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Post-earthquake observations of bridge damage

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Abstract

In various parts of the world, seismic events happen regularly. While engineers have gained an understanding on the behaviour of bridges under seismic loading, this knowledge is still under development as more methods and devices for building seismically-resistant bridges become available. This paper reports on the observed damages from recent events, with a focus on recent earthquakes in Ecuador, Chile, and Turkey. To report the damage that has occurred, this paper presents descriptions of a number of cases of observed damage to bridges after earthquakes. The various types and locations of damage are then analyzed to develop broad categories of problems that can be identified from these cases. This insight then leads to a summary of lessons learned from the presented case studies. The information provided in this work can be used for the assessment of existing bridges and the improvement of the design of new bridges.

Keywords: seismic event; seismic loading; analysis; case studies; recommendations for practice.

1 Introduction

Seismic events are considered among the major natural disasters that can occur. In various parts of the world, earthquakes can happen and happen regularly. Over the past decades, engineers have gained a better understanding of the behavior of structures when subjected to earthquake loading. However, this knowledge is still being developed as more methods and devices for building seismically-resistant structures become available. When it comes to bridges, it is important to compare post-earthquake field observations from various parts of the world, to collaborate on continuous improvements of the seismic design codes and the codes for the assessment of existing bridges to carry out adequate seismic retrofits of existing bridges.

This paper reports the observed damages and provides a critical analysis or comparison about the seismic requirements on bridges from recent earthquake events, with a focus on recent earthquakes in Ecuador, Chile, and Turkey.

2 Seismic design codes and practices

2.1 Turkey

Earthquake codes put into practice in Turkey started to evolve following the 1939 Erzincan earthquake. The first seismic design code was published in 1940 [1] and was translated from the Italian seismic design code. In this specification, the lateral seismic load was calculated as a percentage of the building weight based on the earthquake zone. Recommendations are also provided for foundation types in seismic zones. Masonry and wooden buildings were the main focus. In 1944 [2], a new seismic code was published, and several soil types were defined. Limitations were introduced for building height and number of stories depending on the type of the structural system. Some guidelines about detailing were introduced. The 1944 specifications were revised in 1953 and 1962. In 1968, the revision to the existing code [3] adopted a static equivalent seismic force calculation. Additionally, design rules were provided for reinforced concrete members. The 1968 specification was revised again in 1975 [4], when it took a form that is most similar to the modern codes. The seismic zones are very similar to the current maps. Detailing rules were adopted at the column and beam connections.

Before the 1999 Sakarya Earthquake, a new revision was just published in 1998 [5]. In the provisions of this code, response spectrum and time history analysis procedures were outlined in addition to static equivalent loading. The 1999 Sakarya Earthquake resulted in an immense catastrophe and caused collapse of significant number of reinforced concrete buildings. After this shocking event, it took great effort to publish a new seismic provision and in 2007, the new specification came out [6]. In this specification, displacement-based performance evaluation of existing buildings was developed. Due to the need for post-earthquake repair and retrofitting efforts, this specification provided comprehensive guideline on performance evaluation and repair methods. Seismic design of steel structures was greatly enhanced and covered extensively in this version of the specification.

In 2018, a new specification was published that allows performance-based design and evaluation of both new and existing buildings [7]. It also allowed a site-specific definition of seismic hazard. In this new specification, vertical ground motion was also introduced, and guidelines were provided to be used in design. New definitions of performance levels were proposed compared to the 2007 specification. The definition of response spectrum was updated, and two new seismic acceleration parameters were given for short and long periods.

2.2 Ecuador

As Ecuador is located at the convergences of the Nazca and South American tectonic plates, various major earthquakes have happened. The 1987 earthquake raised concern about seismic bridge design, resulting in the adoption of performance-based design criteria in the early 2000s. This step is reflected by the 2014 national code NEC-SE-DS which prescribes the seismic loading [8]. After the 2016 Pedernales/Muisne earthquake, a new seismic hazard model was derived [9], and updates to the national code are expected to be published in 2024.

2.3 Chile

Chile is considered one of the countries with the highest seismic vulnerability in the world, therefore, it is exposed to the occurrence of medium and large magnitude earthquakes. The contribution to the study of earthquakes in Chile dates back to 1906, the year in which the Chilean Seismological Service was created. However, it was not until the Talca earthquake of 1928 (Mw 8.4) that the first codes for the design and construction of bridges appeared, such as the General Building Ordinance, formalized in 1935. In the 1940s, the design and construction of Chilean bridges were based on design considerations from codes such as the American AASHTO standard, European regulations of the time such as the DIN Code, and primarily the document published by Engineer Alberto Claro Velazco entitled "Norms for the Calculation and Design of Reinforced Concrete Road Bridges".

Since the Valdivia earthquake of 1960 (Mw 9.5), seismic-resistant design specifications began to be adopted, which served as the basis for the generation of the first version of the Chilean Road Manual. From the Algarrobo earthquake of 1985 (Mw 7.8), seismic design criteria began to be incorporated into the Road Manual. In 2002, volume 3 of the Road Manual was published, and it is in this version where, for the first time, seismic design requirements for bridges are available, marking the beginning of a definition of seismic demand specific to the seismic risk zone. Based on the damage observed in bridges as a result of the Maule earthquake in 2010 (Mw 8.8), the Ministry of Public Works in Chile (MOP) issued a regulatory document presenting new seismic criteria for the design of Chilean bridges, which have been part of the official document since 2017 [10].

3 Recent earthquakes

3.1 2023 Kahramanmaraş Turkey earthquake

On February 6th 2023, a Mw 7.8 earthquake hit southern and central Turkey as well as northern and western Syria, with an epicentre in Kahramanmaraş-Pazarcık close to Gaziantep. Approximately nine hours later, an Mw 7.7 at 95 km north-northeast from the first earthquake occurred in Kahramanmaraş-Elbistan. The number of fatalities in Turkey is confirmed at 53,537 and is estimated between 5951 and 8476 for Syria. In the three months after the earthquake doublet, more than 30,000 aftershocks were registered.

The series of earthquakes is the result of shallow strike-slip faulting along segments of the Dead Sea Transform, Sürgü–Çardak, and the East Anatolian faults, where lateral motion predominates, and is triggered by the interaction between the Anatolian Plate and the surrounding African and Arabian plates. The first earthquake resulted from the release of accumulated energy along the East Anatolian Fault zone and resulted in three subshear slip episodes with a delayed rupture initiation to the southwest. The consecutive earthquake occurred with a larger slip and supershear rupture on its western branch [11].

The fault zones were extensively analysed, indicating a rupture length of 370 km producing a maximum slip of 9 m. The large rupture zone contributed to the large and widespread impact of the sequence of earthquakes [11-13].

Traditional seismic hazard analyses underestimate the hazard levels observed in the Kahramanmaras earthquakes [12], and the ground motions were among the most extensively recorded in the region, with measurements indicating very high ground accelerations.

3.2 2016 Muisne Ecuador earthquake

On April 16th 2016, a Mw 7.8 earthquake struck the coast of Ecuador near the towns of Muisne and Pedernales [14-16], leading to 676 deaths and (an estimated) 16,600 injured. The earthquake is caused by the subduction zone processes that are located along the coasts of Ecuador and Colombia, and highlighted again the region's susceptibility to large megathrust earthquakes as a result of the subduction of the Nazca plate beneath the South American plate.

Measurements during this earthquake indicated that there are seismic supercycles in subduction zones, where accumulated strain is released in clusters of large earthquakes over centuries [16]. A historical pattern was identified, in combination with the 1906 and 1942 earthquakes in Ecuador and other earthquakes in the region, which is challenging the conventional understanding of earthquake cycles and reaccumulation of strain after major seismic events. Instead, centuries of accumulated strain is released in clustered large earthquakes, resulting in an increased seismic hazard during an extended period of time.

In addition, measurements from the earthquake offered the opportunity to model the interaction between the Nazca and South American plates. These analyses give us an insight in the complexities of plate boundary mechanics and the role of locked and creeping segments in the generation of megathrust earthquakes, which advances our understanding of seismic risk in subductions zones.

3.3 2010 Maule Chile earthquake

On February 27th 2010, one of the largest earthquakes recorded in recent history hit the central region of Chile [17] and resulted in a death toll of 525. The magnitude of the earthquake was 8.8 Mw, and it originated from the boundary between the Nazca and South American tectonic plates. The earthquake was categorized by a thrust-faulting focal mechanism, caused by subduction, which triggered a series of strong aftershocks as well as a tsunami. The epicentre was near Pelluhue in the Maule region and the length of the ruptured fault zone extended over 700 km in length, leading to a displacement of almost 10 meters, which corresponds to 120 years of accumulated plate movement.

4 Bridge damage observations

4.1 2023 Kahramanmaraş Turkey earthquake

As Turkey is surrounded by active faults, strong earthquakes occurred in different parts of the country, but no bridge collapse study was conducted until 2019. All bridge collapse investigations were kept confidential with very limited information. The aforementioned study reported bridge collapses between the years 2000 and 2019 and revealed that more than 80 bridges experienced failures. Road bridge collapses were attributed to hydraulic events and pedestrian bridge collapses were attributed to vehicle collisions. In 1999, Kocaeli Arifiye Bridge collapsed due to a seismic event (the Kocaeli earthquake) which resulted in fatalities. This bridge collapse drew the public opinion from the first day.

In many cases, failures occur without collapse; in this case the bridge becomes not functional for performance as intended. As a result, the bridge would need a full replacement or a major repair.

Typical engineering problems observed after earthquakes include, but are not limited to the following:

- Bearing failure and superstructure offset, both horizontally and longitudinally,
- Collapsed or tilted bridge piers due to shear or ground failure,
- Bridge spans sliding off the seat and collapsing because of large ground movements ,
- Abutment back-wall failure ,
- Connection failures between bridge bearings and pier caps, resulting shear cracks in the prestressed concrete and concrete beams,
- Bearing and joints movements,
- Expansion joint movements,
- Abutment approach fill settlement,
- Pounding at expansion joints,
- Shear key damage,
- Cable failure in cable-stayed bridges,
- Foundation failure caused by fault rupture or by soil liquefaction.

Figure 1. Bearing movement [18]

Figure 2. Joint movement and joint pounding [18]

Figure 3. Abutment rotation due to soil liquefaction [18]

In the region of the 2023 disaster in Turkey, there are more than 1000 bridges. Only 15 bridges were affected by the earthquake and about 50% were opened to traffic within a day after the two earthquakes.

The engineering problems were observed during the February 6th 2023 earthquake in Turkey are:

- Bearing and joints movements, shown in Figure 1.
- Expansion joint movements, shown in Figure 2.
- Pounding at expansion joints, shown in Figure 2.
- Abutment approach fill settlement, shown in Figure 3.
- Shear key damage, shown in Figure 4.
- Soil liquefaction which causes foundation failure.
- Lack of end diaphragms, shown in Figure 5.
- Column concrete spalling and start of plastic hinges, shown in Figure 6.

Figure 4. Shear Key Failure [18]

Figure 5. Lack of End Diaphragms [18]

4.2 2016 Muisne Ecuador earthquake

During the 2016 Pedernales earthquake, the Universidad Laica Overpass collapsed. This bridge was located close to downtown Guayaquil and at 240 km from the epicentre [19]. Two central piers and the span supported by these piers collapsed and resulted in two casualties. Pounding between the central and adjacent spans occurred as the seismic joint was not large enough to avoid pounding. As the cap beam had an irregular shape, the impact force was transmitted to the deck slabs and top of the pier cap, resulting in an increase in the shear force on the columns. The result was a brittle shear failure of the columns.

Figure 6. Concrete Spalling [18]

Bridge collapses due to earthquakes in Ecuador are relatively rare, and a study of 72 bridge collapses reported between 2000 and 2022 indicated that only 3 cases collapsed due to seismic actions [20]. In fact, most actions after the 2016 Pedernales earthquake focused on identifying the damage to buildings [21], rather than on bridges, for which control by the bridge owner is executed during design and construction, resulting in better code-compliance and better seismic performance.

4.3 2010 Maule Chile earthquake

Traditional bridges in Chile are simply supported beam bridges [22]. In these bridges, failures were mainly observed due to the loss of support of the superstructure, leading to the collapse of the deck. This situation occurred more intensely in those bridges that had structural skew, as rotations were generated due to the lack of retaining elements. Other detected pathologies included damage to main girders, due to impact against the substructure. In the case of steel girders, cases of local buckling and failures in stiffeners were observed.

Regarding the support system, failures were observed in elastomeric bearing devices due to over-compression and sliding. In the case of hold-downs, some experienced failures due to buckling, specifically those arranged diagonally. Finally, the limited-sized stopper systems did not act appropriately in containment. In the case of clamp usage, they suffered fatigue failure problems, especially due to aftershock actions, releasing the constraint of the bottom part of the girder to both lateral and vertical movement. Bridges also suffered damage to their accesses, with loss of fill material and settlements in the abutment area.

To a lesser extent, problems with the soil capacity were observed (especially in the southern zone of the country). Here, issues related to liquefaction and displacement of soil mass were observed. No major problems were detected in the design and resistance of piers and abutments.

5 Main causes of damage

The various types and locations of damage are analyzed to develop broad categories of problems that can be identified from these cases.

In terms of problems observed with the superstructure, the lack of end diaphragms caused damage in the beams ends. Column and abutment wall spalling could be common during a strong ground shaking, but formation of plastic hingers depends on the design and detailing of the elements. The cause of the expansion joint and pounding failure is also the lack of the joint spacing that is needed to accommodate the design displacement. This observation aligns with the bridge collapse reported in Ecuador.

In terms of problems observed with the bridge support devices and connection between super- and substructures, the cause for the bearing and joint movement failure is attributed to the lack of bearing area needed to accommodate the design displacement during the ground shaking. Special attention to bridges with a skewed layout is necessary, as indicated from the Chilean observations. The shear key damage and failure is attributed to the inconsistency in design between the different components, i.e. inconsistency between global behavior and local elements.

In terms of problems observed with the bridge substructure, abutment failure in Turkey is attributed to seismic soil liquefaction inducing foundation failure. In Chile, loss of fill material resulted in problems with accesses.

In terms of geotechnical problems, soil liquefaction and foundation failure was common in parts of the affected region such as the southwest region of the Turkey earthquake zone, particularly in Hatay. Local engineers indicated that soil investigation procedures are not followed properly, which resulted in improper foundation design and maybe soil treatment procedures. Similarly, a reduced soil capacity was observed in Southern Chile.

6 Lessons learned

6.1 Design of new bridges

Based on the February 6th, 2023 Earthquake in Turkey, the following design recommendations have been developed in Turkey:

- Shear key and bearing design needs to be consistent with pier design capacity.
- The shear capacity of connection details needs to be consistent with the design of other components.
- Global system effects need to be compatible with local members.
- Expansion joints need to be designed to accommodate the design displacement for the maximum considered earthquake specified in the applicable codes and standards.
- Generous seat width to accommodate unexpectedly large movements caused by ground failure or strong tremors is a very sound investment.
- Ground failures may cause structural failure; therefore, thorough site and soil investigation is required.

After the 2010 Earthquake Chile decide to modify the Manual de Carreteras code [23] in order to include the following new seismic criteria:

- Increase the length of supports at abutments and piers, following criteria from the Japanese standard.
- For bridges with multiple continuous spans with a significant total length (L_q), where the support length (S_{eq}) is large, it is proposed to reduce the angle of structural skew (less than 30°) and include longitudinal and transverse stoppers.

- For the bearing plate: Transmit deck load to infrastructure using $A_o/2$.
- The maximum displacement of the bearing plate is to be A_o.
- The expansion joint should be designed according to maximum plate displacement (A_o) + DT + concrete shrinkage.
- The vertical anchorage bars (hold-downs) should be calculated based on A_o.
- Use a bearing plate anchoring system.
- Use seismic isolation. Quality control tests should be conducted according to the Guide Specification for Seismic Isolation Design [24].
- Prefer seismic isolators made of natural rubber with damping $z = 10\%$.
- Use end and central crossbeams regardless of seismic zone and beam type.
- Use intermediate and end seismic stops as cut-off keys. The objective is to have impact and damage occur in the crossbeam rather than in the main girder.
- Develop the use of integral bridges.
- Prefer the use of monolithic column and foundation slab connections.

As in Ecuador, only limited damage to bridge was observed, the changes to the upcoming national code NEC are based on a survey of the literature and changes to international codes in recent years.

6.2 Assessment of existing bridges

For the assessment of bridges, it is important to consider the code for which the bridge was designed, and to consider the experience available in terms of the seismic performance of vintage details. In Chile, the pathologies of existing bridges are inventoried and the pathologies are standardized into Performance Indicators. This information is now included in the protocols of inspection as well as in the national dashboard for the management of bridges.

An important aspect to consider for existing bridges is the effect of material deterioration and degradation on the seismic performance of the bridge. Indeed, the seismic performance of a bridge with material deterioration and degradation can differ from the performance of a newly built bridge, affecting the lifetime seismic performance [25].

The necessary data to analyse existing bridges can be obtained by leveraging modern sensing techniques. In Chile, a research program of universities and the Ministry of Public Works is taking place to instrument bridges and monitor the dynamic behaviour of existing bridges.

Future research should also include a multi-hazard approach for the seismic assessment of existing bridges [26]. Topics that should be studied at a broader scale include a disaster (such as a tsunami) occurring shortly after a seismic event, as well as (the probability of) the rapid succession of seismic events. Additionally, we need to consider the acceleration of deterioration as a function of climate change when projecting the lifetime performance [27].

7 Conclusions

By comparing the observations from recent earthquakes in three different countries (Turkey, Ecuador and Chile), we identify the following three elements that are recurring among bridge failures and collapses:

- Pounding failures, which can be mitigated by providing an expansion joint large enough to accommodate the design displacement.
- Failures due to a faulty bearing design. Careful attention needs to be paid to bearing design, as indicated in the new Chilean code and Turkish design recommendations.
- Soil liquefaction can occur and can result in substructure failures. Therefore, a careful site investigation of the soil properties is important.

In conclusion, the three recent earthquakes have resulted in changes to the design codes for bridges based on lessons learned, and provide valuable insights for the assessment of existing bridges.

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