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Observed structural bridge damage report for the 2023 Turkey-Syria earthquake

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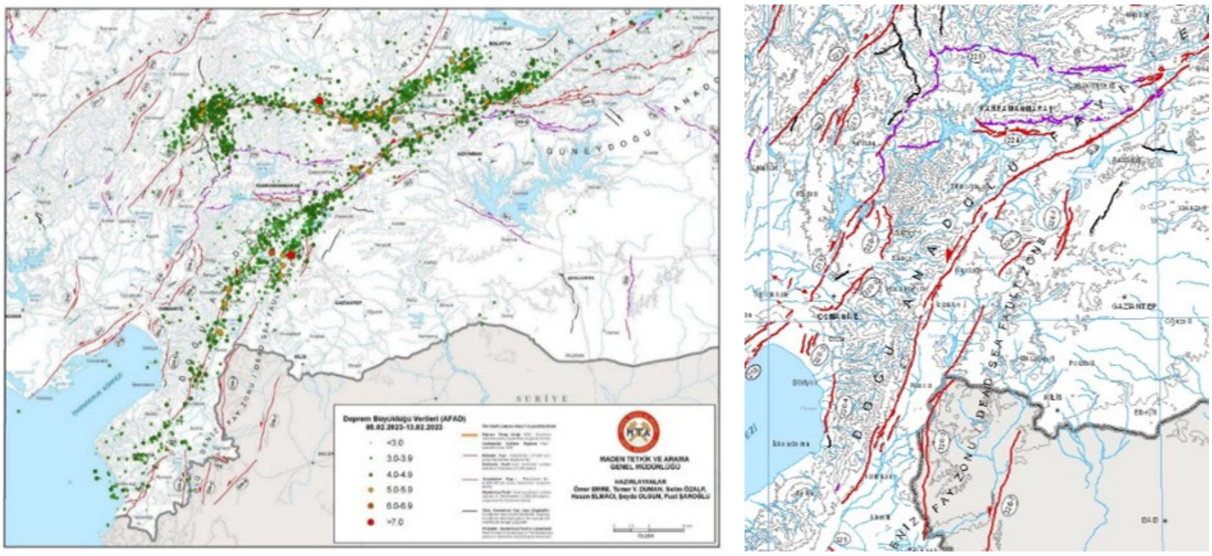
Abstract: On February 6, 2023, a series of seismic events, comprising two consequential earthquakes characterized by robust ground shaking, unfolded in the geographical expanse spanning southern Turkey and Western Syria. The repercussions of these seismic disturbances reverberated across a vast terrain, resulting in widespread devastation to both built structures and critical infrastructural networks. In the wake of these seismic events, the authors embarked on an investigative expedition to the affected region, more than three months after the occurrence of the seismic events. Through a meticulous examination and systematic elucidation of the facets above, this report aims to contribute valuable empirical knowledge to the scholarly discourse surrounding seismic vulnerability and resilience of critical infrastructure networks, particularly focusing on bridges, in regions affected by the events on February 6, 2023.

Key words: Bridge damage, Turkey-Syria Earthquake, Lifeline damage, Seismic performance

1. Outline of earthquakes and its damage investigation

On the 6th of February, 2023, an earthquake measuring Mw 7.8 on the Moment Magnitude Scale (Mw) struck the southern regions of Turkey (Türkiye) and Western Syria at 4:17 am TRT (Turkish Time) [1)]. This seismic event was succeeded by another earthquake of magnitude Mw 7.5 occurring approximately 9 hours later, at 1:24 pm TRT[2)], within the same general vicinity. The respective strike-slip fault rupture lengths associated with these earthquakes were measured at approximately 180 miles (290 km) [3)] and 99 miles (160 km)[4)]. As of the 20th of March, Turkey's Disaster and Emergency Management Presidency (AFAD) has reported a significant escalation in casualties resulting from the catastrophic seismic events of the 6th of February, with the death toll reaching 50,096 and the number of injuries amounting to 107,204[5)]. These seismic occurrences inflicted substantial direct physical damages estimated at $34.2 billion within Turkey, representing approximately 4% of the nation's GDP as of 2021[6)].

It is pertinent to acknowledge Turkey's geographical location within a seismically active zone, characterized by the presence of numerous active fault lines. Particularly notable among these fault systems is the North Anatolian Fault (NAF), renowned as one of the most significant and dynamic fault lines within Turkey as shown in Figure 1. While predominantly traversing the northern expanse of the country, the NAF also extends into the southern regions, contributing to the seismic activity observed in this area. The seismic events precipitated by the aforementioned earthquakes engendered pronounced tremors throughout the afflicted regions, eliciting the manifestation of surface earthquake faults. Furthermore, the phenomenon of liquefaction was documented as an observable consequence in coastal vicinities impacted by the seismic activity. Observational data gleaned from seismic monitoring apparatuses revealed the occurrence of maximum acceleration velocities surpassing 1 G (equivalent to 9.8 m/s^2) and maximum velocities exceeding 1 m/s proximate to the fault lines. These findings underscore the formidable intensity and dynamic nature of the seismic disturbances, illuminating the extent of their impact on the affected locales.



(a) (b)

Figure 1 Active fault maps: (a) Distribution of the epicenter and seismic intensity of the Turkey-Syria earthquakes. Locations of Pazarcık (Kahramanmaraş) and Elbistan (Kahramanmaraş) earthquakes and aftershocks on the Active Fault Map of Turkey[7]. (b) Active faults of the Southern part of Türkiye [8].

Figure 2 shows the location the epicenters, focal mechanism, and magnitude of the earthquakes. The North Anatolian Fault (NAF), a prominent geological feature within Turkey, extends longitudinally across the northern expanse of the country, with certain segments also traversing the southern regions. This fault line exhibits a parallel alignment with the northern coastline of the Sea of Marmara, thereby posing a substantial seismic hazard to the surrounding areas. Similarly, the East Anatolian Fault (EAF) emerges as another significant active fault within Turkey, spanning from the eastern territories near the Armenian border to the southeastern reaches of the nation. Although predominantly characterized by an east-west orientation, the fault's configuration encompasses certain segments that extend in a southerly direction. Moreover, the Dead Sea Fault (DSF), while not entirely confined within the borders of Turkey, constitutes a critical fault system extending from the Jordan Rift Valley to the Gulf of Aqaba. This geological feature impacts the southernmost regions of Turkey, notably including the Hatay province, and is associated with notable seismic activity, underscoring its pertinence in regional seismicity assessments. Further complicating the seismic landscape is the Karliova Triple Junction, situated in eastern Turkey, where the converging boundaries of the North Anatolian Fault, East Anatolian Fault, and the Armenian Plate intersect. This geologically intricate junction engenders a complex tectonic setting characterized by heightened seismic activity. The historical precedent of seismic events in these regions accentuates the recurrent vulnerability to earthquakes. For instance, the Kahramanmaraş Earthquake of 1975, registering a magnitude of 6.7, wrought widespread devastation upon Kahramanmaraş and its environs, resulting in significant loss of life and infrastructural damage. Similarly, the Gaziantep Earthquake of 1949, with an approximate magnitude of 5.7, inflicted extensive structural damage in Gaziantep, leading to casualties and injuries. Moreover, the city of

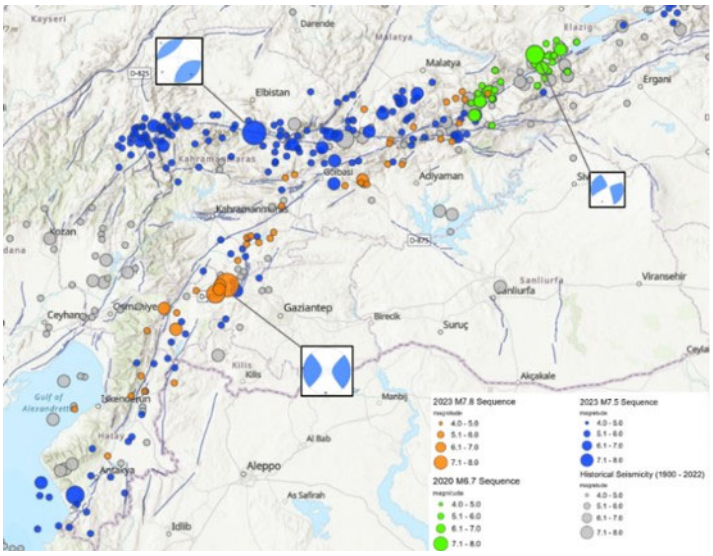


Figure 2 Distribution of the epicenter, focal mechanism, and magnitude of the earthquakes . (Modified and updated USGS Map)

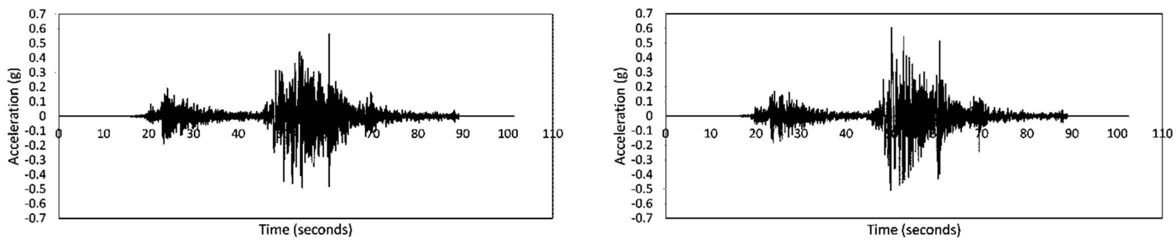
Antakya (Hatay) has experienced seismic turmoil throughout history, notably marked by the Antakya Earthquake of 1822, estimated at a magnitude of around 7.0, which exacted substantial destruction upon the city then known as Antioch. Additionally, the Antakya Earthquake of 1942, with an estimated magnitude of 6.3, precipitated severe structural damage and inflicted numerous casualties, further highlighting the recurrent vulnerability of these regions to seismic events of significant magnitude. Such historical seismic episodes serve as poignant reminders of the persistent seismic hazards inherent in these geologically dynamic regions.

A team of earthquake specialists arrived at the sites on May 11, 2023, which was more than three months after the first event. The search and rescue operation was completed way before removing the debris from the areas and construction and repairs were started in some areas and arrived at southern cities. It was a while after the earthquake occurred but still, the damages of civil structures can be visible most specifically the lifeline structures. During the limited three-day survey period, we visited the cities shown in Figure 3 and inspected a total of 11 bridges near the EAF. This report describes the damage to those bridges in three groups[9)].

Figure 3 Three locations where the damaged bridges were investigated.

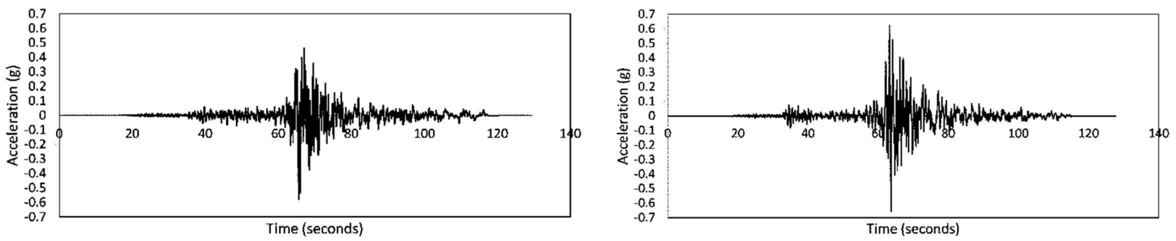
2. Seismic ground motion

Ground motions play a pivotal role in the structural integrity assessment and seismic performance evaluation of bridges. In this report, ground motions were meticulously measured at two distinct bridge sites: the Nurdagi and Antakya in Figure 4. The ground motion data were obtained from nearby strong motion stations, with Station 2712 and Station 3124 in Antakyas shown in Figure 4. The observed ground motions revealed significant insights into the seismic behavior of the bridges. Specifically, in the east-west (EW) and north-south (NS) horizontal directions, the Nurdagi viaduct exhibited peak ground accelerations (PGAs) of 0.607 g and 0.565 g, respectively, while the area in Antakya demonstrated PGAs of 0.66 g and 0.58 g in the same directions, respectively. Moreover, in the vertical direction, the PGAs were recorded as 0.35 g for the Nurdagi viaduct and 0.59 g for the Antakya. It is noteworthy that the measured horizontal accelerations at both locations closely approximated the maximum horizontal acceleration criterion of 0.7 g stipulated in California bridge design guidelines for seismic events of Mw 8.



NS EW

(a) Nurdagi viaduct, horizontal NS and EW direction (Strong motion station 2712, M_w 7.8 earthquake).



NS EW

(b) Antakya area, horizontal NS and EW direction (strong motion Station 3124, M_w 7.8 earthquake).

Figure 4 Strong ground motions recorded at two stations No.2712 and 3124 Mw 7.8.

3. Damage to viaducts at Nurdaği

(1) Case A: Highway multi span bridge in Nurdaği

Bridge damage in Nurdağı concentrated on the viaducts of Highway 52. The development of Highway 52 unfolded through a phased approach, with its inception traced back to the inauguration of the Adana-Ceyhan route on September 30, 1991. Subsequent stages included the opening of the Ceyhan-Osmaniye segment on February 12, 1993, followed by the Osmaniye-Gaziantep stretch in 1995. The final phase, spanning from Gaziantep to Şanlıurfa, was operationalized on December 31, 2009. This highway configuration comprises bidirectional lanes, encompassing six lanes in total, with three lanes allocated to each direction. Notably, direct connectivity to the Adana section of this extensive 365 km highway is facilitated, while the segment from Şanlıurfa to the Habur Border Gate incurs toll charges, with the region between Şanlıurfa west junction and Şanlıurfa east junction exempted from tolls.

Figure 5 shows a full view of the viaduct in Nurdağı on Highway 52. Four bridges named as Case A to Case D (from south to north) in this report are in a series. Case A pertains to the highway multispan bridge located in Nurdağı, Gaziantep, Turkey, featuring a superstructure comprised of prestressed girder and steel girder components supported by a variety of reinforced concrete (RC) columns. This bridge constitutes a crucial segment of Highway 52, which serves as a pivotal linkage connecting the cities of Adana, Osmaniye, Kahramanmaraş, Gaziantep, and Şanlıurfa. Notably, Case A represents the final segment of an extensive highway connection endeavor spanning from Edirne to Habur.

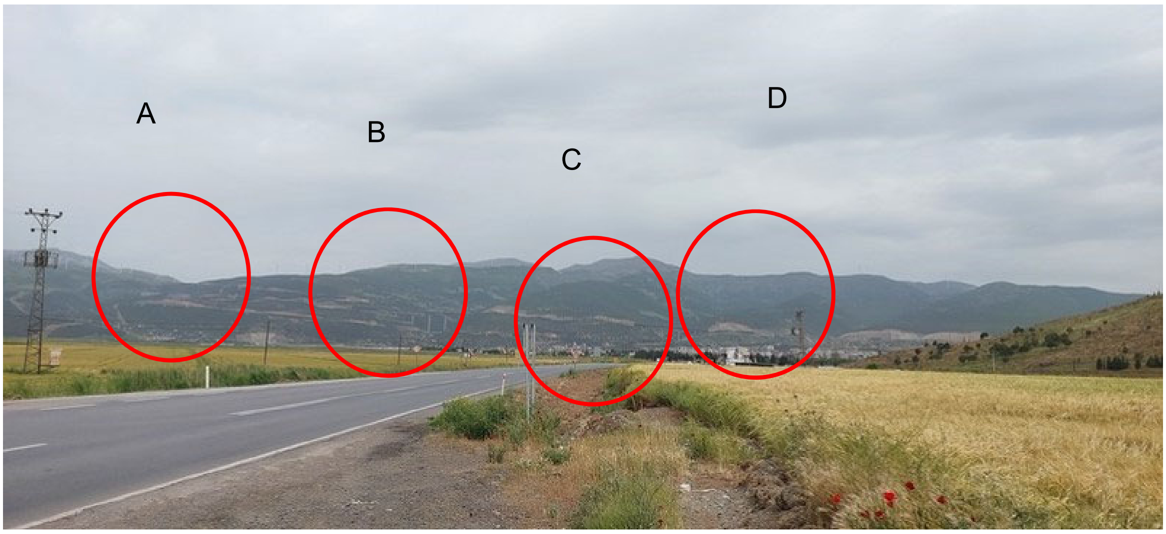


Figure 5 Highway 52 crosses the North side of the city of Nurdağı in multiple elevations.

The physical manifestation of Case A exhibits substantial infrastructure, characterized by large circular-shaped columns measuring approximately 3 m in diameter and towering to a height of around 24 m, complemented by sizable circle-shaped RC footings nestled within the mountainous terrain. The bridge configuration comprises a tandem arrangement of two curved, parallel five-span structures, supported by single column bents outfitted with RC columns and footings, alongside a composite ensemble of precast, prestressed concrete girders, base-isolated, and steel box girders shown in Figures 6, 7 and 8. A visual inspection reveals the presence of bearings atop the columns, suggesting a potential isolation system, albeit necessitating validation through bridge plans.

Despite sustaining damage, the bridge retained its structural integrity, a testament to the underlying design ethos calibrated to withstand seismic forces of significant magnitude. The emergence of plastic hinges within bridge columns signifies a pivotal response mechanism to mitigate structural damage during seismic events or under intense loading scenarios. These localized regions of plastic deformation serve to absorb energy and dissipate forces, thereby safeguarding the structural integrity of the entire bridge. Notably, while the formation of a plastic hinge in one column occurred as anticipated, its occurrence at a disparate location in another column raises pertinent inquiries regarding potential underlying causes.

(a) (b) (c)

Figure 6 Viaduct damage of Case A: (a) Base isolation system of the bridge, (b) Plastic hinge formation, (c) Confining effect of the spiral lateral reinforcement

(a) (b)

Figure 7 Plastic hinge formation and temporary repair of column and settlement and rotation of the column

(a) (b) (c)

Figure 8 Different views of plastic hinge formation

- Design Considerations: It is conceivable that the column's design stipulated the deliberate formation of a plastic hinge at a non-bottom location. This design rationale may be rooted in specific structural considerations aimed at accommodating anticipated load distributions, mitigating stress concentrations, or enhancing overall structural performance.
- Construction Error: The possibility of construction-related discrepancies cannot be discounted, whereby errors or deviations occurred during the implementation phase. Potential misalignments in the placement of reinforcing bars or other structural elements could inadvertently influence the formation of plastic hinges, leading to deviations from the intended design specifications. Construction errors may arise due to various factors, including misinterpretation of design documents, inadequate quality control measures, or human oversight during the construction process.
- Material or Load Variations: Variations in material properties or loading conditions may also contribute to the unexpected formation of plastic hinges in columns. Disparities in material characteristics, such as concrete strength or reinforcing steel properties, could influence the structural response and behavior under seismic loading. Similarly, fluctuations in applied loads or load patterns during the service life of the structure may induce differential stresses within the column, potentially resulting in the formation of plastic hinges at unanticipated locations.
- Seismic Activity: The occurrence of seismic events can significantly impact the structural behavior of bridges, potentially leading to the formation of plastic hinges at locations not originally envisaged during the design phase. Ground motion induced by seismic activity exerts dynamic forces and moments on the structure, thereby subjecting columns to varying levels of stress and deformation. In instances where seismic forces exceed the design assumptions or where localized amplifications occur due to site-specific conditions, the formation of plastic hinges may manifest in unexpected locations.

At two adjacent bridge structures within the broader framework of the examined bridge, the formation of a plastic hinge in two columns is observed shown in Figures 6, 7 and 8, with one located at the bottom as anticipated, and the other positioned elsewhere within the column, contrary to expectations. Specifically, the plastic hinge in the latter column materialized approximately 25% up the column height, manifesting in the transverse bridge direction. This deviation from conventional expectations warrants thorough investigation and analysis. A plausible explanation for the occurrence of the plastic hinge at a location deviating from the column/footing interface, as typically expected, may be attributed to the presence of vertical bar cutoffs at this juncture. These cutoffs could have resulted in a reduction of the moment capacity, thereby exacerbating the moment demand-to-capacity ratio at this elevated position compared to the column base. Notably, the manifestation of spalling of unconfined cover concrete on both sides of this plastic hinge underscores the nonlinear cyclic behavior prevalent in the transverse direction of the bent. The observed compressive concrete strains of at least 0.005 (and potentially surpassing 0.01) in both loading directions corroborate the nonlinear nature of the structural response[10)]. An alternate scenario pertains to the phenomenon of vertical rebar buckling, indicative of nonlinear cyclic behavior characterized by steel yielding and significant strain accumulation in tension before direction reversal. This dynamic results in compressive stresses and forces in the rebar preceding any significant compression from the combined section moment and axial force within the concrete. It is noteworthy that such occurrences typically do not transpire under monotonic loading conditions, where concrete consistently experiences compression on one side of the neutral axis. The manifestation of vertical rebar buckling within a column plastic hinge signifies a precarious structural condition, suggesting imminent failure with only a few additional cycles needed to precipitate complete collapse. While the presence of bar cutoffs stands as the most plausible explanation for the nonconforming plastic hinge location, it is conceivable that other factors may have contributed to the heightened moment demand at this juncture. Notably, the combined effects of transverse mass and rotational mass inertia from the extensive bridge structure may have elevated the moment demand, particularly significant for single-column-bent bridges. The freedom of rotation at the top of the column in the transverse direction, inherent in the displacement of the bridge transversely, underscores the intricacies associated with structural response under dynamic loading conditions.

Upon acquisition of the bridge plans, a thorough investigation of the aforementioned possibilities becomes feasible, thus facilitating a comprehensive understanding of the structural behavior and potential mechanisms underlying the formation of plastic hinges within the column structure. In particular, the investigation may involve an assessment of the size and spacing of transverse spirals or hoops, which play a pivotal role in governing the buckling behavior of vertical rebar. Depending on the configuration and characteristics of these transverse elements, vertical rebar may buckle either between individual transverse bars or across multiple bars, necessitating the initiation of significant tensile hoop strains within the transverse steel. This phenomenon is particularly pertinent to the plastic hinge observed in the bridge structure under examination. Drawing upon the author's experiential insights, optimal plastic hinge performance for reinforced concrete (RC) bridge columns, as measured by cyclic displacement ductility capacity exceeding six, is typically attained when the volumetric ratio of transverse rebar to the column approximates one-half of the volumetric ratio of vertical steel to the column. A fundamental prerequisite for ensuring adequate ductile column performance entails maintaining a minimum vertical steel content of approximately 1 %[11)], necessitating a corresponding transverse steel content of at least 0.5 %. An analysis of the structural configuration reveals that the observed plastic hinge occurred in a region where the transverse steel content may have fallen short of the requisite amount, suggesting potential inadequacies in the structural design or construction execution. The phenomenon of vertical rebar buckling assumes critical significance due to the substantial strains, both in tension and compression, experienced by the rebar on either side of a buckled wave. This dynamic engenders low-cycle fatigue failure and eventual rupture of the vertical steel, compounded by the yielding and rupture of the transverse rebar. The combined effects of vertical rebar buckling and subsequent fracture, coupled with the yielding and rupture of transverse rebar, precipitate a scenario wherein the core concrete becomes suddenly unconfined, thereby facilitating the unimpeded discharge of pulverized concrete from the plastic hinge region. Consequently, the structural integrity of the bridge becomes vulnerable to future seismic events, including moderate to significant earthquakes or aftershocks, which may exacerbate the existing plastic hinge by subjecting it to additional cyclic loading cycles.

(2) Cases B and C: I-girder bridge in Nurdaği

Bridge cases B and C are multiple single piers, Precast, Pre-stressed I girder superstructure with RC Columns, including two parallel lines with a slight minor curve Figure 9, located at GPS coordinates 37°11'20.3"N, 36°43'03.3"E and elevation of 641 m. No structural damages were observed in the main body of the bridge but some minor cracks on the retaining wall created for the piers were observed in Figure 10.

The bridge has remained intact and does not pose an immediate risk of collapse or failure. Regular inspections and assessments are essential for ensuring the safety and structural integrity of bridges, so it's important to continue monitoring and maintaining the bridge to prevent any potential issues from developing over time.

Because of the minor cracks that were observed on the retaining wall created for the piers of the bridge Figure 10, it is still important to take them seriously and assess their potential impact on the overall structure. While these cracks may not immediately jeopardize the main body of the bridge, they could indicate underlying issues that require attention to prevent further deterioration. The cracks should be assessed and determine their severity and potential implications for the bridge's stability. Monitoring the cracks to observe any changes in size, shape, or propagation is important. This can help identify if the cracks are stable or if they are expanding over time. Also, depending on the evaluation, repairs may be necessary to prevent further cracking and address any potential weaknesses. The repairs could involve techniques such as crack injection,

(a) (b) (c)

Figure 9 Bridge in Nurdagi (a) and (b) General view of the bridge piers and (c) General view of the bridge

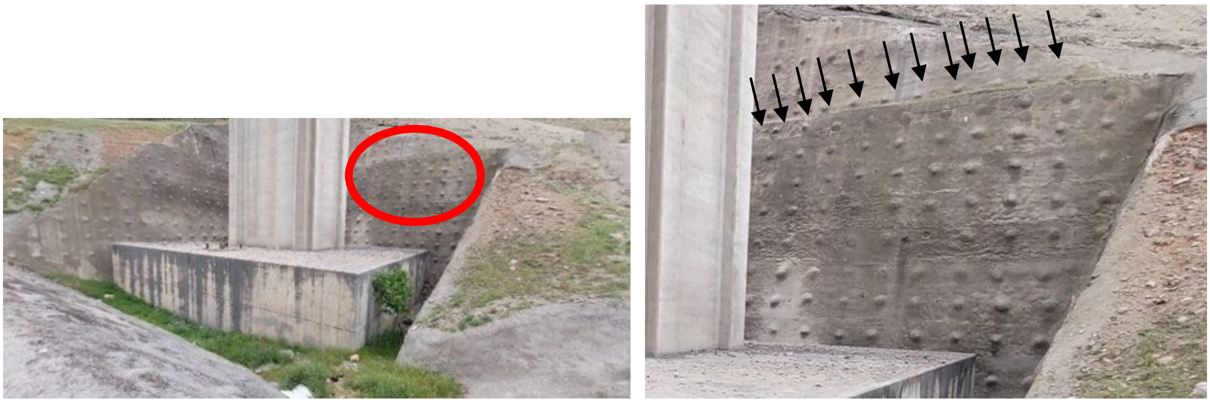


Figure 10 Damage to retaining wall surrounding the pier: (a) View of the bridge pier with minor cracks on the wall and (b) Enlarged view

grouting, or other suitable methods. It is important to have ongoing inspections to establish a schedule for routine inspections to monitor the condition of the retaining wall and the overall bridge structure. This will help ensure that any future issues are detected early and addressed promptly by qualified professionals for any structural concerns to maintain the safety and integrity of the bridge.

This bridge has more spans with unelevated supports. No structural deformation resulting in bending, twisting, or warping of bridge elements, such as beams, girders, or trusses. The columns and piers although experienced strong shaking and induced high lateral forces did not exceed the design limits, leading to partial damage or collapse of the bridge. There was a minor crack on one of the columns which seemed to be generated recently, also it is mostly likely to be a construction flaw, which needs more monitoring and provide real-time data and analysis to ensure the safety and functionality of the bridge during the time which is one of the key components for BMS (Bridge Monitoring Systems).

(3) Case D: Highway 8-span & 7 piers bridge in Nurdaği

Case D pertains to the highway 8-span bridge situated in Nurdaği, characterized by an eight-span configuration supported by seven single piers. The superstructure comprises precast, prestressed I girders, complemented by reinforced concrete (RC) columns. Notably, the bridge exhibits a slight minor curve, delineated by two parallel lines, as depicted in Figure 11 (c). Positioned at GPS coordinates 37°11'20.3"N 36°43'03.3"E, with an elevation of 641 m. This bridge occupies a pivotal transportation artery within the region. One of the predominant vulnerabilities observed in bridges, including the highway 8-span bridge, pertains to the susceptibility of column covers to damage, attributable to the adverse effects of environmental elements. The incorporation of column covers serves to augment protection against external factors, safeguarding the structural integrity and longevity of the bridge. However, the onset of strong ground shaking

(a) (b) (c)

Figure 11 Spalling of column cover during the earthquake and detailed view Spalling of column cover during the earthquake.

during seismic events can engender the development of cracks within the column covers, precipitating instances of spalling and consequent loss of cover material, as illustrated in Figure 11(a) and (b). The occurrence of spalling, characterized by the detachment or disintegration of cover material from the surface of the columns, underscores the deleterious effects of seismic loading on bridge infrastructure. These manifestations of structural distress not only compromise the aesthetic appeal of the bridge but also herald potential structural vulnerabilities, necessitating comprehensive inspection and remedial measures to mitigate further deterioration. The propagation of cracks and subsequent spalling within column covers underscores the paramount importance of robust design considerations and material selection processes aimed at enhancing the resilience of bridge structures to seismic hazards.

The visual representation provided delineates the geographical location of the Atatürk viaduct, a pivotal element in the structural landscape under examination. Situated at an elevated vantage point, the viaduct's lofty positioning presents a formidable challenge in conducting detailed structural assessments. Nevertheless, despite the inherent difficulty in scrutinizing the viaduct's intricate structural components, including the girder system, columns, bearings, and their immediate surroundings, certain observations can be made. Comparative analysis reveals striking similarities between the structural elements of the Atatürk viaduct and those of the Turgut Özal viaduct. Notable resemblances are discerned in the configuration and layout of the girder system, the arrangement of columns, and the design of bearings, as well as the characteristics of their surrounding components. These parallels suggest a commonality in design principles and engineering specifications employed in the construction of both viaducts. The significance of these observations lies in their potential implications for structural performance and integrity assessment. By identifying similarities between the structural features of the Atatürk and Turgut Özal viaducts, engineers and researchers can draw upon existing knowledge and insights garnered from past assessments to inform their evaluation of the former.

The occurrence of spalling in column covers during seismic events serves as a conspicuous indicator of potential deficiencies in the bridge's design or maintenance regimen, warranting thorough investigation and remedial action. If spalling is observed, it may suggest that the thickness of the column cover was inadequate to provide adequate protection against environmental corrosion, thereby unveiling underlying vulnerabilities in the bridge's structural integrity. Inadequacies in the protective coating applied to the column cover, compounded by deterioration over time, may facilitate the ingress of moisture and other corrosive agents into the column, culminating in the corrosion of the underlying structural elements. Figure 11 illustrates instances of insufficient cover observed in the bridge piers, accentuating the urgent need for diligent examination and rectification of such deficiencies. Furthermore, if the column cover fails to effectively shield the reinforcement from moisture or other corrosive agents, it predisposes the steel bars to corrosion-induced degradation. Corrosion compromises the structural integrity of the steel, precipitating spalling and subsequent deterioration of the bridge's load-bearing components.

In the aftermath of spalling incidents during seismic events, which unveil inadequate protection against environmental corrosion, a proactive approach towards corrective measures is imperative to uphold the structural integrity and longevity of bridge infrastructure. The severity of the damage and the overall condition of the bridge dictate the nature and extent of remedial interventions required. Potential solutions encompass a spectrum of strategies aimed at mitigating corrosion-induced deterioration and reinforcing the resilience of the bridge structure. One plausible course of action involves the targeted repair of spalled areas by meticulously removing the damaged concrete and applying new protective coatings or materials to inhibit further corrosion progression. This approach necessitates meticulous attention to detail to ensure the effective restoration of structural integrity and the prevention of future corrosion-related deterioration. Additionally, conducting a comprehensive inspection of the entire bridge is essential to identify other areas vulnerable to corrosion or structural deficiencies, thereby facilitating the formulation of a holistic remediation strategy. The implementation of a comprehensive maintenance plan emerges as a cornerstone of sustainable bridge management practices, encompassing regular inspections, cleaning protocols, and the periodic reapplication of protective coatings. By proactively addressing existing and potential corrosion issues through diligent maintenance activities, authorities can preemptively mitigate the risk of structural deterioration, ensuring the long-term viability of the bridge infrastructure. In considering long-term solutions, it is imperative to deliberate upon strategies aimed at fortifying the bridge columns and enhancing protective measures against environmental corrosion. This may entail the implementation of strengthening measures, such as the addition of supplementary reinforcement or the incorporation of protective layers to augment the resilience of the structural elements. Furthermore, the replacement of column covers with more durable materials or enhanced designs may be deemed necessary to fortify the bridge against future corrosion-induced degradation. Central to the efficacy of remedial interventions is the need for a meticulous assessment of the specific circumstances governing the bridge's condition, enabling the delineation of tailored corrective actions commensurate with the identified vulnerabilities. Through a judicious amalgamation of repair, maintenance, and fortification strategies, the long-term safety and durability of the bridge can be safeguarded, thereby ensuring its continued functionality and resilience in the face of dynamic environmental forces.

4. Damage to steel truss bridge in Türkoğlu

The bridge under scrutiny represents a singular-span steel truss structure designated for railway utilization, featuring a precast superstructure. Situated within the Türkoğlu district of the Kahramanmaraş Province, this bridge assumes significance within the regional transportation network, serving as a critical conduit for railway traffic, Figure 12 (a). The susceptibility of steel bridges to seismic-induced damage underscores the multifaceted interplay of several key factors. Bridges engineered to withstand seismic loading are equipped with features such as robust structural members, flexible connections, and energy dissipation mechanisms aimed at dissipating seismic forces and minimizing structural damage. Conversely, inadequacies in design or construction may render the bridge more susceptible to seismic-induced damage. Furthermore, the geological composition and soil conditions at the bridge's foundation site exert a significant influence on its seismic response. Soil properties such as shear strength, liquefaction susceptibility, and amplification effects can significantly modulate the transmission of seismic forces to the bridge superstructure. Sites characterized by soft or liquefiable soils are particularly vulnerable to seismic-induced settlement or lateral spreading, which can compromise the stability and integrity of the bridge foundation.

(a) (b) (c)

Figure 12 Damage to steel truss bridge in Türkoğlu: (a) General view of the damaged railway bridge, (b) View of the damaged railway bridge abutment, and (c) View of the damaged railway bridge abutment

During seismic events, such as earthquakes, steel truss bridges like the one depicted in Figure 12 are subject to vigorous ground shaking, inducing dynamic forces that reverberate through their components. These forces elicit vibrational responses within the bridge structure, resulting in stress and strain in its structural elements. Steel truss bridges are designed with inherent flexibility to absorb and dissipate seismic energy through ductile deformation mechanisms. However, if the magnitude of the earthquake exceeds the bridge's design thresholds or if deficiencies exist in its design or construction, the structure may incur damage or failure. Pounding, a prevalent type of damage observed in steel truss bridges during seismic events occurs when the bridge lacks adequate provisions to accommodate horizontal movements induced by seismic forces. This can lead to collisions between adjacent bridge elements, as depicted in Figures 12 (b) and (c), resulting in damage or collapse. Addressing the aftermath of such damage requires tailored repair or rehabilitation measures depending on the specific nature and extent of structural degradation. Potential remedial interventions include replacing or reinforcing damaged steel members, rectifying connection failures, and fortifying the bridge foundation. The effectiveness of the repair process relies on specialized expertise and meticulous planning to restore the bridge's safety and structural integrity.

5. Damage to bridges in Antakya

(1) Bridge damage over Orontes river in downtown Antakya city

The examination of non-structural damages to concrete blocks and hangers, as depicted in Figure 13, Figure 13 (a) represents not damaged bridge before the earthquake, and Figure 13 (c) non Structural damages of concrete blocks and hangers which presents a compelling illustration of the repercussions of seismic events on infrastructure. This figure portrays the aftermath of an earthquake event, wherein the integrity of concrete blocks and hangers, integral components of bridge infrastructure, has been compromised. Notably, these damages signify vulnerabilities in the non-structural elements of bridges, which can have profound implications for overall structural integrity and operational safety.

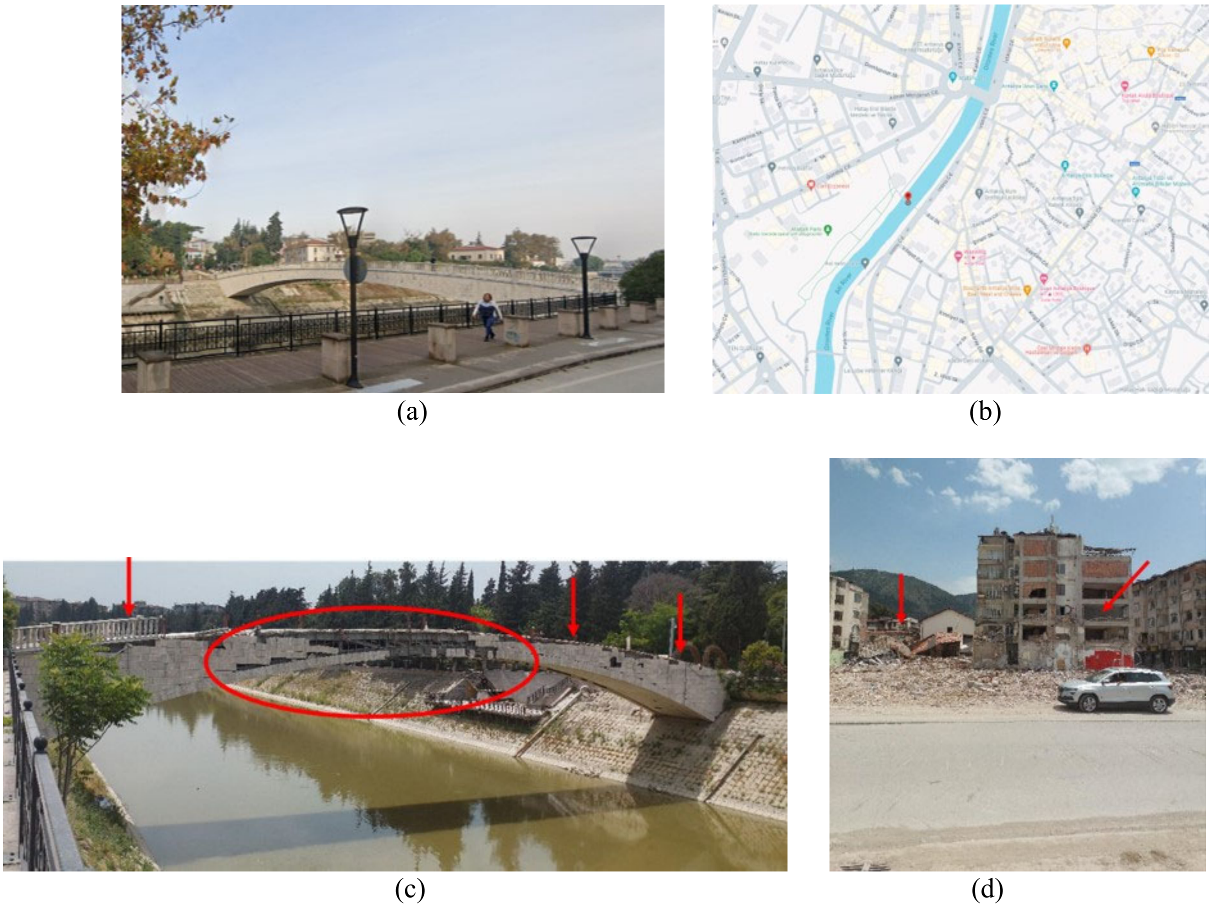


Figure 13 (a) No damaged bridge before the earthquake (b) Google Maps location (c) Non-structural damages of concrete blocks and hangers (d) Damages to structures at the opposite side of the bridge

Concrete blocks and hangers are essential components contributing to the stability and functionality of bridges, supporting various auxiliary systems such as lighting, signage, and utilities. The observed damages, ranging from fractures and dislodgements to deformations and displacements, underscore the susceptibility of these elements to seismic loading. Understanding the nature and extent of non-structural damages is imperative for devising effective mitigation strategies and enhancing the seismic resilience of bridge infrastructure.

Conversely, Figure 13(a) provides a contrasting depiction of an undamaged bridge prior to the earthquake event. Figure 13 (c) damages to structures located on the opposite side of the bridge. This figure serves as a poignant reminder of the imperative for robust seismic design and retrofitting measures aimed at safeguarding critical infrastructure against seismic hazards. The pristine condition of the bridge exemplifies the potential efficacy of proactive engineering interventions in mitigating seismic risks and preserving structural integrity.

The juxtaposition of these figures underscores the dynamic interplay between seismic forces and structural vulnerability, emphasizing the multifaceted challenges inherent in seismic risk management.

(2) Bridge damage in Demirköprü, Antakya

Embankment failure represents a critical geotechnical hazard with profound implications for transportation infrastructure. As depicted in Figure 14 (a), (b) and Figure 16 (i), embankment failure entails the collapse or deformation of earthen structures supporting roadways or railways, often triggered by factors such as inadequate compaction, excessive water infiltration, or seismic activity. Liquefaction, another geotechnical phenomenon, poses significant risks to infrastructure stability, particularly in regions with loose, water-saturated soils. As illustrated in Figure 14 (c) and Figure 15 (d), liquefaction occurs when seismic activity induces a reduction in soil strength, transforming solid soil into a liquid-like state. This phenomenon compromises the bearing capacity of the ground, leading to settlement or lateral spreading. Moreover, significant tilting of bridge piers further complicates the structural integrity of transportation infrastructure in seismic-prone regions. Combining embankment failure, liquefaction, and pronounced tilting of bridge piers, as evidenced in Figure 14 (a) and Figure 15(e), underscores the multifaceted challenges posed by earthquake events. Tilting of bridge piers compromises load-bearing capacity, disrupts traffic flow, and increases the risk of collapse. This is particularly relevant in regions like Antakya, known for seismic activity and its proximity to fault lines. Figures 15 (f) and 15 (g) show the rupture and deck separation at the surface, along with general damages to the road. Moreover, In Figures 16 (h) and (j) Insufficient cover of concrete, coupled with corrosion of the rebars. When concrete cover is inadequate, it fails to provide the necessary protection for reinforcing steel against environmental elements, leading to corrosion. Figures 16 (j) and (k) depict pullouts of the reinforcements and failure of the concrete column which is due to moment demand and moment capacity when bars are cut off. Addressing these complex interactions demands a holistic approach to seismic design, encompassing rigorous structural engineering, comprehensive geotechnical assessments, and effective risk mitigation measures tailored to site-specific conditions. Through proactive planning and diligent implementation of mitigation strategies, the resilience of transportation infrastructure can be enhanced, ensuring the safety and functionality of vital networks in the face of seismic threats.

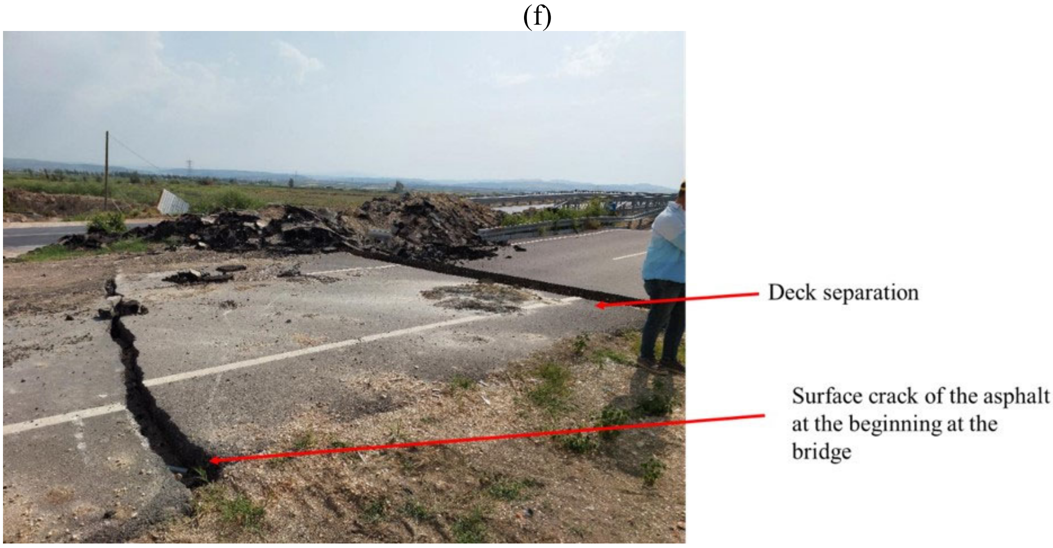
(a) (b) and (c)

Figure 14 Damages in the bridge Demirköprü, Antakya; (a) Shows shear key failure, rotation of the piers, and settlement of the piers (b) another angel of shear key failure (c) location of the damaged bridge

(d)

(e)

(f)



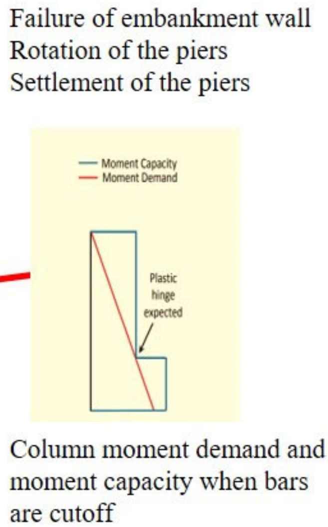
(g)

Figure 15 Damages in the bridge Demirköprü, Antakya; (d) tilted pier (e) embankment failure and column failure (f) rupture and deck separation at the surface including general damages of the road(g) surface crack of the asphalt at the beginning of the bridge with deck separation

(h)

(i)

(j)



(k)

Figure 16 Damages in the bridge Demirköprü, Antakya; (h)insufficient cover of the concrete and corrosion of the rebars (i) failure of embankment wall including rotation of the piers (j) pullouts of the reinforcements and failure of concrete (k) column moment demand and moment capacity when bars are cut off

(3) Bridge damage in Antakya city

The findings presented in Figure 17 reveal substantial damage inflicted upon the ends of girders within the bridge structure, despite the absence of complete collapse. This damage manifests prominently at the shear keys and girder terminations Figures 17 (a) to (e), where severe structural impairment is evident. Notably, the concrete encasing the vertical and horizontal reinforcing bars exhibits signs of deterioration, accompanied by deformation of the reinforcing bars themselves, indicative of a significant reduction in shear strength at the girder ends. Considering the possibility that these girders are prestressed concrete beams, the prevailing stress conditions become a matter of considerable concern, particularly in light of potential failures within the concrete cross-section.

The close proximity between the link slab support and the girder end exacerbates the situation, resulting in collisions between the girder ends, the link slab support, and the shear keys. The absence of diaphragms at the girder ends further compounds the vulnerability of these structural elements Figure 17 (d). Theoretically, such collisions may concentrate energy on the girder ends, particularly in the absence of end diaphragms, thereby exacerbating damage. Alternatively, transverse loading on the girder webs could arise due to inertial loads transmitted from the deck slab to the bearings or shear keys, potentially leading to damage under out-of-plane flexure and shear conditions.

(a) (b) and (c)

(d) (e) (f)

(g)

Figure 17 Viaduct in Antakya city; (a) and (b) failure of shear keys (c) falling off concrete segments (d) shear key failure and shear crack formation in the deck (e) segment falling (f)damages by over height vehicles (g) rebar pullout and insufficient effective length

The observed damage underscores the importance of adhering to seismic principles governing the location and design of damage within bridge structures. The absence of end transverse girders is identified as a critical factor exacerbating the extent of damage observed. Remarkably, similar damage patterns were discerned on the girder ends at the abutment and shear keys of another elevated bridge of identical structural typology within the same city. Given the recurrence of damage across multiple bridges of similar structural composition, there is a compelling imperative to enhance the typical structural details pertaining to girder ends.

Moreover, the presence of shear keys poses logistical challenges for post-event inspection activities at ground level. The narrow spacing between shear keys and girders, as well as between link supports and girder ends, presents impediments to effective inspection procedures. Hence, there is a pressing need to explore and develop feasible inspection protocols tailored to the specific constraints encountered in assessing girder ends and their immediate surroundings.

Figure 17 (f) depicts damages inflicted by over-height vehicles representing a persistent challenge to infrastructure integrity and public safety. Over-height vehicles can shear off signage, scrape against support beams, or even dislodge sections of infrastructure, leading to costly repairs and potential disruptions in transportation networks. Moreover, such accidents may necessitate temporary closures for inspection and repair, causing inconvenience and traffic congestion.

6. Conclusions

The investigative team dedicated three days to conduct on-site assessments aimed at identifying structural impairments and potential failures within bridge infrastructures. This endeavor commenced on May 11, 2023, following the seismic events of magnitude 7.8 and 7.5 that transpired in southern Turkey on February 6, 2023. Despite the considerable devastation witnessed in the collapse of tens of thousands of residential edifices, which tragically accounted for the majority of casualties ensuing from this calamitous event, the incidence of bridge failures was relatively limited to the knowledge of the investigative team. Notwithstanding, numerous bridge frameworks exhibited significant degrees of damage, a phenomenon expected in the aftermath of such a catastrophic natural or anthropogenic disaster. It is noteworthy that although many bridge structures incurred substantial impairments, they remained structurally intact, aligning with the contemporary seismic design paradigm. This paradigmatic approach acknowledges the possibility of severe damage while prioritizing the prevention of structural collapse to preserve human lives. The resilience displayed by these bridge infrastructures underscores the viability of planning and constructing civil engineering marvels that demonstrate remarkable resistance against formidable seismic forces. This observation serves as a testament to the feasibility and efficacy of implementing robust seismic design principles in the development of critical infrastructure, thereby bolstering societal resilience to seismic hazards.

The salient observations from the study are outlined as follows:

- The collapse of the bridge was attributed to the failure of shear keys, influenced by the skew angle of a single-span concrete girder superstructure. This emphasizes the necessity for investigating the design of support length and fail-safe systems.
- Several concrete bridges exhibited failures in concrete shear keys and backwalls, presumed sacrificial elements. However, collision with concrete girders resulted in severe damage, warranting further research on fail-safe systems and shear key design improvements.
- Bridges experienced intense motions in a condensed timeframe, raising uncertainties regarding the performance of shear keys during successive seismic events. This underscores the need for additional research on fail-safe systems and shear key design enhancements.
- Severe damage to girder ends of concrete I-girders was observed in Antakya viaducts. The absence of end diaphragms connecting concrete girders renders them susceptible to damage, necessitating the implementation of full-depth end diaphragms to distribute loads and collision forces effectively.
- Buckling of lower flanges above bearings in the Nurdağı viaduct on Highway 52 is a significant concern, as it can destabilize bridges and prolong repair times. Consequently, further study of seismic details of bearing stiffeners of steel girders is warranted.
- The Nurdağı viaduct exhibited severe damage to a concrete column due to core concrete failure, potentially attributed to proximity to fault lines, structural characteristics, and concrete quality. A comprehensive investigation of bridge response is warranted to ascertain causative factors.
- Addressing embankment failure, liquefaction, and pronounced tilting of the bridge near Antakya cases piers demands a holistic approach to seismic design, integrating rigorous structural engineering, comprehensive geotechnical assessments, and effective risk mitigation measures. Through proactive planning and diligent implementation of mitigation strategies, the resilience of transportation networks can be enhanced, safeguarding against the potentially devastating impacts of seismic events.

Finally, while this report focuses on structural aspects, it is imperative to acknowledge the potential influence of geotechnical factors, such as liquefaction, on bridge damage. Instances of tilting and settlement of roads and bridges attributed to liquefaction were reported in various locations. Considering liquefaction potential when investigating bridge damage during seismic events is recommended, albeit with due consideration to the unique soil characteristics prevalent in Turkey. This holistic approach ensures a comprehensive understanding of the multifaceted factors contributing to bridge damage and informs targeted mitigation strategies.

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