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"INVESTIGATION OF LOCAL SITE RESPONSES AT THE BODRUM PENINSULA (SOUTHWEST OF TURKEY) USING THE MAINSHOCK AND AFTERSHOCKS OF THE 20 JULY 2017 MW6.6 BODRUM-KOS EARTHQUAKE"

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ABSTRACT

Bodrum Peninsula located in the province of Mugla is situated in southwest Turkey. The peninsula is one of the most populated touristic centers of the southwest coast of Turkey, near the Aegean Sea. However, this region is surrounded by numerous active seismic entities. All of those systems have capability of producing large magnitude earthquakes and pose a great threat to settlements in and around of this region. Considering the high seismic risk and population of the peninsula, a strong ground motion monitoring system was deployed in June 2015. So far the network recorded many earthquakes in different magnitude and distances. In this study, a dataset with 51 events with moment magnitudes from 4.0-6.6 occurred within 100 km epicentral distances were selected for site effect calculation. This dataset includes the mainshock and its significant aftershocks records of the Mw6.6 Bodrum-Kos earthquake (20 July 2017, 22:31 UTC). Predominant frequencies and amplification values of shallow soil layers under the stations were estimated through Horizontal to Vertical Spectral Ratio and Standard Spectral Ratios. The results indicate that predominant frequencies change between 2.1 - 2.7 Hz for soft soils, where it is 4.8 Hz for the reference site B5, and relative amplifications are in the range of 1.0 to 6.6. Then, sediments thicknesses beneath the stations were empirically calculated by using predominant frequencies. In addition, the damage distribution of the Bodrum-Kos earthquake was discussed with its relation to the estimated resonance frequencies and relative amplifications. Observations regarding to the Mw6.6 earthquake have revealed that unreinforced masonry structures, in particular, old stone houses were damaged while there were generally no apparent structural damage at reinforced buildings.

1. INTRODUCTION

The most forceful shaking during earthquakes generally occurs near the rupturing fault, and its impact decreases with distance away from the fault. However, the shaking at one site can easily be much stronger than at another site, even when their epicentral distances are the same. There is a general agreement among scientists and researchers that local geology have significant effect on seismic motions [Hinzen et al., 2004; Pancha et al., 2015; Safak, 2001]. Therefore, investigation of this effect, estimation of the local response of a site is an important aspect in the assessment of local seismic hazard [Bour et al., 1998].

Local site response can be investigated by theoretical and empirical methods [Gok and Polat, 2012]. The former method requires a detailed information of the geological structure underlying the site [Dravinski et al., 1996]. A site study composed of drilling boreholes, in situ penetration tests and seismic wave velocity measurements allows investigators to obtain relatively detailed information [Ansal et al., 2001; Parolai et al., 2002]. The latter method is based on the analysis of seismic records of regional earthquakes recorded on site at different geological units and requires of a large number of earthquakes [Gok and Polat, 2012].

Two important parameters infered from site response studies are the resonance frequencies of soil vibration and the amplification factors of ground motion in certain frequency ranges [Birgoren et al., 2009]. These parameters can be estimated using the most common techniques: the standard spectral ratio (SSR) method [Borcherdt, 1970] and the horizontal-to-vertical spectral ratio (HVSR) method [Nakamura, 1989]. The HVSR method generally provides reliable estimates of resonance frequency despite of its inadequacy in estimating amplification [Bard, 1999; Lermo and Chavez-Garcia, 1994], while SSR method is considered as the reliable method in determining the effects of local site conditions [Molnar and Cassidy, 2006; Yalcinkaya and Alptekin, 2005]. Another important parameter for the site effects, in the context of seismic hazard assessment, is the thickness of a sediment fill in sedimentary areas [Hinzen et al., 2004]. Recent studies, based on relationship between the main peak frequency (fr in Hz) of a given soil, its thickness (h in meter) and the average shear velocity (Vs in m/s), have demonstrated the possibility to establish a direct functional relationship between the frequency of resonance and depth to bedrock, without knowing shear velocity [Ibs-von Seht and Wohlenberg, 1999; Kanli et al., 2008; Tun et al., 2016].

The Bodrum peninsula, our study area, is situated on the southwest of Turkey near the Aegean Sea coast (Figure 1 and 2) and is a district in Mugla Province. The peninsula extends, roughly, ~46 km in the east-west direction and ~15 km in the north-south direction between the Gulfs of Gulluk and Gokova. With a population over one and half million in summer seasons, it is one of the most populated touristic centers and is undergoing rapid urbanization. The region is also surrounded by numerous active seismic entities such as Gokova Graben [Iscan et al., 2013], Ula-Oren fault, Milas fault, Mugla fault, Yatagan fault, Datca faults [Dirik, 2007] (Figure 2), eastern part of the Volcanic Arc and Hellenic Arc-Trench System [Papadopoulos et al., 2007; Sakkas et al., 2014].

With the aim of monitoring of local seismic activities, collecting accurate and reliable data for engineering and scientific research purposes, determining the site responses at alluvium sites in urban environments, a network (shortly B-Net) consists of 5 strong-motion stations has been set up in 2015 by Bogazici University, Kandilli Observatory and Earthquake Research Institute (KOERI), Earthquake Engineering Department [Alcik, 2015; Alcik et al., 2015]. So far the network recorded more than 600 earthquakes in different magnitude (M≤6.6) and distance (Δ<350km) ranges. The primary objective of this study is to estimate quantitatively local site effects in important towns of Bodrum Peninsula in terms of fundamental site frequency and amplification factor. A second goal is to decide to a suitable empirical relation from among proposed actual empirical relationships between resonance frequencies and thickness of sediments, especially for the soft layers under the stations deployed in the peninsula. Another objective is to refer to the damage distribution of July 20, 2017 (Mw=6.6) Bodrum-Kos (Turkey-Greece) earthquake and look over its relation to resonance frequencies and relative amplifications. The database used in this study comprised of the strong motion waveforms records includes the Mw=6.6 Bodrum-Kos mainshock (Figure 3) and its aftershocks recorded at B-Net stations. Kos is an island of Greece.

2. SEISMOTECTONIC OF THE REGION

The Aegean-Anatolian plate is located in an active convergent zone between the African, Arabian and Eurasian plates. The northward motion of the Arabian plate relative to Eurasia causes lateral movement and rotation of this Anatolian plate. While the southern Aegean Sea is moving southwest, much of the Anatolian region is moving westward relative to Eurasia along two fault zones: the east and the north Anatolian fault zones into the Aegean domain [Armijo et al., 1999; Taymaz et al., 2007]. These strike-slip zones determine the boundaries of the Aegean-Anatolian microplate that is moving west-southwestwards overriding the subducting oceanic lithosphere of the Eastern Mediterranean Sea [Kocyigit and Deveci, 2007]. This tectonic escape [Dewey and Sengor, 1979] has produced an extensional regime which is leading to development of the horst-graben systems in western Turkey [Kocyigit et al., 2000]. The southwest boundary of the region is dominated by the Hellenic Arc which is a zone of subduction where the African plate moves under the Aegean Sea [Papazachos, 1999] (Figure 1).

Within this complex tectonic framework, our study area is located along the northern edge of Gokova graben which is the most important seismically active region of the southeast Aegean Sea [Kalafat and Horasan, 2012]. The peninsula is also surrounded by numerous seismic faults to which sufficient attention should be paid (Ula-Oren Fault Zone, Datca faults, eastern part of the Volcanic Arc and Hellenic Arc-Trench System). All of those systems have capability of producing large magnitude earthquakes. Frequent occur-

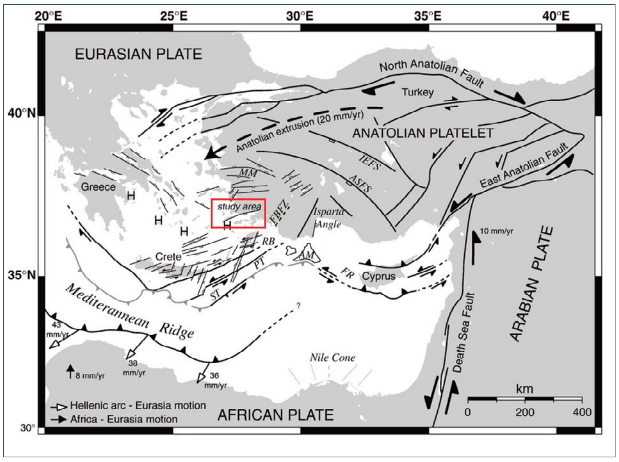

FIGURE 1. The geodynamic framework of the Eastern Mediterranean [TenVeen et al., 2009].

rence of historical destructive and instrumental earthquakes clearly demonstrates high seismic hazard in Bodrum and its surrounding area (Figure 2). The whole region falls into the first-degree hazard zone in the official seismic zonation map of Turkey.

Among destructive historical earthquakes, 1493 Kos event (Mw=6.94±0.32) caused complete collapse of the Bodrum district. 1741 (Mw=7.54±0.30), 1863 (Mw=7.5±0.30) and 1869 (Mw=6.77±0.37) are other the important earthquakes [Stucchi et al., 2012]. In the instrumental period seismic activity in the Gokova region includes M>6 earthquakes: 23 April 1933 (Ms=6.4), 23 May 1941 (Ms=6.0), 13 December 1941 (Ms=6.5) events [Kalafat et al., 2011] and 20 June 2017 (Mw=6.6) [AFAD, 2017; KOERI, 2017] (Figure 2).

Among above mentioned faults, in particular Gokova graben system poses larger hazard due to its close proximity to Bodrum town and the peninsula. Sayil and Osmansahin [2008] stated that the region, which includes the Bodrum peninsula and the island of Kos, has the highest risk and the shortest recurrence periods. This fault zone has a potential to produce earthquakes varying in size from M6.9 to M7.8 and annual probability of occurence of a M7+ earthquake has been estimated as 2% [Demircioglu, 2010].

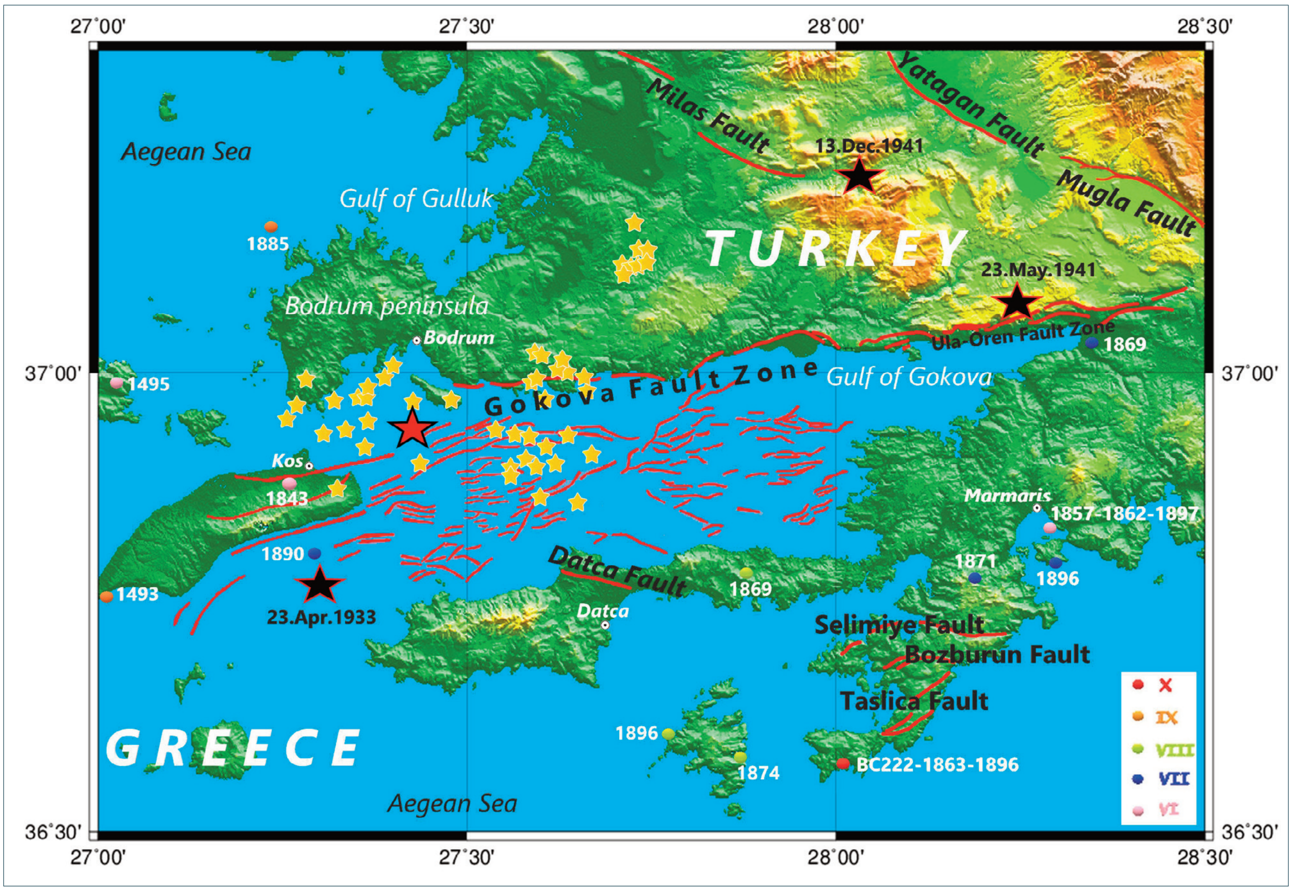

FIGURE 2. Active fault map of the study area and the distribution of historical & instrumental earthquakes in the region. The faults and lineaments were from MTA [2011a,b], Iscan et al., [2013] and Sozbilir et al., [2017]. The historical earthquakes were from Sozbilir et al., [2017]. *Inset* shows the intensity levels for historical earthquakes. The instrumental earthquakes (M>6) shown as black stars were from Kalafat et al., [2011]. Red star and yellow stars show the epicenter of the 20th June 2017 Bodrum-Kos earthquake and aftershocks, respectively. Figure was prepared by using the GMT program of Wessel and Smith [1998].

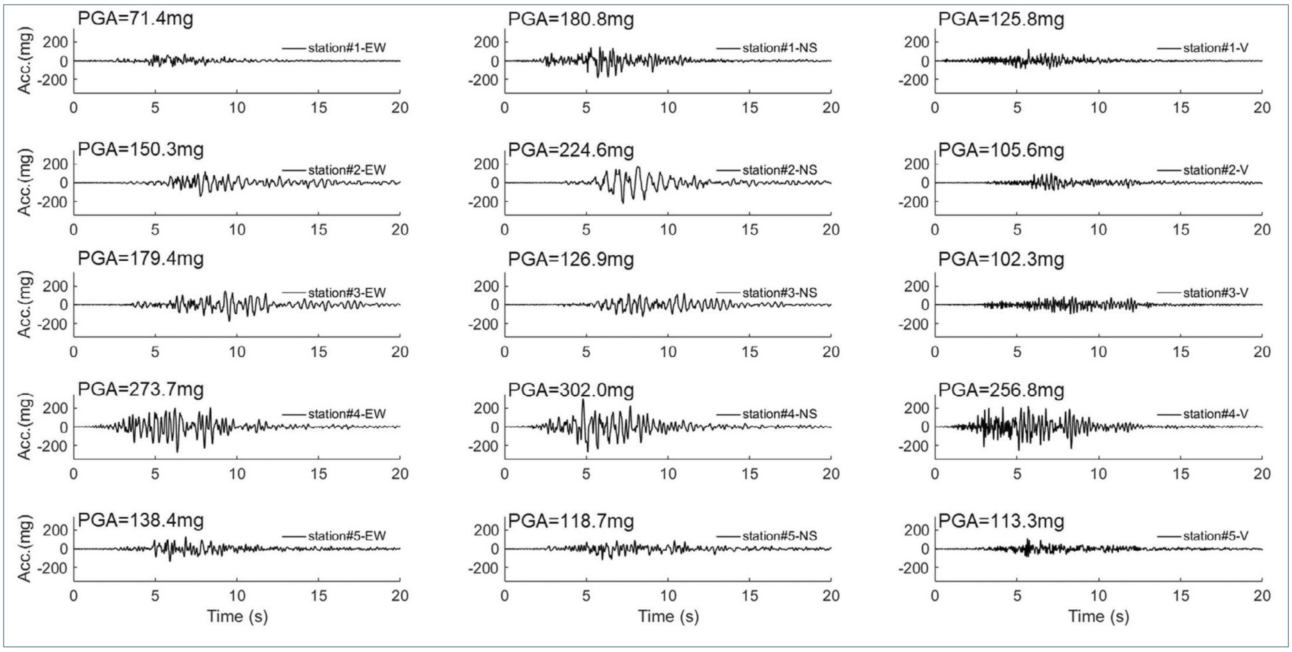

FIGURE 3. Time histories of the Mw6.6 Bodrum-Kos earthquake recorded by all B-Net stations. Maximum peak ground acceleration (PGA) value calculated at station#4 (B4=Yali-Ciftlik) is 0.302g.

The latest strong earthquake (Mw=6.6) of normal faulting, striking about E-W, occurred on July 20, 2017 at 22:31 UTC (July 21, 2017 at 01:31 LT) in the Gokova Gulf, Aegean Sea. The location of event is about 12 km south of the Bodrum town and about 10 km north-east of the island of Kos. This normal faulting is broadly consistent with past earthquakes in the region. The event cracked and damaged many masonry stone buildings in the peninsula and in the island [Lekkas et al., 2017], however, it did not generate an on-land surface rupture [Tiryakioglu et al., 2017]. Besides, a tsunami which affected the coast of Bodrum peninsula and the northeast coast of Kos island was observed [Yalciner et al., 2017].

3. THE GENERAL GEOLOGY OF THE BODRUM PENINSULA

The basement rock at the Bodrum peninsula is a slightly metamorphosed unit of Paleozoic age which is composed of conglomerate-sandstone-shale detritic alternations (Gulluk Formation) [Ercan et al., 1982]. The peninsula contains a number of major tectonic entities including the volcanic associations and the Neogene terrestrial cover sequence [Gurer and Yilmaz, 2002; Yilmaz, 2008]. Sedimentary and magmatic successions were formed in the Mesozoic-Senozoic period above Paleozoic aged basement rocks, crop out in most parts of the peninsula. From older to younger the units forming the lithologies in the Mesozoic age rocks are Triassic-Liassic dolomitic limestones (Pazardagi Formation), Liassic-Malm aged silty and marny limestones (Karadag Formation), Malm-Cenomanian aged cherty limestones (Kisladagi Formation). Upper Cretaceous-Paleocene aged flysch (Bodrum Formation) is overlying these tectonical strata assemblages. Senozoic aged rock sequences were started with Oligosen aged sediments (Koyunbaba Formation) [Ercan et al., 1982]. Two volcanic cycles were effective in the Bodrum Peninsula during Middle-Upper Miocene times [Arslan et al., 1998]. The first commenced with monzonitic plutons in the Middle Miocene and volcanic-pyroclastic products with calcalkali character were formed towards the end of Middle Miocene. [Ercan et al., 1984]. The second, occured in Upper Miocene age, is represented by high-K (HK)-andesitic, andesitic lava flows and pillows, sparse HK-andesitic and dacitic lava domes and associated block-and-ash flows. After the end of the volcanism, limestones were formed in the Lower Pliocene. Travertines, slope debris, alluviums [Ercan et al., 1982] and, possibly, pumice fragments and tuffs from neighboring Kos island [Nomikou and Papanikolaou, 2010], were formed in the Quaternary period [Ercan et al., 1984].

While the middle and the eastern part of the Bodrum Peninsula is dominated mostly by marble, chert marble, recycstallized limestone and very rarely metaflysch, the western part is dominated by magmatic rocks such as andesite and pyroclastic rocks. The Quaternary deposits were formed from varied from place to place and existed at different places in where the most of Bodrum's urban population has been concentrated (Figure 4).

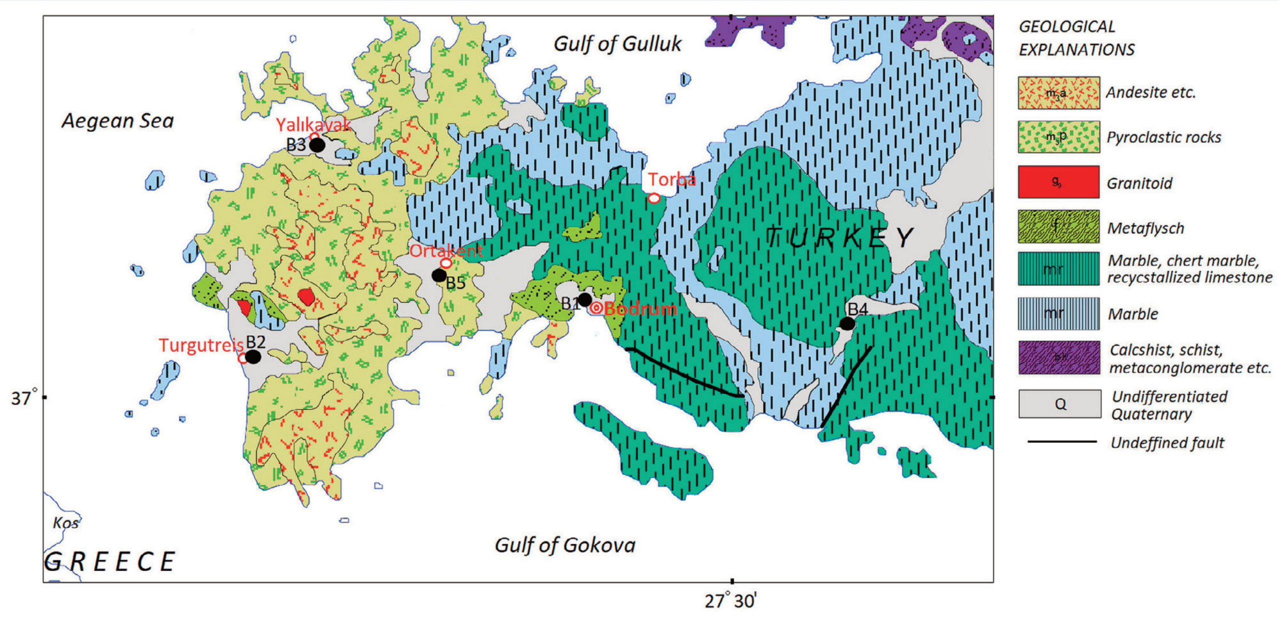

FIGURE 4. Geological sketch map of the Bodrum peninsula [MTA, 2002] was modified. The distribution of the B-Net stations are shown with black circle (B1: Bodrum downtown, B2: Turgutreis, B3: Yalikavak, B4: Yali-Ciftlik, B5: Ortakent).

4. STATION INFORMATION AND SITE CHARACTERIZATION

Seismic activities in the region have been monitoring through two seismic stations which are made up of a broadband seismometer and an accelerometer. These stations, deployed by government agencies, are in service mainly in order to disseminate required seismological information. Hence, with the aim of determining site responses at the Quaternary deposits/alluvial sites in urban environments, 5 strong-motion stations have been deployed in Bodrum downtown (B1) and in its sub-districts: Turgutreis (B2), Yalikavak (B3), Yali-Ciftlik (B4) and Ortakent (B5). These sub-districts are dense settlements in the Bodrum Peninsula.

A strong-motion station consists of 18-bit digitizer and acquisition module of GeoSIG Limited, CMG-5T accelerometer of Guralp Systems Limited, DC battery, GPS unit, 3G modem and some auxiliary equipments. Strong-motion instruments were located at grade level in small and medium-sized buildings. B1, B4 and B5 are the primary schools buildings with one-storey at ground level, three-storeys at ground level and three-storeys with a basement floor, while B2 and B3 station buildings are the municipalitiy buildings with two- and three-storeys, respectively. Only B5 has a basement floor (Table 1). All the buildings are reinforced concrete (RC) structures.

For a better definition of different zones of soil amplification, it is important getting knowledge of actual soil stratification and layer velocities at given site. However, any geophysical or geotechnical investigations have been out-of-scope for this project. Therefore, some information was reached by getting in contact with local authorities (213th Regional Directorate of State Hydraulic Works, Mugla Municipality) and regional geotechnical & foundation engineering companies (ARE Jeoteknik, Deniz Muhendislik, EGE-SU, Su-MET, Z-ETUD).

The collected information is composed of borings, seismic wave velocity measurements and detailed local geological maps, closely related to the stations locations. Due to drilling of boreholes for the purpose of groundwater abstraction is under the control of local Directorate of State Hydraulic Works authority, the number of drilled boreholes to bedrock in the alluvium areas of the Peninsula is really scarce. The majority of works already carried out in the peninsula were conducted by private sectors (engineering companies) within the regulations on construction and urbanization processes. The drilled wells are shallow, up to about 20 meters depth. The collected geotechnical and geophysical surveys data were compiled to the extent permitted by these companies, and summarized as below:

Bodrum station (B1): B1 is a school in the town of Bodrum. The location of this site is within 120 m of the coastline of Bodrum bay in an area that is geologically characterised by wild flysch. It consists mainly of conglomerate, sandstone, milestone and siltstone alternations. This sediment of upper Cretaceous-Paleocene aged, called as Bodrum Formation with an estimated maximum thickness is about 300 m, covers the Mesozoic aged limestones. At the top, there is a very thin alluvium layer [Ercan et al., 1982; Su-MET 1988]. Results of a seismic refraction study at 70 meters away from the B1 station to the north show two distinct velocity layers in a few meters. The data suggest that the thickness of the low-velocity (V_s=280 m/s) layer is around 2 m, but, unfortunately, say little about the high-velocity layer. These data suggest that the low-velocity of the first layer is convenient the consisting geological pieces and/or rubble. The average shear wave velocity down to 30 m depth (V_s30) for this site is 605 m/s [EGE-SU data archive].

Turgutreis station (B2): B2 station, a building of Bodrum Municipality, is located at an elevation of 2 m and approximately 150 m east from the public beach. Results of the 15.5-meters borehole drilled at 90m away from the B2 station to the west show this surface are alluvial materials (alternation of gravel-sand-silt-clay) of Pleistocene and Holocene age. Bedrock units in this area are Miocene aged volcanic tuff-agglomerate. The V_s30 for this site is 480 m/s [Deniz Muhendislik, 2012]. Another study done at 350 m to the north gives the Vs30 value as 430 m/s [EGE-SU data archive].

Yalikavak station (B3): B3 station is also a Municipality building. It is located at an elevation of approximately 3 m. The Yalikavak site is located in a similar geologic setting as the Turgutreis site with the primary difference being that B3 is approximately 180 m inland from the coast and lies in an area of urban development.

A geotechnical study and a geophysical survey conducted at 600 m away from the B3 station to the north demonstrates that there is only one layer composed of poorly graded silty gravelly sand, down to 20 meters in depth. The Yalikavak site has the same geological structures as the Turgutreis site has. Bedrock units in this area are Miocene aged volcanic tuff-agglomerate. Overlying this extrusive layer is Quarternary aged alluvium materials. The V_s30 for this site is 481 m/s [Deniz Muhendislik, 2010].

Another study with 41 well drillings carried out in 2008 within the frame work of local master development plan was applied to all part of the Yalikavak subdistrict. Results of two boreholes which are close to the B3 station within a 250-m distance show similarly the geological lithology is composed of alluvial deposits. Only one primary geologic unit, under the topsoil is represented over the 10-m depth, is sandy silty clay with gravel [ARE Jeoteknik, 2008].

Yali-Ciftlik station (B4): B4 is a secondary school in Ciflik village, Yali. This site is located approximately 3500 m inland from the Gulf of Gokova, at an elevation of approximately 87 m, and lies within the foothills of two hills area along a dry creek in summer times. Geologic mapping indicates that the hills are composed of Mesozoic aged dolomitic limestone. This sedimentary rock unit which is called as Pazardagi Formation has an estimated maximum thickness is about 300 m [Ercan et al., 1982]. The younger units forming the lithology is overlying this eroded surface are Pliosen aged slope debris and river alluvium deposits of Quarternary aged. The slope debris seen in a small area consists of detritus of monzonite, marble and hornfels, whereas alluvium deposits include sandy silty clay with gravels. This information belongs to a field study 1500 m at south from the station site [ARE Jeoteknik, 2016].

A geotechnical study and a geophysical survey done at 400m away from the B3 station to the north-east demonstrate that beneath a thin layer of topsoil, only one velocity layer was identified from the 10-meters boring log. Thin layer is 0.60 m and the rest is slope debris consists of silty gravels. The V_s30 for this point is given as 521 m/s [EGE-SU data archive].

The 1:500.000 scale geological map [MTA, 2002], given in Figure 4, originally indicates that the Yali-Ciftlik site where B4 was installed is marble/chert marble/recyristallised limestone. However, 1:100.000 scale [ARE Jeoteknik, 2015] and 1:25.000 scale [Mugla Municipality data archive] geological maps indicate that this site is Quarternary (Q_{al}) alluvial material. Therefore B4 station was deployed at this site and the geological map of MTA [2002] was modified (Figure 4).

Ortakent station (B5): B5 station is a secondary school in Ortakent town. This site is located at an elevation of 28 m and approximately 3000 m inland from the coast line. Geologic mapping indicates the Ortakent town surficial units are Quarternary deposits and pyroclastic materials [MTA, 2002] and is in the vicinity of hills composed of Tertiary and older bedrock. The geologic setting is Middle-Upper Miocene aged igneous rocks: andesites and pyroclastic, are the bedrock. Uppermost layer are the Quarternary deposits [EGE-SU data archive; Z-ETUD, 2017]

A seismic refraction study at 315 m away from the strong-motion station building to the north-east shows two velocity layers. The thickness of the first layer is 2.5 meters. The Vs30 for this site is 567m/s [Z-ETUD, 2017]. Another seismic refraction application, resulted at 110 m to the north-east, shows similarly two distinct layers. Thickness of the first layer is 1.90 m. V_s30 value for this site is 686 m/s [EGE-SU data archive].

Data of a 10-m borehole at 125 m away to the north-west shows the units from 0 - to 2.5-m depth is silty clay, from 2.5 - to 4.5-m depth is clayey sand and from 4.5 - to 10-m depth are river alluvial deposits [EGE-SU data archive].

Station	Latitude(N°)	Longitude(E°)	Location	Altitude(m)	No. of Storeys	Geological information
B1	37.0370	27.4245	Bodrum downtown	4	G	Alluvial & Flysch
B2	37.0072	27.2576	Turgutreis	2	G+2	Alluvial
B3	37.1027	27.2937	Yalikavak	3	G+1	Alluvial
B4	37.0234	27.5639	Yali-Ciftlik	87	G+2	Alluvial & Slope Debris
B5	37.0476	27.3477	Ortakent	28	B+G+1	Alluvial & Volca-nic Rock

TABLE 1 Stations information (B is Basement, G is Ground Floor).

The information of the B5 site show the geological structure of this region has a variable structure and is not distributed homogenously in a short distance. Comparing the location of B5 station with the geological map of the region (Figure 4), it was found out that B5 station seems to be situated at an area, border of alluvial deposits and volcanic rock.

The average shear wave velocities (V_s30) close to these sites are in the range of 430 m/s - 686 m/s which are NEHRP soil type "C" [BSSC, 1997] and EuroCode8 soil type "B" [ECJRC, 2012]. Their description of stratigraphic profiles are given as "very dense soil/soft rock" and "deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth", respectively [Kanli et al., 2006].

5. DATA SET

Bodrum network (B-Net) was put into action on 2nd June 2015 and till now it is fully operational with 5 stations. So far, the network has recorded more than 600 earthquakes in different magnitude and in different epicentral distances. The dataset used in this study consists of 51 events, 261 three-component records. Their moment magnitudes range from 4.0 to 6.6 and epicentral distances range from ~3 km to 100 km. The information on these earthquakes provided by Kandilli Observatory and Earthquake Research Institute (http://www.koeri.boun.edu.tr/scripts/lst6.asp) is listed in Table 2.

There are quite extensive studies in the literature which can be found on the subject of Gokova graben system. Most of them are related to seismotectonic and geological researchs [Iscan et al., 2013; Kalafat and Horasan, 2012; Ulusoy et al., 2004; Yolsal and Taymaz, 2010]. However, there is little known about the site effects of the Bodrum Peninsula and during the literature survey, the author has not come across any site related studies for this particular region, except one presented by Alcik and Tanircan [2017]. The present study will, in a sense, be a continuation and complement of that work. They have resulted their site analysis using 25 events with local magnitudes (Ml) from 3.0-5.5 occurred within 200 km epicentral distances. However in this study main objective is to calculate predominant frequencies and amplification values of shallow soil layers by utilizing the mainshock of the Mw=6.6, July 20, 2017 Bodrum-Kos earthquake and its aftershocks records.

6. SPECTRAL RATIO METHODS

In this study evaluation of the local site effects for the Bodrum peninsula was carried out using two well-known approaches: Horizontal-to-Vertical Spectral Ratio (HVSR or H/V) and Standard Spectra Ratio (SSR).

The first method, proposed by Nakamura [1989] and known as Nakamura's technique, requires only a 3-components record of one station. The technique has been extensively used in recent times to estimate the site effects. The spectral ratio between the horizontal and the vertical components of the recorded motion eliminates the contributions of the Rayleigh waves, but it conserves the effects resulting from the geological structure of the site [Gok and Polat, 2012; Lermo and Chavez-Garcia, 1994; Nakamura, 1989]. Although the theoretical basis of the method is controversial, technique has been validated by both simulations and earthquake recordings [Flores et al., 2013; Lermo and Chavez-Garcia 1993; Parolai et al., 2002]. The horizontal-to-vertical spectral ratio, HVSR, at the

No	Date and Time (UTC)	Latitude (N°)	Longitude (E°)	Local Magnitude (Ml)	Moment Magnitude (Mw)	Depth (km)
1	20170720 22:31:09	36.9620	27.4053	6.2	6.6	5.0
2	20170720 22:52:58	36.9252	27.3443	4.4	4.3	6.9
3	20170720 23:00:45	37.0050	27.3910	3.8	4.0	6.4
4	20170720 23:23:50	36.9412	27.3008	4.8	4.8	5.0
5	20170721 00:16:40	36.9720	27.3210	4.1	4.1	5.0
6	20170721 00:53:46	36.9913	27.2830	4.2	4.2	2.1
7	20170721 00:57:06	36.8597	27.6563	4.3	4.3	1.0
8	20170721 01:25:34	36.9722	27.4263	4.0	4.0	7.2
9	20170721 01:35:43	36.9423	27.5600	4.3	4.3	5.9
10	20170721 01:38:50	36.8742	27.5950	4.6	4.5	4.0
11	20170721 01:50:29	36.9870	27.3672	4.0	4.2	9.5
12	20170721 01:54:45	36.9530	27.3563	3.8	4.1	1.4
13	20170721 02:12:34	36.8747	27.3210	4.6	4.4	8.8
14	20170721 03:59:01	36.9210	27.5783	4.2	4.4	6.7
15	20170721 05:03:59	36.9135	27.5602	4.5	4.5	1.8
16	20170721 05:13:58	36.9120	27.6122	4.1	4.3	5.0
17	20170721 05:52:13	36.9823	27.3663	4.0	4.2	6.3
18	20170721 07:05:23	36.8922	27.4232	3.7	4.0	1.5
19	20170721 07:28:15	36.9105	27.5907	3.7	4.1	5.0
20	20170721 09:55:54	36.9238	27.6480	4.0	4.1	7.1
21	20170721 17:09:46	36.9537	27.2568	4.9	4.9	6.9
22	20170722 00:34:12	36.9467	27.5355	3.9	4.1	6.4
23	20170722 17:09:20	36.9638	27.2730	4.5	4.5	5.7
24	20170724 21:48:47	36.9730	27.4732	4.0	4.0	5.0
25	20170726 10:55:04	36.9002	27.5585	3.7	4.1	5.0
26	20170730 07:02:13	36.9897	27.5872	4.3	4.3	5.0
27	20170730 10:56:32	36.9902	27.5850	3.9	4.1	5.0
28	20170730 17:51:18	36.9962	27.6552	4.4	4.6	9.7
29	20170731 16:25:36	36.9965	27.6207	3.8	4.0	7.8
30	20170803 13:17:55	36.9433	27.6252	3.8	4.1	5.0
31	20170807 05:18:47	37.0192	27.6017	4.7	4.8	5.2
32	20170807 05:44:24	36.9750	27.5988	4.0	4.2	5.0
33	20170807 18:25:57	36.9933	27.6347	3.9	4.1	6.5
34	20170808 01:46:19	37.0088	27.6247	4.3	4.5	5.0
35	20170808 07:42:19	37.0198	27.6033	5.1	5.3	5.0
36	20170810 22:56:18	36.9843	27.6537	4.0	4.2	6.6
37	20170813 11:16:51	37.1260	27.7182	4.8	4.9	5.8
38	20170813 12:28:14	37.1253	27.7160	4.3	4.3	6.5
39	20170813 16:31:21	37.1317	27.7042	4.0	4.0	7.0
40	20170813 16:35:22	37.1275	27.7292	4.3	4.2	6.0
41	20170813 17:09:06	37.1193	27.7060	4.0	4.0	6.4
42	20170814 02:43:48	37.1403	27.7360	4.8	4.5	6.6
43	20170818 12:47:32	36.9400	27.5800	4.1	4.2	5.0
44	20170818 14:10:47	36.9315	27.6008	4.4	4.6	6.2
45	20170909 23:23:32	37.1650	27.7228	4.0	4.0	8.0
46	20170916 08:33:55	37.1413	27.7233	4.3	4.2	6.4
47	20170924 16:57:16	36.9412	27.3242	4.4	4.3	10.9
48	20171010 19:59:24	36.9803	27.3570	4.1	4.1	12.7
49	20171024 09:36:23	36.9942	27.3878	4.5	4.5	5.7
50	20171122 20:22:51	37.1378	28.5920	5.0	5.0	5.3
51	20171124 21:49:14	37.1412	28.6097	5.1	5.0	6.3

TABLE 2 Earthquake lists used in the study.

measurement point is calculated by the following equation:

$$HVSR(f) = H_c(f) / V_c(f) \quad (1)$$

where $H_c(f)$ is the amplitude spectra of the horizontal components, and $V_c(f)$ is the amplitude spectrum of the vertical component. $H_c(f)$ is the square root of the sum of the squares of the east-west and north-south components of an accelerogram.

The second method, introduced by Borcherdt [1970], requires two horizontal component records of two stations. The records should be from the same earthquake. This popular method to characterize site amplication involves comparison of pairs of records from nearby stations, one representing a soil (an alluvial) site and the other representing a reference (a rock) site [Gok et al., 2012; Safak, 1997]. Distance between the stations must be much smaller than their hypocentral distances, so that the source and path effects on the records are nearly identical [Safak, 2001]. Therefore, any differences in the records can be attributed to site effects. This method is required two horizontal component records of two stations and has been to use spectral ratio, the ratio of the Fourier amplitude spectrum of the soil site recording to that of the rock site recording [Borcherdt, 1970; Mittal et al., 2013; Safak, 1997]. Standard spectral ratio (SSR) of the measurement points is calculated by the following equation:

$$SSR(f) = H_s(f) / H_{rs}(f) \quad (2)$$

where $H_s(f)$ and $H_{rs}(f)$ denote the smoothed horizontal component of Fourier amplitude spectrum at the site of interest and reference site respectively.

In this study, the HVSR and the SSR methods were used to determine site effects at the stations, in particular, in order to compute the resonant frequencies, and to obtained spectral amplifications, respectively. More detail can be found in the references provided.

Data processing was done using MATLAB® (http://www.mathworks.com/) software codes in accordance with the techniques mentioned above. Before computing the spectral ratios, all recorded time-series were visually checked to identify possible inaccurate measurements. The records with signal-to-noise ratio greater than 3 were kept in the analyses. The full-length records were de-trended, baseline corrected and band-pass filtered between 0.05 and 20 Hz. In the analysis of both methods, the same data processing procedure was followed except for data window lengths to be processed. The window lengths were selected 30s after the

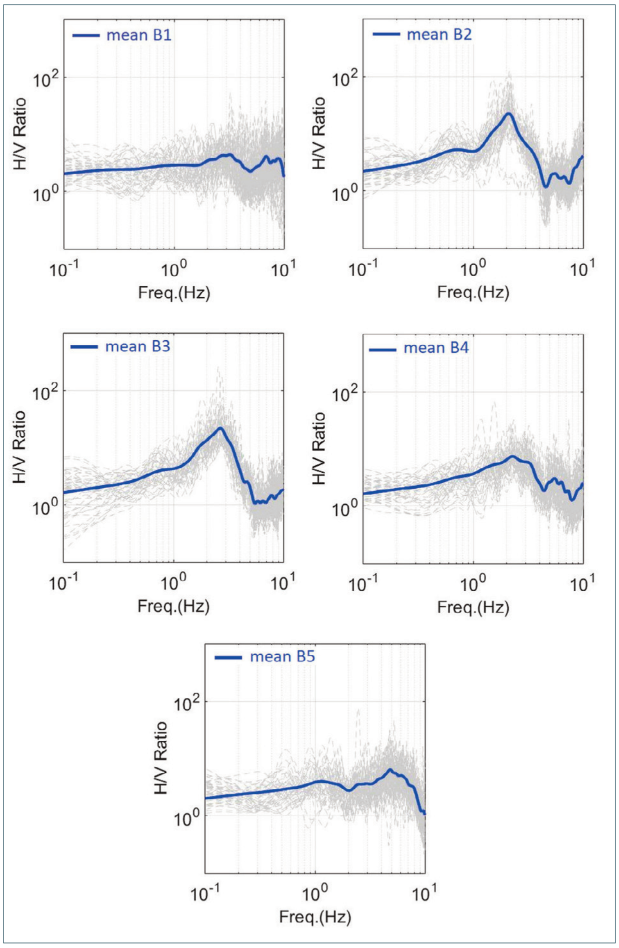

FIGURE 5. Plots of H/V ratios vs frequencies (Hz). Blue lines represent mean values.

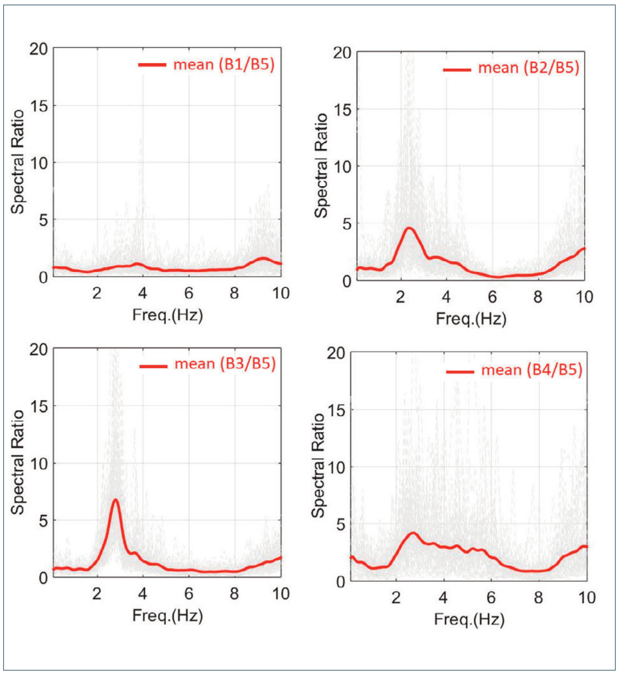

FIGURE 6. Plots of standard spectral ratios vs frequencies (Hz). Red lines represent mean values.

S-wave of earthquake accelerograms for SSR method, and 60s after the P-wave for HVSR method. Selected data were windowed by a 5% cosine taper before performing a Fast Fourier Transform. Each spectrum was smoothed by a Hamming window. Then, spectral ratios, and finally, arithmetic mean of spectral ratios for each site were computed [Parolai, 2012; Alcik and Tanircan, 2017] (Figure 5 and 6).

7. RELATIONSHIP BETWEEN RESONANCE FREQUENCY (FR) AND SEDIMENT THICKNESS (H)

Ibs-von Seht and Wohlenberg [1999] showed that the frequency of resonance (fr) of a soil layer is closely related to its thickness (h) through a relationship could be established using a non-linear regression fits of the form,

$$h = a \cdot f_r^{\,b} \qquad (3)$$

where a and b are correlations coefficients. They stated that their equation is valid for soils from a few tens of metres to more than 1000 m thick. This relationship has became a common practice since their work in the context of seismic hazard assessment [Chia and Lau, 2017; Tun et al., 2016]. Numerous authors, working along similar lines, have developped such relationships which provide a practical means of sediment thickness estimation at different soils [Ibs-von Seht and Wohlenberg, 1999; Delgado et al., 2000a,b; Parolai et al., 2002; Hinzen et al., 2004; Kanli et al., 2008; Birgoren et al., 2009; Ozalaybey et al., 2011; Tun et al., 2016; Chia and Lau, 2017]. Empirical functions established by above scientists are given in Table 3 and were plotted in Figure 7. This inverse proportion fr - h relationship states that if the resonance frequency of a site is known, then the thickness of underlying layer can be estimated. Within this framework, top sediment thickness of the soil underlying the B-Net stations were calculated using these empirical functions.

No	Reference	f_r-h relationship
1	Ibs-von Seht and Wohlenberg,1999	$h=96*f_r^{-1.388}$
2	Delgado et al., 2000a	$h=55.11*f_r^{-1.256}$
3	Delgado et al., 2000b	$h=55.64*f_r^{-1.268}$
4	Parolai et al., 2002	$h=108*f_r^{-1.551}$
5	Hinzen et al., 2004	$h=129.166*f_r^{-1.2804}$
6	Kanli et al., 2008	$h=110*f_r^{-0.392}$
7	Birgoren et al., 2009	$h=150.99*f_r^{-1.1531}$
8	Ozalaybey et al., 2011	$h=141*f_r^{-1.278}$
9	Tun et al., 2016	$h=136*f_r^{-1.36}$
10	Chia and Lau, 2017	$h=54.917*f_r^{-1.314}$

TABLE 2 Empirical functions related to f_r-h.

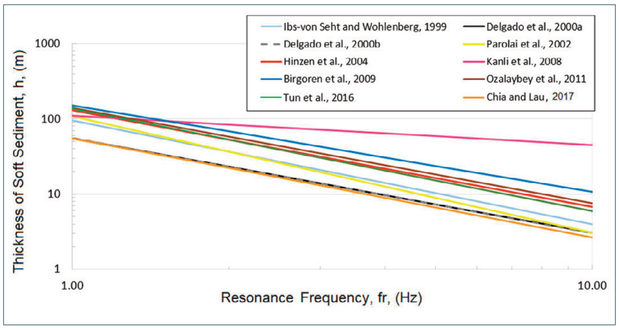

FIGURE 7. Empirical relationships for thickness of soil layer and resonance frequency.

8. DAMAGE ASSESSMENT INFORMATION

Preliminary damage assessments were conducted in the earthquake area by the government experts, competent in disaster affairs and emergency management. The final results have not been completing due to certain legal disputes and disagreement arising from presented assessment results. As of November 2017, the damage assessment results reported by the Bodrum Governorate are briefly: totally 646 buildings were low damaged; 93 buildings were medium damaged; 202 buildings were heavy damaged and totally 26 were collapsed. There is no information related to the peninsula's building stock. The earthquake caused damage in 47 of 53 sub-districts of Bodrum (Figure 8). The distribution of damaged buildings particularly in where our strong-motion stations had been installed, are given in Table 4. It was reported that during the earthquake there was no loss of life in Bodrum peninsula but at least 90 people were injured.

Macroseismic data which describes the effects of a seismic event, permits to examine the interaction between shaking and buildings. Regarding this issue, a one-person post-event field survey was held on July 22, a day after the main shock for 5 days. This individual survey was only performed in the Bodrum peninsula. The island of Kos has not been visited by the author. During this survey period, primarily structural damages were mapped and pictured at a substantial part of the peninsula. Some example photos are given in Figure 9-13.

FIGURE 8. Damage distribution in the Bodrum neighborhoods. MD and HC represent *Medium Damage* and *Heavy Damage and Collapsed* buildings, respectively.

Neighborhood	Light damage	Medium damage	Heavy damage	Collapsed
Bodrum: Tepecik	5	5	6	-
Turgutreis: Turgutreis downtown	56	1	4	-
Yalikavak: Yalikavak downtown	8	-	6	1
Yali: Ciftlik & Kizilagac villages	109	11	86	17
Ortakent-Yahsi: Ortakent downtown	4	-	3	-

TABLE 4. Damage distribution at the sites in where strong-motion stations installed. Indicated digits are the total numbers of damaged buildings.

The housing parks in Bodrum peninsula are heterogeneous due to the history of its economical development. The peninsular villages have a vaguely Hellenic feel with one - and two-storey old stone houses. These houses are located in the flat, alluvial area close to the coast and in the hills at villages. They were built with local materials such as stone, sand, mortar and wood. Houses with rubble stone in mud/lime mortar and load-bearing masonry constructions are widely used structural types of buildings in this part of Turkey. These unreinforced houses are built by local builders or by owners themselves without any formal training and engineering considerations. They represents affordable and cost-effective housing constructions. The rapid development period of tourism in Bodrum has started the use of RC for public and residential buildings, and has increased in building density consistent with the code based regulations. The buildings in the peninsula range from one- to three-storey and the quality of construction in urban (coastal) areas is generally superior to that found in rural (hinterland) areas. It is stated that Bodrum building stock is unknown, but estimated as being

FIGURE 9. Heavily damaged 3-storey stone masonry building at the Kizilagac village (Yali).Typical earthquake damage: falling of plaster and shear cracking of the walls.

FIGURE 10. (left) Damaged traditional dome-shaped water cistern on the road of Ciftlik village to Bodrum centrum; (right) Shear cracking of masonry walls of a house, with upper floor added, at the same village.

comprised about 200,000 housing units (flats or individual homes). Most of them are accommodated only in summer seasons by the people, temporarly moves from metropolitan cities of Turkey.

Throughout the peninsula, the observed performance of RC buildings, regardless of vintage, performed well and as expected. Some houses have joint/wall shear cracks in non-structural walls and plaster cracks. It can be noted that no apparent structural damage was observed at the reinforced buildings in Bodrum peninsula. However, the observed performances of the stone buildings were not so good and the load bearing masonry constructions did not perform very well in the earthquake. Most of these unreinforced masonry structures were damaged. The common damage type was the typical “x-type” shear cracks due to brittle behavior of the construction material and poor strength of the connection between members. In some of the buildings, infill walls were partially collapsed due to the lack of restraint in the out of plane direction. Addition to these issues, structural alterations (added floor), improper construction and site, poor concrete and mortar quality etc. can be cited as the technical causes of the observed building damages or collapses (Figure 9-13).

FIGURE 11. (left) Partial collapsed of a single-storey stone masonry house in Ciftlik village (Yali). This picture is a good example to common failures of unreinforced masonry systems: diagonal cracking; vertical cracking at the corner joint and out of plane failure; (right) Collapsed houses at the same village.

FIGURE 12. An unreinforced masonry roof floor built contrary to relevant regulations onto an existing two-storey reinforced concrete building (from an area close to Turgutreis).

9. RESULTS - DISCUSSIONS

The spectral ratios, H/V and standard spectral, obtained from these five regions are illustrated in Figure 5 and 6, respectively.

The spectral H/V ratio of each measurement location enabled an estimation of the resonance frequency at that site. Figure 5 shows H/V spectra and their arithmetic mean for five different sites. Selection of the resonance frequencies are made visually using these arithmetic means. The average H/V spectral ratio plots show dominant maxima at frequencies above 2 Hz and vary up to 5 Hz. Average spectral curves of B2 and B3 give a similar shape, while the rests do not resemble to each other. Sites B2 and B3 are situated in almost high sedimentary thickness than the others. Examining HVSR data, it was found out that predominant frequencies change between 2.1-3.2 Hz for very dense soils, where it is 4.8 Hz for soft rock (Table 5). For SSR analyses B5 was selected as the reference site.

SSR spectra show that relative amplifications are in a range of 1.5 to 6.6 across the frequency axis (Figure 6). The lowest-amplification site is located on alluvial-

FIGURE 13. (left) Affected two-storey stone house in Bodrum center; (right) Damaged of minaret of a mosque constructed in the year of 1990 in Ortakent-Yahsi.

flysch at B1 and the highest-amplification sites on alluvial sites, B2 and B3. Maximum relative amplification with 6.6 unit is observed at B3, and as shown in Figure 6, amplification at B3 has a peak at 2.7 Hz; this peak has similarity in its H/V ratio (Figure 5). Turgutreis site, B2, has the same geological structures as the Yalikavak site. B2 gives the second highest amplification at frequency at 2.3 Hz by a factor of about 4.5 relative to station B5 site. The Vs of 605 m/s obtained at close site to B1 site is higher than the Quaternary unit located at other sites. This site, B1, yields almost a flatter response around a factor of about 1.0. This situation can be as result of flysch sediment of upper Cretaceous-Paleocene aged situated under thin alluvium layer at the top. Similarly, the Vs of 521 m/s in the vicinity of B4 is somewhat high when compares to B2 and B3 have. The younger units forming the lithology at B4 site are alluvium deposits and slope debris cover the Mesozoic aged limestones. The unit thickness at this site is uncertain, but, it may be more than 10 meters when the geotechnical data from EGE-SU data archive is taken into account. The average spectra plot shows that the S-waves at station B4 are amplified by a factor of about 4.2 at frequency 2.6 Hz relative to station B5. Amplifications at fundamental frequencies are given in Table 5.

Possibility to estimation the bedrock depth of the soil under stations based on empirical equations is mentioned at the previous chapter. These relationships derived for different places around the world are almost close to each other and show similar trends. They were stated as to be valid for soils several tens of metres thick. Therefore, using together with the equations given at Table 3 and the predominant frequencies at Table 5, upper sediment thickness of the soil underlying the B-Net stations were calculated. The results related to stations were presented at Table 6. As can be seen in the table, the lowest bedrock depth values were obtained from the Chia and Lau [2017] and Delgado et al., [2000a,b] relationships. In contrast the highest values are calculated at the equations of Kanli et al., [2008] and Birgoren et al., [2009]. In either case, thicknesses to bedrock were concluded as being the highest at Turgutreis valley, the largest alluvial valley of the region, and lowest at the Bodrum downtown, the smallest alluvial valley of the region. It is not conducive to make comparisons between these empirical relationships in order decide to a suitable empirical relationship due to the absence of boreholes reached to bedrock and lack of Vs30 versus depth profiles nearly to the B-Net stations. There are only two drilled wells with a 15.5-m and a 20-m in depths that do not tap bedrock at Turgutreis and Yalikavak sites, respectively. A simple comparison analysis can be done by considering only 20-m well depth at Yalikavak in where a single lithological unit was emerged. The dominant frequency obtained at B3 is 2.7 Hz. The depths corresponding to this frequency appear to have values ranging from 14.9-74.5 m. However, taking into consideration this 20-m borehole depth, one can decide that estimated bedrock depth at B3 site should be more than the current depth. In this case, the empirical relationships give small values less than 20 meters can be eliminated. As a result of these circumstances, seven approaches except Delgado et al., [2000a,b] and Chia and Lau [2017] seem to be appropriate for applying to thickness determination for the soft layers under the B-Net stations. The results indicate that sediment thicknesses

Station code	Predominant frequency (fp in Hz) (HVSR)	Ratio	Soil Amplification at fp (SSR)
B1	3.2	B1/B5	1.0
B2	2.1	B2/B5	4.0
B3	2.7	B3/B5	6.6
B4	2.3	B4/B5	3.4
B5	4.8	-	-

TABLE 5. HVSR and SSR values.

Table 4, on the other hand, relative amplification value of B4 does not conform to its HC building number. Damages or collapses were mostly occured at Yali district (Table 4) while its relative amplification value is low (Table 5).

Taken together these findings suggest that no direct relationships exist between damage distribution in the Bodrum peninsula and the resonance frequencies & the relative amplifications.

References	Estimated bedrock depth (h in meter)				
	B1	B2	B3	B4	B5
Ibs-von Seht and Wohlenberg, 1999	19.1	34.3	24.2	30.2	10.9
Delgado et al., 2000a	12.8	21.7	15.8	19.4	7.7
Delgado et al., 2000b	12.7	21.7	15.8	19.4	7.6
Parolai et al., 2002	17.8	34.2	23.1	29.7	9.5
Hinzen et al., 2004	29.1	50.0	36.2	44.5	17.3
Kanli et al., 2008	69.7	82.2	74.5	79.4	59.5
Birgoren et al., 2009	39.5	64.2	48.0	57.8	24.7
Ozalaybey et al., 2011	32.2	55.0	39.9	49.0	19.2
Tun et al., 2016	28.0	49.6	35.2	43.8	16.1
Chia and Lau, 2017	11.9	20.7	14.9	18.4	7.0

TABLE 6. Estimated bedrock depth.

beneath the stations change between 17.8-69.7m for B1; 34.2-82.2m for B2; 23.1-74.5m for B3; 29.7-79.4m for B4 and 9.5-59.5m for B5.

Hays [1986] suggested the relationship Tb = N/10 for estimating the natural period (Tb, in seconds) of a building with its number of stories (N). This is an useful and commonly used equation. The building stock in the peninsula is comprised of one- to three-storey buildings, which correspond to resonance frequencies of about 3-10 Hz. The resonance frequencies of B1 and B5 sites are in this range, indicating the possibility of the resonance effect. On the contrary, the range of resonance frequencies of the soil in the alluvial sites in the Bodrum peninsula is 2.1-2.7 Hz, suggesting that only buildings with more than 3.5 stories have resonance problem. However, no buildings in these heights were presented in the observed areas and majority of damaged or collapsed structures were un-reinforced masonry buildings built at the alluvial sites in the Bodrum peninsula (e.g. Yali sub-district, Yalikavak downtown and Turgutreis neighborhood) (Figure 8). The relative amplifications in where strong-motion stations installed, are in a range of 1.0 to 6.6 and considerable damage was occurred at these sites. Relative amplification values at B2 and B3 sites seem to be in agreement with their heavily damaged+collapsed (HC) building numbers given in

10. CONCLUSION

In the present study an attempt mainly has been made to calculate predominant frequencies and amplification values considering local site effects related to the Bodrum peninsula. Site effects were done using the standard spectral ratio and horizontal-to-vertical ratio techniques. For this purpose, a set of time histories contains 261 three-components acceleration records, totally 54 earthquakes with moment magnitudes greater than 4.0 and with epicentral distances less than 100 km were analysed.

The resonance frequencies revealed by HVSR curve peaks for sites B1 to B5 were measured. So that, the amplification ratios obtained by SSR spectra peaks for sites B1 to B4 relative to station B5 are calculated (Table 4). The aim of the second part of the study was to apply ten fR-h empirical equations to determine the thickness of soft soils in the Bodrum peninsula, an area where types of soils are known but where the available geotechnical & geophysical information is insufficient for such determinations. Seven of ten empirical equations seem to be appropriate for applying to thickness determination for the soft layers under the B-Net stations.

Comparing these findings with the geological map of the region (Figure 4), it was found out that thicknesses associated with resonance frequencies (Table 5) seem to be in agreement with surface geology information. Besides, the Vs velocities of first layers and the Vs30 velocity values belonging to the sites are directly proportional to the amplification ratios. However, it is difficult to say that there is a linear relation between the site amplification and the estimated thickness as a result of the maximum amplification was calculated at B3 station, since amplification is also directly related with impedance contrast of the layers.

The observations regarding to the Mw6.6 earthquake have revealed that buildings of low construction quality or buildings built contary to relevant regulation were subjected to different levels of damage, and damages or collapses were mostly occured at the unreinforced masonry structures, in particular, old stone houses while there were generally no apparent structural damages at the reinforced buildings.

The results of analyses indicate that (1) predominant frequencies change between 2.1 - 2.7 Hz for soft soils, where it is 4.8 Hz for the reference site B5; (2) relative amplifications are in the range of 1.0 to 6.6; (3) estimated thicknesses of sediments beneath the stations vary between 9.5m and 82.2m; (4) even if local geology contributes significantly to the damage patterns observed following an earthquake, by amplifying or diminishing the ground-motion intensity, a linear relationship could not be found between the damage distribution and both the resonance frequencies and the relative amplifications in the Bodrum peninsula.

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