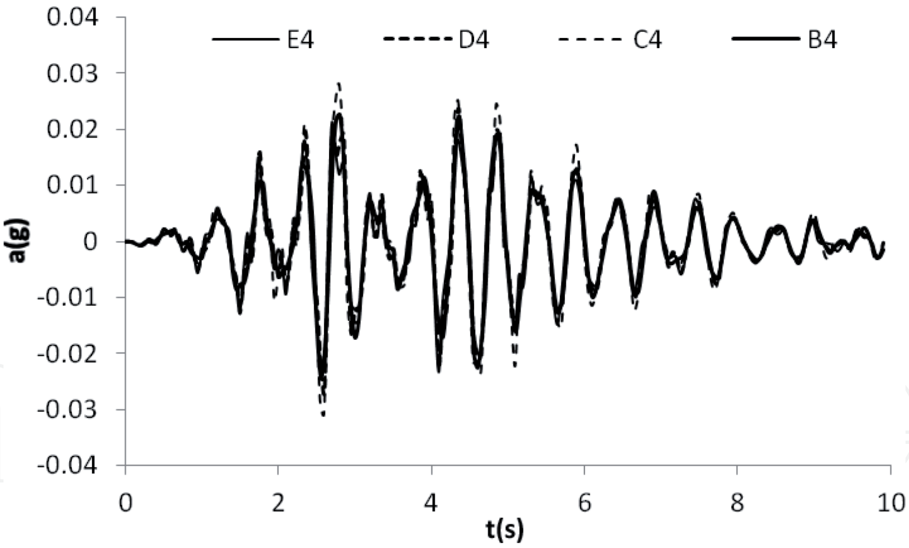

Figure 10.
The dynamic response of Model 4 with the big tunnel (R2 = 10 m) subjected to the Upland excitation.

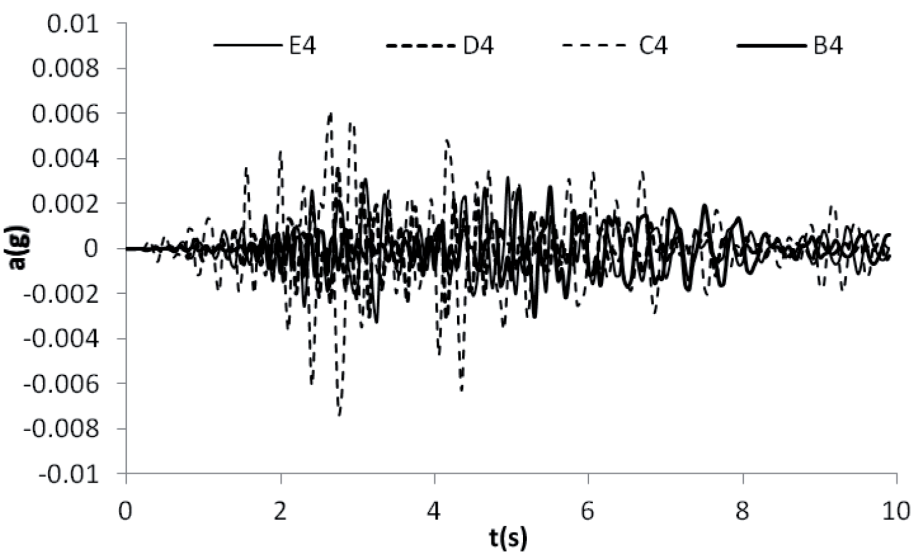

Figure 11.
The vertical dynamic response of Model 4 with the big tunnel (R2 = 10 m) subjected to the Upland excitation.

3. Dynamic interaction between tunnel, ground, and structure

The seismic response of any structure founded at the ground surface is an issue that depends on various factors, such as the mechanical and geometrical properties of the structure and the characteristics of the seismic excitation.

When the structure is a single-degree-of-freedom (SDOF) structure with a fixed base, then it is characterized by its eigen-period T_o, which is given by the following simple expression:

$$T_o = 2\pi\sqrt{\frac{M}{K}} \tag{1}$$

where M is the concentrated mass of the structure and K is its stiffness.

Therefore, if the fundamental period of the seismic excitation is close to T_o, resonance phenomena are expected, and therefore, the dynamic distress of the structure may have its maximum value.

Nevertheless, according to [21, 22], the potential existence of soft soil layers under the structure will lead to the following phenomena:

a. Soil amplification (or de-amplification in very few cases) will take place, which will certainly lead to an alteration of the seismic excitation of the structure.

b. Dynamic soil-structure interaction, which actually consists of the following phenomena:

- The soil compliance will reduce the stiffness of the structure, a fact that will certainly lead to an increase of the eigen-period of the structure.

- The overall damping of the system will be increased since the existence of soil layers will introduce other means of energy dissipation apart from the material damping of the structure, such as the material damping of the soil and the radiation damping.

Although the increase of the damping is always beneficial, the reduction of the stiffness (and the subsequent increase of the eigen-period) may be either beneficial or detrimental for the distress of the structure, depending on the circumstances.

In this section all the previous numerical models have been modified in order to include four identical simple structures (4) at the ground surface. As shown in **Figure 12**, the four structures are above the tunnel, while the distance between them is the same (15 m). All of them are single-degree-of-freedom (SDOF) structures, and they are characterized by (a) a material damping of 5% and (b) an eigen-period T_o = 0.5 s or eigenfrequency f_o = 2 Hz (identical to the first eigenfrequency of the soil layer). Note that in Model 3 and Model 4, the actual eigenfrequency of the structures is smaller due to the soil compliance.

The following figures show some indicative numerical results. More specifically, **Figure 13** shows the horizontal acceleration time histories that have been developed on the top of the structures in the case of Model 4 with the big tunnel subjected to the Upland excitation. It is evident that the acceleration levels are relatively high (of the order of 0.1 g). This fact is attributed to the resonance phenomena between the soil and the structures (since they have comparable eigenfrequencies). The initial peak ground base acceleration (of 0.01 g) has been amplified up to 0.03 g (i.e., almost three times) at the ground surface, while the peak ground surface acceleration has been amplified again, reaching a value of the order of 0.1 g.

In parallel, minor differences exist between the structural responses of the four structures. As it was expected, the minimum response is observed in the case of the structure located at point B, while the maximum response is on the structure located at point C.

Figure 14 shows the corresponding (parasitic) vertical accelerations that have been developed on the top of the structures. The maximum response is also observed in the case of the structure located at point C. Note that these accelerations are comparable to the acceleration levels at the ground surface (see **Figure 11**).

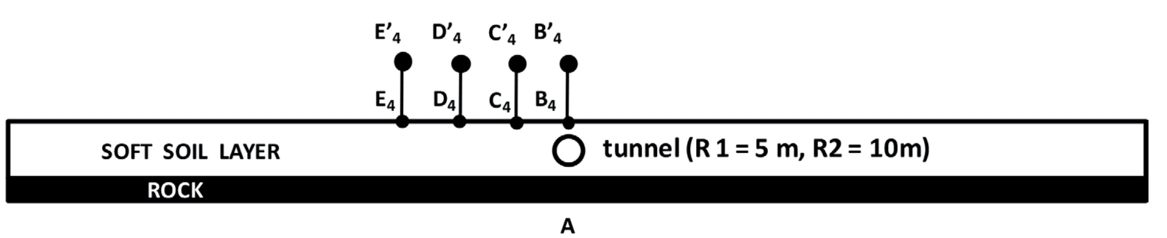

Figure 12.
The modified Model 4 including four (4) equally spaced single-degree-of-freedom structures at the ground surface.

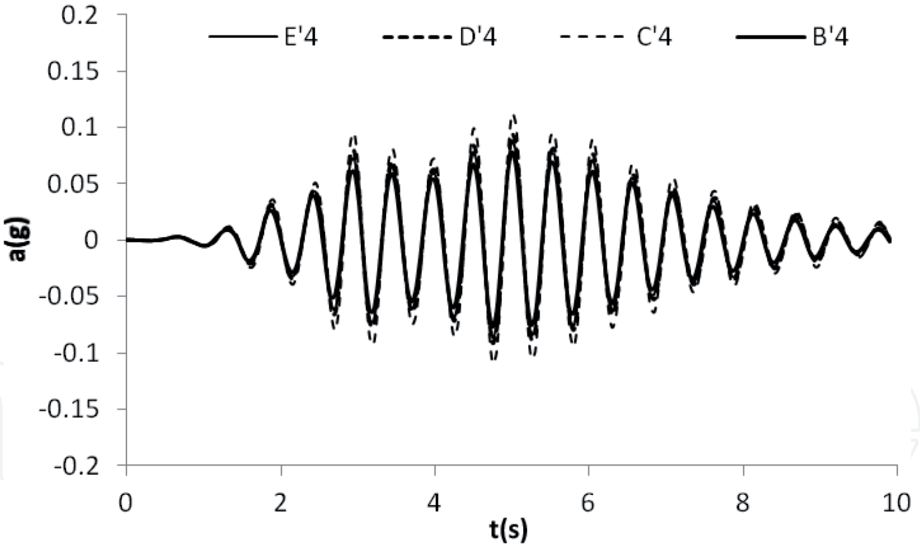

Figure 13.
The horizontal accelerations developed on the top of the four structures in the case of the modified Model 4 with the big tunnel subjected to the Upland excitation.

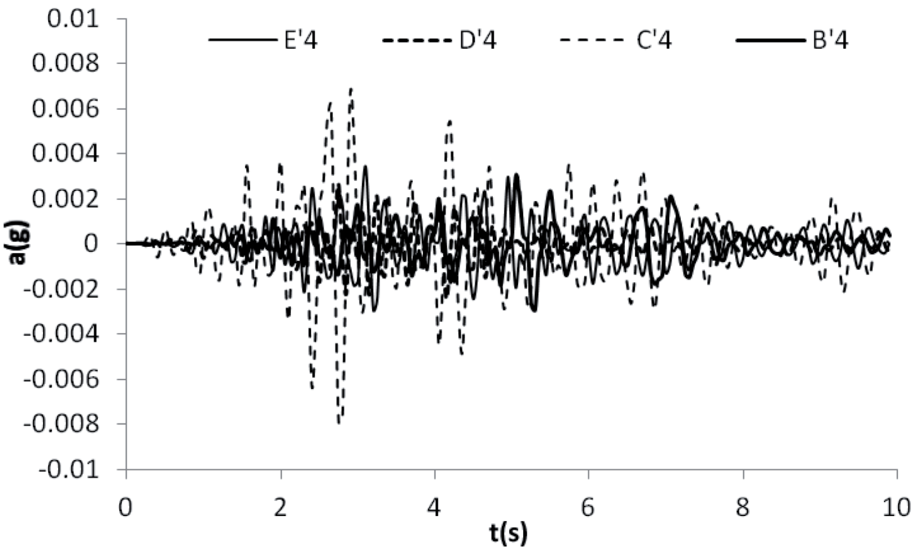

Figure 14.
The vertical accelerations developed on the top of the four structures in the case of the modified Model 4 with the big tunnel subjected to the Upland excitation.

This phenomenon was actually expected since the single-degree-of-freedom structures have no vertical response. Note that in a more realistic case with multi-degree-of-freedom systems, the vertical component would have been amplified.

4. Conclusions

In urban areas and especially in big cities, the increase in population and the need for fast transportation means will lead to the development of metropolitan railways (i.e., subways), and therefore, there will be a large increase in the number and size of underground structures (i.e., metro stations and tunnels).

In areas that are characterized by moderate or high seismicity, it is evident that the construction of an underground project (e.g., tunnel or underground space) under a pre-existing structure may alter more the seismic excitation of the structure, modify the soil-structure interaction pattern, and consequently have an impact on the structural response and distress.

The numerical results that have been presented in the previous sections have shown that the existence of a tunnel may alter the pattern of horizontal acceleration at the ground surface in the time domain (and in the frequency domain). This fact means that the construction of a tunnel under a pre-existing structure will complicate more the aforementioned dynamic soil-structure interaction phenomena.

Finally, it has to be emphasized that the anticipated vertical parasitic acceleration may have an impact on the structural response and distress of structures with many degrees of freedom, especially when the acceleration levels of the seismic excitation are high and a nonlinear behavior of the structure is expected.

Based on all aforementioned, when a new underground structure is constructed in urban areas, a special study should be performed in order to assess quantitatively the impact of the underground structure on the seismic response and distress of any pre-existing overlying structure.

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