Simplified method to simulate wave transformations across coral reefs

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With the rapid developments along the Egyptian Red Sea coastal area, simulation of wave transformations across the coral reefs becomes an important task. An attempt is held to increase the validity of the Perlin and Dean models in simulating the coral reef coastal area. To get the target, the dissipation of energy due to breaking and friction are added to the equation of energy, which governed the wave height calculations. The new model includes also the check to turn off wave breaking. Two calibration parameters, for dissipation of energy due to wave breaking and, friction coefficient are used to improve the model accuracy. Ala Moana Beach waves data is used to calibrate the model. The model is applied at Red Sea Aquarium, Hurghada, as a typical case of the Red Sea coastal area, to identify the effect and the range of the calibration parameters. The results show that the new model is capable of predicting the wave distribution across the coral reefs with relatively small errors of about 10%. The wave height increases with increasing the breaking coefficient outside the surf zone and decreases with increasing the breaking coefficient inside the surf zone. The friction coefficient has an opposite effect.

شهدت منطقة البحر الأحمر طفرة حضارية كبيرة في الاونة الأخيرة تواكبت مع المشاريع السياحية الضخمة بالمنطقة وقد استلزم ذلك توافر البيانات والبرامج المساعدة اللازمة لإتمام أعمال التصميم للمنشآت البحرية وتحديد القوى المؤثرة عليها ومن أهم هـذه المتطلبات دراسة توزيع الأمواج فوق الشعاب المرجانية. ولتحقيق هذا الهدف تم تطوير البرنامج الخـاص بـ Perlin and Dean (1983) حتى يتمكن من تحديد توزيع الأمواج فوق الشعاب المرجانية. حيث تم تزويد النموذج بمعادلات لحساب الفواقد الناتجة عن الاحتكاك مع القاع وكذلك تكسر الأمواج. كما تم إضافة معاملين للمعايرة وذلك لزيادة مرونة البرنامج أحدهم خـاص بالفواقد الناتجة عن الاحتكاك والثاني خاص بالفواقد الناتجة عن تكسر الموجة. تم معايرة النمـوذج باسـتخدام بيانـات الأمـواج المقاسه بمنطقة Ala Moana Beach ، كما تم تطبيق النموذج وعمل دراسة لحساسية معاملات المعـايرة بمدينـة الغردقـة. وأظهرت النتائج صلاحية النموذج لحساب توزيع الأمواج فوق الشعب المرجانية بنسبة خطأ في حدود ١٠% فقط. كما وجـد أن معامل المعايرة الخاص بالفواقد الناتجة عن تكسر الأمواج يتناسب عكسياً مع ارتفاع الموجة بمنطقة التكسر بينما يتناسب طردياً مع ارتفاع الموجة خارج منطقة التكسر.

Keywords: Coral reef, Red Sea, Wave transformation's Numerical model

1. Introduction

Egypt has more than 1000km of beaches along the Red Sea. Most of shorelines of the Red Sea are fronted by discontinue series of extensive fringed coral reef. Coral reef ecosystems are composed of networks of complex feedback systems. The least under-stood parameters in these feedback systems are those associated with the physical forcing functions, wave and current. There are no available data for wave measurements along the Egyptian Red Sea coast. The only way to get the wave characteristics is by using the wind data. Roberts, et al. [1] showed that trade wind waves do not all have directions parallel to the wind direction. This variability in direction of wind waves has been shown to have an important effect on wave conditions on the shelf along shorelines that are irregular in their orientation. Observations of wave directional properties by Longuet-Higgins [2] have shown that wave height decreases off the wind direction and they are generated up to 90° to wind direction. Generally, the height of the waves generated at an angle θ to the wind direction is given by $H_o \cos^2\theta$, where H_o is the height of the wave in the wind direction (θ= 0).

However, wave characteristics are modified significantly within the coral reef but information on such modification is very limited, particularly for correlated field measurements. Knowledge of wave characteristics leeward of reef is necessary in numerous engineering endeavors, such as the assessment of beach stability, design of coastal structures, prediction of dynamic response of small boats in marinas partly protected by a reef, artificial shoal, and submerged breakwaters. Lack of such knowledge has led to grave uncertainties for designing an economical and sound structure.

The role of physical forces on coral reefs has received little attention. Von Arx [3] started initial investigations of such interactions. Few coastal process studies followed this effort. Roberts et al. [1] summarized some of this works which are ; study of wave refraction and wave energy on small coral islands of Campeche Bank, investigation of the littoral processes on reefs of Kauai in the Hawaiian Islands, measuring of the wave thrust and the wave-induced currents in shallow reefs, investigation of the swell on the island of Aruba, study of the variation of reefs with regard to the wave power climate, and measuring physical processes in the fringing reef system of Grand Cayman Island. Young [4] measured the wave characteristics and study the wave reflection on Yonge reef, part of the Great Barrier reef in Australia. Frnandez et al. [5] measured wave characteristics at Tague Reed, St. Croix. Frihy et al. [6] evaluated the importance of the fringing reef in protecting the coastal area against waves and currents.

These studies help in understanding the behavior of different coastal processes. A qualitative schematic of the wave transformation is shown in fig. 1. Offshore, waves tend to arrive in-groups, modulated at a beat frequency. As they shoal on the reef, secondary waves are formed indicative of a highly nonlinear process. The shoaling waves typically plunge and produce a saw-tooth profile. The reformed waves inside the breaker zone have a shortened period, due to the formation of multiple crests. The wave height will decay quickly on the outer portion of the reef due to breaking, until it reaches a stable value. On the inner portion of the reef, the reformed wave will decay slowly due to bottom friction. The breaking and reformation process is strongly dependent on the width of the reef and the water depth over the reef.

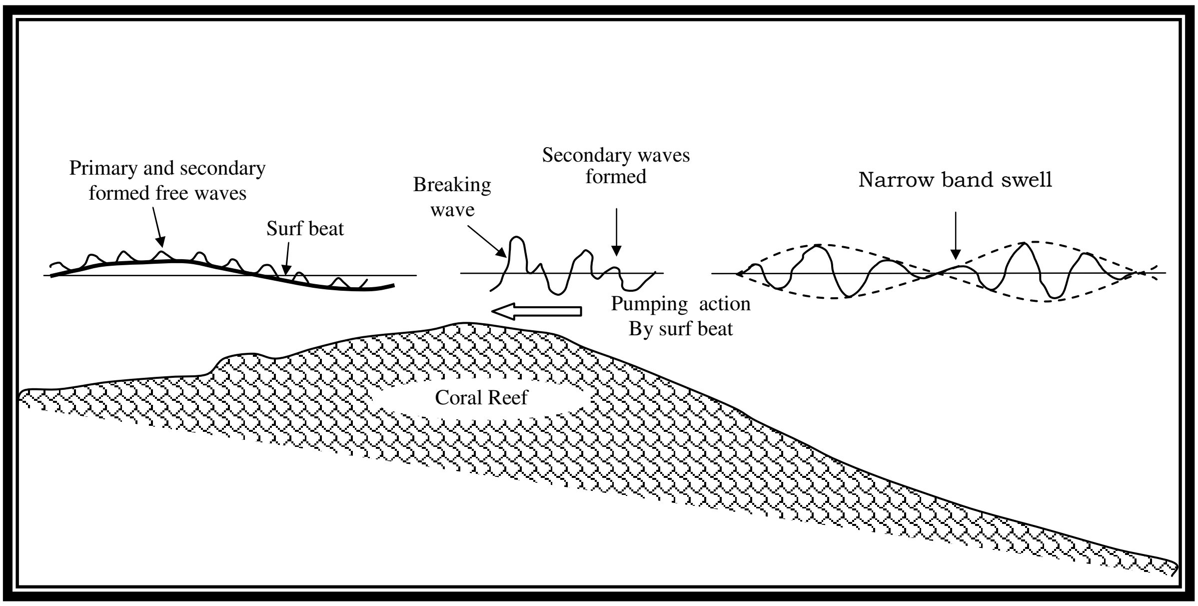

Fig. 1. Qualitative schematic of wave transformation across a reef, with typical probe locations, ala moana, honolulu, after lee and black [7].

Many trials are executed to simulate the wave distribution on a coral reef. Gerritsen [8] first applied wave breaking methods developed for mildly sloping beaches to reefs, with the inclusion of dissipation due to bottom friction. Gerritsen applied the random breaking wave model developed by Battjes and Janssen [9] but found that the truncated Rayleigh distribution of wave heights assumed by Battjes and Janssen was a poor representation of broken waves over a reef. Young [4] used a similar approach, but included a check to turn off wave breaking when the height to depth ratio was less than 0.78 to simulate wave reformation. Dally et al. [10] developed a wave breaking and reformation model, which has been extensively verified for plane beaches, composite beach slopes, and barred beach profiles. The model is based on the transformation of individual waves, but may be applied to a random wave field using a statistical approach. Hardy et al. [11] developed a wind wave generation model especially for use in complex geometry of the Great Barrier Reef.

The present study is focused on a new trial to simulate the wave characteristics over coral reef. The numerical model of Perlin and Dean [12], that was originally initiated for sand beaches, is modified by using the similar procedure of Dally et al. [10]. The energy dissipation due to breaking and bottom friction are included in the energy balance equation which governs wave propagation. The field wave measurements at Ala Moana Beach on the southern shore of the island of Oahu, Hawaii, U.S.A. is used to calibrate the model. Two parameters are added to the new model, which are the friction coefficient and the breaking coefficient to increase the model competence. The new model is applied in a typical case of the Red Sea coastal area - Red Sea Aquarium, Hurghada, Egypt - to identify the effects and the range of the introduced two parameters.

2. Description of the modified model for wave transformation

The wave module of Perlin and Dean (1983) model is modified to adapt the case of coral reef beaches. The methodology described here includes the processes of wave shoaling, refraction, depth-limited breaking, and bottom friction. The assumptions include linear wave theory, Rayleigh wave height distribution in offshore, and longshore homogeneity. The method neglects energy shifts within the wave spectrum and wave-current interaction. Although it may seem that wave reflection off a nearly vertical reef would be significant, field data have shown reflected wave height to be on the order of only 10% of the incident height due to the porosity of the reef and can be neglected, Young [4]. The governing equations of the numerical model are summarized as follows:

2.1 . Wave angle

The wave conservation equation:

$$\frac{d\sigma}{dt} + \overrightarrow{\nabla_H} * \overrightarrow{K} = 0 , \qquad (1)$$

where $\overrightarrow{\nabla_H}$ is the horizontal differential operator, t is the time, $\vec{K}$ is the wave number, and σ is the angular frequency.

$$\vec{\nabla} = \vec{i}\frac{\partial}{\partial x} + \vec{j}\frac{\partial}{\partial y} , \qquad (2)$$

where $\vec{i}$ and $\vec{j}$ are the unit vectors in the x and y directions, x is the longshore direction, and y the offshore direction. Fig. 2 shows the definition sketch.

$$\vec{K} = \vec{i} * K_x + \vec{j} * K_y . \qquad (3)$$

For the steady - state case, eq. (1) yields:

$$\frac{\partial}{\partial x}K_y - \frac{\partial}{\partial y}K_x = 0. \qquad (4)$$

Where K_x and K_y are the wave number in the x and y directions, respectively.
The equation can be written in final form as:

$$\frac{\partial}{\partial x}K \cos\theta - \frac{\partial}{\partial y}K \sin\theta = 0. \qquad (5)$$

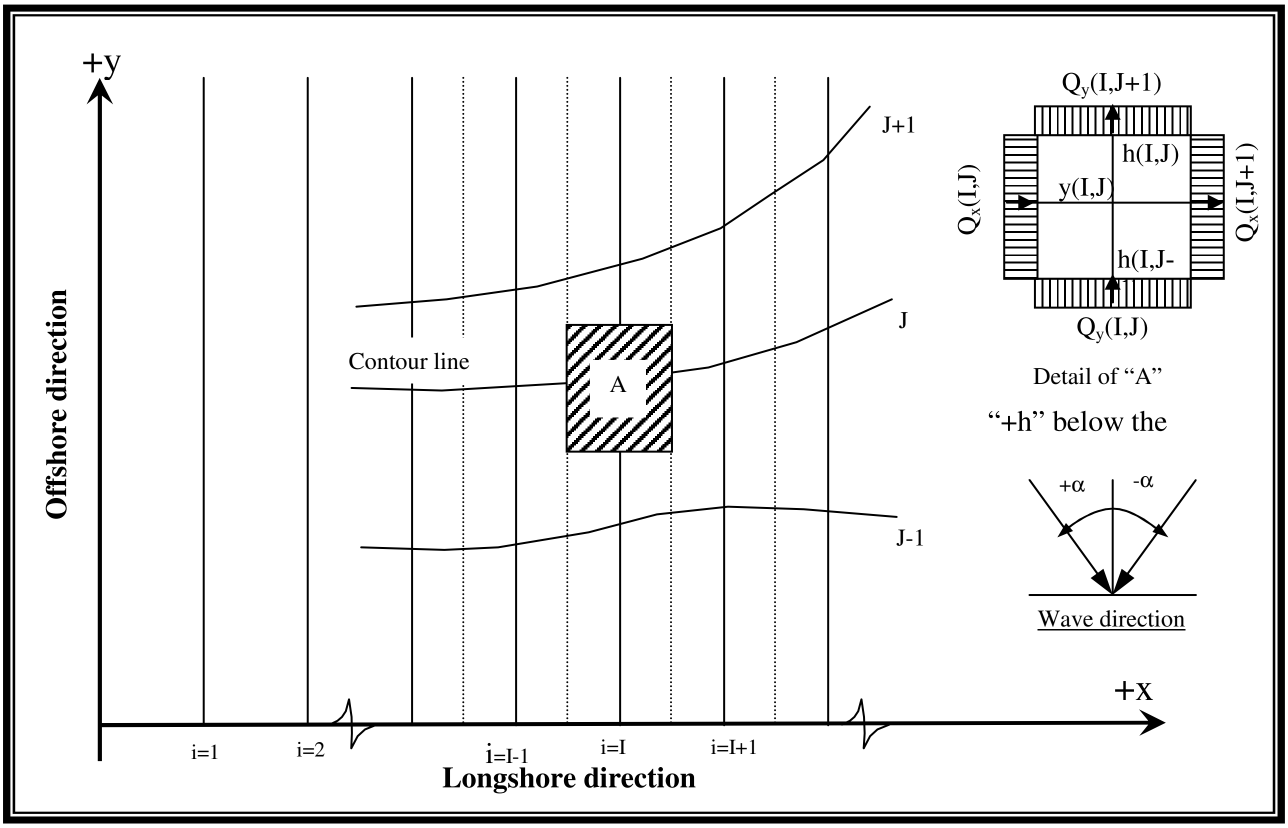

Fig. 2. Definition sketch for the numerical model of Perlin and Dean 1983.

Where θ is the wave angle.

The numerical solution made by Noda [13] is used to solve eq. (5). This equation was initiated with Snell's law to specify the boundary conditions on the offshore boundary and on the wave angle approach side. Numerical smoothing is used at the conclusion of the wave field calculation to simulate the lateral transfer of wave energy along the wave.

3.2. Wave height

There are two methods used to define the wave height decays inside the surf zone. The first method depends on solving the energy balance equation, Hwang and Divoky [14]; however, the second method assume a shelf-similarity in the surf zone, such that the wave height decays in constant proportion to the local depth, Battjes [15]. The first approach is preferable for a number of reasons:

1. It has a sound physical basis.
2. It depends not only on the local depth but also on that further seaward.
3. It includes all kinds of dissipation mechanism.
4. It can be applied in bar-trough or coral reef profiles.

The governing equation for wave height calculations is the conservation of energy equation. This equation can be expressed as:

$$\vec{\nabla}(E\,\overrightarrow{C_G}) = D_1 + D_2\,, \qquad (6)$$

where E is the average energy per unit surface area, $\overrightarrow{C_G}$ is the group velocity, D_1 is the energy dissipation due to wave breaking, and D_2 is the energy dissipation due to bottom friction. Eq. (6) can be written in final form as:

$$\frac{\partial}{\partial x}\left(\frac{\ell g H^2}{8} C_G\, Sin\theta\right) + \frac{\partial}{\partial y}\left(\frac{\ell g H^2}{8} C_G\, Cos\theta\right)$$

$$= D_1 + D_2 , \quad (7)$$

where ℓ is the mass density of water, g the gravitational constant, H the wave height, and θ the wave angle. C_G is determined by the linear wave theory:

$$C_G = \frac{C}{2}\left(1 + \frac{2Kh}{Sinh(2Kh)}\right) . \quad (8)$$

In which h is the water depth and C is the wave celerity.

The energy losses mentioned in eq. (7) can be calculated as follows.

3.2. Energy losses due to breaking waves

The problem of energy dissipation in breaking waves is highly complex and so far no completely satisfactory solution has been proposed.

There is no systematic quantitative knowledge of the internal structure of breaking waves, so the energy dissipation rate here will be estimated from that in a bore of corresponding height, Le Mehaute [16].

Consider a bore connecting two regions of uniform flow, with depths Y_1 and Y_2, respectively fig. 3-a. The macroscopic bore properties are determined by the conservation of mass and momentum across the bore. The power dissipated in the bore per unit span, written as, $D^{/}$, can then be calculated:

$$D^{/} = \frac{1}{4}\rho g(Y_2 - Y_1)^3 \left(\frac{g(Y_1 + Y_2)}{2Y_1Y_2}\right)^{\frac{1}{2}} . \quad (9)$$

For the case of sloping beach, the flow condition on either side of the bore is non-uniform. Thus eq. (9) can not be expected to apply in any exact sense. The modification of eq. (9) to adapt with the actual condition is summarized as follows, fig. 3-b, Battjes and Janssen [9]:

$$Y_2 - Y_1 \cong H, \quad (10)$$

$$\left(\frac{g(Y_2 + Y_1)}{2Y_1Y_2}\right)^{\frac{1}{2}} \cong \left(\frac{g}{h}\right)^{\frac{1}{2}}, \quad (11)$$

where H is wave height, and h is the mean water depth.

Substitution of eqs. (10), (11) in eq. (9) yields:

$$D^{/} \cong \frac{1}{4}\rho g H^3 \left(\frac{g}{h}\right)^{\frac{1}{2}} . \quad (12)$$

If the waves were periodic with frequency f, then the average power dissipated in the breaking process, per unit area D_1, would be,

$$D_1 = \frac{D^{/}}{L} = \frac{fD^{/}}{C} \cong \frac{fD^{/}}{(gh)^{\frac{1}{2}}} \cong \frac{1}{4} f\rho g \frac{H^3}{h} . \quad (13)$$

where L and C denote wavelength and wave celerity, respectively.

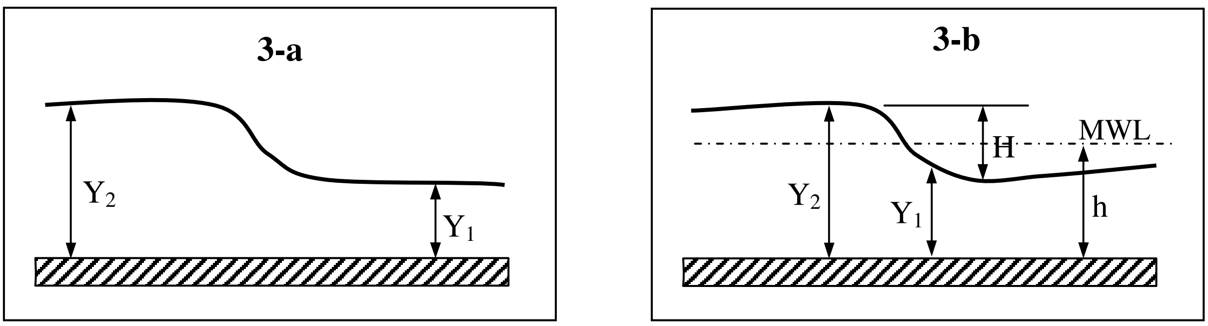

Fig. 3. Sketch of single, steady bore (3-a) and of one out of a sequence of broken waves on a beach (3-b), after Battjes and Janssen [9].

For the random waves, a simplified method which is based on the mean energy of the wave spectrum, appears to give adequate results for engineering purposes, Gerritsen [8]. This method is based on the attenuation of the root mean square wave height and does not take into account energy shifts between frequency components. We used the mean frequency $\overline{f}$ of the energy spectrum instead of f, maximum limited wave height H_m, and a probability of occurrence equal to Q_b. The final form of the mean dissipation power per unit area is:

$$D_1 = \frac{C_b}{4} Q_b \overline{f} \rho g \delta^3 h^2. \tag{14}$$

Where:
C_b is a constant,
δ is the breaking index, and
Q_b is the probability of occurrence of breaking wave at a fixed point, where:

$$\frac{1 - Q_b}{ln(Q_b)} = -(\frac{H_{rms}}{H_m})^2, \tag{15}$$

where:
H_m is the maximum possible wave height at any point, and
H_{rms} is the root mean square wave height, Q_b taken one in this model.

3.2.2. Energy losses due to bottom friction

There are extensive information about the bottom friction in low amplitude, and harmonic waves, (Thornton and Guza [17] Gerritsen [8] and Riedel et al. [18]). The concepts introduced by these authors have been extended to waves under shoaling and breaking conditions, whereby the assumption was made that even under breaking waves the orbital velocities near the bottom retain oscillatory characteristics.

It can be shown that both the nonlinearity of the waves and turbulence induced by breaking will affect the numerical value of the bottom friction coefficient, if the latter is based on a linear wave formulation, Gerritsen [8].

The wave energy dissipation per unit volume due to bottom friction, D_2, is:

$$D_2 = \frac{1}{h} \rho C_f \overline{/U_b/U_b^2} \ , \tag{16}$$

Where:
C_f is a bottom friction coefficient, and
U_b is the bottom water particle velocity and overbar indicates a time average.

For linear waves, eq. (16) can be reduced to:

$$D_2 = \frac{1}{6\pi} \frac{\rho}{h} C_f (\frac{2H\pi}{T\, sinh(Kh)})^3. \tag{17}$$

where, K is the wave number.

Gerritsen [8] suggested values of C_f = .05 to .25 for prototype conditions of coral reef. It indicates that the role of friction in energy dissipation in the breaking zone is of considerable significance.

The finite difference form of eq. (7) can be easily solved by iterative techniques with wave height boundary conditions along the same boundaries as the wave angles using linear theory shoaling and refraction coefficients. Waves are estimated on the basis of a wave height distribution with an upper cut-off, which in shallow water is determined mainly by the local depth. The local wave heights are limited by the value of 0.78 of the water depth or the ratio between each two adjacent depths, which is less.

Fig. 4 shows the flow chart of the model.

4. Model calibration

Field measurements of water level versus time were made in the ocean at seven points, fig. 5 along a 500m long transect at the Ala Moana Beach on the southern shore of the island of Oahu (21°17′ N,157°52′ W) in Hawaii from July through September 1976.

Five capacitance type probes were supported on tripods in shallow water on the reef in depths from 0.3 to 1.0m. Another capacitance probe was mounted on a tower in 10m of water. A floating buoy was moored on the outer edge of the reef (1.8-2.4m depth) and data was recorded by filming the motion of the buoy.

The above field data was used to calibrate the model. The available case is H_{rms}= 0.3 m

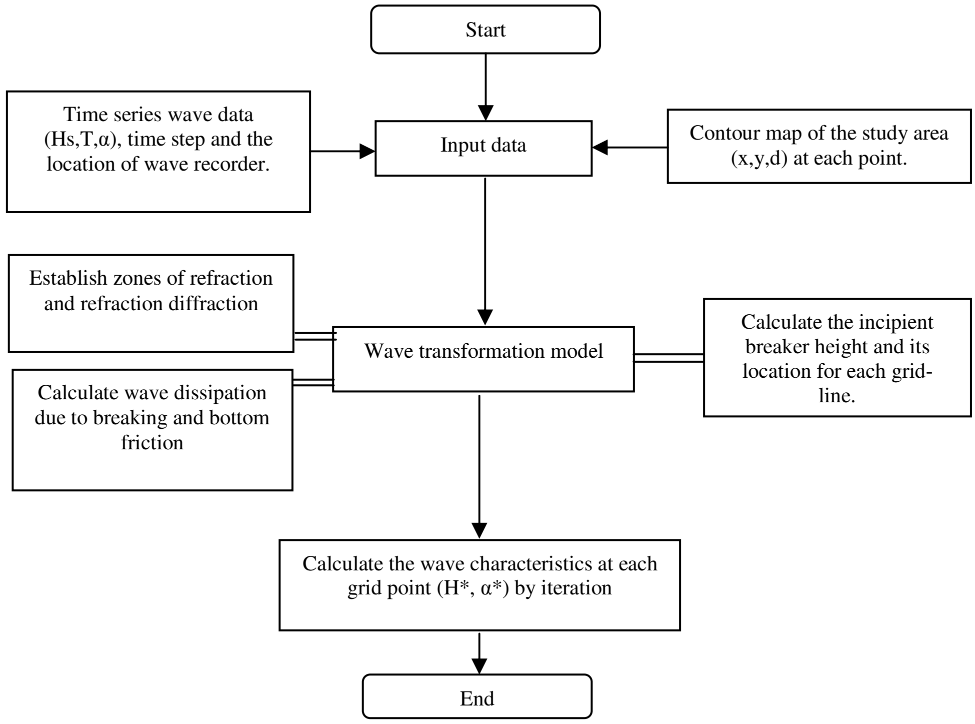

Fig. 4. Flow chart for the numerical model to simulate wave transformation across coral reef.

with T= 4.0sec at water depth 10m "station 7". The bottom friction coefficient used in the model was 0.05 and the wave breaking index was 0.78 which is identical to those applied in the Gerritsen model, Gerritsen [8]. Fig. 6 shows the results of the modified model. The comparison between the result of the modified model and each of the field measurement, Gerritsen model and the original Perlin and Dean model are shown in the same figure. The results show satisfied agreement among the data from observation, the new model data, and Gerritsen model with error of ±5.0% except for very shallow water " depth < 0.40m" where the error increase to ± 30%. Part of this error may be attributed to difficulties concerning the accurate wave height measurements in shallow water. The result of original Perlin and Dean model is far from the actual field data measurements and the error reach 86% in some points with absolute average error of 50%. Changing the calibration parameter of the breaking dissipation equation C_b can modify the model results. Figs. 7-a, 7-b show the effect of the calibration parameter C_b on wave height transformations. The results show that changing C_b from 1.0 to 1.075 decreases the absolute average error from about 12% to about 10% only.

5. Sensitivity analysis

To increase the flexibility of the model and to cover the point of the nonlinearity behavior of impinging wave, two empirical coefficients are used as calibration parameters. The first coefficient C_b is added to the energy loss equation due to breaking wave. The second coefficient is the bottom friction coefficient C_f. To check the effect of these two coefficient on wave height and the range of each parameter, data of Red Sea Aquarium, Hurghada, Egypt is used, which is a typical case of the red sea coastal area.

6. Site description

The study area is situated at the waterfront of Hurghada City, Egypt "Latitude 27^o 17$^/$, longitude 33^o 48$^/$". It is located at about 10km east of Hurghada Airport, fig. 8. The nearshore profile is simply composed of coastal plain, reef flat, reef crest, reef edge, and reef slope. The tidal flat area is occasionally exposed during low tide and partially submerged at high tide "maximum tidal range 1.0m". The reef flat zone varies in width and extends up to 270m offshore. This is followed by the reef slop, sloping 1:20.

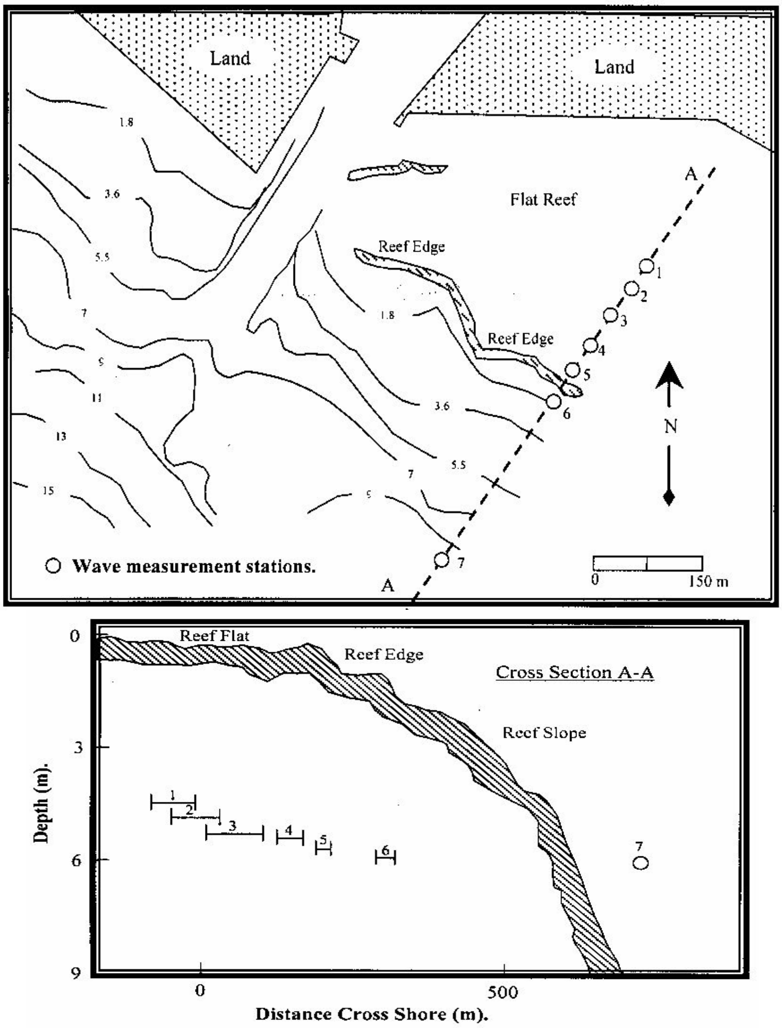

Fig. 5. Offshore bathymetry and measurement stations at Ala Moana Reef, Honolulu, After Gerritsen [8].

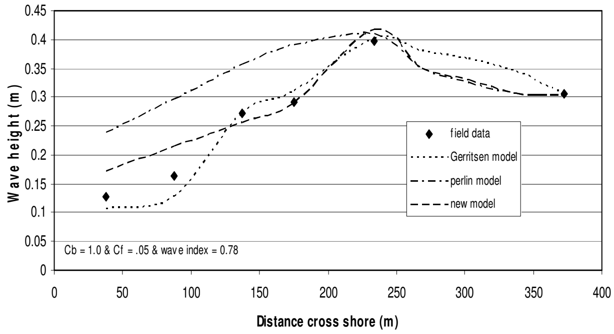

Fig. 6. Wave heights attenuation cross the coral reef from measured and models.

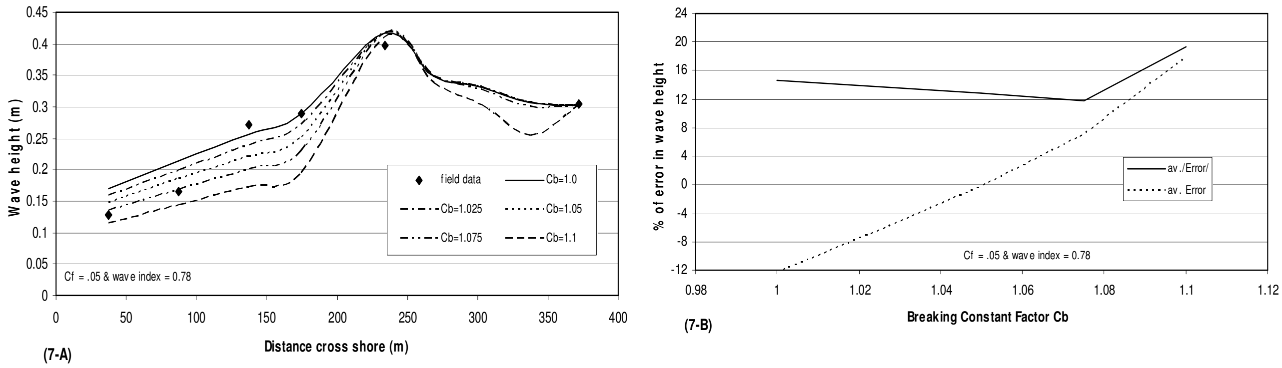

Fig. 7. The effect of the calibration parameters Cb on wave heights distribution.

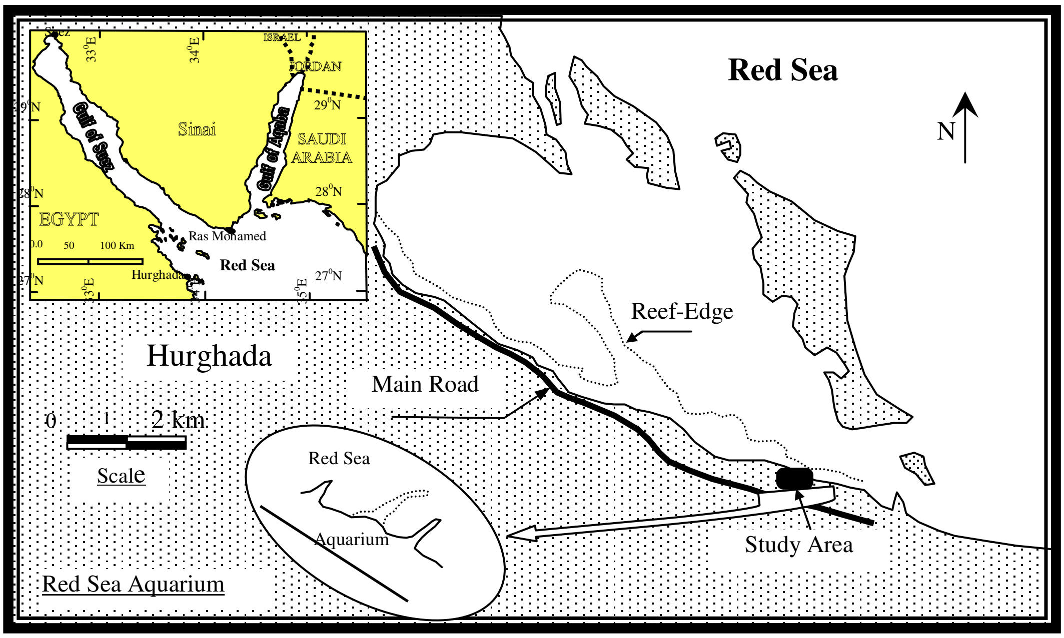

Fig. 8. General location of the red sea aquarium, Hurghada, Egypt.

A marine survey up to reef slope was undertaken on 30 September 1999. The an area of 300m along shore and 300m cross-shore. The average wind speed in the study survey covers area varies from about 7 km/h in June to about 20km/h in February with east to southeast predominant wind direction. The offshore wave characteristics have been evaluated theoretically from the available wind data. Computed average wave height and predominant period are 0.8m and 3.0sec, respectively. Results of wave hind-cast at extreme conditions were shown in table 1.

Table 1
Wave characteristics at extreme condition hind-caste from wind data recorded at Hurghada

Direction / Wave characteristics	NE	E	SE
Height H_{rms} "m"	.95	1.13	.95
Period "sec"	3.9	4.25	3.9
Length "m"	24	28	24

6. Results

The case study chooses is the extreme condition with wave height H_{rms}= 1.13m, wave period 4.25 sec, and in the case of high tide. Fig. 9 shows the wave distribution along the study area using the new model. The effect of the breaking coefficient and the friction coefficient are shown in figs. 10 and 11 respectively. The result shows that the wave height decreases with increasing the breaking coefficient inside the surf zone and the opposite condition happened outside the surf zone. The wave height decreases with increasing the friction coefficient outside the surf zone and increases with increasing the friction coefficient inside the surf zone. The instability of the model happened when the breaking coefficient ≤ 0.60. However, the friction coefficient of order ≥ 0.10 gives the same result as Perlin and Dean model.

7. Conclusions and recommendation

From the presented work the following conclusions are summarized:

1. The new modification introduced by the authors for Perlin and Dean 1983 model which took into consideration the energy dissipation due to wave breaking and bottom friction with wave height limitation to 0.78 from the average water depth succeeded in simulating the wave transformations across the coral reefs.

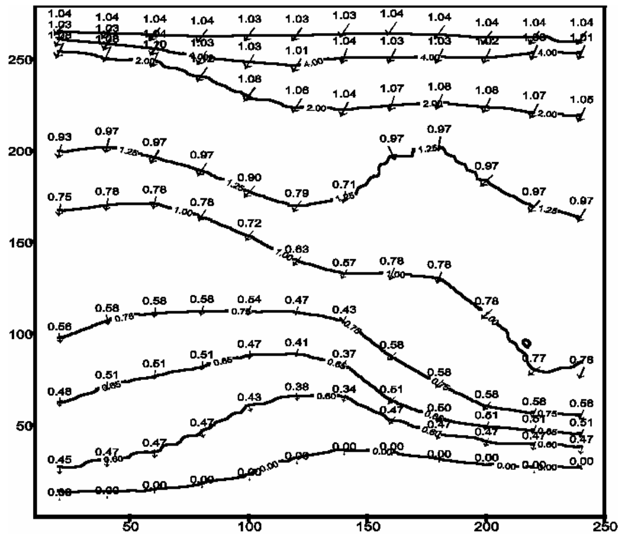

Fig. 9. Wave distribution due to a single wave in deep water with: H_{rms} = 1.13m, T= 4.25 sec, local direction = -35 degree, C_f= .05, and C_b = 1.0 at Red Sea Aquarium, Hurghada, Egypt.

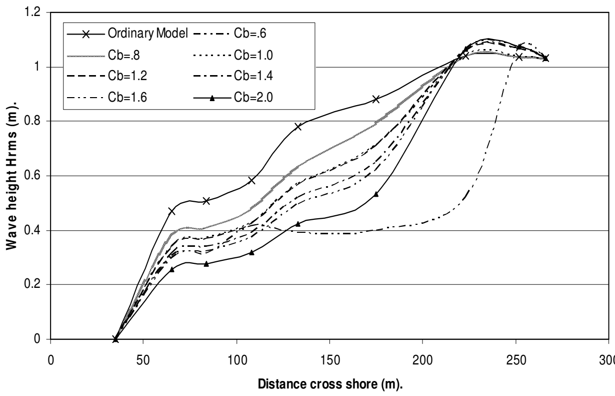

Fig. 10. The effect of the breaking parameter C_b on the distribution of wave height cross-shore at Red Sea Aquarium, Hurghada, Egypt.

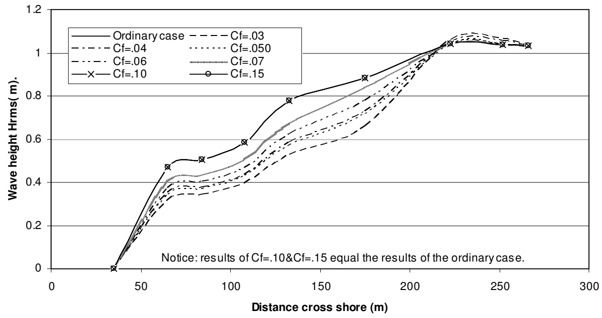

Fig. 11. The effect of the friction parameter C_f on the distribution of wave height cross-shore at Red Sea Aquarium, Hurghada, Egypt.

2. The two calibration parameters of wave breaking and bottom friction increase the accuracy of the model.
3. The new model is suitable to be used across the coral reef coastal area with absolute average error of about 10%; while, the Perlin and Dean 1983 model gives an absolute average error of 50%.
4. The wave height decreases with increasing of the friction coefficient outside the surf zone and increases with increasing of the friction coefficient inside the surf zone; however, the breaking coefficient has the opposite effect.
5. Using the wind data to predict the wave characteristics and applying the ordinary models to identify the wave transformation across coral reefs gives over estimated wave condition, which is not economically acceptable for design of any coastal structure.

6. A program of wave measurements is highly recommended to make the sustainable development along the Red Sea more efficiency.

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