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Unexpected soil amplification effect on seismic performance of highway bridges during the Aegean earthquake of October 2020, Mw 6.6

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Abstract. On October 30, 2020, an earthquake about 70 km away from the city center of Izmir with a 4.3 million population has shaken the city tremendously and has resulted in destruction of many building type of structures due to an unexpected high soil-amplified vibrations very similar to the Mexico City earthquake in 1985. The bridges at the soil-amplified sites has performed in elastic range with no damage at all. In the city of Izmir, the 42 year old twin bridges located on the main transportation route, were tremendously shaken by the earthquake had observed to have no seismic induced damage. Surprisingly twin bridges suffering from the alkali silica reaction (ASR) over the years did not even pound to each other despite the small size of longitudinal gap between them. As it has been known, the past performance of Turkish designed bridges are typically succesfull with almost no damage as observed in the Van 2011 and Sivrice 2020 earthquake mainly due to allowing movements at their joints and to flexible type of framing. The focus of the paper is given to understand the successful performance of bridges and to investigate the non-pounded twin bridges of the Izmir city. In this scope, a bridge inspection has been performed and the twin bridges have been analyzed for the recorded ground motion. The results have indicated that the structures have been subjected to 0.3 g at their vibration modes and the twin bridges have a synchronized motion due to having the identical vibration mode shape with a period of 1.5 seconds

1. Introduction

On October 30, 2020 an earthquake with Mw = 6.6 near-by Sisam Island about 70 km away from Izmir has shaken the city and resulted in destruction of many building type structures. Soil site is composed of medium sand and stiff clay, classified as ZD (the weakest soil type in Turkish Seismic Code) referring to a medium stiff sand or clay having an average seismic shear-wave velocity from the surface to a depth of 30 meters (Vs30), shear wave velocity in top 30 meters, between 180 and 360 m/s. Suprisingly, the Aegean Earthquake on October 30, 2020 have resulted in a similar site amplification effect as Puebla–Morelos, Mexico earthquake on 19 September 2017, having Mw = 7.1. In the Turkish seismic codes such a soil amplification has been unexpected for this region.

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Since the Michoacan 1985 earthquake, Mexico City has been affected from soil amplification depending on the period of the sites [1]. During this time period most recent Puebla-Morelos 2017 Earthquake has not caused significant damages in the Mexico city and can be classified as a less damaging earthquake. Similar to the Puebla Earthquake, 2020 Aegean Mw = 7.1 earthquake is also less damaging to the bridges but not to the building type structures in the Izmir city. The Puebla earthquake 2017 has experienced soil amplification effects based on analysis of the ground motion records taken in the two lake zone stations, and the two hilly zone stations. Amplification ratios are taken as the response acceleration spectrum at station soft soil lake zone stations with respect to the response acceleration spectrum at the rock soil hill stations [1]. In one of the lake stations amplification peaks occur at nearly the same period range $T = 1.8–2.3$ sec. for both rock motions and in the other one amplification peaks occur at nearly the same period range $T = 2.5–4.0$ sec. for both rock motions [1].

Based on damage observations and ground motions after the 2017 Mexico earthquake, it is stated that for any structure seismic risk increases if structural response is amplified, which occurs when natural periods of the structure and the soil overlap [2].

Recently, Çelebi et al. [3] analyzed the spectral ratios during the Mw = 7.1 Puebla-Morelos 2017 earthquake to figure out basin response to strong motion. By this way, knowledge about the dominant period of ground motion may be obtained. Two methods are used in the paper while computing spectral ratios, named as horizontal to horizontal (H/H) ratio method and horizontal to vertical (H/V) ratio method. These ratios represent the amplifications of ground motions. It can be inferred that, using the amplifications of ground motions spectral ratios are inferred. These two methods can be studied using strong ground motions and microtremor data. If there is no reference station, H/V method is used instead of H/H. In the study area, there exist hills, transitions and lake zones. In zone III (lake zone, divided into 4 sub zones), as it can be inferred from the spectral ratio results, frequencies are increasing from zone IIId to zone IIIa, since shear wave velocities are highly varying in depth in zone III [3]. It is concluded that spectral ratios computed are consistent with the site period map of the 2004 Mexican seismic design code [3].

In Asimaki et al. [4] it is shortly summarized that damage from 1985 Mw = 8 Michoacan Earthquake was mostly in the deep lake zone sediments, however; damage from 2017 Mw = 7.1 earthquake was mostly in transition and shallow lake zones. While the 1985 event has affected mostly taller structures, the 2017 event has affected shorter period structures. The 2017 event had a high frequency content, and site amplifications are due to shallow sediments [4].

After the 1985 Mw = 8.1 event, large damage was observed. This damage arises from site effects caused by clay deposits with high plasticity in the basin [5]. These clay deposits caused significant amplifications. This characteristics of the ground motion resulted in large site amplification on the shallow sandy silts and silty sand layers, therefore; short period structures are affected more [5].

After the recent earthquakes, it has been observed that the majority of the bridges in Turkey, have showed a very succesful seismic performance. Eventhough the destructive effect of the earthquake increases when the distance between the structure and epicenter decreases, the bridges close to the epicenter of the earthquake are not damaged and available for service immediately after the earthquake. Some of the bridges underwent minimal structural damage which can be intrepreted using ATC-32 [6].

In Sivrice 2020 earthquake Mw = 6.8, all bridges including a 70 year old bridge structure in the vicinity of fault line has been observed to have no seismic damage and the performance of this old steel bridge has been analyzed thru the elastic dynamic analysis. Consequently, investigated bridges did not show large deformations due to the flexible supports between bridge superstructure and substructure that allows some movement and such movement can help to reduce force transfer from superstructure to substructure [7].

On October 23, 2011, a destructive earthquake with a thrust fault mechanism with Mw = 7.1 occurred in Van. The area was not seismically well-monitored (with very few strong ground motion stations around), and the fault was not known previously or studied in detail. A major hanging-wall effect was observed in this event, which resulted in an uneven distribution of damage in the region. Even though the lack of a dense strong ground motion network in the area did not make it possible to observe this fact in terms of measured ground motions. The bridges designed using the approach defined by the Turkish Highway Officials (KGM) show successful seismic performance [12]. The designers in Turkey utilize a well-tested seismic design approach, most of it modified from the Standard Specifications for Highway Bridges [8].

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The bridge seismic design practice is noted to be significantly successful compared to building design and construction practice in Turkey. Bridges survived the earthquake with no or minimal damage, mainly owing to the fact that the design approach used for these structures was targeting an essentially elastic response rather than a highly plastic response during the design earthquake. The damages to the bridges were observed at the support locations in the form of support movement or shear key cracking.

The focus of this paper is given to investigate the succesful seismic performance of the Turkish bridges once again. In this scope, a bridge inspection has been performed, unexpected soil amplification characteristics has been studied, and the twin bridges has been analyzed for the recorded ground motion.

2. Observed bridge performances

The bridges on Mürselpaşa Caddesi - Zafer Payzın highway line were examined in detail after the Mw 6.6 Aegean Earthquake that took place on October 30, 2020. These bridges are approximately 70 km from the earthquake epi-center. No permanent movement has been observed in the superstructure beams and supports. The bending or shear capacity of the bridge columns and foundations has not been exceeded and no cracks have occurred due to the recent earthquake. There was no settlement on the foundation over soft soil. No movement was observed at the bridge expansion joints. No loss of function such as rupture or fracture has been observed in non-structural bridge elements (precast panels, pedestrian railings, lighting poles, etc.). The earthquake performances of longitudinal joints between twin bridges are adequate as expected and some small concrete pieces not more than 2-3 cm fall on the ground only one location for 1000 + meter long multi-span bridge. After the examination of the superstructure and infrastructure of the bridges, no earthquake-related damage was detected.

The structural history of the bridges could not be documented after the transfer of ownership from KGM to the municipality. Mürselpaşa Street-Zafer Payzın bridge highway line rehabilitation and widening project has been started in September 2019 about one year before the earthquake. The engineering project includes the maintenance, repair and identification of seismic performance of the bridges along the route. The route has about 15 bridges with connection roads. Bridge design drawings are regenerated based on field studies involving some rebar detection, concrete compressive strength tests, foundation inspection excavations and some old construction photos.

During the bridge inspections, most of the cracks observed since the beginning of the project caused by rainwater and are ASR (Alkali-Silica Reaction) type cracks, which are the result of a chemical reaction that occurred years ago in the bridge elements as shown in Fig. 1. These chemical cracks did not grow after the earthquake. The repair of these cracks will be carried out within the scope of the related project.

About 6 months prior to the erthquake, static and dynamic live load tests were conducted to observe the girder design performance under traffic loads and it had been concluded that the superstructure had a very good performance in carrying heavy loads as expected.

All the bridges have performed successfully during the earthquake and have been in service immediately after the earthquake without the need for any emergency intervention or maintenance. Such observations in the past earthquake mainly lies in the succesful seismic design policies followed by the KGM.

At an old construction site abondened for the last 20 years, some bridge girders with no lateral stability over piers fell during the earthquake. These bridges were not on the highway line or service.

3. Revised design spectrum curves for soil amplification

The Turkish seismic design code could not adress the observed gound shaking characteristics of the Izmir region. The response was unexpected for many experts researching this field of engineering. A revised version of the design spectrum is needed and research by Garini et al. [1] has been followed. The location of the main earthquake and aftershocks were shown in Fig. 2.

For this purpose, records of the stations with rock and weak soil profiles having very similar distances to the earthquake epicenter are analyzed to calculate the magnification factors. The station locations within the close vicinity of the investigated route is shown in Fig. 3. The ratio between weak soil S_{aZD} (T) and rock soil S_{aZB}(T) is used to calculate the soil magnification factor. The result is compared with the predictions given in the specification. The magnification factor used is calculated by the formula given below.

$$F_{zb} = \frac{S_{aZD}(T)}{S_{aZB}(T)} \quad (1)$$

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Fig. 1. ASR based cracks (non-seismic) and a general view of twin bridges.



Fig. 2. Epicenter of the Earthquake and the Seismic Focuses with Mw > 4 (30 October 2020 – 08 January 2021) (tadas.afad.gov.tr).

In calculating, Sa values mentioned above, only two components perpendicular to each other, E-W and N-S, are investigated. The resultant value is calculated by taking the square root of each value's square's summation as the formula given below.

$$S_a = \sqrt{{S_{aEW}}^2 + {S_{aNS}}^2} \qquad (2)$$

The stations used in calculations in terms of soil properties and distance to the epicenter are shown in Table 1. The soil classes is compatible with the current earthquake specification for buildings [9]. Soil class is taken as "ZD" due to the fact that all the weak soil stations are on ZD type of soil.

Significant earthquakes that occurred with in the last five years have been investigated to study the traces of soil amplification if any. All the selected earthquakes with Mw between 4.0 and 6.6 are observed with in 60 to 130 km away from the city center so that the ground motion recording stations are almost the same distance to the epi-center. Suprisingly with in the 60 km radius of the city, the magnitude of the largest erathquake is 4.9 and the city has not been tested for a large eartquake yet and hopefully will not be tested soon. Even the researchers do not have an agreement on the magnitude of the next largest earthquake within the 60 km radius, the future maximum magnitude can be a Mw of 6.5 at most per online Izmir Seismic Risk Assessment report (https://www.izmir.bel.tr/izmirdeprem/#47 accessed 2021).

The acceleration spectrums for the recorded seven earthquakes are given below. The recorded ground motions are tried to be selected from the earthquakes that give the maximum soil amplification values in the region. In most cases, it can be observed that soil amplification has been elongated to 2.0 seconds that

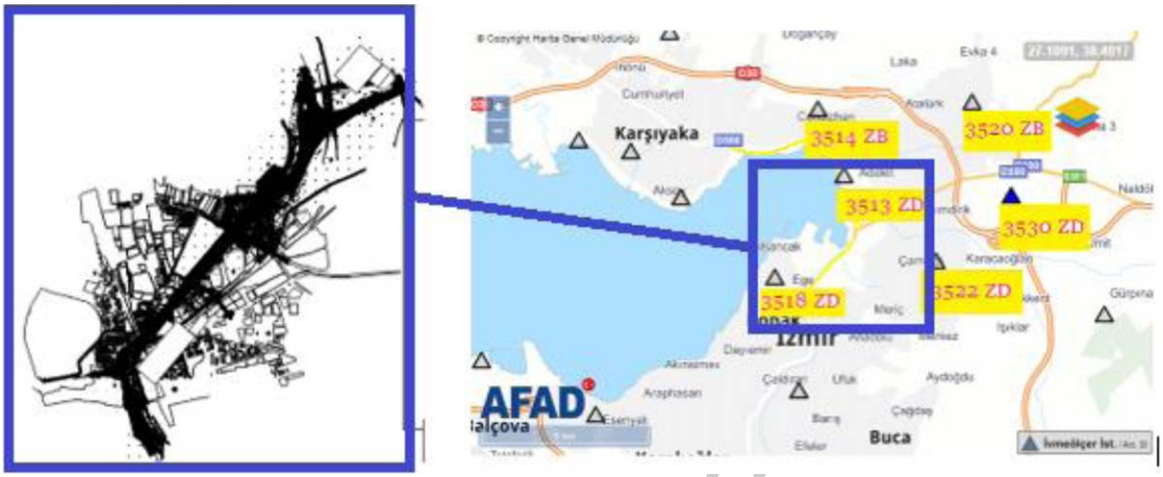

Fig. 3. The Line Consisting of Bridges, Earthquake Stations and Stations' Soil Class(tadas.afad.gov.tr).

Table 1
Selected Earthquakes and Stations (2019-2020)

Station No	M_w	Year	Location of Epicenter of the Earthquake		Location of the Stations		V_{s30} (m/s)	Soil Class	Distance to the Epicenter of the EQ
			Latitude	Longitude	Latitude	Longitude			
3513	6.6	2020	37.879	26.703	38.458	27.167	196	ZD	76
	6.2	2017	38.458	27.167					86
	4.8	2020	39.100	27.841					92
	4.7	2020	39.013	27.870					87
	4.6	2019	39.443	27.933					128
	5.5	2020	38.476	27.158					65
	5.0	2020	37.870	26.830					72
3514	6.6	2020	37.879	26.703	38.476	27.158	836	ZB	77
	6.2	2017	38.458	27.167					87
	4.8	2020	39.100	27.841					91
	4.7	2020	39.013	27.870					86
	4.6	2019	39.443	27.933					127
	5.5	2020	38.476	27.158					65
	5.0	2020	37.870	26.830					73
3522	6.6	2020	37.879	26.703	38.435	27.198	249	ZD	75
	6.2	2017	38.458	27.167					90
	4.8	2020	39.100	27.841					93
	4.7	2020	39.013	27.870					87
	5.5	2020	38.476	27.158					64
	5.0	2020	37.870	26.830					71
3520	6.6	2020	37.879	26.703	38.476	27.211	876	ZB	80
	6.2	2017	38.458	27.167					
	4.8	2020	39.100	27.841					88
	4.7	2020	39.013	27.870					82
	4.6	2019	39.443	27.933					124
	5.5	2020	38.476	27.158					82
	5.0	2020	37.870	26.830					75
	6.2	2017	38.458	27.167					90
	4.8	2020	39.100	27.841					89
	4.7	2020	39.013	27.870					84
	4.6	2019	39.443	27.933					124
	5.5	2020	38.476	27.158					61
3518	6.6	2020	37.879	26.703	38.431	27.144	298	ZD	73
	6.2	2017	38.458	27.167					86
	4.8	2020	39.100	27.841					96
	4.7	2020	39.013	27.870					90
	5.5	2020	38.476	27.158					68

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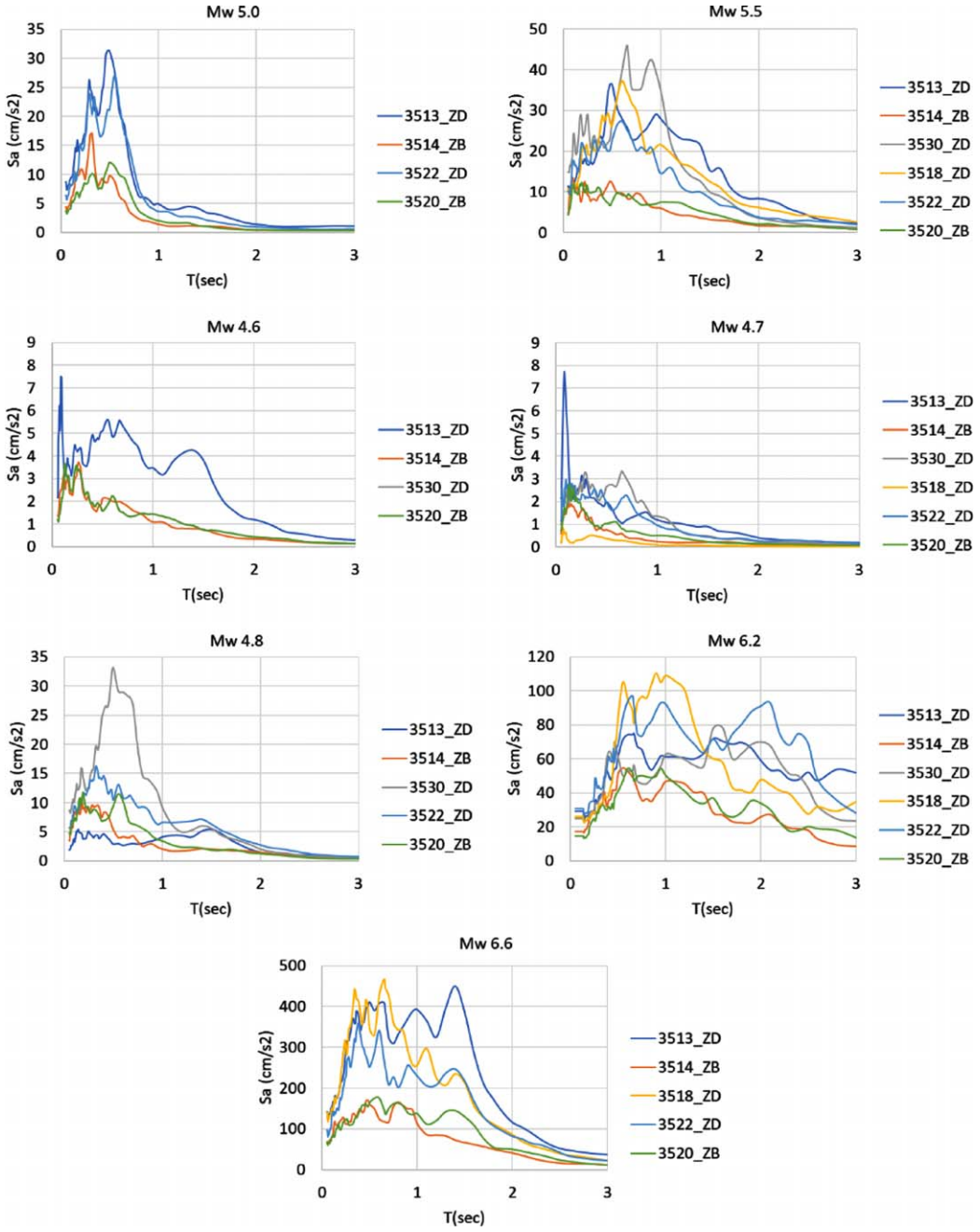

Fig. 4. Observed Response Acceleration Spectrums.

is very much unexpected for this region based on the findings of the Turkish Seismic Code writers.

It has been observed that the distance between stations and epicenter did not vary much. Most of the stations have almost the same distance to the epicenter that indicates that the ground motion attenutaion should be the same for all cases. Therefore, the method described by Garini et al. [1] can be used to determine the soil amplification.

For the same earthquake, the Turkish seismic specification predicted soil magnification factors lower than the observed soil magnification factors. In this study, as the upper limit, soil magnification factors are calculated by dividing maximum values to minimum

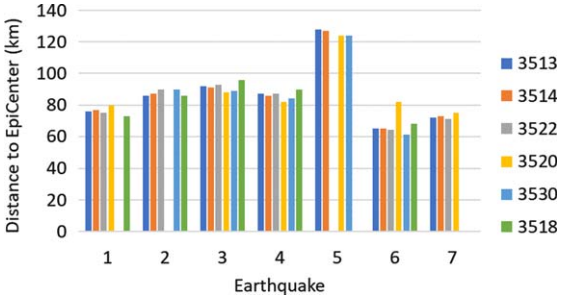

Fig. 5. Distance between Recordings and Epicenter.

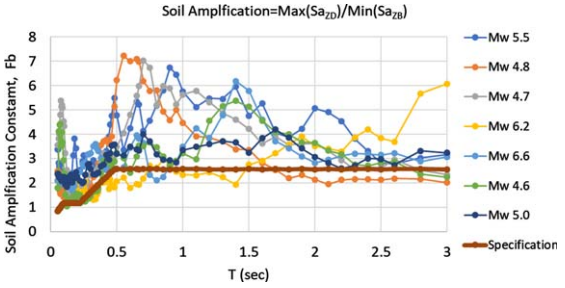

Fig. 6. Observed and Specification Based Soil Amplification Factors - Upper Limit.

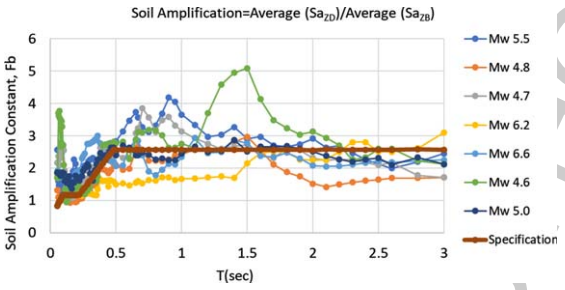

Fig. 7. Observed and Specification Based Soil Amplification Factors - Average Limit.

values for each earthquake record. As the lower limit, the ratio of the average values is used. Consequently, values obtained from specification based prediction formulas are exceeded, and revision for the earthquake response accelerational spectrum is needed as depicted in Figs. 6 and 7.

The revised spectrum is defined for the two conditions mentioned. As an upper limit design curve, average of maximum Sa values of the earthquakes are used. As an lower limit design curve, sum of standard deviation and average Sa values are utilized. For both conditions, revised response spectrum values are above the current design curves as shown in Figs. 8 and 9.

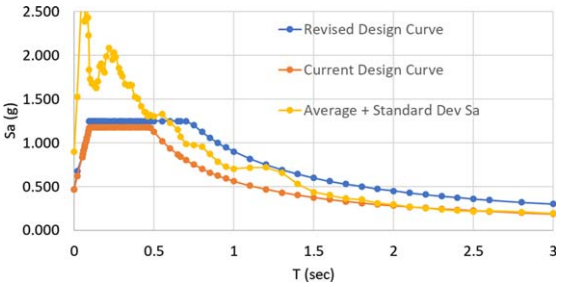

Fig. 8. Revised Design Curve - Based on Average + Deviation of Sa.

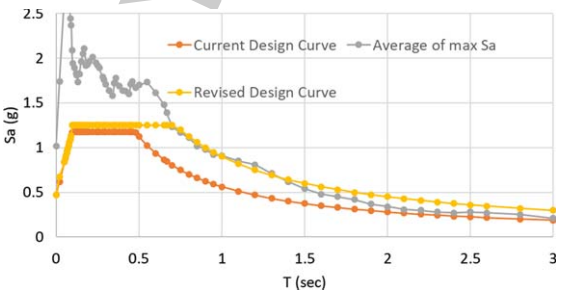

Fig. 9. Revised Design Curve – Based on average of max Sa.

4. Case study

The twin bridges have been analyzed for the recorded ground motion in close vicinity of the bridge. The reported gap between the twin bridges shown in Fig. 1 is about 20 mm. The total length of the 32 span bridge is 566 meters. Each span is about 17.7 meters from one pier to other. The structural analysis model has been developed to account for the potential pounding at the gap as shown in Fig. 10. The pile foundations believe to provide full fixity at the bottom of the columns.

Pounding is a complicated structural phenomenon that includes various uncertanities. Pounding might be caused structural damages such as plastic deformations and local crucks at contact region. There are two approches for pounding modelling which are stereomechanical approach and contact element approach [10]. In this study, to consider non-linear effects and to obtain more realistic results, contact element approach is used for pounding model. Therefore, pounding effect is represented by a non-linear gap spring in the model. The spring element develop compression forces only if the gap between two structures are closed. Otherwise, the element will carry no force between structures from each others.

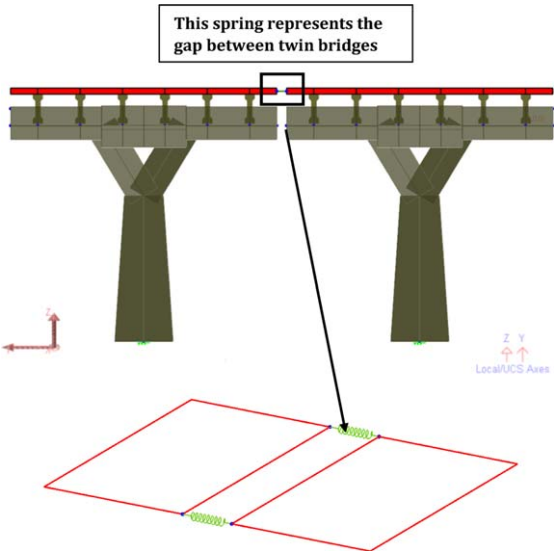

Fig. 10. Pounding component of the model.

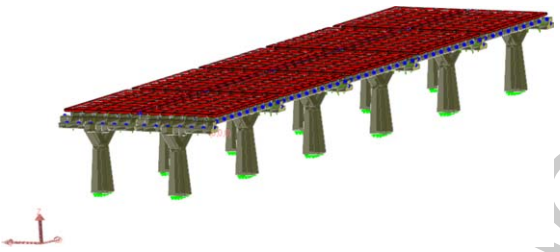

Fig. 11. 3D view of the bridge model.

Table 2
Model parameters

Deck length	16.6	m
Deck width	11	m
Slab thickness	0.25	m
Gap at deck level	0.4	m
Gap at sidewalk level	0.02	m
Bearing stiffness, k_x	2000	kN/m
Bearing stiffness, k_y	1.0E+06	kN/m
Bearing stiffness, k_z	1.0E+06	kN/m
Concrete grade	C25	

To examine pounding effect, two adjacent bridges that is called twin bridges are modelled according to Caltrans Seismic Seismic Design Criteria with LARSA 4D Software. These concrete bridges modelled with 5 spans, T-shape beams and Y-shape columns as shown in Fig. 11. The outer spans are modeled just to have the proper boundary conditions for the inner three spans. Some of the model input is given in Table 2.

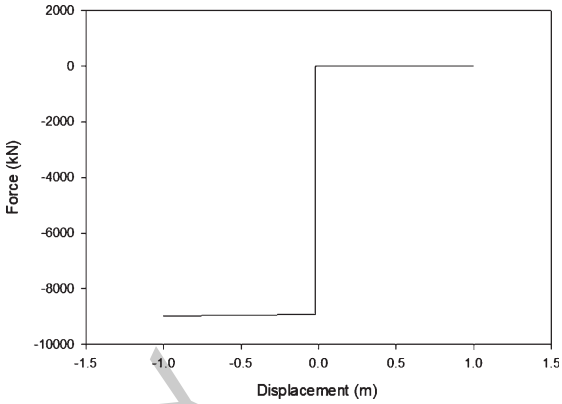

Fig. 12. Displacement-Force graph for pounding spring, gap = 2 cm.

As mentioned above, to represent the pounding effect nonlinear spring is defined in the finite element model of the twin bridges. The springs are placed at every 2 meters along the deck. The spring compression force is limited to the design compression strength of the concrete and the springs can not take any tension. The compression resistance will only be activated if the 20 mm gap will be closed.

The non-linear time history analysis is performed for the 2020 Izmir Earthquake magnitude 6.6 on soil type ZD. These records is obtained from AFAD web site (https://tadas.afad.gov.tr/) for the nearest station, named 3513. Properties of this selected ground motion are given in Fig. 13.

As illustrated in the below Fig. 14, displacements graphs, there is almost no relative deck displacement both in transverse and longitudinal directions. Therefore, the gap between structures is not closed. It means that pounding is not observed.

Maximum moment and force values are given in the following Fig. 15. These moment and force values are less than the column capacities. Also note that no flexural cracking or plastic hinging has been observed at the columns during the post seismic inspection of the bridges.

The seismic analysis of bridge with observed motions show no damage similar to observations at the post earthquake inspections. Also, note that the AASHTO-LRFD specifications allows such seismic analysis with predicted site specific ground motions to account for uncertainties in standard seismic design such as observed in Izmir. The design seismic curves for the Izmir region needs to be updated in the future based on the new findings.

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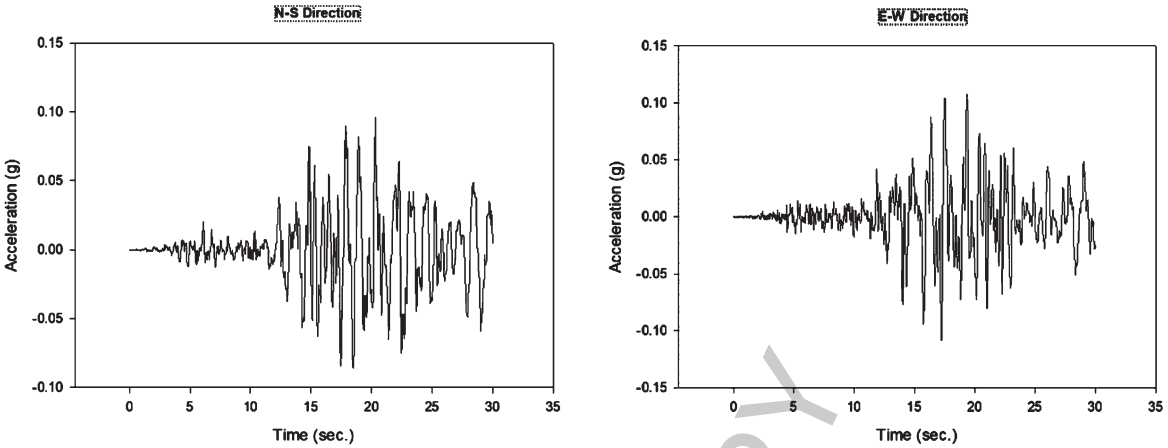

Fig. 13. E-W and N-S componets of the recorded ground motion.

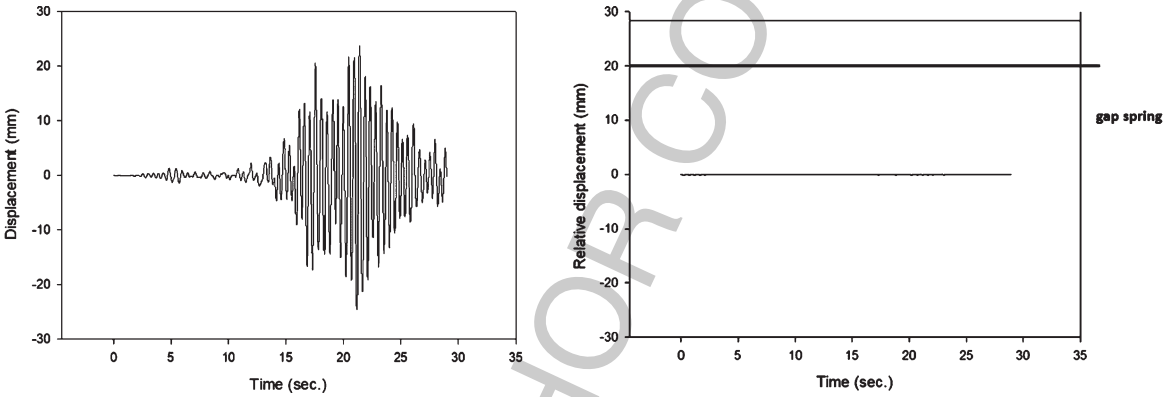

Fig. 14. Transverse gap never closed.

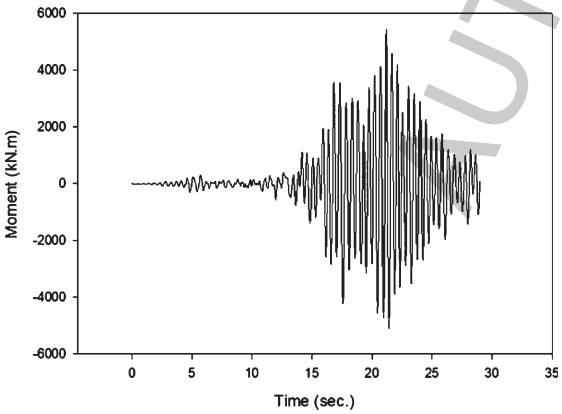

Fig. 15. Member moment (z direction).

5. Conclusions

The unexpected soil amplification has tremendously shaken the Izmir city resulting in many destructions for the building structures. As happened in the past earthquakes almost no seismic damage was observed and the bridges were open to traffic just after the earthquake. The following conclusions can be drawn from this study.

- A revised seismic design curve is needed and the curve can be established based on the comparison of soft soil response to rock soil response as shown in this study.
- The pounding of twin bridges have not been observed at the site and analysis of the bridges have shown that the structures with identical vibration characteristics did not result in pounding and the structures vibrated in a very synchronized way.
- One of the main reason bridges do not get much damage in Turkey is based on the design philosophy that allows some movement between the substructure and the superstructure.

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