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Structural assessment of the Puerto Real de Portoviejo bridge piers under seismic action

Structural evaluation of the piers of the Puerto Real Bridge in Portoviejo 1under seismic action

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Palabras claves:
Evaluación,
Puente
Vigas, Pilas,
Pilotes

Resumen

Introducción: La infraestructura de puentes son una parte fundamental de la vialidad, los puentes en la actualidad sirven para la interconexión de puntos geográficos que no pueden ser alcanzados por vía sólida. El Ecuador, al ser un territorio con un peligro sísmico alto requiere un análisis bajo cargas laterales provenientes de la acción sísmica. En el presente caso de estudio se abordará la capacidad estructural y el nivel de desempeño de la infraestructura del puente Puerto Real, mismo que comprenderá el análisis a flexión y a cortante de las vigas cabezales, el análisis a flexo-compresión y a cortante de las pilas y pilotes, además de la evaluación del desempeño de las pilas tipo pórticos. **Objetivo:** Evaluar el comportamiento estructural y el nivel de desempeño sísmico de las Pilas del puente Puerto Real ubicado en la ciudad de Portoviejo, ante la acción de las cargas verticales y las cargas laterales provenientes de la acción sísmica, mediante la elaboración de un modelo matemático en el programa CSI Bridge y aplicando la normativa vigente de la AASHTO LRFD, para la formulación de posibles estrategias de mejora estructural en las pilas del puente. **Metodología:** Revisión de los planos y especificaciones del puente existente, evaluación de las cargas actuantes en la infraestructura. Elaboración del modelo matemático de la estructura del puente Puerto Real en el programa CSI Bridge. Elaboración de un Análisis estático no-lineal al pórtico del puente conformado por pilas y viga cabezal, con el propósito de obtener el desempeño sísmico del sistema estructural existente del puente. **Resultados:** Las vigas cabezales 1 y 2 demuestran un comportamiento apropiado, es decir dentro del rango elástico para momento negativo con una relación demanda/capacidad crítica de 0.72 y 0.72 respectivamente. El diseño a cortante es satisfactorio, la viga cabezal 1 tiene una relación demanda/capacidad de 0.41 y la viga cabezal 2 de 0.30. Las pilas cumplen con la capacidad a flexo-compresión requerida, la demanda/capacidad crítica de 0.484 para la pila 1 y 0.465 para la pila 2, mientras que la relación demanda/capacidad a cortante es de 0.52 para la pila 1 y 0.47 para la pila 2, comprobando así que estos elementos disponen de un buen confinamiento para el sismo AASHTO con Tr=1000 yr. Los pilotes tienen un adecuado comportamiento a flexo-compresión con una relación demanda/capacidad crítica de 0.756 en los pilotes de la pila 1 y en los pilotes de la pila 2 es de 0.945, mientras que la relación demanda/capacidad a cortante es de 1.23 para los pilotes de la pila 1

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y 0.91 para los pilotes de la pila 2. Respecto al nivel de desempeño sísmico, para el Pórtico Y-Y de la Pila 1 está en Daño Severo (Sd3) con un punto de desempeño de Sa=0.66g, Δ=14.60 cm, para el Pórtico X-X de la Pila 1 está en Daño Severo (Sd3) con un punto de desempeño de Sa=0.384g, Δ=21.60 cm. Por otra parte, al nivel de desempeño sísmico, para el Pórtico Y-Y de la Pila 2 está en Daño Moderado (Sd2) con un punto de desempeño de Sa=0.63g, Δ=4.70 cm, para el Pórtico X-X de la Pila 2 está en Daño Severo (Sd3) con un punto de desempeño de Sa=0.50g, Δ=20.80 cm. **Conclusión:** El análisis de cargas permitió obtener la condición más crítica y desfavorable para la infraestructura del puente, de esta forma se determinaron las máximas demandas del puente Puerto Real a través del modelo numérico tridimensional en CSI Bridge. Las vigas cabezales están diseñadas a flexión correctamente de manera elástica para un R=1 para momento negativo y momento positivo, Las columnas disponen de la resistencia a flexo-compresión necesaria, además poseen un adecuado confinamiento que garantizara la incursión al rango inelástico. La propuesta de pilotes para el puente Puerto Real cumple con la relación demanda/capacidad a flexo-compresión y a cortante. **Área de estudio general:** Ingeniería Civil y Mecánica. **Área de estudio específica:** Estructuras de Hormigón Armado. **Tipo de artículo:** Artículo original.

Keywords:
Evaluation, Bridge Beams, Steel, Diaphragms

Abstract

Introduction: Bridge infrastructure is a fundamental part of the road system; bridges are currently used for the interconnection of geographical points that cannot be reached by solid road. Ecuador, being a territory with a high seismic hazard, requires an analysis under lateral loads coming from seismic action. This case study will address the structural capacity and performance level of the Puerto Real bridge infrastructure, including the flexural and shear analysis of the header beams, the flexural-compression and shear analysis of the piers and piles, as well as the evaluation of the performance of the portal piers. Objective: Evaluate the structural behavior and seismic performance level of the piers of the Puerto Real bridge located in the city of Portoviejo, under the action of vertical loads and lateral loads from seismic action, through the development of a mathematical model in the CSI Bridge program and applying the current AASHTO LRFD standards, for the formulation of possible structural improvement strategies in the bridge piers. Methodology: Review of the drawings and specifications of the existing bridge, evaluation of the loads acting on the infrastructure. Elaboration of the mathematical model of the Puerto Real bridge structure in the CSI Bridge program. Development of a non-linear static analysis of the bridge gantry consisting of piers and header beam, to obtain the seismic performance of the existing structural system of the bridge. Results: Header beams 1 and 2 demonstrate appropriate behavior, ie within the elastic range for negative moment with a critical demand/capacity ratio of 0.72 and 0.72 respectively. The shear design is satisfactory, head beam 1 has a demand/capacity ratio of 0.41 and head beam 2 of 0.30. The piles comply with the required flexural compression capacity, the critical demand/capacity of 0.484 for pile 1 and 0.465 for pile 2, while the shear demand/capacity ratio is 0.52 for pile 1 and 0.47 for pile 2, proving that these elements have a good confinement for the AASHTO earthquake with Tr=1000 yr. The piles have an adequate flexural-compression behavior with a critical demand/capacity ratio of 0.756 for piles in pile 1 and 0.945 for piles in pile 2, while the shear demand/capacity ratio is 1.23 for piles in pile 1 and 0.91 for piles in pile 2. Regarding the seismic performance level, for Pile 1 YY portal is at Severe Damage (Sd3) with a performance point of Sa=0.66g, Δ=14.60 cm, for Pile 1 XX portal is at Severe Damage (Sd3) with a performance point of Sa=0.384g, Δ=21.60 cm. On the other hand, at the seismic performance level, for the YY Gantry of Stack 2 is in Moderate Damage (Sd2) with a performance point of Sa=0.63g, Δ=4.70 cm, for the XX Gantry of Stack 2 is in Severe Damage (Sd3) with a performance point of Sa=0.63g, Δ=4.70 cm, for the XX Gantry of Stack 1 is in Severe Damage (Sd3) with a performance point of Sa=0.384g, Δ=21.60 cm. Conclusion:The load analysis allowed obtaining the most critical and unfavorable condition for the bridge infrastructure, thus determining the maximum demands of the Puerto Real bridge through the three-dimensional numerical model in CSI Bridge. The head girders are designed to flex correctly in an elastic manner for an R=1 for negative moment and positive moment. The columns have the necessary flexural and compressive strength, as well as an adequate confinement that will guarantee the incursion into the inelastic range. The pile proposal for the Puerto Real Bridge complies with the demand/capacity ratio at flexo-compression and shear. Type of article: original.

Introduction

A fundamental part of road construction is the construction of bridges that serve to interconnect geographical points that cannot be reached by solid road; bridges link and shorten distances, as well as enable the care of water sources (Rodríguez, 2022). As Moran (2023) mentions, these bridges produce development, progress, economic and infrastructure strengthening worldwide. According to Jiménez & Carreño (2023), the loss of lives generated by the partial or complete collapse of a bridge during the effects of an earthquake has been evident, which is why the evaluation of structures of this type is of utmost importance because our country is in a zone of high seismicity. In addition, Chuquipoma (2020) mentions that bridges are the structural response to pedestrian safety that is in harmony with road structures and development.

The structural evaluation of the Puerto Real bridge will be carried out by analyzing a mathematical model of the structure using the CSI Bridge program. As mentioned by Mañueco (2018), CSi Bridge is one of the most widely used programs today, a program with a high capacity for modeling, analysis and sizing of this type of structures. Regarding the present case study, the evaluation of the seismic-structural behavior of the Puerto Real Bridge infrastructure will be addressed, which consists of: header beam, piers, and piles.

Methodology

The methodology used will be the quantitative method, which is characterized by the numerical measurement of results, whose type of design is non-experimental descriptive, which is based on observation, which does not intend to intervene with the environment. On the other hand, the deductive method will be used, a method that is characterized by demonstrating, understanding and explaining the particular aspects of reality. The procedure for the case study will be as follows:

- Determine the theoretical-conceptual foundations on the pile as a fundamental structural element for construction and earthquake resistance of bridges.
- Review of the plans and specifications of the existing bridge, structural survey of the elements that make up the Puerto Real bridge, as well as the evaluation of the loads acting on the infrastructure.
- Development of the mathematical model of the Puerto Real bridge in the CSI Bridge program, with the aim of reflecting the real behavior of the structure to obtain the most critical demand/capacity relationship of the structural elements, which will be: header beam, piers and piles.

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- Perform a non-linear static analysis on the bridge portico consisting of piers and a header beam, with the purpose of obtaining the seismic performance level of the seismic resistance system.

Analyzed elements that make up the infrastructure

The elements analyzed in the infrastructure of the Puerto Real bridge are piers 1 and 2, which are made up of a header beam, piers and piles, these are shown in figures 1 and 2, in addition the cross sections of the piers are shown in figures 3 and 4.

Figure 1

Head beam and pier columns 1

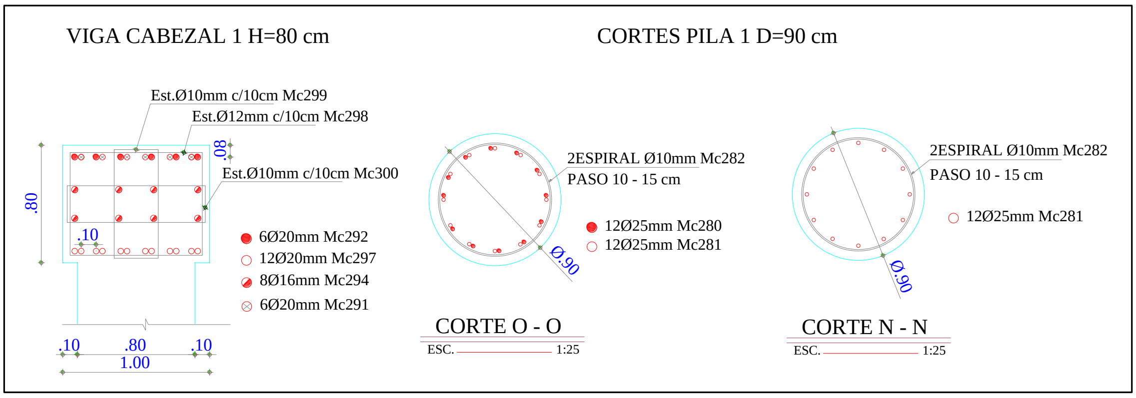

Figure 2

Header beam and pier columns 2

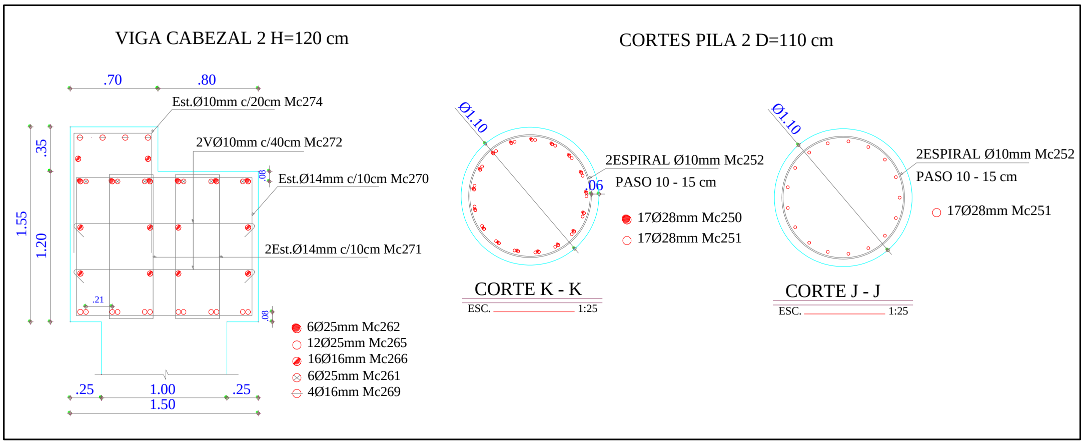

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Figure 3

Cross sections of piers 1 and 2 of the Puerto Real Bridge

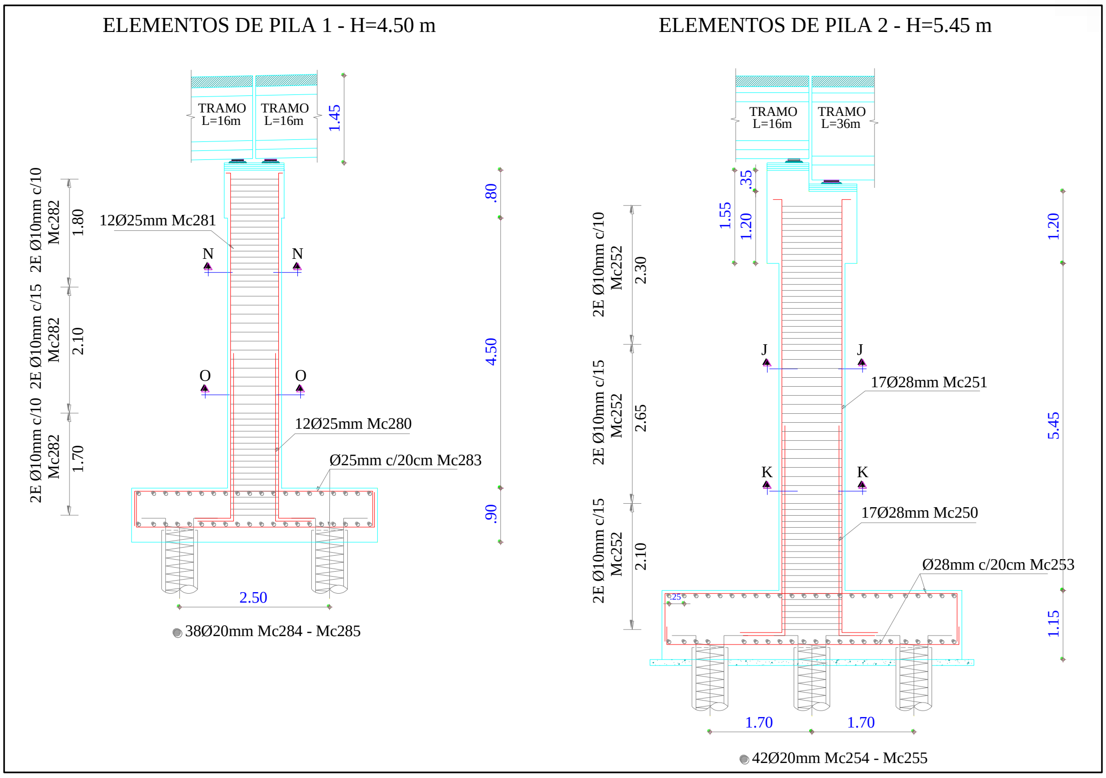

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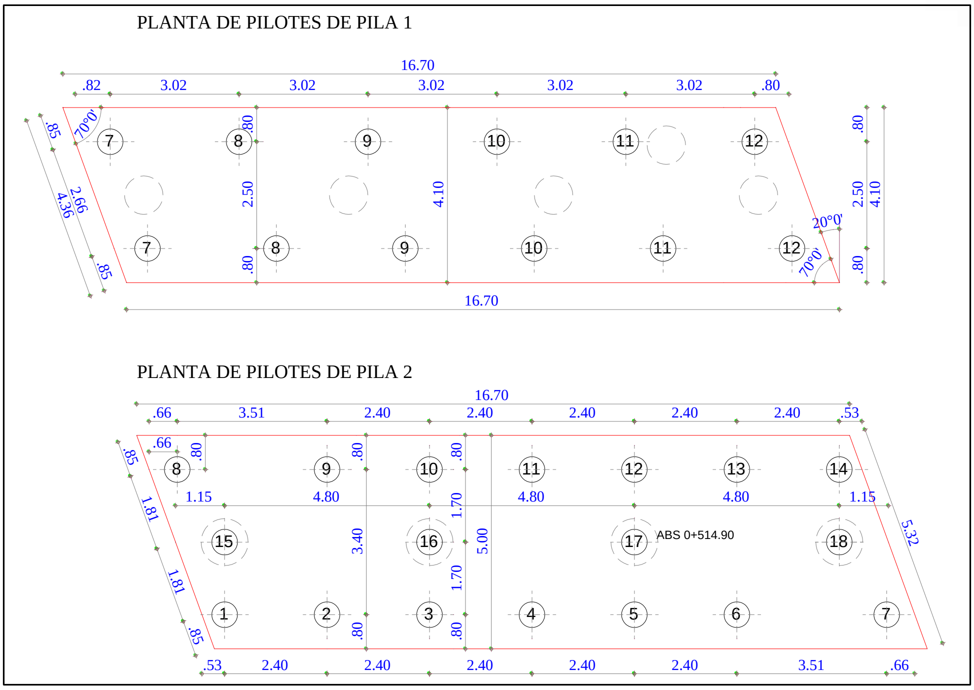
Figure 4

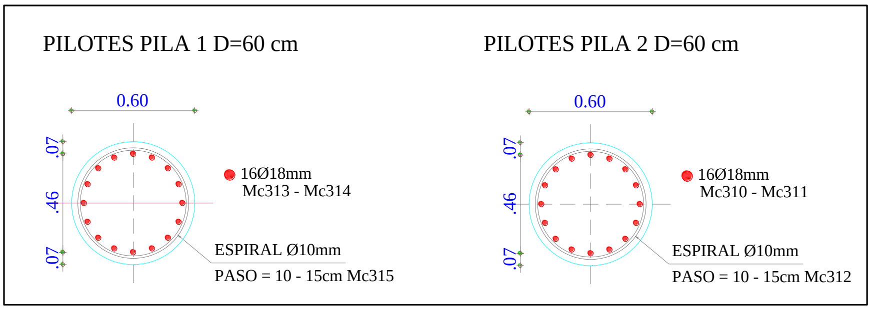
Pile plant 1 and 2



On the other hand, the sections of the piles for pier 1 and 2 are shown in Figure 5.

Figure 5

Section of piles of pier 1 and 2



Materials and resistances used

For the analysis of the Puerto Real Bridge, the materials shown in Table 1 were considered.

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Table 1

Materials used

Element	Guy	Endurance
Slab ts=18 cm	Reinforced concrete	f'c = 350 kgf/cm²
Longitudinal Beam	Prestressed Concrete	f'c = 420 kgf/cm²
Head Beam, Piles, Footings, Piles	Reinforced concrete	f'c = 250 kgf/cm²

Dead loads

The loads used in the numerical model are those described in Table 2.

Table 2

Dead loads

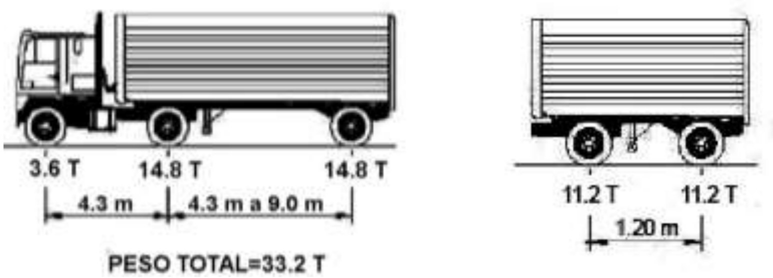
Element	Thickness (m)	P. Specific (ton/m³)	Uniform load (ton/m²)	Guy
Slab	0.2	2.4	0.48	DC
Sidewalks	0.2	2.4	0.48	DC
Asphalt	0.075	2.2	0.165	DW
Facilities	-	-	0.05	DW
Railings	-	-	0.088	DC

Live load vehicle

As shown in Figure 6, the design vehicle considered was the HL-93. In addition, a pedestrian live load of 0.366 ton/m² was considered.

Figure 6

Design Truck



Seismic load

The seismic load was defined as a design acceleration spectrum for a return period of Tr=1000 years with a factor z=0.75g, a type D soil, as established in the NEC-SE-DS standard (Norma Ecuatoriana de la Construccion [NEC], 2014). Regarding the seismic

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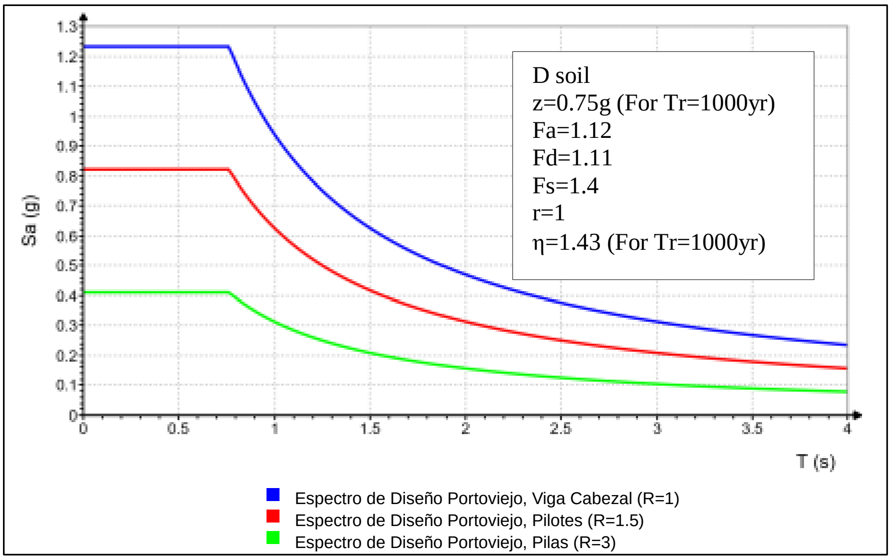
response modification factor R, R=1 was considered for the cap beam, R=3 for the piers and R=1.5 for piles according to the standard (American Association of State Highway and Transportation Officials [AASHTO], 2020).

The spectra for the Puerto Real bridge are shown in Figure 7.

Figure 7

Design Spectra Province of Portoviejo



Design combinations

The maximum internal forces were analyzed for the combinations of the AASHTO LRFD standard.

- Service 1: DC + DW + LL + IM + PL(1)
- Resistance 1: 1.25DC + 1.5DW + 1.75(LL+IM + PL)(2)
- Extreme Event 1: 1.25DC + 1.5DW + 0.5(LL+IM+PL) + EQ (3)

Three-dimensional mathematical model of the Puerto Real bridge

The mathematical model of the structure created in the CSI Bridge program allowed obtaining the most realistic behavior of the structure. The mathematical model is made up of 3 simply supported sections with spans of 16 m, 16 m, 36 m, 10 longitudinal beams are available and the separation between them is 1.55 m. The mathematical model can be seen in Figure 8.

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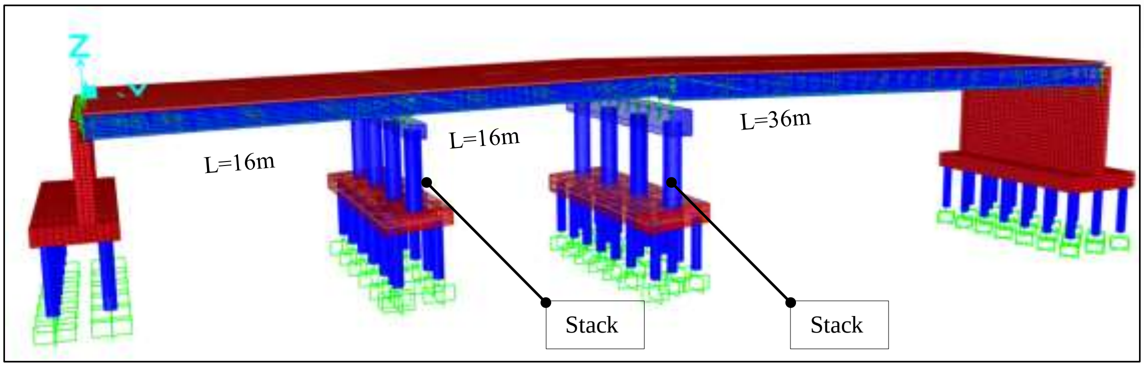
Figure 8

Three-dimensional numerical model of the Puerto Real Bridge



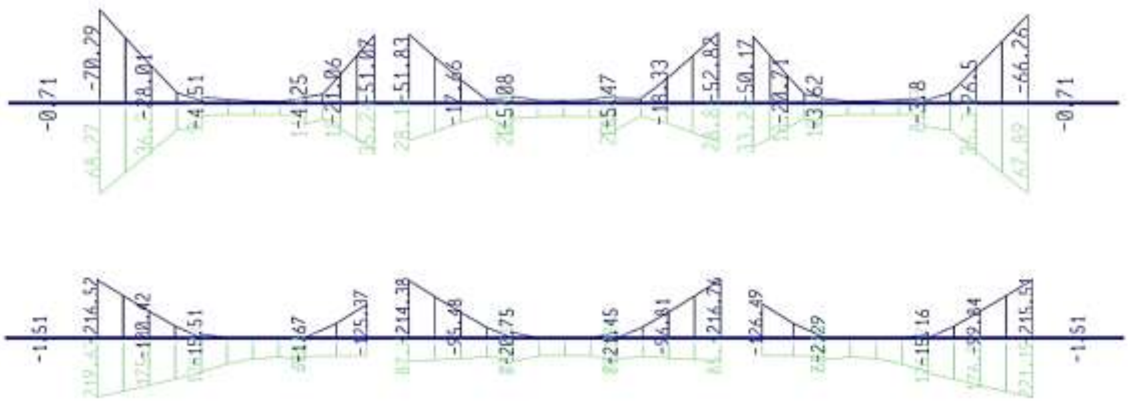
Demand/capacity relationship in header beam

The header beam was verified for the different design combinations according to (AASHTO, 2020), the most predominant being the following, Service, Resistance and Extreme Event, dThis element was verified to work elastically (R=1). The bending moments must be less than the resistant moments (Peña & Yunapanta, 2022).

Figure 9 below shows the maximum bending moments that occur in the header beam 1 and 2:

Figure 9

DMF envelope – head 1 and head 2



The following mathematical expressions were used to obtain the flexural design capacity according to AASHTO LRFD 9th Ed.

Mcr: Cracking Moment, Chapter 5, Section 5.6.3.3.

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fr: Modulus of Rupture, Chapter 5, Section 5.4.2.6.

Ø: Reduction Factor, Chapter 5, Section 5.5.4.2.

$$a=\frac{A_s \cdot f_y}{0.85 \cdot f'_c \cdot b} \qquad c=\frac{a}{\beta_1} \qquad \varepsilon_t=\varepsilon_c \cdot \left(\frac{d-c}{c}\right)$$

$$f_r=2.01 \cdot \sqrt{f'_c} \qquad (kgf/cm^2)$$

$$M_{cr}=\gamma_3 \cdot (\gamma_1 \cdot f_r \cdot S_{nc}) \qquad S_{nc}=\frac{b \cdot h^2}{6}$$

$$M_{u\_min}=min(1.33\ M_u, M_{cr})$$

$$\phi M_n=\phi \cdot A_s \cdot fy \cdot \left(d-\frac{a}{2}\right) \qquad \phi M_n \geq M_{u\_min}$$

$$\phi=\begin{cases} 0.65 & \text{if } \varepsilon_t \leq 0.002 \\ 0.65+(\varepsilon_t-0.002) \cdot \frac{150}{3} & \text{else if } 0.002<\varepsilon_t \leq 0.005 \\ 0.9 & \text{else} \end{cases} \tag{4}$$

The maximum moments were compared with the bending capacity of the head beams, thus obtaining the demand/bending capacity relationships, which are shown in Table 3, thus verifying the good bending behavior of these elements, as Lombeida (2023) mentions, these beams must have elastic behavior.

Table 3

Bending ratios - end beams

Element	Dimensions	Moment	Mu (ton-m)	Armed	φMn (ton-m)	Mu/φMn
Beam Head 1	100x80	(+)	68.27	12φ20	97.29	0.70
Beam Head 1	100x80	(-)	70.29	12φ20	97.29	0.72
Beam Head 2	150x120	(+)	221.19	12φ25	301.42	0.73
Beam Head 2	150x120	(-)	216.76	12φ25	301.42	0.72

The following expressions were used to obtain the shear design capacity for beams according to AASHTO LRFD 9th Ed.

Vn = Vc+Vn: Nominal shear strength, chapter 5, section 5.7.3.3.

Vc: Nominal shear strength of concrete, chapter 5, section 5.7.3.4.1 simplified process.

dv: Effective cutting height, chapter 5, section 5.7.2.8.

Smax: Transverse reinforcement, Chapter 5, Section 5.7.2.5.

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$$d = h - r_{eje} \qquad d_v = max\left(\left(d - \frac{a}{2}\right), (0.9\ d), (0.72\ h)\right) \qquad V_c = 0.0632 \cdot \sqrt{f'_c} \cdot b \cdot d_v \quad (ksi)$$

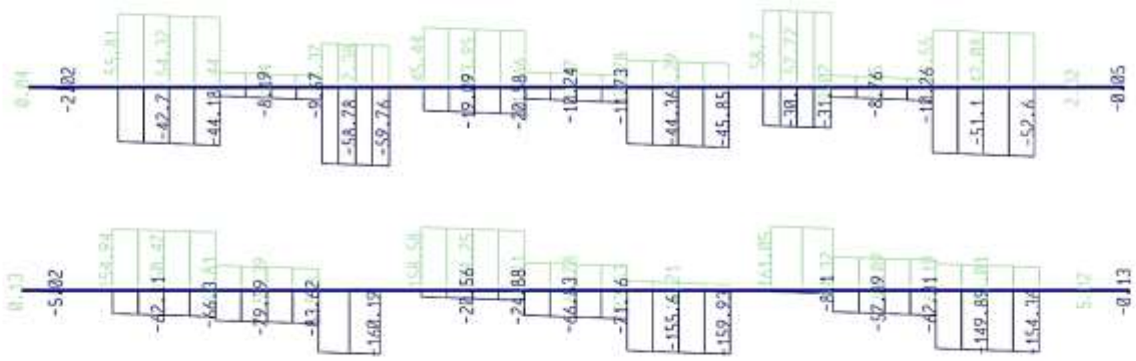
$$V_s = \frac{V_u}{\phi} - V_c \qquad S = \frac{A_v \cdot fy \cdot d_v}{V_s} \qquad S_{max\_1} = \frac{A_v \cdot fy}{0.0316 \cdot b \cdot \sqrt{f'_c}} \quad (ksi) \qquad v_u = \frac{V_u}{\phi \cdot b \cdot d_v} \tag{5}$$

$$S_{max\_2} = \begin{cases} \text{if } v_u < 0.125\ f'c \\ \quad min(0.8\ d_v, 24\ in) \\ \text{else} \\ \quad min(0.4\ d_v, 12\ in) \end{cases} \qquad S_{max} = min(S_{max\_1}, S_{max\_2})$$

Figure 10 below shows the shear forces that occur in header beam 1 and 2:

Figure 10

DFC Enclosure – Head 1 and 2



The maximum shear forces were compared with the shear capacity of the header beams, thus obtaining the demand/shear capacity relationships, which are shown in Table 4.

Table 4

Shear Ratios - Head Beams

Element	Dimensions	Vu (ton)	Armed	φVn (ton)	Vu/φVn
Beam Head 1	100x80	58.78	4 Branches φ10/c10cm	145	0.41
Beam Head 2	150x120	161.05	6 Branches φ14/c10cm	592.23	0.30

Demand/Capacity Relationship in Flexo-Compression Piles

The demands for the circular columns were obtained from the square root of the sum of their demands in both directions (Bravo, 2021).

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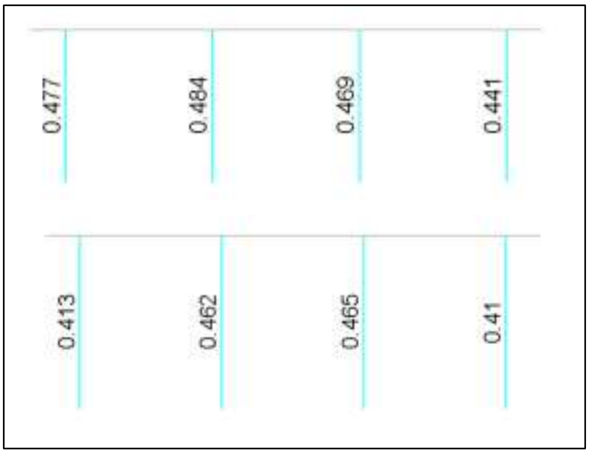
$$M_u = \sqrt{(M_{22})^2 + (M_{33})^2} \qquad \textbf{(6)}$$

Figure 11 shows these demand/capacity relationships for piers 1 and 2, and these results are satisfactory for the analysis of the real port bridge.

Figure 11

PMM Ratios, Stacks 1 and 2



The interaction diagrams of these circular stacks are shown in Figure 12 and 13.

Figure 12

Pile 1 Interaction Diagram – D=90cm

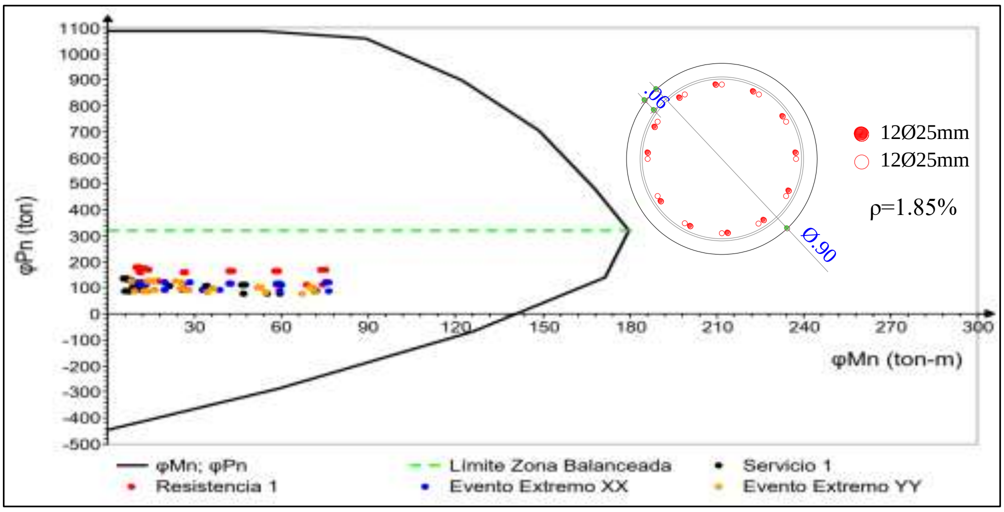


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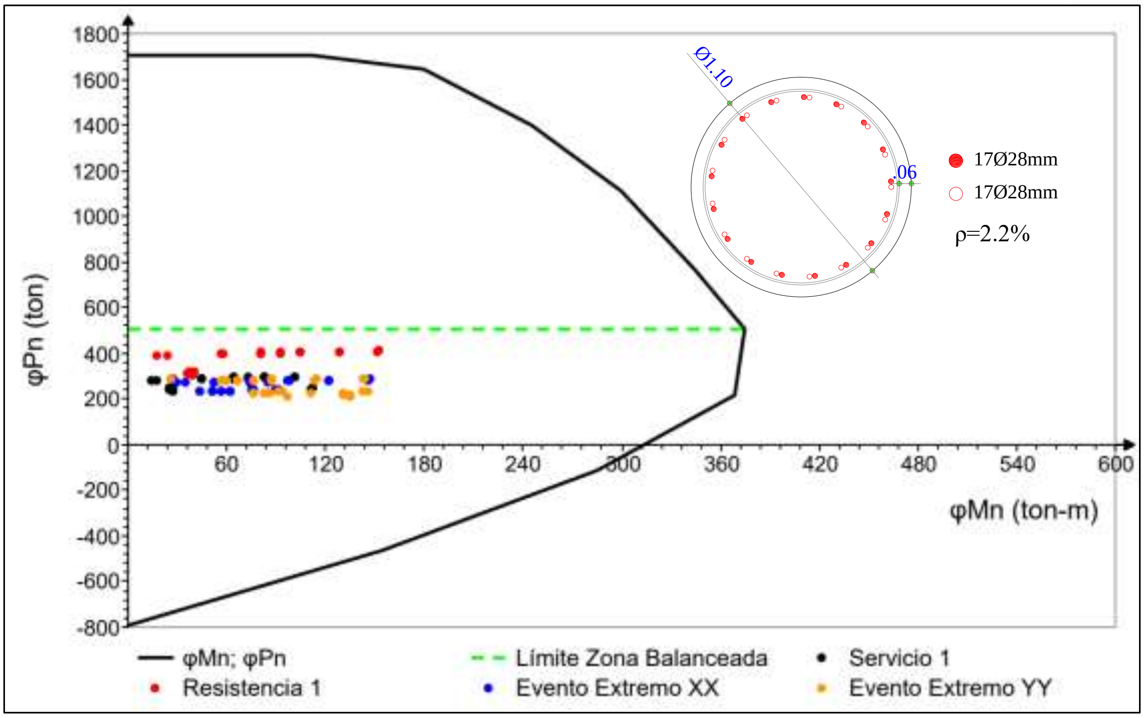
Figure 13

Interaction Diagram Pile 2 – D=110cm



These interaction diagrams allowed to verify the flexural-compression behavior of the columns of the piers and the results show that the demands are below the balance point, thus demonstrating their ductile behavior (Huerta, 2022). And as Quispe, J. (2023) mentions, the piers turn out to be the main elements in dissipating energy in bridges.

On the other hand, the shear of the columns of piers 1 and 2 was also verified for elastic shear using R=1, such that confinement is guaranteed in the incursion into the inelastic range (Salcedo, 2021). Table 5 shows the demand/capacity relationships for shear of the piers.

Table 5

Demand/capacity relationship to shear - piles

Element	Dimensions	Vu (R=1) (ton)	Band	φVn (ton)	Vu/φVn
Stack 1	D=90 cm	41.96	2∅10 c/10	81.22	0.52
Stack 2	D=110 cm	90.51	2∅10 c/10	192.82	0.47

Pile capacity

The interaction diagrams of piles 1 and 2 are shown in Figure 14. The results demonstrate satisfactory behavior.

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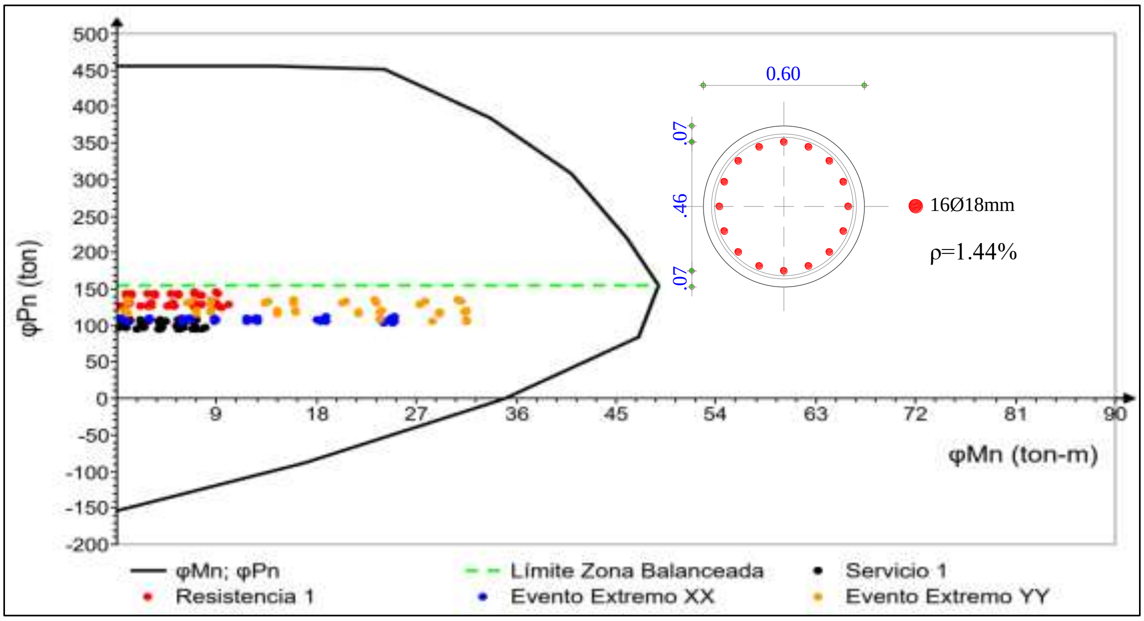
Figure 14

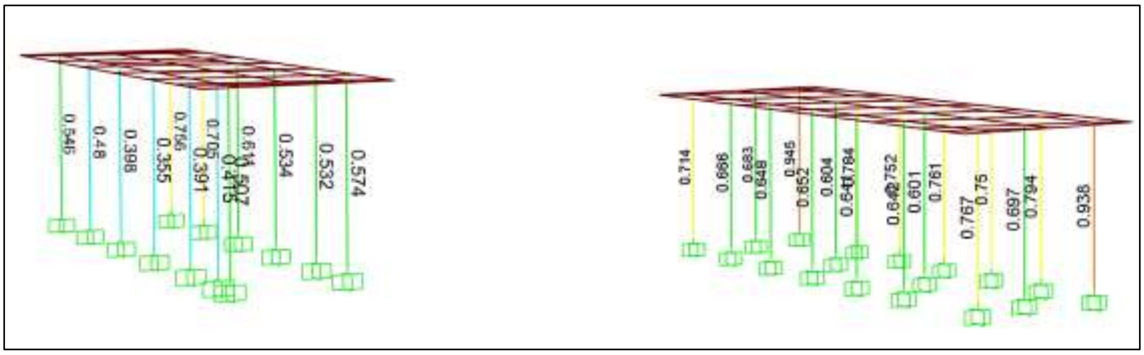
Pile interaction diagram of pile 1 and 2 – D=60cm



The PMM ratios of the piles are shown in Figure 15.

Figure 15

PMM ratios, piles of piers 1 and 2



The confinement of the piles of piers 1 and 2 was also verified; the shear ratios of the piles are shown in Table 6.

Table 6

Shear ratios - piles

Element	Dimensions	Vu (R=1) (ton)	Strap (cm)	φVn (ton)	Vu/φVn
Pile Pile 1	D=60 cm	31.02	1∅10 c/10	25.19	1.23
Pile Pile 2	D=60 cm	23.04	1∅10 c/10	25.19	0.91

Seismic performance level

A nonlinear static analysis was performed in the Sap2000 software, according to the Department of Homeland Security Federal Emergency Management Agency (2005), this procedure is an inelastic analysis that allows estimating the response of the structure to an earthquake Blas & Sosa (2019), on the other hand, the performance levels were obtained in accordance with the European RISK-UE project (Milutinovic & Trendafiloski, 2003).

As Aguiar (2003) mentions, this is one of the most practical and efficient non-linear methods for obtaining performance levels. Evaluating the capacity of a structure in the event of an earthquake is crucial to guarantee people's lives (Zambrano, 2023).

The longitudinal direction of the piles (YY) and the transverse direction (XX) were analyzed; the analysis of both directions is crucial as mentioned by Vargas (2017), because they have different behaviors.

As Pierre & Hidayat (2020) mention, in this type of analysis it is important to represent the monotonic seismic load that will make the structure enter the inelastic range and obtain a performance level for each element.

The results are presented in figures 16, 17, 18 and 19.

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Figure 16

YY portal performance level (pier 1)

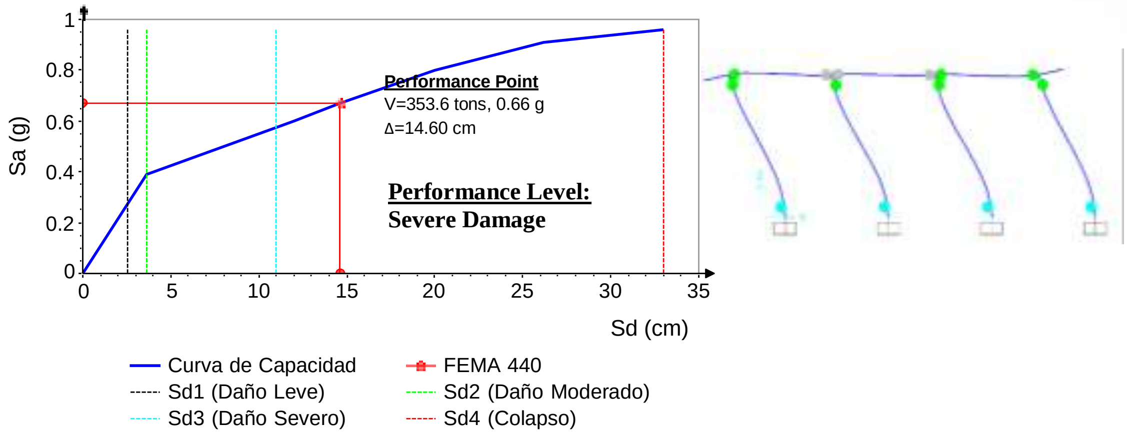

Figure 17

Level of performance XX portal (pier 1)

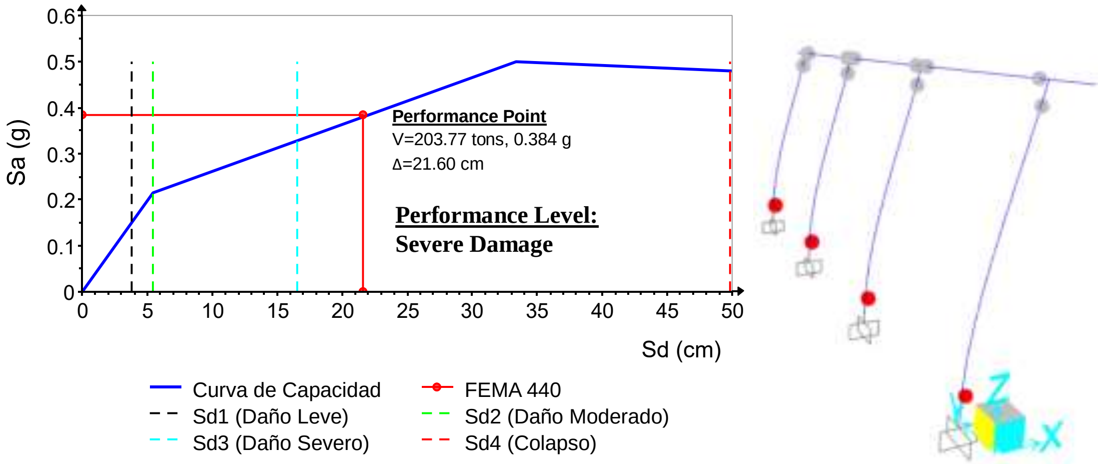

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Figure 18

YY portal performance level (pier 2)

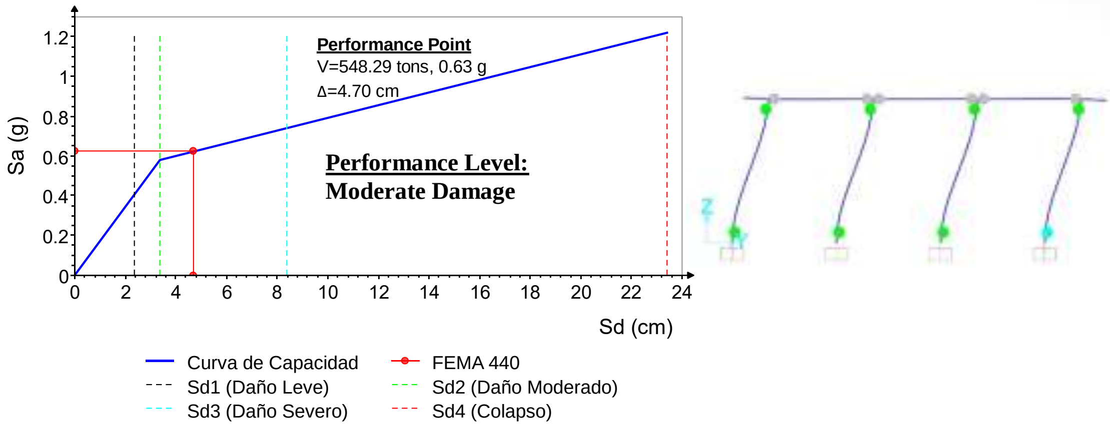
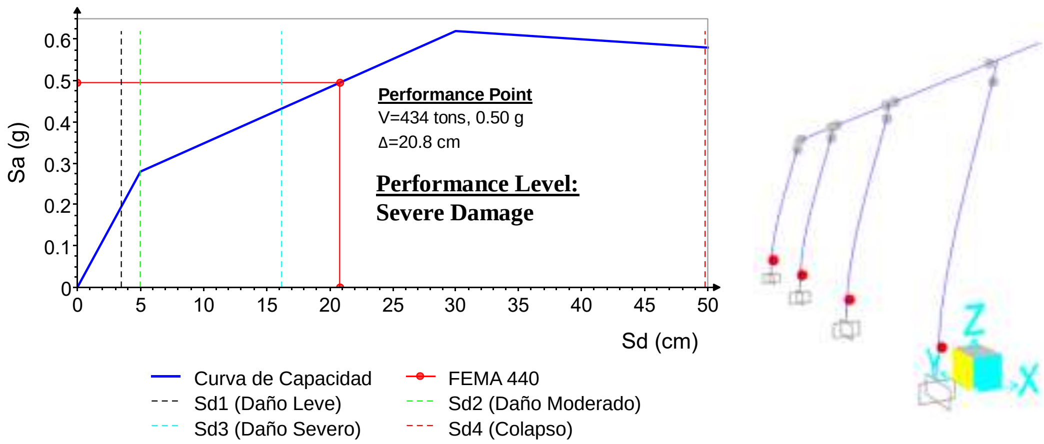


Figure 19

Level of performance XX portal (pier 2)



Conclusions

- The theoretical-conceptual foundations of the piles were determined, which allowed the analysis of said element and obtaining consistent results.
- With the definition of the acting loads, the most critical condition for gravity loads was established considering the dead weights and seismic load considering its effect as an acceleration spectrum according to NEC-15.
- The mathematical model of the Puerto Real bridge was developed in the CSI Bridge program, this allowed obtaining the most realistic behavior of the bridge, the Structural Analysis allowed obtaining the maximum demands for the headers, piers and piles, the headers work in an elastic manner (R=1).

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- The critical flexural demand/capacity ratio in header beam 1 and 2 for negative moment is 0.72, the shear demand/capacity ratio is 0.41 for header beam 1 and 0.30 for header beam 2. Satisfactory behavior.
- The columns of the piles have PMM demands below the balanced zone, which is an indication of the ductility of these elements, thus verifying that the design is satisfactory.
- The PMM critical demand/capacity ratio for pile 1 is 0.484 and for pile 2 it is 0.465, the critical shear demand/capacity ratio is 0.52 for pile 1 and 0.47 for pile 2, this is an indication that the confinement is adequate for the piles to enter the inelastic range.
- While the piles of pile 1 have a critical demand/capacity ratio PMM of 0.756 and in the piles of pile 2 it is 0.945, in addition to a demand/shear capacity ratio of 1.23 for the piles of pile 1 and 0.91 for the piles of pile 2.
- The non-linear static analysis was performed on both piles and the performance point was obtained under the FEMA-440 methodology, pile 1 in the longitudinal direction and in the transverse direction develops a performance point above the Severe Damage (Sd3), for pile 2 in the transverse direction it develops a performance point above the Moderate Damage (Sd2) and in the longitudinal direction above the Severe Damage (Sd3).

Conflict of interest

The author declares that there is no conflict of interest in relation to the submitted article.

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