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Discussion on the parameters of design waves

WANG Yan-ying (王言英)

School of Naval Architecture and Marine Engineering, Dalian University of Technology, Dalian 116024, China

Abstract: In order to respond the discredit on the design wave standard and to recommend new consideration on design wave parameters, based on the long-term distribution of statistic characteristics of waves and the short-term probability properties of sea state defined by giving the return period, the calculation of the return period, the height, the period, and the oceanic wave parameters of the design wave and the forecasting methods are discussed in this paper. To provide references for the operation reliability of floating structures in the extreme sea state, the method of determining the design wave parameters is resurveyed. A proposal is recommended that the design wave, which can be either significant wave with 500-year of the return period, or the maximum wave with 1/N of exceeding probability, 100-year of the return period, can be applied in the engineering design practice.
Keywords: ocean waves; short-term distribution; long-term distribution; design waves
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1 Introduction

The condition of ocean environment is very important to the design for marine structure in the ocean engineering practice. The responses of hydrodynamic and structural performance due to waves generated by wind are the major factors that directly affect the reliability of existing structures and the efficiency of operation and therefore are taken noticed in the design for floating structure. It is well known that wave motion is a random process. The statistical characteristics of wave parameters are different in the probability functions both in the short-term and long-term. At present, there are two approaches for analyzing the data in wave observation, namely, the design wave method and the spectral analysis method. The so-called design wave is the maximum significant wave in the given return period[1-2]. The design standard for the return period of significant wave stipulated in the DNV Code was 100-year[3]. Generally, the probability density function of wave height for the short-term sample is fitted by Reighly distribution and the probability density function of the statistical characteristics in the short-term is fitted by Weibull distribution. Based on the linearized Weibull function, the wave height of the design wave can be determined when the return period is given, and the corresponding wave periods with different statistical significations can also be determined by analog approach[2]. In the extreme sea state with the return period of 100-year, the occurring probability for significant wave height is a small probability event, equaling about 10^{-9}; the probability of exceeding this significant wave height is about 14%; and the probability for floating structure encountering this significant wave height is 18% for the 20-year design life. All of the above data is the so-called probability state of the design wave. Apparently, the floating structure designed based on the design wave will still face larger risk in the operation state. It should be indicated that the ocean environmental data are determined on the basis of the ocean engineering practice. In view of the perils occurred at the North Sea in the 1980s, the computational methods for wave loads on the floating structures were changed in succession, from linear wave theory to 5-order wave theory and then to 8-order wave theory, in the light of DNV Code. Specially, after the perils of the sea occurred at the Gulf of Mexico in 2005 due to the hurricane Katrina, the ocean environmental condition for the design of floating structures with the standard of 100-year return period was oppugned. Whether longer return period was needed instead of 100-year? Whether the wave height with shorter exceeding probability was needed instead of the significant wave? Whether the encountering probability for floating structures could be further decreased to less than 18%?

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*Corresponding author Email: yygwang@dlut.edu.cn

Although the risk can not be completely avoided in the ocean engineering operation, reducing risk to the fullest extent is always highly regarded by designers, builders, and operators.

2 Definition of the design wave

Based on the recorded observation data of the sea level elevations, the significant wave height H_S and up-zero period T_Z can be determined in the target sea area. These are the statistical characteristics for a short-term sea state and they can be accumulated into a sample in the long-term as follows:

$$\left[(H_S;T_Z)_i\right],\quad i=1,2,\cdots,N\ (N\to\infty).\qquad(1)$$

The so-called design wave is a statistical characteristic of the extreme sea state, which can be ascertained with given probability, using the sample as listed in Eq.(1). Generally, the probability density function of significant wave height can be fitted by the three-parameter Weibull function[3-5]. Then the accumulative probability function can be written as follows:

$$P(H_S)=\int_{H_0}^{H}p(H_S)\mathrm{d}H_S=1-\exp\left[-\left(\frac{H_S-H_0}{H_C-H_0}\right)^{\xi}\right],\qquad(2)$$

where the parameters H_0,H_C,ξ are respectively the minimum threshold level (m), the scale factor (m), and the shape governing factor. Based on the linearization processing of Eq.(2) and the data base provided by Eq.(1), the parameters H_0,H_C,ξ can be ascertained for the target sea area by the optimization arithmetic method, which has given target function of the minimum fitting standard deviation, and the iterative arithmetic method for the minimum threshold level H_0 ($H_0\ge 0$).

The mean wave period for the short-term sea state, together with corresponding significant wave height, can form a single wave, which is stochastic in the long-term sample of significant wave height. Therefore, the wave period of significant wave height depends on the combined probability of significant wave height and its period.

For the analysis of short-term sample of waves, the mean value of 5 up-zero periods T_Z round the maximum wave is defined as the mean period T_M for this sample[3], i.e.

$$T_M=\alpha T_Z,\qquad(3)$$

where $1.15<\alpha<1.54$. The 2-parameter Weibull distribution function based on the sample of significant wave height H_S and mean up-zero period T_Z for the North Atlantic Ocean is established:

$$P\left(T_Z|_{H_S}\right)=1-\exp\left[-\left(\frac{T_Z}{\alpha}\right)^{\gamma}\right],\qquad(4)$$

where $\alpha=6.05\exp(0.07H_S),\gamma=2.36\exp(0.21H_S)$.

One of the design methods in the engineering practice of floating structures is the design wave method. The so-called design wave is the maximum wave in the defined return period T_R; it equals to 100 years according to DNV criterion. Based on the mean wave period $\bar{T}$, the occurring amount of waves N in the return period T_R can be calculated. In fact, the maximum wave is measured by the significant wave height H_S and it is defined as the design wave height H_D, with corresponding exceeding probability listed as follows:

$$1-P(H_E)=\exp\left[-\left(\frac{H_D-H_0}{H_C-H_0}\right)^{\xi}\right]=3.17\times10^{-8}\frac{\bar{T}}{T_R}.\qquad(5)$$

Now wave height H_D for the design wave can be solved from the above equation, i.e.

$$H_D=(H_C-H_0)\left[17.27+\ln T_R-\ln\bar{T}\right]^{\frac{1}{\xi}}+H_0.\qquad(6)$$

Thus, the design wave height H_D and corresponding wave period T_Z can be used to construct a single wave, which is called the design wave.

In Europe, based on a decade's wave observation data (1966-1976) in the North Sea, the design wave parameters were given[2], in which the design wave height could be calculated:

$$H_D=2.07\left[2.3(\lg T_R-\log T_Z+7.5)\right]^{0.91}\qquad(7)$$

For T_R=100 year, $H_D\approx32$ m, this is the so-called 100-year wave height, which is just the defined value given by DNV. It can be derived from Eq.(7) that the wave period for the 100-year wave height equals 6.3 s. However, it should be further discussed as follows:

1) According to Eq.(7), when the wave period is in

the range of T_Z = 6~32 s, the 100-year wave height H_D only change with an amplitude of 2.4 m or so, and decline with increasing of the wave period, see Fig.1.

2) It is well known that the wave steepness is limited due to gravity. Generally, $H/L = 1/7$ (L is the wavelength). In deep water, $L = gT^2/2\pi$, the limited wave period will be 12 s or so when the wave height is 32 m.

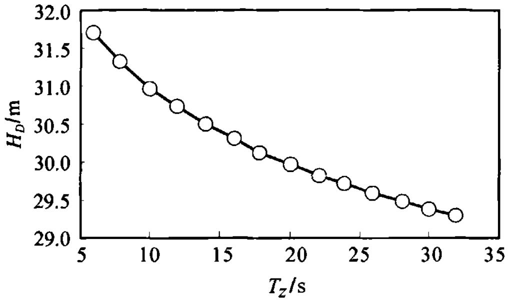

Fig.1 Relation between the design wave height and corresponding wave period

3) For the statistical characteristics of extreme sea state, the significant wave height is corresponding to an up-zero period, which has larger probability, and usually, such wave period can be determined by Wiegel formula[1].

$$T_Z\big|_{H_S} = 15.6\left(\frac{H_S}{g}\right)^{\frac{1}{2}}. \tag{8}$$

For the design wave of 32 m high, the limited wave period should be 28 s or so, as shown in Fig.2.

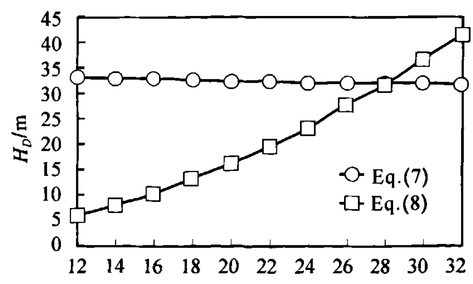

Fig.2 Determination of the wave height and up-zero period for the design wave

It can be seen that for a design wave of 32 m high, the corresponding wave periods are stochastic values also. When T_Z =12 s, the wave steep H/L =0.142 9 for a significant wave of 32 m high, which means a higher nonlinear wave. When T_Z =28 s, the wave steep H/L =0.026 1 for a 32 m significant wave with higher probability. This can be almost regarded as a linear wave. Thus from the engineering point of view, as for the small probability events in the sea with significant waves of 32 m high, the sea state with 32 m waves and 12 s wave period is more dangerous and should be paid with more attention.

3 Return period of the design wave

The definitions on the return period for extreme events are different in different engineering fields and subjects. It depends on occupancy of historical observation data, grade of risk, level of existing analysis and prediction technologies, and actual experience in engineering practice.

In the ocean engineering field, the return period of extreme sea state originated from the initial period of developing the petroleum resources in the North Sea (1960s ~ 1970s), and then it was defined by DNV Code. The design wave height for floating structures is the maximum wave occurred once in a hundred years in the operating sea area. As to the application of return period, there're some points for attention[6].

1) The computation of the design wave height as listed in Eq.(7) is established based on a basic assumption that the probability density function of long-term distribution of significant wave height, which is the statistical characteristic of short-term sea state, is fitted by Weibull probability function.

2) The calculation of significant wave height for statistical characteristics is based on the short-term samples, which come from the observation records in more than 10 years in the target sea area. In this data base, the average occurring probability for each sea state is about 10^{-7}, and the average occurring probability for 100-year wave height is about 10^{-9}, which was obtained by extrapolation with the 2-order magnitude.

3) For the ocean structure with T_L years of the service life, the encountered probability can be calculated under the assumption of independence

between the wave less than the design wave height and that equaling the design wave height:

$$P_E = 1 - \exp\left(-\frac{T_L}{T_R}\right). \tag{9}$$

Obviously, as to the oceanic structure with 20 years of the service life, the probability of encountering extreme 100-year wave height ($\sim 10^{-9}$) can be up to 18%.

4) In the days after hurricane Katrina surprisedly attacked the Gulf of Mexico, people became puzzling: whether the design standard for 100-year wave was reasonable, whether the design code for oceanic structures was feasible. The crux is the determination of return period. By Eq.(7), when the return period was extrapolated up to 500-year, it can be seen that comparing with the 100-year return period, the design wave height rose from 32 m to 34 m, which is shown in Fig.3.

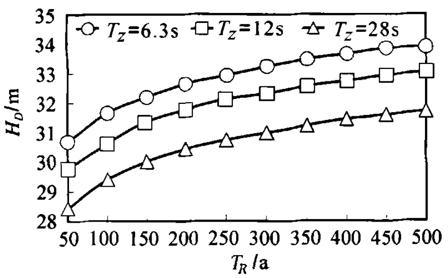

Fig.3 Relation between the design wave and the return period

5) Similarly, by Eq.(9), when the return period was extrapolated to 500-year, the encountering probability of structure with 20 years of the service life was decreased to 4%, fell 14% points, see Fig.4. That means the risk of oceanic structures in waves will be reduced remarkably.

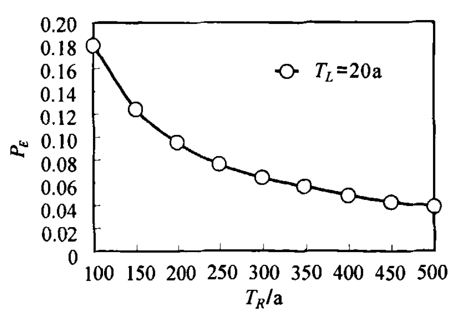

Fig.4 Relation between the return period and the encountering probability

It should be pointed out that the above analysis is based on the wave observation data of 10 years' records. In fact, if the return period is extended to 500-year, the observation term of waves, the capacity of sample, the fitting probability density function, the manner of extrapolation, and the arithmetic of every probability characteristics should be reconsidered. Although the risk can be decreased in above analysis, higher investment is undoubted for the design, construction, operation, and maintenance. The balance of gain and loss for determination of the return period is important to the design.

4 Sea state of the design wave

The design wave is a single wave in random waves, and is defined by significant wave height and corresponding wave period. In fact, the probability exceeding significant wave height can be up to 14%. Approximatively, the lower limit value of wave height with $1/N$ of exceeding probability can be given as follows:

$$H_{1/N} = H_S\sqrt{\frac{1}{2}\ln N}. \tag{10}$$

From Fig.5, it can be found that the lower limit value of the maximum wave height with 1/10 of exceeding probability $H_{1/10} \approx 34$ m, which is equivalent to the wave height with 500 years of the return period.

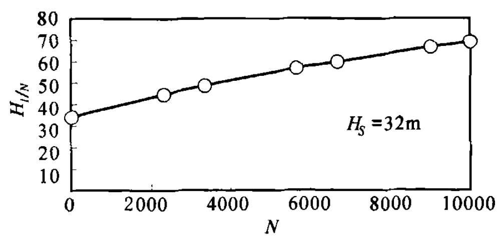

Fig.5 Distribution of wave heights when the wave height of the design wave exceeds significant wave

Spectral analysis method for hydrodynamic and structural performance of oceanic structures in the extreme sea state is one of the computational procedures. In the target sea area, the design wave measured by significant wave height denotes both the extreme sea state and the characteristics of energy spectral density function for wave motion.

Based on the design wave height and appropriate selection of wave energy's spectral density function, obtain the frequency response function of performance for the target structure by numerical or physical simulation, and derive the response spectrum of such performance from the transform in frequency domain, and finally all kinds of data needed in the design can be ascertained by characteristic analysis of responding spectrum.

In order to complete the above computation and analysis, there are still some problems to be further discussed:

1) On the transform system in frequency domain. In frequency domain, the following linear transform system is still used up to now:

$$S_Y(\omega)=\left|H(\omega)\right|^2 S_X(\omega), \tag{11}$$

where $S_X(\omega)$ is the input energy's spectral density function, $H(\omega)$ and $S_Y(\omega)$ are the frequency response function and the output energy's spectral density function respectively. As the extreme waves are remarkably nonlinear and the response is nonlinear also for structures, the use of Eq.(11) is limited in the engineering computation. To overcome this problem, two approaches are applied in the design at present. The first one is direct computation, in which the response process is calculated in the time domain and then the statistical characteristics can be determined according to the response time history. The second one is approximative computation, in which the response function is determined by nonlinear CFD only and the transform system in frequency domain still keeps the relation given by Eq.(11).

2) On the return period and the exceeding probability for the design wave sea state. Increasing the return period will induce rising of the design wave height and declining of the encountering probability. On the other hand, to maintain the return period occurred once in a hundred years, the maximum wave height with 10% of the exceeding probability can also reduce the encountering probability.

3) On sample capacity. Either to determine the return period for the long-term distribution, or to extend small probability event for the short-term distribution, the capacity of wave observation data in the target sea area is an important problem in the design. The capacity not only includes the sample length, but also includes the sample quality, such as continuity, veracity and creditability.

5 Conclusions

Design wave is the base of the environment data for oceanic structure design and the rationality of determining design wave parameters will affect economics, security, and reliability of the oceanic structure design, construction, and operation. The following conclusions are concluded from this discussion:

1) The return period of the design wave is increased from 100-year to 500–year, and the significant wave height of extreme sea state is also increased from 32 m to 34 m, with an increment of 2 m (about 6%); the encountering probability is decreased from 18% to 4%, falling 14% for oceanic structures with 20 years of the design service life. It can be convinced that applying 500-year of the return period can observably decrease the design risk.

2) The integration of the design wave method and the spectral analysis method will be the best computational approach. The design wave height is a statistical characteristic of extreme sea state, i.e. significant wave height. In this sea state, the spectral analysis method can be used to determine the hydrodynamic and structural performance of oceanic structures. The statistical characteristic is increased to the maximum value of 1/10 exceeding probability (the increment of wave height is about 2 m also) and the probability of encountered can be decreased to 10% or so.

3) Pay attention to the period or wave length of the design wave. In order to determine the period of the design wave, the investigation on the joint probability of wave height and wave period is necessary. Both nonlinear steep waves and long waves need to be attended in the design.

The first suggestion from this discussion is that the maximum wave height with 1/10 exceeding probability and corresponding up-zero period should be the design wave parameters instead of the signification wave in the sea state occurred once in a hundred years, if the 100-year of the return period is used continually. The second suggestion is that the 500-year return period should be considered and researched.

Of course the design standard for environmental condition is a complicated problem, therefore, further research is important and urgent. Besides, the weighting analysis is necessary for both engineering expenses and operative risk.

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WANG Yan-ying was born in 1938. He is a professor and PhD supervisor at Dalian University of Technology. His current research interests include marine hydrodynamics and ocean environment dynamics.

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作者： WANG Yan-ying
作者单位： School of Naval Architecture and Marine Engineering, Dalian University of Technology, Dalian 116024, China
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