Wave Dynamics and Revetment Design on a Natural Reef

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Abstract

In connection with hydraulic studies of a new coastal resort development on the south-east coast of Bali in Indonesia, a three-dimensional (3D) physical model study was carried out. The study was aimed at the determination of the wave transformation over a shallow natural reef in front of the resort and for the design of the rubble mound revetments to be built for coastal protection. Due to the heavy wave breaking on the reef, physical model tests were the only viable avenue for obtaining a reliable design of the revetment structures located behind the shallow reef area. The stability of the armour layer as well as the overtopping of the revetments were equally important aspects of this part of the study, since not only should the resort be protected against storm waves, but visitors should also be able to comfortably visit the coastal areas during more normal wave conditions.

This paper mainly concerns the wave dynamics on the reef. Due to the limited water depth the wave conditions were dominated by heavy wave breaking and the associated release of the bound long-period wave components in the wave groups of the incident wave train. These long-period wave components caused a dynamic water level set-up with long-period variations in front of the revetments (surf beats). The depth-limited wave conditions on the reef and the dynamic water level set-up had major influence on the evolution of damage and overtopping of the revetments and made the design of the revetments particularly complex.

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Introduction

Bali Turtle Island Development Project is a major tourism-related coastal development project located on the south-east coast of Bali, Indonesia. The site location is shown in Figure 1. The project involves around 3.7 km^2 of land reclamation constructed on an existing reef facing the Lombok Strait, which connects to the Indian Ocean. The completed reclamation will include three artificial lagoons, four artificial pocket beaches, six artificial headlands and a causeway/bridge connection to the Balinese mainland. Figure 2 shows the existing and the reclaimed Turtle Island and Figure 3 shows an aerial photo of the land reclamation in progress.

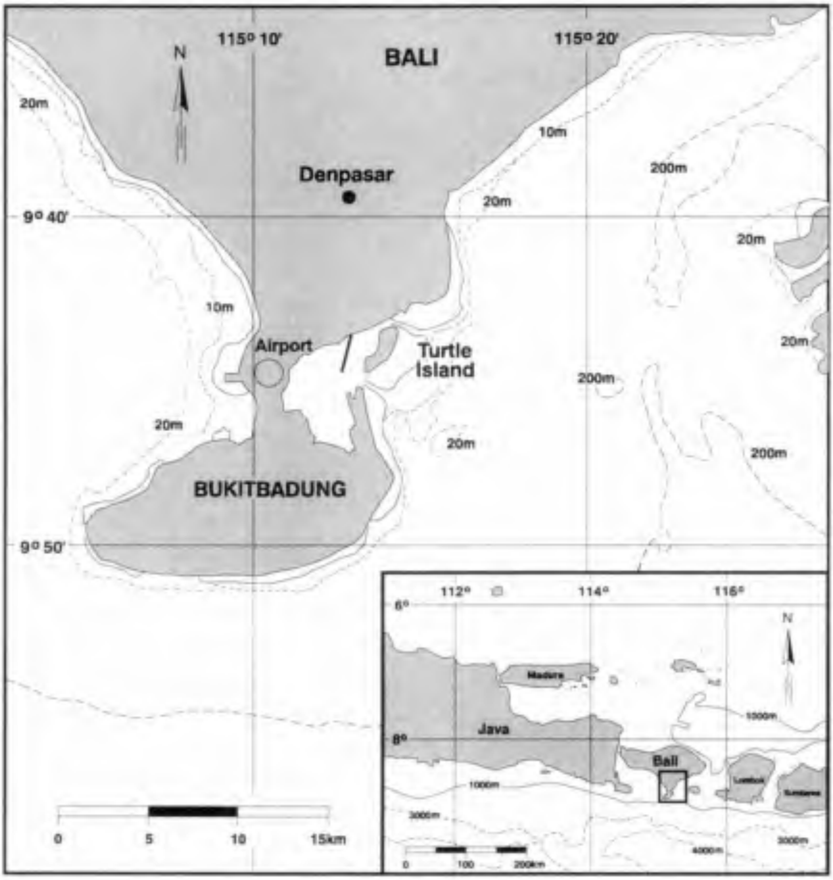

Figure 1. Site location.

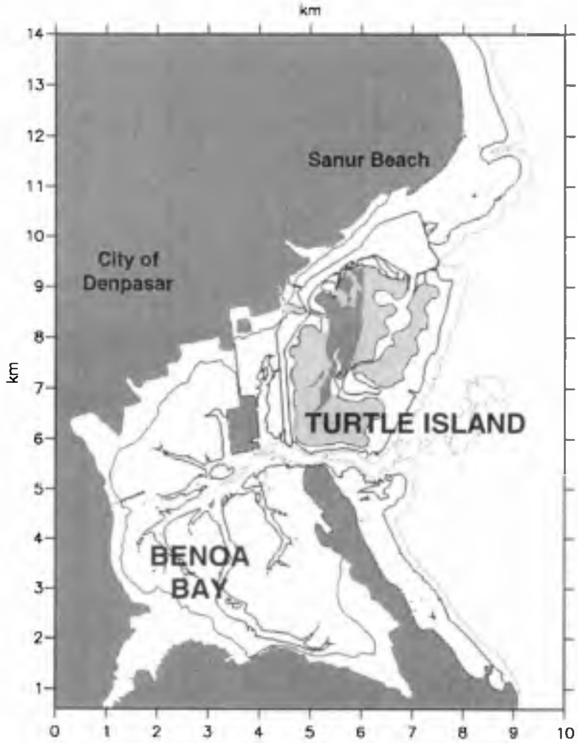

Figure 2. The existing and the reclaimed (light shaded) Turtle Island.

Figure 3. Aerial photo of the reclamation works in progress.

To aid the contractor, Penta Ocean Construction Company, in the detailed design works for Bali Turtle Island Development, hydraulic investigations were carried out by Danish Hydraulic Institute (DHI). Thc overall project involved the following aspects:

- Determination of environmental design conditions (waves, water levels, etc)
- Hydraulic design of the primary revetment protection using physical modelling
- Assessment of impact upon navigation
- Spreading of dredged material
- Water quality impact assessment
- Coastal impact assessment (beach stability and sediment morphology)
- Environmental monitoring during dredging.

This paper concerns the physical modelling used for design and optimisation of the revetments and for studying the wave transformation over the reef in front of the extended Turtle Island. An overview of the development project as a whole and detailed information on the other aspects of the project are given in the accompanying ICCE '98 paper by Driscoll et al (1998) as well as in Driscoll et al (1997) and Sloth et al (1997).

Physical Modelling

Onc of the challenges faced in the project was the design of the revetments used as coastal protection of the headlands. Due to the heavy wave breaking and complex wave dynamics on the reef in front of the revetments, the design procedure was far from trivial. Physical model tests were the only viable avenue for obtaining a reliable design of the revetment structures located behind the shallow reef area. The physical model tests comprised the following two tasks:

- Wave transformation tests
- Revetment stability and overtopping tests

In addition to predicting the necessary information on the wave conditions on the reef for revetment design, the results of the wave transformation tests were used to calibrate numerical models used for the prediction of eg beach stability (see Driscoll et al, 1998).

The purpose of the revetment stability and overtopping tests was to optimise the design of the revetments to be built as coastal protection of the headlands on the extended Turtle Island. This optimisation involved the determination of the required size of stones for the revetment armour as well as the determination of the optimum crest height of the revetments to obtain both an aesthetic design and acceptable levels of overtopping discharge. Not only should the resort be protected against storm waves, but visitors should also be able to admire the scenery at sea and comfortably visit the area during more normal wave conditions. Therefore, both stability and overtopping were equally important aspects of the investigations in the physical model.

The model was constructed in scale 1:40 in one of DHI's wave basins, and covered a prototype area of approximately 1200 m by 1200 m. The extent of the physical model is shown in Figure 4. Based on detailed local surveys, the reef was modelled to detail out to a water depth of 13 m relative to Port Datum (PD~LAT) corresponding to 14.3 m relative to mean sea level (MSL). Figure 5 shows a sketched cross-section of the reef, and Figure 6 shows the overall layout of the physical model.

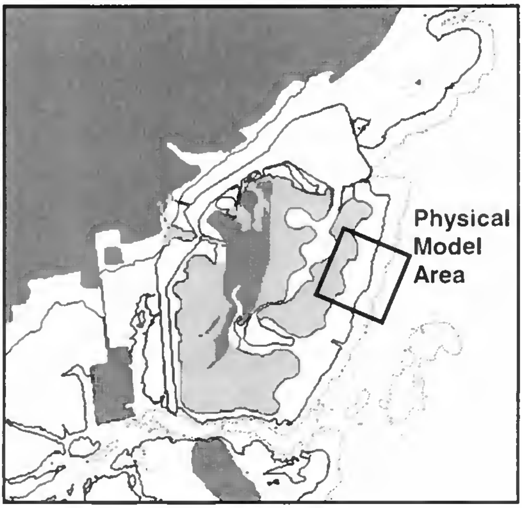

Figure 4. Extent of physical model area.

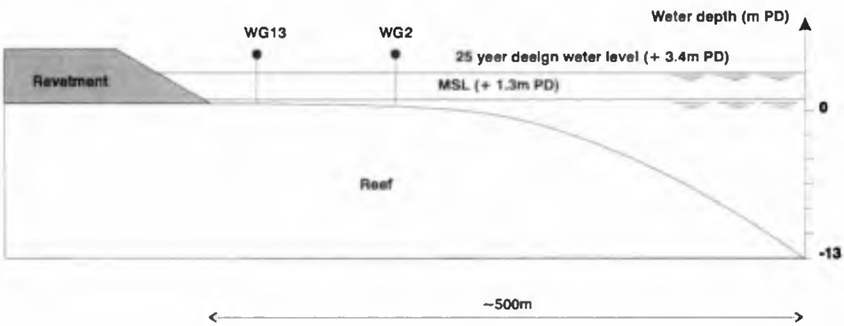

Figure 5. Sketch of a typical cross-section of the reef (distorted length scale).

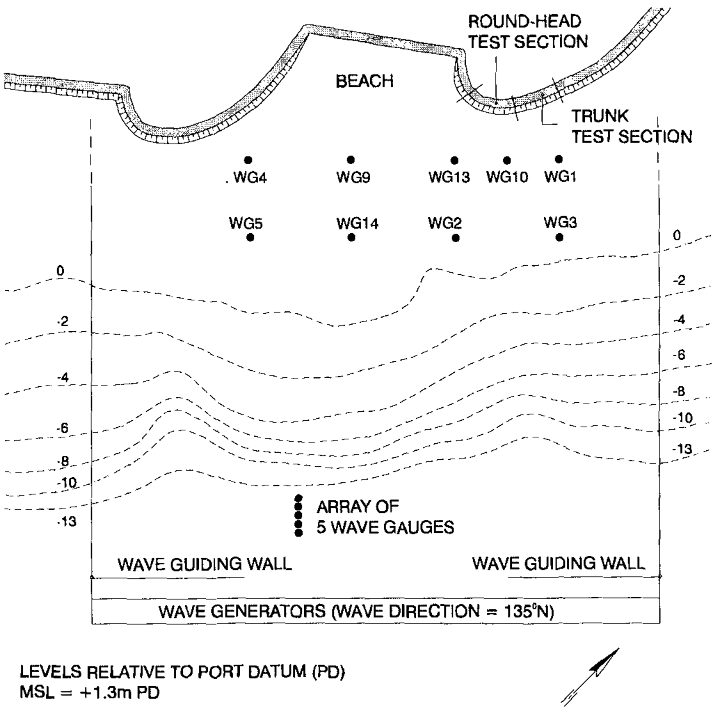

Figure 6. Layout of physical model.

All model tests were carried out with long-crested, irregular waves (Pierson-Moskowitz spectra) with significant wave heights (H_{m0}) ranging from $H_{m0} \approx 1$ m to $H_{m0} \approx 5$ m and peak periods (T_p) of between $T_p \approx 8$ s and $T_p \approx 17$ s. Two different water levels were used in the tests, one corresponding to mean high water spring (+1.1 m MSL or approximately 1.5 m of water depth on the reef), and one corresponding to the 25-year design water level (+2.1 m MSL or approximately 2.5 m of water depth on the reef). Two different angles of wave incidence were investigated in the tests, 135°N (head-on waves) and 155°N (oblique waves). Only the results obtained with the 25-year design water level (+2.1 m MSL) and head-on waves (135°N) are addressed in this paper. The applied wave conditions at the boundary of the physical model were based on an extensive numerical model study of the nearshore wave climate, in which offshore wave conditions from the Indian Ocean were transformed into the area of interest. This aspect of the study is described further in Sloth et al (1997). The following extreme wave conditions were identified:

- 1-year condition: $H_{m0} = 3.0$ m, $T_p = 12.7$ s
- 10-year condition: $H_{m0} = 4.0$ m, $T_p = 12.7$ s
- 100-year condition: $H_{m0} = 4.5$ m, $T_p = 12.7$ s

During the tests, waves were measured at nine locations on the reef (see Figure 6). The incident waves were determined by reflection analysis using an array of five wave gauges in front of the reef. In the revetment stability and overtopping tests, the overtopping discharge and the stability of the revetment armour were monitored for a number of different revetment configurations (size of armour stone, crest height and crest width). A sketch of the general layout of the revetments test section is shown in Figure 7. Figure 8 shows a photo of the revetment test section.

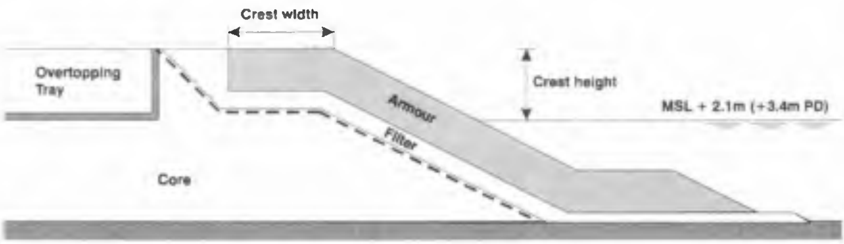

Figure 7. Cross-section of revetment test section.

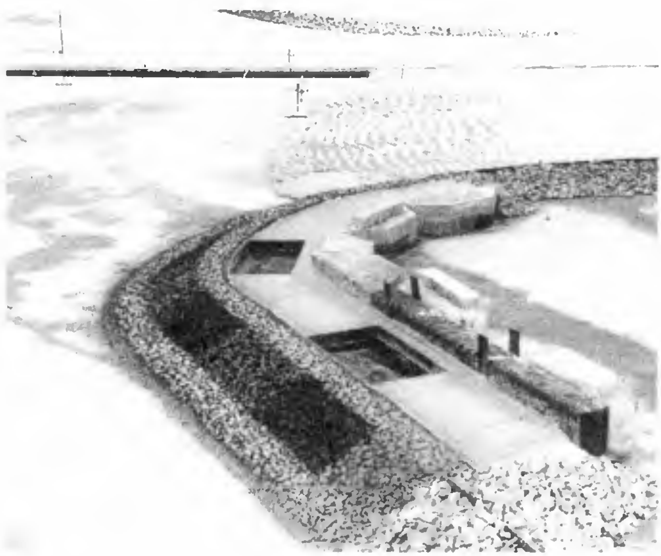

Figure 8. Photo of revetment test section.

Wave Dynamics on the reef

During severe wave conditions, a relatively large rise in the mean water level on the reef was observed. This stationary water level set-up increased with the incident significant wave height ($H_{m0,i}$) reaching approximately 0.4 m for the 25-year wave conditions.

In addition to this stationary water level set-up, a dynamic set-up was also observed on the reef. When the individual waves in a wave group break, the bound long waves associated with the wave groups are released on the reef as free long waves. These long waves cause a dynamic water level set-up or surf beat. Figure 8 shows wave spectra of surface elevations measured outside the reef (WG12) and on the reef (WG2) for four different incident wave conditions. The long-period waves on the reef are seen clearly in the spectra obtained at WG2 as substantial energy at frequencies below 0.05 Hz (periods (T) longer than 20 s).

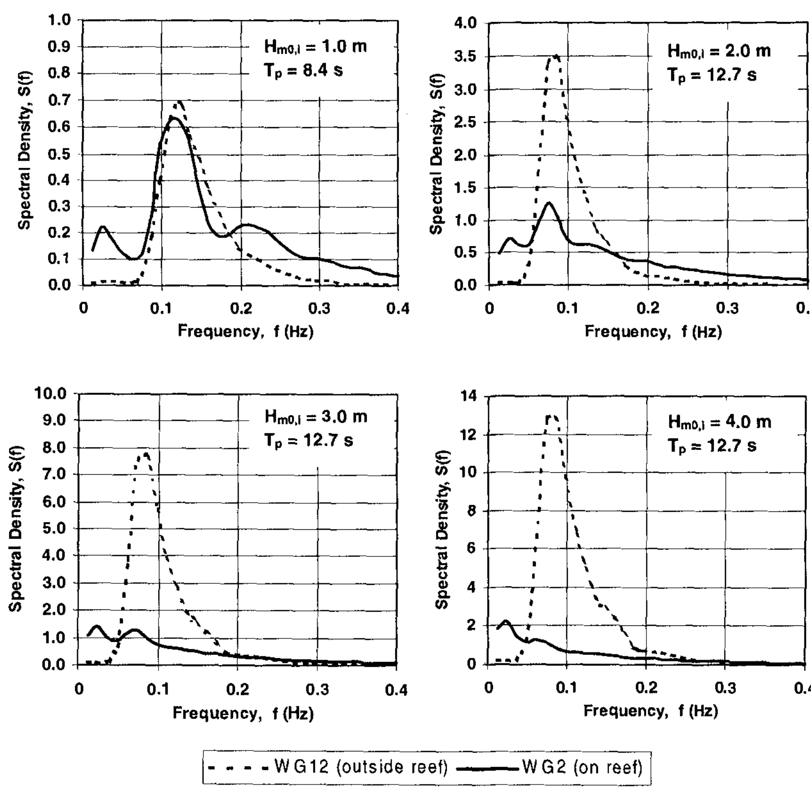

Figure 8. Measured wave spectra on the reef and outside the reef.

The dynamic water level set-up caused by the long-period waves on the reef is also seen in the time series in Figure 9, which shows the measured surface elevations at WG12 (outside the reef) and at WG2 (on the reef). For WG2 low-pass filtered and high-pass filtered signals (for T < 25 s and T > 25 s) are also shown. It is seen from Figure 9 that for this incident wave condition, the amplitude of the dynamic set-up is occasionally in the order of 1 m.

It should be noted that even though the model (as any other physical model) cannot be deemed totally free of model effects, the observed dynamic set-up was proven not to be significantly influenced by eg seiching of the laboratory basin or re-reflections from the wave paddle.

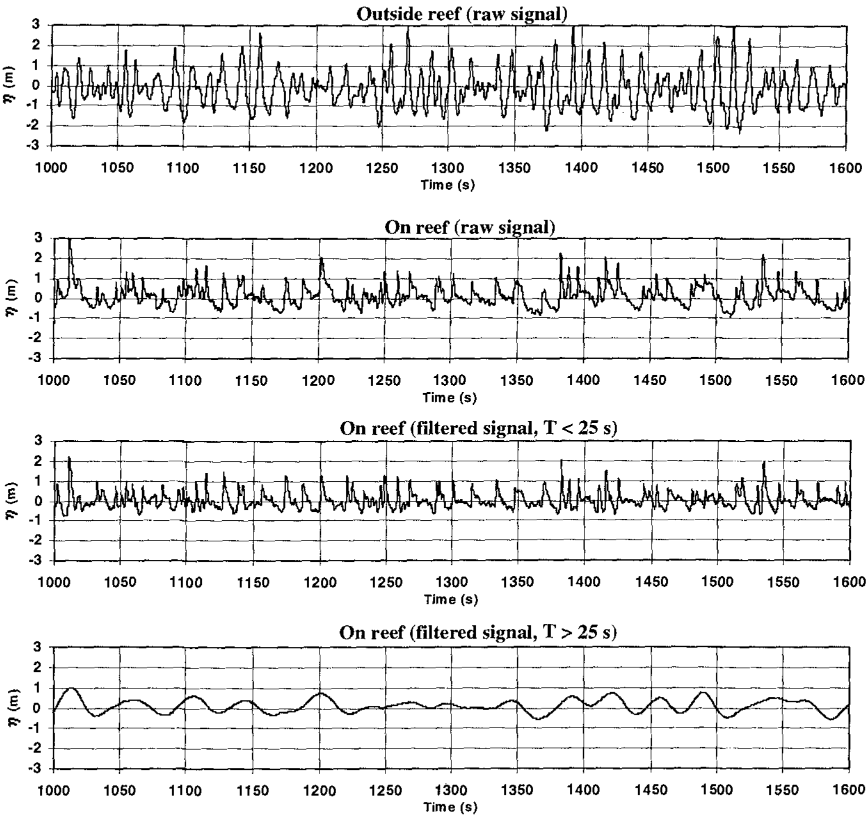

Figure 9. Time series of surface elevations on the reef ($H_{m0,i}$ = 4.0 m, T_p = 12.7 s).

Prototype wave measurements presented by Sulaiman et al (1994) for the reef off Sanur Beach just north of Turtle Island on the Balinese mainland (see Figure 2) also showed the presence of long-period wave components on the reef.

Since the long-period waves on the reef were generated by the wave breaking, the amount of long-period energy on the reef increased with the incident significant wave height ($H_{m0,i}$). This can be seen in Figure 10, which shows the standard deviation of the long-period wave components (T > 25 s) at WG13 on the reef as a function of $H_{m0,i}$. The standard deviation has been derived from time series low-pass filtered at 0.04 Hz.

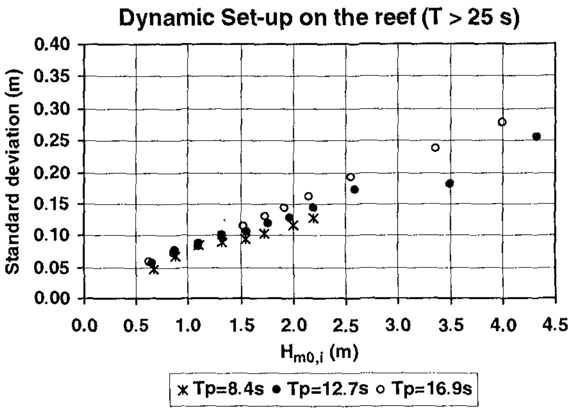

Figure 10. Standard deviation of the dynamic set-up on the reef versus $H_{m0,i}$.

So far only the long-period wave components (T > 25 s) have been addressed, but also the short-period wave components (T < 25 s) were analysed. The wave parameters presented in the following have been derived from time series where all energy with periods longer than 25 s has been removed by high-pass filtering. For the three different wave periods investigated in the wave transformation tests, Figure 11 shows wave parameters (H_{m0}, H_{max}, H_{mean} and T_z) at WG13 on the reef as a function of the incident significant wave height, $H_{m0,i}$.

H_{m0} is the spectral estimate of the significant wave height on the reef (calculated as four times the standard deviation of the surface elevation). The three parameters H_{max} (the maximum wave height), H_{mean} (the mean wave height) and T_z (the mean zero-crossing period) have been estimated from zero-crossing analysis of the high-pass filtered time series.

It should be noted that due to the altered wave height distribution on the reef, the presented H_{m0}-values on the reef do not necessarily correspond to $H_{1/3}$, which is often used to define the significant wave height as the average of the highest one-third of the waves in a sea state.

From Figure 11, it is seen that irrespective of the incident wave period, the mean zero-crossing period on the reef approaches a constant value of approximately 6 s. This general reduction in wave period is a consequence of the heavy wave breaking occurring over the reef. The changes in wave period and reduction of wave energy on the reef can also be seen from the recorded surface elevations and the wave spectra on the reef (Figures 9 and 8, respectively). The wave spectra on the reef cover a wider range of frequencies than the incident spectrum. The field measurements at Sanur Beach by Sulaiman et al (1994) also showed broader wave spectra and reduction in wave period on the reef.

Figure 11 also shows that the incident wave periods have minor influence on the wave heights on the reef. The effect of depth-limited waves is clearly illustrated, since the maximum wave height on the reef is reached for an incident significant wave height of approximately $H_{m0,i}$ =2 m, corresponding to less than the 1-year wave condition outside the reef.

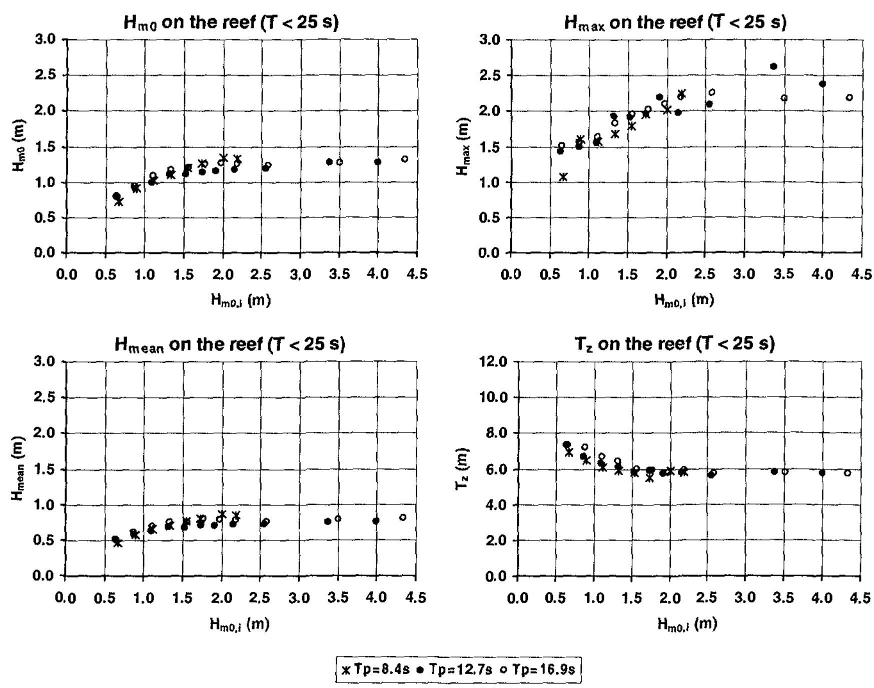

Figure 11. Wave conditions at WG13 on the reef (short-period wave components).

Consequences of Wave Dynamics on Revetment Design

The following two phenomena induced by the shallow reef were particularly crucial with respect to design and optimisation of the revetment structures:

- The depth-limited wave condition
- The dynamic water level set-up

Depth Limited Waves – Size of Revetment Armour Stones:

The maximum wave condition on the reef was reached for a significant wave height outside the reef of approximately $H_{m0} = 2$ m, which is substantially lower than the 1-year wave condition outside the reef.

As a consequence of this depth-limited wave condition on the reef, the more frequent wave conditions will impose almost the same wave impacts on the structure as rare events such as the 25-year design condition. This means that the damage induced by the 25-year condition outside the reef will also be induced by a 'normal' wave condition with a return period of less than one year. Since the damage to the revetment armour is cumulative, it was of paramount importance to weigh the consequences of the depth-limited waves into the considerations of an appropriate design criterion for the damage to the revetment armour. Furthermore, the depth-limited wave conditions eliminated any use of empirical formulae for predicting the necessary size of the armour stones to be used on the revetments.

Basically, the depth-limited wave conditions cause the design waves for the structure to occur more often, and as a consequence of this, the probability of failure of the structure within a given lifetime increases. Therefore, a 'no damage' criterion was adopted for the design of the revetment armour. This means that no progressive damage to the revetment armour should occur for the maximum wave condition on the reef. This 'no damage' design criterion led to the recommendation of revetment armour stones somewhat larger than expected.

Dynamic Set-up – Revetment Crest Dimensions:

With the highest amplitudes of the dynamic set-up (surf beat) exceeding 1 m for the most severe wave conditions, it is evident that the long wave energy on the reef was a crucial parameter as regards the overtopping on the revetments. Any use of existing empirical formulae for predicting the consequences of a given revetment profile with respect to overtopping was eliminated due to these special conditions.

Basically, the dynamic set-up on the reef results in increased water level in front of the structure, and thereby a lower revetment free board. Hence, the overtopping is increased dramatically. The results of the model tests led to the recommendation of a revised crest height and crest width of the revetments to meet the requirements of acceptable overtopping.

The effect of long waves on the design of coastal structures has previously been addressed by eg Kamphuis (1996) and Kamphuis (1998), the latter also presented at ICCE '98. Kamphuis argues that the presence of long waves and the resulting increase of water level in front of a structure cause an increase of the design wave height for a structure in shallow water. Essentially, this means that in areas with more typical slopes towards the coastline the design wave height in shallow water is not only a function of the water depth at the toe of the structure but also a function of the long wave activity. However, this is not seen from the results of the present model study (see Figures 10 and 11) because of the relatively wide and shallow reef.

Conclusions

In connection with hydraulic studies of the Bali Turtle Island Development Project, 3D physical modelling was carried out for determination of the wave transformation over the shallow reef in front of the new resort and for the design of the rubble mound revetments to be built for coastal protection.

In the design of the revetments, stability of the armour layer as well as overtopping of the revetments were equally important aspects, since not only should the resort be protected against storm waves, but the aesthetic value of the design should also be taken into account.

The physical model study showed that the maximum wave height on the reef was limited by the water depth on the reef and that this wave height corresponded to less than a 1-year wave condition outside the reef. This depth-limitation eliminated the use of any empirical formulae for predicting the necessary size of the stones for the revetment armour, and made the implementation of a 'no damage' design criterion essential.

The presence of significant amounts of long wave activity (dynamic set-up) was identified on the reef as a consequence of the heavy wave breaking and the associated release of bound long waves into free waves. This dynamic set-up caused a significant increase of the overtopping on the revetments and prevented the use of existing empirical formulae for overtopping prediction.

The present case study is a perfect example of a study in which the use of physical modelling as a design tool was essential in order to develop a sound and viable solution to a problem which offhand may seem rather simple to the design engineer.

The study also illustrates how important non-linear wave phenomena such as bound long waves released by wave breaking can be for the design of a coastal structure. For many years the importance of these non-linear wave phenomena on for example movements of floating bodies and seiching in harbours has been recognised, but their effect on the design of coastal structures such as rubble mound revetments and breakwaters in shallow water has to some extent been neglected. The present study clearly shows that when designing coastal structures in shallow water, the effect of long waves should be taken into account.

Acknowledgement

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