Ocean Engineering 153 (2018) 60–70

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Current profile analysis and extreme value prediction in the LH11-1 oil field of the South China Sea based on prototype monitoring

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ARTICLE INFO

Keywords:
South China Sea
Current
Profile characteristic
Prototype monitoring
ACER
Extreme prediction

ABSTRACT

Current is a key ocean-environmental factor and exhibits strong non-stationary random characteristics. The complexities of current modeling present significant challenges for deep sea oil exploitation. The multiyear return period extreme current model is one of the key factors for the reliable design of marine structures. Recently, due to limitations of design specifications and guidelines, improved methods to predict extreme values for the South China Sea based on prototype monitoring are required. In contrast to the traditional extreme value analytical method, the newly developed Average Conditional Exceedance Rate (ACER) method is robust and shows good accuracy for estimations of ocean environmental loading. The method offers good reliability for short-term prototype monitoring data. This study performs multiyear return period extreme value prediction of the current profile based on prototype monitoring data collected in the Liuhua (LH11-1) oil field that was recorded by an in-situ monitoring system. The 1-year and 10-year return period current velocity design indexes were obtained using the ACER method. The present current velocity profiles of multi-year return periods were compared with two design current load indexes of two floating platforms in Liuhua area. The consistency with comparison to TLP platform design indexes shows that the ACER method provides the accuracy and flexibility of the results needed in the construction of current load models in the South China Sea. These results could provide the basis and reference for the design of offshore structure.

1. Introduction

Although the South China Sea is rich in oil and gas resources with great exploration value, development of the deep-water fields is faced with significant challenges and uncertainty due to difficult observation and prediction of main environmental loads like wind, wave, and current. The ocean current has become a major load factor in the structural design of offshore oil and gas exploitation equipment, especially for use in deep-water regions. There are several influences of ocean current on offshore engineering structures. First, a large drag force will be generated on the structure under the effect of high-velocity current, causing strong resistance for towing and positioning. This can cause the tension in the anchoring and riser system of the platform to exceed acceptable limits. Second, VIV (Vortex Induced Vibration) of pipes will be generated in addition to the interaction of drag force, when the ocean current flows through the middle part of the riser. This long-term VIV will bring about fatigue failure to the riser. For these reasons, a study of the current distribution is critical to solve the load problem in the design of offshore engineering structure in the deep sea.

Many recent studies (He et al., 2012; Liu et al., 2002; Yang et al., 2013) have been performed to analyze ocean currents in the South China Sea. Numerous studies based on meteorological observations and ocean hydrological telemetering have been conducted with a main focus on the description of the regularity of observation results. However, extensive studies of the loading targeted for engineering applications are still in their preliminary stage. In general, prediction and analysis of current velocity of multiyear return periods are important to understand current loading for offshore engineering structures. To predict potential extreme values, extreme value theory and curve-fitting methods are usually adopted to determine the long-term distribution of offshore loads. Then, an appropriate theoretical frequency curve can be determined by coordinate transformation and then extended to obtain the extreme value for

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https://doi.org/10.1016/j.oceaneng.2018.01.064
Received 5 June 2017; Received in revised form 26 November 2017; Accepted 13 January 2018

multiyear return periods (Ma, 2006; Wang, 2005). Carollo et al. (2005) utilized GEV (Generalized Extreme Value) distribution and GPD (Generalized Pareto Distribution) to negotiate the vertical structure of current extreme values in the Faroe Bank channel and compared these methods to the FOAM (Forecasting Ocean Assimilation Model) numerical model. Jonathan et al. studied multivariate extreme value problems of ocean engineering including ocean current profile and wave height (Jonathan et al., 2010, 2012; Ewans and Jonathan, 2014) based on the model of multivariate conditional extreme value proposed by Heffernan and Tawn (2004). Dong (2009) adopted the Pearson Type III distribution to calculate the extreme values of wind-driven currents at Bohai Gulf and determined the final extreme value distribution of currents with tide vectors. Ge et al. (2009) used a 3-parameter Weibull extreme value distribution based on numerical simulation and data assimilation to calculate the return values of wind, waves, and current in four representative deep-water areas of the South China Sea. These estimation methods of extreme values are empirical models, like experience frequency and Pearson type III methods, or models based on extreme value theory, like Gumbel, Weibull, and the POT model (Chen, 1991). The latter is derived from the extreme value theory with a theoretical basis, and is widely used to determine the major distribution form of extreme values of ocean variables. And these methods are mostly based on asymptotic theory (Smith, 2002), where extreme value samples are assumed to comply with a particular form of asymptotic distribution. However, the distribution of samples is hard to predict in advance, and the applicability of the above prediction methods should be further improved. Recently, researchers have paid attention to the analysis of the interlayer inherent correlation of current profiles (Forristall and Cooper, 1997; Lima et al., 2009). But due to the difficulties such as modal losses, linear assumptions, the research achievements are still limited. Prediction using current profile models by considering inherent correlation is still in the preliminary stage. The authors are studying the regularities of current distributions and the interlayer inherent correlation, and results from this work will be published in the future.

To overcome the indicated defects of traditional asymptotic extreme value prediction methods, Naess and Gaidai (2009) proposed a more flexible extreme value analysis method, the Average Conditional Exceedance Rate (ACER) method, which does not depend on traditional asymptotic extreme value theory. This method can adopt the forms of asymptotic distribution indirectly and maintain the asymptotic characteristics of the original data samples. This increases the accuracy of the prediction and reaches the asymptotic consistency of traditional extreme value theory. The ACER method was based on the average conditional exceedance rate function, or the mean upcrossing rate function in earlier time. In 2008, Naess and Gaidai utilized the mean upcrossing rate function to perform numerical simulation on the extreme value response of the dynamical system through Monte Carlo simulation with verification of universality and robustness of the method, greatly reducing calculation time. Next, they improved the original method using revised ARE functions to be applicable to a generalized time series and even a non-stationary random process (Naess and Gaidai, 2009). The random responses of narrow-band and dual peak spectra were utilized to carry out numerical verification of the ACER method, and the results indicated the reliability and accuracy of the ACER method (Naess et al., 2007, 2010; Naess and Gaidai, 2009). Karpa and Naess (2013) conducted extreme value predictions of wind speed samples from three observation stations in Coastal Norway through the ACER method and compared the results with results obtained from traditional Gumbel and POT methods. The comparison showed that the ACER method provided better accuracy, stability, and insensitivity to anomalous points.

The design of offshore engineering equipment in China has always adopted API and DNV design criteria due to the lack of long-time prototype measured data. The specification of DNV NO. 30.5 has been adopted as the design basis of ocean environment loads (Veritas, 2000; NDRC, 2004). The specification provides a mechanical description of environmental conditions and environmental loads. However, the current load was presented as a general formula of drag force, unlike the more detailed descriptions of the wind and wave loads. Thus, the current load design basis and computational method has not yet been demonstrated clearly. The spatial distributions in existing specifications were obtained from beach and coastal areas. Due to the lack of applicability for the deep-water environment, it is insufficient to serve as an actual reference basis to define the current load for offshore engineering design. At the same time, current load models including international specifications were obtained based on data analysis of other sea regions. However, the applicability of these models must be verified due to the complexity of the South China Sea. Overall, it is essential to study current loads based on prototype data measured in the South China Sea. To address this need, the goal of this study was to investigate current loads at the LH 11-1 sea region based on the prototype monitoring system built by "NanHaiTiaoZhan" FPS and the ACER extreme value analysis method. In this paper, an ACER based extreme value prediction method was applied to predict the extreme current, and two design indexes are subsequently verified. The achievements of the current model for multiyear return periods can provide significant guidance for load selection and application in offshore engineering design, especially in the South China Sea.

2. Prototype monitoring of offshore engineering structure

Theoretical analysis, numerical simulation, and model testing are the main research methods applied to the design of offshore equipment structures. However, integral analysis of the structure of large offshore platform systems containing a variety of complex substructures cannot be conducted with full dependence on the theoretical analysis, derivation, and calculation. The inevitable simplifications of the structure may distort the analysis results. Numerical simulations include model approximation, linearization, decoupling calculation, and other processes of simplification that can produce large errors. Model testing is an essential aspect of offshore engineering equipment design, but there are limits due to complex real sea conditions. Limited by the size of the testing pool, truncation and scale effects are inevitable in the test. Designed to overcome the above defects of traditional methods, the prototype monitoring method aims to obtain the actual load and structural dynamic response through prototype testing under real sea conditions. Structural analysis based on data from prototype monitoring should be more reliable. Unfortunately, without enough data from prototype testing, only limited specifications and guides could be applied to offshore structural design in the South China Sea. For example, related specifications (NDRC, 2004) indicate that the following formula can be employed to calculate the gradient of current velocity if there is no available current data for a shallow ocean area (water depth less than 150 m).

$$V_c = V_T\left(\frac{y}{H}\right)^{\frac{1}{7}} + V_W\left(\frac{y}{H}\right) \tag{1}$$

where, V_T is the current velocity of the tide, V_W is the velocity of the wind-driven current, y is the depth from the ocean bottom, and H is the water depth. However, the computation of Eq. (1) is complex, especially when it is generally difficult to obtain actual values of V_T or V_W. Additionally, the formula is only valid for the estimation of currents in shallow water, but not the actual current load distribution in deep water or a complex sea region. Therefore, it has become increasingly important to analyze the current model using prototype monitoring.

2.1. *The prototype monitoring system of the "NanHaiTiaoZhan" FPS (NHTZ FPS)*

The NHTZ FPS is a semi-submersible drilling platform serving the LH11-1 oil field (Fig. 1 and Fig. 2) in the South China Sea. It has a weight of 16735 tons, total length of 90 m, molded breadth of 75 m, molded depth of 40 m, and total height of 110 m. In this region of the LH11-1 oil