Discussions on wave energy period in higher wave energy potential marine waters of Taiwan

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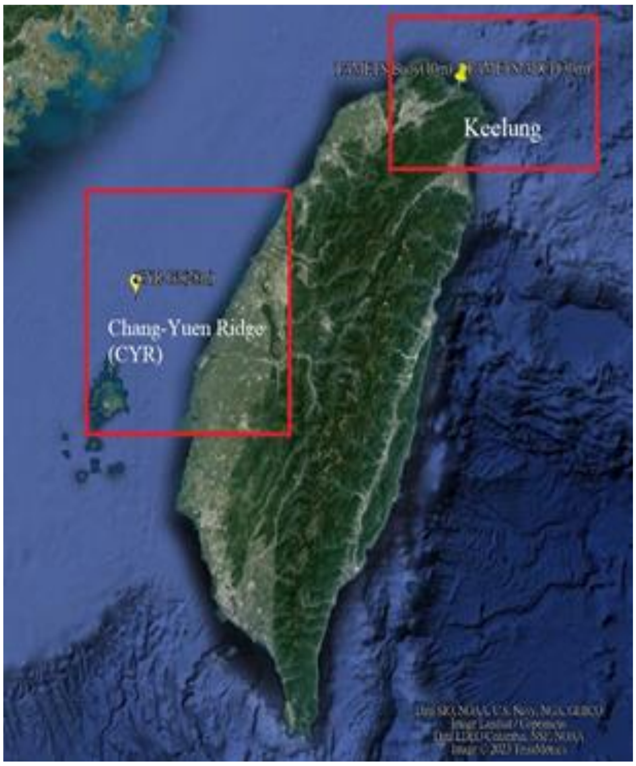
Abstract—**For evaluating wave energy resources, wave energy period T_e is commonly adopted. However, the in-charge government agencies traditionally provided with peak period T_p without giving information on the transfer relationship between T_e and T_p. This results in difficulties on evaluating wave energy potentials at certain marine waters. Thus, spectrum data need to be derived to calculate values of T_p and T_e so as to derive representative transfer coefficient C_{ep} for long-term evaluations on wave energy. This study aims at deriving values of C_{ep} at relatively higher potential marine waters of Taiwan. The data were collected from two stations in Keelung and one station in Changhua within marine waters for offshore wind. By choosing different criteria for *Cep* evaluation, selected data were regressed for obtaining representative C_{ep} in different seasons. For conservative point of views, the values of C_{ep} ranging from 0.85~0.87 from those in northeaster monsoon months, being generally slightly smaller than those from the annual ones, were adopted at the three stations. Further analysis gave findings that the representative values were derived mainly from data comprising of exploitable wave power densities of between 2~80 kW/m².**

Keywords—**Changhua marine water, energy period, Keelung marine water, period transfer coefficient, wave energy.**

I. INTRODUCTION

IT is generally acknowledged in Taiwan that wave energy resources are potentially higher in northeast (NE) and central-west (CW) marine water of Taiwan. In Keelung of NE Taiwan, a permitted field test site for wave energy converters was established. In Changhua close to Chang-Yuen Ridge (CYR) of CW Taiwan, there were top choices of zones for offshore winds in the world. To evaluate the potential wave energy resources in both marine zones, field measurements of wave data were collected and analysed in three field stations. Most of the existing historical wave data in Taiwan were used to be provided with hourly information on parameters for coastal engineering application. They consist of significant wave height H_s and peak wave period T_p. For calculating wave power, the formula particularly adopts the wave energy period T_e instead of the peak wave period T_p. Thus, it became an urgent need to first derive the period transferring coefficient (C_{ep}) between T_e and T_p so as to further correctly calculate the wave power. Values of C_{ep} would be derived based on the spectra for calculating respectively values of T_e and T_p. Thus, the relationship C_{ep} can subsequently be derived. Several authors had reported the ranges of for different peak enhancement factor γ of the JONSWAP spectrum. So far, [1]'s proposal on the ratio C_{ep} decreasing from 0.9 to 0.86 with reducing γ of from 3.3 to 1.0 was widely referred. It is generally acknowledged that spectrum characteristics in marine waters around Taiwan be of JONSWAP-type with typical values of $\gamma \approx$ 2.08 in the middle & northern Taiwan Strait [2] and with $\gamma \approx$ 1.7 in the northern and eastern nearshore Taiwan [3]. Recently, [4] reported the analysis on collected wave data offshore the Keelung Port in NE Taiwan for three years from May 2012 to May 2015. They found C_{ep} to be about



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Digital Object Identifier: https://doi.org/10.36688/ewtec-2023-539

Fig. 1 Locations of higher wave energy potential marine waters in Keelung and Changhua of Taiwan and field wave stations.

0.86 for JONSWAP spectra with a peak enhancement factor γ=1.6.

II. WAVE DATA AND FORMULAE

The wave spectra were first collected from the two stations in the test site in NE Taiwan, which is called TAMETS. The two field stations were located in a depth of 40 m with a wave buoy, TAMETS-Buoy (TRIAXYS，AXYS Tech. Inc.) and in another depth of 30 m with an ADCP, TAMETS-ADCP (Workhorse Sentinel 600k, RDI). The time series of the collected hourly data of spectra of the two stations were from Aug. 2016~Nov. 2021 and June 2014 ~ Aug. 2022, respectively. Data from a station in CYR by a wave sensor equipped on a FLIDAR system, CYR-G3 (G3，AXYS Tech. Inc.) had already provided with both periods of T_e and T_p in every 20 minutes from Sep. 2017 to Oct., 2019 and thus, values of C_{ep} can be directly derived. As shown in Table 1, all databases were first quality-controlled and the surplus rates, i.e. ratios of the remaining data for analysis, for three stations were listed annually and for different seasons. It is noted that the lowest surplus rates of seasonal data were 75%, 66% and 64% at TAMETS-Buoy, TAMETS-ADCP and CYR-G3, respectively. As a result, the resulting annual surplus rates at three stations were well higher than 76%.

The data of the two stations in TAMETS were first processed for deriving from the spectra for calculating the regressed relationship of C_{ep} with the reciprocal of peak frequency f_p by [5] and energy period T_e by [6] expressed as follow

$$C_{ep} = T_e/T_p \tag{1}$$

$$f_p = \frac{\int_0^\infty f S^4(f)df}{\int_0^\infty S^4(f)df} \tag{2}$$

$$T_e = m_{-1}/m_0 \tag{3}$$

where m_i is the ith order wave spectral moment. [1] pointed out that the values of C_{ep} to be positively corelated to the peak enhancement factor γ of a JONSWAP spectrum. In general, as γ decreasing from 3.3 to 1.0, the values of C_{ep}

TABLE 1
SURPLUS RATES IN DIFFERENT SEASONS AT THREE FIELD STATIONS

Season / Surplus Rate % / Field Station	TAMETS-ADCP	TAMETS-Buoy	CYR-G3
Annual	76.9	75.8	78.7
NEM season	77.9	70.3	69.6
Non-NEM season	75.9	81.3	87.8
Winter	74.9	74.4	76.2
Spring	74.6	66.4	85.8
Summer	77.9	81.8	93.4
Autumn	79.9	79.4	64.2

would also reduce from 0.9 to 0.86. All the claculated values of C_{ep} would then be screened based on certain criteria so as to derive from the surplus data for the regressed values of C_{ep} for further caluculations of the wave energy.

III. RESULTS AND ANALYSES

3.1 Screening Criteria

Due to the three studied stations being located in coastal waters of Taiwan, the past observations indicated that most of wave periods were generally smaller than 15 s. Thus, for those data with periods higher than 16 s would be considered abnormal to be firstly deleted. For present study, the screening process adopted upper and lower limited values of C_{ep} to be between 1.0 and 0.76. Both limited values were selected for ±0.1 of the reported ranges of 0.9 to 0.86 by [1].

3.2 Regressed values of annual C_{ep}

In Table 2, results from annual data for different screening criteria were listed. It is clearly noted that the surplus rates by screening data with periods larger than 16 s were all quite high implying those occurred waves with periods larger than 16 s be few and not considered to be potential wave energy resources. In addition, as screening criteria for narrower bands of period, the surplus rates decreased as well but the correlation coefficients R^2 of the data regression became higher.

By further deleting data with values of R^2 lower than 0.8 with surplus rate higher than 65% at the three studied stations, data with values of C_{ep} ranging from 0.76 to 1.0

TABLE 2
REGRESSED VALUES OF C_{EP} FOR DIFFERENT SCREENING CRITERIA FROM ANNUAL DATA

TAMETS-ADCP h=30m	Raw data	Surplus data	Surplus Rate	C_{ep}	R^2
Delete Tp>16	51579	51340	99.5%	0.89	0.38
Keep Cep1.0-0.7, Delete Tp>16	51579	36961	71.7%	0.87	0.73
Keep Cep1.0-0.76, Delete Tp>16	51579	34390	66.7%	0.88	0.81
Keep Cep1.0-0.8, Delete Tp>16	51579	30843	59.8%	0.89	0.87
TAMETS-Buoy h= 40m	**Raw data**	**Surplus data**	**Surplus Rate**	C_{ep}	R^2
Delete Tp>16	41276	38394	93.0%	0.85	0.79
Keep Cep1.0-0.7, Delete Tp>16	41276	35729	86.6%	0.85	0.87
Keep Cep1.0-0.76, Delete Tp>16	41276	33894	82.1%	0.86	0.90
Keep Cep1.0-0.8, Delete Tp>16	41276	31000	75.1%	0.87	0.93
CYR-G3 h= 28m	**Raw data**	**Surplus data**	**Surplus Rate**	C_{ep}	R^2
Delete Tp>16	43758	43740	100.0%	0.83	0.66
Keep Cep1.0-0.7, Delete Tp>16	43758	35326	80.7%	0.84	0.85
Keep Cep1.0-0.76, Delete Tp>16	43758	31359	71.7%	0.85	0.90
Keep Cep1.0-0.8, Delete Tp>16	43758	26226	59.9%	0.87	0.93

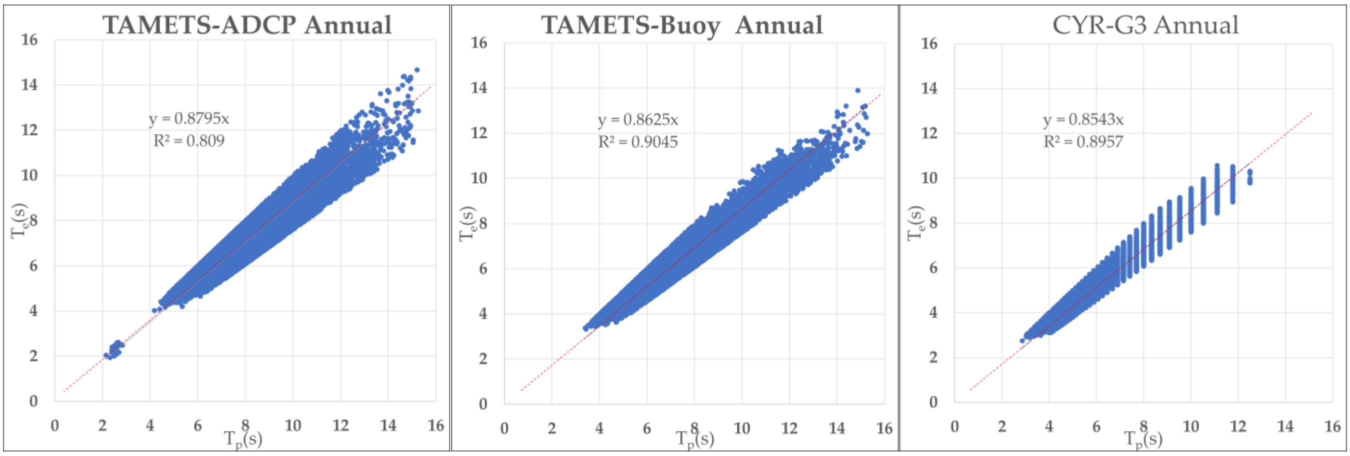

Fig. 2 Regressed values of C_{ep} from annual wave data

were kept for regression analysis. As a result, the finalized screening criteria were waves with periods smaller than 16 s and derived values of C_{ep} in the range between 0.76 to 1.0. As shown in Figure 3 and summarized in Table 2, resulting regressed values of C_{ep} annually were found to be 0.86, 0.88 and 0.85 at stations of TAMETS-Buoy, TAMETS-ADCP and CYR-G3, respectively.

3.3 Seasonal variations of C_{ep}

The regressed values of C_{ep} for each season were further studied with the same screening criteria. The months in each season were defined according to local experiences in Taiwan as Winter of from November to next January, Spring of from February to April, Summer of from May to July and Autumn of from August to October. It is particularly important for the so called northeast monsoon season (NEM) to be pointed out since most of the wave energy resources being contributed by waves in them [7]. According to previous reports from wave data in Keelung coastal waters [8], the months of NEM consisted of October to next March. That is, for the rest of half a year, from April to September, the wave energy resources were generally quite small while extreme wave conditions due to typhoons were intermittently occurring.

The results were summarized in Table 3. It is seen in all the three stations that the surplus rates were higher in Winter and Autumn seasons than in Spring and Summer seasons. Accordingly, the surplus rates were seen to be higher in winter-centered NEM seasons than in summer-centered non-NEM seasons. From data of both TAMETS's stations, the resulting correlation coefficients R^2 of the regressions were noted to be higher in Summer and non-NEM seasons than those from annual ones. Meanwhile, the values of R^2 were lower from data in Winter and NEM seasons than those from annual ones. It seemed to be due to the distributions of waves in TAMETS waters being more focused in Summer than in Winter, as reported by [8]. However, from data of CYR-G3 station, the resulting correlation coefficients R^2 of four seasons were noted to be lower than those of annual ones. Meanwhile, the values remained almost the same in both NEM and non-NEM seasons. Since seasonal variations could be well represented by those in both NEM and non-NEM seasons,

TABLE 3

REGRESSED VALUES OF C_{EP} FOR DIFFERENT SCREENING CRITERIA FROM DIFFERENT SEASONAL DATA

TAMETS-ADCP WD=30m	Raw data	After deletion	Remaining ratio	Cep	R^2
Annual	51579	34390	66.67%	0.88	0.81
Winter	13157	10135	77.03%	0.87	0.72
Spring	12177	8132	66.78%	0.88	0.79
Summer	13464	7112	52.82%	0.89	0.86
Autumn	12781	9011	70.50%	0.88	0.82
Northeast monsoon	27277	20383	74.73%	0.87	0.74
Non-northeast monsoon	24302	14007	57.64%	0.89	0.86
TAMETS-Buoy WD= 40m	**Raw data**	**After deletion**	**Remaining ratio**	**Cep**	R^2
Annual	43441	35665	82.10%	0.86	0.90
Winter	12198	11671	95.68%	0.86	0.83
Spring	8323	6262	75.24%	0.86	0.84
Summer	11153	8572	76.86%	0.86	0.93
Autumn	11055	8511	76.99%	0.86	0.91
Northeast monsoon	22597	19249	85.18%	0.86	0.84
Non-northeast monsoon	20844	16416	78.76%	0.86	0.93
CYR-G3 WD= 28m	**Raw data**	**After deletion**	**Remaining ratio**	**Cep**	R^2
Annual	43758	31360	71.67%	0.85	0.90
Winter	9919	8496	85.65%	0.85	0.88
Spring	11354	7838	69.03%	0.86	0.90
Summer	11245	5866	52.17%	0.85	0.83
Autumn	11240	9169	81.57%	0.86	0.89
Northeast monsoon	19824	16855	85.02%	0.85	0.89
Non-northeast monsoon	23934	14515	60.65%	0.86	0.88

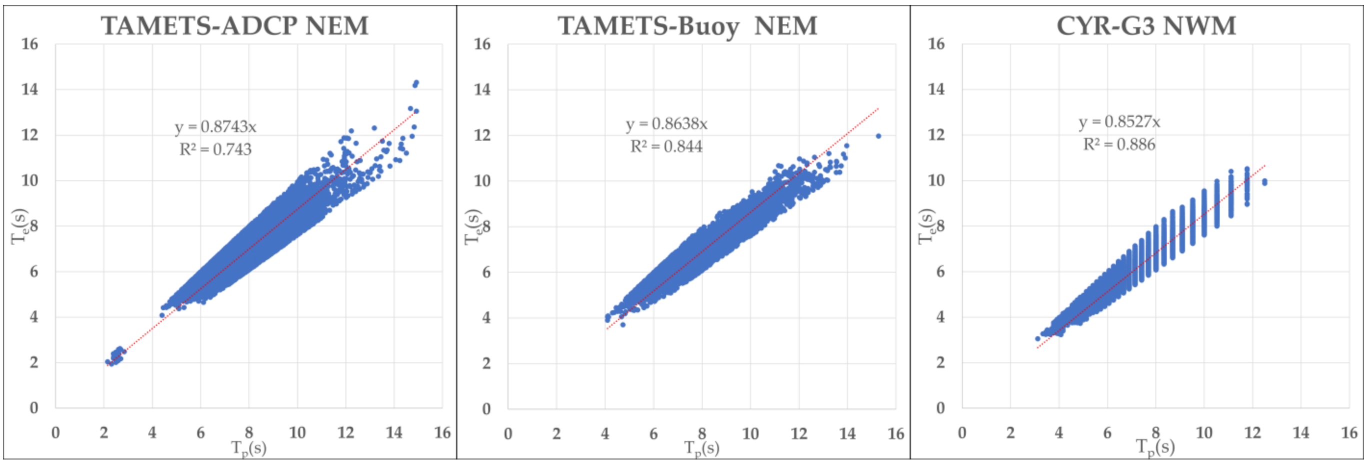

Fig. 3 Regressed values of C_{ep} from NEM seasonal wave data

the regressed values of C_{ep} in both seasons shall further be discussed.

Table 3 clearly illustrated that values of C_{ep} from data of both TAMETS-ADCP and CYR-G3 stations in NEM seasons were smaller than those in non-NEM seasons while the values remained almost the same in both seasons from data of TAMETS-Buoy. Previous studies [2] had reported that exploitable wave energy resources with power densities of between 10-80 kW/m were mainly contributed by waves in NEM seasons. Figure 3 gave the regressed values of C_{ep} in TAMESTS-Buoy, TAMESTS-ADCP and CYR-G3 stations from data in NEM seasons to be 0.86, 0.87 and 0.85, respectively. The value of C_{ep} of 0.85 in CYR-G3 to be slightly smaller than the lower limit of 0.86 proposed by [1] could be due to strong wind fields over the same marine waters. The possible correlations need to be further assessed by IEC-Specifications [11]. It is clearly noted that the values of C_{ep} based on data in NEM seasons were quite similar to those based on annual data or even slightly smaller. The values of C_{ep} in NEM seasons were also recommended to be adopted for calculating annual wave energy resources from point of views of conservation.

3.4 Seasonal variations of C_{ep}

In the end, the surplus rates within different classifications of the exploitable wave energy resources in both annually and NEM seasons were further investigated. Represented results at all three field stations, i.e. TAMESTS-ADCP, TAMETS-Buoy and CYR_G3 were given. By deleting The above mentioned values of C_{ep} in NEM seasons were adopted for calculating power densities in deep water as expressed in (4)

$$P = 0.49 T_e {H_s}^2 \quad (4)$$

The exploitable wave resources were defined by combining local standards ranging from 10-80 kW/m [4] and international one ranging greater than 2 kW/m [10]. The results of numbers of surplus data and of full raw data were illustrated in Figure 4. It is seen in Figure 4, at TAMETS-ADCP station the surplus rates for annual data and those in NEM seasons for different classifications of wave power density x were all quite similar. As a result, the ratios of accumulated wave energy in NEM seasons to annual one within the ranges of between 10-80 kW/m and 2-80 kW/m amounted to 84% and 73%, respectively. The surplus rates became as low as around 50% for the data with power densities less than 2 kW/m, which were mainly contributed by waves in non-NEM seasons. At TAMETS-Buoy station the surplus rates for annual data and those in NEM seasons in the density ranges of between 20 to 80 kW/m were all quite similarly higher than 85%, which were much higher than those at TAMESTS-ADCP. As a result, the ratios of accumulated wave energy in NEM seasons to annual one within the ranges of between 10-80 kW/m and 2-80 kW/m amounted to 88% and 77%, respectively. The surplus rates became as low as around 50% for the annual data and even lower of 23% for power densities less than 2 kW/m, which were also mainly contributed by waves in non-NEM seasons. The results of the two neighbouring stations in TAMETS seemed to differ significantly from each other on surplus rates of wave data

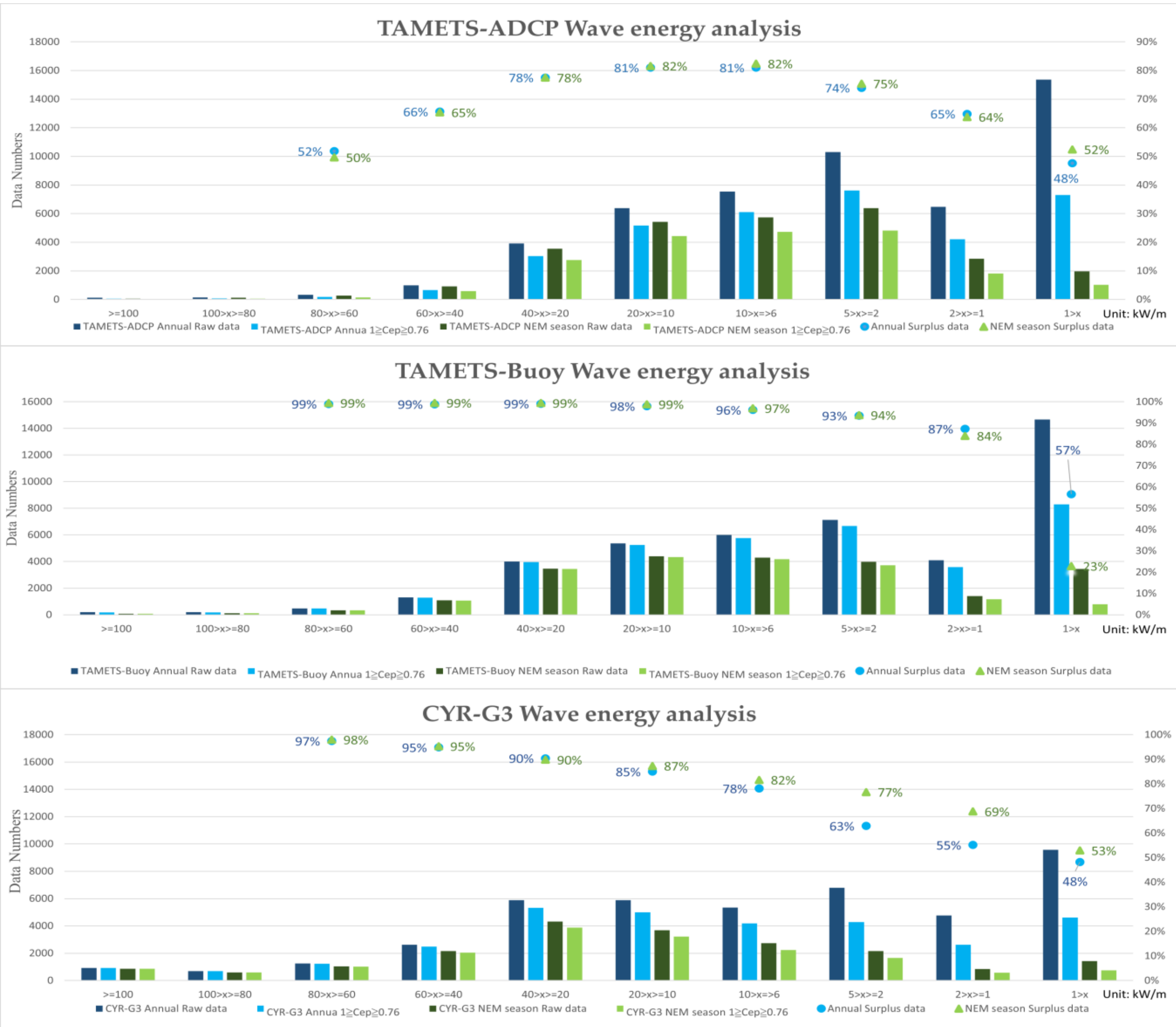

FIG. 4 Numbers of surplus rates in different classifications of power density x annually and in NEM seasons

annually and in NEM seasons for different classifications of wave power density.

At CYR-G3 station, the surplus rates for annual data and in NEM seasons for different classifications of wave power density were all almost the same in the density ranges of between 20 to 80 kW/m. But the rates in NEM seasons became higher than those annually in power densities smaller than 20 kW/m. As a result, the ratios of accumulated wave energy in NEM seasons to annual one within the ranges of between 10-80 kW/m and 2-80 kW/m

amounted to 72% and 62%, respectively. At CYR-G3 station, the ratios of the accumulated wave energy resources in ranges of power densities from 2 to 80 kW/m were generally smaller than those at TAMETS-ADCP and TAMETS-Buoy stations. But being similar to those at TAMETS-ADCP station, the surplus rates were around 50% for the data with power densities less than 2 kW/m, being mainly contributed by waves in non-NEM seasons. The results further confirmed that in both coastal waters of Keelung and Changhua the surplus rates could be at least higher than 50 %

IV. CONCLUSIONS

Field wave data were collected from three stations with higher potential wave energy resources in northeast and central-west coastal waters of Taiwan. Wave spectra were first calculated for deriving values of energy period T_e and peak periods T_p so as to derive represented period transferring coefficient (C_{ep}) between T_e and T_p. The screening criteria consisted of wave period less than 16 s and C_{ep} ranging from 0.76 to 1.0. The derived results of C_{ep} in NEM seasons were adopted. The values at three stations were generally slightly smaller than those annually to provide with more conserved annually accumulated wave energy resources. At three stations, surplus rates of wave data were seen to be higher in NEM seasons than those in non-NEM seasons. Based on data form represented stations, i.e. TAMESTS-ADCP and CYR_G3, the resulting ratios of accumulated wave energy in NEM seasons to annual ones within the ranges of between 2-80 kW/m were seen to be 77% and 62%, respectively. For the three stations at TAMESTS-Buoy, TAMESTS-ADCP and CYR-G3, the adopted values of C_{ep} for calculating wave energy resources were proposed to be 0.86, 0.87 and 0.85, respectively.

ACKNOWLEDGEMENT

The authors are sincerely grateful for the financial support of Ministry of Science and Technology of Taiwan under the contract No. MOST 110-2221-E-019-032 and the wave data provided by F3 offshore wind developing team.

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