Geotechnical Study on the Hellenistic stone retaining wall of the Upper Agora in Ephesus under static and seismic loading

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ABSTRACT

This study presents a geotechnical investigation on the Hellenistic retaining wall of the Upper Agora in Ephesus, western Türkiye. Stability analyses under static and seismic loading conditions were carried out to evaluate the long-term performance of the Hellenistic retaining wall, which was built without mortar in the 2nd century BCE. To achieve this, a multidisciplinary study was carried out in the fields of archaeology and building research, geology, and geotechnical engineering. The motivation of this study is to perform stability analyses of the ancient retaining wall in accordance with conventional standards and norms. The Mononobe-Okabe (M-O) method was applied to calculate the dynamic earth pressure coefficients in the earthquake analyses. Thus, in the seismic stability analyses a pseudo-static approach was used. The 30 October 2020 Samos Island earthquake was adopted as the reference seismic event due to its proximity, well-recorded ground motions, and relevance to the active tectonic regime of western Anatolia. According to the Kandilli Observatory and Earthquake Research Institute (KOERI), the magnitude of the earthquake is Mw = 6.9 and the depth is 10 km. The results of the analyses under static loading according to the sliding and bearing capacity failure show that the stability design numbers μ are satisfied, and that the overturning safety is almost fulfilled. Under seismic loading, the μ values were obtained less than 1,0 according to the sliding and bearing capacity failure analyses taken into consideration the peak ground acceleration a_{gr} values recorded by the Kusadasi station (code 0905) corresponding to the Samos Island earthquake event.

Keywords: Upper Agora, Ephesus, Hellenistic stone wall, stability, static loading, earthquake

INTRODUCTION

A geotechnical study was carried out for the Hellenistic stone retaining wall of the Upper Agora in the ancient city of Ephesus, located in western Türkiye. The Upper Agora was investigated between 2014 and 2016 as a part of research project funded by the German Research Foundation (DFG) in collaboration with the Austrian Archaeological Institute, the Institute of Classical Archaeology at the University of Regensburg (UR), and the Archaeological Building Research Department of the Regensburg University of Applied Sciences (OTH Regensburg). Since 2015, the Technical University of Berlin (TU Berlin) has contributed geotechnical and structural analysis expertise to the project. The upper Agora is situated between the Panayırdağ and Bülbüldağ hills (Figures 1-I). It was constructed by filling a rectangular area with earth material between these hills as shown in Figure 2. The artificial platform was supported by the stone retaining walls in the north-south and in east-west directions (Figure 1-II). The present study focuses on the western segment of the retaining wall, which was built without mortar in the 2nd century BCE. Stability analyses under both static and seismic loading conditions were carried out for Hellenistic stone retaining wall. The Mononobe-Okabe (M-O) method based on pseudo-static approach was used for the stability analyses under seismic loading condition in this study. In the following sections, the geotechnical study aspect, simplified calculation method, and the results of the stability analyses with the evaluations are presented.

Figure 1. *(I)Views from Bülbüldağ toward the Upper Agora, illustrating the geomorphological setting of the Ephesus (II) the western retaining-wall segment of the Upper Agora*

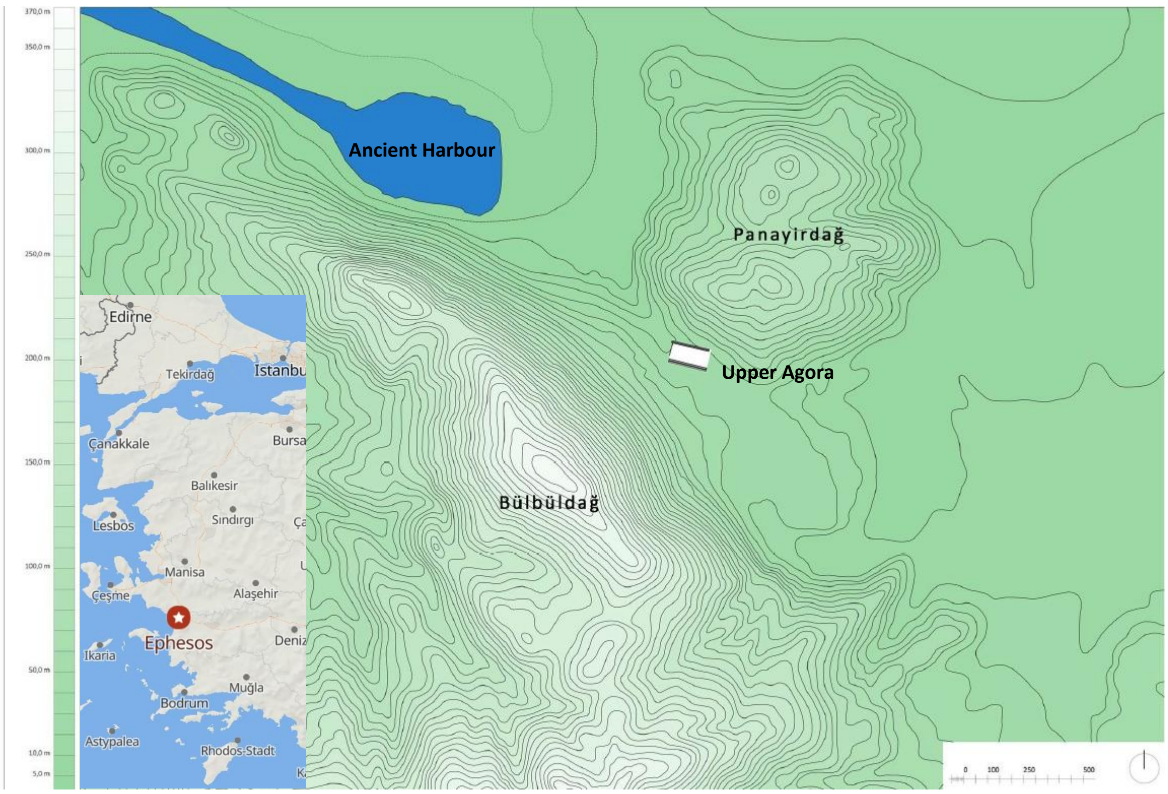

Figure 2. *Topographical map of Ephesus showing the Roman harbour basin, the two city hills, and the location of the Upper Agora (drawing: D. Musall, 2022)*

GEOTECHNICAL STUDY ASPECT

Western Anatolia and the Aegean region, where the ancient city Ephesus are located, are among the most seismically and tectonically active areas in the Euro-Mediterranean region. Accordingly, the stability analyses were carried out for the retaining wall under both static and seismic loading conditions. The current state of the western end of the Upper Agora in Ephesus is shown in Figure 3 (I), and Figure 3 (II) depicts the reconstruction. The Hellenistic retaining wall is marked in green in Figure 4 in both the plan view and the cross-section. It should be noted that the part of the wall labelled (a) in Figures 3 and 4 is one of the highest parts of the retaining wall.

Figure 3. *(I) The current state of the western retaining-wall segment of the Upper Agora (II) Archaeological reconstruction of the original Hellenistic configuration (Musall et al., 2025)*

Due to its seismically active characteristics, the ancient city of Ephesus and its surrounding area have experienced numerous moderate-to-large earthquakes throughout history and in recent years. The Ephesus region is structurally controlled by the Ephesus Fault, a NW–SE-trending basin-bounding normal fault forming the southern margin of the Küçük Menderes Graben. The fault zone has undergone polyphase reactivation (strike-slip to normal) during the Miocene–Quaternary period, resulting in a steep fault geometry with dips of 59–65°, as documented in Sümer (2015). This structural configuration places the Upper Agora directly within the footwall domain of this active normal-fault system. Figure 5 shows the historical earthquakes with a moment magnitude of between 5.0 and 7.0 (M_w/MS) in the region around Ephesus between 1900 and 2024 (AFAD). The Samos Island earthquake which is also depicted in Figure 5 is selected as the reference earthquake for this study because this earthquake is a very recent and strong earthquake that occurred near Ephesus. The magnitude of the earthquake was reported as M_w 6.9 and the depth as 10 km according to the Kandilli Observatory and Earthquake Research Institute (KOERI). The epicentre of the earthquake was north-east of Samos Island, approximately 70 km south of Izmir and approximately 50 km west of the Ephesus in Selçuk, Izmir. The study by Gülerce et al. 2022 states that the area around Samos Island is mainly dominated by north-south (NS)-directed extension, accompanied by east-west (EW)-oriented normal faults and lateral movements along north-east-south-west (NE-SW) and north-west-south-east (NW-SE) - oriented strike-

Figure 4. *(I) Cross-section showing the retaining-wall highlighted in green (II) Plan view of the western end of the Upper Agora*

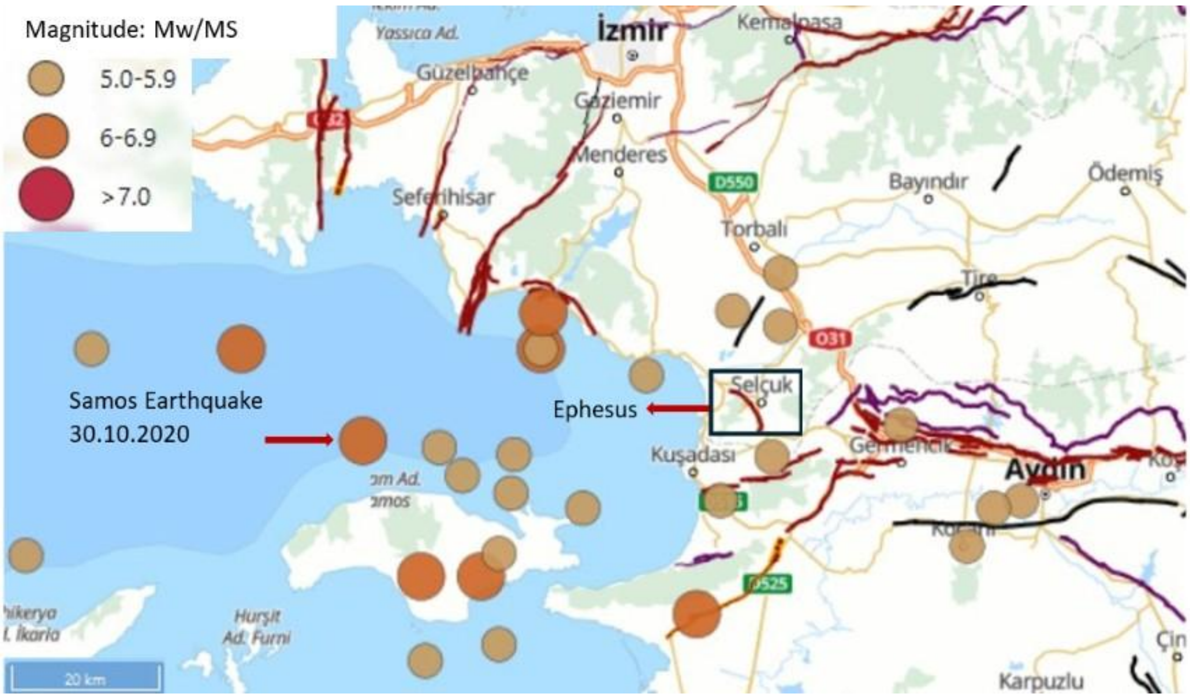

Figure 5. *Historical earthquakes (Mw 5-7) in the Ephesus region between 1900 and 2024 (AFAD)*

slip faults. It is reported in the studies that the peak ground acceleration (PGA) values in Izmir Bay during the earthquake were between 0.10 g and 0.20 g (Demirci et al., 2022) According to the Global Earthquake Model (GEM) of the Global Seismic Hazard Map (version 2018.1), the estimated PGA value around the Selçuk region is between 0.20 g and 0.35 g. The PGA value ranges recorded by the accelerometric stations around the Ephesus during the Samos Island earthquake is given in Figure 6. In this study, the acceleration records from Kusadasi station (code 0905-see Figure 6) in Aydin are taken into consideration for the analyses. The 0905 station is the closest station, at an approximate distance of 15 km from Ephesus and 49.38 km from the epicentre of the Samos earthquake. The ground acceleration records, a_{gr}, in EW and NS directions at the Kusadasi station 0905 during the Samos Island earthquake are given in Figure 7 and Figure 8. In this study, the maximum a_{gr} values are used as the reference peak ground accelerations as shown in Figure 7 and Figure 8 in the stability analyses for the earthquake load case.

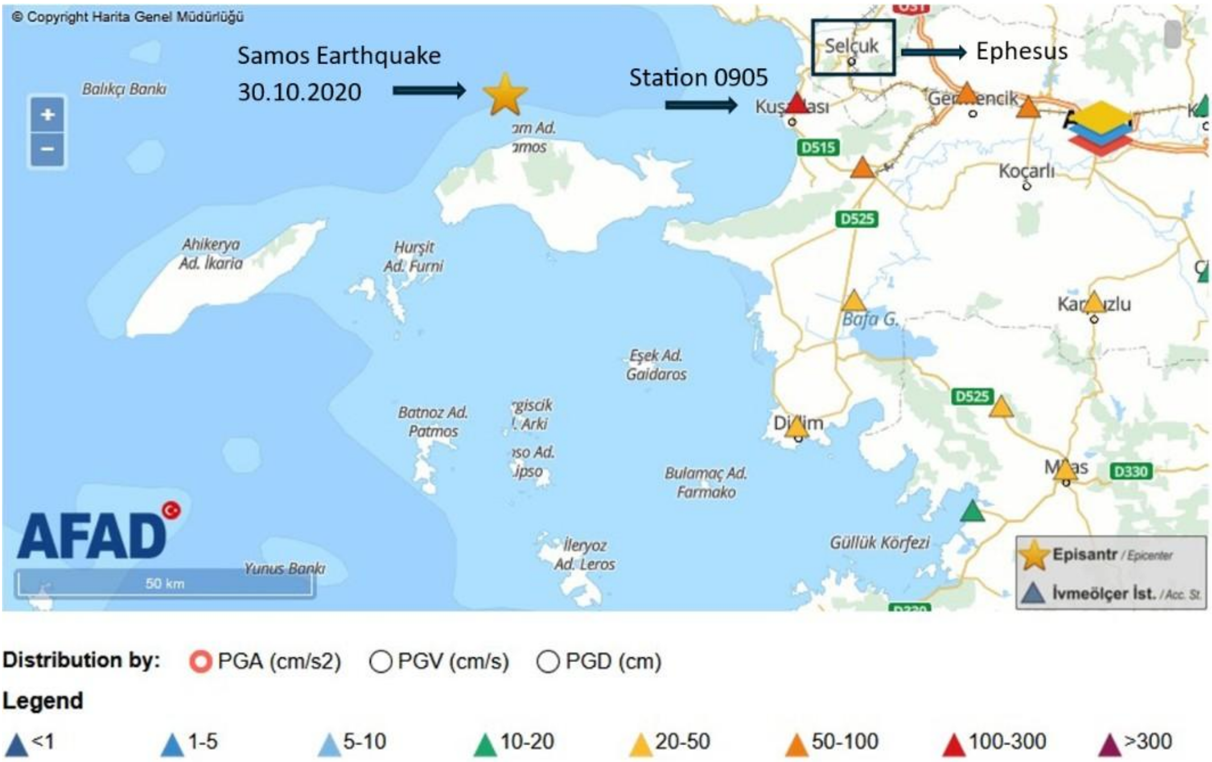

Figure 6. *The accelerometric stations around Ephesus and the considered Kusadasi accelerometric station code: 0905 (AFAD)*

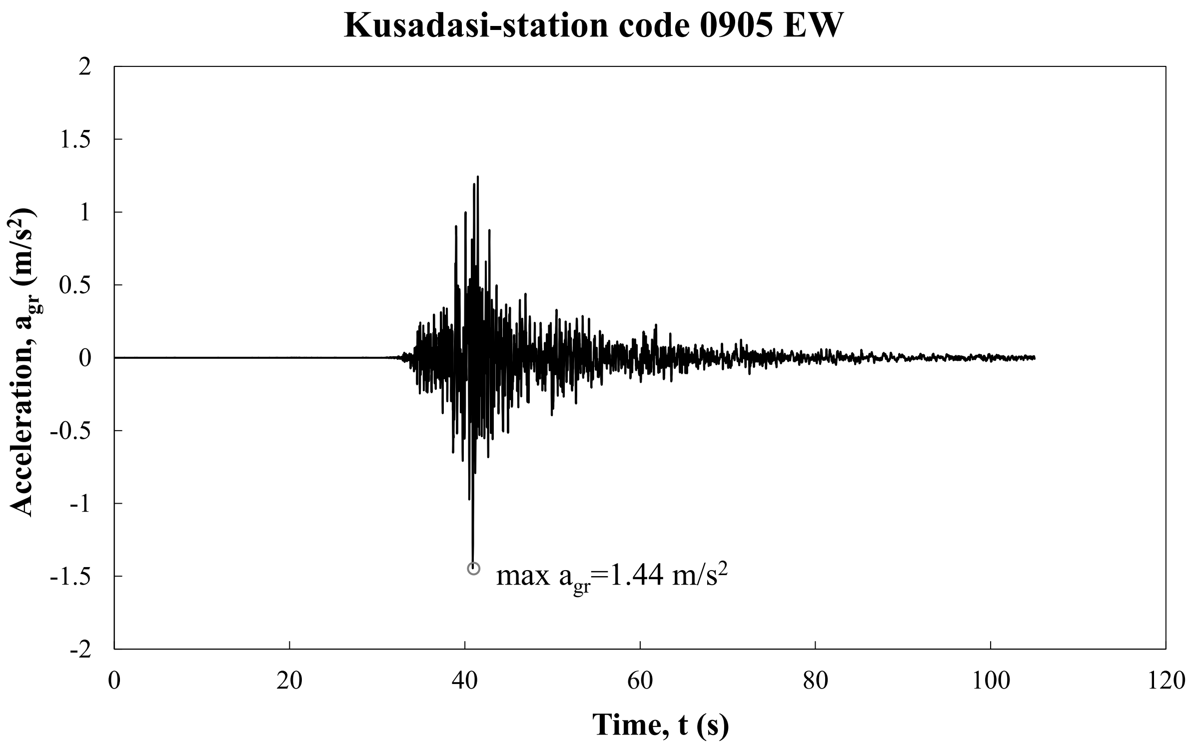

Figure 7. *Acceleration record at the Kusadasi station 0905 EW during the earthquake (AFAD)*

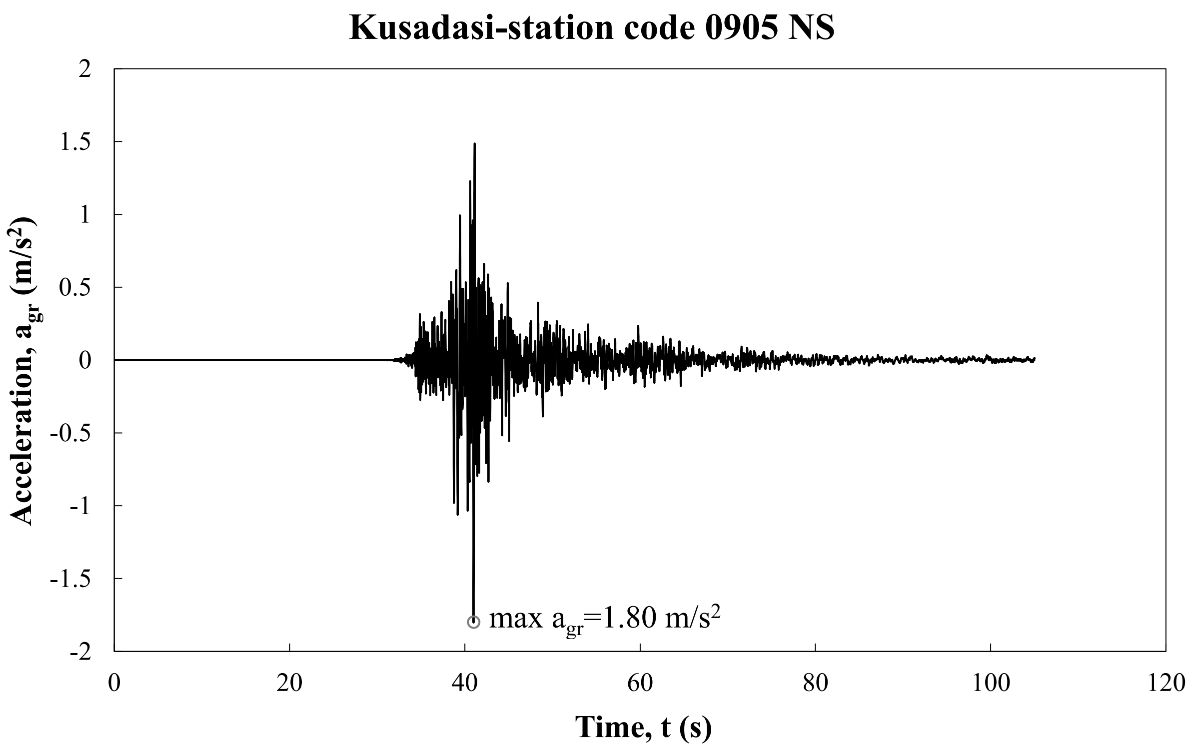

Figure 8. *Acceleration record at the Kusadasi station 0905 NS during the earthquake (AFAD)*

SIMPLIFIED CALCULATION MODEL

The section of the retaining wall considered for stability analyses is marked in reconstruction in Figure 9. Photographs show the front and overview of this section of the wall which is 6.70 m heigh and 1.50 m wide (Figure 9). The simplified calculation model used for the stability analyses is presented in Figure 10.

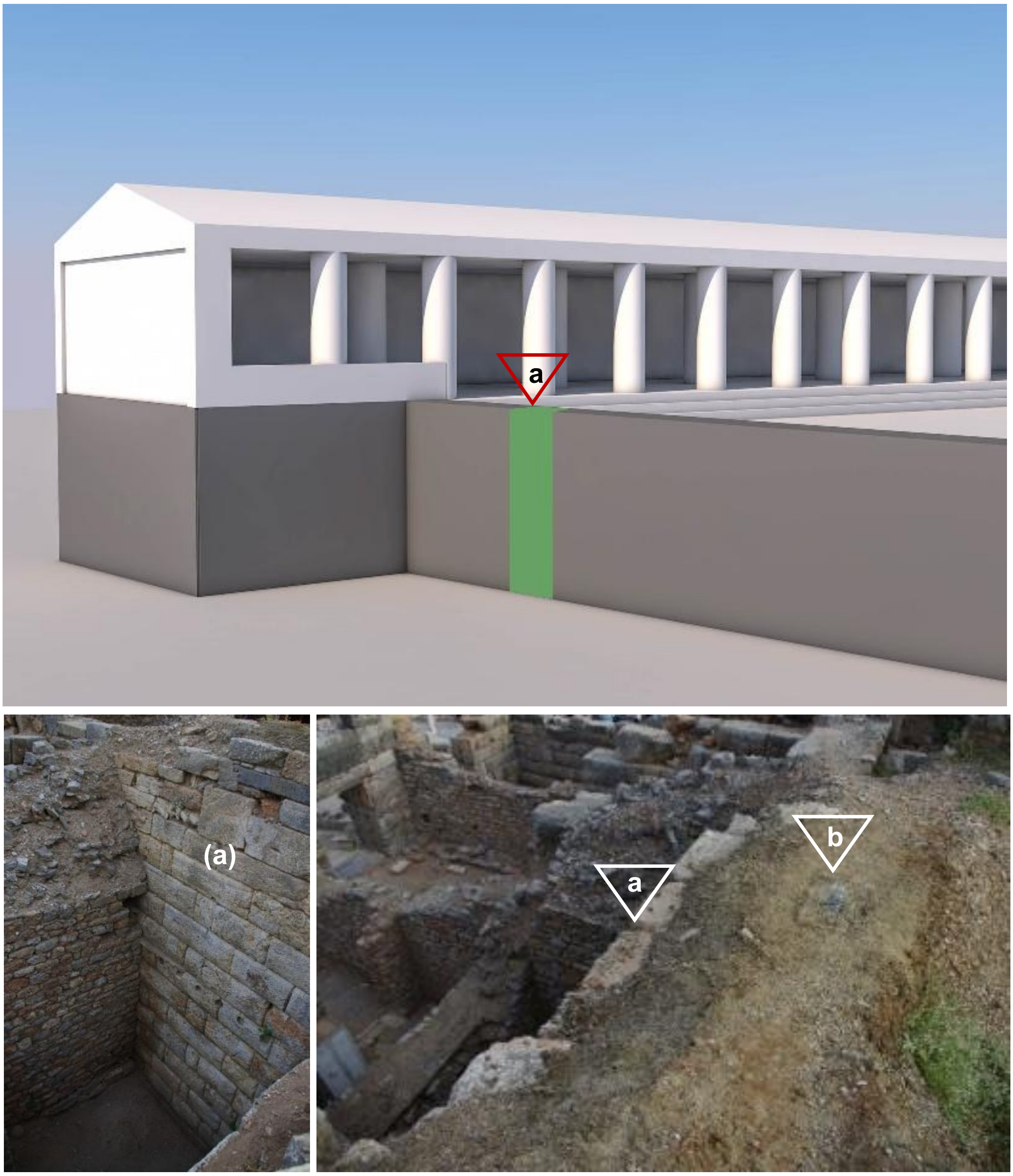

Figure 9. *The considered section and the views of the retaining wall for stability analyses*

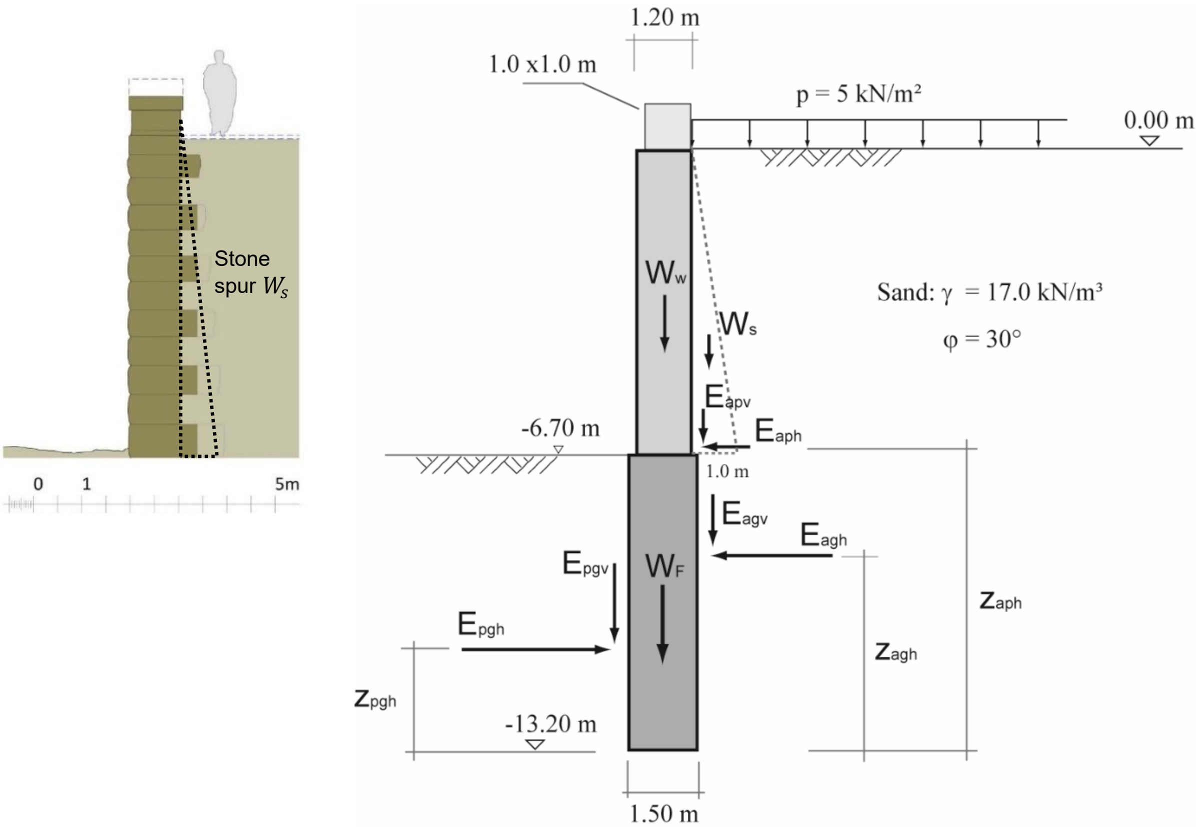

Figure 10. *(I) Sketch of the considered section of the retaining wall (II) Simplified calculation model used in the analyses*

The foundation features of the wall are unknown. The foundation dimensions were estimated based on findings and knowledge of Hellenistic architecture in the former metropolis of Pergamon. Klinkott (1990) stated that the Gymnasium terrace in Pergamon was supported by a deep wall foundation reaching approximately the height of the retaining wall. Therefore, a foundation depth of 6.50 m was assumed for the stability analyses of retaining wall in this study. There is also very limited information on the material properties of the wall and the soil. The material used to construct the retaining wall is depicted as conglomerate rock and was obtained from Panayırdağ (Musall et al., 2023). Hence, the unit weight of the wall and the foundation was defined to be $\gamma = 28\ kN/m^3$. As can be seen in Figure 10(I), some of the stone blocks were designed to be longer in the direction of the backfill and were placed at regular intervals along the wall depth. These stone blocks extend into the soil, which is referred as "stone spur" in this study. This stone spur was defined as a triangular geometry along the wall to obtain the weight of the stone spur construction as shown in Figure 10 (II). The unit weight of it assumed as to be $\gamma_{spur} = 23\ kN/m^3$ considering the soil between the stone spur construction. The surcharge loading was assumed to be $5\ kN/m^2$ as given in Figure 10. Laboratory tests results for soil properties are not available. Stock (2015) obtained samples from a three-meters borehole located very close to the wall, as marked *(b)* in Figure 9. Based on this limited information, it was decided that the soil is dry sand without layering and its assumed properties are given in Figure 10. The friction angle between the wall and the sand on the active and passive earth pressure sides was set to be $\delta_A = \frac{2}{3}\ \varphi$ and $\delta_P = -\frac{1}{3}\ \varphi$, respectively. The friction angle between the foundation base and the sand was assumed to be $\delta_{Rk} = \frac{2}{3}\ \varphi$, where $\varphi = 30°$.

The basement beneath the retaining wall consists of massive marbles of the Menderes Massif, forming the regional metamorphic core of Panayırdağ and Bülbüldağı. These marbles, described in detail by Sümer (2015), are overlain unconformably by a thick sequence of fault-derived colluvial deposits, composed mainly of angular marble and limestone clasts sourced from repeated activity along the Ephesus Fault. Toward the basin interior, this colluvium grades upward into younger alluvial and deltaic sediments, consistent with shallow coring data at Ephesus (Kraft et al., 2007, and references therein). Combined borehole and structural information indicate that marble bedrock lies at ~10–12 m depth, while the retaining wall foundation sits entirely within these unconsolidated colluvial–alluvial units. The horst structure of Panayırdağ uplifts the basement toward the archaeological terrace, resulting in a shallow bedrock geometry beneath the wall (Figure 2). Therefore, the subsurface beneath the retaining-wall foundation is interpreted as coarse, fault-derived colluvium overlying shallow metamorphic basement, which is compatible with the assumed foundation depth and the mechanical behaviour expected in an active graben-margin setting.

RESULTS OF ANALYTICAL DESIGN ANALYSES AND EVALUATIONS

The analyses under static and seismic loading conditions were conducted in accordance with current design standards. The simplified calculation model given in Figure 10 (II) was used for the analyses. The earth pressures and related eccentricities Z_i of the lateral and vertical resultant forces were obtained for each static and seismic loading condition.

The active and passive earth pressures were determined according to DIN 4085:2017 for static loading condition. The limit state analyses for static loading case were then carried out in accordance with Eurocode 7 ENV:1997-1 and the supplementary DIN 1054:2021 regulation. After the determination of the resultant lateral forces shown in Figure 10 (II) the sliding stability analysis was conducted. The overturning stability and bearing capacity failure analyses were carried out both resultant lateral and vertical forces with taken into consideration the related eccentricities presented in the simplified calculation model in Figure 10. The partial safety factors as permanent situation BS-P according to DIN 1054:2021 were used in the analyses. The results of the stability analyses under static loading conditions using design loads and characteristic loads are given in Table 1. The analyses results show that the stability design numbers are satisfied for the sliding stability and bearing capacity failure and that the overturning safety is almost fulfilled.

Table 1. *Limit state stability analyses results under static loading*

Stability analyses	Stability design number, μ	Design load situation BS-P	Characteristic load situation
		μ	μ
Overturning stability	$\mu = M_{d,dst}/M_{d,Stb}$	1.01	0.81
Sliding stability	$\mu = E_d/R_d$	0.45	0.25
Bearing capacity failure	$\mu = V_d/R_{v,d}$	0.40	0.21

The main standards used for the stability analyses under earthquake loading are Eurocode 8*: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings* (DIN EN 1998-1) and *Part 5: Foundations, retaining structures and geotechnical aspects* (DIN EN 1998-5). DIN 4017:2006 and the National Annex to Eurocode 8 DIN EN 1998-5/NA 2021 were used to determine the bearing capacity of the retaining wall under seismic loading conditions. The Mononobe-Okabe (M-O) method was applied to calculate the dynamic earth pressure coefficients during the earthquake analysis, as recommended by Eurocode 8 EN 1998-5 (Okabe, 1926, Mononobe and Matsuo, 1929, Deutsches Institut für Normung e.V., 2010). This approach extends the conventional earth pressure theory to include components for horizontal and vertical earthquake loads (Studer et al., 2008). Application of the M-O method simplifies the consideration of the additional inertial forces that act during an earthquake.

The main steps conducted for the stability analysis under earthquake loading are presented below:
Determination of
(I) design value of ground acceleration a_g-see equation (1)
(II) horizontal seismic coefficient k_h and vertical seismic coefficient k_v
(III) active earth pressure coefficient K_a and passive earth pressure coefficient K_p

(IV) Determination of Mononobe-Okabe dynamic earth pressure coefficients for active K_{ae} and passive K_{pe} states
(IV) the total design force (static + dynamic) acting on the retaining wall, E_{da}: Active resultant force; E_{dp}: Passive resultant force.

For the stability analyses, the partial safety factors in the design state BS-E/BS-A according to DIN 1054:21-04 were used, whereby BS-E represents earthquake situation and BS-A represents an accidental situation. In this study, acceleration records by Kusadasi 0905 station during the Samos Island earthquake as shown in Figure 7 and Figure 8 were taken into consideration for the stability analyses. The maximum a_{gr} values, $a_{gr} = 1.44\, m/s^2$ in the EW direction and $a_{gr} = 1.80\, m/s^2$ in the NS direction, were taken into consideration as the reference peak ground accelerations in the stability analyses. Furthermore, the parameter α, which is the ratio of the design ground acceleration a_g to the acceleration of gravity *g,* was obtained and used in the analyses as given in equation (2).

$$a_g = a_{gr} \cdot \gamma_I \; (m/s^2) \tag{1}$$

$$\alpha = a_g/g \; (\text{-}) \tag{2}$$

In equation (2) $g = 9.807\ (m/s^2)$ is the acceleration of gravity and γ_I is the importance factor. In this study, the importance class II was selected which is defined as ordinary buildings, not belonging in the other categories as defined in Eurocode 8-Part 1. The recommended importance factor value is $\gamma_I = 1{,}0$ for importance class II.

The maximum stability design numbers μ determined for the Samos Island earthquake event using the M-O method are presented in Table 2. The results show that the stability design numbers for the analyses of sliding stability and bearing capacity failure were obtained $\mu < 1{,}0$ in various α or for different max a_{gr} considering the EW and NS directions. It should be noted that these results were get using pseudo-static approach (M-O method) for the seismic stability analyses of the Hellenistic retaining wall. Further investigation should be implemented using time history analysis method in dynamic numerical simulations.

Table 2. *Limit state stability analyses results according to the Samos Island earthquake (30.10.2020) loading case*

Stability analyses	Stability design number, μ	Design load situation BSA/BSE	
		μ_{max}	
		$\alpha = 0,15$	$\alpha = 0,18$
Sliding stability	$\mu = E_d/R_d$	0.47	0.49
Bearing capacity failure	$\mu = V_d/R_{v,d}$	0.20	0.29

CONCLUSIONS

This investigation presents a geotechnical assessment for the Hellenistic stone retaining wall of the Upper Agora in Ephesus, western Türkiye. Stability analyses under both static and seismic loading conditions were conducted in accordance with current design standards and norms. In this initial phase, the study is limited to apply analytical design methods to evaluate geotechnical limit states. In the earthquake analyses, the Mononobe-Okabe (M-O) method was utilized to calculate the dynamic earth pressure coefficients. It should be noted that the M-O method based on pseudo-static approximation. Following studies are planned to use time history analysis method to extend the investigation performing dynamic response analysis.
The Samos Island earthquake, which occurred on 30 October 2020, was selected as the reference earthquake for the analyses, which is a very recent and strong earthquake that happened near Ephesus. The results under static loading conditions show that the stability design numbers are less than one ($\mu < 1{,}0$) for the sliding stability and bearing capacity failure analyses. The result for the overturning stability analysis was obtained almost one ($\mu = 1{,}01$). Under seismic loading, the μ values were obtained

less than 1,0 according to the sliding and bearing capacity failure analyses taken into consideration the peak ground acceleration a_{gr} values corresponding to the Samos Island earthquake event.

It should be noted that this initial study has certain limitations. During the stability analyses some assumptions were made regarding the dimensions of the foundation, the soil layering, and the soil saturation condition. Firstly, further investigations are required to determine dimensions of the foundation. Secondly, the layering and properties of the soil, as well as the saturation condition, need to be determined. Subsequently, further stability analyses can be performed using these updated soil and foundation features. The next step is to conduct numerical simulations under static and earthquake loading conditions, developing two- and three-dimensional (2D and 3D) finite element models (FEM) of the stone retaining wall–soil system. The time history analysis method will be used for the numerical simulation in the FE modelling.

NOMENCLATURE

Symbol	Name	Unit
E_{agh}	Active lateral earth pressure	kN/m
E_{agv}	Active vertical earth pressure	kN/m
E_{pgh}	Passive lateral earth pressure	kN/m
E_{pgv}	Passive verticalearth pressure	kN/m
E_{aph}	Active lateral resulting force due to surcharge loading	kN/m
E_{apv}	Active vertical resulting force due to surcharge loading	kN/m
p	Surcharge loading	kN/m^2
W_w	Weight of wall	kN/m
W_F	Weight of foundation	kN/m
W_s	Weight of spur	kN/m
$M_{d,dst}$	Sum of the overturning (destabilizing) moments	kNm/m
$M_{d,Stb}$	Sum of the resisting(stabilizing) moments	kNm/m
E_d	Driving (destabilizing) forces	kN/m
R_d	Resisting (stabilizing) forces	kN/m
V_d	Resulting vertical load	kN/m
$R_{v,d}$	Bearing capacity	kN/m
H	Heigth of the wall	m
K_{ae}	Mononobe-okabe dynamic earth pressure coefficient for active state	-
K_{pe}	Mononobe-okabe dynamic earth pressure coefficient for passive state	-
γ	Unit weight	kN/m^3
B	Foundation width	m

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