International Conference on Case Histories in Geotechnical Engineering

(2004) - Fifth International Conference on Case Histories in Geotechnical Engineering

17 Apr 2004, 10:30am - 12:30pm

Near Source Effects and Engineering Implications of Recent Earthquakes in Turkey

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Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

NEAR SOURCE EFFECTS AND ENGINEERING IMPLICATIONS OF RECENT EARTHQUAKES IN TURKEY

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ABSTRACT

The variation of both structural and geotechnical consequences of near-source effects are shown for densely populated environments, Kocaeli and Düzce (Turkey), situated on an alluvial fan at the western part of the 1500 km long North Anatolian fault (NAF) that resembles the San Andreas fault in California with its right-lateral and strike slip faulting mechanism as well as remarkably similar length and capability of generating damaging earthquakes. Recordings from two recent destructive earthquakes occurred in 1999 on the NAF suggest that near-source impulse type ground motions may generate large input energy demands that have to be dissipated with few large displacement excursions. The discussion is therefore focused on the seismic wave propagation mechanism related to the unexpected damages at the near-field sites. The observation results proved the high intensity velocity at the damage suffering areas due to the soil layer resonance and, furthermore, due to the "bump effect" by wave interferences traveling vertically and horizontally. While there are potentially other factors contributing to damage (such as topographic and basin effects, liquefaction, ground failure, or structural deficiencies), the amplification of ground motion due to local site conditions plays an important role in exacerbating the seismic damages in disaster belt area. The field observations regarding this phenomenon supplemented with the near-field strong motion interpretations are presented, and significance of local soil effects in the near-field region is assessed in the course of this study.

INTRODUCTION

In 1999, Turkey was struck by two major earthquakes, which occurred 86 days apart on the 1500 km long North Anatolian Fault (NAF) that is a close analogue of the San Andreas Fault in California in terms of many of its features. The first event (17 August 1999, Kocaeli earthquake) hit the most densely populated urban environments, namely Kocaeli and Sakarya provinces, situated on an alluvial fan at the western part of the NAF with magnitude (M_W) 7.4. The second M_W 7.2 event (12 November 1999, Düzce earthquake) destroyed the city of Düzce that had the misfortune of experiencing the strong shaking of the former event as well. The Kocaeli earthquake was the largest on record to hit a modern, industrialized and highly populated area since 1906 San Francisco and 1923 Tokyo earthquakes (Sari and Manuel, 2000). The strongly shaken area is home to more than 15 million people and about 40 percent of Turkish industry.

These two earthquakes are first widely recorded and well studied NAF events. They provided the most extensive strong ground motion data set ever recorded in Turkey within about 170 km of the surface fault rupture. The first event generated 34 ground motion recordings associated with a 130 km surface rupture involving four distinct fault segments on the northernmost strand of the western extension of the NAF. The second event triggered 20 instruments and caused 35 km of surface rupture on the eastern extension of the former event. In total, these two earthquakes produced six near-field strong motion recordings within 20 km of the active faulting system adding considerably to the near-field strong motion database worldwide.

Kocaeli and Düzce events were the latest among successive westerly propagating earthquake sequence on the NAF which began with the magnitude 7.9 Erzincan earthquake in the eastern part of Turkey in 1939, and has generated ten destructive earthquakes having magnitudes greater than seven since this date. This earthquake sequence is illustrated in Fig. 1 with the dates of the events and extend of rupture they created. As inferred from this figure, occurrence of large magnitude earthquakes close to cities in Turkey is inevitable due to high seismic-rate of the NAF, and its crossing to the most densely populated environments. In fact, this earthquake sequence similar to the toppling of domino pieces has now arrived at the gates of the most densely populated and the industrialized heart of Turkey, namely the Istanbul metropolitan area. Likelihood of experiencing strong earthquakes on such a high profile area in the near future accentuates the need to understand the near-field strong motion characteristics of the NAF and its unexpected damages occurred during the Kocaeli and Düzce earthquakes. For that purpose, a critical examination of near-field records from these events has been accomplished herein by emphasizing the wave propagation effects of near-source ground motions. The primary findings are presented in this paper aiming at extending the concepts and results based on the supplemental information from post-earthquake field observations.

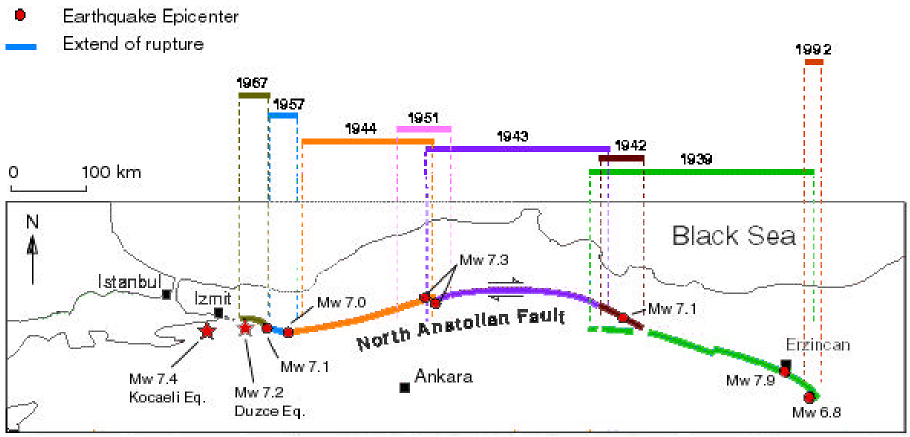

Fig.1. Successive earthquake sequence on the North Anatolian Fault since 1939 (modified from the USGS website, 1999)

NEAR-FIELD IMPULSE-TYPE GROUND MOTIONS

In the vicinity of an active fault system, the wave propagation pattern of ground motion is strongly affected by radiation pattern, directivity, rupture model, stress drop and also by stratigraphy, geo-morphology and lateral scatterers. At longer periods (T >1.0 sec), near-fault ground motions within the diameter of less than 15 km from fault rupture are exposed to high amplifying effects of the earthquake faulting mechanism and orientation of the site. Particularly, when the rupture propagates in forward direction toward the site, and the direction of slip on the fault is aligned with the site, ground motions oriented in this forward rupture directivity path may follow certain radiation patterns and generate long period pulses perpendicular to strike of the fault. Ground motions having such a distinct pulse-like characters (i.e., fling) arise in general at the beginning of the seismogram, and their effects tend to increase the long-period portion of the acceleration response spectrum (Galesorkhi and Gouchon, 2000). This type of ground motions may generate large energy demands that force the structures to dissipate such a high energy with few large displacement excursions. During such an instantaneous energy demand and release sequence, structures may experience large amplitude plastic cycles that may yield high levels of inter-story drift. In this condition, the risk of brittle failure for poorly detailed systems is seriously enhanced (Manfredi et al, 2000). The detrimental effects of such phenomenon have been recognized during several worldwide earthquakes including 1992 Erzincan, 1992 Landers, 1994 Northridge, 1995 Kobe and finally 1999 Kocaeli and Düzce earthquakes.

To clarify the phenomenological impacts of the above mentioned near-field effects, we revisited the near-field strong motion records measured during the recent earthquakes in Turkey. The evident near-source effects were observed from both the recordings and also from field observations of two events. These observations exemplified in the forthcomings suggest the strong influence of rupture directivity and strong velocity and displacement pulses (fling) in increasing the damage in the epicentral area. Locations of the near-field recording stations are shown in Fig. 2. The two stations closest to the fault rupture during the Kocaeli event are Sakarya (SKR, 3.2 km) and Yarimca (YPT, 3.3 km). Sakarya station is located on rock and the Yarimca station is founded on soft-soil. Of these the largest peak ground acceleration was about 0.4 g recorded at Sakarya station. On the other hand, the maximum peak ground accelerations recorded during the Düzce earthquake were much more than the first event and in the order of 0.8 g at Bolu station (BOL, 20.4 km) and 0.5 g at Düzce station (DZC, 8.2 km). Both of the recording stations are located on soft-soil sites (Gülkan and Kalkan, 2002). The peak ground accelerations recorded by the Sakarya and Yarimca stations are shown in Figs. 3 and 4, respectively. The peak accelerations from near-field records are not as high as expected. That serves as a reminder that these recent earthquakes in Turkey are in agreement with other significant major earthquakes, the 1985 Michoacan earthquake (M=8.1), the 1999 Chi-Chi earthquake (M=7.6), and the 2002 Denali earthquake (M=7.9) for generating considerably lower accelerations than expected. On the other hand, the peak velocities and corresponding peak displacements are more significant for the Kocaeli and Düzce events, and this has been confirmed by highly concentrated structural damage in the disaster belt area. The recorded peak accelerations and general characteristics of near-field recording stations during these events are listed in Table 1. Among the other near-field recordings Sakarya (SKR) and Yarimca (YPT) records exhibited remarkable strong velocity pulses and static offset along the EW direction in the order of 1.8 m and 1.0 m, respectively. As inferred from Figs. 3 and 4 the dominant pulse period is around 2-3 sec.

Generally, the peak value of the vertical component of motion may exceed those of the horizontal components in the vicinity of the active faulting systems (Ambraseys et al., 1996; Kalkan and Gülkan, 2003). Surprisingly only Düzce record during Kocaeli earthquake follow this general trend, and for the remaining five near-field records, vertical component of motion is remarkably less than that of horizontal. The values of V/H ratio are also marked on Fig. 2 for each recording station.

Besides the computed evidences of impulsive ground motion in the stations of Sakarya and Yarimca, its damaging site effects were clearly observed in Kaynasli (a small town 10 km east of

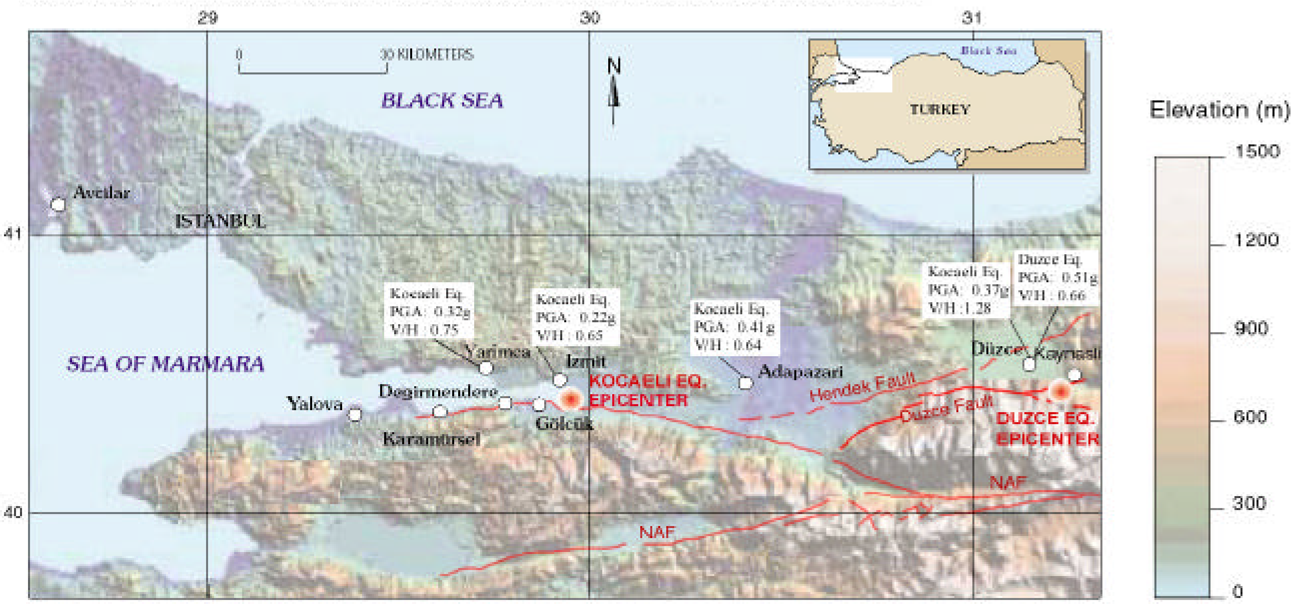

Fig.2. Locations of near-field strong ground motion stations during 1999 Kocaeli and Düzce earthquakes

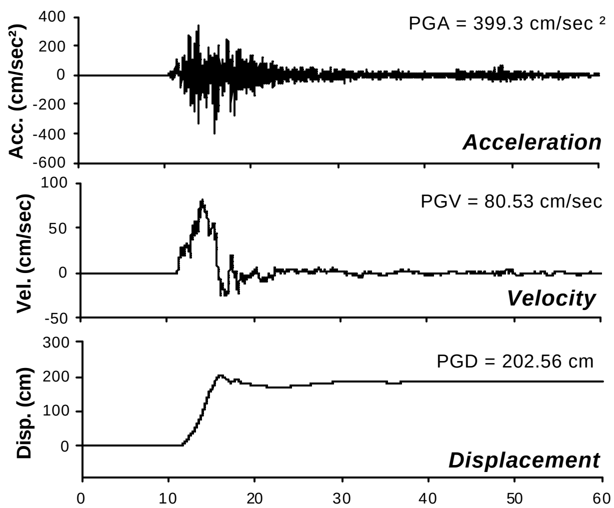

Fig.3. EW direction Sakarya station recordings during the Kocaeli earthquake

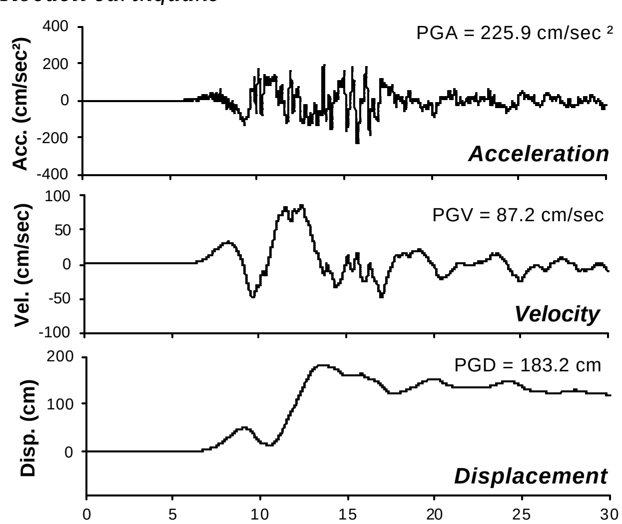

Fig.4. NS direction Yarimca station recordings during the Kocaeli earthquake

Table 1. Peak ground accelerations recorded during 1999 Kocaeli and Düzce events at strong ground motion stations

Event	M_w	r_d (km)	Recording Station		Site Soil Class	Peak Ground Acc. (g) NS	EW	Ver.
KOCAELI	7.4	11.0	DZC	Düzce: Meteoroloji Ist.	Soft Soil	0.315	0.374	0.480
KOCAELI	7.4	3.2	SKR	Sakarya: Bay. ve Iskan Müd.	Rock	N/A	0.407	0.259
KOCAELI	7.4	4.3	IZT	Izmit: Meteoroloji Ist.	Rock	0.171	0.225	0.146
KOCAELI	7.4	3.3	YPT	Yarimca: Petkim Tesisleri	Soft Soil	0.230	0.322	0.241
DÜZCE	7.2	20.4	BOL	Bolu: Bay. ve Iskan Müd.	Soft Soil	0.740	0.806	0.200
DÜZCE	7.2	8.2	DZC	Düzce: Meteoroloji Ist.	Soft Soil	0.408	0.514	0.340

Düzce), which is located in the immediate vicinity of the seismic source of the second event. This unfortunate town suffered high damage during the strong shaking of Düzce event. The damage distribution in Kaynasli is exhibited in Fig. 5. The bounded and marked areas in this figure demonstrate the concentration of damage based on the site-survey conducted by USC-GEES. Zones of high damage were marked as 4 and 5. This figure does not include all the details of the region but comprises a representative snapshot of the observed damage scatter.

High concentration of damage in Kaynasli region was mainly caused by detrimental effects of the surface fault rupture crossing the town. The surface fault rupture in Kaynasli ran parallel to the Highway-100 and went up the hill, and it is also clearly visible in Fig. 6. Also shown in this figure is the collapsing of many residential buildings due to surface fault traversing their foundations. That caused unrecoverable static displacements and consequently sudden failure of many buildings in Kaynasli. Damaging effects of faulting offset are also shown in Fig. 7 where the water pipe was highly deformed due to striking of the fault. In fact, none of the buildings in this area or even the one designed strictly to the Turkish Seismic Code (1998) could not recover such a destructive faulting offset passing through their foundations. Besides that, the strong near-fault effects exacerbated the damage in the central part of the city as exhibited in Fig. 8. The damaged area in this figure falls in the zone of four according to damage classification given in Fig. 5.

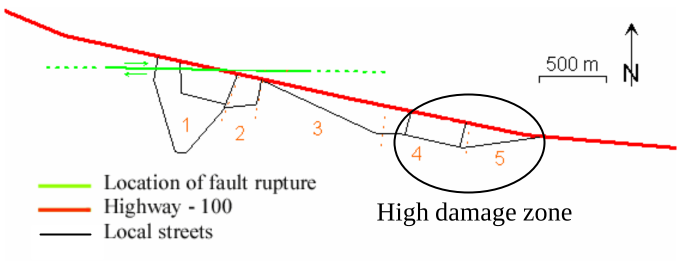

Fig.5. Map of Kaynasli and location of high damage zone (modified from the USC-GEES web-site)

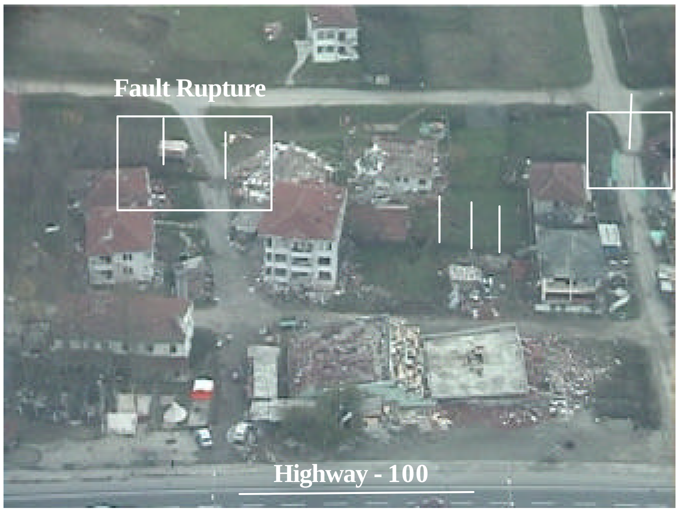

Fig.6. Collapsed and damaged residential buildings along Highway-100 due to fault surface rupture (modified from the USC-GEES web-site)

Fig.7. Highly deformed water pipe due to fault striking

Based on the observations in Kaynasli, it is our contention that the great part of the damage was due to a single large amplitude plastic excursion that can be prescribed as "bump effect" that generate instantaneous vertical and horizontal impulsive motions in the beginning of the accelerogram. This type of motion is particularly prevalent in the forward direction, where the fault rupture propagates towards a site at a velocity close to the shear-wave velocity (Alavi and Krawinkler, 2000). The radiation pattern of the shear dislocation of the fault causes the pulse to be mostly oriented normal to the fault-strike, causing the fault normal component of the motion more sever than the fault parallel component (Sommerville, 1998). Indeed, significant damage of bump effect generated due to fault normal component of motion in Kaynasli can also be witnessed in Figs. 8 and 9. In these figures, overturning of fully loaded trucks parked in the parallel direction to fault strike, and fling of several passenger cars parked in the normal direction of the fault serve as a clear evidence of the bump effect.

Fig.8. Heavily damaged central section of Kaynasli, (source: USC-GEES)

Fig.9. Strong near-field motion at filling station, Kaynasli, Düzce

Unfortunately, the observed evidence of strong pulse effects in disaster belt area (Figs. 8-9) has been veiled due to the lack of densely distributed strong motion transducers in Turkey. Thus, the rare opportunity was missed in understanding the clear mechanism of the directivity and consequently strong pulses (filing) that caused the bump effect from the computed accelerograms in the epicentral area. Nevertheless the synoptic picture that can be drawn from the visual observations suggests that near-field records with large peak acceleration and long-duration pulses may generate large and rapid displacement excursions. These effects are particularly detrimental to the performance of long-period structures. In fact, the near-field strong-motion records of Kocaeli and Düzce events display such long-period pulses that show the ground motion have frequency bands within the range of vibration period of the 4-5 story buildings that collapsed and/or severely damaged.

Fig.10. Powerful velocity fling in near field, Kaynasli, Düzce

It is also noteworthy that the resulting strong ground shaking during both events in the near-field regions due to large generated rapid displacement pulses are not represented in current regulatory Turkish Seismic Code (1998). As mentioned earlier, such effects tend to increase the long-period portion of the acceleration response spectrum. The 1997 Uniform Building Code (UBC) considers these effects by providing near-source factors N_a and N_v to modify code level spectra for distances less than 15 km from major faults. These factors amplify the average design spectra by about 30 to 60 percent for earthquakes with magnitude (M_W) 7.5 in the near-source region (0 to 15 km from fault rupture) in the normal direction. That suggests the introducing of such representative amplification factors of near-field effects into the future revision of the Turkish Seismic Code (1998).

GEOLOGICAL FEATURES OF EARTHQUAKES

The majority of the damages during Kocaeli and Düzce earthquakes were also directly related the amplification of ground motion due to local site conditions. The peak ground accelerations in the basin were amplified compared to that recorded at stiff soil sites. As such, the ground motion recorded at Düzce and Yarimca on soft-soil sites have significantly higher intensities than rock motions recorded at Izmit station during the Kocaeli earthquake, as compared in Table 1. Notably, Sakarya station gave exceptionally higher peak ground acceleration though it is located on hill side in Adapazari where damage was low. Whereas enormous structural damage was occurred at the center of Adapazari located over lake bed sediments containing layers of liquefiable silts and sands.

The amplification of motion due to softer layered media and basin effects caused substantial geotechnical hazards in the form of liquefaction, lateral spreading, bearing capacity loss, landslide and subsidence along both coastal regions as well as inlands. Particularly liquefaction ground motion weakened soils beneath reinforced mat foundations. That caused many buildings settled, tipped or toppled (Fig.11). More than 60 percent of multistory buildings in the severe liquefaction areas suffered partial or total collapse due to liquefaction induced foundation failure.

Fig.11. Liquefaction induced foundation failure in Adapazari during the Kocaeli earthquake

NEAR-FIELD EFFECTS ON HIGHWAY STRUCTURES

Several highway bridges and freeway viaducts also suffered damage during recent earthquakes due to faulting rupture passing beneath or close to their foundations. As such, the Bolu viaduct located at Kaynasli was crossed by fault rupture during the Düzce event (Fig.12), and that caused significant geotechnical and structural complications. This viaduct is the longest (2.5 km in length) in Turkey, and composed of a pair of independent sixty parallel decks (each has 40 m long and 17.5m width). The fault traversing caused 1.5 m relative displacement of adjacent piers due to high right-lateral permanent deformations in their foundations. Although the bridge deck was equipped by seismic dampers mounted between pier caps and end of the diaphragms of the deck, they were completely damaged during the main shock of the Düzce event. This high damage on the viaduct caused significant and costly repairs.

Another example of significant damage induced by fault traversing was observed at Arifiye overpass. The fault-offset and insufficient seating length on the piers caused total collapsed of this four-span bridge onto the Trans European Motorway (TEM) (Fig.13). The approach fill of this bridge reinforced with a double-faced mechanically stabilized earth wall (MSEW) system was lightly damaged. The wall system provided a unique case history under extreme loading conditions as such they show significant flexibility that they can withstand large ground deformations without losing their structural integrity. The details of near-field effects on the performance of MSEW system of the Arifiye Bridge is discussed in elsewhere (Pamuk et al., 2004).

Fig.12. Piers of Trans-European-Motorway (TEM) traversed by surface fault rupture, Kaynasli, Düzce

Fig.13. Unseating of bridge decks from piers of the Arifiye Bridge traversed by surface fault

CONCLUSIONS

Near-fault ground motions are strongly influenced by the earthquake faulting mechanism exhibiting distinct long-period pulses with amplitudes depending on the orientation of the site with respect to the rupture direction. The recent earthquakes in Turkey once again emphasize the significant effects of rupture directivity and strong velocity pulses (fling) on the observed damage in the near-source regions. Our major limitation of building a bridge between the observed damage conditions and field evidences and recorded near-field strong ground motions is the low number of recordings in the near-fault region and their sparsity. Nevertheless, to augment understanding of near-fault seismic site effects, this paper reports the findings based on the post-earthquake observations to emphasize the unexpected damage patterns due to the bump effect and also fault–offset. Still, further researches are necessitated for our comprehensive understanding of the phenomenon and for an accurate quantification of their detrimental effects on structures.

ACKNOWLEDGEMENTS

The authors appreciate the generous support of Prof. Polat Gülkan in the Disaster Management Research Center at Middle East Technical University (METU/DMC).

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