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Structural reliability of platforms

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ABSTRACT: The high to moderate seismic risk and the investment represented by infrastructure of the Venezuelan Oil Industry, led to the establishment of a global effort for safety evaluation of its existing facilities. In this paper a structural realibility study of an existing gas compression platform is presented. The platform in study, located in Lake Maracaibo, is subjected to moderate to strong earthquakes. The methodology of the reliability assessment includes: structural modelling, ground motion characterization, structural dynamic response analysis and reliability analysis of structural and non-structural elements of the platform. The reliability is presented, in terms of the first passage probability of the response of critical points of the structure and vibration of equipments installed in the platform. The results obtained from the analysis show that the performance of the structural elements is acceptable, but the operation of the equipment, have low reliability even in the first seconds of the dynamic excitation.

1 INTRODUCTION

Experience has shown an increased tendency of industrial and public facilities destruction, caused by natural disasters in highly industrialized and/or populated areas. The impact of these disasters can be summarized in death, operational disruption in industrial facilities and structural damage of public and industrial facilities.

The Lake Maracaibo platforms are one of the most important facilities of the Venezuelan Oil Industry and are located in a high to moderate seismic risk area and exposed to moderate wave loading. The platform dynamic excitation is of a stochastic nature, therefore a probabilistic safety or reliability analysis must be performed.

Many methods have been developed to analyze the reliability of existing or design stage structures (Rice, 1945; Shinozuka, Hwang and Reich, 1984; Vanmarke, 1975).

An analysis method to evaluate the reliability of structures based on the distribution of the first-passage time for normal stationary random processes, is used in this study. The estimates of the first-passage probability depend on the limiting decay rate parameter defined by the system performance to the random excitation and its limit state (threshold) (Rice, 1945).

The gas compression platform in study is located at 10,12°N, 71,54 °W, and consist of a reinforced concrete (R/C) and steel structures, interconnected to each other by steel plates. The platform is modelled three-dimensionally taking into account the effect of the water and the soil foundation to which that portion of the pile is embedded. The earthquake ground motion is represented by artificial accelerograms of finite duration. On the basis of linear structural behavior, the structural response is modelled as a Gaussian random process and consequently, its spectral density function can be easily calculated. The limit analysis is defined by the structural capacity. The reliability curve of the structure is given for the peak ground acceleration obtained from a seismic risk analysis of the platform site location (Cascante, Gajardo and Quijada, 1992).

2 STRUCTURAL MODELLING

The platform is study is show in figure 1. It consists of a R/C and steel structure. The interconnection between the R/C and steel structures in achieved through steel plates fixed at the pile heads of the R/C structure. The function of the steel structure is to shelter the compression gas plant equipments, meanwhile the function of the R/C structure is to support the steel structure and the gas compression plant.

The R/C structure is composed by 24 beams, 21 prestressed piles and 15 connecting head piles. The piles have a hollow circular section of 0,91m external diameter, 0,66m internal diameter and a length of 50m (25m submerged in water and 25m embedded in soil). The beams have a rectangular section of 0,60m x 0,40m. The head piles geometry is 1,35m x 2,80m x 1,30m, and behaves as rigid connection between piles and beams.

The platform was modelled three-dimensionally through a finite element analysis program, and divided into more than 600 frame elements of six degrees of freedom per node. The soil-structure interaction effect was taken into account through linear springs located every 2m of the pile in contact with the soil foundation. The springs represent the soil resistance to the lateral pile movement and its stiffness were obtained from the soil-pile system dynamic analysis. The water-structure interaction effect was taken into account through the modification of the mass matrix of the system due to the water dragged when the system water-pile experienced movement.

The dynamic properties of the model were obtained from the numerical modal analysis and validated from its experimental modal analysis (Martínez and Quijada, 1992). TABLE 1 shows that the periods of vibration obtained from the numerical analysis and those obtained from the experimental modal analysis of the platform, the values agree very closely.

TABLE 1. Structure periods of vibration

Mode	Experimental Modal Analysis (seg)	Numerical Modal Analysis (seg)
1	0,98	1,07
2	0,88	1,03
3	0,70	0,79
4	0,49	0,43

3 GROUND MOTION CHARACTERIZATION

Strong ground motion is simulated by synthetic accelerograms obtained from the seismic risk analysis data of the platform site location.

3.1 Seismic risk analysis

In this study the seismic risk analysis was performed using the method developed by Cornell, 1968. This method consists in determining the probability of occurrence of an earthquake of a given ground motion intensity within the time period of interest, which depends on local seismicity, geological data and motion attenuation of the facility site location.

The location of the platform is shown in Figure 2. The seismic risk analysis for this location is evaluated using the World Data Center (WDC), and INTEVEP'S attenuation laws, and the output is expressed in the form of peak acceleration versus mean return period plot as it is shown in Figure 3 (Cascante et al., 1992).

From seismic risk analysis, it was determined that a ground motion of 0,18g peak acceleration will occur on the average once every 475 years, corresponding to an exceedence probability of 10% in 50 years.

3.2 Ground motion characterization in the frequency and time domain

Seismic excitation is modelled as artificial accelerograms generated from a series of sinusoidal waves (SIMQKE, 1976). The input parameters for the simulation are the amplitudes and phase angles of the contributing sinusoids, and the duration of the ground motion. The amplitudes are determined from the response spectrum of the ground motion.

COVENIN 1756-80 82 seismic code and seismic risk analysis data were used to construct the response spectrum. Furthermore, the earthquake time duration was obtained from a probabilistic strong motion time duration analysis for the site location of the platform.

4 STRUCTURAL ANALYSIS

A linear dynamic analysis of the three-dimensional structural model of the platform was performed, using the finite element program SAP90 (Wilson and Habibullah, 1988). The structure was excited in three orthogonal directions by an artificial accelerogram.

For the purpose of dynamic analysis of the platform, the structural system equation of motion is

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = \{F(t)\} \quad (1)$$

in which $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $\{x(t)\}$, $\{\dot{x}(t)\}$ and $\{\ddot{x}(t)\}$ are the displacement, velocity and acceleration vectors of the platform structural system, and $\{F(t)\}$ is the earthquake excitation vector to which the system is subjected.

The platform response is expressed in time series of the displacement, shear forcing axial forcing, torsional and/or flexural moments. Due to the Gaussian character of the response process, it can be completely be specified by the mean ux(t), autocorrelation function $Rx(t_1,t_2)$ and spectral density function Sxx(w), obtained from the following expressions

$$ux(t) = E\,[x(t)] \quad (2)$$

$$Rx(t_1,\, t_2) = E\,[x(t_1),\, x(t_2)] \quad (3)$$

$$Sxx(w) = \frac{1}{2\pi}\int_{-\infty}^{\infty} Rx(\zeta)e^{-iw\zeta}dw \quad (4)$$

in which

$$\zeta = t_1 - t_2$$

5 RELIABILITY ANALYSIS

The reliability analysis of a structure subjected to random excitation can be defined as the probability that the response x(t), will be kept within prescribed bounds during the operating time of the structure or as the probability distribution of the time of the first passage across threshold specified by the limit state of the structure.

The first-passage probability estimates are of the form

$$L(t) = A\exp(-\beta t) \quad (5)$$

in which L (t) is the probability of no crossing during a time interval (0,t), A is the probability of starting below a threshold defined by the limit state of the system, and β is the limiting decay rate parameter of the first crossing probability which depends on the system performance to the random excitation and its threshold (Vanmarcke, 1975; Cornell, 1968).

The structural response x(t) can be characterized as an ergodic Gaussian process described by a spectral density function Sxx(w) about its central frequency w, and the first spectral moments αi, i = 0, 1, 2

$$\alpha i = \int_0^{\infty} wi\; Sxx(w)\,dw \quad (6)$$

Since the random variable x(t), follows a Gaussian distribution, then the mean rate response crossing the threshold λ from below is given by

$$\nu\lambda = \frac{1}{2\pi}\,\frac{\sqrt{\alpha_2}}{\sqrt{\alpha_0}}\exp\left(-\frac{\lambda^2}{2\alpha_0}\right) \quad (7)$$

$$\nu\lambda = \nu_0\exp\left(-\frac{\gamma^2}{2}\right)$$

where ν_0 is the zero-upcrossing rate and $\gamma = \frac{\lambda}{\sqrt{\alpha_0}}$ is the reduced level.

The response crossigns out of the safe region defined by $|x(t)| < \lambda$, follows a Poisson process with mean rate $\beta = 2\nu\lambda$. Additionally if $\lambda \longrightarrow \infty$ then A = 1 and the probability of no crossing the threshold during the time interval (0,t), can be calcuted from equation (5) and (7), as

$$L(t)=\exp(-2\ \nu_o t \exp(-\frac{\gamma^2}{2})) \qquad (8)$$

However, for λ levels of practical interest, numerical simulation studies indicate that L(t) strongly depends on the bandwidth of the process, therefore the first passage probability can be expressed in the form

$$L(t)=\exp(-2\nu_o t \exp(-\frac{\gamma^2}{2}) C_1) \qquad (9)$$

where

$$C_1 = \frac{1 - \exp(-\frac{\sqrt{\pi}}{2} q_x \gamma)}{1 - \exp(-\frac{\gamma^2}{2})}$$

in which q_x is the bandwidth parameter expresed as

$$q_x = (1 - \frac{\alpha_1^2}{\alpha_0\ \alpha_2}) \qquad 0 \leq q_x \leq 1$$

6 NUMERICAL EXAMPLE

The platform structural and operational reliability analyses are presented, in terms of the first passage probability of the response of critical structural elements and plant equipments, respectively. For the purpose of analysis of the gas compression platform it was taken into account the importance of ensuring a good structural performance of the platform in order to avoid damage of the compression plant equipment; therefore, the structural reliability analysis is based on the linear behavior of the structure, and the operational reliability analysis is based on the continued operation of the plant.

6.1 Platform structural reliability

The structural limit state is defined by the flexural failure of critical beams and columns of the platform. Critical structural elements are those expose to the highest response level and consequently, have the highest probability of failure. The structural reliability of the entire platform is represented by the lowest value of the probability of no crossing in the duration of an earthquake.

The thresholds are defined by the resistance of critical structural elements, which are determined from COVENIN R/C and steel design codes. The critical structural elements capacity, is shown in TABLE 2. The response in the frecuency domain, that is, the spectral density functions, of the R/C beam and pile, are shown in Figs. 4, 5, and the platform structural reliability curve to the earthquake excitation, is shown in Fig. 6.

TABLE 2. Resistance capacity of critical elements

Structural Element	Mu (N-m)	Pu (N)
Pile N° 184	1050.000	200.000
	600.000	4.800
	300.000	220.000
R/C Beam N° 182	360.000	-
Steel Beam N° 756	1236.6520	-
Steel Columnn N° 602	175.200	352.176

6.2 Platform operational reliability

The operational limit state is defined by the maximum vibrational displacement that the equipment can withstand to avoid functional disruption. The operational reliability of the gas compression plant is represented by the probability that the vibration of the equipments do not cross the limit state during a given earthquake.

The barriers defined by the maximum vibrations supported by the equipment are given by the manufacturer. The translational earthquake response of the equipment support, is expressed in the frequency domain and is shown in Fig. 7. The platform operational reliability curve to the earthquake excitation, is shown in Fig. 8.

7 CONCLUSIONS

The reliability analysis is presented for an earthquake of a peak ground acceleration of 0,18g corresponding to a 10% of exceedence probability in 50 years. The reliability analysis of the platform should be extended for different values of the peak ground acceleration.

The existing platform presents a high structural reliability during the first seconds of excitation of the given earthquake. A structural optimization study, can be perrformed for desing stage platforms in Lake Maracaibo.

The plant presents a very low operational reliability even though a good structural performance was observed during the earthquake excitation. It is recommended to perform a detail study of the equipments connection.

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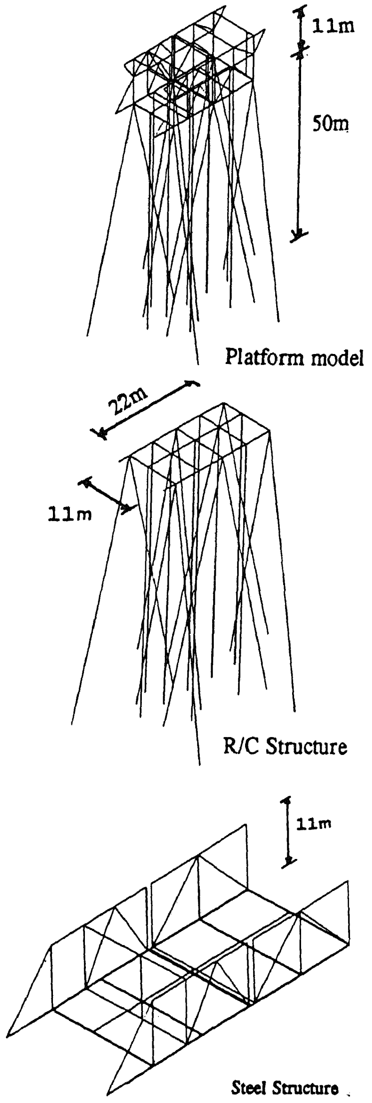

Fig 1. Platform structure.

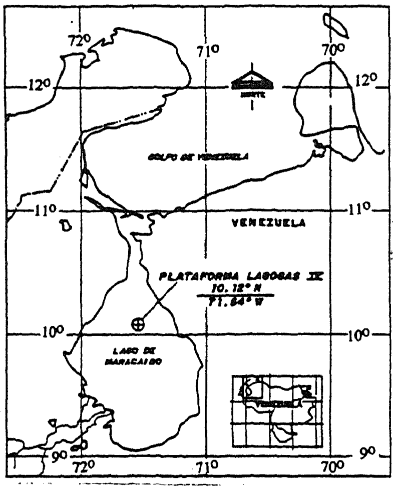

Figure 2. Platform location.

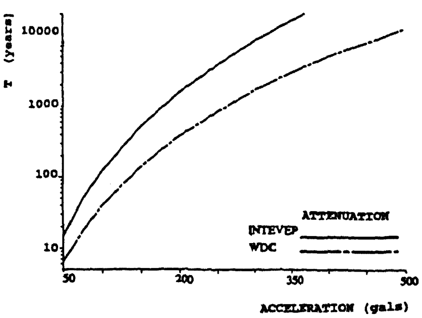

Figure 3. Peak ground acceleration vs. return period.

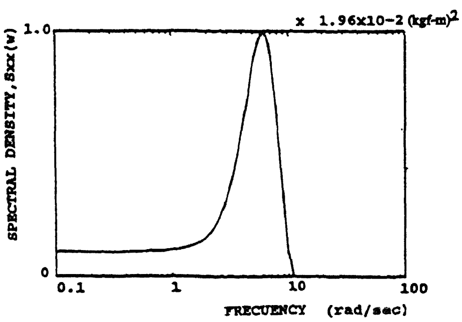

Figure 4. R/C beam response spectral density function.

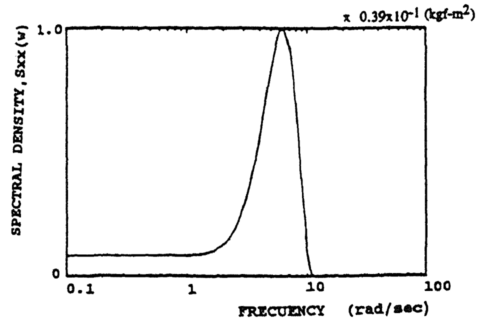

Figure 5. Pile response spectral density function.

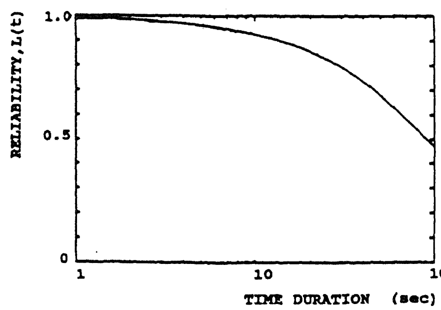

Figure 6. Platform structural reliability.

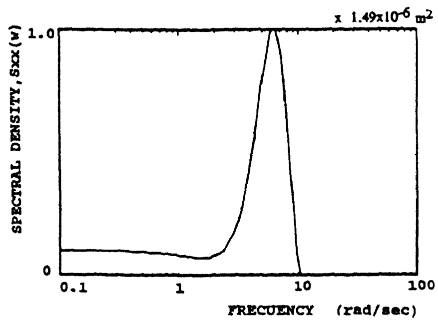

Figure 7. Equipment displacement response spectral density function.

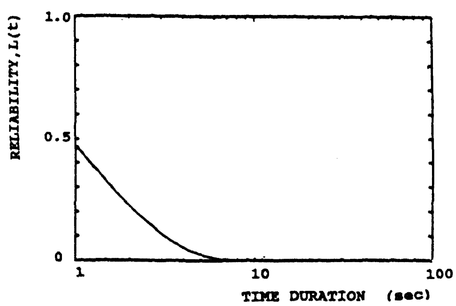

Figure 8. Platform operational reliability.