3. Summary and suggested research topics to update seismic design practice and the Japanese Specifications for Highway Bridges

The key features of the observations were as follows:

1. The skew angle of a single-span concrete girder superstructure affected the failure of the shear keys, resulting in the bridge collapse. This damage highlights the need to study the design of the support length and fail-safe systems.

2. Failure of concrete shear keys and backwalls was observed in several concrete bridges. The shear keys and the backwalls were assumed to be sacrificed elements; however, the collision of these elements with concrete girders was considered to cause severe damage to the concrete girders. Further research is required for fail-safe systems and improving shear key design.

3. Moreover, bridges underwent several intense motions within a short period, and it is unclear how well their shear keys performed during multiple events in a short span of time. This highlights the necessity for additional research on fail-safe systems and enhancing the design of shear keys.

4. The viaducts in Antakya suffered severe damage in the girder ends of the concrete I-girders. The same damage to a same bridge type occurred during the 2010 Chile earthquake (Kawashima et al., 2011; Yen et al., 2011). These facts reveal that the lack of end diaphragms connecting concrete girders makes them susceptible to damage. The implementation of full-depth end diaphragms should be recognized as a required seismic detail for bridges to avoid severe damage to girder ends. These end diagrams function to distribute the transverse inertial loads of the deck slabs and the collision forces from the shear keys and the backwalls over themselves.

5. The lower flanges of a steel-box girder buckled above the bearings in the Nurdağı viaduct on motorway O52. This type of damage is frequently considered a significant concern because it can destabilize a bridge and consume much time to repair. Accordingly, the seismic details of the bearing stiffeners of steel girders should be studied further.

6. In addition, the Nurdağı viaduct on motorway O52 showed severe damage to a concrete column with the failure of the core concrete. The causes may range from the effect of the location of the bridge near fault lines, structural characteristics of the transition of the steel girder system to a concrete girder system at one of the columns, and quality of the concrete casting under the conditions of double bundles of hoops and dense longitudinal reinforcement in a small cross-sectional area. Further investigation of bridge response is required.

7. As exhibited by the Turgut Özal viaduct on motorway O52 and the Tohma bridge on D875, continuous bridges supported by tall piers employing dampers and stoppers suffered only minor damage. Accordingly, further numerical simulations regarding the effectiveness of seismic design concepts with dampers and stoppers may provide helpful information for proving the present seismic design practices of long-natural period bridges near fault areas.

8. In the Erkenek tunnel on D850, severe cracks developed in the lining concrete and concrete blocks fell throughout the tunnel length. The damage was similar to that observed during the 2004 Niigata Chuetsu Earthquake (Konagai et al., 2005; NILIM/PWRI, 2005a; NILIM/PWRI, 2005b) and the 2016 Kumamoto Earthquake (Fukuhara and Nakahara, 2018; NILIM/PWRI, 2017). Accordingly, the seismic design of mountain tunnels to prevent similar damage can be studied by collecting damage case histories from earthquake-prone countries.

The Japanese Specifications for Highway Bridges (JRA 2017) is issued by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) to road administrators. It is the legally-binding design code for national highways and expressways and the de-facto standard for other roads. Based on the damage cases of this earthquake, the authors raise the following three points that could be relevant for improving the Japanese seismic design specifications for highway bridges: 1. Seismic details for robustness and post-event inspectability, 2. Seismic responses of bridges with long natural periods, and 3. Post-event inspection.

(1) Seismic details for robustness and post-event inspection

This earthquake had some notable characteristics. Strong earthquakes occurred in succession within a short period with multiple fault ruptures. In addition, some roads and bridges were located near the fault zones. The 2016 Kumamoto Earthquake of Japan had similar characteristics. It is unrealistic to assume that all possible future earthquake situations can be predicted; therefore, a different approach is required to render roads more resilient and repairable. For example, the design should consider fail-safe systems, structural ductility, robustness, inspectability, and repairability. Several damage examples from this earthquake provide valuable insights into the seismic details of girder ends.

Seating length and strength and ductility capacity of shear keys

During this earthquake, a single-span concrete girder superstructure with a skew angle collapsed following the failure of the shear keys. Therefore, the design of bearings and super-substructure connections must be improved to prevent failure. However, this earthquake also indicated the need to improve fail-safe considerations, such as support lengths and displacement restrainers, which would serve after bearings and connections collapse. In addition, this earthquake had the peculiar characteristic of several earthquakes with high intensities occurring within a short period. A similar feature was observed during the 2016 Kumamoto Earthquake in Japan (NILIM/PWRI, 2017; Bromenschenkel et al., 2023). In the 2016 Kumamoto Earthquake, displacement restrainer concrete blocks failed, raising questions regarding whether they collapsed during the first major earthquake or subsequent major earthquakes and how to design such restrainers. Therefore, the possibility of multiple earthquakes occurring within a short period should always be considered. Installing a fail-safe system, such as displacement restrainers separated from a shear key system, is feasible. The toughness of shear keys is another issue that needs to be addressed.

End diaphragms

During the earthquake, the girder ends of concrete I-girders suffered severe damage. As previously mentioned, the absence of end diaphragms connecting concrete girders makes them vulnerable to damage similar to that which occurred in the 2010 Chile Earthquake (Kawashima et al., 2011; Yen et al., 2011). Two reasons could account for this type of damage. Firstly, the forces resulting from the girder colliding with the backwall were concentrated at the girder end, causing damage to the concrete inside the stirrups. Secondly, the transverse inertial loads from the deck slabs to the bearings were concentrated on the girder webs because they were not distributed without an end diaphragm. This led to severe out-of-plane bending and shear deformation of the girder webs. In Japan, girder bridges have full-depth end diaphragms and this type of damage is rare. Based on the earthquakes in Chile, Turkey, and Japan, installing full-depth end diaphragms should be regarded as one of the seismic details of concrete T- or I-girder bridges.

Bearing stiffeners of steel girders

In the Nurdağı viaduct on motorway O52, the lower flanges buckled above the bearings. In Japan, similar insights from earlier earthquakes have improved the details of bearing stiffeners in steel girders. **Figure 3-1** shows a typical example of a vertical stiffener arrangement above a bearing in Japan. This is based on the repeated experiences of similar damage during earlier earthquakes. However, further studies are required to obtain better structural details.

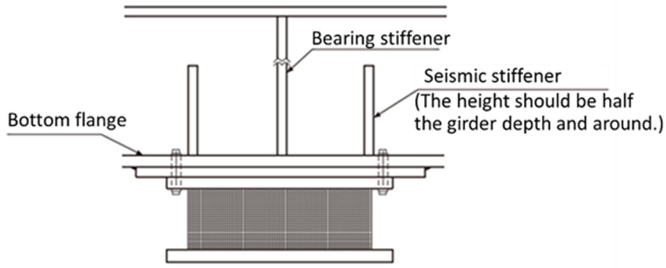

Figure 3-1. Present typical details of bearing stiffeners in Japan (JRA, 2021)

Inspectability of bearings

In addition, the damage to bearings and surroundings in this earthquake suggested the need to improve the structural details of these parts to facilitate post-event inspection. In Turkey, the bearings of several bridges were covered with materials. In the old Tohma bridge, superstructures were misaligned with each other, and bearing damage was highly suspected. However, there was no access to the bearings. In the Tohma bridge and the viaducts observed in Antakya, the shear keys collapsed. However, because of the insufficient spacing between the shear keys, backwalls, and girders, checking the conditions of the bearings and girders was hindered. The structural details for providing sufficient and smooth access to girder ends and bearings should be designed from the perspective of post-event inspectability.

(2) Seismic response of bridges with long natural periods

Several records of this earthquake showed strong intensities of long-period components, and several bridges with tall columns, dampers, or shock absorbers can have long natural vibration periods, such as the Tohma bridge and the Turgut Özal viaduct. Accordingly, it is necessary to conduct dynamic analyses to check whether their seismic design concepts worked as designed and to identify the factors that caused or prevented damage to the bridges with long natural periods. This type of proof study will provide important knowledge for future seismic strengthening of such bridges and the effective use of dampers in seismic design. In addition, several bridges and tunnels were located close to the faults, such as the Turgut Özal and Nurdağı viaducts. The Turgut Özal viaduct suffered minor damage, whereas the Nurdağı viaduct was severely damaged. Therefore, studying the seismic behavior of such bridges and obtaining knowledge for the design of new bridges near faults are important.

(3) Post-earthquake inspection

Roads were indispensable for recovery work in the affected areas and were pressured to remain open, and rapid post-earthquake inspections and assessments of bridges were required. The damage cases in this report were observed approximately one month after the disaster. Some bridges had severely damaged girders and bearings; however, the girder ends and the bearings were difficult to reach using only patrols from the bridge surface. A similar situation is probable to occur worldwide. Therefore, studying post-earthquake inspection methods for all bridges is desirable. Sharing damage case history reports worldwide is helpful for improving post-event inspection manuals and developing innovative inspection methods, instead of patrolling at the bridge surface level.

Finally, this report focuses on structural aspects and not on geotechnical damage to roads and bridges. However, according to several news reports, liquefaction was considered as the primary cause of the tilting and settlement of buildings, road embankments, and road bridges in different locations such as Gölbaşı in Adıyaman, Iskenderun in Hatay, and Demirköprü in Antakya, Hatay (UNDR, 2023; Lider Gazetesi, 2023). Accordingly, considering the liquefaction potential when examining the cause of bridge damage during this earthquake is also desirable. However, the influence of the soil locality in Turkey on liquefaction should be considered when using liquefaction potential assessments developed for other countries.