ISSN 0454－4641

運輸省港湾技術研究所

港湾技術研究所報告

REPORT OF THE PORT AND HARBOUR RESEARCH INSTITUTE

MINISTRY OF TRANSPORT

VOL.39 NO.4 Dec. 2000

NAGASE, YOKOSUKA, JAPAN

港湾技術研究所報告（REPORT OF P. H. R. I.）

第 39 巻　第 4 号（Vol. 39, No. 4），　2000年12月（Dec. 2000）

目　次（CONTENTS）

REPORT OF THE PORT AND
HARBOUR RESEARCH INSTITUTE
Vol.39 No.4 (Dec.2000)

Wave Groups and Low Frequency Waves in the Coastal Zone

Albena VELTCHEVA*
Satoshi NAKAMURA**

Synopsis

Low frequency waves (LFWs) with periods of 1 to several minutes often grow in the surf zone and occasionally cause rapid beach erosion over the berm crest. The mechanism of developing LFWs in the surf zone seems to be the resonance of LFWs with the beach from shoreline to breakpoint of the incident waves that have the characteristics of groupiness.

To analyze the relationship between wave groupiness and incident wave characteristics in the surf zone and offshore, a new method for determination of individual waves using the orbital criterion, which has advantage that there is no subjective criterion to eliminate small zero-crossing waves, is proposed. The change of wave groupiness characteristics from offshore to the shoreline is theoretically derived by a wave transformation model based on the statistical wave height distribution in consideration of wave shoaling and breaking.

The major conclusions are as follows:

1) The proposed method has a good performance to treat with small waves in order to ensure the constancy of number of waves from deep to shallow water.
2) Mean height of wave groups before and after wave breaking which is estimated from the theoretical wave transformation model has a good relation with one from field data analysis.
3) To predict the height of low frequency wave inside surf zone, both the period of wave groups and height of wave groups must be considered simultaneously. The physical reason of the dependence is not clear.

Key Words: Wave groupiness, Orbital criterion, Wave group transformation, Low frequency wave in the surf zone

---

* Visiting Scientist of Littoral Drift Laboratory, Marine Environment Division
** Senior Research Engineer, Marine Environment Division
3-1-1 Nagase, Yokosuka, 239-0826 Japan
Phone : +81-468-445012 Fax : +81-468-419812 e-mail : velcheva@ipc.phri.go.jp

港湾技術研究所報告
第39巻第4号(2000.12)

沿岸域における波群構造の変化と
砕波帯内長周期波の発達・減衰特性

Albena VELTCHEVA* ・中村聡志**

要　旨

砕波帯内ではしばしば周期 1～数分の長周期波が発達し，その振幅は汀線部で最大となるため，長周期波による平均水位のゆっくりとした変動と個々の波の遡上とによって，時折，前浜頂を越えるような越流による急激な砂浜侵食が起きることが観測されている．この砂浜海岸における長周期波は，沖から伝播してくる波群特性を持った波が浅水変形・砕波することによって砕波帯内で励起されると考えられている．

本研究では，新しい個別波定義を用いた統計的手法に基づくデータ解析法を提案し，波崎海洋研究施設とその沖合いで得られた同時多点波浪観測データを用いて，波の伝播による沿岸域の波群特性（波群の繰返し周期と波群高さの変動）の変化と沿岸域における長周期波の発達・減衰特性を調べた．また，沖波の波群特性から砕波帯内長周期波の発達・減衰，およびその大きさを予測する手法を開発するため，波の浅水変形および砕波変形を考慮した沿岸域の波高出現確率分布を用いて波群高さの変化を理論的に導出し，現地観測から得られた波群特性変化との比較を行った．

得られた主要な結論は以下の通りである；

1) 波の重要な特性である波群特性パラメータを沖波から汀線ごく近傍まで求めるための Orbital Criterion による個々波の定義および，波群性パラメータ導出手法を提案した．この手法によって，解析者の経験や恣意の入らない方法で波群特性の解析を行うことができる．

2) 砕波後の波高出現確率分布が沖波波高分布からの浅水変形と砕波変形との重ねあわせで表わせると仮定し，沖波波浪諸元から波群高さの岸沖変化を理論的に求めた．また，現地データ解析による砕波前後の波群特性結果との検証を行い，よい一致を示した．

3) 沖波波群パラメータによる砕波帯内長周期波の波高推定を試みた．長周期波の推定には平均的な波群の高さと継続時間を同時に考慮することが必要であることがわかった．

キーワード：波群特性，Orbital Criterion、波群特性の岸沖変化，砕波帯内長周期波

---

* 海洋環境部漂砂研究室客員研究員
** 海洋環境部主任研究官
電話：0468-44-5012　Fax：0468-41-9812　e-mail：velcheva@ipc.phri.go.jp

CONTENTS

1.Introduction

Wave groups are considered as a forcing mechanism for various type oscillations in the coastal area. The transformation of the wave group structure in the process of wave breaking is closely related with increasing the energy of low frequency wave (LFW) in the surf zone. Low frequency waves (LFWs) are oscillations with frequency less then 0.04Hz and the denotation long period waves (LPWs) is also used for the same type of waves. The LFWs could be directly forced by short wave grouping as bound LFWs outside the surf zone and could be release from wave groups as free waves n process of breaking – Longuet-Higgins & Stewart (1962). The time variations of break position due to the group structure of short waves is also another mechanism of LFWs generation – Symonds *et al.* (1982). The model of Schaffer (1993) combines the incident bound LFW model with time varying break point model. At the same time, it takes into account a partial transmission of wave grouping into the surf zone. The group structure of short waves and its cross-shore transformation is the main factor for inducing LFWs. In addition, Bowen & Guza (1978) identified wave groups as a source of edge waves and Haller *et al.* (1999) mentioned that wave groups could perturb the nearshore velocity fields and force the shear instability waves.

In the present work, an attempt to estimate statistically the dependence of surf zone LFWs from wave groupiness s made on the base of field data. The variation of wave group structure during the wave transformation from deep to shallow water is examined. The relationship between wave groups and sea wave characteristics is statistically investigated outside and inside the surf zone. The model of transformed probability density function of wave heights – Dally (1990) is adopted for the theoretical investigation of transformation of sea waves due to shoaling and breaking. The relationship between sea waves and wave groups inside the surf zone is derived theoretically on the base of this model.

The alteration of wave groupiness and the height of LFWs during the changes of offshore sea conditions is checked. The height of LFWs in the surf zone is examined in dependence of offshore wave groupiness, estimated by group characteristics, both mean group height and mean group period.

2. Field Data and Methods for Analysis

2.1 Field Data

The data, used in this work, was collected at the Hazaki Oceanographical Research Station (HORS) during the period from 25th February to 1st March 1989. The measurements were performed by 6 wave gauges, mounted at the 427m

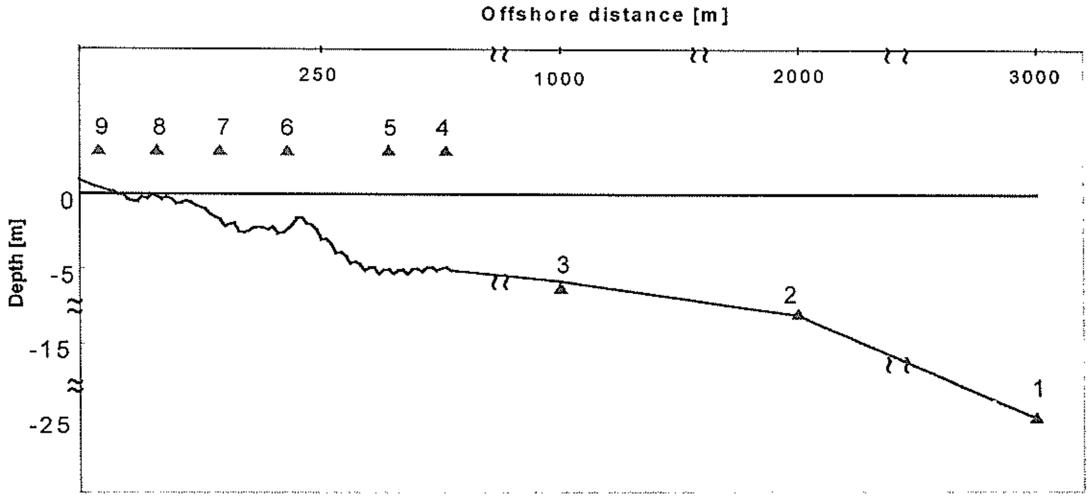


Fig. 1 Location of wave gauges during the observation

long pier, extended perpendicular to the shore, as well as by three deepwater bottom wave gauges in extension line of the pier, shown in **Figure 1**. The sea surface elevation was recorded every 6 hours. The duration of records is 2 hours with a sampling interval $\Delta t = 0.5s$. More detail description of these observations can be found in Katoh *et al.* (1991) and Nakamura & Katoh (1992).

2.2 Orbital Criterion for Determination of Individual Oscillations

The wave records in the surf zone usually contain a larger amount of small zero-crossing (ZC) waves due to the breaking and nonlinear behavior of waves in comparison with deepwater records. In order to ensure the constancy of the number of waves from deep to shallow water, as first linear approximation of wave process, some criteria for neglecting these small waves are necessary. The conventional criteria for removing the small waves relied on the height of small wave, which is less than some value – Mizuguchi (1982), or the period of small wave, which is less than some value – Hamm & Peronnard (1997). In both ways some subjectivity is introduced in the determination of discrete waves.

The orbital criterion, introduced by Gimenez *et al.* (1994) for determination of individual waves, eliminates small waves without the checking of individual waves in time or height domain in contrast with the above-mentioned criteria for neglecting the small waves. In orbital criterion, the complex presentation of wave process is used. In complex plane, the analytical function

$$\xi(t) = \eta(t) + j\hat{\eta}(t) \tag{1}$$

corresponds to the vertical displacement of sea surface $\eta(t)$. Here the Hilbert transform $\hat{\eta}(t)$ of the stationary random function of sea surface elevation $\eta(t)$ is

$$\hat{\eta}(t) = \frac{1}{\pi} P\int \frac{\eta(X)}{t-X} dX, \tag{2}$$

where P indicates the Cauchy principal values.

Function of the wave envelope $A(t)$ and phase $\varphi(t)$ then can be obtained by

$$A(t) = \sqrt{\eta^2(t) + \hat{\eta}^2(t)} \tag{3}$$

$$\varphi(t) = arctg \frac{\hat{\eta}(t)}{\eta(t)} \tag{4}$$

The phase $\varphi(t)$ is called the wrapped phase $\varphi(t) \in [-\pi, \pi]$ or the unwrapped phase $\varphi(t) \in [-\infty, \infty]$ as the difference of its interval of definition. Usefulness of the unwrapped phase for studying the local properties of waves was mentioned by Huang *et al.* (1992) and was used by Cherneva & Velcheva (1993) also for the investigation of wave groups.

As far as the sea surface elevation process can be considered as modulated process with some carrier frequency ω_0 – Melville (1983), the unwrapped phase function $\varphi(t)$ can be decomposed by linear part $\omega_0 t$ and the deviation part $\theta(t)$.

$$\varphi(t) = \omega_0 t + \theta(t) \tag{5}$$

By definition, the time derivative of the phase function $\varphi(t)$ is a local frequency of the time series

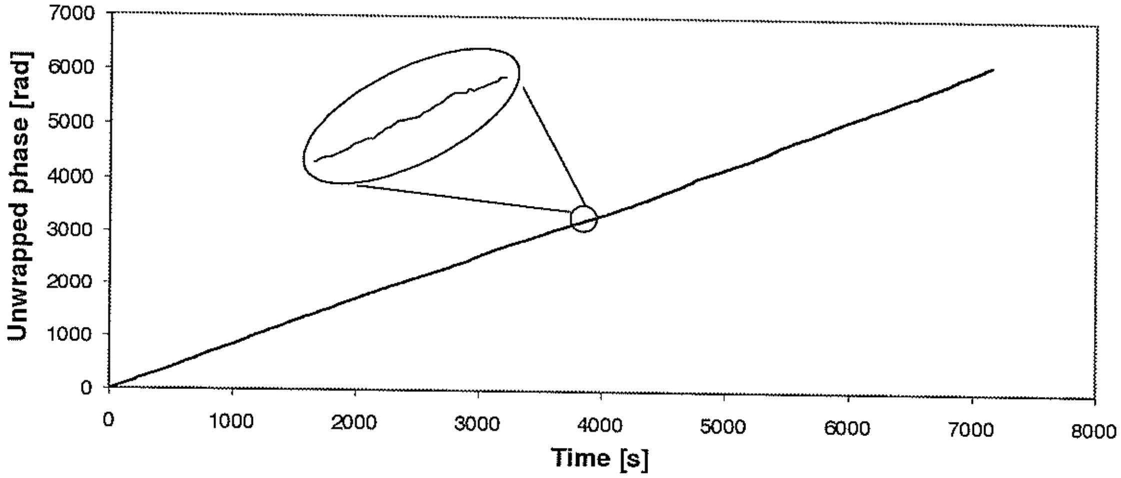
$$\omega(t) = \frac{d\varphi}{dt} = \omega_0 + \frac{d\theta(t)}{dt} \quad . \tag{6}$$

The unwrapped phase of the sea surface elevation $\eta(t)$, which is measured at 24m depth for an observation term, is shown in **Figure 2a** while the wrapped phase is in **Figure 2b**. From the mean slope of unwrapped phase, mean frequency $\omega_0 = 0.852$ rad/s is determined easily or mean period 7.375s is defined.

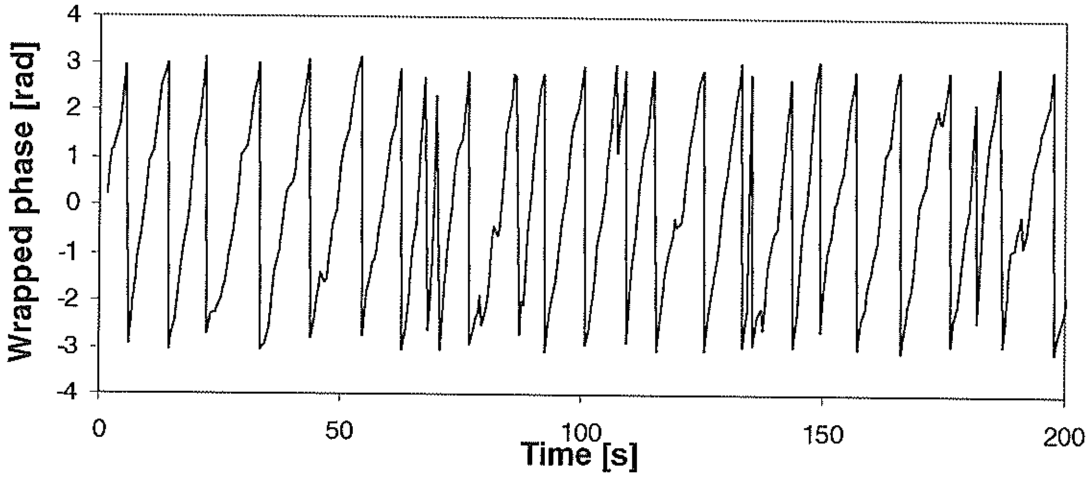
The random wave process $\eta(t)$ then can be presented by a radius-vector, rotating in the complex plane as seen in **Figure 3a**. The magnitude of the vector is equal to the wave envelope $A(t)$ and the angle of rotation is equal to the unwrapped phase function $\varphi(t)$. The mean velocity of rotation of radius-vector is ω_0.

Orbital criterion determines a discrete wave as corresponding to 2π advance of a phase angle in complex plane - Gimenez *et al.* (1994). For the case of zero-down crossing waves, an individual wave is defined by those consecutive two crossings of the positive part of the imaginary axis, which correspond to 2π advance of the angle of this rotating vector.

Figure 3b illustrates the portion of sea surface elevation $\eta(t)$, which included also small ZC wave. Usual zero-down crossing procedure regards a small ZC wave as an individual wave. In the corresponding polar diagram on **Figure 3a**, the phase angle of the small wave does not advance 2π. Using the orbital criterion, the small ZC wave is eliminated.

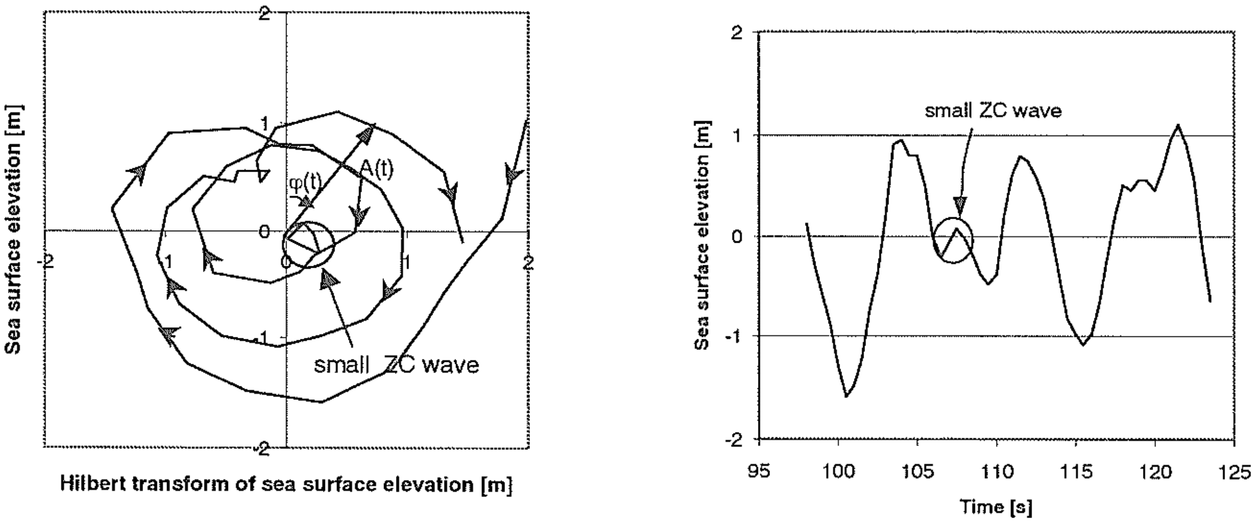


(a) Unwrapped phase



(b) Wrapped phase

Fig. 2. The phase $\varphi(t)$ of analytical process.



(a) In complex plane (b)As a function of time

Fig.3 Presentation of wave process

Figure 4 shows the number of waves, defined by the orbital criterion and usual zero-down crossing method in a storm stage. The orbital criterion determined nearly constant number of waves across the shore and correspondingly, the mean wave frequency ω_0 keeps constant cross-shore.

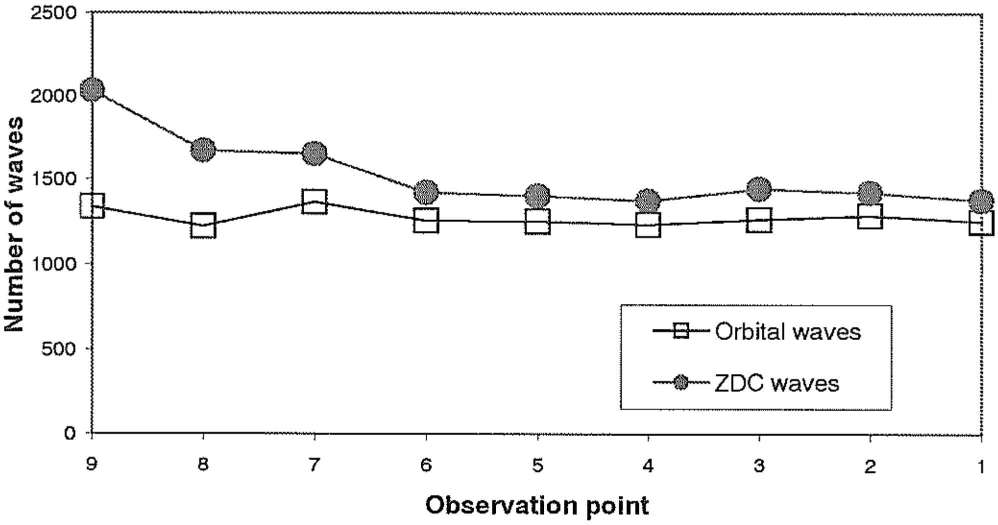


Fig. 4 Variation of number of waves per record across the shore

2.3 Method for Analysis of Wave Groups

The wave groupiness is analyzed in terms of the wave envelope $A(t)$, as oscillations around the mean value of wave envelope, see **Figure 5**.

If the wave process is wide, then the envelope will contain a lot of high frequency oscillations, which are not of interest for the wave group analysis. For this reason the wave envelope is necessary to be low-passed filtered. In this work, the proposed cut-off frequency of the filter is set as $\omega_0 / 2$ in order to ensure at least two individual waves per group as the carrier frequency ω_0 is determined by the linear part of unwrapped phase.

Individual wave groups are determined again applying the orbital criterion. The main characteristics of wave groups, such as mean group height and mean group period, are calculated as:

$$H_{gr\_mean} = \frac{1}{N}\sum_{j=1}^{N} H_{gr\_j}$$
$$T_{gr\_mean} = \frac{1}{N}\sum_{j=1}^{N} T_{gr\_j} \qquad (7)$$

where N is the total number of determined discrete groups (H_{gr_j}, T_{gr_j}) in the record.

2.4 Method for Analysis of Low Frequency Waves

The low frequency oscillations are separated from sea surface elevation data by low-passed filtering – the thin line on **Figure 5**. The cutoff frequency for low-pass filtering operation is 0.04 Hz. Since wave spectrum has minimum in that frequency, LFW energy can be separated from the energy of short wind waves – Nakamura & Katoh (1992). The individual LFW heights H_{LFW} are determined again by the orbital criterion.

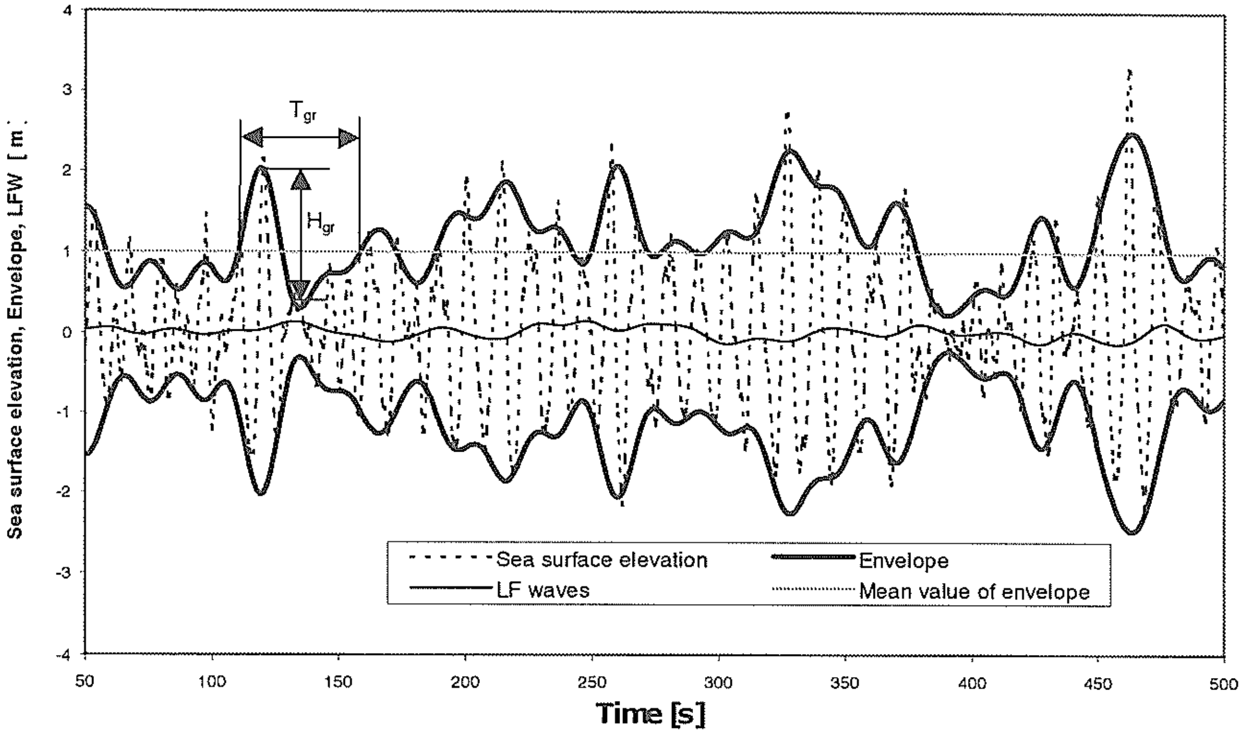


Fig.5 Sea surface elevation, envelope and low frequency waves as function of time.

3. Results of Field Data Analysis

The collected data of sea surface elevation were analyzed by the described methods. The characteristics of offshore sea waves and their group structure as well as LFWs in the surf zone are presented in the **Table 1**. Sea waves are characterized by significant wave height H_s and mean wave period T_{mean}. Mean group height H_{gr_mean} and mean group period T_{gr_mean} are characteristics of wave groupiness. H_{LFW_surf} is an averaged value of the measured LFW heights inside the surf zone.

The offshore sea conditions are classified into four different sea stages – calm, wave growing, wave decay and post-storm stage, after Katoh *et al.* (1991). Initial three terms of the measurements (up to 26.02-06:00) were comparatively calm sea stage, when sea waves are with period of less then 6s and significant wave height less than 2m. Under the direct influence of the passing atmospheric depression with strong north wind, the growing sea stage was observed in the next three terms. At that time waves became greater than 3m of H_s, but their periods were still short. In the wave decay stage, when the wind speed dropped, the periods of the waves were longer than 9s. At the end of the observation, noticed here as the post-storm stage, the wind changed its direction and registered waves are small as amplitude, but with long periods.

Table 1 Offshore sea condition and LFW

Stage	Term of	Observation point 1 - offshore zone				Surf zone
	observation	H_s	T_{mean}	H_{gr_mean}	T_{gr_mean}	$H_{LFW\ surf}$
	dd.mm-hh:mm	[m]	[s]	[m]	[s]	[m]
calm	25.02-18:00	1.53	5.2	0.54	25.6	0.18
	25.02-24:00	1.93	5.5	0.67	27.6	0.22
	26.02-06:00	1.98	5.7	0.68	28.1	0.25
wave growing	26.02-12:00	3.18	7.0	1.05	36.1	0.38
	26.02-18:00	3.25	7.4	1.13	45.7	0.39
	26.02-24:00	3.56	7.9	1.18	45.1	0.44
wave decay	27.02-06:00	3.58	9.4	1.30	65.5	0.59
	27.02-12:00	3.18	10.0	1.18	67.7	0.61
	27.02-18:00	2.86	10.0	0.98	59.7	0.46
	27.02-24:00	2.62	9.5	0.80	60.6	0.51
	28.02-06:00	2.60	10.6	0.91	64.5	0.54
post storm	28.02-12:00	2.15	9.2	0.74	65.1	0.48
	28.02-18:00	2.21	8.8	0.66	56.9	0.44
	28.02-24:00	2.15	8.5	0.68	47.2	0.38
	01.03.-06:00	1.86	7.8	0.61	38.9	0.32

The group structure at the offshore demonstrates different peculiarities during these four sea stages. The mean

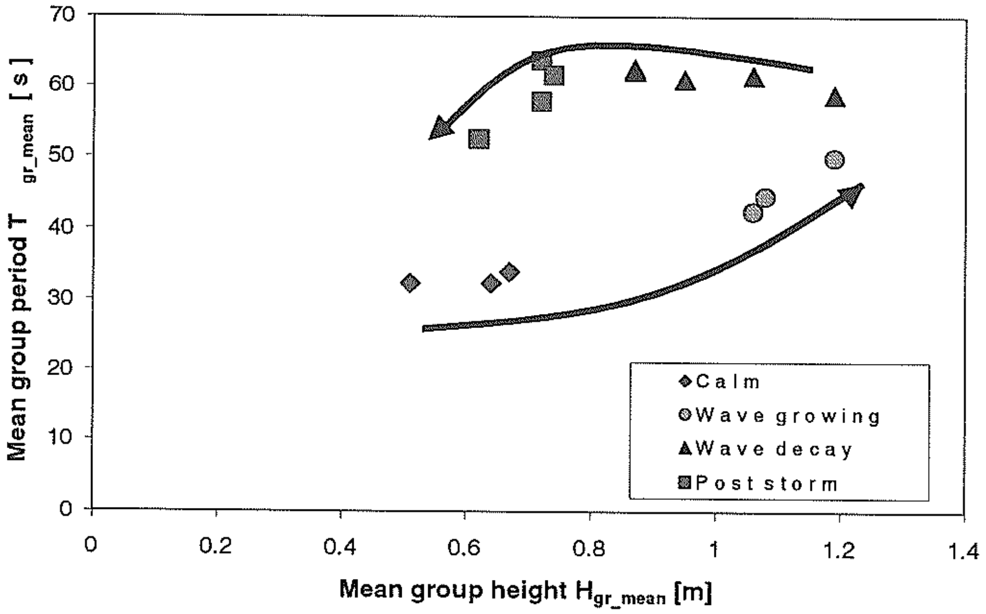


Fig. 6 The characteristics of offshore wave groups during different sea stages

group period T_{gr_mean} is plotted against the mean group height H_{gr_mean} on **Figure 6** for the offshore data, measured at 24 m depth. The evolution of offshore conditions during the observation period is also sketched on the figure as solid lines. The wave group characteristics can be separated for four different sea stages. In the calm condition, mean group period is short and mean group height is low. The growing stage wave groups become steeper with large mean group height, (higher than 1m), while the wave group length is still short. Wave process during the decay is characterized with both, the high level of amplitude modulation and the long wave groups. The wave groups keep comparatively long T_{gr_mean} during the post-storm stage, but the mean group heights decrease. It can be concluded that well-grouped sea waves with long group period and high group height is observed during the wave decay stage.

The variations of group characteristics – mean group height and the mean group period, together with the LFW height are plotted along the beach profile during each different sea stage on **Figure 7 (a), (b), (c) and (d).** Only one observation term for each sea stage is chosen for presentation. An arrow shows the position of the break point. There is a clear tendency of increasing of height of LFWs after breaking, while the value of H_{LFW} keeps nearly constant shoreward. The breaking process leads to the reduction and destroying of well-developed group structure. The values of the mean group period T_{gr_mean} and the mean group height H_{gr_mean} decrease after the break point. It has to be noticed that the biggest change of wave groupiness after breaking is observed at wave decay stage. This big reduction is accompanied with the appearance of the highest LFW height H_{LFW} in the surf zone namely during the wave decay stage.

The mean group characteristics are statistically investigated in dependence of wave statistics. On **Figure 8**, the mean group height is presented as a function of the local significant wave height. The all obtained data from different sea tages are plotted together into two groups, before and after breaking.

Before breaking, the mean group height is approximately one third of the corresponding significant wave height. This well-organized group structure is changed significantly in the process of wave transformation due to shoaling and breaking. After breaking, the level of wave amplitude modulation, estimated by the mean group height, reduces and becomes in average one fifth of the corresponding local significant wave height. In shoreward direction, of course, the evel of the amplitude modulation continues to decrease and tends to zero.

4. Modeling of Transformation of Wave Groups by Wave Transformation Model

4.1 Wave Groups Outside Surf Zone

The mean group height H_{gr_mean} is defined as mean deviation around the mean wave height $\overline{H}$ as follow:

$$H_{gr\_mean} = \overline{H}\left(\int_0^\infty (1-x)^2\, pdf(x)\,dx\right) \tag{8}$$

where $pdf(x)$ is a probability density function of the normalized wave height $x = H/\overline{H}$, H and $\overline{H}$ is a value of height of each wave and its mean value.

Nakamura and Katoh (1992) adopted the Rayleigh distribution for wave heights outside the surf zone, where sea waves are unbroken. The Rayleigh distribution is expressed as

$$pdf(x) = \frac{\pi}{2}x\exp\left(-\frac{\pi}{4}x^2\right) \tag{9}$$

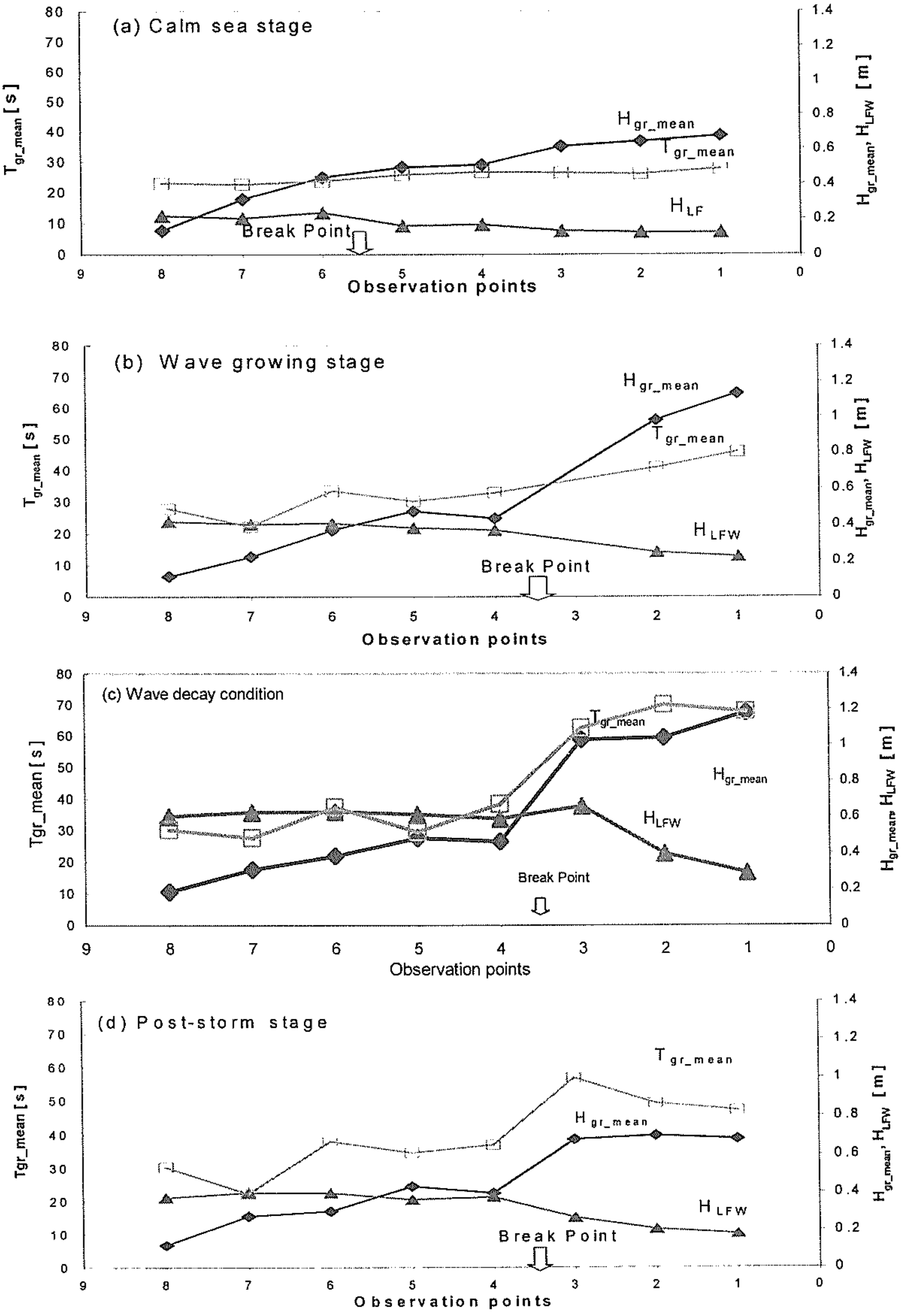


Fig. 7 Variation of wave groupiness and LFW height along the beach in different sea stages.

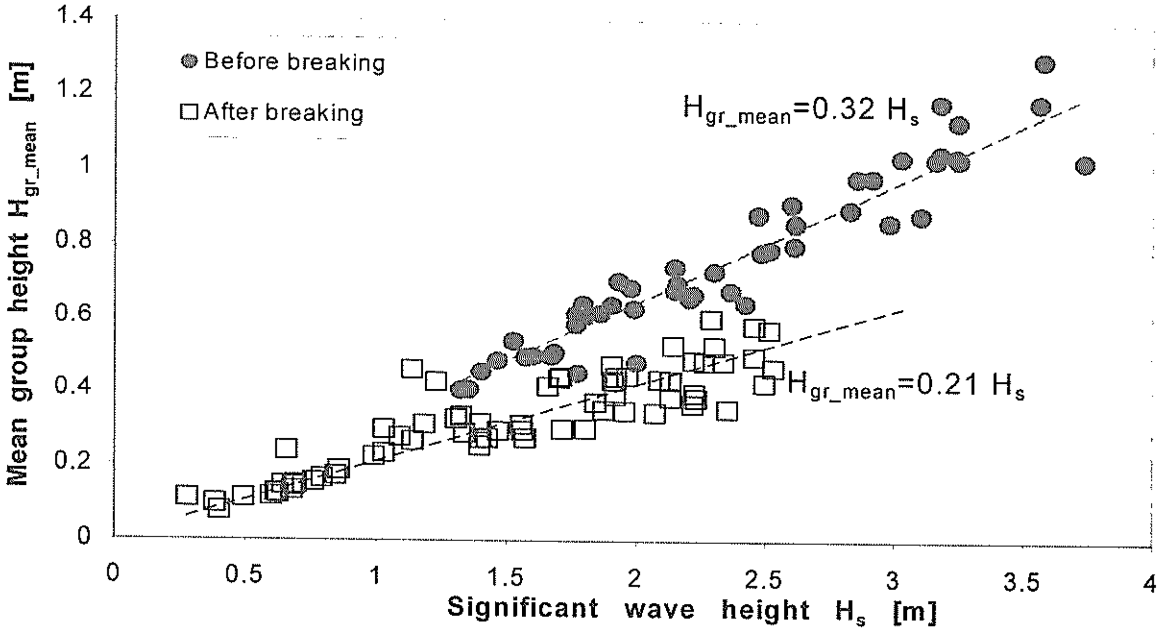


Fig.8 The mean group height as a function of local significant wave height before and after breaking.

They derived theoretical relationship between the mean group height H_{gr_mean} and the significant wave height H_s in the offshore as

$$H_{gr\_mean} \sim \frac{1}{3} H_s \qquad (10).$$

This theoretical relationship is close to the proportional parameter of 0.32, observed for the waves before breaking as seen on **Figure 8**.

4.2.Wave Groups Inside Surf Zone

For the explanation of the observed relationships between characteristics of sea waves and wave groups, a model of wave transformation from deep to shallow water is adopted, which consists of the nonlinear shoaling model of Shuto (1974) and the wave transformation model of Dally (1990) after breaking.

The process of shoaling and breaking of sea waves leads to significant changes of the wave groupiness. In order to investigate these variations of wave groups along the beach profile, a probability density model of Dally (1992) for the wave transformation is used. The wave-by-wave approach is applied to the random wave transformation, caused by shoaling, breaking and reforming in cross-shore direction.

The wave characteristics far outside the surf zone are used as input data of this model. The transformations of wave heights due to shoaling are estimated by the model of Shuto (1974) for the nonlinear shoaling as

$$\begin{cases} H^2 C_g = const & for \quad gHT^2/h^2 < 30 \\ H^2 h^{2/7} = const & for \quad 30 < gHT^2/h^2 < 50 \\ H^2 h^{5/2}\left[\left(gHT^2/h^2\right)^{1/2} - 2\sqrt{3}\right] = const & for \quad 50 < gHT^2/h^2 \end{cases} \qquad (11)$$

where C_g is the group velocity, g is the gravitational acceleration, H and T are the wave height and the period, and h is the water depth.

Individual waves shoal in the model until waves start to break. For the judgment of incipient breaking, the incipient break index γ - Weggel (1972) is used. The index γ is the ratio of the characteristic wave height to the local water depth, which takes into account the deepwater steepness of waves and the beach slope. The γ is expressed as

$$\gamma = b(m) - 0.0827a(m)S_0^{4/5} \tag{12}$$

where

$$\begin{aligned} a(m) &= 43.8[1.0 - \exp(-19m)] \\ b(m) &= 1.56/[1.0 + \exp(-19.5m)] \end{aligned} \tag{13}$$

in which m is the bottom slope and S_0 is the deepwater steepness, equal to H_0 / L_0, where H_0 and L_0 are the deepwater height and the wave length, respectively.

Inside the surf zone, the analytical expression of Dally (1990) is used for the transformed probability density function for wave heights due to shoaling and breaking. This expression is based on the assumption that random waves behave as a collection of individual regular waves in the surf zone.

At the location outside the surf zone, it is assumed that the Rayleigh distribution is valid and it is truncated at some realistically large wave height for this location. The probability density function is

$$pdf(H_i) = 2\frac{H_i}{H_{rmsi}}\exp\left[-\left(\frac{H_i}{H_{rmsi}}\right)^2\right], \quad H_i < \gamma h_i \tag{14}$$

where H is the wave height, H_{rmsi} is the root-mean-square wave height and subscript "i" denoted initial conditions of the model for the transformation of $pdf(H)$ inside the surf zone.

Since in any location of the surf zone, simultaneously exist breaking and non-breaking waves, the wave height distribution inside the surf zone is derived by the contribution of both - the probability density function of non-breaking waves and the probability density function of broken waves.

Non-breaking waves shoal in the surf zone and the linear theory of shoaling is assumed. The transformed Rayleigh distribution due to linear shoaling gives the portion of probability density function due to shoaling waves:

$$pdf(A)_{sh} = 2A\hat{h}^{1/2}\exp\left\{-\left(A^2\hat{h}^{1/2}\right)\right\} \quad \text{for} \quad A < A_b \tag{15}$$

where random variables are non-dimensional $A = H/H_{rmsi}$, $A_b = \gamma h / H_{rmsi}$, $\hat{h} = h/h_i$.
This distribution is truncated at the highest non-breaking wave height that can occur at the local depth $H_b = \gamma h$. The subscript "sh" denotes the probability density function of shoaling waves.

As waves start to break, the turbulent dissipation of the wave energy is the dominant dissipation mechanism and breaking processes dominate wave transformation. However, in contrast with monochromatic waves, there is no well-defined breakpoint for random waves. Because of the randomness of waves, the occurrence of breaking is itself a random process.

The contribution of broken waves to the probability density function at a particular point inside the surf zone is derived on the base of the analytical solution of the D^3 model of Dally *et al.* (1985). The model was developed for regular waves breaking on a planar beach. This is an energy flux difference model, derived on the assumption that waves are breaking until another stable wave height is attained after breaking. Horikawa & Kuo (1966) and Thorton &Guza (1983) found that a stable criterion can be expressed as

$$H_{stable} = \Gamma h \tag{16}$$

in which H_{stable} is the stable wave height and Γ is a dimensionless coefficient, called also stable wave factor, equal to the ratio of the wave height to the water depth at the point where the wave stops to break and reforms. The value of this parameter appears to be 0.35-0.4. The rate of energy dissipation per unit area is presented in D^3 model of Dally *et al.* (1985) as:

$$\frac{d\left(H^2 h^{1/2}\right)}{dx} = \frac{-K}{h}\left(H^2 h^{1/2} - \Gamma h^{5/2}\right) \tag{17}$$

where K is a decay coefficient. In this work the values of $K = 0.15$ and $\Gamma = 0.4$ is used as recommended by Dally (1990) for the case of neglecting set-up fluctuations.

The portion of the probability density function inside the surf zone due to broken waves is derived as:

$$pdf(A)_{br} = \frac{5A\gamma^2 \hat{h}^{(1/2-K/m)}\left[F(A)\right]^{K/m}}{\left|(5/2-K/m)(\gamma^2+\alpha_*)\right|}\exp\left\{-A_{bi}^2\left[F(A)\right]^{5/2}\right\}, \tag{18}$$

where $F(A) = \left[\frac{(H_{rmsi}/h_i)^2 A^2 + \alpha_* \hat{h}^2}{(\gamma^2+\alpha_*)\hat{h}^{(K/m-1/2)}}\right]^{1/(5/2-K/m)}$, $\quad A_{brm} \le A \le A_b$.

This distribution is truncated at upper limit A_b - largest wave height that can occur at the local depth, but also at the lower limit given by the breaking wave height that corresponds to the largest wave of original $pdf(H_i)$. The lower limit A_{brm} is determined by initial condition as

$$A_{brm} = \left[\hat{h}^{(K/m-1/2)}\left(\gamma^2+\alpha_*\right) - \alpha_*\hat{h}^2\right]^{1/2}\left(\frac{h_i}{H_{rmsi}}\right) \tag{19}$$

and $\alpha_* = \frac{(K/m)\Gamma^2}{(5/2-K/m)}$, $A_{bi} = \gamma h_i / H_{rmsi}$.

Then the probability density function inside the surf zone is

$$pdf(A)_{inside\_surf} = pdf(A)_{sh} + pdf(A)_{br} \tag{20}$$

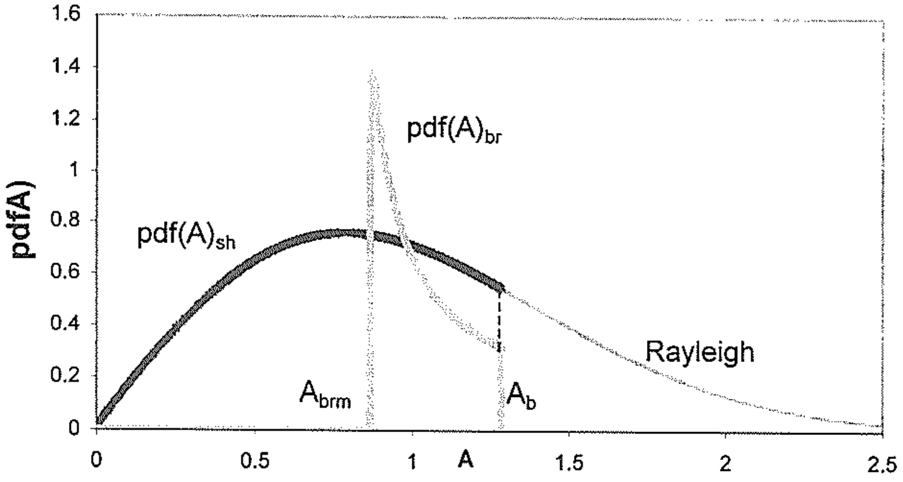


Fig.9 Probability density function inside surf zone

One example of probability density function of wave height inside the surf zone is presented in **Figure 9** for the non-dimensional height A .

The closed form of probability density function of wave heights facilitates the calculation of the characteristic wave heights as the significant wave height H_s, the mean wave height H_{mean} and the root-mean-square wave height H_{rms}. In dimensionless form they are derived as,

$$A_{mean} = \frac{H_{mean}}{H_{rmsi}} = \int_0^{A_b} A\,pdf\,(A)_{sh}\,dA + \int_{A_b}^{A_{bm}} A\,pdf\,(A)_{br}\,dA \tag{21}$$

$$A_{rms} = \frac{H_{rms}}{H_{rmsi}} = \int_0^{A_b} A^2\,pdf\,(A)_{sh}\,dA + \int_{A_b}^{A_{bm}} A^2\,pdf\,(A)_{br}\,dA \tag{22}$$

In the calculation of significant wave height (z=1/3)

$$A_s = \frac{H_s}{H_{rmsi}} = \frac{1}{z}\left[\int_{\tilde{A}}^{A_b} A\,pdf\,(A)_{sh}\,dA + \int_{\tilde{A}}^{A_b} A\,pdf\,(A)_{br}\,dA\right] \tag{23}$$

the integration limit $\tilde{A}$, which is the value of A above which z percent of the waves are found, have to be first determined from

$$\int_0^{\tilde{A}} pdf\,(A)_{sh}\,dA + \int_{A_{bm}}^{\tilde{A}} pdf\,(A)_{br}\,dA = 1 - z \tag{24}.$$

The expression of mean group height H_{gr_mean} inside the surf zone then can be derived on base of the closed form of probability density function inside the surf zone $pdf(A)_{inside\_surf}$ as

$$H_{gr\_mean} = \overline{H}\left(\int_0^{x_b} (1-x)^2\,pdf\,(x)_{sh}\,dx + \int_{x_{bm}}^{x_b} (1-x)^2\,pdf\,(x)_{br}\,dx\right)^{1/2} \tag{25}$$

where some variable changes are performed. Instead of normalized by initial condition wave height $A = H/H_{rmsi}$, non-dimensional height by local mean wave height $x = H/\overline{H}$ is used.

4.3 Comparison between Observation and Calculation Inside Surf Zone

The proposed model of wave group transformation across the shore is applied for the field data. The wave characteristics of the deepest wave gauges (24 m water depth) are used as the input. After that, waves are nonlinearly shoaling by the Shuto's model until incipient breaking is reached. Inside the surf zone, the Dally's wave transformation model is applied and the significant wave height and the mean group height are calculated by (23) and (25) respectively. Then, the ratio H_{gr_mean}/H_s is calculated and compared with the ratio, which is categorized in "after breaking" data group on **Figure 8**. The results of comparison can be seen in **Figure 10**.

The ratio H_{gr_mean}/H_s, calculated by the wave transformation model shows almost the same tendency of variation as the observed ratio $H_{gr\_mean}/H_s = 0.2$ (see **Figure 8** "after breaking"). The data presented on **Figure 10** can be separated into two groups. One is the data in the outer surf zone, which is seaward part of the surf zone, indicated by triangles. Another is the data of the inner surf zone, which is shoreward part of the surf zone, indicated by squares. After initial breaking in the outer surf zone the ratio decreased from 1/3 for outside the surf zone to approximately 0.25, while for the observation in the inner surf zone this ratio became less then 0.20, approximately 0.15. This is a consequence of further breaking of the waves in the inner surf zone and correspondingly, completely destroying of its group structure in shoreward direction.

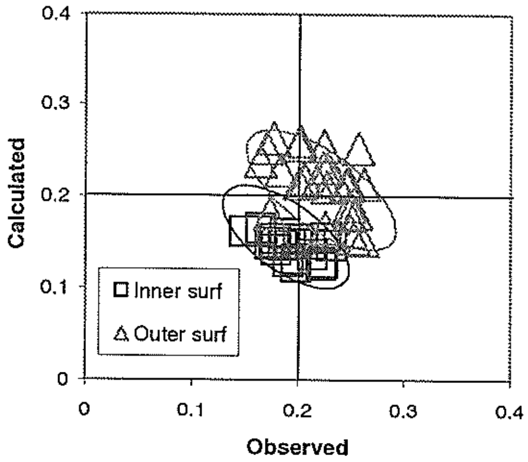


Fig. 10 Comparison between observed and model calculated ratio H_{gr_mean} / H_s inside surf zone.

4.4 Low Frequency Waves Inside Surf Zone in Dependence of Offshore Wave Groupiness

The destroying of wave groupiness in process of breaking is accompanied with increasing of low frequency energy in the surf zone. Since after break point the LFW height keeps comparatively constant across the surf zone (**Figure 7**), the LFW height inside the surf zone H_{LFW_surf} is defined here as averaged value of surf zone observations.

Figure 11 shows that the height of LFW in the surf zone H_{LFW_surf} depends on the function of offshore wave groupiness. The function of wave groupiness here is determined as product of group height H_{gr_mean} and group period T_{gr_mean}. The high value of H_{LFW_surf}, greater than 0.5m, are observed in the wave decay stage, when wave groups have simultaneously high H_{gr_mean} and long T_{gr_mean}. In contrast, the weak groupiness in calm stage produced less than 0.3m LFW height H_{LFW_surf} in the surf zone. It can be concluded that the group period T_{gr_mean} and the group height H_{gr_mean} must be both considered as important factors for the generation of low frequency oscillations in the surf zone.

Yamamura & Aoki (2000) and Kim *et al.* (1999) also reported the influence of space-time characteristics of sea waves, estimated by the product of wave height and wave period, on the observed values of the low frequency wave height. The physical reason of this dependence is not clear at the moment.

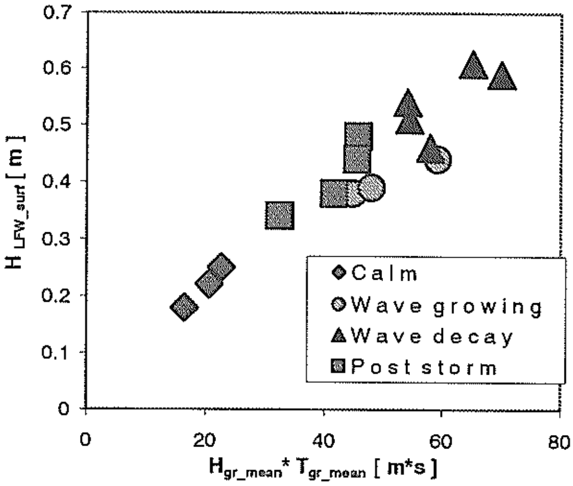


Fig.11 Observed LFWs inside surf zone in dependence of offshore wave groupiness

5. Conclusions

Determination of individual waves by orbital criterion is found to be very powerful for the treatment of surf zone wave data. The orbital criterion has advantage to eliminate by the definition small zero-crossing waves. In this way additional subjective checking of individual waves in time or height domain can be avoided. Wave groupiness is analyzed in terms of wave envelope and the orbital criterion is used for determination of individual wave groups.

The transformation of group structure of sea waves from deep to shallow water as well as during the different offshore sea conditions is investigated on the base of field data. Well-grouped sea waves with long group period and high group height is observed during the wave decay conditions. The ratio of wave group height to the local wave height is different for the waves before and after breaking.

The changes of wave group structure due to shoaling and breaking is theoretically derived on the base the wave transformation model. The theoretical changes of wave group height agree well with the observed changes of the groupiness. This theoretical approach for cross-shore variations of wave groupiness could be applied in the models for generation of low frequency wave in the coastal area.

The high low frequency oscillations inside the surf zone is observed, when offshore wave groups are well formed simultaneously in height and duration. The obtained results can be used for prediction of surf zone LFW on the base of knowledge of offshore wave groupiness, but further investigations are necessary in this direction.

(Received on August 31, 2000)

Acknowledgements
This study has been supported by Japan International Science and Technology Exchange Center, Science and Technology Agency.
Authors are very grateful to Dr. Kazumasa Katoh for the discussions and commends. Special thanks to the chief Dr. Y. Kuriyama and members of the Littoral Drift Laboratory for a creative work atmosphere and support during our research.

References

Bowen, J.A. and Guza, R.T. (1978): Edge waves and surf beat, *J.Geophys.Res.*, 83, pp.1913-1920.

Cherneva, Zh. and Velcheva, A. (1993): Wave group analyses based on phase properties, *Proc. of the First Int. Conf. on the Mediterranean Coastal Environment*, MEDCOAST'93, November 2-5, Antalya, Turkey, Vol.2, pp.1213-1221.

Dally, W.R. (1990): Random breaking waves: a closed-form solution for planar beaches, *Coast. Eng.* 14, pp.233-263

Dally, W.R. (1992): Random breaking waves: field verification of wave-by-wave algorithm for engineering application, *Coast. Eng.* 16, pp.369-397.

Dally, W.R., Dean, R.G. and Dalrymple, R.A. (1985): Wave height variation across beaches of arbitrary profile, *J.Geophys.Res.* 90 C6 pp.11917-11927.

Gimenez, M.H., Sanchez-Carratala, C.R. and Medina, J.R. (1994): Analysis of false waves in numerical sea simulations, *Oc. Engng*, Vol.21, No.8, pp.751-764.

Haller, M. C., Putrevu, U., Oltman-Shay, J. and Dalrymple, R.A. (1999): Wave group forcing of low frequency surf zone motion, *Coastal Eng. J.* 41, 2, pp.121-137.

Hamm, L. and Peronnard, C. (1997): Wave parameters in the nearshore: A clarification, *Coast. Engng*, 32, pp.119-135.

Horikawa, K. and Kuo, C.T., (1966): A study of wave transformation inside surf zone, *ASCE Proc. 10th Conf. Coastal Eng.* Vol.1, pp.217-233.

Huang,N.E., Long,S.R., Tung,C.C., Donelan,M., Yuen,Y. and Lai,R.J (1992): The local properties of ocean surface waves by the phase-time method, *Geophys. Res. Letters*, 19, 7, pp.685-688.

Katoh, K. Nakamura,S. and Ikeda,N. (1991): Estimation of infragravity waves in consideration of wave groups – An Examination on basis of field onservation at HORF, *Rep. Of PHRI*, Vol.30, No.1, 137-163.

Kim, K.H., Kim,J.H. and Pyun,C.K. (1999): A study on characteristics of long-period waves by field observation, Int. Symposium on Progress in Coast. Eng. And Oceanography, Sep 9-11, Seoul, Korea.

Melville, K. (1983): Wave modulation and breakdown, *J. Fluid Mech.* 128, pp.489-506.

Mizuguchi, M. (1982): Individual wave analysis of irregular wave deformation in the nearshore zone, *Proc. ICCE'82*, pp.485-504.

Longuet-Higgins, M.S., and Stewart, R.W. (1962): Radiation stress and mass transport in gravity waves with application to surf beat, *J. Fluid Mech.* 13, pp.481-504.

Nakamura, S. and Katoh, K. (1992): Generation of infragravity waves in breaking process of wave groups, *Proc. 23-rd ICCE*, pp.990-1003.

Schaffer, H. A. (1993): Infragravity waves induced by short-wave groups, *J. Fluid Mech.* Vol.247, pp.551-588.

Shuto, N. (1974): Nonlinear long waves in a channel of variable section, *Coast. Eng. In Japan* 17, pp.1-12.

Symond, G., Huntley, G.A. and Bowen, A.J. (1982) Two dimensional surf beat: long wave generation by a time-varying break point, *J.Geophys.Res.* 87, C1, pp.492-498.

Thornton, E.B. and Guza, R.T. (1983): Transformation of wave height distribution, *J.Geophys.Res.*, 88, pp.5925-5938.

Weggel, J.R. (1972): Maximum breaker height, *ASCE J.Waterways, Harbors, Costal Eng.Div.*, 98, WW4, pp.529-548.

Yamamura, Y. and Aoki, S. (2000): A practical method for estimating bound long waves and its application to the analysis for free long waves, will be published in *Proc. of ICCE'2000*, Sydney,Australia.

List of Symbols

$A(t)$: wave envelope
$A = H/H_{rmsi}$: non-dimensional wave height
A_b : highest non-breaking wave height that can occur at the local depth
A_{brm} : breaking wave height, corresponds to the largest wave of initial *pdf*
A_{mean}, A_{rms}, A_s : dimensionless mean wave height, root-mean-square wave height and significant wave height
C_g : group velocity
g : gravitational acceleration
h : water depth
h_i : water depth in initial condition
h_b : water depth, where incipient breaking occur
$\hat{h} = h/h_i$: non-dimensional water depth
H : wave height
$\overline{H}$: mean wave height
H_s : significant wave height
H_{rmsi} : root-mean-square wave height initial
H_0 : deepwater wave height
H_{stable} : stable wave height
H_{LFW} : height of low frequency wave
H_{LFW_surf} : low frequency wave height inside the surf zone
H_{gr_j} : height of discrete wave group
H_{gr_mean} : mean group height

K : decay coefficient
L_0 : deepwater wave length
m : bottom slope
N : number of groups in record
$pdf\,()$: probability density function
$pdf(A)_{sh}$: probability density function of shoaling waves
$pdf(A)_{br}$: probability density function of broken waves
$pdf\,(A)_{inside\_surf}$: probability density function of wave height inside surf zone
S_0 : deepwater steepness
T : wave period
T_{mean} : mean wave period
T_{gr_j} : period of discrete wave group
T_{gr_mean} : mean group period
$x = H/\overline{H}$: normalized wave height
γ : incipient breaking index
Γ : stable wave factor
Δt : sampling interval of measurements
$\eta(t)$: sea surface elevation
$\hat{\eta}(t)$: Hilbert transform of sea surface elevation
$\varphi(t)$: wave phase
$\theta(t)$: deviation part of wave phase
ω_0 : mean wave frequency