A Potential Mitigation Measure for the Seismic Distress of the Circuit Wall at the Acropolis of Athens

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Abstract The seismic design of new retaining structures is usually performed following modern seismic norms. Nonetheless, there are various monumental retaining structures (e.g., fortifications) with high seismic vulnerability, which must be protected against earthquakes, while there exist several limitations on the type of mitigation measures that can be applied to such cultural heritage structures. The present study investigates numerically the seismic response and distress of the Circuit Wall of the Athenian Acropolis. The Wall is a monumental masonry retaining structure surrounding the world-class archeological monuments of the hill of the Acropolis. Given the fact that the wider region of Athens is characterized by moderate seismicity, it is necessary to protect the Wall from strong ground motions. For this purpose, the geological, seismological, and topographic conditions of the Acropolis hill, as well as the geometry and the mechanical properties of the Wall, are realistically taken into account. A realistic finite-element model has been developed for a critical section of the Wall, which has been validated with available records from accelerometers being installed on the Wall. Subsequently, an efficient and suitable—according to international monument restoration guidelines—seismic mitigation measure is proposed. The results of dynamic earth-pressure distribution on the Wall are presented before and after the application of expanded polystyrene (EPS) blocks behind the Wall. A detailed parametric study illustrates a substantial reduction of dynamic pressures on the Wall when the EPS blocks are applied, either along the entire height or only at the lower part of the Wall.

Keywords Retaining walls · Dynamic earth pressures · Mitigation measures · Acropolis circuit wall · Expanded polystyrene · Numerical simulations

1 Introduction

Retaining systems are used in many engineering projects in order to support one or more soil layers, and in some cases, various structures founded on the top soil layer(s). Bridge abutments, basement walls, harbor quay walls or most simple forms, such as a typical gravity wall, comprise the most frequent applications of retaining structures. Generally, the seismic response of even a simple retaining wall is
a very complex problem of dynamic soil-structure interaction (Kramer 1996). The backfill material can impose high earth pressures on the wall under static and dynamic (i.e., seismic) conditions. This fact may lead to local or global structural failures with severe economic losses. According to Psarropoulos et al. (2005), the magnitude of the earth pressures depends, not only on the mechanical and geometrical properties of the wall and the retained soil, but on the various "degrees of freedom" of the system (i.e., structural flexibility, base compliance, sliding phenomena, etc.) as well, while the characteristics of the seismic motion have also a significant impact.

Many researchers have examined the response of a retaining wall under seismic conditions with analytical, numerical, and/or experimental studies. Regarding analytical methods, there are two main categories to estimate the dynamic (i.e., seismic) earth pressures acting on the wall due to the backfill material: (a) the limit-equilibrium methods and (b) the elasticity-based methods. The limit-equilibrium methods are usually pseudo-static approaches that consider yielding walls and plastic behavior of the backfill material (Mononobe and Matsuo 1929; Seed and Whitman 1970). In contrast, the elasticity-based methods consider that the backfill materials have a viscoelastic behavior (Wood 1973). In addition, a viscoelastic behavior of the backfill materials and an elastic behavior of the wall has been assumed in several numerical studies (e.g., Psarropoulos et al. 2005).

Nowadays, the design of a retaining structure is based on modern seismic norms and guidelines, such as Eurocode 8 (EC8, 2004). In these norms, the soil-structure interaction is considered in a simplified manner and the calculation of the seismic pressures is mainly achieved via the Mononobe-Okabe method (Okabe 1926; Mononobe and Matsuo 1929), which is actually a pseudo-static extension of Coulomb's static method. Nevertheless, the walls are designed to withstand the earth pressures from the backfill material under static and seismic conditions. Hence, few damages have been reported for recently designed walls subjected to seismic earth pressures. In addition, various seismic mitigation measures can be applied during the wall construction to enhance its dynamic performance. In contrast, old retaining walls have not been designed using any seismic norms, a fact that certainly increases their vulnerability against seismic loading. Therefore, local or global damages, or even collapse may appear during a severe seismic event. In such cases, the application of seismic mitigation measures is more pronounced to protect the retaining wall.

The protection of cultural heritage is an important issue from every aspect and extremely challenging from an engineering perspective. A detailed set of guidelines has been developed for the restoration and conservation of all types of monuments, known as Charter of Venice, was established in 1964. Many existing retaining walls have been characterized as monuments (e.g., old fortification walls with backfill materials). These ancient retaining walls are made of stone and have suffered various damages (e.g., corrosion, cracks and local failures) over the years due to human interventions and/or natural hazards. A strong ground motion could affect the structural integrity of these retaining walls, due to the increased dynamic earth pressures that may lead to local or global failures (Egglezos et al. 2013). The application of seismic mitigation measures on ancient retaining walls is a very difficult and challenging task for engineers due to their monumental character and the related restrictions. Therefore, the number of such interventions on ancient retaining walls worldwide is rather limited.

The current study investigates the seismic response of a characteristic section at the southern Acropolis Circuit Wall via two-dimensional dynamic analyses utilizing the finite-element method. A thorough investigation has been performed with respect to the reduction of the dynamic pressures imposed on the Wall, which can be achieved via the potential application of an inclusion of expanded polystyrene blocks (EPS) behind the monumental structure. This seismic mitigation measure has been efficiently used in modern retaining walls and its application for protecting monumental retaining systems is proposed for the first time in this work. Moreover, EPS can be characterized as a mild intervention scheme, which is compatible with the regulations for monumental structures, and can provide adequate seismic protection to the Wall. The proposed EPS application does not alter the monumental character of the Wall both visually and architecturally, as it can be covered by the excavation backfill material. A detailed parametric analysis regarding the type, the height and the thickness of EPS behind the Wall has been conducted. Despite the various uncertainties related to the numerical simulation of this complex problem, the results are very
promising since they reveal a substantial beneficial impact of EPS on the reduction of seismic distress of the Wall.

2 Seismic Distress of Retaining Walls and Mitigation with EPS

2.1 Dynamic Analysis Methods of Retaining Walls

As aforementioned, various analytical and numerical methods have been developed to determine the seismic earth pressures and the dynamic distress of a retaining wall. Although a detailed review is beyond the scope of the present study, a brief description of several characteristic studies is provided in this section. Mononobe and Matsuo (1929) and Okabe (1926) developed a pseudo-static analytical approach to calculate the total (i.e., static and seismic) earth force acting on the wall. According to this method, pseudo-static inertial forces act in both horizontal and vertical directions on the retained soil wedge. The proposed simplified mathematical formulas can be applied to calculate the active (and passive) seismic pressures on a wall. For typical values of internal angle of friction of the soil, the simplified method of Seed and Whitman (1970) can alternatively be used.

Wood (1973) investigated the seismic response of an isotropic homogeneous elastic soil within two rigid walls, located on the top of a rigid base. This study revealed that when the two rigid systems have an adequate distance (i.e., approximately five times the height of the wall), the dynamic earth pressures acting on both walls do not exhibit any interaction. In addition, for seismic excitations with low frequency and especially for frequencies lower than the half of the fundamental frequency of the soil layer for horizontal conditions \( f_0 = \frac{V_s}{4H} \), the seismic pressures acting on the wall can be calculated considering that the system (wall and backfill material) exhibits elastic behavior.

Veletsos and Younan (1994, 1997) estimated the magnitude and the distribution of the seismic earth pressures on the wall imposed by a horizontal seismic excitation using a simplified analytical methodology. They considered that the wall consists of a flexible beam with rotational flexibility at its base, while the soil was considered to be homogeneous and viscoelastic. In general, the flexibility of the wall and its rotational base affected the distribution of the seismic earth pressures, while an increase of the wall flexibility led to a decrease of the dynamic earth pressures.

Psarropoulos et al. (2005), utilizing the finite-element method, developed a numerical model in order to reproduce the results from the analytical method of Veletsos and Younan (1994, 1997). The retaining wall was simulated with beam elements, while a rotational spring was installed at its base to simulate the rotational flexibility. The finite-element software ABAQUS was used for the performance of dynamic analyses under harmonic excitations. The obtained numerical results were in agreement with the corresponding analytical solutions. Additionally, different cases of wall and base stiffness were examined in order to investigate their impact on the distribution of the dynamic earth pressures.

2.2 Application of EPS in Retaining Walls

Expanded polystyrene (EPS) is a composite material frequently used in many geotechnical projects, such as road and railway embankments, pipelines, retaining systems, etc. Typically, large parts of the soil can be replaced by EPS blocks to reduce the vertical and/or horizontal static and dynamic loads. The main reasons for using EPS are the following: low weight and relatively high strength, relatively low cost, ease of construction, and durability. Moreover, EPS can be produced in different shapes and types with varying mechanical properties, which serve better the needs of each engineering project. One of EPS applications in geotechnical engineering is its use as a compressible inclusion between a retaining wall and the retained soil. Several researchers have studied the performance of EPS as a mitigation measure, i.e., aiming to decrease the dynamic earth pressures from the backfill materials.

Zarnani and Bathurst (2009) presented a numerical model in which a compressive inclusion of EPS was installed between the wall and the soil in order to examine the reduction of the seismic pressures due to EPS inclusions. A parametric study was conducted regarding the thickness of the compressive inclusion, the type of EPS, the geometry of the wall as well as the frequency characteristics of the ground motion. The EPS and backfill interaction was modeled via a special interface element with zero thickness and a realistic friction angle (equal to 20°) derived from
relevant tests. The results of this study showed that
the application of EPS between the wall and the soil
backfill material led to a significant reduction of the
dynamic pressures. In particular, the reduction was
greater than 55% when the ratio of the thickness of
EPS to the wall height was ≈0.4.

Athanasopoulos-Zekkos et al. (2012) developed
two finite-element models of a retaining yielding
wall, utilizing the geotechnical software PLAXIS 2D.
A parametric study was performed for two retaining
wall heights and different thicknesses and shapes of
the EPS compressive inclusion and different seismic
intensity levels. The study revealed that the inverted
triangle was the most efficient EPS scheme. However,
a rectangular shaped inclusion can be used, since the
differences were marginal and it is a more viable solu-
tion from a practical viewpoint. Moreover, the results
illustrated that the efficiency of EPS in reducing of
the seismic pressures was increased for higher thick-
ness of EPS and decreased for higher magnitude of
the imposed seismic excitations. However, this trend
was observed up to a certain EPS thickness, since a
further increase did not improve its efficiency.

Dabiri and Notash (2020) investigated the effi-
ciency of EPS on a retaining wall under static and
seismic conditions. They examined different types of
walls (yielding and non-yielding) with 6 m and 9 m
height, while two types of EPS (EPS15 and EPS20)
were used with normalized thickness to wall height
equal to 0.1 and 0.2. Two seismic records, one near-
field and one far-field, were used for the dynamic
finite-element analyses. The results showed the benefi-
cial impact of EPS under static and dynamic loading
conditions. Lastly, very recently Psarropoulos et al.
(2022) investigated the application of EPS in order to
alleviate the impact of the so-called "dynamic wall-
soil-structure interaction" (DWSSI) phenomenon. It
was shown that a vertical, only 1 m-width, EPS in-
clusion can lead to a "frequency tuning" of the response
and reduce the detrimental effects of DWSSI both on
the wall and on the retained structure.

In all aforementioned studies, EPS was modeled
as a linear elastic material. Apart from the numeri-
cal studies, some experimental investigations have
also been reported. Athanasopoulos et al. (2007)
performed a centrifuge test of a small-scale model of
a retaining wall with and without an EPS compres-
sive inclusion. The results revealed a decrease of the
dynamic pressures due to the EPS, while the density
of the EPS affected its efficiency. More specifically,
EPS with lower density exhibited a greater efficiency.
Zarnani and Bathurst (2007) also performed an
experimental study at a shaking table using a small-
scale model of a rigid wall, which was also examined
numerically. The results of this study also illustrated
the reduction of the seismic pressures due to EPS.

3 Description of the Circuit Wall of the Acropolis

3.1 The Acropolis Hill

Acropolis of Athens is one of the most impressive
monumental complexes in the world, and it has been
included in the World Heritage Sites List of UNE-
SCO since 1986. On the hill of the Acropolis, which
dominates the center of the modern city of Athens,
great monuments are located. Apart from Parthenon,
which is the most prestigious ancient structure,
the hill includes several other monuments, such as
Propylaia and Erechteion, with great historical and
architectural importance. One of them is the perim-
eteric Circuit Wall, which is depicted in Fig. 1. The Cir-
cuit Wall is a masonry structure retaining the backfill
materials that are used to flatten the surface of the
hill. The Hellenic Ministry of Culture and the Acrop-
olis Restoration Service (YSMA) have great interest
in maintaining the structural integrity of the Wall.
For this purpose, optical fiber sensors and acceler-
ographs have been installed for the multi-disciplinary
real-time monitoring of this complex historical site,
as described by Kapogianni et al. (2019).

The seismic response of any structure depends
directly on the local site conditions (i.e., soil layers,
seismic bedrock morphology, and/or topography),
which can amplify the seismic motion at the ground
surface and alter its frequency content. Addition-
ally, in the case of retaining systems, the properties
and the typology of their foundation, the inclination
of the bedrock, as well as the mechanical proper-
ties of the retained soil can also play a crucial role.
As shown in Fig. 2, the Acropolis hill is composed
of a limestone layer, which is located on top of the
Athenian schist. The limestone is actually a hard
rock, while schist is considered to be a soft rock
(Psarropoulos et al. 2018). The thickness of the
limestone does not exceed 40 m. The slopes of the
hill are almost vertical with a varying height up to
On the other hand, the backfill material is thicker on the south side of the hill and it is retained by the Wall, while it is characterized as a soft soil material (Koukis et al. 2015). In addition, rockfall phenomena and additional erosion phenomena have occurred due to limestone karstification that has created cavities that facilitate the water flow (Higgins and Higgins 1996; Koukis et al. 2015).

In general, the earthquake hazard for the ancient part of Athens around the Acropolis hill is relatively low (Ambraseys and Psycharis 2012). Thus, most probably, the structures on the hill have not been seriously damaged by a strong seismic event. Nonetheless, in recent history, the wider region of Athens has suffered from quite strong ground motions. Two of the most disastrous seismic events were the eastern Corinth gulf \((M = 6.6)\) earthquake in 1981, and especially the Parnitha \((M = 5.9)\) earthquake in 1999, from a fault rupture very close to Athens that caused many human losses. Some other seismic events that could have affected the monuments in recent history are the earthquakes of 1705 in Athens \((M < 6)\) and 1837 in Troezen \((M = 5.5)\) (Psarropoulos et al. 2018).

In the context of the seismic activity monitoring on the hill, a network of accelerographs has been installed by the Institute of Geodynamics of the National Observatory of Athens (IG-NOA) and the Acropolis Restoration Services (YSMA). The network includes ten accelerographs, which are mounted at different locations on the hill, while two of these accelerographs have been installed on the south Wall. More specifically, the first accelerograph is installed at the base of the Wall at the limestone, while the second is located at the backfill material on the top of the Wall (Kapogianni et al. 2019).

The construction of the first fortification wall dates back to 1,200 BC and it is called the 'Cyclopean' Wall. This Wall was built at the top of the hill until 480 BC, when it suffered extensive damages during the Persian wars. Then, the north side of the Wall was built again by Themistocles (Themistoclean Wall) and the south side by Kimon (Kimonion Wall). The total length of the Wall is approximately 800 m,
and its height varies between 5 and 20 m, having a width ranging from 1 and 6 m, depending on the local topography (Egglezos et al. 2013). The Wall, which is based on the inclined limestone bedrock (Eleftheriou 2015), is characterized by various construction and intervention phases. Its main construction materials are stones and marble blocks, while mortar and exterior coatings have also been used.

In the past, the Wall has been damaged during wars and also due to natural hazards. For this reason, many modifications and restorations have been performed. As shown in Fig. 3, static and dynamic pressures from the backfill materials have caused cracks on the Wall (Egglezos et al. 2013). Hence, the protection of the Wall against static and dynamic loads is an extremely important issue, since its failure could cause structural damages to some other monuments and buildings on the top of Acropolis hill and/or human losses due to the high number of tourists visiting the hill every day.

3.2 Numerical model of the Circuit Wall

In this study, the seismic response of a specific Wall section, presented in Fig. 4a, has been investigated via two-dimensional dynamic analyses. The selection of the specific location has been based on the following criteria:

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![Fig. 3](image_url)  
**Fig. 3** Cracks at the southeast corner of the Wall: **a** view from the east, **b** view from the south

![Fig. 4](image_url)  
**Fig. 4** **a** Location of the examined section at the south part of Acropolis hill, and **b** installed accelerographs at the base (ACRJ) and at the top (ACRD) of the Wall
(a) The Wall height at this section is approximately 18 m, which leads to increased earth pressures under both static and seismic conditions.

(b) Some local failures (i.e., wide cracks) have been observed at this specific location (see Figs. 3a and b).

(c) Two of the accelerographs of the Institute of Geodynamics have been installed at the base (ACRJ) and the top (ACRD) of the Wall, as displayed in Fig. 4b. Therefore, the recordings can be used for the verification of the numerical model(s).

The south Circuit Wall in the study area is a heavy masonry retaining system that supports the backfill material. The geometry of the numerical model is based on the architectural representation shown in Fig. 5a. As displayed in Fig. 5a, the Wall at this location is based on the inclined bedrock.

The inclination of the bedrock is approximately 20° (Trikkalinos 1977). In general, local site conditions, including topography effects, play an important role, as it has been presented in many relevant studies (e.g., Gazetas et al. (2002), Bouckovalas and Papadimitriou (2005), Tripe et al. (2013), Rizzitano et al. (2014) among others). The impact of the special topographic conditions in the dynamic response of the whole Acropolis hill has been highlighted in a recent study (Kapogianni et al. 2020). The two-dimensional numerical model depicted in Fig. 5b has been developed utilizing the geotechnical finite-element software PLAXIS 2D (Brinkgreve et al. 2010).

Taking into account aging, damages, interventions, etc. and the limited available geotechnical data from the non-uniform backfill and Wall materials, it is very difficult to derive the accurate mechanical properties of the materials. In the present investigation, a uniform material has been used to simulate the Wall section, i.e., not distinguishing different types of materials (stones and mortars). Despite the simplified approach and the various material and geometrical uncertainties, the adopted numerical methodology can produce quite realistic results. Table 1 presents the mechanical properties of the Wall, the backfill material and the limestone bedrock, which have been taken from a recent study by Psarropoulos et al. (2018).

In addition, as depicted in Fig. 5c, a sufficient dense mesh has been developed, consisting of 15-noded triangular finite elements, which offer a relatively high computational accuracy. The Wall has also been discretized using plane-strain triangular finite elements, which provide a more accurate representation of the complex Wall geometry and rigidity, compared to simple beam elements. Since the imposed seismic excitations are characterized by low acceleration levels, the materials are realistically considered to behave in a linear elastic

### Table 1  Mechanical properties of rock, backfill and the Wall

|                     | Rock | Backfill | Wall |
|---------------------|------|----------|------|
| Unit weight, \( \gamma \) (kN/m\(^3\)) | 26   | 20       | 26   |
| Shear-wave velocity, \( V_s \) (m/s)    | 1,500| 300      | 1,090|
| Young’s modulus, \( E \) (MPa)           | 16,000| 480     | 7,900|
| Poisson’s ratio, \( v \) (–)             | 0.30 | 0.30     | 0.25 |
manner. Rayleigh damping, $\xi$, is set equal to 0.5%, in the frequency range between 5 and 10 Hz.

The base of the model is rigid rock (limestone of Acropolis Hill, see Fig. 2) with high $V_s$ (1500 m/s) and it is considered to be fully fixed. Moreover, the rock has inclined geometry, as shown in Fig. 5. On the other hand, the backfill has a substantially lower $V_s$ (300 m/s). Generally, in numerical simulations of problems of soil dynamics it is required to use transmitting boundaries (e.g., Tripe et al. 2013, Rizzitano et al. 2014). Nonetheless, in this specific case it is not necessary to apply them at the left side of the models, since simple horizontal fixity conditions also provide a realistic representation. This is due to the high ($\approx 5$) contrast of $V_s$ between limestone and backfill, which leads to trapping of seismic waves within the backfill and diminishes any reflections back to the limestone.

The employed numerical approach has been previously validated using the same mechanical and geometrical properties by Psarropoulos et al. (2018). The validation was based on two real seismic excitations from the installed accelerographs at the Wall shown in Fig. 4b. A comparison was performed in terms of amplification factor (AF) in the frequency domain, which is actually a transfer function that denotes the ratio between the Fourier spectra of the acceleration time-histories at the top and at the base of the Wall due to an imposed excitation. It was proven that the numerical results are in a good agreement with the available in-situ measurements, i.e., the AF derived from the recorded data and the numerical analyses exhibited marginal discrepancies. Therefore, based on the aforementioned realistic modeling approach of the current Wall structural and geotechnical conditions, the current study examines its current dynamic distress and further proposes an efficient and suitable mitigation measure for its seismic protection.

4 Dynamic Response of the Circuit Wall

4.1 Dynamic Response Characteristics

In order to assess the dynamic response of the system (i.e., rock-backfill-Wall), a Ricker pulse has been used. In general, Ricker pulses cover a sufficiently wide range of frequencies, leading thus to a more realistic calculation of the amplification factor (AF), which can be used to predict the dynamic response of the system for other seismic excitations. Figure 6a presents the acceleration time-history of the Ricker pulse. The maximum acceleration of the pulse is set equal to 0.1 m/sec$^2$. Due to the low acceleration levels, all dynamic analyses can be considered to be linear elastic. The central frequency of the Ricker pulse is selected to be 6 Hz in order to cover the whole frequency range of interest for the examined case study. Figure 6b depicts the 6 Hz Ricker Fourier spectrum that has been used for all dynamic analyses.

Figure 7 presents the acceleration amplification factor (AF) in terms of frequency, which denotes the ratio between the computed Fourier spectra at the top and at the base of the Wall for the imposed Ricker 6 Hz excitation. It has to be stressed that the accurate
assessment of the developed acceleration levels at the top of the hill is crucial for the Acropolis monuments. As it can be observed, the fundamental frequency of the whole system (i.e., rock, backfill material, Wall) is approximately 7.8 Hz, for which the maximum acceleration AF is almost 120. Hence, the south Circuit Wall is more vulnerable to high-frequency seismic excitations with dominant frequencies close to 8 Hz.

4.2 Dynamic Pressures

Obviously, the dynamic pressures on the Wall are time-dependent. A snapshot of the height-wise distribution of the dynamic pressures on the examined Wall section due to the Ricker pulse excitation is presented in Fig. 8 at the occurrence of the maximum dynamic force, i.e., at the time when the area of the plot in Fig. 8 is maximized. As it will be shown in the sequence, the time-history of dynamic force, $\Delta P_{AE}(t)$, is used to derive a suitable transfer function, which can be used to assess the variation and potential amplification of dynamic earth forces in the frequency domain.

As presented in Fig. 8, at the lower part of the Wall, near to its base, the dynamic pressures from the backfill material are lower, compared to those in the upper part. Note that in all relevant plots, the pressures are shown only at the backfill, i.e., they are not calculated at the base of the Wall due to the inclined bedrock and the approximately 3 m "embedment" of the Wall at its lower part, as shown in Fig. 5. It should be mentioned that the pattern of the dynamic pressures depends on the geometry of the Wall and the thickness of the backfill material. Due to the complexity of the geometry of the Wall, the distribution is different from the corresponding one of a typical cantilever wall. Dynamic earth pressures present high values in the upper part of the Wall, due to the inclined bedrock that results in a triangular geometry of the backfill (see Fig. 5). As it can be noticed in Fig. 8, pressures present a maximum value of the order of 25 kPa/m at the thicker upper part of the Wall.

In the sequence, the Pressure Amplification Factor (PAF) is introduced, which can be used to assess the variation and potential amplification of dynamic earth pressures in the frequency domain (Psarropoulos et al. 2009). This parameter is defined as follows:

$$ PAF = \frac{\text{FFT}[\Delta P_{AE}(t)]}{\text{FFT}[A(t)]} $$  \hspace{1cm} (1) $$

where $\text{FFT}[\Delta P_{AE}(t)]$ is the Fourier spectrum of the normalized induced dynamic earth force time-history $\Delta P_{AE}(t)$ and $\text{FFT}[A(t)]$, is the Fourier spectrum of the acceleration time-history imposed at the base of the model (i.e., the Ricker pulse excitation shown in Fig. 6b). It is noted that PAF, being -analogously to AF- a transfer function in the frequency domain, can provide a reliable assessment of the distress levels of the Wall (in terms of earth pressures) by utilizing the Fourier spectrum of any seismic excitation.

It is evident from Fig. 9 that PAF reaches its maximum value at the fundamental frequency of the rock-backfill-Wall system. Hence, for high-frequency excitations (i.e., close to 8 Hz), the dynamic pressures on the Wall present their highest values, which may lead to severe damages of the Wall for extreme seismic intensity levels. In contrast, PAF exhibits low values for low- to medium-frequency excitations (i.e., up

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**Fig. 8** Height-wise distribution of the dynamic pressures on the examined section of the south Circuit Wall for the Ricker excitation

**Fig. 9** Pressure Amplification Factor (PAF) in the frequency domain for the south Circuit Wall section under Ricker pulse excitation
to 6 Hz). Thus, comparatively less amplification is expected regarding the dynamic pressures exerted on the Wall.

5 Seismic Mitigation with EPS

As aforementioned, old masonry retaining walls, such as the Wall at the Acropolis hill, are sensitive structures that are quite vulnerable to seismic loading. Therefore, their protection should be ensured. The seismic behavior of such retaining structures depends on their mechanical and geometrical properties, as well as on the characteristics of: (a) the backfill material(s), and (b) the seismic excitation (i.e., peak values, frequency content, duration).

As the aim of the engineers is to reduce the anticipated dynamic earth-pressures, the protection of old masonry retaining walls can be achieved by the application of various inclusions between the wall and the retained soil, such as the proposed expanded polyethylene (EPS). Since any intervention modifies the natural frequencies of the system, the impact of any inclusion may be beneficial or detrimental, depending on the circumstances. Therefore, a case-by-case study is required in order to choose the optimal mitigation measure.

In this specific case study, the excavations, and the subsequent replacement with EPS blocks, of the backfill material must be performed with extra caution due to the special requirements that are imposed in all interventions in monuments. Nonetheless, it is noted that a limited number of EPS blocks will be required (especially in the case of partial replacement of backfill with EPS), thus, the excavations will not be so extensive. More specifically, they will be implemented with a careful and partial (i.e., not along the full height and width of the Wall) excavation of a trench with adequate dimensions, in which EPS blocks can be placed according to the preferred design solution. This process will not endanger the integrity of the Wall and the other monuments on the Acropolis Hill. Moreover, the extracted backfill will be placed nearby and will be reused, if required. During the excavation, depending on the prevailing conditions, temporary supporting systems may be required. Certainly, if the proposed mitigation measure will be adopted by the authorities, a detailed technical study is required prior to its application.

| Table 2  | Mechanical properties of EPS19 and EPS39 |
|----------|----------------------------------------|
|          | EPS19     | EPS39     |
| Young’s modulus, E (MPa) | 4         | 10.3      |
| Density, ρ (kg/m³)     | 19        | 39        |
| Poisson’s ratio, ν (-) | 0.05      | 0.05      |

Fig. 10 South Circuit Wall section with EPS inclusion along its height with average thickness: a 2.4 m, b 4.3 m, c 6.3 m

5.1 Application of the EPS Along the Total Height of the Wall

The improvement of the dynamic response, i.e., the reduction of the dynamic earth pressures on the Circuit Wall, is achieved by applying EPS inclusions between the Wall and the backfill material. The current investigation includes two types of EPS with different densities. The main mechanical properties are presented in Table 2. Evidently, EPS39 is more stiff, due to the higher Young’s modulus. A parametric analysis has been conducted considering three different average thicknesses of EPS: 2.4 m, 4.3 m, and 6.3 m, as presented in Fig. 10. Evidently, the
thickness of EPS between the Wall and the backfill material cannot be uniform due to the complex geometry of the Wall.

Note that in reality, potential sliding between EPS blocks as well as between EPS and backfill and EPS and Wall may occur. These interactions can be realistically simulated via interface elements or contact constraints, by adopting realistic parameters (e.g., friction angle values) that can be obtained from physical tests. However, there is a great variation of the interface properties, depending on the type of contact materials (EPS-EPS, EPS-soil, EPS-concrete, etc.), the density of EPS, the applied normal loads on the geofoam blocks, etc. On the other hand, EPS blocks can be quite easily tied together using stainless steel connectors (such as barbed steel plates), while similar connectors (e.g., simple steel rods, which apart from friction exhibit pull-out resistance) can be used to ensure their full contact with the soil, i.e., to avoid sliding/debonding. Moreover, the EPS blocks are "interlocked", i.e., not placed exactly on top of each other following the same vertical alignment.

Furthermore, the surfaces of the EPS blocks that are in contact with the soil and the Wall can be roughened in order to increase the friction at the soil-EPS interfaces, while geogrids/geomembranes can also be placed between soil and EPS blocks. In general, EPS has been applied in many engineering projects and relevant guidelines provide technical specifications for their proper usage. Thus, very detailed practical aspects are not included herein. Hence, considering the various uncertainties related to the Wall current status and the aforementioned technical details regarding practical implementation of EPS, this preliminary investigation considers that geofoam blocks form a monolithic, homogeneous body, fully tied with the backfill and the Wall materials.

According to related studies (Athanasopoulos et al. 1999), the response of EPS is also assumed to be linear elastic, while its damping is very small for low strain levels. Thus, Rayleigh damping, $\xi$, is considered to be equal to 0.5%, as for the other materials. It has to be noted that under static conditions the flexibility of the retaining system due to EPS inclusions leads to active earth pressures on the Wall. Nonetheless, the present study deals only with dynamic earth pressures, and in parallel for low acceleration levels, in which the behavior of all materials is expected to be linear elastic. This has been verified in the validation of the dynamic response of the Wall in terms of the developed accelerations versus recent recordings (Psarropoulos et al. 2018).

Apart from the inclusion of EPS, the developed two-dimensional numerical models are similar to the reference model describing current Wall status in Fig. 5. More specifically, Fig. 10 displays the numerical models when EPS is installed along the total height of the Wall, for the three average EPS thickness. Similar to the backfill and the Wall, EPS is also simulated with plane-strain elements. For the discretization of all models, a dense mesh is used with 15-noded triangular plane-strain elements. Lastly, the Ricker pulse shown in Fig. 6 has been used for all dynamic analyses, as its frequency content is suitable both for the initial and all modified (due to EPS inclusion) models of the Wall.

Figures 11a and b present the amplification factors (AF) in the frequency domain for the cases where EPS19 and EPS39 blocks have been placed between the Wall and the backfill. As it can be noticed, the application of both types EPS increases the flexibility of the system and reduces its fundamental frequency. The flexibility of the system is increased for higher
EPS thickness; however, as the EPS thickness further increases (i.e., from 4.3 to 6.3 m), the reduction of the fundamental frequency is smaller. Comparing the two types of EPS, it can be observed that the EPS19 contributes to a greater reduction of the fundamental frequency for all the examined thicknesses. As it can be observed, the application EPS decreases the AF for all the examined thickness values in a similar manner for EPS19 and EPS39 in all cases.

Analogously to Figs. 8, 12a and b (as well as the similar subsequent plots with EPS inclusions) illustrate a snapshot of the distribution of dynamic pressures on the Wall at the time of the occurrence of the maximum dynamic force for each case. Results are provided for both types of EPS and the three examined thickness values when the EPS is applied along the entire height of the Wall, compared to the initial dynamic earth pressures. The shape of the distribution does not seem to be significantly affected compared to the initial case, i.e., without the addition of EPS blocks. Dynamic pressures are also greater at the upper part of the Wall for all the examined thickness values. However, a substantial reduction of the dynamic pressures is observed due to the application of EPS. The reduction is bigger as the thickness of the EPS increases from 2.4 to 4.3 m. As the thickness of both EPS19 and EPS39 further increases from 4.3 to 6.3 m, the beneficial impact of EPS is smaller. By comparing the two types of EPS, it can be seen that EPS19 provides a greater reduction of dynamic pressures on the Wall for all the examined thickness values.

The variation of the PAF in the frequency domain, when the EPS is installed along the total height of the Wall, is depicted in Figs. 13a and b for the two EPS types compared to the PAF of the reference backfill model. Obviously, the maximum PAF occurs at the fundamental frequency of each model, which is influenced by the thickness and EPS type. The addition of EPS between the Wall and the backfill leads to a reduction of the maximum PAF. The reduction is bigger when the EPS thickness is increased. The only exception is when using EPS39 with an average thickness of 2.4 m, in which an increase of the PAF is observed. Therefore, it can be concluded that an EPS inclusion with small thickness is neutral or even detrimental for the seismic distress of the Wall. In contrast, for greater EPS thickness, a substantial reduction of the PAF value is observed, especially when applying the softer geofoam material.

**Fig. 12** Height-wise distribution of the dynamic pressures for: a EPS19 and b EPS39

**Fig. 13** Pressure Amplification Factors (PAF) for: a EPS19 and b EPS39
In general, EPS19 provides a better protection to the Wall against dynamic loads compared to EPS39. Hence, taking into account the minimization of backfill excavations and removal as well as EPS material quantities, the use of EPS19 with a 4.3 m thickness is considered preferable.

5.2 Application of EPS at the Upper Part of the Wall

In this section, the application of EPS at the upper part of the Wall is investigated in order to determine its potential impact on the dynamic pressures. In this case, the EPS is placed up to 7.9 m below the surface of the backfill, thus covering almost 45% of the total Wall’s height. The purpose of this configuration is to further improve—if possible—the seismic response of the Wall and mainly to reduce the total time and cost by reducing the required quantities of EPS blocks as well as the required excavations and backfill removal from the Acropolis hill, which are not easy tasks. The type of EPS that has been used is EPS19, with the three average thicknesses of 2.4 m, 4.3 m, and 6.3 m. The resulting numerical models are similar to the ones shown in Fig. 10, while the same Ricker pulse has been used. Figures 14a, b and c present the numerical model when EPS is placed at the upper part of the Wall.

Firstly, the dynamic response of the system is examined in terms of AF in the frequency domain. The variation of AF is presented in Fig. 15 in the case of EPS19 inclusion at the upper part of the Wall. The application of EPS19 decreases the fundamental frequency, as it reduces the mass and increases the flexibility of the system. As in the previous case with EPS inclusion along the whole Wall height, in the case of greater EPS thickness (i.e., 4.3 m and 6.3 m) the differences in the fundamental frequencies of the system are marginal. As it was expected, the fundamental frequency of the system is bigger compared to the approach when the EPS is placed along the total height of the Wall; nonetheless, an analogous reduction of AF is obtained.

As it can be noticed by observing Fig. 16, which again presents a snapshot at the time of the occurrence of the maximum dynamic force for each case, the shape of the height-wise dynamic pressures distribution when the EPS is applied at the upper part of the Wall, is completely different compared to the initial backfill pressures. More specifically, dynamic pressures are smaller at the upper part which is covered with EPS19 blocks, while at the lower part dynamic pressures exhibit a dramatic increase compared to the current backfill conditions. Maximum dynamic pressures occur at a height between 6 and 8 m from the base of the Wall. The increase of the dynamic pressures at the lower part of the Wall can be attributed to the accumulation of seismic waves in the area between the inclined bedrock, the
EPS inclusion and the Wall. The seismic waves are trapped and reflected within this area, amplifying thus the dynamic pressures on the Wall. These trends are observed for all the examined EPS thickness values. Nonetheless, as the thickness of the EPS19 increases, the dynamic pressures are reduced along the whole height of the Wall.

Figure 17 presents the variation of the PAF in the frequency domain when the EPS19 is placed at the upper part of the Wall, for all the examined EPS thicknesses. The maximum PAF occurs at the fundamental frequency for each model. A significant increase is observed for the maximum PAF with the addition of EPS19 compared to the reference case irrespective of inclusion thickness. The increase is higher for small EPS thickness. Moreover, compared to the soil model, PAF reaches higher values throughout the frequency domain. Hence, the inclusion of soft geofoam at the upper part of the Wall is highly detrimental, while the application of stiffer EPS39 leads to even worse results and it should also be avoided.

5.3 Application of EPS at the Lower Part of the Wall

In the sequence, the dynamic response of the system has been examined for the case when EPS blocks are placed at the lower part of the Circuit Wall. Both EPS19 and EPS39 have been used for all the examined average thickness values (i.e., 2.4 m, 4.3 m, 6.3 m) as in the previous cases. EPS is considered to be placed up to 10.6 m from the base of the Wall, covering almost 60% of its total height. Regarding the practical implementation of EPS configurations shown in Fig. 18, first the backfill will be partially removed along the total Wall height, followed by the placement of EPS blocks, which will be covered by the excavated backfill. The three corresponding numerical models presented in Fig. 18a, b, and c, have been developed in the same manner as when EPS is applied along the total height.

Figure 19 depicts the variation of AF when EPS19 and EPS39 blocks are applied at the lower part of the Wall, for all examined thickness values, and also for the current backfill conditions without EPS. As it can
be noticed, the Wall has a similar seismic response for both EPS19 and EPS39, as the differences are insignificant. The application of EPS makes the system more flexible, reducing thus its fundamental frequency. When the thickness of EPS is increased, the reduction of the fundamental frequency is higher. The fundamental frequency for each average thickness is bigger compared to the corresponding ones when the EPS is applied along the entire height of the Wall or only at its upper part. The values of the AF are considerably lower compared to the two previously examined cases of EPS height-wise configuration for all thickness values, while an almost identical response for both EPS19 and EPS39 types is observed.

The height-wise dynamic pressures distribution when either EPS19 or EPS39 are applied at the lower part of the Wall are presented in Fig. 20 at the time of the occurrence of the maximum dynamic force for each case. As it can be observed, the distribution is quite similar for EPS19 and EPS39, for all EPS thickness values. In contrast, it presents significant differences compared to the initial model without EPS. At the lower part of the Wall, where the EPS inclusion is placed, dynamic pressures are substantially reduced compared to the current soil conditions. On the other hand, they become much higher at the upper part. This increase can be attributed to the reflections of seismic waves within the area between the Wall and the EPS at the upper part of the backfill material. In addition, like in the EPS layouts presented in previous sections, the reduction of the dynamic pressures along the whole height of the Wall is increased for larger EPS thickness. Nevertheless, the increase is lower compared to the case in which the EPS is placed only at the upper part, due to the greater thickness of the backfill material behind the Wall.

The variation of PAF in the frequency domain when EPS19 and EPS39 are applied at the lower part of the Wall is depicted in Fig. 21. As it can be easily observed, PAF values are approximately identical for EPS19 and EPS39. The maximum PAF, which occurs at the fundamental frequency for each EPS-retrofitted model, is smaller compared to the reference backfill model. Nevertheless, in contrast to the previous two EPS configurations, PAF is becoming slightly higher as the thickness increases, i.e., when the EPS is applied at the bottom of the Wall, a smaller EPS thickness contributes to a lower seismic distress of the Wall. Lastly, it is also worth noting that compared to the case that EPS is applied along the total height of the Wall, PAF is bigger for all EPS thickness values.

6 Conclusions

The present study investigates the dynamic distress of the south Circuit Wall of Acropolis and the impact of EPS inclusions as a potential seismic mitigation...
measure. For this purpose, finite-element models for a critical section of the Wall have been developed and a series of linear elastic dynamic analyses has been performed. Based on the calculation of the fundamental frequency of the system rock-backfill-Wall, which is approximately equal to 7.8 Hz, the Wall can be affected more by high-frequency near-field ground motions due to potential resonance phenomena. The inclusion of the EPS between the Wall and the backfill increases the flexibility of the system, thus, reduces its fundamental frequency. In addition, larger EPS thickness further increases the flexibility of the system. On the other hand, the inclusion of stiffer EPS (e.g., EPS39) is less efficient compared to the softer geofoam (e.g., EPS19). The reduction of the fundamental frequency is greater when EPS is applied along the total height of the Wall and smaller when the EPS is applied only at its lower or upper part. In all the examined cases, EPS reduces AF (i.e., the acceleration levels at the top of the hill) for high-frequency seismic excitations with dominant frequencies in the range of 7–8 Hz.

The height-wise distribution of the dynamic pressures is significantly affected by the complex geometry of the Wall. Dynamic pressures of the earth fill are smaller at the base of the Wall and they are higher at the top. The inclusion of EPS along the total height of the Wall reduces substantially the dynamic pressures compared to the ones due to backfill, but does not alter their distribution. In contrast, when EPS is applied only at the upper part or at the lower part, the distribution is much different from the current soil conditions. In these cases, dynamic pressures are significantly increased at the part of the Wall that is not protected with EPS. It is noted that the type and the thickness of the EPS do not alter the pattern of the dynamic pressures, but only their values.

In all cases, the maximum dynamic pressures occur at the fundamental frequency of the system. The application of the EPS along the entire height reduces the dynamic pressures on the Wall, mainly for larger thickness and for softer EPS material. In contrast, when stiffer EPS with small thickness is used, a minor increase of the dynamic pressures is observed. Moreover, when EPS is placed only at the upper part of the Wall, a significant increase of the dynamic pressures is noticed. Therefore, the potential application of EPS only at the upper part of the Wall may have a detrimental impact and should be avoided. The application of EPS at the lower part of the Wall leads to a reduction of the dynamic pressures at the protected part and it is more efficient for small thickness of EPS inclusion. In this case, the differences between the two EPS types that have been examined are negligible.

Conclusively, the optimal intervention to protect the Wall is the application of a soft type of EPS (e.g., EPS19) along the total height of the Wall and having a high thickness (e.g., 4.3 m or 6.3 m). Alternatively, soft EPS material can be placed only at the lower part of the Wall with a small EPS thickness (e.g., 2.4 m). Nevertheless, given the fact that the Circuit Wall has great variations in materials and geometry, the present study should be extended by developing more elaborate three-dimensional models in order to examine more realistically the impact of the proposed EPS inclusion configurations. In addition, since the material non-linearities, that usually take place during a strong seismic event, play a crucial role in structural and soil dynamics, their impact should be investigated by incorporating advanced constitutive models.

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