THE 2010 EARTHQUAKE IN CHILE – LESSONS AND ROAD MANUAL UPGRADE

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Abstract

Chile, like Japan, is one of the countries with the highest seismic activity in the world, where intense earthquakes have occurred in the past and will continue to occur in the future. For this reason, the Chilean government seeks to improve, based on the experiences, various disaster risk mitigation systems: increase awareness of the public in disaster prevention, improve early warning systems, improve evacuation routes, include maps of flood risk in coastal areas, improve the capabilities of emergency institutions and, in the field of engineering, investigate and generate improvements to design standards, both for bridges and buildings.

The last intense earthquake in Chile (Mw 8.8) on 2010 has been very important in that sense, since it has been the subject of various investigations and studies on field about Structural Design, Seismic and Geological Engineering. In particular for the Ministry of Public Works of Chile (MOP), the earthquake made evident the need to analyze and reformulate aspects of the design that were violated, reflected in the road disconnection of the country after the seismic event. That is why MOP establishes the need to generate legislation in a state of emergency to identify and quickly correct the various design parameters that were overwhelmed during the earthquake with the aim of giving continuity to the review, approval, construction, and repair projects in the country.

For this reason analysis and research had been done and Seismic Design Criteria were issued consequently. The research concluded that the design parameters that had been violated during the earthquake of 2010 were: ignorance about superstructures behavior related to skew, small support length, lack of side stoppers, and insufficient connections; that is, failure of vertical support and movement control of the system. It should be noted that the seismic design criteria in a state of emergency provided solutions to issues raised; but not efficiently.

In order to make more efficient and safer regulations, four years later, with the cooperation of the Japanese government through JICA, the Department of Projects Structures began updating the seismic criteria of state of emergency. This process ended on March 2017 with the addition of Annex 3.1000-A (Seismic Design Criteria of Highway bridges in Chile) to Road Manual of Chile.

There are two targets with this work; the first is sharing Chilean experiences about the 2010 earthquake in Chile (27F) by showing various kinds of damage to bridges and how these issues made Chilean engineers propose seismic design criteria, upgrading from Standard Road Manual (before 2010), the emergency code of Seismic Design Criteria on 2010 to final version of Seismic Design Criteria on 2017 (Annex 3.1000-A). These two Seismic Design Criteria versions are similar in topics but they have differences related with design. For example, the emergency code required that each lateral stopper was designed to resist all seismic force due to superstructure acceleration during an overdesign earthquake; however, Annex 3.1000-A requires lateral stoppers are designed as an energy dissipation system so that the lateral stoppers will fail during an overdesign earthquake. The second target of this work is making comparison between before 2010 Road Manual version and Annex 3.1000-A in order to show the advantage of the final version. Bridges designed according to the two versions are compared and their differences related to vertical support system, lateral containment system, and seismic behavior are presented and discussed.

Keywords: intense earthquake in Chile, bridges damages; lateral stopper; Seismic Design Criteria; Road Manual of Chile

1. Introduction

This document explains the damages in bridges observed after 2010 earthquake of Chile and explain the main differences between oldest version of the Road Manual and the newest version. This newest version correspond an upgrade related with lessons learned from 2010 Chilean earthquake, mainly with the prevention of lateral displacement of the slab. The analysis sequence of this document is the following: type of damage, damage analysis, upgrade of the Road Manual, and some comparison between oldest version of Road Manual and newest version of Road Manual.

2. Ministry of Publics Works

2.1 Values

Compromise and love for Chile, honest management, excellence in the tasks develop, and finally, great teamwork.

2.2 Mission.

Recovering, strengthen, and get better the management of structures and improve the web connection with structures in addition to increase people and territory safety. Moreover, the idea is taking advantage of optimally water resources taking care of the environment. On the other hand, contribute to the economic, social, and cultural development promoting the equality, life quality, and similar opportunities to all Chilean people.

2.3 Vision

Contribute to the construction of an integrated, including, and developed country through service standard, quality standard, efficiency, sustainability, and honesty with which it provides all structures and roads but taking care of hydraulic balance that country need. Also, it is used public and private forces in a participative territorial planning process to give citizens whatever they specifically need.

2. Type of Damage

2.1 Data

The recollection of damages' data started a few days after the earthquake in 2010. Many Chilean engineers made fields visit in all the country, principally from epicenter zone to Santiago. The objectives were to discover damages routes or damages highway, find collapsed bridges or damaged bridge, localized it, and make a database with this structural damage, then categorized them according to the type of damage. Furthermore, in

2010 Japanese experts are dispatched to Chile post-earthquake survey working with Chilean engineers of MOP under the framework of KIZUNA Program.

The results obtained with all the activities to recollect damage information is show in the next table. The damage classification is from 1 to 5, where 1 means no damage, and 5 means the collapse of the structure.

Table 1: Classification according to Type of Damage

Classification	Damage Type	Damage Description
1	No damage	No damage
2	Slight damage	Damages that must be repaired, without structural compromise
3	Considerable damage	Damage that must be repaired, without structural compromise but affects service bridge
4	Serious damage	Bridge out of service, there are structural damage, unstable structure
5	Collapse	Collapse, fall of deck

The following Table contains just a part of the total database recompiled after the 2010 earthquake, in specific this information is related to concessioner bridges. This information was obtaining from reports that each concessioner company must to send, two times in a year, to the Department of Structural Project of Ministry of Public Works. In addition, this information has been checked with engineers of MOP. The total number of bridges considered in this research is 487.

Table 2: Number of Bridges per Concession

Concession Sector	Nº Bridges
Collipulli - Temuco	108
Chillán - Collipulli	100
Talca - Chillán	112
Route 68 y R-62	57
Route 78	77
Américo Vespucio Norte	37
Total	487

Table 3: Percent of Damage

Porcentaje bridges	Damage Type
1%	Collapse
39%	Slight damage
28%	Considerable damage
5%	Serious damage
27%	No Damage

Table above show that just 6% of the bridges were out of service after earthquake 2010. Furthermore, 27% of them do not suffer damage, and the remaining 67% eventually, could continue in service, depending on each safety standards. As preliminary conclusion is possible to say that this information confirms the good quality in the materials, good construction process and good design of bridges in Chile.

2.2 Source of Damage

There were many different sources for each different damage in a bridge. However, in this particular case, all the damage converges in big one condition, the excessive displacement of the superstructure or slab.

The follow table summarized different damage and sources.

Table 4: Damage - Source data

Damage	Source
Over design transversal displacement of slab	Lateral Displacement of slab
Rotation of the slab	The skew of the bridge
Fracture in beams	Hit against a lateral stopper or hit with seat length
Fracture in the lateral stopper	Hit against beam
Fracture in pier or column	Lateral Spreading
Concrete peeling with steel exposure	Hit against another rigid element
Crack in beams	Hit against a lateral stopper or hit with seat length
Crack in the lateral stopper	Hit against beam
Crack in abutment	Hit against beam
Crack in abutment wall	Hit against beam
Crack in pavement carpet	Deformation of slab
Deformation in vertical anchorage	Lateral Displacement of slab
Rotation of abutment	Lateral Spreading
Fissures in beams	Hit with a lateral stopper or hit with seat length
Fissures in pavement carpet	Deformation of slab
Fissures in abutment wall	Hit against beam
Fissures in the lateral stopper	Hit against beam
Damage in Dilatation Joint	Longitudinal or Lateral Displacement
No damage	No damage

The Table above shows a list of typical damage founded in bridges after the 2010 earthquake. Also, table 4 contains the source for each damage. Almost, all damage in bridges was due to excessive lateral displacement or rotation of the desk. There are few cases of failure due to inappropriate design or calculation of the bridge or any structural element. The next pictures show different types of damage and different level of damage for the same type.

Table 5: Type of damage and damage level

Type of Damage in Lateral Stopper	Damage Level.	Type of Damage in Beam	Damage Level.
	Fissures in the lateral stopper		Fissures in beam
	Crack in the lateral stopper		Crack in beam
	Fracture in the lateral stopper		Fracture in beam

3. Upgrade of the Road Manual. Annex 3.1000-A

3.1 ANNEX 3.100-A

Since 2010 to date, comments have been received from private consultants, generated various internal discussions, and observed construction processes, which has led to the need to revise and improve the seismic design specifications. In addition, the Chilean government requested for a cooperation program with the Japanese Government through JICA support. Under the framework of that Cooperation Program (KIZUNA), Japanese experts from the MLIT (Ministry of Land, Infrastructure, Transport and Tourism), NILIM (National Institute for Land and Infrastructure Management) and the PWRI (Public Works Research Institute) co-worked with Structural Project Department engineers from MOP, seeking to improve the Road Manual. All the improved topics are presenting in this document.

3.2 Seismic Coefficients Method

The seismic coefficient method indicated in article 3.1004.309 (1) of Road Manual is modified and will be valid for one (1) span bridge. Bridges of two (2) spans with expansion joints at the ends of the abutments and continuity on the piers must be designed using other methods like the seismic coefficient method modified by structural response or the spectral modal method, to obtain structure's fundamental period and displacement. When using the seismic coefficient method, must considering acceleration design on the connection bridge system. Examples of connection bridge systems are bearing and expansion joints.

a. Acceleration design for Bearings

Bridges with one (1) span have a fundamental period very near to zero, so the design acceleration value to be used corresponds to the effective acceleration Ao. Due to these, the above bearing must be calculated according to the maximum displacement. This maximum displacement is generated by an acceleration equal to Ao*S, where S is the soil coefficient and Ao is a design acceleration. See equation number (1)

In the oldest version the displacement analysis trough software was not consider in the design and also, the acceleration design value was just Ao, without the soil effect. See equation number (2)

$$K_h = K_1 S Ao/g \quad (1)$$

$$K_h = K_1 S Ao/g \quad (2)$$

Where,

K_1 is the importance coefficient. This value is considered than 1 for all the structures.

K_h is the seismic coefficient. Must be used in the Seismic Coefficient Method.

Graphic 1: Comparison acceleration design

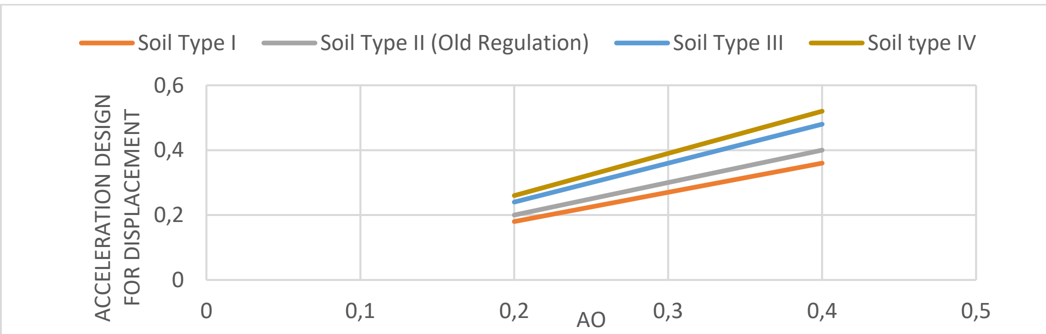


Table 6: Acceleration Design Ao

Seismic Zone	**Ao**
1	0,2
2	0,3
3	0,4

3.3 Seismic behavior of skew bridges and curved bridges

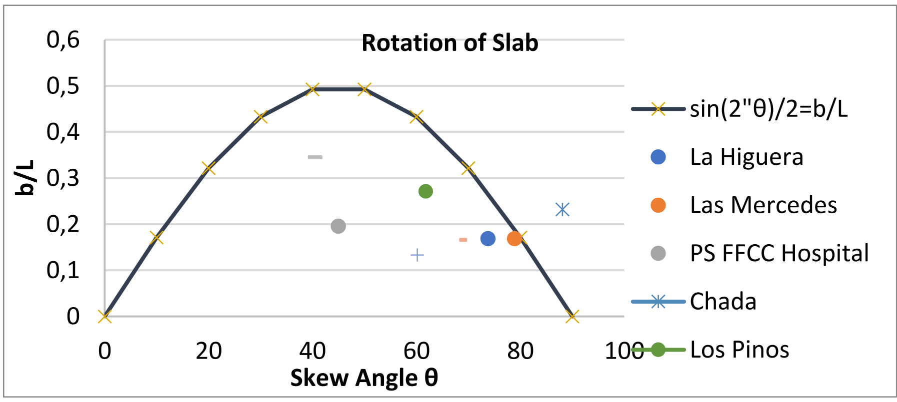
Avoid bridges with wide skew and curved bridges. If this is not possible, must consider related between width versus continuous length of the deck should be considered as a function of skew. The calculation of the possibility of rotation of a superstructure is possible using the following equation for bridges with skew according to section 16.1 "General" of the Japanese Standard "Specifications for Highway Bridges, March 2012, Part V Seismic Design**”.** The possibility of rotation of a superstructure can be evaluated simply, using the equation number (3). For curved bridges using equation number (4).

$$\frac{sen2\theta}{2} > \frac{b}{L} \quad (3)$$

$$\cos\theta'' > \frac{b}{L} \quad (4)$$

Is necessary evaluate the geometry of the bridge. If the calculated point is under the curve, it means that there will be excessive lateral shifts of the board, due to to rotation. In that case will be necessary incorporate internal seismic stops according to section 5.4, in addition to the external stops.

Graphic 2: Slab Rotation



Bridge	Condition
La Higuera	No Collapse
Las Mercedes	No Collapse
PS. FFCC. Hospital	Collapse
Chada	No Collapse
Los Pinos	Collapse
Lo Echevers	Collapse
PS. Miraflores	Collapse
El Parrón	Collapse

The Graphic 2 shows the rotation slab of few structures in Metropolitan Region. The results are coincident with the condition of the bridge. If the bridge that are located outside the curve, as Chada Bridge or very near of curve, as La Higuera and Las Mercedes, didn’t has big displacement.

3.4 Support Loss prevention System

The following requirements must be consider in the following structures: Bridges with their infrastructures built on liquefiable soils, Bridges with a notable difference in the conditions of the infrastructure or the type of soil, Bridges with very different contiguous superstructures in type or length of span, Bridges with high-rise piers, Continuous bridges with multiple openings with the force of inertia concentrated in a small number of infrastructures, Straight bridges or curved bridges.

a. Minimum support length.

The minimum beam support length for Straight Bridges is calculated with the following equation.

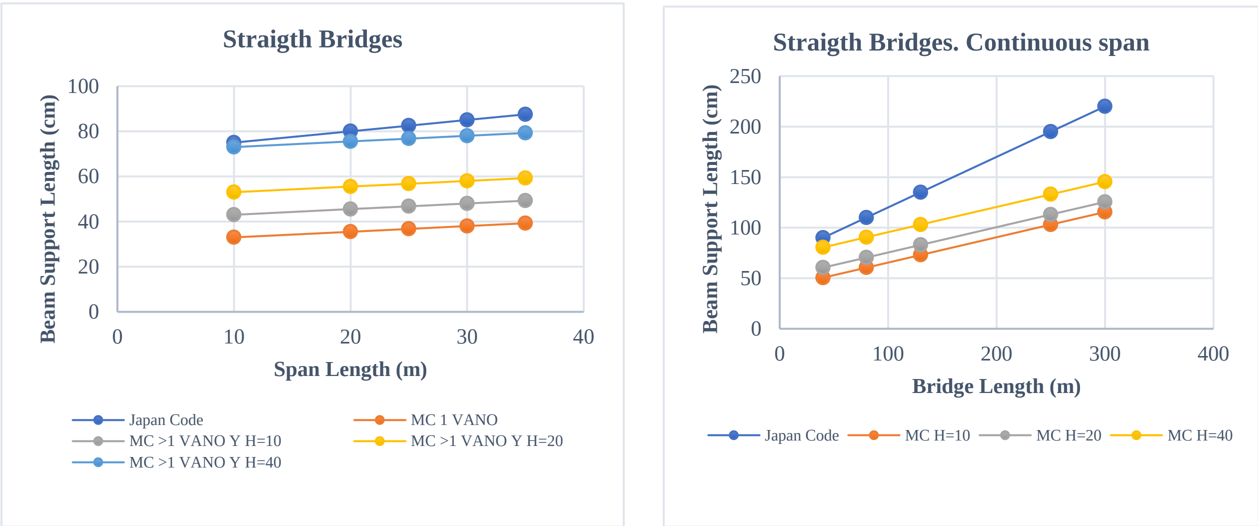
$$S_{EM} = 0.7 + 0.005l \quad (5)$$

Where,

S_{EM} = Minimum support length of a beam on the support table (m).

L = Length of the span (m). In a strain head that supports two superstructures with different lengths of span, the longest span for the value of 1 should be considered.

Graphic 3: Beam Support Length. Straigth Bridges



The minimum beam support length for Skew Bridges is calculated with the following equation.

$$S_{E\theta R} \geq 2L_{\theta} sen(\alpha_E / 2)\cos(\alpha_E / 2 - \theta) \tag{6}$$

Where,

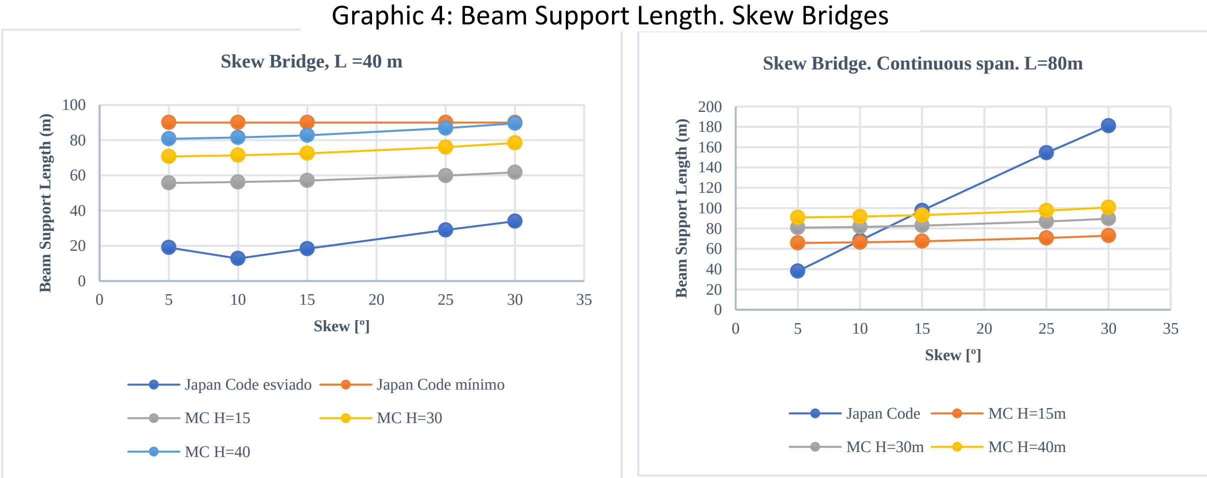
$S_{E\theta R}$ = Required length of support on a bridged or curved bridge in (m).

L_{θ} = Continuous length of the superstructure in (m).

θ = Deviation angle corresponding to the acute angle of the board in degrees (°).

α_E = Marginal rotation angle, can be taken as 2.5 (°).

Graphic 4: Beam Support Length. Skew Bridges



b. Lateral Stopper.

The use of internal seismic stops, in addition to the outer stops, should be considered according to next Table. The incorporation of external seismic stops should always be considered and must be distributed in a symmetrical arraignment.

Table 7: Number of Internal Lateral Stopper

	Minimum number of Lateral Stopper	
N° of beams	**Considering excessive displacement***	**No considering excessive displacement***
3	0	2
4	1	2
5	2	2
6 or more+	2	3

*: Excessive displacement according point 3.3

The internal Lateral stopper must form a cutting key with the crossbars, so that no damage to the beams occurs, in a probable lateral movement that exceeds the design displacement, due to an important earthquake, the impact must be produce between the stops and the crossbar, generating some kind of repairable damage in them.

The minimum width of the lateral stopper must be 40 (cm) and the maximum 70 (cm). It is not recommended to place larger widths because being more robust they will not behave like a fuse and it is likely that when the impact on them occurs, important requests are transmitted to the infrastructure, and can cause cracks in the heads and walls of temper.

Lateral Stopper should be calculated considering a horizontal acceleration equal to AoS where S is the soil coefficient. Each internal or external lateral stopper must be able to withstand the horizontal force transmitted by the board divided by the total number of internal lateral stopper and the external lateral stopper that will oppose the direction of movement of the board.

In the old version of the Road Manual, this disposition doesn't exist.

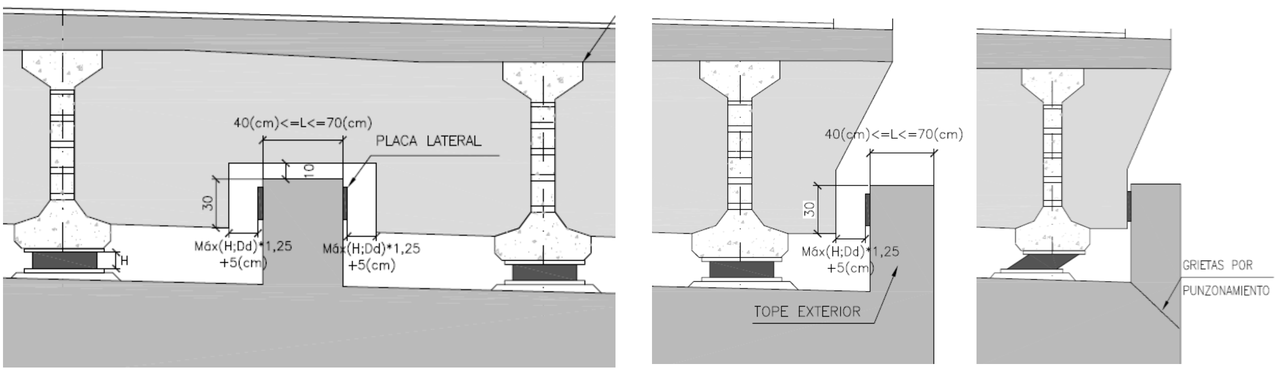


Fig. 1: Lateral Stopper

c. Vertical Seismic Bars

In cases where there is a history that significant vertical accelerations have been measured in the soil, a spectrum of vertical accelerations must be generated. For the rest of the cases, the seismic bas must be calculated considering a vertical acceleration of the superstructure equal to A_{VT}*S, where S is the soil coefficient and A_{VT} is equal to horizontal design acceleration Ao. It is obtained from the following table.

Table 8: Avt

Seismic Zone	Superstructure vertical Acceleration Avt
1	0,2g
2	0,3g
3	0,4g

The next graph show Ratio between Vertical Peak Ground Acceleration and Horizontal Peak Ground Acceleration. From 2010 earthquake data was possible to observe than several vertical acceleration value were similar to horizontal acceleration value.

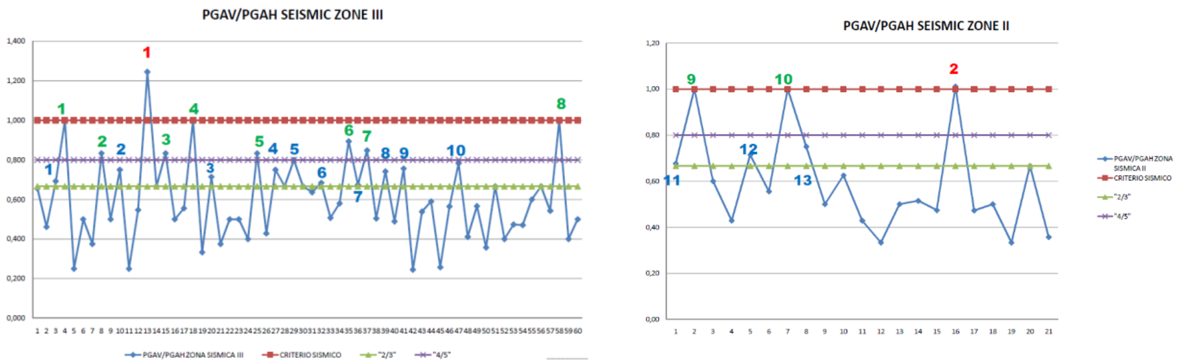


Fig. 2: PGA/PGH

For the oldest version of the Road Manual the vertical acceleration value was equal to 0.5Ao. Ao is defined in table 6.

d. Transversal Beams

All bridges should consider extreme crossbars (on stirrups and strains) and central (in the middle of the bay), regardless of the location or seismic area of the bridge and the type of beam (metal, reinforced concrete, post-tensioned or prestressed). The interaction of the crossbars with the seismic stops must be designed with a force equal to that specified for the lateral stopper.

The central crossbar is not necessary in spans smaller than 15 (m). Also, the minimum thickness of the crossbars must be 25 (cm) and must be monolithically attached to the upper slab.

e. Continuous Span.

The use of “thin slab” prevents the relative movement or collision of structured boards with beams, in an important seismic event. The continuity tile must have a minimum thickness of 15 (cm).

f. Semi-Integral Bridges

A semi-integral bridge is when slab and abutment wall are connected. The use of semi-integral and integral bridges will be accepted, in bridges that have up to 4 openings, where the light of each opening does not exceed 30 (m) and the total length of the bridge does not exceed 90 (m).

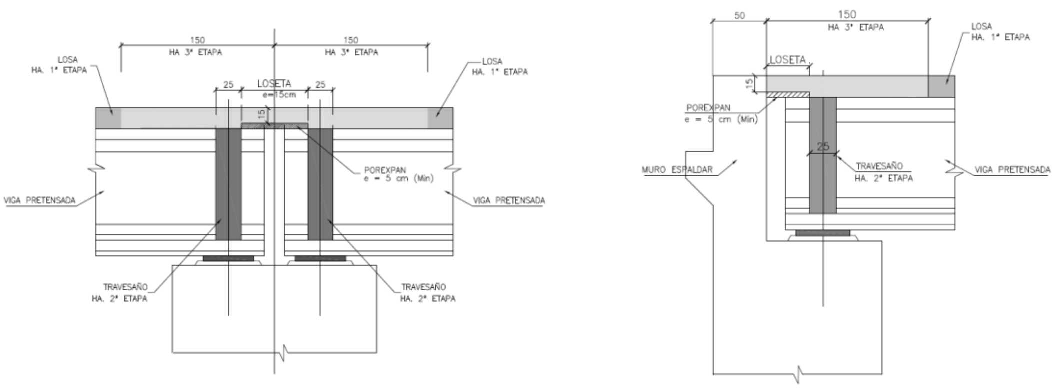


Fig. 3: Continuous Span or Semi Integral Bridge

g. Elastomeric Bearings.

The minimum lateral coating for the internal steel plates must be 10 (mm), due to the impact of ozone on the rubber and UV rays (ultra violet). Moreover, it is advisable to consider an upper and lower outer (cover) plates of at least 22 (mm). In addition, all bearings must be anchored to the infrastructure and to the respective beam as show next figures.

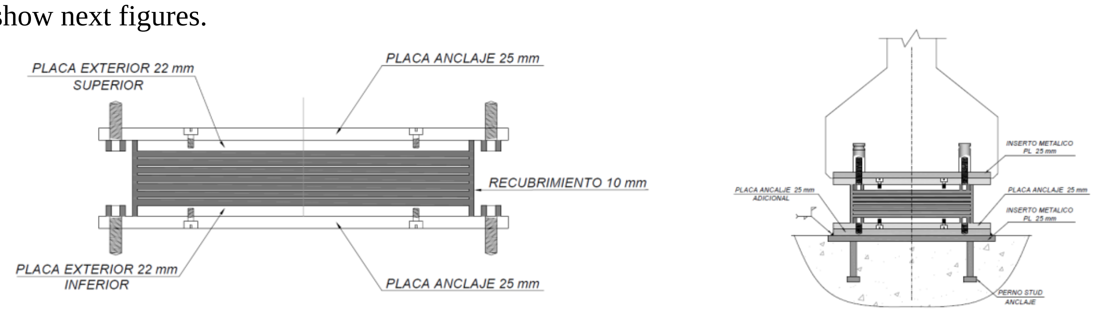


Fig. 4: Bearing detail

The minimum distance between the axis of the anchor bolt of the metal insert to the edge of the support table must be at least the following value:

$$S \geq 0.2 + 0.005l \tag{7}$$

Where,

S = Distance between the axis of the anchor bolt of the metal insert and the edge of the support table (m).

L = Length of the span (m).

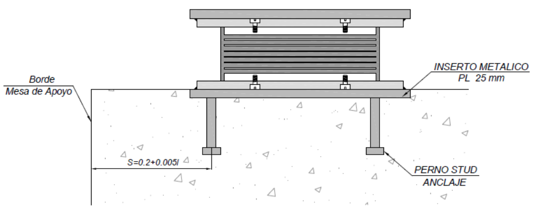


Fig. 5: Distace S

4. Acknowledgements

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5. Copyrights

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