Structural and Geotechnical Impacts of Surface Rupture on Highway Structures

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Abstract—**The most dramatic and significant damages on highway bridges during the recent earthquakes in Turkey (Mw 7.4 Kocaeli and Mw 7.2 Duzce earthquakes) and Taiwan (Mw 7.6 Chi-Chi earthquake) were the result of the fault rupture traversing the bridge span that devastated many of such transportation structures. The veiling of this phenomenon during the design of highway bridges and its unfortunate consequences accentuated the need to examine the surface rupture hazard, identify possible risk of failures and present remedial actions from both structural and geotechnical engineering stand points. Towards that purpose, damage conditions of highway bridges during these events were overviewed in general, and a totally collapsed highway overpass located in Arifiye during the Kocaeli earthquake was investigated in details. The major problem under consideration is twofold: first, dislodging of bridge span, and consequently, total separation of the reinforced concrete (RC) girders from their decks, that phenomenon necessitates the revision in the design of girder and deck connections. Second, the stability problems of a mechanically stabilized earth wall (MSEW) system under extreme loading conditions. The results of the structural and geotechnical investigations presented herein are considered to be an essential step regarding the maintenance and improvement of the bridges of concern against surface rupture hazard.**

Keywords—**Highway bridge, Kocaeli earthquake, Arifiye bridge, reinforced earth wall, surface rupture, near-field effect**

INTRODUCTION

Revolutionary developments have taken place over past fifty years in the design and construction of transportation facilities against seismic hazards. However, earthquakes occurred in 1999 in Turkey (Mw 7.4 Kocaeli and Mw 7.2 Duzce earthquakes) and Taiwan (Mw 7.6 Chi-Chi earthquake) are a breakthrough in a way that they revealed the detrimental consequences of near-field site effects, particularly surface fault rupture hazard on transportation structures. Several bridges and freeway viaducts incurred significant damages due to fault rupture passing beneath or close to their foundations, although they were designed and constructed under modern seismic provisions and codes. The veiling of this phenomenon in current design standards and practical engineering applications are the motivations to identify the reasons of damage and also the risk of failures from both structural and geotechnical standpoints, and finally, present practical retrofitting solutions against surface rupture hazards. For that purpose, a totally collapsed highway overpass bridge in Arifiye, Turkey, was investigated in detail, while similar damage patterns observed from other highway bridges that experienced the strong shaking of Kocaeli and Duzce earthquakes in Turkey were examined in general. The selection of the Arifiye Overpass is due to the observed problem that is twofold: the first aspect of the problem is related to its typical structural damage that was considered in reference to shear-key and bearing design, load paths, column-to-cap connections, and effects of near-fault ground motion. The second aspect of the problem is associated with the geotechnical damage condition of the bridge, particularly its mechanically stabilized earth-wall (MSEW) system. It is also noteworthy that such MSEW system is the first one ever subjected to a substantial near-field ground motion and tectonic deformations. For that reason the Arifiye Overpass not only serves as a typical case in terms of its structural damage but also serves as a unique case in terms of its geotechnical damage condition.

1999 KOCAELI, DUZCE AND CHI-CHI EARTHQUAKES

In 1999, Turkey was struck by two major earthquakes, which occurred 86 days apart on the 1500 km-long North Anatolian Fault (NAF). 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. Both earthquakes had right lateral strike-slip movements. During the Kocaeli earthquake most of the highway damage was concentrated in the section of the Trans European Motorway (TEM), where the road was parallel to fault rupture at a distance of less than 3 km and in some parts it was crossed by fault, and the surface rupture was clearly observed. After the strong shaking of Kocaeli event, one of the TEM overpass (Arifiye Overpass) collapsed, and one viaduct (Mustafa Inan Viaduct, Fig. 10) sustained the dislodging of its girders, and failure of shear keys and damage of elastomeric bearings were observed in the Sakarya

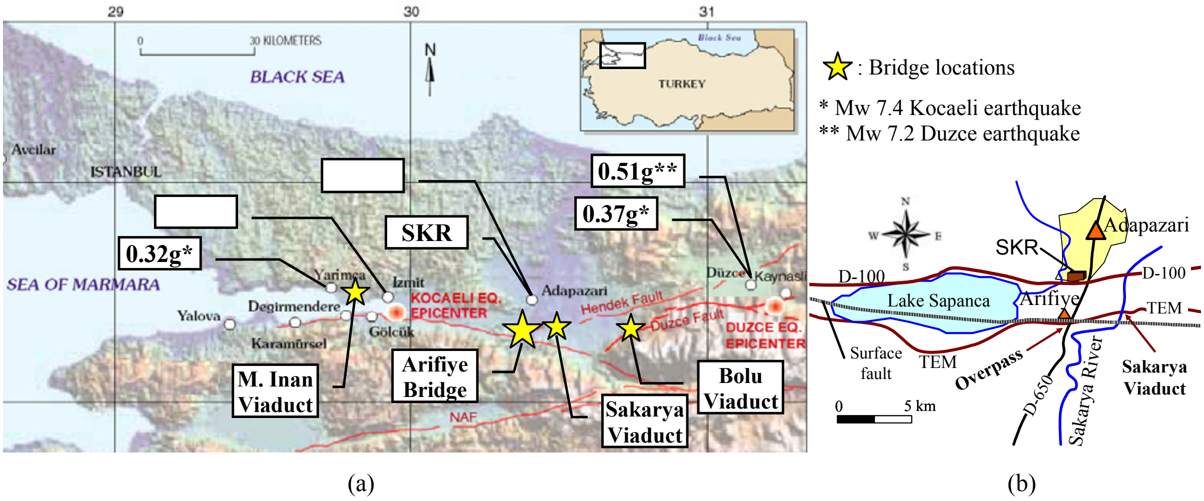


Fig. 1: (a) Locations of damaged highway bridges and recorded PGA at the nearest stations during 1999 Kocaeli and Duzce earthquakes, (map adopted from [1]); (b) detailed map of Arifiye bridge overpass and TEM.

Viaduct (Fig. 7a). The location of these bridges on the TEM and the recorded PGA at their nearest strong motion recording stations were shown in Fig. 1. Near-fault effects and surface fault rupture were the primary reasons of their damages.

On September 21, 1999, another strong earthquake (Mw 7.6 Chi-Chi earthquake) hit the central part of Taiwan. The earthquake was induced by a thrust fault (Che-Long-pu) and damaged at least nine bridges including three which were under construction [2]. Fault rupture hazard caused the most extensive damage and detrimentally affected two bridges and a modern cable-stayed bridge [3]. These earthquakes serve as a reminder for the surface fault rupture and its unfortunate consequences.

BRIDGE OVERPASS IN ARIFIYE

The Arifiye Overpass was a four-span, 104m long simply supported prestressed concrete bridge located on the TEM close to city of Adapazari, Turkey (Fig. 1). The bridge was built in the late 1980s in accordance with AASHTO Standard Specifications for Highway Bridges [4]. This bridge is a typical overpass on the TEM as shown in Fig.2. Its two center spans overpassed the TEM and each side span on both sides overpassed a local service road. The bridge had a skewed configuration with a skew angle of about 60°. It was supported by three RC wall type piers and two end-abutments (Fig.3). The piers were 1m thick and 14m wide in longitudinal and transverse directions, respectively. The RC footings supporting piers were 5.3m wide and 14.4 m long. Each footing was supported by eight 1m diameter cast-in-place RC piles (each has twelve 20mm in diameter plain bars) extending 40~50 m below the ground surface. Fig. 3b shows northern abutment supported by 16 cast-in-place RC piles (D=1.2m) extending to 48-50m below the ground surface.

Following to construction of the overpass bridge, the 10m high bridge approach fill with a double faced MSEW system was constructed adjacent to the Northern bridge abutment (Fig. 2). The deck of the bridge constituted five precast and prestressed concrete U-beams supported by five elastomeric bearings (300mm x 300mm in length and 100mm in height). Details of the deck girders and piers are exhibited in Fig. 3.

NEAR-FAULT GROUND MOTION AT BRIDGE SITE AND STRUCTURAL DAMAGE

The bridge overpass at Arifiye is located less than 50km of the Kocaeli earthquake epicenter. The closest recording station to the bridge was Sakarya station (SKR), located between downtown Adapazari and Arifiye, about 4 km northward from the bridge site and 3 km from the nearest fault rupture (Fig. 1). The largest peak horizontal ground acceleration of about 0.4g (EW direction), and peak vertical ground acceleration of 0.26g were recorded at this station during the main shock of the Kocaeli earthquake. The EW direction acceleration and its computed velocity and displacement time-histories are presented in Fig. 4 (NS component of motion could not be recorded due to the malfunction of the transducer). This record exhibits typically near-field characteristics with a displacement offset in the fault parallel direction. This is characterized by strong velocity and displacement pulses of relatively long periods [5].

Notably, Sakarya (SKR) station was founded on a stiff soil site. Based on the site measurements, shear-wave velocity of 400 m/sec was reported for this station [6]. On the other hand, the Arifiye Overpass was located on soft soil site based on the SPT results as presented in the forthcoming. Therefore, one may expect that the actual

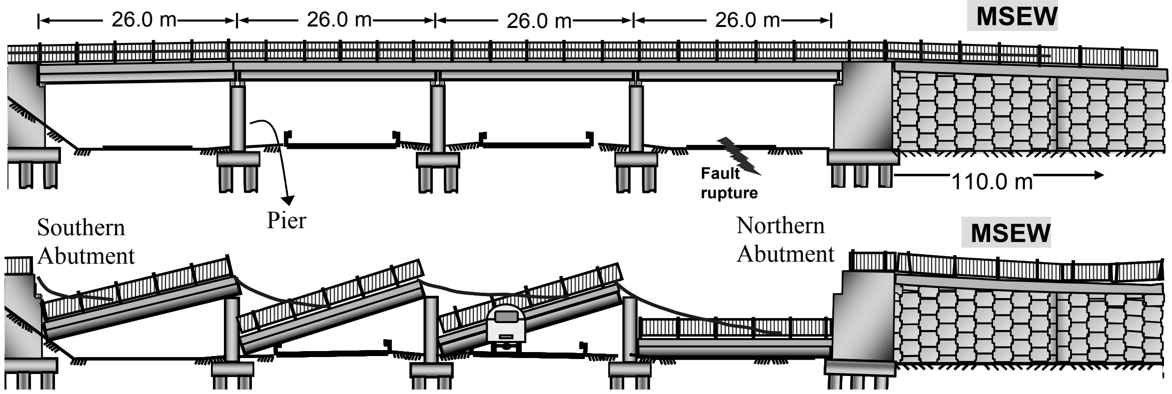
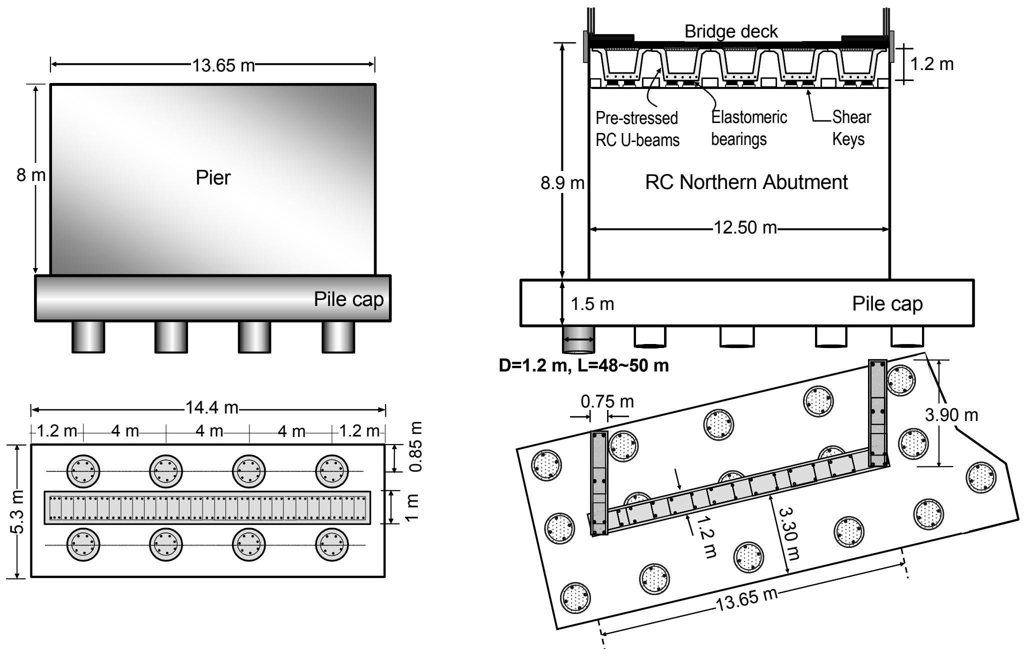


Fig. 2: The bridge overpass in Arifiye and mechanical stabilized bridge approach fill walls before and after the Kocaeli earthquake.



(a) Detailing of bridge pier and pile foundation (b) Detailing of northern bridge abutment and deck, and its girders

Fig. 3: Structural details of the bridge overpass in Arifiye, units are in meter.

accelerations at this site would be even higher than what was measured at SKR due to site amplification effects. Nevertheless, no structural collapse or serious damage was observed on the neighboring residential units (at both sides of the surface fault) in the vicinity of the Arifiye Overpass [7]. On the other hand, the structural damage gradually increased northward where it became most destructive in the center of Adapazari (Fig. 1) located on a soft soil site. Due to this paradigm and sparsely located strong motion transducers in the epicenter area, it is not possible to draw accurately the isoseismic map of peak ground acceleration at Arifiye region. Rather than PGA at the site of interest, the surface fault rupture passed beneath the northernmost span of the overpass, while originating substantial surface deformations with its associated strong near-field effects caused unseating of the bridge girders and their collapse as well as damage to MSEW of the reinforced approach fill.

It was observed that the major damage to MSEW system was not due to its seismic design, yet a combination of adverse effects by the nearby fault movement and possibly bearing capacity problems associated with underlying foundation soil. Figs. 2, 5, and 6 show the overpass and the reinforced walls before and after the shaking. Regarding this, the collapse of Arifiye Overpass may reveal the following deficiencies that may also valid for the other bridges that suffered surface fault rupture hazard during the recent earthquakes. The fault traversing at Arifiye caused 1.40m of displacement of adjacent piers due to high right-lateral permanent

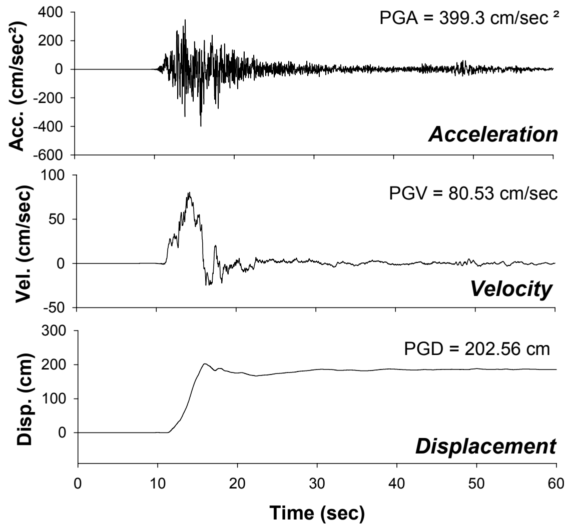


Fig. 4: Sakarya station recordings (EW direction) during the Mw 7.4 Kocaeli earthquake.

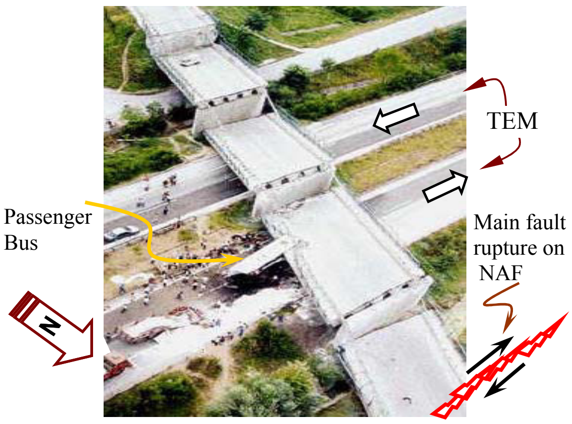


Fig. 5: Aerial view of the Arifiye Overpass, after [8].

deformations in the longitudinal direction that was more than the available seating length of deck girders 0.60m. In addition, tilting of bridge piers located in the north direction and close to surface rupture (Fig. 5) exacerbated the dislodging of girders from their elastomeric bearing supports. Insufficient seating length of deck girders and elastomeric bearings, as well as dysfunctional shear keys (Fig. 7b) triggered the total collapse of the bridge span.

In general, surface fault rupturing may cause an instantaneous energy demand and result in strong velocity and displacement pulses that force the structures (in the immediate vicinity of the rupture) to release such an energy with few cycles of plastic displacement excursions [5]. Particularly long period structures such as bridges are most vulnerable to these effects. The observed damage of the Arifiye Overpass, especially unseating of girders, conveys this conclusion, and emphasizes the detrimental consequences of near-source site effects typically

Fig. 6: Unseating of bridge deck from piers of the Arifiye Overpass traversed by surface fault during Kocaeli earthquake.

observed in several places during the recent earthquakes. The observed damages in other TEM bridges also showed that shear keys for purpose of restraining the transverse movement of these bridge girders were not designed and detailed or constructed properly. Therefore the fault tectonic movement could not be tolerated by their superstructures. In fact, if the shear keys were able to provide tolerable lateral restraining to those TEM bridges and overpasses, much of the associated damage could have been eliminated. For that reason, the capacity of shear keys should be in consistent with other superstructure components.

The collapse of Arifiye Overpass further indicated that the bridges with skewed geometry are more vulnerable to support failure as well as bearing damages. For such structures, extended seating width will be a reasonable solution to avoid deck failures particularly if the fault rupture has the potential to cross the bridge span. Many bridges along the TEM, especially those located close to the Istanbul Metropolitan Area, are prone to threat of the North Anatolian Fault (NAF) and consequent surface rupture and near-field hazard. Therefore, any

(a) Sakarya Viaduct [9] (b) Arifiye Overpass

Fig. 7: Bearing damages in elastomeric bearing supports and shear-keys during Kocaeli earthquake.

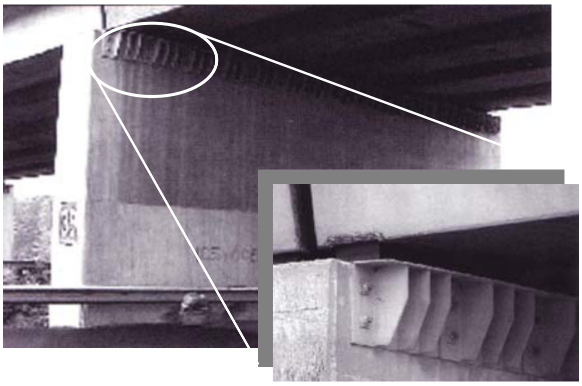


Fig. 8: Retrofitting by L-shaped steel profiles to increase seating length of bridge girders [10].

Fig. 9: Piers of Bolu Viaduct traversed by surface fault rupture during 1999 Duzce earthquake.

Fig. 10: Hinge joint restrainers at Mustafa Inan Viaduct [10].

anticipated strong earthquake in this area may replicate the observed damages at Arifiye on many other TEM transportation infrastructures. Particularly due to this reason the seating length of those bridges are being widened by mounting additional L-shaped steel profiles (Fig. 8), and their elastomeric bearings and shear keys are being redesigned and strengthened.

Another possible solution to prevent span failures might be the installation of cable restrainers across the deck joints. In fact, during Duzce earthquake the Bolu viaduct had the similar misfortune of surface rupture hazard crossing the bridge span. This viaduct is the longest (2.5km in length) in Turkey, and composed of a pair of independent sixty parallel decks (each has 40m long and 17.5m width). 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 Duzce event when the tectonic movement caused 1.50m of right lateral fault offset under the viaduct as shown in Fig. 9. However, at the expansion joints of its decks, cable restrainers prevented end girders from falling off from their supports [10]. Fig. 10 shows a typical hinge joint restrainer installed to prevent excessive longitudinal joint separation. In fact, such retrofit measurements were shown to be effective during the 1989 Loma Pieta earthquake [11].

GEOTECHNICAL DAMAGE AT ARIFIYE OVERPASS

The majority of damage at Arifiye Overpass from geotechnical stand points concentrated on its 100 m-long MSEW system. This wall system was built as a "double-faced" or "back-to-back" type wall having parallel reinforced concrete facings with ripped metallic reinforcing inclusions to accommodate a two-way divided roadway as shown in Fig. 11. A reinforced concrete culvert was designed beneath the approach ramp possibly to facilitate storm or flood water discharge in approach ramp area (Fig. 12b). Two slip joints (S1 and S2, Fig. 12) were also designed on each wall face on top of the rigid culvert to protect the walls damaged from differential

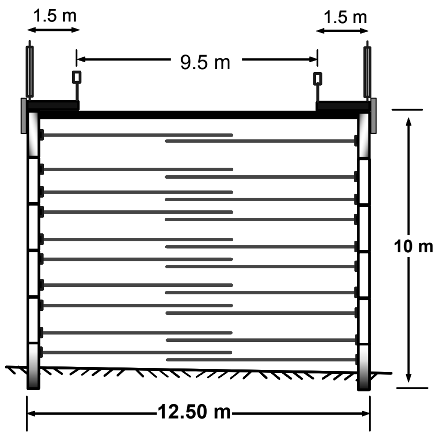


Fig 11: Schematics of the cross section of the reinforced wall system in Arifiye.

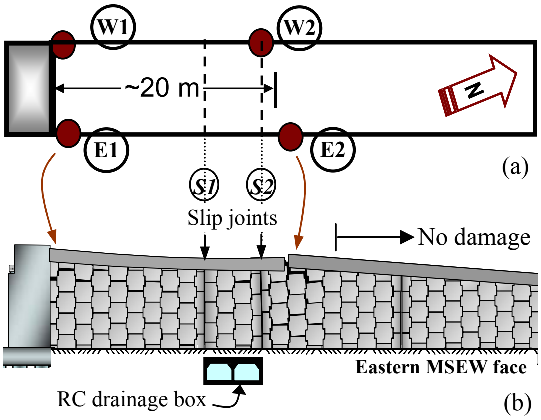


Fig. 12: Reinforced bridge approach (a) plan view of damage-concentrated locations; (b) schematics of eastern wall face after the earthquake.

settlement. Despite the fact that the construction site for MSEW system constituted undesirable alluvial subsoil layers that were prone to significant seismic hazards, no subsoil remediation were done. Accordingly, the MSEW approach ramp experienced large settlements during and after the construction. However, this did not cause substantial damage on the walls [12].

The entire Adapazari region (Fig. 1) is located in a large valley covered by alluvium deposits from a nearby lake and surrounding rivers. Soil deposition extends about 45km long east to west, and 30km long north to south with a varying thickness of more than 200m-deep [14]. The geology of the bridge site in Arifiye is dominated by Pliocene to Pleistocene sedimentary which lie at least 50 m below the younger sedimentary deposits [15]. Standard penetration tests were conducted by the Turkish General Directorate of Highways to gain sufficient subsurface information between both ends of the bridge overpass soon after the earthquake. The locations of the subsurface borings are depicted in Fig. 13. This figure also indicates the 2D visualization for the local subsoil conditions along the axis of the bridge overpass. The ground water table was approximately 5m below the ground surface. Boring No.1 indicates that very soft layers of soil deposits lie under the southern abutment and extend to a depth of 22m where a dense (N_{30}=100) layer of sedimentary deposit of silty sand with some gravel was encountered. The loose layers became thicker to the depth of 34m below the northern abutment where Boring No.2 was drilled. Boring No.2 was the nearest boring to the MSE walls and consisted of a 2.5m thick fill followed by varying thicknesses of silty sand and silty clay deposits. Loose silty sand and silty clay layers (N_{30}< 20) below the reinforced walls might have been prone to liquefaction or seismic-induced densification during the seismic event.

These field measurements obtained after the earthquake might reflect denser states of the soil layers than those prior to the earthquake. Field observations revealed that there were a number of factors that caused damage in the MSEW system in Arifiye. These are (i) large tectonic movements along the main fault line, (ii) presence of a drainage culvert, (iii) strong near-field shaking, and possibly, (iv) cyclic-induced soil densification and settlement. Only a limited section of the MSEW approach ramp was damaged to a great extent in between the bridge abutment and RC culvert as shown in Fig. 12. The most damage-affected locations within this section along the eastern and western wall faces are highlighted in Fig. 12a as E1 and E2, and W1 and W2, respectively, while their detailed views are presented in Figs. 14 and 15. Right-lateral strike-slip fault rupture along the main fault line passed under the northernmost span of the bridge (Figs. 2 and 5) with large transverse and vertical displacements of approximately 3.5m and 0.5m (e.g., [15], [16]), respectively. Among these, the vertical ground deformation appeared to be the main source of the damage state in the reinforced walls of the approach ramp. The deformation on the main fault rupture extended through the RC culvert under the reinforced ramp (Fig. 12). Cracks due to vertical deformation were clearly observed on asphalt-covered side roads, especially on the western side of the ramp (Fig. 15). It should also be pointed out that the final permanent ground deformation in this section may possibly include cyclic-induced settlement due to soil densification in addition to the subsidence from the fault rupture. However, the undamaged section of the wall did not exhibit any settlement due to earthquake shaking, indicating that the majority of the ground failure under the MSEW was from the nearby tectonic activity.

The greatest disturbance in the wall faces was concentrated at higher elevations above the culvert. Because the vertical displacement in the eastern wall face was larger than other side, the approach ramp tilted eastward in the cross section above the RC drainage box

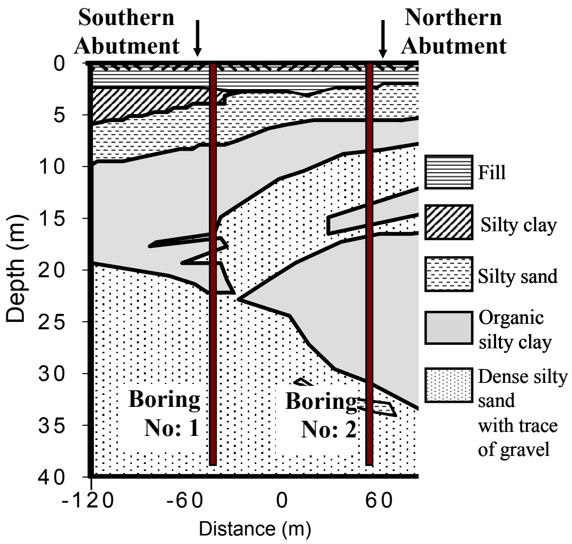


Fig. 13: Visualization of subsoil geology along the axis of Arifiye Overpass (modified based on[15]).

(a) (b)

Fig. 14: Damage details on eastern wall face (photos after Ozbakir).

(a) (b)

Fig. 15: Damage details on the western wall face (photos after Ozbakir).

culvert. This tilting was most probably due to the presence of the rigid culvert which prevented interaction between the ramp and its foundation soil; therefore, the walls could not uniformly accommodate the underlying fault-induced ground deformations and cyclic-induced soil densification. The tilting in the cross section resulted in different damage states above the culvert at E2 and W2 such that the western wall buckled in the vicinity of W2, whereas the eastern wall face were stretched outward (Figs. 15a and 14a). The buckled side increased compression on the facing panels at W2, while crashing and forcing the panels displaced at this locality. On the other hand, the largest damage in the reinforced walls was observed on the eastern side at E1. At this location, the wall displaced both vertically and horizontally for about 25-30cm. The displacements at this location were so large that they exceeded the allowable design limitations for an independent panel movement. Thus, the panels could not accommodate the ground deformations, and finally, large panel separations and cracks occurred. However, the facing panel connections with the metallic reinforcements did not fail, and their flexible joints allowed large displacements and differential settlements.

At E1 and W1 (Figs. 14b and 15b), the facing panels interacted with the pile supported bridge abutment. The damage states at both locations were also different. At E1, the vertical ground deformation was so large that the flexible wall face was forced to be displaced both vertically and longitudinally. However, the movement in the longitudinal direction was greatly prevented by the rigid abutment. This caused large panel separations and cracks at the higher levels, but no damage observed at lower wall elevations. At W1, the vertical ground deformation was not appreciably large as opposed to E1. On the other hand, a gap occurred between the panels and the abutment as shown in Fig. 15b. This gap appeared to result from the buckling in the same wall face as indicated in Fig. 15a. That is, the buckling pulled the western wall face longitudinally through W2 as a whole. However, this did not cause any damage in the facing panels between

W1 and W2, indicating that the reinforced wall system was highly flexible, and the large ground deformations were abruptly accommodated by the flexible joints of the facing panels during the earthquake.

CONCLUSIONS

The recent earthquakes in Turkey and Taiwan demonstrated severe damages of surface rupture hazard on transportation structures. The fault crossed the bridges resulting in large lateral forces in the piers. Overturning and failure of the piers triggered the collapse mechanism. The observed deficiencies in bridge structural systems suggest that the wall type piers should have enough seating place with stabilized elastomeric bearings to accommodate the possible large movements. Regarding that partial continuous spans and/or hinge joint restrainer may help to prevent catastrophic failure of bridge decks.

It was also observed that mechanically stabilized earth wall system was lightly damaged under high near-field effects. 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.

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