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Optimum selection of design parameters for transportation of offshore structures

J.L. Alamilla, D. Campos *, C. Ortega, A. Soriano, J.L. Morales

Mexican Institute of Petroleum, Eje central Lázaro Cárdenas 152, Col. San Bartolo Atepehuacan, Del. Gustavo A. Madero, 07730 México DF, México

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ABSTRACT

A probabilistic framework is presented to select the design significant wave height and design transverse rotation for typical barges used in the Gulf of Mexico for marine transportation of structural elements and/or systems. The selection of design transverse rotation is based on optimization procedure that trade-off between the performance of the barge subjected to a meteorological-oceanographic (metocean) hazard along the route and losses by structural damage. For this purpose probabilistic models to estimate the metocean hazard for marine transportation are shown. Afterwards, the design rotation is linked to the design of significant wave height and to the return period associated with such wave conditions. The formulation is applied to an offshore transportation route in the Gulf of Mexico.

1. Introduction

The design of offshore structural systems considers two phases. The first one is related to structural performance subjected to loads and possible deterioration conditions during the structure lifetime. The second considers the works required to transport the structural systems from the fabrication yard to the site of their placement and during the installation itself. The purpose of the design for transportation, in this last phase, is to avoid loss of stability of the barge-structure system as well as the possible damage in joints and elements of the structural system transported. As shown in Fig. 1, structural systems are placed on the barge, and this is towed by a small vessel called tug boat. The transportation starts from the fabrication yard and ends at the installation site or vice versa. During this phase, the barge-structure complex is subjected to dynamic loads, originated by possible oceanographic and meteorological conditions prevailing along the transportation route. During the design phase, the barge-structure system is subjected to an ergodic and stationary sea state, represented by spectral density of the wave in multiple directions. The spectral density is characterized by a spectral peak period and a significant wave height that is associated with a given recurrence period. As a result of the dynamic analysis, the stress state in structural elements and joints is checked not to exceed the allowable stress. In the opposite case, the structural system is strengthened. Together with this, mooring system characteristics (marine securing) for the structure fastening to the barge are determined. Mooring system must be able to stand the stress state it is subjected to during the travel.

In Mexico, two reference codes in use are combined to make the design for marine structure transportation, NRF-003-PEMEX-2000 (PEMEX, 2000) and NRF-041-PEMEX-2003 (PEMEX, 2003). The first one recommends a significant wave height with its associated meteorological and oceanographic parameters, valid for manoeuvres performed on typical routes within the Gulf of Mexico and out of the hurricane season. This code mentions that for manoeuvres performed during hurricane season, a reliable forecast of environmental conditions should be available in order to ensure sea states favorable for transportation. For other routes and seasons, one should refer to NRF-041-PEMEX-2003 code (PEMEX, 2003). This code recommends extreme environmental conditions with the 10-year return period, without providing any parameter, in the most exposed parts of the routes and furnishes prescribed values of movements dependent upon transport season, load magnitude and ship dimensions.

The American Petroleum Institute (API, 2000) recommends a probability of environmental conditions from 1% to 5% to be exceeded during transportation. Besides mentioned that must be taken into account the barge-structure transition time (duration of transportation), the accessibility to safety zones in the coast, the climate and the characteristic of the barge. Similar recommendations are given in references (LOC, 2003; NDI, 2002, 2005; IMO, 1998).

A rigorous formulation to obtain in optimum manner the design parameters for transportation of offshore structures is presented. This formulation takes into account the possible

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* Corresponding author.
E-mail address: dcampos@imp.mx (D. Campos).

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Fig. 1. Structural systems transported by a barge.

systematic reconstructions of the structure, the associated economical losses and the structural performance due to the corresponding metocean hazard are evaluated. A general methodology is presented to estimate the sea state and the dynamical response of barge-structure, with the corresponding returns of periods recommended to the design of transportation of marine structures. Here the sea state is characterized by a spectral density, specified in terms of a spectral peak period and a significant wave height of a given recurrence period. The dynamical response is specified by the transverse rotation (roll) of the barge. The annual exceedance rate of significant wave height is estimated here for a specific case; it is associated with a known climate-time-route window and applied to every barge. However the methodology can be applied to other cases where the characteristics of the set of barges and the transportation routes are known. To achieve it, a probabilistic model is developed to estimate the metocean hazard along the transportation route and its influence on the dynamic response of barges used for transportation. The ideas of seismic hazard studies (Esteva, 1976, 1968; Cornell, 1968) are extended to the evaluation of the metocean hazard for marine transportation of given duration. The formulations provide a logic form to evaluate the metocean hazard of the marine route and the vulnerability of barges in these routes. To take into account the transition time of the barge, a formulation is presented to estimate the exceedance probabilities of significant wave heights associated with transport of given time duration, based on the first-passage problem (Ditlevsen and Madsen, 2007; Madsen et al., 1986).

With the purpose of evaluating the design requirements specified in the established codes (PEMEX, 2000, 2003; API, 2000), the formulations are applied to real sea states and real structures transporting in a region of the Gulf of Mexico. This evaluation consists of determining in optimum manner the barge rotation for a transportation route associated with a given time interval (5 and 10 days). Afterwards, the return period associated with such rotation and the corresponding significant height wave are determined. Finally, the estimated values are compared with the corresponding values specified in the codes (PEMEX, 2000, 2003).

2. Theoretical framework for the optimum selection of design parameters

In this section a probabilistic formulation to select the design transverse rotation for typical barges used in the Gulf of Mexico for marine transportation of structural systems is described. Here the characteristics of the barges are given; however the formulation can be used to select the optimum characteristics of the barge. The optimum design rotation φ^*_D corresponds to the transverse design rotation that minimizes the economical losses and satisfies the safety conditions of the barge-structure system among a set of the possible design rotations φ_D values. To the end, the value of the design rotation to be specified in codes should be the optimum design rotation.

During the route, the performance of the barge-structure system, characterized by its stability and integrity, can be affected by one or more sea states. In general the transportation results can be synthesized in the following two possible scenarios:

1. The barge survives; however the transported structural system can present certain level of damage. This scenario include the extreme cases: (a) the structural system does not have any damage, and (b) the structural system is completely damaged.
2. The barge-structure system fails by instability.

In the following, these scenarios are taken into account in a probabilistic formulation to establish a trade-off between economical losses and barge-structures system safety. To select the design transverse rotation, the total economical losses C_T are minimized, which include the losses by damages in the transported structure and the total losses of the barge-structure system. An important point to consider is the systematic restitution in case the structure is damaged during the voyage. The expected value of C_T is obtained as follows:

$$E[C_T(\varphi_D)] = C_0(\varphi_D) + C_D(\varphi_D)\sum_{n=1}^{\infty}(1-p_{F_T})p_{F_T}^{n-1}e^{-\gamma(n-1)t_F} + (C_0(\varphi_D)+C_F)\sum_{n=1}^{\infty}p_{F_T}^{n}e^{-\gamma(n-1)t_F} \qquad (1)$$

The linear operator $E[\cdot]$ denotes expectancy. The first term of right side of this equation denotes the expected initial cost $C_0(\varphi_D)$, which includes the costs of mooring system designed to fix the structure onto the barge, the structural evaluation, the construction and the installation of the mentioned mooring system. The second term denotes the expected value of possible structural damages occurred during the transportation, given that the barge-structure system survived during the route; that is to say the barge does not fail by instability at the nth shipping out to sea. The second and third terms take into account the possible structural reconstructions and their systematic shipping out to sea. In Eq. (1), p_{F_T} denotes the failure probability of instability of barge-structure system associated to the marine transportation route. This instability is associated to the barge rolling over. The term $(1-p_{F_T})p_{F_T}^{n-1}$ denotes the survival probability at the nth shipping out to sea, given that in previous $n-1$ shipping out to sea, the barge failed by instability. The term $p_{F_T}^{n}$ denotes the instability failure probability at the nth shipping out to sea, given that in previous $n-1$ shipping out to sea, the barge failed by instability. The capitalization function $e^{-\gamma(n-1)t_F}$ takes into account the future costs expressed in present value, with the discount rate γ corrected by inflation (Rosenblueth, 1987), and t_F is the time spent in the new planning and structural reconstruction. For the first shipping out to sea ($n=1$), the capitalization function is equal to one.

On the other hand, C_F denotes the expected total loss of the barge-structure system and includes the cost by structural design and construction, economical losses by deferred production, barge, human injuries and human losses. In the last term of Eq. (1), the cost $C_0(\varphi_D)$ is added due to the reconstructions and shipping out to sea. The expected economical loss $C_D(\varphi_D)$ corresponds to the expected structural damages and it is