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Article

Static and dynamic seismic analysis for the construction of structural concrete portal frames in Manzanillo, Colima

Análisis sísmico estático y dinámico, para la construcción de marcos pórticos de concreto estructural en Manzanillo, Colima

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Abstract

The port of Manzanillo is located on the Mexican Pacific coast, due to its proximity to the Cocos Plate and the North American Plate, it has had significant events recorded from 1932 [where three earthquakes occurred on the coast of Colima and Jalisco with a magnitude greater than 7] until January 12, 2025 with an epicenter in Coalcoman, Michoacan with a magnitude of 6.1. The goal is to determine the basal shear, direct shear and torsional shear, as well as the angular frequencies and nodal stiffnesses of a building consisting of four concrete portal frames. The results were the determination of tangential forces, as well as moment in columns and beams in each floor. It is concluded that the application if the E.030 Seismic Resistant Designs Standard gives us the certainty that the relative displacements are within the standard, and the calculated eccentricities are adequate for an asymmetric architectural plan.

Shear, Frequency, Stiffnesses

Resumen

El Puerto de Manzanillo se encuentra ubicado en las costas del pacífico mexicano, por su proximidad a la Placa de Cocos y la Placa de Norteamérica, ha tenido grandes eventos significativos registrados a partir de 1932 [donde ocurrieron tres sismos en las costas de Colima y Jalisco superior a 7 de magnitud] hasta el 12 enero de 2025 con epicentro en Coalcomán, Michoacán con magnitud de 6.1. El objetivo es determinar el cortante basal, cortante directo y cortante torsional, así como las frecuencias angulares y las rigideces nodales de una edificación que consta de 4 marcos pórticos en concreto resultado. Los resultados fueron la determinación de fuerzas tangenciales, así como momento en columnas y trabes en cada entrepiso. Se concluye la aplicación de la Norma E.030 Diseño Sismorresistente, nos da la seguridad que los desplazamientos relativos están dentro de la norma, y las excentricidades calculadas son adecuadas para una planta arquitectónica asimétrica.

Cortante, Frecuencia, Rigidez

Area: Advocacy and attention to national problems

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Introduction

The port of Manzanillo is the country´s main exported to the Pacific. Through it operate routes to Japan; Hong Kong, Australia and New Zealand [Guzman, 1995]. Due to its geographical location, it is the best link with the industrial and commercial areas of the country, which has established itself as one of the most important ports in Mexico for its commercial activity and exchange of products of all kinds for the West, as shown in figure 1 [SEMAR, 2018].

In seismic engineering the only way to prevent the occurrence of disasters caused by natural hazards is by means of characterization and studies that allow taking preventive measures to be taken and, when appropriate, mitigation measures for possible disaster scenarios [Núñez, 2012].

The state of Colima is one of the regions with the highest seismicity in the country and therefore where the seismic hazard is very high, however this hazard is not only due the subduction process of the tectonic plates, but also to other unidentified continental structures that have generated new historical earthquakes.

The goal of this work is to review and evaluate the historical seismicity of the state of Colima as well as correlate recent seismicity data, related and carried out in the region.

Box 1

Figure 1

Satellite image of the port of Manzanillo

Source: earthgoogle.com

Background

Seismological context and seismic regionalization for the state of Colima

At the national level, the seismic hazard of the country is divided into four main zones ranging from A to D, where A represent low seismicity and D representing a very high seismic hazard.

In the seismological context, the state of Colima, including Manzanillo, is located in zone D. The threat is generated mainly in the so-called Jalisco block located by the convergence of the Cocos Plate, the Rivera Plate and the North American Plate in the Pacific coastal zone [Garduño, *et al*, 1998]. México is located between the aforementioned plates in the so-called belt of fire, characterized by the presence of very active volcanoes and high seismicity.

The most destructive earthquakes in the country have occurred on the border between the aforementioned plates [with magnitudes greater than 7 on the Richter scale and intensities of VIII on the Modified Mercalli scale], causing severe damage in cities such as Colima, which is located in zone D, Guadalajara [seismic zone C] and in the states of Michoacán and México, as seen in table 1 and figure 2.

Box 2

Table 1

Main earthquakes that occurred in the Colima-Jalisco region.

No.	Date	Latitude N	Length W	Magnitude Mw	Intensity MMI	
1	03-06-1932	19° 80´	104° 00´	8.0	VIII	R and NA
2	18-06-1932	18° 95´	104° 42´	7.8	IX	Replica of 1
3	15-04-1941	18° 85´	102° 94´	7.6	X	C and NA
4	30-01-1973	18° 39´	103° 21´	7.6	VIII	C and NA
5	09-01-1995	18° 79´	104° 47´	8.0	VII	R and NA
6	21-01-2003	18° 63´	104° 13´	7.5	VIII	C and NA

Source: UCOL et al., 1997, Zobin. 2004 and Preciado, 2011

Box 3

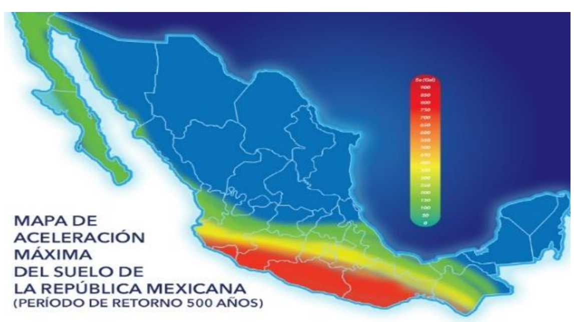

Figure 2

Map of maximum ground acceleration of the Mexican republic [Return Period 500 years].

Source:https://www.uv.mx/cienciauv/blog/hablemosunpocosobreamenazasismic/

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State or art

Soil liquefaction: causes, effects and solutions
Soil liquefaction can occur when saturated loose sands experience a loss of strength and stiffness under the repeated application of a large load, such as during an earthquake. The cyclic stress causes a rapid increase in pore water pressure, which decreases the strength soil strength. Under these conditions, the sands begin to flow like a liquid [Lees, 2024].

On the other hand, the earthquakes in Mexico and Chile have left experiences and lessons learned about the importance of redesigning new structures based on stricter regulations, in order to reduce the risk of disaster, as well as implementing safety protocols for earthquakes and tsunamis.

For example, in Mexico, the 1985 and 2017 earthquakes remind us of the vulnerability of living in a highly seismic zones, we must continue to train ourselves in civil protection and allow us to act appropriate to prevent risk situation [Salcido, 2020].

The structural conception

The general process of activities that lead to a structural project, implies a series of work stages, which require a sequence and the same time an interdependence of the same, these stages can be considered as basic activities structural design [González, 1990].

a) Structural design
b) Load analysis
c) Structural analysis
d) Dimensioning

The structure conception will be the result of experience imagination and above all of the intuitive ability of the designer, but this professional intuition can only be developed with a good academic support and constant and updated professional practice [Corrales, 2010].

As an experience in Manzanillo in the 1995 earthquake, as a society-government we did very badly because we did not give the importance that is due to the structural design, most of the collapsed buildings had deficiencies, some of the most characteristic were:

a) Irregular "T" or "L" shaped floors that caused strong torsions.
b) Concentration of masses in upper levels
c) Corner buildings exposed to unacceptable torsional stresses
d) Vulnerability of buildings with very flexible soils.

Methodology [Static Method Analysis]

Vertical distribution of the basal shear

Known as basal shear V in the two orthogonal directions, it is distributed over the total height of the building, where the masses are supposed to be concentrated in the floors, since the design acceleration should be an increasing function of the height above ground when causing horizontal accelerations, the structure will deform laterally, and its accelerations will be greater than those of the ground on which it rests.

Shear force at the base

The shear force at the base of the structure, corresponding to the direction considered, will be determined with the following expression:

$$V = \frac{Z\,U\,C\,S}{Ro}\,P \qquad [1]$$

Zoning

The Mexican territory is considered to be divided into four zones as shown figure 2. The proposed zoning is based on the spatial distribution of observed seismicity, the general characteristics of earthquake movements and their attenuation with epicentre distance.

Each zone is assigned a z-factor, as shown in table 2, this factor is interpreted as the maximum horizontal acceleration in rigid soil with a 10% probability of being exceeded in 50 years, the z-factor is expressed as a fraction of the acceleration of gravity.

Use Factor [U]

Each structure must be classified according to the type of building. The use factor or importance [U] will be used according to the classification made. For buildings with seismic isolation at the base, U = 1 may be considered [Ministerio de Vivienda, Construcción y Saneamiento, 2003].

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Fundamental period of vibration [T]

The fundamental period of vibration for each direction shall be estimated with the following expression:

$$T = \frac{hn}{Cr} = \frac{14}{35} = 0.40$$
[2]

when:
hn = total building height = 14 m
Cr = 35 for buildings whose resistant elements in the considered direction are only:

a) Reinforced concrete frames without shear walls.
b) Ductile seal frames with moment resisting connections, without bracing

Box 4
Table 2
Zone factor

Zone	**Z**
4	0.45
3	0.35
2	0.25
1	0.10

Source: *Technical standard E.030 "Earthquake resistance design"*

Box 5
Table 3
Soil factor [S]

	S0	**S1**	**S2**	**S3**
Z4	0.80	1.00	1.05	1.10
Z3	0.80	1.00	1.15	1.20
Z2	0.80	1.00	1.20	1.40
Z1	0.80	1.00	1.60	2.00

Source: *Technical standard E.030 "Earthquake resistance design"*

Box 6
Table 4
Period defining the value of the C-factor [Tp] and period defining the beginning of the C-factor zone with constant displacement [T_L]

	Soil profile			
	S0	**S1**	**S2**	**S3**
Tp [seg]	0.30	0.40	0.60	1.00
T_L [seg]	3.00	2.50	2.00	1.60

Source: *Technical standard E.030 "Earthquake resistance design"*

Seismic amplification factor [C]

According to the site characteristics, the seismic amplification factor [C] is defined by the following expressions:

$$T < Tp \qquad C = 2.5$$
$$Tp < T < TL \qquad C = 2.5\left(\frac{Tp}{T}\right)$$
$$T > TL \qquad C = 2.5\left(\frac{Tp * TL}{T}\right)$$

For our case C = 2.5, due to the fact that our soil is S3, therefore the value of Tp = 1.00.

Coefficient of reduction of seismic forces [Ro]
Structural systems are classified according to the materials used and the seismic-resistant structuring system in each direction of analysis, as shown in table 4.

Box 7
Table 5
reduction coefficient in structural elements

Structural system	**Basic reduction coefficient [Ro]**
Steal Moment resisting frames Concentrically braced frames Eccentrically braced frames	 8 8 8
Reinforced concrete Portal frames Dual Structure walls	8 7 6 4
Reinforced confined masonry	3
Wood [For permissible stresses]	7

Source: *Technical standard E.030 "Earthquake resistance design"*

Lateral stiffness

The form of vibration of the building is a function of the masses $\left(\frac{w}{g}\right)$ and the stiffness of the supporting elements, the latter is called floor stiffnes7s or spring constant and is defined as the ratio of the shear force $[V]$ on the floor under study to the relative displacement $[\Delta]$ of the two levels that limit it.

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The stiffness will depend on the greater or lesser stiffness of the column or wall itself and the rotation of the ends [nodes] according to the stiffness of the beams and columns concurrent to the node.

Angular frequencies [wi] and natural modes of vibration

A vibrating structure has four basic properties: mass, stiffness, damping and displacement, a mechanical vibration is the oscillation of the mass around its equilibrium point the nature of the oscillation is determined not only by the mass but also by the stiffness and damping in nature [Molero, 2016].

Chopra [2014] proposed the determinant matrix for trivial solution which is mentioned below:

$wi = Det\ (k) - (w1^2\ M) = 0$ [3]

Expanding the determinant yields a polynomial of order N at $w1^2$, equation 3 is known as characteristic equation or frecuency equation. This equation has N positive roots the structural mass and stiffness matrices are symmetric and positive definite.

The positive definite matrix property of K is ensured for all structures supported in such a way as to prevent the motion of rigid body, as is the case with civil engineering structures *[ibid].*

Results

The results obtained were the load metering for a four-level structural concrete portal frames, as well as the seismic weight, the calculation of the basal shear, direct shear and torsional shear for the port of Manzanillo, which as previously mentioned is a zone of very high seismicity, these results were obtained from the Seismic Resistant Guadalajara regulation and the Technical Standard E.030 "Earthquake Resistant Design" of Peru. [Rupay, 2023].

Load metering:

- Weight of the beams = 44.77 ton*f
- Slab Weight = 36 ton*f
- Weight of finishes and partition walls = 30 ton*f
- Weight of columns = 41.47 ton*f
- Weight of overload = 30 ton*f
- Weight of roof overload = 12 ton*f

Box 8

Table 5

Load metering and seismic weight

Level	beam	column	slab	finishes	LL	DL	Ps
1	43.7	29	36	30	30	138.7	153.7
2	43.7	37.3	36	30	30	147	162
3	43.7	37.3	36	30	30	147	162
4	43.7	17.6	36	30	12	127.3	133.3

Source: *Caro, 2025*

Obtaining Basal shear

$$V = \frac{0.45 * 1.0 * 2.5 * 1.10}{8} * 611 = 94.5\ ton$$

when:
Z = 0.45 [Zone four]
U = 1.00 common use [dwellings and offices]
C = 2.5 because $T < Tp$
S = 1.10 because it is a very poor soil and belongs to Z4
Ps = 611 ton, total seismic weight of the building
Distribution of seismic force at each level
The horizontal seismic forces at any level i, corresponding to the direction considered are calculated with the following equations:

$$Fi = \alpha * V \quad [4]$$

$$\alpha = \frac{Pi\ (hi)^k}{\sum_{j=1}^{n} Pj\ (hj)^k} \quad [5]$$

Box 9

Table 6

Title: Distribution of seismic forces

Level	h	H	Ps	PH^k	αi	Fi
1	4.0	4.0	153.7	614.8	0.1096	10.35
2	3.6	7.6	162	1231.2	0.2195	20.74
3	3.6	11.2	162	1814.4	0.3235	30.57
4	3.4	14.6	133.3	1946.6	0.3471	32.8
				Σ = 5607	Σ = 1.0	Σ = V

Source: *Caro, 2025*

Lateral stiffness

$$Kc = \frac{12\ EI}{h^3} \quad [6]$$

when:

$f'c = 250\ kg/cm^2$

$$I = \frac{0.60^4}{12} = 0.0108\ m^4$$

replacing:

$$K1c = \frac{12 * 151000 * \sqrt{250} * 0.0108}{4^3} = 4834.74\ tonf/m$$

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Kc = 58016.72 tonf/m, for level 1

$$K2c = \frac{12 * 151000 * \sqrt{250} * 0.0108}{3.6^3} = 6632\ tonf/m$$

Kc = 79,584 tonf/m, for level 2 = level 3

$$K4c = \frac{12 * 151000 * \sqrt{250} * 0.0108}{3.4^3} = 7872.54\ tonf/m$$

Kc = 94470.55 tonf/m, for level 4

Having a calculated the stiffness of all the columns of the building, we apply the displacement matrix:

$$F = [K * U] \rightarrow U = [K^{-1} * F] \quad [7]$$

The calculation of the matrix of lateral stiffness and seismic forces is show below:

$$k = \begin{bmatrix} (k1+k2) & -k2 & 0 & 0 \\ -k2 & (k2+k3) & -k3 & 0 \\ 0 & -k3 & (k3+k4) & -k4 \\ 0 & 0 & -k4 & k4 \end{bmatrix}$$

$$k = \begin{bmatrix} 137600 & -79584 & 0 & 0 \\ -79584 & 159168 & -79584 & 0 \\ 0 & -79584 & 159168 & -94470 \\ 0 & 0 & -94470 & 94470 \end{bmatrix}^{-1}$$

$$F = \begin{bmatrix} 10.35 \\ 20.74 \\ 30.57 \\ 32.8 \end{bmatrix}$$

$$U = k^{-1} * F$$

$$U = \begin{bmatrix} 0.004 \\ 0.0068 \\ 0.0094 \\ 0.0097 \end{bmatrix} \text{m}$$

Finally, it is verified that the displacements comply with the Peru seismic-resistant technical standard, the drift is calculated, that is to say, the relative displacement of each level between the corresponding height.

$$\Delta i = \frac{u_{i+1}+u_i}{hi} * 0.75\ R \quad [8]$$

$$\Delta = \begin{bmatrix} 0.006 \\ 0.0046 \\ 0.0043 \\ 0.00005 \end{bmatrix}$$

Which complies with the maximum relative displacement, calculated with equation 8, should not exceed the fraction of the height of the mezzanine, that for reinforced concrete is:

$$\left(\frac{\Delta 1}{hei} = 0.007\right)$$

The stiffness of columns and beams were obtained using Wilbur formulas, conditioned for regular frames with elements of constant inertia and when the beams are stiffer that the columns, since this method gives errors of less than 10% in the floor to ceiling distortions as follows:

$$R1 = \frac{48\,E}{h1\left[\frac{4\,h1}{\sum kc1} + \frac{h1+h2}{\sum kv1 + \frac{\sum kc1}{12}}\right]} \quad [9]$$

$$R1 = \frac{48 * 2{,}188{,}198}{4\left[\frac{4*4}{0.0081} + \frac{4.00+3.60}{0.00288+\frac{0.0081}{12}}\right]}$$

R1 = 6384 ton/m

$$R2 = \frac{48\,E}{h2\left[\frac{4\,h2}{\sum kc2} + \frac{h1+h2}{\sum kv1 + \frac{\sum kc1}{12}} + \frac{h2+h3}{\sum kv2}\right]} \quad [10]$$

$$R2 = \frac{48 * 2{,}188{,}198}{3.60\left[\frac{4*3.60}{0.009} + \frac{4+3.60}{0.00288+\frac{0.0081}{12}} + \frac{3.60+3.60}{0.00288}\right]}$$

R2 = 4677 ton/m

$$R3 = \frac{48\,E}{hn\left[\frac{4\,h3}{\sum kc3} + \frac{h2+h3}{\sum kv3} + \frac{h3+h4}{\sum kv4}\right]} \quad [11]$$

$$R3 = \frac{48 * 2{,}188{,}198}{3.60\left[\frac{4*3.60}{0.009} + \frac{3.60+3.60}{0.00288} + \frac{3.60+3.40}{0.00288}\right]}$$

R3 = 4467.6.62 ton/m

$$R4 = \frac{48\,E}{h4\left[\frac{4\,h4}{\sum kc4} + \frac{h3+h4}{\sum kv3} + \frac{h4+h0}{\sum kv4}\right]} \quad [12]$$

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$$R4 = \frac{48 * 2{,}188{,}198}{3.40\left[\frac{4*3.40}{0.00953} + \frac{3.60+3.40}{0.00288} + \frac{3.40}{0.00288}\right]}$$

R4 = 6132 ton/m

Total x-axis stiffness in the four frames
K_1 = 25,536 ton/m, level 1
K_2 = 18,709 ton/m, level 2
K_3 = 17,870 ton/m, level 3
K_4 = 24,528 ton/m, level 4

$$k = \begin{bmatrix} (k1+k2) & -k2 & 0 & 0 \\ -k2 & (k2+k3) & -k3 & 0 \\ 0 & -k3 & (k3+k4) & -k4 \\ 0 & 0 & -k4 & k4 \end{bmatrix}$$

$$k = \begin{bmatrix} 44245 & -18709 & 0 & 0 \\ -18709 & 36579 & -17872 & 0 \\ 0 & -17872 & 42398 & -24528 \\ 0 & 0 & -24528 & 24528 \end{bmatrix}$$

$$\lambda i\, m = \begin{bmatrix} 15.66\,\lambda i & 0 & 0 & 0 \\ 0 & 16.51\,\lambda i & 0 & 0 \\ 0 & 0 & 16.51\,\lambda i & 0 \\ 0 & 0 & 0 & 12.07\,\lambda i \end{bmatrix}$$

$$\lambda i = \begin{bmatrix} 192.46 \\ 1665.54 \\ 3740.27 \\ 5362.15 \end{bmatrix}$$

$$wi^2 = \begin{bmatrix} 13.87 \\ 40.811 \\ 61.15 \\ 73.22 \end{bmatrix}$$

Therefore, the frequency periods at each level are equivalent to:

Level 1

$$T1 = \frac{2\pi}{w1^2} = \frac{2*3.1416}{13.87} = 0.453\ seg$$

Level 2

$$T2 = \frac{2\pi}{w2^2} = \frac{2*3.1416}{40.611} = 0.153\ seg$$

Level 3

$$T3 = \frac{2\pi}{w3^2} = \frac{2*3.1416}{61.15} = 0.102\ seg$$

Level 4

$$T3 = \frac{2\pi}{w4^2} = \frac{2*3.1416}{73.22} = 0.085\ seg$$

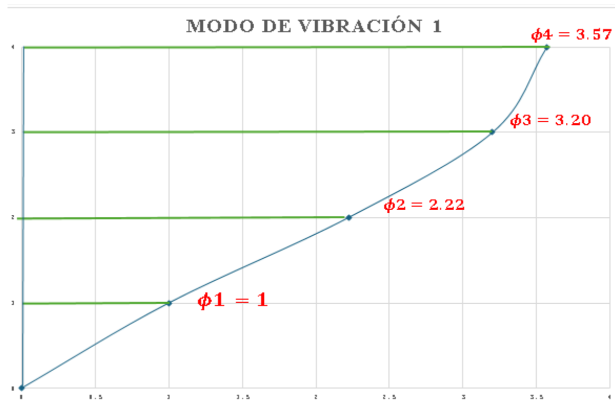
Vibration modes

With modal seismic analysis, the modes of vibration are identified and analyzed to study how the structure will respond to different types of seismic movements.

Vibration mode 1

$$\phi 1 = \begin{bmatrix} 41620 & -18709 & 0 & 0 \\ -18709 & 34032 & -17870 & 0 \\ 0 & -17870 & 39890 & -24528 \\ 0 & 0 & -24528 & 21984 \end{bmatrix}$$

Box 8

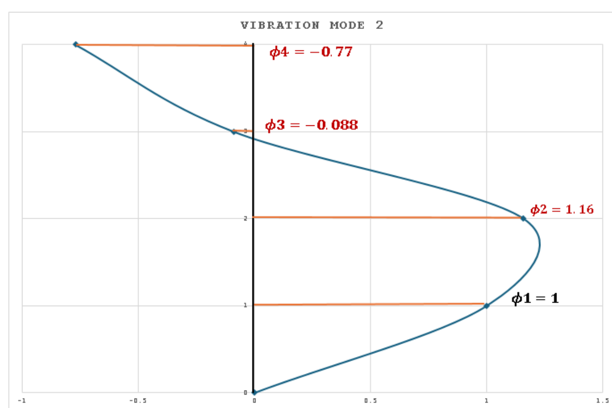


Graph 1
Vibration mode level 1
Source: Caro 2025

Vibration mode 2

$$\phi 2 = \begin{bmatrix} 21527 & -18709 & 0 & 0 \\ -18709 & 14544 & -17870 & 0 \\ 0 & -17870 & 20362 & -24528 \\ 0 & 0 & -24528 & 2826 \end{bmatrix}$$

Box 9



Graph 2
Vibration mode 2
Source: Caro, 2025

Vibration mode 3

$$\phi 3 = \begin{bmatrix} -6772 & -18709 & 0 & 0 \\ -18709 & -12904 & -17870 & 0 \\ 0 & -17870 & -7082 & -24528 \\ 0 & 0 & -24528 & -24207 \end{bmatrix}$$

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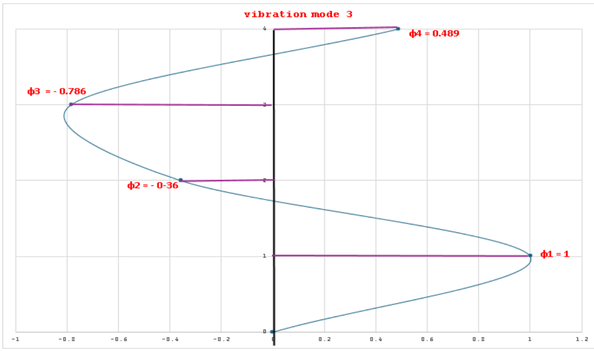
Box 10



Graph 3

Vibration mode 3

Source: Caro 2025

Conclusions

This research shows us that Manzanillo, Colima, faces a high level of seismic risk, but above all vulnerability to the liquefaction phenomenon, due to several factors including its geographical location since the port is located on the Pacific Ocean coast, as well as its interaction with the Cocos and North American tectonic plates.

It is utmost importance to continue disseminating research in seismic analysis, since earthquakes particularly in Manzanillo, have caused significant damage to the infrastructure, affecting the port economy and endangering the low-income population, since a large percentage of them live in high-risk areas.

Comply with the regulations and specifications on structural safety and design for earthquakes, assures us a better response capacity to seismic events, in order to safeguard the safety of its inhabitants, as previously mentioned.

Seismic analysis together with the review of construction regulations and wave propagations models, has allowed us to visualize the response capacity of buildings during an earthquake, which has allowed us to obtain additional forces or deformations that are generated as a result of an earthquake, such as what happened in the cities of Myanmar and Bangkok.

Therefore, recommends an optimization of structural materials in terms of analysis and design, as well as training of the population in safety protocols, both are key strategies to reduce the impacts of seismic events in the future.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest.

Author contribution

Caro-Becerra, Juan Luis: His contribution has been fundamental in the development of the article, it is worth mentioning that it is not the area of his research, but nevertheless, he documented with great richness both technically and scientifically, with a social sensitivity of how vulnerable we are, the beings of this planet.

Martinez-Hernández, Wilfrido: His contribution has been without any doubt in the structural design as far as the drawing in CAD format, in addition he ran the project data in the PRODISIS software [Seismic Design Program], to determine both the design spectra and the vibration modes. Criteria contained in the Civil Works Design Manual-Seismic Design CFE-IIE Version 2015.

Mayoral-Ruiz, Pedro Alonso: Without a doubt, Mr. Mayoral is the main author, his experience in soil mechanics and geotechnical engineering for the company "Soils and Control" for more than 30 years, as one of the most recognized in Guadalajara and experts on the subject, he has published articles on the phenomenon of liquefaction in the port of Manzanillo. I proposed him to write an article on the subject and he accepted my invitation.

Hernández-Magdaleno, Alfonso Manuel. He Contributed to the final draft of the article, before submitting it for review to the Scientific Committee of the 10th CIERMMI Congress. He also sponsored the article with funds from his Department of Basic Sciences at the University of Guadalajara.

Availability of data and materials

The results were obtained with quantitative methods, such as those mentioned in this article: Newmark, Holzer, Wilbur, NTC-CDMX, E.030 and those mentioned by the regulations Norms and Specifications, for Studies, Projects, Construction and Installations, vol. 4 Structural Safety, num. 2 Seismic Design.

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Abbreviations

EBF Eccentrically Braced Ordinary Portal Frames
GDL Degrees of Freedom
IMF Special Resisting Intermediate Frames
OCBF Concentrically Braced Ordinary Portal Frames
OMF Ordinary Moment Resisting Portal Frames
SMF Special Moment Resisting Gantries
SCBF Concentrically Braced Special Frames

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Discussions

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