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Article

Skirt piles in foundation: a structural rehabilitation solution for fixed offshore platforms

Pilotes faldón en cimentación: una solución de rehabilitación estructural de plataformas marinas fijas

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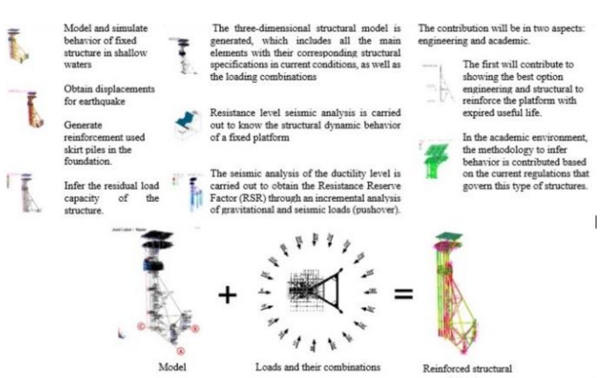
Abstract

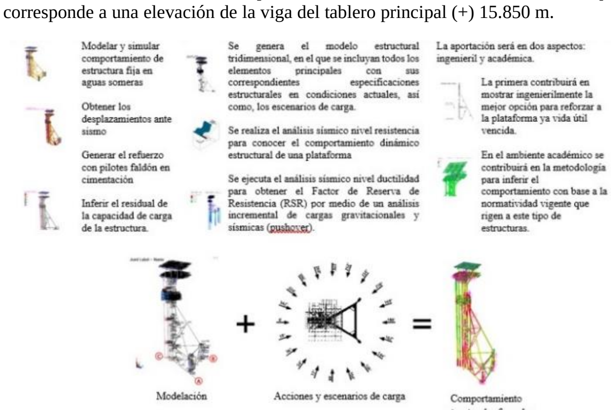
An analysis and structural design of strength and ductility level earthquake is presented in this paper. Numerical results show that structural failure under seismic loads is sensitive to the degree of deterioration of structural steel. The structural elements do not present any excess stress, that is, all stress ratios are less than unity. The maximum stress ratio is 0.942, in the superstructure of element 1586-1571, which corresponds to a main deck beam elevation (+) 15,850 m..



Fixed offshore platforms, Seismic analysis of ductility level, Seismic analysis of resistance level

Resumen

En este artículo se presenta un análisis y diseño estructural del nivel de resistencia y ductilidad sísmica. Los resultados numéricos muestran que la falla estructural bajo cargas sísmicas es sensible al grado de deterioro del acero estructural. Los elementos estructurales no presentan ningún exceso de tensiones, es decir, todas las relaciones de tensiones son menores que la unidad. La relación de esfuerzos máximos es de 0,942, en la superestructura del elemento 1586-1571, lo que corresponde a una elevación de la viga del tablero principal (+) 15.850 m.



Plataforma fija, Análisis sísmico nivel ductilidad, Análisis sísmico nivel resistencia

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Introduction

Offshore structures built in the ocean to explore for and exploit oil and natural gas are found at depths ranging from shallow ocean waters to the deep sea, so the arrangement or structuring that will be possible to extract hydrocarbons will vary depending on the depth, Figure 1.

Box 1

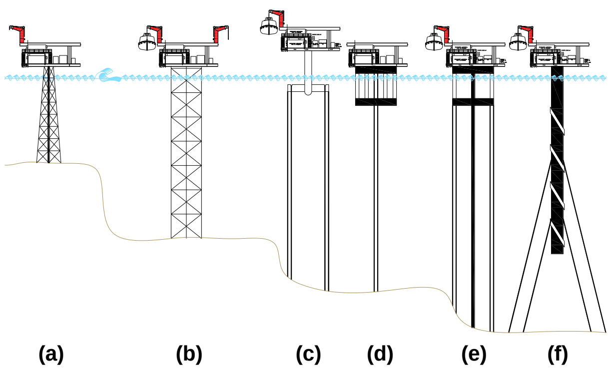

Figure 1
Offshore structures for hydrocarbon exploitation, (a) shallow water fixed platform, (b) shallow water tower platform, (c) intermediate water structure, (d) seabed anchored platform, (e) tensioned leg structure, (f) deep water platform, and (g) deep water platform.

Offshore platforms must operate for their entire lifetime and a remnant thereof, which is typically a minimum of up to 25 years. In shallow waters up to 120 m, the common type of platforms are fixed platforms, known as jackets in the offshore industry (Figure 1a), with a space on top, providing area for crew quarters, or to house facilities or to perform necessary exploration, production or exploitation manoeuvres, which consist of tubular structures fixed to the seabed by driven or drilled and grouted piles. The economic water depth limit for fixed platforms varies according to the environment, however, the fixed platform is economically feasible for installation in water depths of up to 450 metres (Sadeghi, 2007), i.e. beyond this water depth these platforms cannot be used, because it is simply not economical to build such slender structures. When the water depth exceeds these limits, compatible towers or floating production platforms become economically attractive (Schneider & Senders, 2010).

For shallow waters where fixed platforms are economically attractive, they consist structurally of three main parts: pile foundation, jacket and manoeuvring platform (Wilhoit & Supan, 2009; Poulos, 1988). During their lifetime they are subjected to various lateral dynamic loads, such as earthquakes, wave forces, ocean currents, wind forces and ship impacts. Their dynamic behaviour depends to a large extent on their structure and foundations.

The study area will be in the Gulf of Mexico, which is located in the southern part of the United States, surrounded by the Atlantic and Pacific Oceans, Figure 2, specifically in Ciudad del Carmen, Campeche, located at 18°38'18″N and 91°50'07″W in the Gulf of Mexico off the Yucatan Peninsula.

Box 2

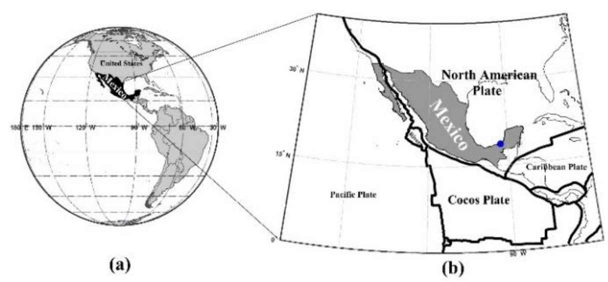

Figure 2
Study area, (a) Mexico in the world and (b) tectonic plates of Mexico

Methodology

Earthquakes are natural phenomena resulting from the interaction and release of enormous amounts of stored energy due to the elasticity and deformation of rocks which, when they yield or fail, produce telluric motion that travels radially in waves in all directions through the layers of the earth, reflecting and refracting at each interface, It is therefore necessary to perform strength and ductility seismic analysis, which is required to ensure that the platform has adequate strength and stiffness levels, as well as to avoid significant structural damage in the presence of an earthquake that has a reasonable probability of not being exceeded during the lifetime of the structure.

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The seismic analysis by resistance is carried out with the Structural Analysis Computer System (SACS) using its modules PSI, DYNAPAC, DYNAMIC RESPONSE, JOINT CAN and COLLAPSE with which the fundamental period of the structure has been obtained, the mechanical elements in the structural members, the nodal displacements, the stress ratios in elements (Unity Check), the revision of the piles and the analysis of joints under penetration shear stresses (Punching Shear), as well as obtaining the Resistance Reserve Factors (RSR) and determining the collapse mechanism (Sadeghi, 2007).

A three-dimensional structural model was generated, including all the main elements with their corresponding structural specifications collected in the field and the information gathered from the interventions that the platform has undergone. Likewise, the main accessories were modelled, such as the jetty, the conductor defence and the reinforcements foreseen for the correct functioning of the structure, Figure 3.

Box 3

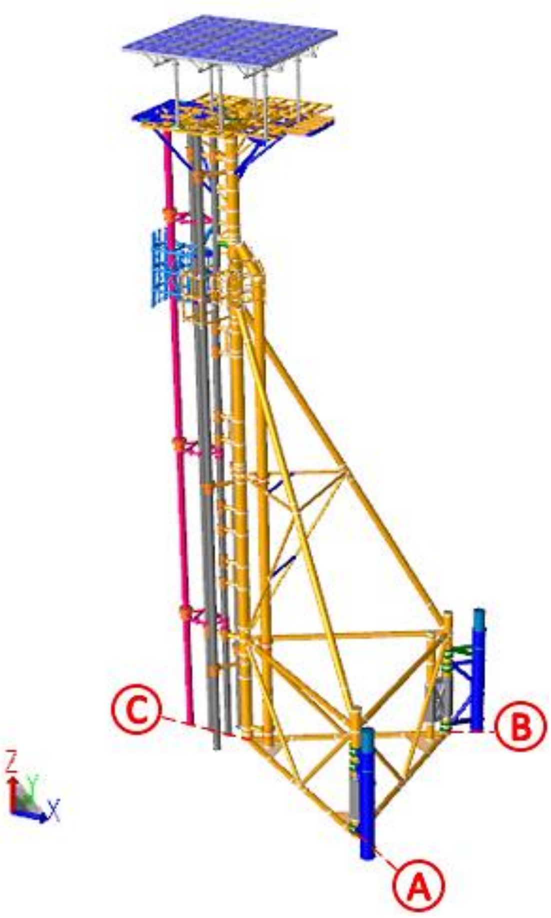

Figure 3
Three-dimensional model of the structure.

- The resistance level seismic analysis is to know the structural dynamic behaviour of a platform under seismic conditions, as well as to determine whether the stresses and displacements are less than those permissible according to current regulations.

- Ductility level seismic analysis is to obtain the Resistance Reserve Factor (RSR) by means of an incremental analysis of gravity and seismic loads (pushover), which shall comply with the provisions of the specification P.2.0130.01:2015 (PEMEX, 2015) Minimum Resistance Reserve Factor (RSR) required for ductility level analysis (design).

The presented Seismic Resistance Analysis consists of four steps or stages:

- The soil data for the first step corresponds to the Report of the platform, located in the Bay of Campeche, Gulf of Mexico, Geotechnical Report dated October 1988, from the company Solum, S.A. de C.V. The static soil conditions were factored by 1.4 to account for the temporary hardening of the soil that occurs during a seismic event. The stiffnesses at the pile heads were obtained using the PSI module of the SACS program iteratively considering initially a shear produced by environmental loads and subsequently adjusting with the seismic loads obtained in the third step of the analysis.

- The dynamic properties are obtained from a modal dynamic analysis where the modal shapes and their associated periods are obtained. The dynamic analysis must include the mass associated with gravity, the mass of the fluids contained in the legs of the structure and the aggregate or virtual mass. The distributed consistent mass criterion is used and is appropriate for fully or partially submerged structures.

- The specification P.2.0130.01:2015 states that the Resistance Level analysis shall be performed with the loads obtained from the resistance level design spectrum shown in Figure 4 and from the specification P.2.0130.01:2015 given in Table 1.

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Box 4

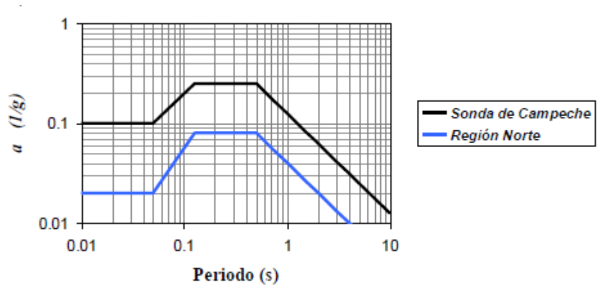

Figure 4
Design spectra at strength level for a critical damping coefficient of 5% for 200 years return period

Box 5

Table 1
Numerical data of the acceleration spectra for a return period of 200 years and a critical damping coefficient of 5%

Campeche Sound	
Period	Acceleration (g's)
0.010 – 0.050	0.100
0.125 – 0.504	0.250
10	0.013

- In addition, 5% structural critical damping will be used. Further guidelines for the analysis can be found in API-RP-2A WSD (2014), the full quadratic combination method (CQC) will be used to combine the modal responses and the sum of squares square root (SRSS) to combine the directional responses; the spectrum will be applied simultaneously and fully for two horizontal orthogonal directions and at 50% for the vertical direction. The SACS DYNAMIC RESPONSE module generates the equivalent static seismic forces in 20 different directions at every 18°. It is then possible to determine in which of these directions the greatest effects of the earthquake on the structure occur.

- The last step in the Strength Level Seismic Analysis is simply the application of the seismic forces generated in the previous step together with the gravity loads in a Linear Analysis. An increase of the allowable stresses of 70% must be applied in the Strength Analysis and the main structural elements resisting the seismic motion against the application of twice the seismic force must be checked. That is, for joints, piles, legs, columns and wind bracing. The rest of the members are checked against the single seismic force.

- To calculate the ultimate forces in joints and elements, the gravity, seismic, buoyancy and hydrostatic pressure loads must be combined simultaneously.

Through a Collapse Analysis of the platform, the Resistance Reserve Resistance Factors (RSR) of the platform to seismic loads will be known. For this purpose, it is necessary to apply the gravity loads in their totality, as well as to gradually apply the Seismic Loads until the collapse mechanism of the structure is achieved. This will be achieved by taking into account the following considerations:

- After having obtained the seismic loads, the Collapse Analysis is carried out. The collapse analysis is carried out for twenty directions of incidence of seismic loads separately, corresponding to 0°, 18°, 36°, 36°, 54°, 54°, 72°, 90°, 108°, 126°, 144°, 162°, 180°, 198°, 216°, 234°, 252°, 270°, 288°, 306°, 324° and 342°.

- The detailed results are presented only for the most critical direction, while for the remaining directions only the calculation of the corresponding RSRs is included.

The Ductility Seismic Analysis presented consists of 4 distinct steps or stages:

- Soil Liberalisation. In order to carry out a Dynamic Analysis it is necessary to represent the soil and the foundation in the form of an equivalent linear system. This is in accordance with the curves presented in the structure, Bahía de Campeche, Gulf of Mexico, Geotechnical Report dated October 1988, Cía. Solum, S. A. of C.V.

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- Obtaining the Dynamic Properties. In this part, the mass, stiffness and modal forms or modes of vibration of the structure are obtained, which define the structural behaviour under dynamic loads.

- Dynamic Response. With the dynamic properties and by means of the Response Spectrum Method, the equivalent static earthquake loads in different directions are obtained.

- Incremental Load Analysis. This is carried out by increasing the gravity loads up to 100% and then increasing the seismic loads until the structure collapses. This stage of the analysis must be carried out for each of the directions of incidence of the seismic loads considered.

The basic loads to which the structure was subjected are shown in Table 2.

Box 6

Table 2
Basic loads on the offshore platform

Position ID	Description	Weight (ton)
1	Self-weight of the structure	750.948
2	Dead load on substructure	41.223
3	Dead load on main deck	10.819
4	Live load on main deck	81.605
5	Pipe load on main deck	9.535
6	Load of equipment on main deck	18.895
7	Dead load on sub level	8.303
8	Live load on sub-level	8.475
9	Heliport dead load	4.710
10	Heliport live load	40.748
20-39	Seismic Loads @ 18°	

For the case of the foundation

Because dynamic analysis employs a linear, modal superposition theory, the non-linearity of the foundation must be represented by an equivalent linear system for the purposes of dynamic analysis.

The linear model of the foundation (super-element) by means of a series of "fictitious" elements or "springs" located at the pile-head whose elastic stiffness matrix replaces the non-linear behaviour of the real soil-pile.

To obtain the above-mentioned super-element, environmental loads have been initially considered under operating conditions for the orthogonal pairs of directions 0º-90º, 45º-135º, 180º-270º and 225º-315º. Subsequently, after step three of the analysis and returning to this first step, the combinations in the 0°, 90° directions are used to generate the equivalent linear foundation with more typical stresses.

Subsequently, the stiffness matrices of the super element corresponding to each of the piles are presented and will be included in the subsequent steps of this analysis. All this information is available in the output file DYNSEF which is to be used as input for the next step of the analysis.

Results

The SACS software converts weights into masses by means of its DYNAPAC module, therefore, the model must contain the loads to be converted into masses in addition to the structural self-weight. Dynamic degrees of freedom were incorporated at the appropriate nodes to participate in the modal shapes of interest and represented by 222000 in the JOINT lines.

In this section, the Spectral Modal Seismic Analysis of the Drilling Platform is shown, considering the masses and dynamic properties obtained previously.

The seismic forces were obtained using the SACS program by means of the Earthquake module with the recommendations of API-RP-2A (2014).

For the analysis, the seismic design spectrum was considered at the resistance level for a critical damping coefficient of 5% of the P.2.0130.01:2015 standard and in accordance with NRF (PEMEX, 2009 and 2007).

The dynamic response of the structure to seismic loads is shown below, consisting of basal shear and overturning moment.

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************ CQC SHEAR AND MOMENT VERSUS DIRECTION **************

POINT	ANGLE DEG	BASE SHEAR KG	OVERTURNING MOMENT KG-M	VERTICAL LOAD KG
1	0.0	97862.0	1206949.6	50571.9
2	18.0	96125.4	1287308.4	50571.9
3	36.0	90911.9	1442057.6	50571.9
4	54.0	85848.5	1611309.9	50571.9
5	72.0	80669.9	1732999.9	50571.9
6	90.0	75186.2	1790784.2	50571.9
7	108.0	76293.3	1757502.6	50571.9
8	126.0	83503.6	1641223.6	50571.9
9	144.0	91003.6	1466123.6	50571.9
10	162.0	96139.9	1284960.9	50571.9
11	180.0	97862.0	1206949.5	50571.9
12	198.0	96125.4	1287308.2	50571.9
13	216.0	90911.9	1442057.5	50571.9
14	234.0	85848.5	1611309.9	50571.9
15	252.0	80669.9	1732999.9	50571.9
16	270.0	75186.2	1790784.0	50571.9
17	288.0	76293.3	1757502.6	50571.9
18	306.0	83503.5	1641223.6	50571.9
19	324.0	91003.6	1466123.9	50571.9
20	342.0	96139.9	1284960.9	50571.9

The analysis was carried out in 20 directions applied to the structural model.

Box 7

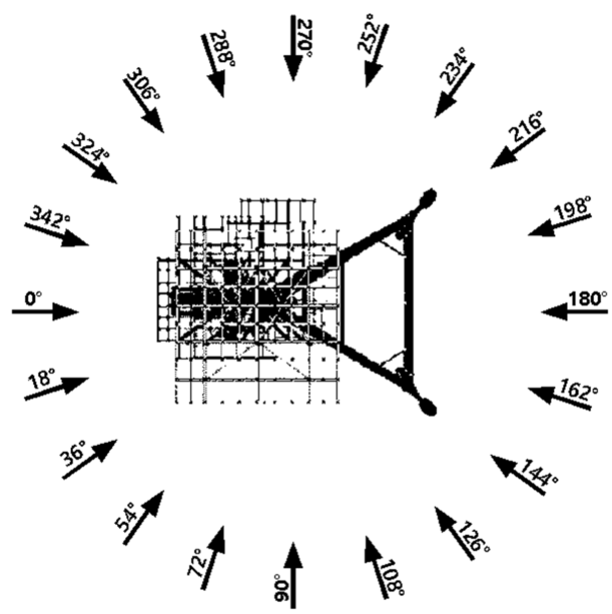

Figure 5

Analysis directions to obtain the Basal Shear and Tipping Moment

The maximum displacements that occurred during the seismic events on the simulated platform are described below. It is worth mentioning that the actual combinations to check the displacements are when the single seismic load is applied, i.e. the load combinations (C000, C018, C036, C342). **Figure 6** is also shown with the displacements in the -X direction (C180º) which was the most critical of the analysis.

**************** MAXIMUM JOINT DEFLECTION REPORT ****************

LOAD CASE	**X-DIRECTION** JOINT	DEFLECTION CM	**Y-DIRECTION** JOINT	DEFLECTION CM	**Z-DIRECTION** JOINT	DEFLECTION CM
C000	H001	15.5123	H187	21.8839	1559	-3.9230
C018	H011	7.2424	H195	18.3887	1677	-6.8887
C036	H011	5.9577	H195	16.4703	1677	-6.5305
C054	H001	4.8052	H010	13.5045	1677	-6.5420
C072	H001	4.9445	H010	13.6896	1677	-6.5825
C090	H001	4.9619	H010	14.6268	1677	- 6.9954
C108	H187	- 9.0742	H196	13.5675	1677	-6.2149
C126	H187	-8.8109	H196	13.2527	1663	-5.9613
C144	H187	-9.2739	H196	13.9388	1663	-6.1266
C162	H187	-10.3418	H196	15.5691	1663	-6.3308
C180	H187	21.7288	H196	30.1005	H001	-6.1655
C198	H196	11.6676	H187	10.2114	H011	-3.8751
C216	H196	10.3439	H187	-8.2927	1809	-3.6812
C234	H187	10.9113	H001	-7.1093	1809	3.8820
C252	H187	11.0541	H001	-7.2942	1809	-3.9054
C270	H187	11.1789	H001	-8.2415	1809	-4.3350
C288	H011	4.0333	DN82	-6.6600	1559	-3.7507
C306	H011	3.7881	DN82	-6.2553	1559	-3.8259
C324	H011	4.2659	H001	-6.8580	1559	-3.8742
C342	H011	5.3960	H001	-8.5953	1559	3.9513

Box 8

Figure 6

Maximum Displacement in the 180º Earthquake Condition (X).

The structural elements of the KAX-1 Drilling Platform were checked considering the combination of Gravity forces with the forces of the Spectral Modal Seismic Analysis following the recommendations of API-RP-2A (WSD) 22nd edition.

The review of the platform members was performed with the SACS program by means of the Element Code Check module. It should be noted that the review of the elements was performed as described below.

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The main elements of the structure were checked with a Factor 2.0 of the seismic load, in accordance with API-RP-2A (WSD) 22 edition, Figure 7.

Box 9

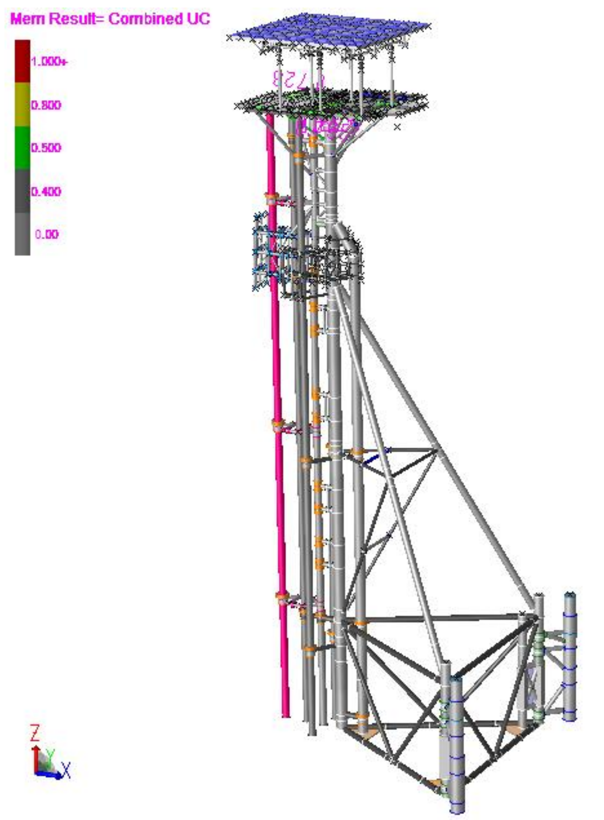

Figure 7
Interaction relations (Unity Checks).

Box 10

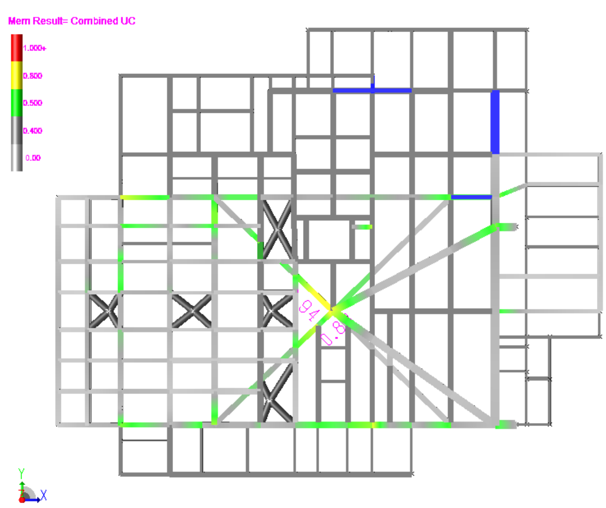

Figure 8
Interaction relationships in superstructure secondary elements.

The secondary elements of the structure were checked with a factor of 1.0 of the seismic loading only as described in API-RP-2A (WSD) 22nd edition, Figure 8. The stress ratios are shown separately in Substructure and Superstructure.

The stress ratios in the skirt piles above the seabed Platform are shown in Figure 9.

Box 11

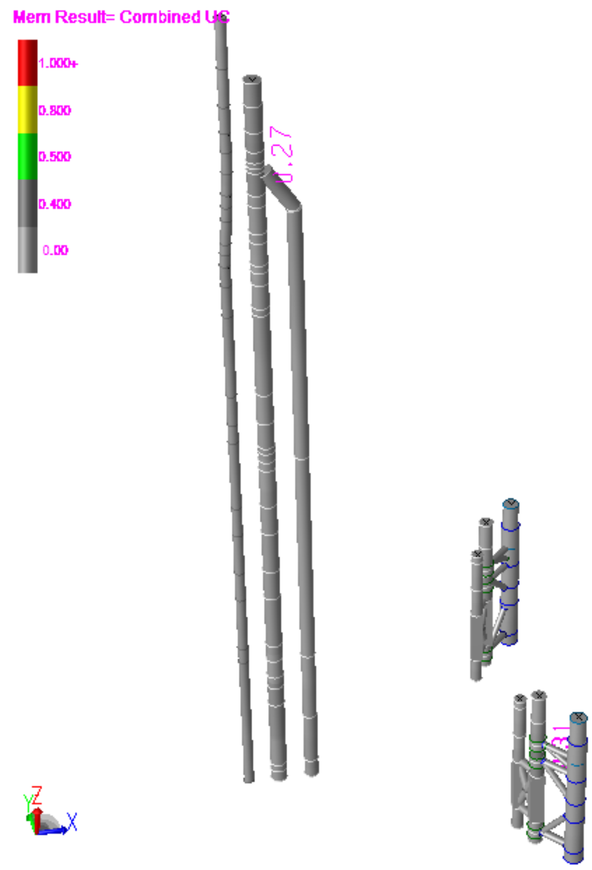

Figure 9
Interaction ratios in the pile skirt piles

The Resistance Reserve Factor (RSR) shall comply with the minimum required for ductility level analysis considering the specification P.2.0130.01:2015.

$$RSR = \frac{V_{last}}{V_{ref}} \quad (1)$$

Where:

V_{last} = Ultimate basal shear associated with the load at which the collapse mechanism of the structure is present.

$Vref$ = Cutting

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The ultimate shear considering a 180° direction is:

** SACS COLLAPSE PILE HEAD REACTIONS REPORT **
INCREMENT 66 LOAD FACTOR 5.600
*** STRUCTURAL PILE HEAD REACTIONS ***

PILE JOINT	FX KG	FY KG	FZ KG	MX CM-KG	MY CM-KG	MZ CM-KG
C100	11803.71	-8144.59	518386.03	2418061.2	1397208.5	-548425.6
P11	79714.23	-71821.85	531197.88	**********	**********	886690.2
PR1A	49951.71	-20453.39	179672.75	-325098.4	**********	-2261247.8
PR2A	49968.40	-4575.62	-25179.59	-3281179.2	**********	1701761.2
PR3A	30249.70	-3912.69	105998.98	-1701143.6	**********	2043134.1
P31	39678.51	-754.46	91382.59	293280.5	**********	2560363.0
P21	77496.11	-7200.65	-140690.27	-7533638.0	**********	1880843.4
C400	11989.19	-5698.38	32124.92	178561.3	2293584.5	21030.8
C200	11626.64	-10785.41	59035.50	1243584.6	1690722.9	33580.1
C300	16261.89	-12071.82	59276.41	5588.6	228449.8	278996.3
11CN	9168.25	-4129.87	32633.64	2671727.2	3587292.0	-598217.7
PN1	42754.63	25041.86	9463.22	19185356.0	*********	3525187.8
PN21	117207.11	-23559.22	-428325.16	*********	*********	1570184.6

*** TOTAL PILEHEAD REACTION ***

FX .... 547870.06 KG
FY .... -148066.08 KG
FZ .... 1024976.88 KG

REACTED BASE SHEAR 567525.50 KG

Substituting the magnitudes gives an RSR of 5.80, which is higher than the regulation of 1.60.

$$RSR = \frac{567.53ton}{97.86\ ton} = 5.80 \quad (2)$$

Conclusion

From the results obtained from the seismic analysis at Resistance Level for the Platform it is concluded:

The structural elements do not present any overstress, i.e. all stress ratios are less than unity. The maximum stress ratio is 0.942, in the superstructure of element 1586-1571, which corresponds to a main beam of the deck of elevation (+) 15.850 m; which belongs to group T7E, while in the substructure it is 0.31 in element C131-P1S which corresponds to group D10.

Regarding the analysis of tubular joints, the joint with the highest stress ratio is P2X with a ratio of 0.931, which is less than unity and is therefore considered acceptable.

The periods presented in the structures are within the tolerance range for this type of structure. In accordance with the above, it can be concluded that the Platform structure adequately supports the stresses imposed during the occurrence of an earthquake, with acceptable levels of stresses in both joints and elements, in accordance with the applicable regulations.

For the conditions of the seismic analysis by Ductility, the following is concluded:

The platform has been analysed by means of an incremental process of loads (pushover) which was applied in increments of 10% in Gravity Loads and 5% in Seismic Loads, until the collapse in the superstructure, specifically in the main beams, occurred. The Resistance Reserve Ratio (RSR) of the PP-KAX-1 Platform was calculated in 20 directions analysed 0°, 18°, ..., 342°, the lowest factor being in the 180° direction with an RSR of 5.80 and in all cases it is greater than the minimum (1.60) required by the regulations.

The collapse mechanism is present in the main beams of the deck (+) 15.850 m of the superstructure (see figure 5).

The Resistance Reserve Resistance Factors (RSR) of the platform are higher than the minimum required value of 1.60 by the specification P.2.0130.01:2015 in the Campeche Sound. Therefore, the structure has sufficient ductility reserve required by the specification, consequently, the structure forming the platform is considered acceptable.

Declarations

Conflict of interest

The authors and co-authors declare that they have no conflict of interest. They have no known competing financial interests or personal relationships that could have influenced the article reported in this paper.

Authors' contribution

The first author performed the analysis and interpretation of the results; the first co-author contributed to the modelling and simulation of the structure; the second co-author performed the processing of raw data for input into the model; and the third co-author performed the comprehensive review as well as the conclusion of the research results.

Availability of data and materials

The data obtained from this research are available for consultation at any time as required.

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Abbreviations

API American Petroleum Institute

CQC Complete Quadratic Combination

NFR Reference Standards

PSI Stack-Soil Interaction

RSR Resistance Reserve Factor

SACS Structural Analysis Computational System SACS

SRSS Sum-of-Squares Square Root

WSD Working Stress Design

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Background

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