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SEASONAL VARIATION IN EXTREME WAVE HEIGHT ESTIMATION FOR NIGERIAN OFFSHORE OILFIELDS USING GUMBEL DISTRIBUTION

By

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ABSTRACT

Accurately estimating extreme wave heights for various return periods is critical in the design of offshore structures. This study employs Gumbel distribution to analyze historical wave data and predict extreme wave heights for 10-year, 50-year, and 100-year return periods in the West African offshore region, focusing on four key oilfields: Asabo, Bonga, Bonny, and Forcados. Findings reveal significant variations between seasonal and annual extreme wave heights, with the highest values consistently occurring during the rainy season. The percentage variation in extreme wave heights computation between annual and rainy season data sets was found in Bonny and Forcados to the tune of about 14% for 10-year extreme wave height, 10% in Bonny for 50-year and 100-year EWH. It became evidenced that EWH computed based on annual data is underpredicted compared to extreme wave heights of rainy seasons. It is also found that these variations appear to be increasing as the water depth is decreasing, this study stresses a path ahead for sustainable and robust extreme wave determination for offshore structural design activities considering large weather variations in the two seasons in West Africa. Moreso, understanding the seasonal and annual variations of these extreme waves is crucial for improving offshore engineering design and risk assessment in this region.

Keywords: Extreme Wave Height, Gumbel Distribution, Return Period, Peak Period, Estimated, Forcados, Asabo, Bonny, Bonga, Offshore, Generalized Extreme Value, Peak-Over-Threshold, Hindcast, seasonal variation.

1.0 Introduction

Extreme waves represent the highest wave heights recorded in a specific area during a given period. Accurate extreme wave calculations are essential for offshore structural design, ship safety, flood risk mapping, and coastal infrastructure planning (Caires, 2011). Typically, significant wave height time series originate from hindcasts spanning only 50 years, necessitating extrapolation beyond available data to estimate return values (Caires, 2011).

For risk-based offshore design and operations, precise extreme wave predictions are crucial (Bitner-Gregersen, 2015). The standard approach involves estimating wave heights for 50-year or 100-year return periods based on short-term recorded wave height series. For instance, a 100-year return period wave represents the maximum wave height expected once in a century. Since direct wave measurements over 50 or 100 years are unavailable, probability distributions are fitted and extrapolated to determine return period values. The accuracy of this approach depends on the length of recorded data and the ability of the chosen probability distribution to represent the extreme tail (Caires, 2011). Long-term wave data is rarely available for specific locations, making numerical hindcast models a practical alternative. Several extreme wave studies have been conducted in West Africa (Agbakwuru, Akaawase & Gudmestad, 2020, Akinsanya, Gudmestad & Agbakwuru, 2017, Agbakwuru & Idubor, 2019, Agbakwuru & Akaawase, 2019). However, West Africa's rainy and dry seasons result in significant oceanographic variability, which this study addresses by investigating extreme wave estimation from a seasonal perspective using Gumble distribution.

The proposed aims to achieve in the long run of this research work are stated as follows:

i. With offshore activities increasing along Nigeria's coastline, understanding sea state dynamics is essential for planning marine operations and ensuring the safety of floating vessels.
ii. Characterizing met-ocean conditions is critical for designing offshore facilities suited to the region. Using an appropriate mathematical model, this study examines annual and seasonal extreme wave predictions across four sites to develop a robust estimation framework for the region.
iii. Using Gumbel distribution to fit data, the study also aims to examine annual and seasonal extreme waves prediction of for all four sites to be able to suggest a robust approach for extreme wave estimation in the region.

2.0 Literature Review

Agbakwuru, Akaawase & Gudmestad (2020) described the sea state of Asabo offshore in Nigeria. Three (3) years' worth of data, including spectral periods (Tp) and significant wave heights (Hs), were subjected to statistical analysis. The data was split into two (2) groups; one group includes the data spanning from October to April and the second group includes the data from May to September. The outcomes were contrasted with those of comparable investigations conducted elsewhere offshore in West Africa. It was discovered that the study location (the Asabo site) is not directly affected by swell waves from the Southern Ocean. This research reveals that the North Atlantic storms are the primary source of the wave system. Asabo is protected from the effects of storms from the south-west and consequently from swells from the Southern Ocean by the presence of numerous islands close by. Agbakwuru, Akaawase & Gudmestad (2020) also estimated the EWH of 100-year return period of Asabo to be 3.20 m completely neglecting seasonal variations during their predictions.

Akinsanya, Gudmestad & Agbakwuru (2017) described the swell of Bonga offshore Nigeria. The monthly and yearly values of the swell significant wave height and zero-mean crossing period in the presented data show a respectable amount of fluctuation. The comparison reveals notable differences between the Hs and Tp's temporal histories. Although it is not reasonable to anticipate that Hs and Tp will always be at the same values, there is little change in the Hs values recorded for the two years under consideration (1998 and 1999).

Elkersh, Atabay & Yilmaz (2022) computed extreme wave analysis distributions to determine significant wave heights for various return periods. The results assisted engineers with the construction, maintenance, and repair of structures on the Dubai coast. In the investigation of Elkersh, Atabay & Yilmaz (2022), a 40-year long-term wave hindcast data set from 1971 to 2018 derived from numerical modeling was employed. The storms were filtered out of the data using the Peak-Over-Threshold technique with threshold of 2.5 m. By fitting Log-normal, Gumbel, Weibull, Exponential, and GPD distributions, H_s for various return periods were calculated. When compared to the Palm Jumeirah revetment's design wave height, the considerable wave heights obtained reveal a distinct disparity.

Katalinić & Parunov (2020) conducted a thorough analysis on a long-term database for a site in the Adriatic Sea. EWH estimations over lengthy return periods were shown together with trends illustrating their variabilities. Seasonal variations were neglected, as these estimations were predicted using only annual dataset.

Salah et al. (2020) displayed computation of Hmax using various n-year return values for the Port Said offshore region, which is situated on Egypt's northern coast. The Peak Over Threshold technique is considered for the Long-Term analysis. To develop several offshore platforms in this area, the findings of this study were compared with those of the hindcast model that was used in the study area. In contrasted with Hmax values derived from the hindcast model, it was clear that the values from the measured data of the research area were more accurate. Future platforms will likewise be more cost-effective when the Hmax (from the measured data) is employed in their design. A different and most likely more appropriate approach will be to calculate for Hmax considering seasonal variations.

Shajitha & Perera (2014) estimated the 50-year and 100-year return periods of wave heights in Colombo by examining two approaches: the Block Maxima (BM) technique and the Peak-Over-Threshold (POT) method. The BM data and POT data were each fitted with the generalized extreme value (GEV) distribution and generalized Pareto (GP) distribution, respectively. GEV and GP Param were calculated using the maximum likelihood estimation approach. Gumbel distribution and GP distribution both worked well with the BM and POT approaches. Seasonal variations were not considered while estimating these return values using both approaches. To assess the capabilities and biases in wave hindcast for the Rio Grande shelf in South Brazil, Aguiar et al. (2021) analyzed a 29-month wave dataset produced from the NCEP/NCAR Reanalysis and WAVEWATCH III.

De-Hauteclocque et al. (2020) conducted wave analysis that contains extreme significant wave height and not only standard deviation and mean. In De-Hauteclocque et al. (2020) investigation, five alternative hindcast datasets were chosen and compared to buoy and altimeter data. The furthest location from the coast of interest is the North Atlantic, which is thought to be the most challenging for sailing ships. Global wave models are predicted to produce good outcomes in this area (compared to places near coast where a local mesh is needed). The ECMWF database provides ERA5 and ERA-Interim, these two datasets use a model called WAM, two from NOAA/NCEP and IFREMER that use a model called WaveWatchIII, and conclusively, the Copernicus program

provides the WAV-ERYS dataset that employs MFWAM. The wave parameters predicted by these models varies slightly, especially in extreme conditions. The causes are briefly explained, but the impact on ship response is emphasized.

Räämet et al. (2010) used numerical hindcast wave properties for the entire Baltic Sea and visual wave observations across the Baltic Proper and the Gulf of Finland to determine various combinations of heights of waves and periods in extreme storms, in addition to long-term changes in EWH and the propagation of waves directions. The Northern Baltic Proper experiences exceptional wave heights and periods of around 7 m and 10 s -12 s, 6 m and 8 s -11 s at the entryway to the Gulf of Finland, and 4 m and 6s -8 s in the eastern part of this gulf. No statistically significant trends are shown by wave hindcasts within the 95% and 99% of intervals of confidence for heights of wave. Seasonal variations are not represented in these hindcasts' extreme predictions. The wave height estimate based on wave hindcast data for a period of 31 years for a site in the eastern Arabian Sea is subjected to the classical extreme value theory based on generalized extreme value (GEV) distribution and generalized Pareto distribution (GPD).

The estimations of design wave heights connected to return periods of 30- and 100-year are covered in detail by Samayam et al. (2016). To create a comprehensive and trustworthy model, the wave height design was predicted using four separate models. Four sites in Indian waters, two each in the Bay of Bengal and the Arabian Sea, one in the Mediterranean Sea, and two in North America, one in each of the North Pacific Ocean and the Gulf of Maine were taken into consideration for the analysis. For this purpose, global atmospheric reanalysis ERA-interim wave hindcast data covering a period of 36 years have been used for the Indian water carried out by European Centre for Medium-Range Weather Forecasts. Both ERA-interim hindcast wave and buoy readings are considered for the different sites in the North America and Mediterranean Sea. In-depth analysis is done on the causes of the variations in return value estimates of the ERA-interim data and the buoy data using several estimation models. This analysis was done without considering seasonal variations.

Meucci et al. (2020) developed a new method for calculating the predicted global changes in extreme wave conditions by 2100. To increase statistical confidence in anticipated shifts in extreme wave scenarios, Meucci et al. (2020) constructed a synthetic dataset using a group of wave models influenced by distinct climate simulation winds. They demonstrate that the magnitude of a 1 in 100-year significant wave height (H_s) occurrence increases by 5 to 15% over the Southern

Ocean by the end of the 21st century, relative to the 1979-2005 period, using RCP4.5 and RCP8.5, two IPCC representative greenhouse gas emission scenarios.

Akinsanya, Gudmestad & Agbakwuru (2017) described the swell of Bonga offshore Nigeria. The monthly and yearly values of the swell significant wave height and zero-mean crossing period in the presented data show a respectable amount of fluctuation. The comparison reveals notable differences between the Hs and Tp's temporal histories.

Agbakwuru & Idubor (2019) The wave system's sea state characteristics in the Bonny site offshore of Nigeria are investigated. The wave data used in this study spans the years 1979 to 1982, and the data was analyzed using statistical techniques, with a particular emphasis on the probability distributions, number of peaks, and return cycle for extreme wave conditions. Agbakwuru & Idubor (2019) also estimated the EWH of 100-year return period of Asabo to be 2.45 m completely neglecting seasonal variations during their predictions.

Agbakwuru & Akaawase (2019) described the waves in the southern Nigerian port of Forcados. at order to enable short- and long-term predictions of extreme significant wave heights at this area, wave data collected between 1980 and 1982 are partitioned and fitted using various acceptable statistical models. These predictions are determined to be appropriate for the Weibull model utilized in the study.

It is crucial to note that these estimations only considered yearly data. These authors neglected seasonal variations which may result in inaccurate predictions. These seasonal variations may have significant change in extreme predictions, and they ought to be regarded. By assembling all available data into a single sample and using one of the probability distributions such as Log-Normal distribution, Gumbel distribution, or Weibull distribution, many other researchers including Smith (1984), Goda (1992), Van Valedder et al. (1994), Coles (2001), de Zea Bermudez & Kotz (2010), Scarrott & MacDonald (2012), and Julio Salcedo-Castro et al. (2018), have estimated the return periods of significant wave height.

3.0 Methodology

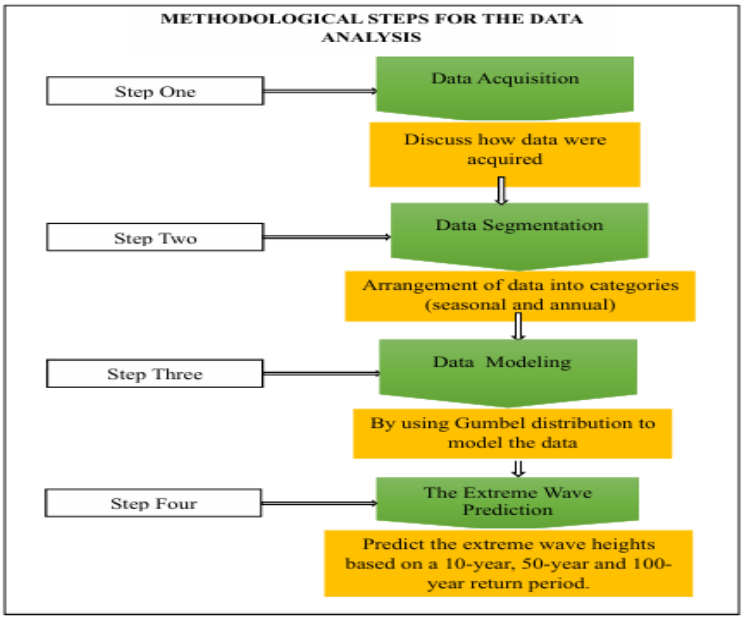


Plate 3.1 Flowchart of the Proposed Method

3.1 Data Acquisition

A Baylor Wave staff was used to gather wave data at the Nigeria Asabo platform site between 1981 and 1983. Both the spectrum period and time series of wave heights were recorded. Significant wave heights (Hs), maximum height of wave, (Hmax), orientations of wave, and periods peak (Tp) related to these Hs are all included in the data supplied for this study. A directional wave rider (DWR) was used to gather wave data at the Bonga field between 1997 and 1999. Both the spectrum period and time series of wave heights were recorded. The significant wave heights (Hs), wave orientations, and periods peak (Tp) related to these Hs are all included in the data supplied for this study. Wave data was collected at the Bonny field between 1979 and 1983. Both the spectrum period and time series of wave heights were recorded. The significant wave heights (Hs), maximum wave height, (Hmax), wave orientations, and peak periods (Tp) related to these Hs are all included in the data supplied for this study. Wave data provided for Forcados was gathered between 1980 and 1982. Both the spectrum period and time series of height of wave were recorded. The significant wave heights (Hs), maximum wave height, (Hmax), wave orientations, and peak periods (Tp) related to these Hs are all included in the data supplied for this study. The data used in this study were provided by Shell, Nigeria.

3.2 Data Segmentation

In different years, several days and months lack data. This served as the foundation for segmenting the data that was available into different categories (Seasonal and Annual) in order to provide the best perdition of extreme waves. Data partitioning and cleaning were done using Microsoft Excel 2019.

3.3 Data Fitting

This study requires running tests for various groupings and fitting each unique wave division to Gumble distribution.

3.4 The Extreme Wave Prediction

The maximum wave height (Hmax) was used for prediction of extreme wave of Asabo, Bonny and Forcados, while significant height of wave (Hs) was used for prediction of extreme wave of Bonga but was later converted to Hmax by multiplying Hs by 1.86. The Gumbel models was considered for this study. This probability model is thought to be sufficient to predict the extreme wave accurately. Std error, a statistical measurement tool was produced and used to estimate the efficiency, accuracy and consistency of the results after the prediction. Microsoft Excel 2019 and R Version 4.3.0 programming language which are very useful wave prediction tools with very high data analysis accuracy was employed for this investigation.

$$\text{Standard Error} = \frac{\sigma}{n} \qquad 3.1$$

Where σ = Standard Deviation

n = Number of samples

3.5 Description of Locations Under Consideration

The four offshore sites used in this work are briefly described below;

3.5.1 Asabo

Asabo offshore is a medium-sized offshore terminal found in Nigeria's Gulf of Guinea at coordinates N 04° 06' 34.71" and E 007° 48' 19.54". A floating unit with 464 beds connected to a stationary platform via a heave-compensated telescopic gangway is employed to exploit the Asabo field. Asabo offshore is in shallow water at a depth of 47 m (Agbakwuru, Akaawase & Ove, 2020).

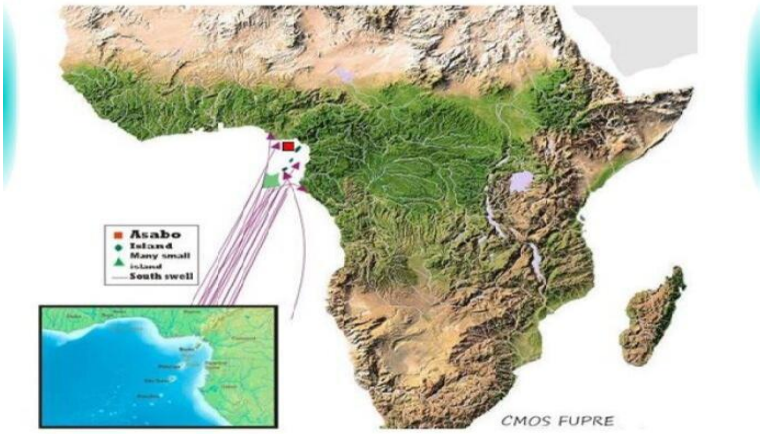


Figure 3.2: Map showing Asabo, Nigeria *(Image credit: Agbakwuru, Akaawase & Ove, 2020).*

3.5.2 Bonga

Bonga Field is situated in License Block OPL 212, which was renamed OML 118 in February 2000, off the coast of Nigeria. The area is roughly 60 km^2 and the water is typically 1,000 m (3,300 feet) deep. The field was found in 1996, and in 2002 the government approved its development. In November 2005, the field started producing its first oil. An FPSO vessel is used to operate the field. Both natural gas and petroleum are produced by the field; the gas is piped back to and exported via an LNG plant, while the oil is discharged into tankers. Bonga field development partners are Exxon (20%), Nigerian AGIP (12.5%), and Elf Petroleum Nigeria Limited (12.5%) together with Shell Nigeria, who owns 55% of the license and operates the field. Its coordinates are 04° 33' 45" North, 04° 37' 28" East (Offshore technology, 2020)

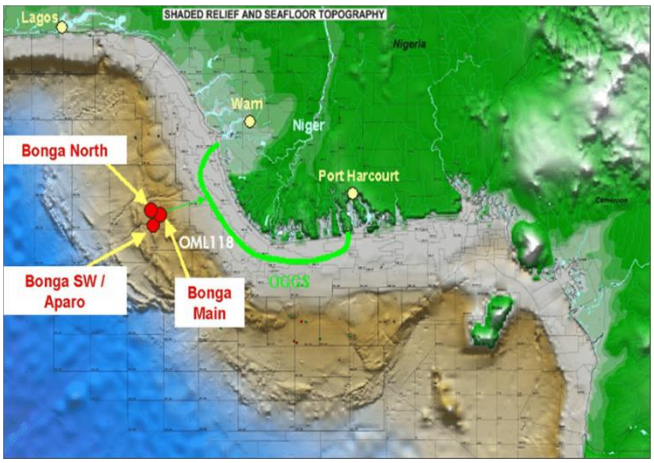


Figure 3.3: Location of Block OML118 and Bonga Field area offshore Nigeria *(Image credit: Huyen T. Bui)*

3.5.3 Bonny

Bonny, one of the busiest offshore locations is located to the east of the river Niger at a shallow depth of only 19 meters off the coast of the Atlantic Ocean. As a result of the oil and gas development, neighboring ports and islands, and the Nigeria Liquefied Natural Gas Company in the area. Shell Petroleum Development Company manages the Bonny Offshore Terminal, which has two SBMs and is supplied by a submerged pipeline. The terminal is situated at 04° 11.00′ N, 007° 14.00′ E, 22 kilom off the southern coast of Nigeria (Agbakwuru & Idubor, 2019)



Figure 3.4: Maps Showing Bonny Offshore (*Image credit: Distancesto.com*)

3.5.4 Forcados

Forcados Offshore is a shallow offshore area in Delta State, Southern Nigeria, near Burutu Local Government Area (see Figure 1.5). The Forcados Offshore Platform, which is located at latitude 5.341936 (5°20'30.97"N) and longitude 5.349472 (5°20'58.1"E), with a water depth of approximately 22 m, provided the metocean data used in this work. According to discussions by Agbakwuru & Idubor (2019) and Akinsanya, Gudmestad & Agbakwuru (2017), understanding this location is essential for prosperous maritime activity.



Figure 3.5: Map of Forcados, Nigeria (*Image credit: Distancesto.com*)

4.0 Results and Discussion

4.1 Results

Gumbel distribution method is applied to analyze the data, and the results are presented in Tables 4.1 to 4.5.

Table 4.1: Yearly Extreme Wave Distribution of Asabo for Different Return Periods.

RETURN PERIOD	ASABO (1981 to 1983)
10-year	2.59 m
50-year	2.91 m
100-year	3.03 m
μ	2.12
σ^2	0.13
Std Error	0.004

Table 4.2: Yearly Extreme Wave Distribution of Bonga for Different Return Periods.

RETURN PERIOD	BONGA (1997 TO 1999)
10-year	3.38 m
50-year	3.81 m
100-year	3.97 m
μ	2.83
σ^2	0.18
Std Error	0.004

Table 4.3: Yearly Extreme Wave Distribution of Bonny for Different Return Periods.

RETURN PERIOD	BONNY (1979 TO 1982)
10-year	2.29 m
50-year	2.65 m
100-year	2.79 m
μ	1.86
σ^2	0.11
Std Error	0.003

Table 4.4: Yearly Extreme Wave Distribution of Forcados for Different Return Periods.

RETURN PERIOD	FORCADOS (1980 TO 1982)
10-year	2.26 m
50-year	2.59 m
100-year	2.74 m
μ	1.84
σ^2	0.10
Std Error	0.003

4.2 Discussions

The results of presented for this study are validated by using related literature works of similar investigations on the same locations. However, it is evident that the results, based on annual data (combined data for dry season and rainy season) are practically undistinguishable as seen in (Table 4.5) below

Table 4.5: 100-year Extreme Wave Distribution comparison

S/N	Author	Asabo	Bonga	Bonny	Forcados

1.	Agbakwuru et al., (2020)	3.20 m			
2.	Akinsanya et al., (2017)		4.11 m		
3.	Agbakwuru & Idubor (2019)			2.45 m	
4.	Agbakwuru & Akaawase (2019)				3.02 m
5.	Akpere & Agbakwaru (2023)	3.20 m	4.22 m	3.00 m	2.90 m
6.	Present Study	3.04 m	3.97 m	2.79 m	2.74 m

This closed relative outcome promotes confidence in the present research work.The largest EWHs are observed in the rainy season. This is a period of large wind and rainfall. The percentage variation between annual and rainy season EWHs computation is found within 0.33% and 2.92%. It is evident that EWHs computed on annual basis is underpredicted compared to EWHs of rainy seasons.

The analysis shows that rainy season produced results with greater extreme wave values and dry season produced results with lesser extreme wave values in comparison to the same analysis conducted using the annual full dataset. The percentage variation in extreme wave heights computation between annual and rainy season combined data sets was found in Bonny and Forcados to the tune of about 6% for 10-year extreme wave height, 3% in Bonny and Forcados for 50-year and 3% in Forcados for 100-year EWH. It is evident that EWH computed on annual basis is underpredicted compared to extreme wave heights of rainy seasons. Therefore, seasonal (rainy) approach produces robust extreme wave values

DNVGL (2015) states that the extreme wave of 100-year return values should be considered when designing offshore structures (also see DNV-RP-C205, 2014). Extreme wave value analysis should be employed to include metocean data into offshore constructions design (API, 2005). Engineers base their design requirements on historical wave data and predicted models which may result in overdesign or under design. To account for uncertainty in wave conditions, safety margins are often incorporated into the design of structures offshore. Safety margins may not be sufficient when extreme waves are underpredicted, thereby increasing the possibility of structural failure or damage. For instance, if seasonal fluctuations are not considered, adding an air gap safety margin of 1.5m to the 100-year condition using annual extreme wave prediction may be disastrous. In survival mode, the hull elevation is frequently adjusted to the 50-year or 100-year extreme wave scenario with an additional 1.5m safety margin. It is crucial to maintain an adequate air gap between the hull construction and the overall water level to prevent the increased environmental

loading and the corresponding decreased stability. The extra safety margin's objective is to enable the structure to resist exceedingly uncommon but highly significant catastrophes like wave inundation. Variations in seasonal and annual projections of EWH have substantial impact on safety of offshore constructions and their integrity.

5.0 Conclusion

The study concludes that seasonal approach is found to be robust compared to those computed from annual datasets. The results of this study can be used as the metocean data design values of structures' offshore to be installed in West Africa, as these four oil fields are typical of all West African oceanographic weather and seasonal conditions

Limitations

- Actual maritime environmental data may not wholly represent offshore structural design conditions because of the limited historical record length. Many hindcast datasets for Nigeria waters only span 20-40 years hence too short to rely on capturing 50-100-year return period extreme wave design.
- Sparse in-situ buoy and gauge data adopted in Nigeria maritime environment proves that hindcast models are poorly and locally substantiated hence, errors and biases may appear undiscovered.
- Under uncertain climate changes, designed based on historical data never rationalizes for rising baseline sea levels, affecting storm surg and imposing coastal flooding in low-lying Nigerian environments.

Recommendations

i. Seasonal variation should always be considered when predicting extreme waves in any location as it helps to eliminate under design/overdesign and enhance marine operational safety and maintenance plans.

ii. Regional monitoring programs to gather data regularly on wave conditions, coastal dynamics, and climate changes. These systems must cover specific regions of West Africa with planned or existing offshore structures.

iii. When longer time series data is available, additional research should be done on the prediction of extreme wave for Asabo, Bonga, Bonny, Forcados and other offshore locations in West Africa. Historical data alone may not be sufficient, and understanding trends and potential changes in extreme wave conditions over time is crucial for robust computations.

iv. Implement detailed risk assessment procedures that consider the vulnerability of offshore structures as well as the likelihood of extreme events. Create strong risk management plans to help structures avoid being negatively impacted by extreme waves.

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