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# Development of the Historical Analysis of the Seismic Parameters for Retroffiting Measures in Chilean Bridges

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**Abstract:** Chile is exposed to the occurrence of medium- and large-magnitude earthquakes. As a result, national and international design codes have been developed, whose objectives are to grant an ideal behavior to the structures. However, in Chile, many of these structures do not comply with the design and construction standards of current regulations. Therefore, we propose to carry out a historical compilation that allows establishing the components that present the seismic vulnerability in bridges built from 1920 to 2010. We explored information gathered from the Government of Chile. We analyzed 553 bridges out of a total of 6835, considering superstructure and infrastructure components and seismic design evolution. The analysis emphasizes the elements that help improve the seismic performance of a bridge when natural or induced dynamic forces act on it, such as the length support, elastomeric bearing, seismic hold-down bars, transverse girders, seismic stoppers, bracing, and expansion joints. We identified that the most significant problems in bridges are the lack of seismic stoppers, both interior and exterior; lack of development length in the support tables; use of deficient expansion joints; and the inefficient construction of cross girders and baring support; in addition to the presence of differential settlements in elements of the infrastructure.

**Keywords:** bridges; historical analyses; seismic hazard; seismic provisions



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## 1. Introduction

Chile is one of the countries most subject to seismic hazards worldwide; thus, it has sustained several large earthquakes. As a result of such events, scholars and practitioners are interested in improving the design, construction, and maintenance of structures. Thus, several research studies focused on seismic demand, vulnerability [1], performance indicators [2], and the performance design carried out in buildings [3].

In the case of bridges, the existing construction methodologies and technical specifications are permanently revised and modified in order to improve seismic behavior [4,5]. Earthquake background and records in Chile date back to 1906, when the Seismological Service of Chile was created. After the Talca earthquake in 1928 (Mw 8.4), the first bridge design and construction codes were developed, such as the *Ordenanza General de Construcciones* (General Ordinance of Constructions), which were officialized in 1935 [6–8]. During the 1940s, the design and construction of Chilean bridges were based on international codes, such as the AASHTO, and European norms, such as the DIN Code, and national guidelines based on the document published by Engineer Alberto Claro Velazco, called *Normas para el cálculo y proyectos de puentes carreteros de hormigón armado* (Norms for the calculation and projects of reinforced concrete road bridges), which were used until the 1960s. Since the Valdivia earthquake in 1960 (Mw 9.5), design specifications to resist earthquakes were adopted, which were the baseline for preparing the first version of the *Manual de Carreteras* (Manual for the Highways) of Chile. However, such a version did not contain seismic design requirements for bridges. As from the Algarrobo earthquake in 1985 (Mw 7.8), seismic design criteria were incorporated into the *Manual de Carreteras*, promoting the use of elastomeric supports under the girders and the implementation of the vertical seismic bars (hold-downs), which efficiently control the vertical displacement. Additionally, this earthquake was a test for the proper behavior of pre-stressed girders [9–11].

By the mid-1990s, the international institute for the construction and handling of transportation facilities was introduced in Chile when the pre-stressed girders acquired prominence [7]. In 2002, a new version of the *Manual de Carreteras* (vol. 3) was published. In this version, for the first time, there are seismic design requirements included for bridges, providing specific seismic demand definitions according to the seismic hazard area where the structure is located, as well as the classification of the foundation soil, the influence of the mode of vibration in the importance and plastification capacity of the structure, the use of transverse diaphragms located on the ends of the longitudinal girders, the use of the vertical seismic coefficient to design the vertical anchor seismic bars, and the use of seismic stoppers on abutments and piers to constrain the transversal displacement of the superstructure [12,13]. This version of the *Manual de Carreteras* was used until 2008 [12,14]. Until the new update of the manual in 2010, many of the bridge construction projects were designed by foreign consultancy companies, mainly Spanish, who made modifications to the seismic design (see Figure 1), such as the modification of the design of the reinforced concrete girders and the elimination of the external and internal seismic stoppers and the diaphragm, in order to reduce construction times and costs.

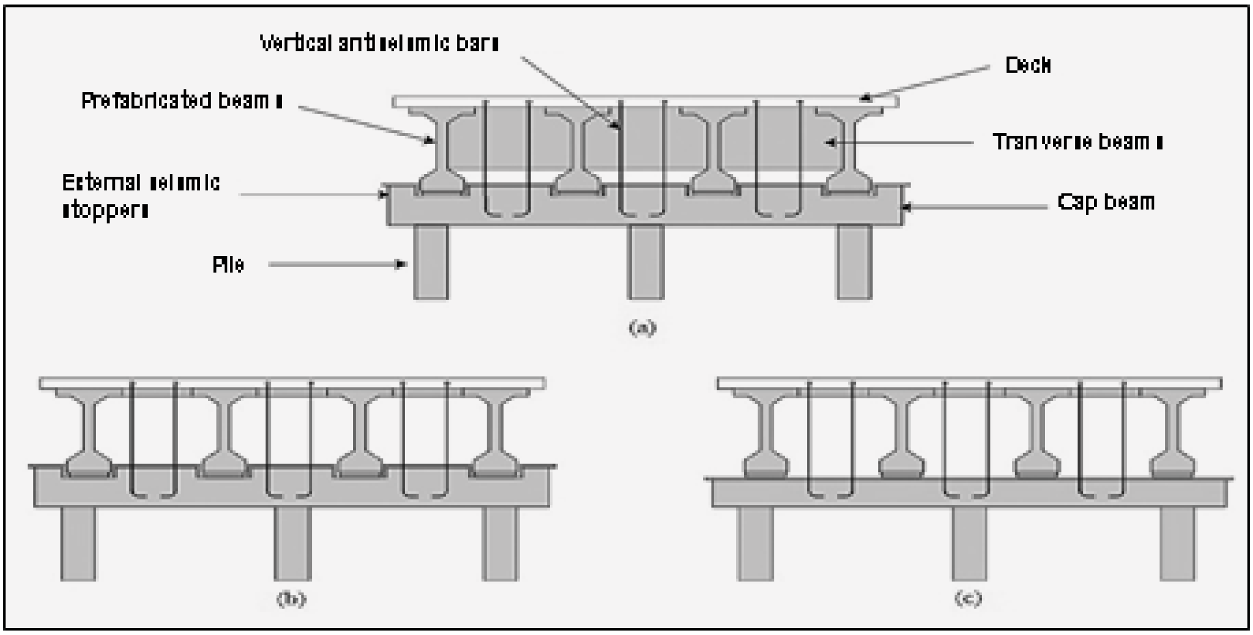


**Figure 1.** Original blueprint—typical section of Chilean bridges: (**a**) Typical section established by the *Manual de Carreteras* of Chile. (**b**) Section where the diaphragm was eliminated. (**c**) Section where seismic stoppers were eliminated.

Based on the damage observed on the bridges after the Maule earthquake in 2010 (Mw 8.8), the Ministry of Public Works, through the Department of Structures Projects, the Engineering Division, and the Highways Agency, issued a normative document indicating the new seismic criteria for the design of bridges in Chile. However, said stipulations have been constantly revised and discussed due to the updates made to the *Manual de Carreteras* after the Iquique earthquake in 2014 (Mw 8.2) and the Illapel earthquake in 2015 (Mw 8.3), which concluded in the publishing of the new version of the *Manual de Carreteras 2019*.

Considering the presented context, in Chile, several bridges with old seismic standards do not meet the current seismic provisions defined in the *Manual de Carreteras 2019*. Different periods of the historical evolution of the bridge typology challenge the Chilean engineer to provide a project that meets appropriate standards. Thus, we aim to provide a historical analysis of typologies, seismic provisions, and parameters that mainly affect the vulnerability of the existing bridges.

Thus, the paper contributes to the state of knowledge of the maintenance bridge engineering, providing a comprehensive review of the most important typologies for each historical period to offer helpful information for future guidelines regarding the retrofit of existing bridge projects.

## 2. Theoretical Background

Regarding the framework of maintenance bridge engineering, three research lines are considered to provide a comprehensive analysis for applying an adequate rehabilitation project. The three research lines are:

1. Seismic demand and structural analysis behavior, including the phenomena of extreme events on bridges and vulnerability;
2. Bridge management and inspection programs, including pathologies and performance indicators related to extreme events;
3. Performance design and seismic design provision, including the structural elements and mechanical outfitting.

These research lines are required to provide data for repair and strengthening projects. The following subchapter reviews the current research as a baseline background for this study.

### *2.1. Evolution of Bridges and Seismic Events Studies*

The evolution of studies of seismic events on bridges has been an important research area over the past few years due to the need to ensure the safety and integrity of bridges during earthquakes. We have developed a streamgraph to understand how this research has been evolving. A streamgraph is a data visualization resource to understand the evolution of a topic over time [15,16]. These are stacked area charts where the baseline is free. This change in the baseline makes it easier to see the thickness of the layers in the graph [17].

For this analysis, we searched for scientific articles in the Web of Science. We used the following search query: (bridges AND seismic) in the Web of Science (title). The search was conducted on 30 December 2022. We only considered English articles and articles as document types. As a result, we recovered a total of 2200 scientific articles.

With this dataset, we collected the keywords of the articles and ordered them by year of publication. We performed a data cleansing step, where we removed synonymous words and fields without information. In addition, we removed the keywords "bridges" and "seismic" from the analysis since we use them as part of the query. Figure 2 presents the streamgraph considering the developed dataset's top 15 most used keywords.

As a result, the graph shows the evolution of the leading research lines considering the seismic and bridge keywords. It is possible to highlight that currently, the main topic is related to seismic response and seismic performance (with an increase from 2014). The seismic fragility curve is required to provide a damage scale and define the main element to provide adequate performance in the design [18]. The graph also shows these topics during the last decade.

Regarding the seismic design in Chile, the national code considers an R-Factor design. Despite this, from 2010 until the present, several international studies on seismic design considered displacement design [19,20] and performance design methodologies.

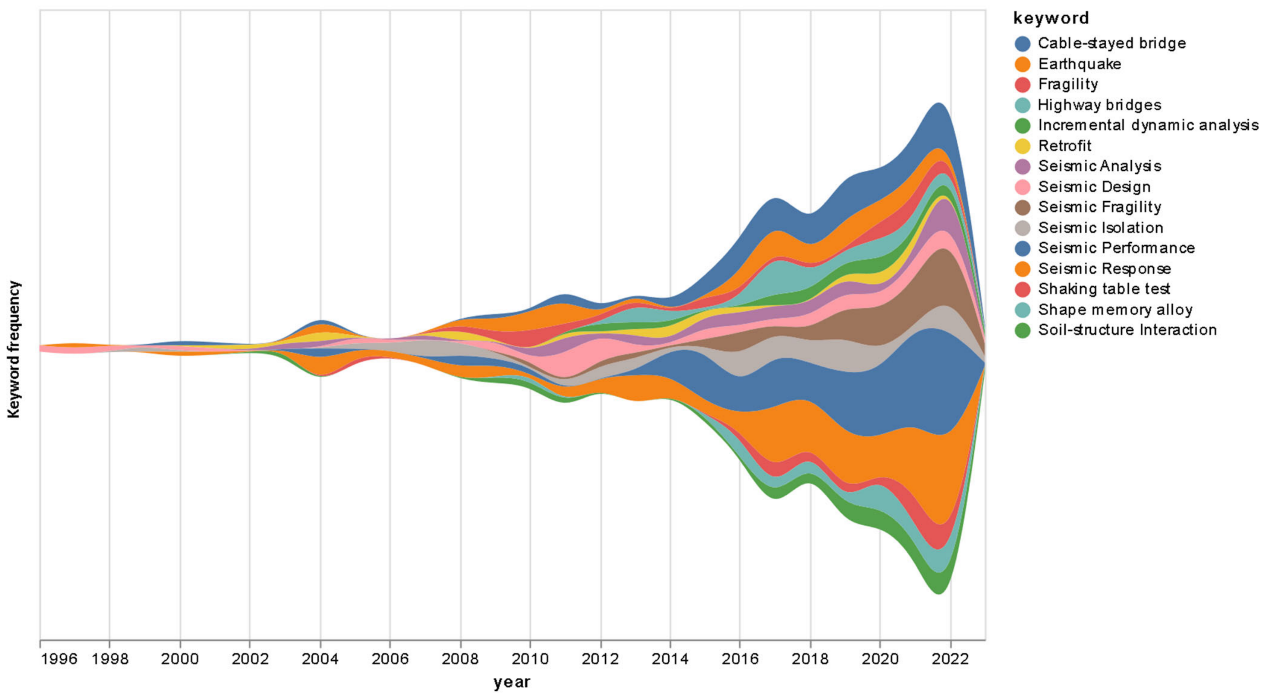


**Figure 2.** Top 15 most frequent keywords in academic papers considering bridges and seismic topics.

On the other hand, retrofit was trendy during the beginning of the 2000s, and it is still reviewed but with less focus than the other topics. This shows how the existing structures are less analyzed than the new design provision.

In this way, a study of specific parameters to define the retrofit projects as structural behavior analyses of the existing structures, observed pathologies, and bridge management programs is required.

### 2.2. *Bridge Management System and Inspections*

Bridge management systems and inspections are important because they collect information regarding the pathologies and damage. On the international level, these activities have an important relevance because they define the parameters for the seismic assessment and provide the resilience network system [21]

After the 2010 earthquake, Chile developed studies inside the ministry of public works with the following objectives: (1) to improve the design provision and (2) develop I3MOP.

I3MOP is a platform that collects and compiles inspection documents for bridges under the responsibility of the Ministry of Public Works in a progressive process of updating information on the state of existing bridges. This process is under review and will provide better information in the next decade for seismic provision and structural and durability information for the strengthening and repair projects of these bridges.

With this information, it was possible to detect pathologies related to extreme events and the aging decay of Chilean bridges in local inspections.

The platform and special inspections enabled categorizing the most common seismic damage observed in road bridges in Chile [22], highlighting collapses due to the unseating of the superstructure, and damage to the main girder, settlement, etc. Main girder and slab damage was mainly observed in the simple supported bridges.

From that inspection, and following the research lines of TUCOST 1406 in Europe [23], the Chilean academia and Ministry of Public Works focused on performance indicators, providing the PI related to the state of the art, analyzing the seismic condition of the bridge, such as damage to stoppers or hold-downs [2]. From these studies, vulnerability analysis is possible using damage-scale and fragility curves [24]. Finally, seismic provision for new structures was included in the new Chilean code. This information is also a reference for the retrofitting project.

### *2.3. Theoretical Analysis of the Seismic Provision of the Manual de Carreterras (2019)*

This section comprehensively analyzes the new seismic provisions included in the current Chilean code. These parameters have been considered the baseline standard to be compared with the seismic provision developed in the historical analysis from the method's section. Regarding the current Chilean code applied to the seismic design for bridges, we set the following performance targets:

- Bridges facing moderate earthquakes have to provide an elastic behavior;
- Bridges facing medium earthquakes have to mitigate damage to the non-structural elements;
- Bridges facing large earthquakes have to avoid the collapse of the structure.

Each performance target applies to traditional bridges, whose main span lengths do not exceed 70 m [25]. After the Maule earthquake in 2010 (Mw 8.8), new stipulations for seismic design were developed, mainly based on the Japanese code for the design of bridges and the AASHTO 2002. Such considerations were formally included in the *Manual de Carreteras* of 2015 [7,12]. From 2017 to 2019, the *Manual de Carreteras* was updated, providing more and better details on the seismic design criteria than the document issued in 2010. The following are the most important modifications [7,25]:

- The use of external and intermediate diaphragms, regardless of the seismic area or the type of girders to be installed;
- The use of external and intermediate seismic stoppers, located both on the abutments and piers. The stoppers must act as fusible elements when they impact the diaphragms due to the transversal displacement of the superstructure;
- The external and intermediate seismic stoppers must be designed for an Ao vertical acceleration. The gap between the internal stoppers and diaphragm must be equal to the maximum height of the bearing supports, plus 5 cm. The intermediate seismic stoppers have to be 7 cm;
- Increase the minimum length of the bearing support based on the following formulae:

$$SE \geq 0.7 + 0.005L \text{ (For straight bridges)}$$

$$SE\theta \geq 2L\theta \sin\left(\frac{\alpha E}{2}\right) * \cos\left(\frac{\alpha E}{2} - \theta\right) \text{ (For skew bridges)}$$

where $SE$ and $SE\theta$ represent the length of the bearing support, $L$ is the length of the superstructure, $L\theta$ is the total length of the bridge, $\alpha E$ is the rotation angle (generally 2.5°), and $\theta$ is the crabbing of the bridge.

- The elastomeric support for the girders must be fully anchored to the infrastructure and the corresponding girder;
- Vertical bars must be used to restrict the vertical displacement and reduce efforts on the bearing supports;
- Devices must be used to prevent the loss of longitudinal support on the girders.

The last update of the *Manual de Carreteras* was made in 2019, mainly based on the AASHTO (2011) and its variant AASHTO LRFD (2011), as well as the Japanese norm JRA 2012. The updates provided more conservative design criteria for Chilean bridge design. As a result, we have achieved a robust and trustworthy performance of the structures during important seismic events [7]. Finally, this is the baseline seismic provision for the Chilean bridge design applied for new structures.

## 3. Methods Section

International research focuses on defining the main seismic parameters [26] to determine two main activities: (1) classes and taxonomy and (2) dataset of the existing bridges. Our research was based on a data gathering of main parameters about traditional bridges granted by the Ministry of Public Works of Chile. We gather all the available bridge drawings (10% of the country's total bridges), which results in 762 bridge drawings. From this data collection, we were able to analyze 553 bridge projects, as those were the ones with legible information. For the data analysis, we studied the evolution of the superstructure and infrastructure components and seismic design considerations from 1920 to the 2010s, focusing on the elements that improve the behavior of the bridge.

The main elements studied were the length support bearing, bearing devices, seismic bars, diaphragms, seismic stoppers, and expansion joints. The information provided by the Ministry of Public Works is organized into decades, enabling chronological analysis. Additionally, the drawings were fully digitalized. In the data analysis, we detected some misleading information about certain bridges. For instance, some images are unclear, making it challenging to analyze structures; however, we are able to provide the following considerations:

- Classification of information about each bridge was made, setting general parameters, such as the name, location in the region, province, and route where the bridge was built. Additionally, specific parameters were considered, such as typology, length of the bridge, the main span, number of existing spans, width of the carriage way, total deck width, and materials of the deck;
- The elements considered in the infrastructure were the length of the bearing support, the presence of seismic stoppers, the configuration of the wing-wall abutment, and the typology of piers and foundations. For the superstructure, we considered the number, separation, material, and dimension of the girders, the arrangement of the seismic bars, the location and material of the diaphragms, the typology of bearing, and the expansion joints;
- After determining the parameters of each bridge, we clustered the bridges of similar typology to set a sort of seismic provision per decade.

## 4. Results

The results respond to the modifications that have been made in Chile at the regulatory level. Below are the main statistical analyses performed on the dataset.

- AASHTO: 1935–1953;
- Norm for the project calculations of reinforced concrete road bridges (Alberto Claro Velazco): 1954–1980;
- *Manual de Carreteras:* Vol. 3—1980;
- *Nuevos Critérios Sismicos*—2010–2011;
- *Manual de Carreteras* Vol. 3—2017–2019.

The next subsections show the details of the main seismic structural provisions of traditional Chilean road bridges.

### *4.1. General Typology*

A historical analysis of bridge typologies led us to understand Chile's most implemented structural bridge typology. Such typology is the simple support and straight span, with a deck of slab and girder (Figure 3). This typology represents more than 93% of the analyzed bridges (Figure 4). They were implemented in the 1970s, replacing continuous straight-span bridges, arch bridges, and suspension bridges.

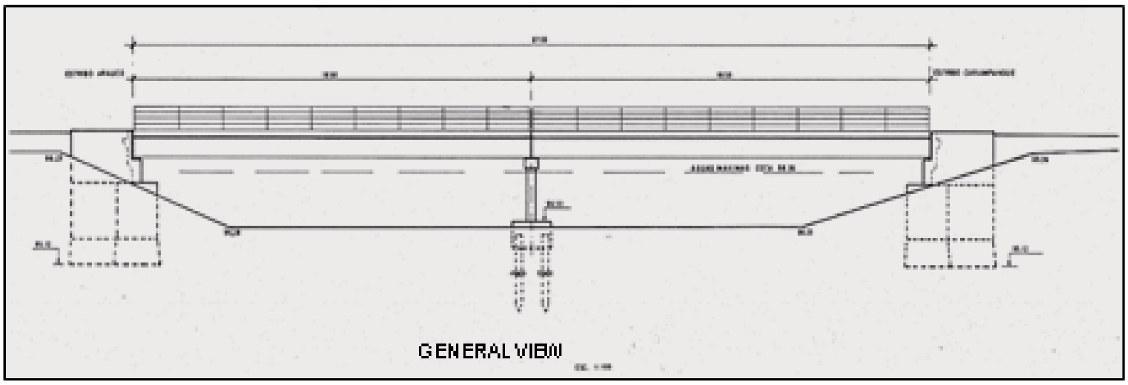


**Figure 3.** Original blueprint—Huillines Bridge No. 2.

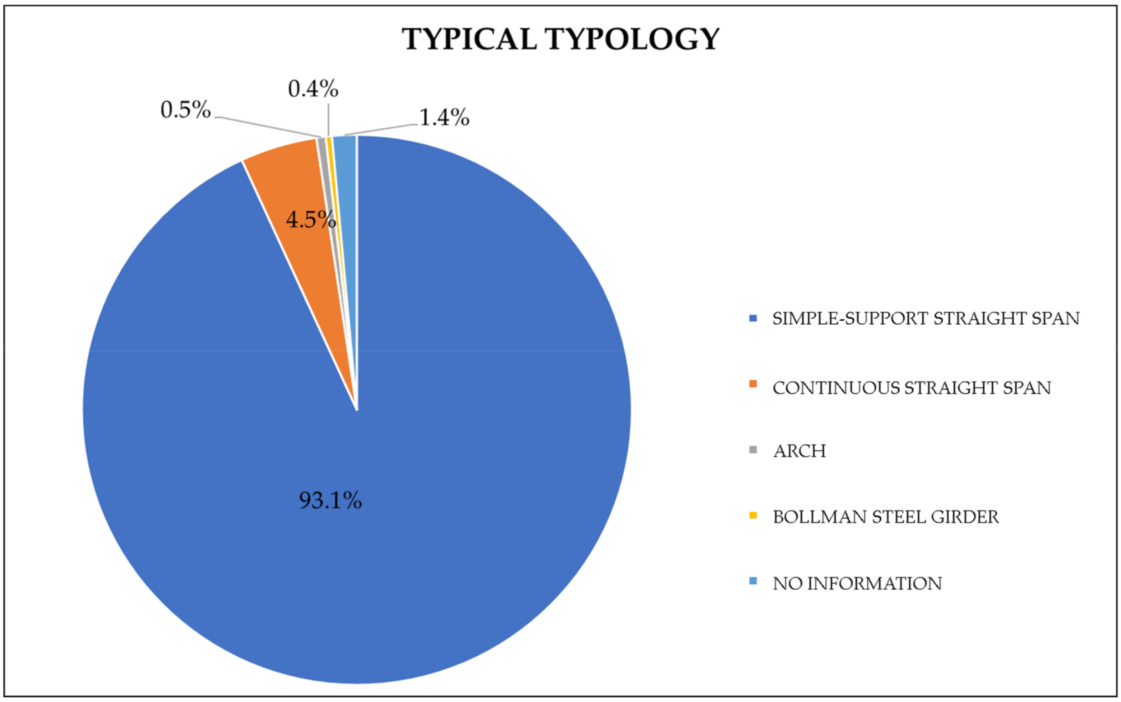


**Figure 4.** Historical classification of Chilean bridge typology.

*4.2. Main Girders*

Throughout the historical analysis, different girders have been implemented with varied design factors, dimensions, and materials. Table 1 specifies the percentage of the girders and the typology of bridges. Steel girders were frequently implemented until the 1990s. Between the 1920s and the 1950s, reinforced concrete girders prevailed, mainly Gerber-type girders, because they improved continuous-span bridges. In the 1950s, the quality standards and use of materials to build reinforced concrete girders materials were improved. Nevertheless, their implementation in bridges was reduced until the 1980s. From that day until the present, pre- and post-stressed girders replaced steel girders.

From the 1960s to the 1990s, Chilean bridges used steel girders (Figure 5). That is because of their economic and structural characteristics, which use A37-24ES and A52-34ES steel. The flange and web of the girder are welded. The girder also has stiffer load and distribution plates, as well as transverse bracings. However, the link between the girder and slab has different connectors. From the 1950s to the 1990s, it used spiral connectors. From the 1990s to the present, it used c-connectors and Stud bolts.

**Table 1.** Historical classification of girders in Chilean bridges.

| Type of Girders | Quantity | Percentage |
|---|---|---|
| Post-stressed | 236 | 42.68% |
| Pre-stressed | 70 | 12.66% |
| Steel | 184 | 33.27% |
| Slab | 20 | 3.62% |
| Box Girder | 5 | 0.90% |
| Arch | 3 | 0.54% |
| Reinforced concrete | 14 | 2.53% |
| Reinforced concrete Gerber | 7 | 1.27% |
| N/I | 14 | 2.53% |
| Total= | 553 | 100% |

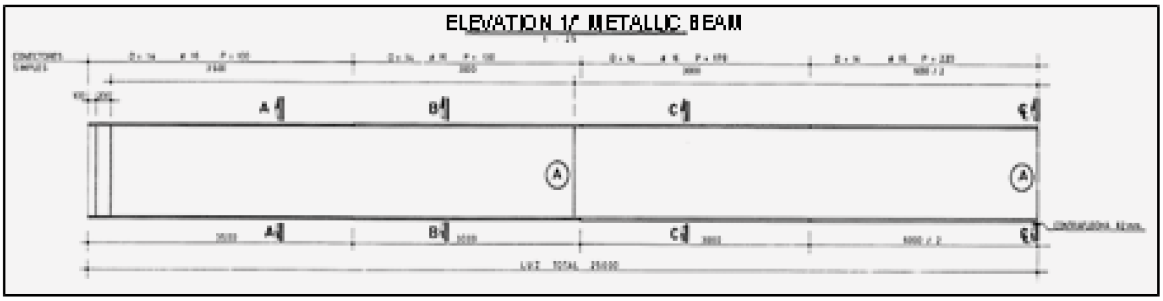


**Figure 5.** Original blueprint—steel girder in Chañar Blanco bridge.

Girders with pre-stressed reinforcement appeared in the 1960s, and from the 1990s, their use became more frequent, with a particular focus on post-stressed girders. Such girders are made of high-strength concrete, with a compression stress of between 350 kg/cm$^2$ and 380 kg/cm$^2$. The pre-stressed reinforcement rebars are generally each made of seven-wire cables (Figure 6). The reinforcement is made of longitudinally and transversely assembled ribbed rebars, with A63-42H (fy = 420 MPa).

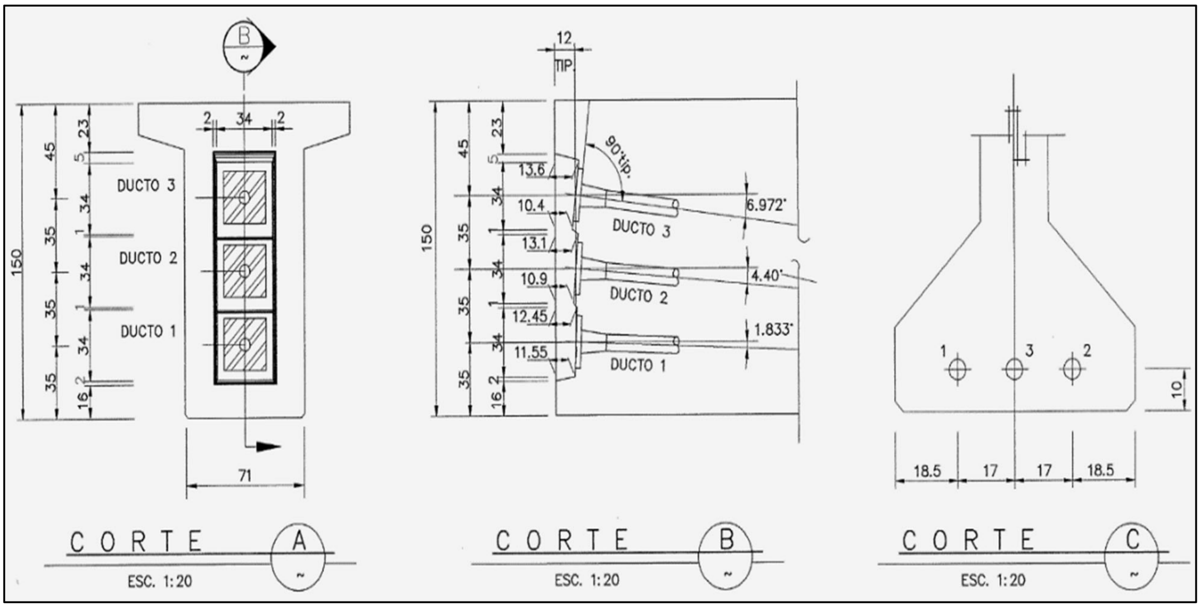


**Figure 6.** Original blueprint—pre-stressed girders on Guayacán bridge.

### 4.3. Foundation

It can be seen that Chilean bridges are based on two types of foundations: a jacked-box shallow foundation into the soil and a deep foundation created with a piles system. The more frequent material used is reinforced concrete (Figure 7). The depth and dimensions depend on the soil's characteristics and the load requirements that the bridge can bear.

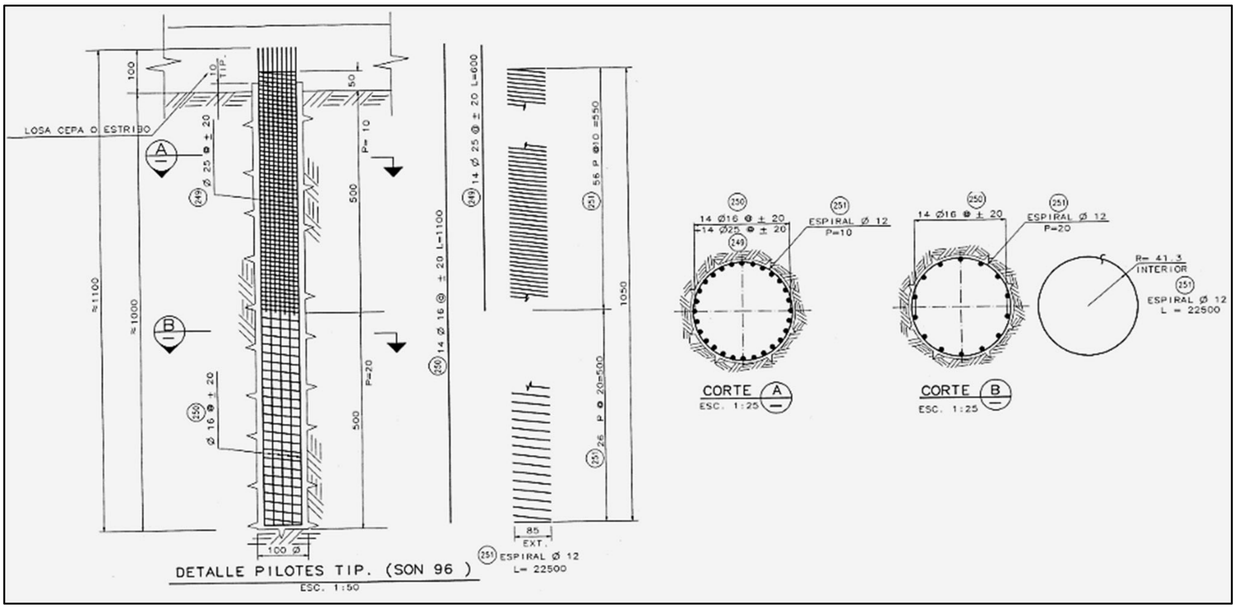


**Figure 7.** Original blueprint—the pile-type foundation of Río Blanco bridge.

### 4.4. Piers

There were 280 bridges with piers in their infrastructure, 133 of which had wall-type piers, which were mainly used in multi-supported bridges. The remaining 142 bridges are considered as possessing pile piers, which have been more frequently used since the 1980s. These pile piers are preferred for scouring conditions. Both types of foundations are generally made of reinforced concrete. More detail on the Chilean typologies of the pier is shown in Table 2.

**Table 2.** Type of piers in Chilean bridges.

| | Type of Piers | |
|---|---|---|
| Wall | 133 | 24.05% |
| Pile-pier | 142 | 25.68% |
| Portal frame | 3 | 0.54% |
| Steel portal frame | 2 | 0.36% |
| N/I | 273 | 49.37% |
| Total= | 553 | 100% |

### 4.5. Bearing Support

Several bridges with larger skew angles can be seen, which were mainly built in the 2000s. Most curved bridges had a skew angle greater than 45° concerning the standard longitudinal axis of the bridge and the river flow direction or obstacle they faced. Before 1950, girders used to lay mainly on fixed steel supports. The use of slide-bearing supports was also noted, predominantly used in Gerber girders. As from the Valdivia earthquake in 1960, steel supports were replaced with elastomeric supports. However, these were not adequately connected to the infrastructure or the superstructure, causing them to move during an intense seismic event. Therefore, as from the Algarrobo earthquake in 1985, these components were enhanced and designed to comply with seismic requirements. This elastomeric support is located on the abutments and cap girders of the piers, and their structure has to include steel plates from 2 mm to 4 mm thick and with elastomers of 40°, 50°, and 60° SHORE hardness. Figure 8 presents the distribution of the typology of bearing support. Note that Chile used cardboard painted with tar between the beams and the concrete support in order to protect them from both elements.

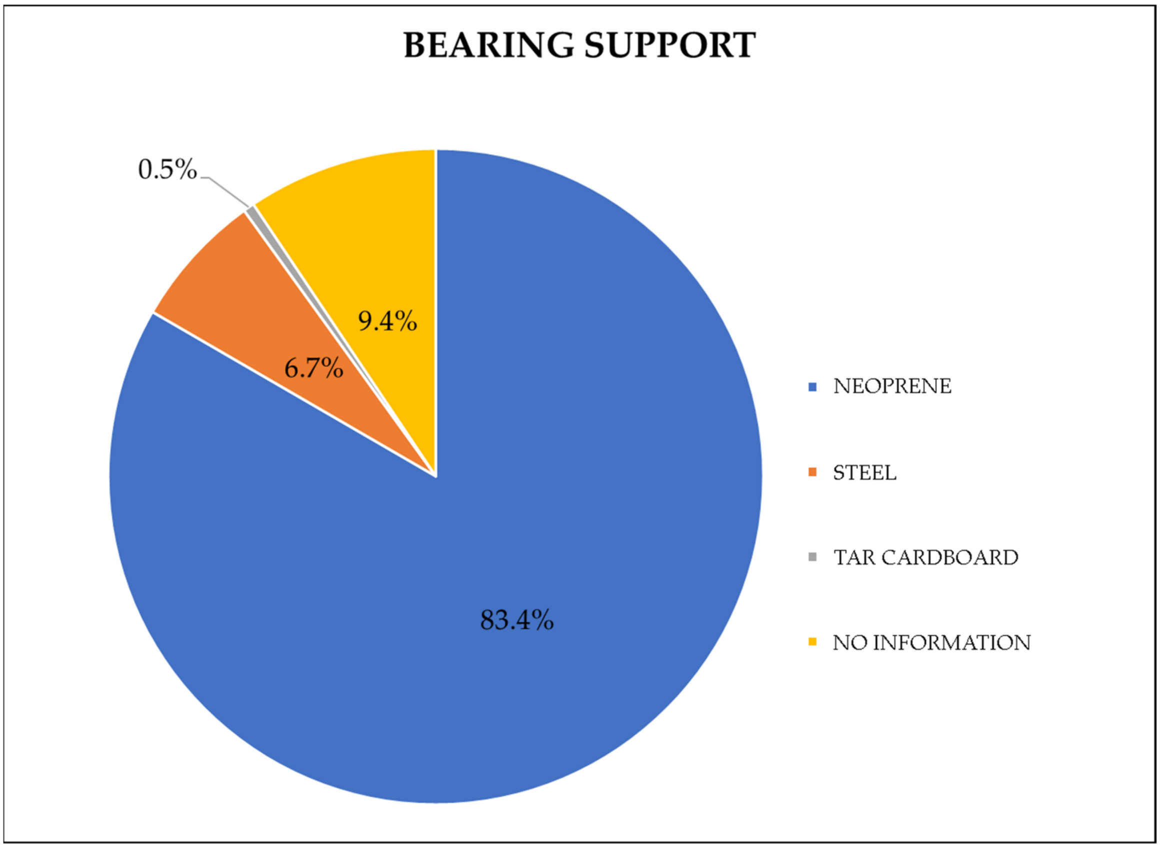


**Figure 8.** Historical classification of types of Chilean bridges.

### *4.6. Seismic Bars*

Regarding seismic bars (hold-downs), Chilean bridges included hold-downs with a diagonal arranged until the 1970s to prevent the deck from moving vertically and transversally. They also controlled horizontal movements, given the lack of seismic stoppers. These anchor bars were made of smooth, round steel rebars and were directly embedded to connect the slab with the abutment and/or cap girders; however, as from the 1970s, diagonal bars were replaced with vertical bars. Since 1980, thermo-mechanically treated steel has been protected by PVC or galvanized steel pipe to ensure that the slab with the abutment and/or cap girders is appropriately secured. They were used as helical bolts, and once they were tightened at their spot, a welding spot was made at the end to ensure that the lock nut would remain in place. More details of the seismic bar are shown in Table 3 and Figure 9.

**Table 3.** Types of anti-seismic bars in Chilean bridges.

| | **Seismic Bars** | |
|---|---|---|
| Vertical | 471 | 85.17% |
| Diagonal | 30 | 5.43% |
| Vertical/diagonal | 2 | 0.36% |
| Horizontal | 2 | 0.36% |
| N/I | 48 | 8.68% |
| Total= | 553 | 100% |

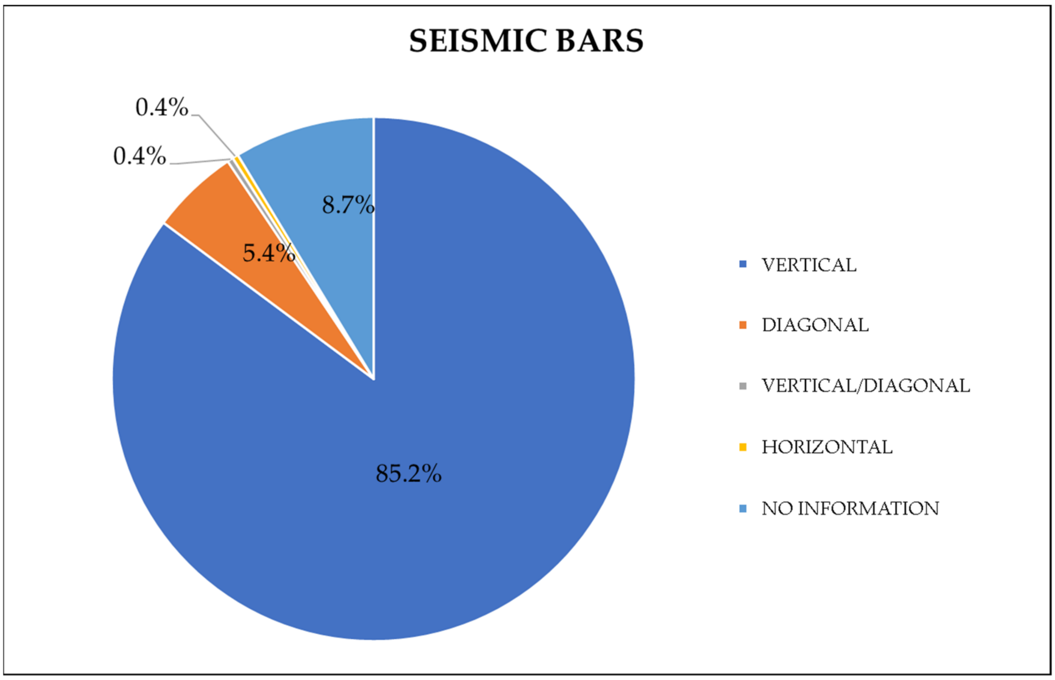


**Figure 9.** Historical classification of seismic bars.

### 4.7. Seismic Stoppers

Seismic stoppers were implemented in the 1970s and were referred to as thin-small-wall (called wall-plugs in Chile), located at the ends of the abutments and pier caps. As of 1990, the seismic stoppers were widely implemented and began to be considered part of a bridge's seismic protection components. However, from 2000 to 2010, there was a decrease in their use in construction because foreign contractor companies amended the seismic design requirements in force at the time (Figure 10), including removing external seismic stoppers to minimize runtimes and construction costs [14].

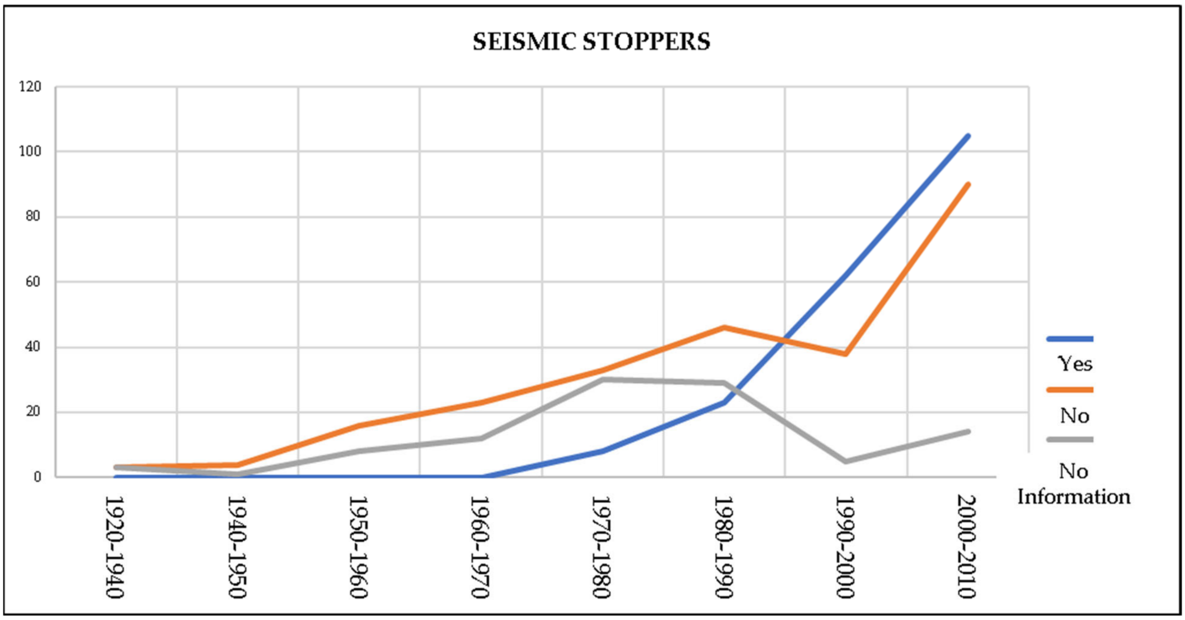


**Figure 10.** Historical evolution of the implementation of seismic stoppers.

### *4.8. Bearing Length*

The length bearing was the parameter that showed more significant variability in their dimensions throughout time (Table 4), although there was a tendency toward standard dimensions for each decade. However, these lengths were not enough, as one of the pathologies more frequently sustained by the bridges affected by earthquakes was deck collapse, mainly due to undersized lengths in the development of length bearings.

**Table 4.** Dimensioning type of the length bearing throughout history.

| **Bearing Table** | | | |
|---|---|---|---|
| **Year** | **Min.** | **Max.** | **Mode** |
| 1920–1940 | 0.30 m | 0.65 m | Not applicable |
| 1940–1950 | 0.40 m | 0.50 m | Not applicable |
| 1950–1960 | 0.35 m | 0.50 m | 0.40 m |
| 1960–1970 | 0.35 m | 1.10 m | 0.50 m |
| 1970–1980 | 0.30 m | 0.75 m | 0.50 m |
| 1980–1990 | 0.30 m | 1.17 m | 0.50 m |
| 1990–2000 | 0.35 m | 1.25 m | 0.70 m |
| 2000–2010 | 0.50 m | 2.05 m | 0.70 m |

### *4.9. Expansion Joints*

The expansion joints showed significant changes to their configurations, particularly during 2000–2010, since during this decade, in addition to the edge reinforcing-type and elastomeric-type expansion joints, there were variations such as ProFlex, VSL, JNA, and PVC joints. Elastomeric expansion joints were the most commonly used, whilst the edge-reinforcing expansion joints were the ones that experienced significant structural changes, such as the adherence of serrated, elastomeric plates. Table 5 details expansion joint types.

**Table 5.** Expansion joint type.

| **Expansion Joint Type** | | |
|---|---|---|
| Edge reinforcing-type | 295 | 53.35% |
| Elastomeric | 179 | 32.37% |
| Transflex | 5 | 0.90% |
| ProFlex | 1 | 0.18% |
| VSL | 1 | 0.18% |
| JNA | 2 | 0.36% |
| PVC (polyvinyl chloride) | 1 | 0.18% |
| Neoprene | 1 | 0.18% |
| No Information | 68 | 12.30% |
| Total= | 553 | 100% |

## 5. Discussion

### *5.1. Seismic Provision Analysis*

Regarding the historical analysis of the seismic-controlling elements, it was possible to determine the structural components that showed more significant variability throughout history, including those that influenced the final performance of the structure when undergoing medium- and large-magnitude earthquakes. In order to determine these components, a Pareto chart was used. This basic statistical tool allows us to prioritize the number of bridges to be analyzed based on identifying their most relevant issues, bearing in mind that 20% of the components showing significant differences lead to 80% of the incurred issues on a global scale [27].

Regarding the criteria for the identification of relevant issues, a classification was made based on the seismic design criteria for seismic protection elements of bridges presented in Vol. 3 of the *Manual de Carreteras*. In addition, the structural typology and length of the bridge, the type and number of girders implemented, the number of spans, and the presence of piers in them were considered.

From the 553 bridges analyzed, we determined that the main issues associated with the seismic performance of Chilean bridges built from 1920 to 2010 are the lack of seismic stoppers, undersized bearing lengths, and the use of expansion joints. However, it is worth mentioning that there is a lack of proper construction criteria in bearing support from 1920 to 1990, in addition to the differential settlements in piers. These pathologies make up 80% of the seismic issues of the bridges analyzed. These issues shall be analyzed in detail to establish proper retrofitting projects. Figure 11 shows the Pareto chart with the results mentioned earlier. The Pareto analysis provided in this study match with the evidence observed in the I3MOP data collection.

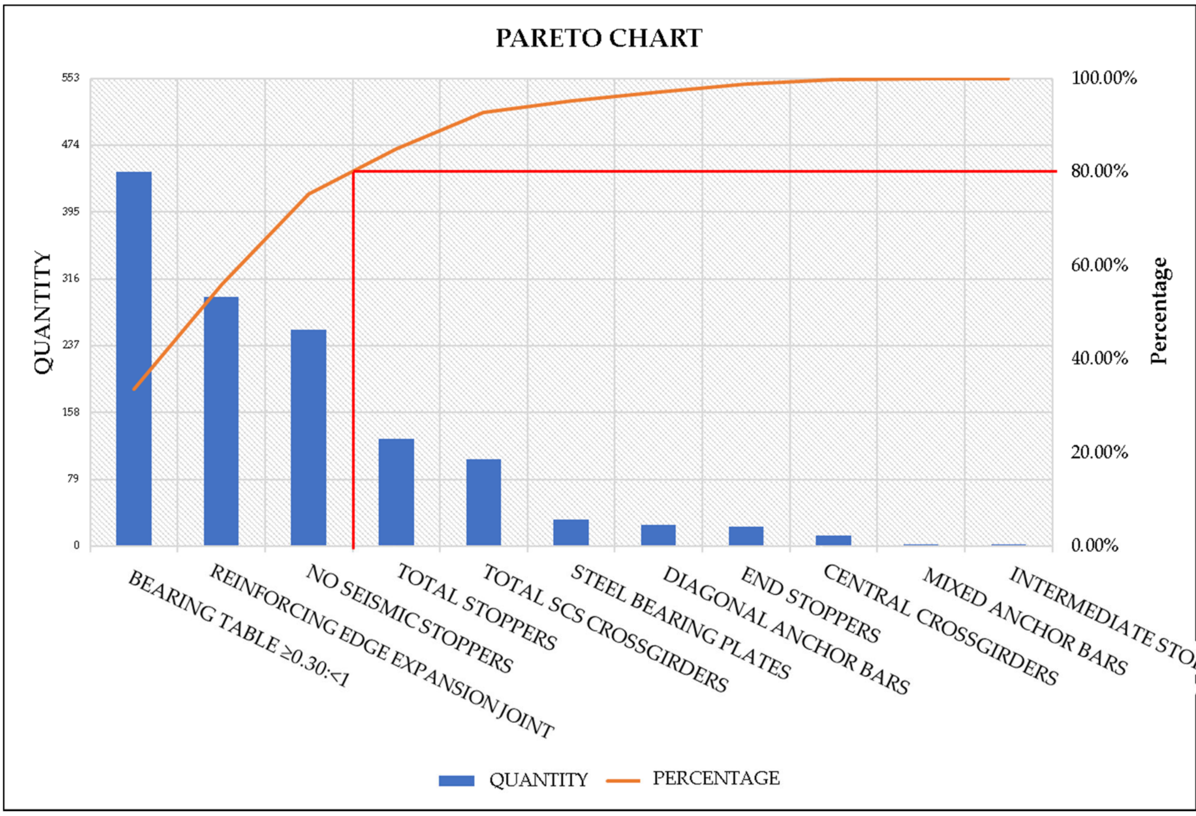


**Figure 11.** Global Pareto chart that shows the variability of the seismic protection components of bridges throughout history.

When we focus on this provision, it is possible to comment that:

1. The main pathologies observed in several earthquake events in Chile include: horizontal displacement of the superstructure, settlement and damage on structural elements (main girders), and seismic provision (buckling of seismic bar, impact and damage of bearing support and expansion joint) [28];
2. The three main parameters are the lack of seismic stoppers, undersized bearing lengths, and the use of expansion joints. This seismic provision has to be considered a comprehensive mechanical outfitting system. The system applied to the traditional Chilean bridges of simple supported bridges, as well as straight and skewed, and their subsequent performances, must consider the superstructure's constraints due to excessive horizontal displacement:
    (a) In that case, not using seismic stoppers produces an uncontrolled horizontal displacement of the superstructure. If we use a stopper with a reduced dimension, the constraint could be ineffective and possibly collapse due to the

aftershock. On the other hand, using a seismic stopper can impact the main girder and not the crossbeam, making it possible to reduce the transverse displacement. However, this provokes damage in the main girder. This condition is against the performance target: to protect the main elements;

(b) An undersized bearing length is considered for longitudinal and transverse displacement. This condition is most relevant in curved or skewed bridges because their displacement is combined, with undersize parameters even further reduced due to the superstructure's torsional effects. The use of a stopper and the length size have to be studied and correlated. The longitudinal and transverse stoppers have to be considered in curved bridges and sloped ones;

(c) The typology of the expansion joint is fitted due to the original structural analysis of the typology. The pathology observed on several bridges under seismic events is a collapse of this device. Change to the expansion joint modifies the superstructure's general displacement and provides a better seismic performance. Despite this, a careful study must be performed to reduce the intervention on old concrete slabs and ensure the adequate compatibility of base materials. Similarly, a dimension study of each element must be considered.

The seismic bar (hold-downs) is also considered part of Chile's mechanical outfitting. The performance expected is to control the vertical displacement. This condition is related to reducing tension effort on the bearing support. The use of a diagonal seismic bar shows a lack of performance due to buckling phenomena. Compression and tension are presented during an earthquake event and aftershocks. Such a situation reduces the capacity because the use of vertical bars is mandatory. Additionally, the dimension size and steel quality have to be reviewed. Lab tests demonstrated that transverse displacement affects the hold-down behavior due to the yielding and loss of torque in the connection zone of the hold-downs [29].

The mechanical outfitting behavior has to be considered for retrofitting projects due to the consequences provoked by changing one of these provisions. For instance, modifying the support-bearing device can alter the stiffness, and the displacement inducing stoppers and expansion joints could be out of the original design range or induce forces lower or greater than the original design.

Finally, there are structural elements required for seismic provision. Bracing and crossbeams (diaphragm) are included in structural performance for two main purposes: to provide a better transfer to deformation and tension on the whole superstructure and because they are also used as a secondary element to impact with the seismic stoppers. In existing bridges, the main issue is that the fusible elements have to be the stoppers and provide enough strength in the crossbeam. Still, this analysis has also considered the piers and abutment. The main issues are the axial effort introduced on the wall and columns of the piers due to the weight of the crossbeam. Additionally, it is relevant to include any effort induced by the crossbeam and stopper impact. The piers and abutment design have to be checked regarding the safety margin or R-factor design. This design methodology was implemented from the first *Manual de Carreteras* (1980). For that reason, the older bridges must consider a specific structural analysis including these phenomena.

### *5.2. Practical Implications*

Currently, the guidelines of the *Manual de Carreteras* consider the following retrofitting projects for existing bridges in Volume 7 [25]:

- Replacement of bearing support;
- Replacement of expansion joint;
- Retrofitting of girder (steel and precast).

Nevertheless, after this research, as practical implications of the presented results, the technical team of the Ministry of Public Works started a review of the *Manual de Carreteras* in order include the following retrofitting projects for existing bridges:

- Increasing the length bearing support in abutment and piers;
- Including intermediate and external stoppers;
- Replacement of hold-downs;
- Including crossbeam or bracing.

The retrofitting projects have to be analyzed considering individual bridge typology and the specific requirements of each decade. Therefore, all of the information provided in this research is the baseline for that study.

### *5.3. Limitations*

Our review process considers about 700 drawings of existing bridges. It represents 10% of the total bridges constructed from 1920 to 2020. However, the database is limited because, during the 1980s, a fire destroyed several blueprints and drawings collected in the Ministry of Public Works. About 500 drawing considered for review were selected due to the visualization and digitalization limitations of the data. Regarding the methodology proposed, the seismic criteria are focused on traditional bridges. Traditional bridges correspond to simple supported or continuous bridges, with a superstructure of a main girder and collaborative slab, abutments, and concrete piers. These bridges are the most frequently constructed in Chile, and this typology suffered substantial damage during the Earthquake of 2010. This study does not consider singular bridges as cable-supported bridges or arch bridges. The study also does not consider a direct in situ analysis of each bridge. However, our discussion considers the match between the cadaster of pathology observed during the 2010 Earthquake and the inspection process collected in recent years using the I3MOP platform [22].

## **6. Conclusions**

A total of 762 files were revised, of which 553 bridges were analyzed; thus, it was possible to determine the impact that national and international codes have on establishing typologies to create construction standards. As relevant parameters in the historical evolution of seismic-controlling elements and their incidences in Chilean construction, a predominant configuration typology was evidenced for each decade analyzed.

Seismic parameters implementation for bridge design emerged as normative in the 1990s. Such parameters were applied to design and construction criteria until the 2000s, given the changes to the seismic design of bridges that the foreign consultant companies made in the same decade, probably aiming to minimize construction times and costs. Changes to designs were mainly focused on eliminating internal and external seismic stoppers and crossbeams (diaphragm), causing various structural issues that were highly evident during the Maule earthquake in 2010 (Mw 8.8).

In general, the failure modes that caused the most significant problems on bridges are the absence of seismic stoppers, both internal and external, undersized lengths in bearing support, the use of weak expansion joints, the inefficient construction of crossbeams and bearing support, as well as the presence of differential settlements in infrastructural elements, which are shown in the Pareto chart herein. Finally, this investigation highlights the high seismic vulnerability of bridges in Chile due to the constant changes to Chilean construction regulations throughout history, explaining the need to continuously improve the design and construction codes to develop better execution techniques for future bridges.

From this historical analysis, we obtained information on the structural typology and main seismic provisions that facilitate the preparation of a classification or taxonomy of Chilean bridges for seismic risk assessments. From 2022, scholars and Chile's Ministry of Public Works have developed this topic with the objective facilitating future studies.

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