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Judith Bosboom

Wind-Wave Induced Oscillatory Velocities Predicted by Boussinesq Models

Judith Bosboom

Ms Bosboom graduated in 1995 from Delft University of Technology in Civil Engineering (MSc Honours). She is presently employed at WL | Delft Hydraulics and associated with the Netherlands Centre for Coastal Research (NCK), Department of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands.

Abstract

Sediment transport predictions are critically dependent on the prediction of near-bed wave-induced velocities. Especially the asymmetry between the forward (onshore) and backward (offshore) velocities plays an important role in determining the magnitude and direction of the wave-induced sediment transport.

Boussinesq wave models are amongst the most advanced wave models presently available to the coastal engineer. Moreover, they are highly efficient from a computational point of view. They are generally applied for wave propagation studies in which the focus is on the prediction of surface elevations.
The knowledge about the capability of these models to predict the horizontal velocities under waves is limited.

This work aims to explore the possibilities of using such a Boussinesq model for the prediction of the near-bed velocities. A spectral Boussinesq model is used in which wave breaking and dissipation in the surf zone are included. The model is tested against measurements of irregular (partially) breaking waves performed in WL | Delft Hydraulics' Delta flume.

The comparison of measured and computed velocity asymmetry indicates that for moderately long waves the Boussinesq model can be succesfully used for sediment transport purposes. For shorter waves the crest velocity values of the higher waves are underestimated and as a result the velocity asymmetry as well.

The work was started as part of the MAST-2 G8 Coastal Morphodynamics Research Programme and finalised as part of the MAST-3 SAFE project. It was funded jointly by the Commission of the European Communities, Directorate General for Science, Research and Development under contract no. MAS2-CT92-0027 and MAS3-CT95-0004, and Delft Hydraulics and Delft University of Technology in the framework of the Netherlands Centre of Coastal Research (NCK).
The laboratory data used was obtained during experiments in the framework of the "Access to Large-scale Facilities and Installations Programme" (LIP), which were funded by the Commission of the European Communities, Directorate General for Science, Research and Development under contract no. GE1*-CT91-0032 (HSMU).

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Introduction

Waves in the nearshore zone play a major role in influencing the design of coastal structures, assessing the impact and sustainability of dredging activities and determining the topographical evolution of beaches (Figure 1). In order to answer practical questions related to those issues, it is important to develop wave models which are able to predict the wave propagation from deep water to the shore. As will become clear further on, Boussinesq models are amongst the most advanced and efficient wave models available in coastal engineering today. In this paper the focus is on the application of this type of wave models for the prediction of non-cohesive sediment transport and resulting beach evolution, but it should be recognised that these models are just as important a tool in the determination of for instance wave-agitation in harbours, harbour resonance and seiching.

Questions to be answered about beach evolution concern such issues as the rate of beach erosion to be expected after a certain storm, whether natural beach recovery will take place and how the beach evolution can be influenced by means of for instance nourishments or structures. In order to adequately answer those questions we need to be able to make predictions of sediment transport rates. One of the crucial items in doing so is a proper description of the near-bed velocities under waves, since they are an important agent in stirring up sediment which is then moved by mean currents or by the waves themselves.

Although it has been recognised that Boussinesq models are a powerful tool in describing wave phenomena, not much is known about their capability to predict the near-bed velocity which is needed for sediment transport predictions. This paper presents the results of the verification of the prediction of near-bed velocities by such a Boussinesq model against wave channel measurements of irregular (partially) breaking waves propagating over a monotonic sandy beach.

First, some background is given on the role of waves in sediment transport and on Boussinesq models and their advantages over other models. Second, the wave channel experiments and the results of the verification are described.

How Waves Move Sediment

Surf zone related sediment transport is initiated by the stirring up of sediment by waves. This sediment can then be transported by amongst others currents such as the tidal currents, wind-driven currents or the offshore directed undertow. The undertow is generated by the breaking of waves in the surf zone. It is responsible for the major part of the offshore transport occurring

The IADC "Most Promising Student" Award

This year an IADC student award was granted to Judith Bosboom at the recommendation of Prof. Kees d'Angremond of Delft University of Technology, The Netherlands. Ms Bosboom graduated from Delft University of Technology in Civil Engineering (MSc Honours). She performed her MSc thesis on wave kinematics computations at WL | Delft Hydraulics where she is now employed. Her thesis was then selected as the best Masters thesis of the Civil Engineering Department, Delft University, for the academic year 1995-96. The paper is based on her thesis and published with permission.

In order to stimulate technical universities worldwide to increase their attention to the dredging industry in general, and to improve the quality of their students in dredging-related technologies in particular, the IADC has instituted an awards programme for the most interesting final theses on dredging-related subjects. Each award carries with it a prize of US$500, a certificate of recognition, and the possibility of publication of *Terra et Aqua*.

Professors who would like to recommend students for this award are encouraged to contact Mr Peter Hamburger, Secretary General of the IADC (info@iadc-dredging.com).

Figure 1. Waves in the nearshore zone play a major role in influencing the design of coastal structures and assessing the impact of dredging activities.

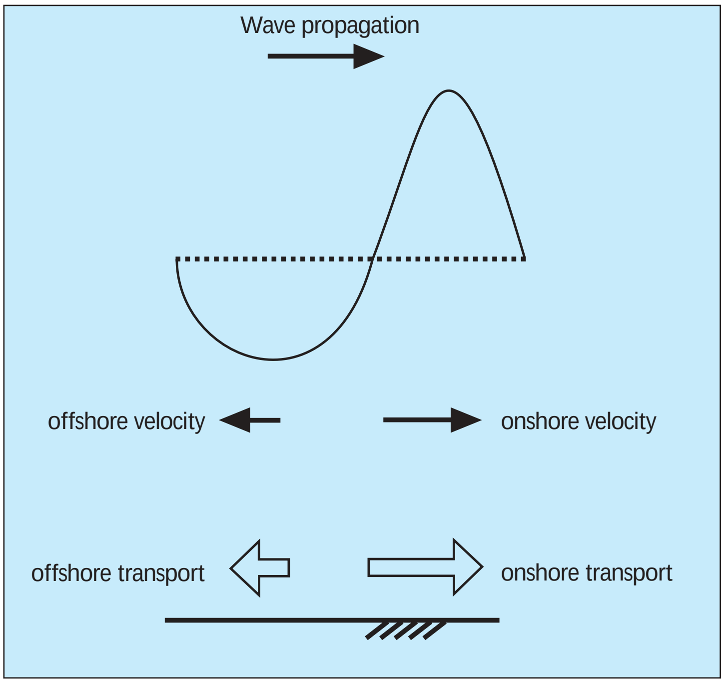


Figure 2. Transport owing to short wave asymmetric wave motion.

along a coastal profile, and therefore for the erosion a beach suffers under storm conditions when the wave breaking in the surf zone and the resulting undertow is strong.

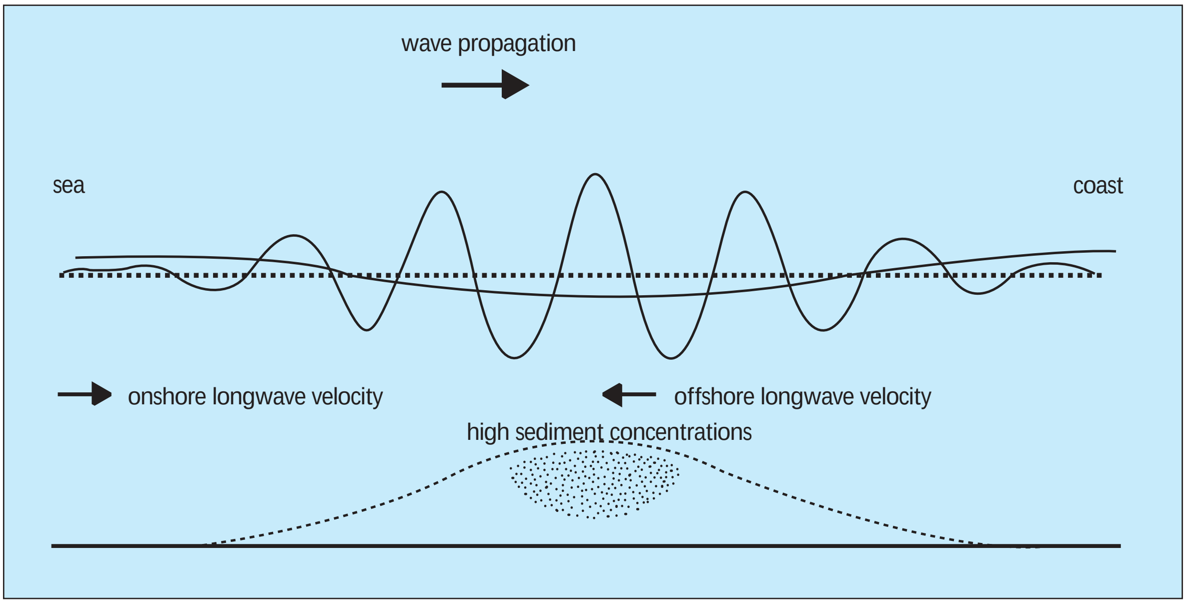
Under gentle conditions with lower waves it can be observed that some natural beach recovery takes place as a result of sediment transported in onshore direction. Again currents play a role in this transport of sediment; it is known that close to the bed a small net onshore current, called wave-induced streaming, exists which transports the material stirred up by waves in onshore direction. However, an important part of the onshore transport is not related to this net current but to direct transportation by the asymmetry of waves in the nearshore zone.

It can be visually observed that waves propagating into shallow water become increasingly asymmetric with peaked wave crests and flat troughs. The forward (onshore) velocities under the wave crests are therefore higher but of shorter duration than the backward (offshore) velocities under the troughs (see Figure 2). More sediment will be stirred up and transported by the onshore directed velocities under the wave crests than by the offshore directed velocities under the wave troughs. In this situation a net onshore transport occurs. This transport owing to wave asymmetry is generally called short wave wave-related transport.

In addition to this short wave induced sediment transport, long waves can give rise to a net transport as well. When observing wind-generated waves, one can see that they travel in groups in which higher and lower waves exist (see Figure 3). Such a wave group typically consists of seven to eight waves, from which the rule-of-thumb results, that every seventh wave is a high wave.

When propagating to the shore those groups of short waves are accompanied by longer waves with the length of the group, and which travel at the same speed of the group. In shoaling waves, the highest waves in a wave group occur more or less simultaneously with the trough of the accompanying long waves. Therefore, the highest sediment concentrations, stirred up by the short waves, occur simultaneously with the

Figure 3: Transport owing to long waves accompanying wave groups.



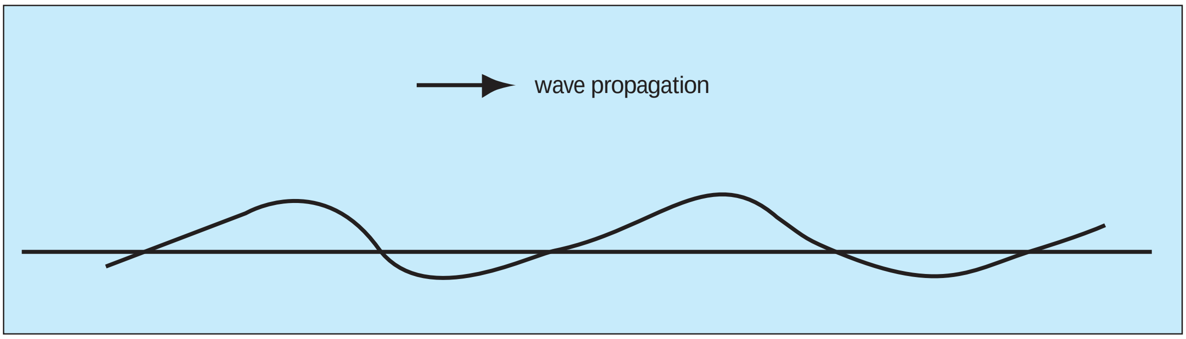


Figure 4: Wave profile as waves propagate from deep water to the shore. The waves develop peaked crests and flat troughs and a shoreward tilt until they finally break.

offshore directed long wave velocity. As a result the larger part of the sediment is transported in offshore direction by the negative trough velocity of the long wave.

Why Use Boussinesq Models?

In most state-of-the-art morphological models the computation of the near-bed velocity is performed in two steps. First time-averaged wave-transformation models are used to determine the wave parameters in the nearshore zone for given offshore wave conditions. An example of such a time-averaged model is the ENDEC/HISWA model (Delft University of Technology). These types of models compute only time-averaged parameters as wave height and set-up. The second step is the determination of the details of the wave-shape and the near-bed velocity. These have to be estimated locally by a non-linear theory which very often assumes a horizontal bottom. In this approach many important wave phenomena can only be treated in a schematised way. In order to overcome this problem more advanced wave models, such as Boussinesq models, can be used to describe the wave propagation from deep water to the shore.

As described above, it can be visually observed that the wave profile changes as waves propagate from deep water to the shore. Their crests become more peaked and the troughs become flatter. In addition, they develop a shoreward tilt until they finally break (see Figure 4). The velocities under the waves exhibit similar asymmetries with higher onshore velocities and smaller offshore velocities and a forward tilting which gives them more and more a sawtooth shape when getting in more and more shallow water. These two shallow water effects influence the asymmetry between backward and forward velocities, which is important for the wave-related sediment transport, and should be represented in a numerical wave model.

The first effect, the increasing asymmetry between backward and forward motion, is the result of the generation of shorter wave components owing to non-linear shallow water effects; the more shorter wave components are generated the more asymmetric the wave becomes. To describe this a model is therefore needed which includes the generation of higher harmonics owing to non-linearities. To describe the second phenomenon, the forward tilting of the waves, it is important that the speed at which the different wave components travel is described well. Freely moving wave components which are not locked anymore to a wave group as would be the case in deep water move at their own speed which depends on the wave length. If those phase speeds or in other words propagation characteristics are wrongly predicted, the resulting wave form will be completely wrong.

Boussinesq models include both of these shallow-water effects. Moreover, models based on Bousinesq equations are efficient from a computational point of view, such that they provide a good and economical tool for the determination of, for instance, wave agitation in harbours and harbour resonance.

Figure 5. Vertical structure of horizontal velocity field in shallow water (left) and intermediate water depths (right). The uniform velocity in shallow water is well described by classical long wave theory, whereas the Boussineq equations will also be able to describe the non-uniform velocity field in larger water depths.

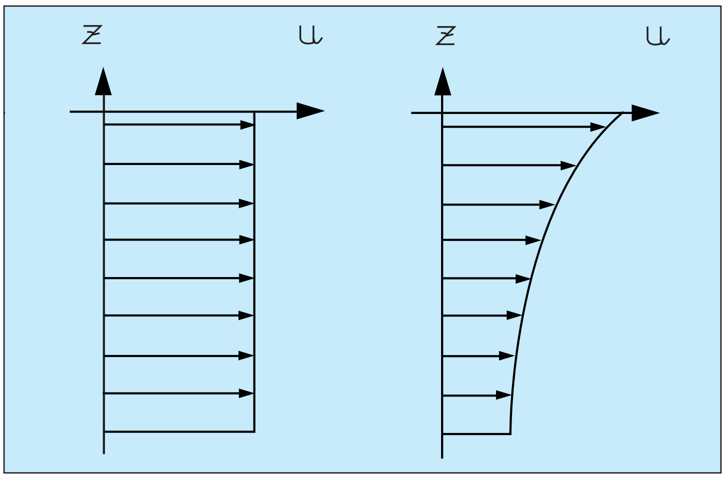


Figure 6. Fundamental research project on the stability of placed block revetments at prototype scale in the large wave flume (Delta flume) of WL | Delft Hydraulics (1992).

Boussinesq Models Compared to Classical Long Wave Theory

The classical shallow-water wave theory or long wave theory is obtained from the Navier Stokes equations by making the assumption of a hydrostatic pressure distribution or, equivalently, a uniform distribution of the velocity over the depth (Figure 5, left plot). In this way the effect of the curvature of the streamlines on the pressure distribution is neglected. By making such an assumption about the vertical structure, the equations can be integrated over the vertical resulting in equations formulated in the horizontal space only, which is attractive from a computational point of view. Since the phase velocity in the shallow water approximation is independent of the wave length, this theory cannot predict the differences in propagation speed of various wave components and will therefore result in correct wave forms only when applied in shallow water.

The Boussinesq equations can be thought of as an extension of the shallow-water theory for somewhat shorter waves or equivalently somewhat larger water depths. In the Boussinesq equations extra terms are introduced in the equations as compared to the shallow-water theory which account for the curvature of the streamlines on the pressure distribution, which is now no longer assumed to be hydrostatic. This implies that the velocities are not uniformly distributed over depth as would be the case in the shallow water theory but that the velocities decrease towards the bed (Figure 5, right).

The Applied Boussinesq Model

A frequency-domain version of the time-domain Boussinesq equations as derived by Madsen and Sørensen (1993) assuming uni-directional wave propagation and using a spectral form of the Boussinesq equations with improved propagation characteristics has been applied here. Herewith, the applicability of the equations is extended to deeper water. In order to extend the applicability of the model to the surf zone, Elderberky and Battjes (1996) incorporated a dissipation formulation to account for wave breaking, which is relatively easily done in a frequency domain model.

Since the Boussinesq equations are integrated over the vertical, the equations only provide the surface elevations and the depth-averaged velocity. To determine the velocity variation over depth, which is necessary for the computation of the near-bed velocity, a parabolic expression is used consistent with the Boussinesq approximation. Reference is made to Bosboom *et al.* (1997) for the exact formulations.

Wave Parameters Relevant to Wave-Related Sediment Transport

The most commonly applied models for the prediction of wave-induced sediment transport relate sediment transport to some power of the instantaneous near-bed velocity. Bed load and suspended load transport rates in the Bailard model, for instance, are proportional to the third and fourth power of the velocity, respectively. The time-averaged transport rates are then proportional to the time-averaged value of the velocity raised to the third or fourth power, the so-called velocity moments, which are non-zero only for a non-linear (asymmetric) wave motion. In this study we focus on the third velocity moment or velocity skewness. Besides, only the oscillatory part of the near-bed velocity is considered here; the mean current such as the undertow generated by wave breaking is not considered here.

As described above, short waves travel in groups – typically consisting of seven to eight waves – in which higher and lower waves occur. When propagating to the shore those groups of short waves are accompanied by longer waves with the length of the group and which travel at the same speed of the group. Therefore the surface elevation but also the velocities under the waves consists of high-frequency short-wave components and a low-frequency long-wave component.

Assuming that the oscillatory velocity signal consists of a relatively small low-frequency component and a dominant high-frequency component , the most important contributions to the velocity skewness are given by Roelvink and Stive (1989):

$$\langle u^3 \rangle \approx \langle u_{hi}^{\;3} \rangle + 3\langle u_{hi}^{\;2} u_{lo} \rangle,$$

in which the brackets indicate averaging over the short wave and wave group scale. The first term in the right-hand side of this equation is related to the short wave asymmetry and reflects the fact that only owing to an asymmetric short wave motion, a net sediment transport in wave propagation direction occurs (see Figure 2).

The second term is associated with the stirring of sediment by the short waves and the subsequent transportation of the sediment by the velocity under the long wave which accompanies the wave group (see Figure 3).

As explained above, this second term is therefore usually negative in shoaling waves, i.e. before the waves actually start breaking. In breaking waves a different story holds, since the long waves travelling with the groups are released in the surf zone and continue their travels to the shore at a speed differing from the wave group velocity.

From the above, it becomes clear that for a good prediction of sediment transport rates the prediction of the third moment or skewness of the near-bed velocity is crucial. Therefore the below comparison between measured and computed near-bed velocity, focuses on this parameter. Besides the total velocity moment, the short wave and long wave contribution to the velocity moment will be considered separately.

Experimental Data from the Delta Flume

The prediction of horizontal velocities and velocity moments was verified against wave channel measurements of irregular (partially) breaking waves propagating over a concave sandy beach. The experiments were carried out within the framework of the EU-sponsored Large Installations Plan (LIP) (Arcilla *et al.* 1993) in WL I Delft Hydraulics' Delta flume, a large-scale facility with a length of 240 m, a width of 5 m and a height of the walls of 7 m (see Figures 6 and 7). Two different experimental data sets (i.e. test 1a and 1c) were used. These two experiments were already used by Eldeberky and Battjes (1996) for the comparison of measured and computed surface elevation time series and spectra.

The incident wave conditions are listed in Table I, in which T_p is the peak period and H_{m0} the significant wave height.

Table I. Wave parameters for experiments 1a and 1c.

test	T_p (s)	H_{m0} (m)
1a	4.9	0.9
1c	8.0	0.6

Figure 7. Measurement carriage used during the LIP 11D programme in the Delta flume.

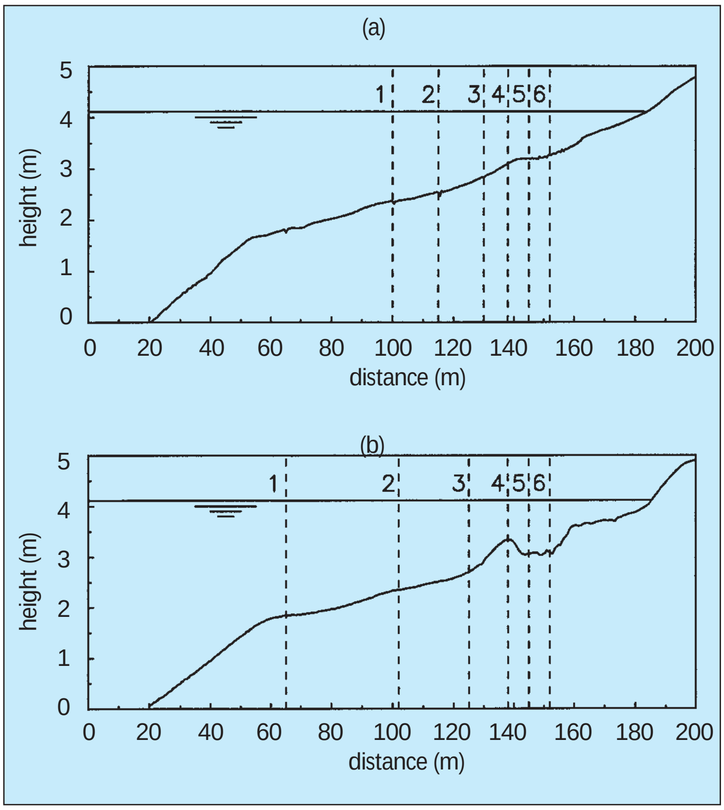


Figure 8. Bed profile and location of electronic current meters for (a) experiment 1a and (b) experiment (1c).

In the experiments the low-frequency wave channel resonances were prevented by an active wave absorption system at the wave-maker. Surface elevations and velocities were measured at several locations along the wave channel. The velocity measurements were carried out at several distances from the bed. The velocity measurement locations are indicated in Figure 8, for both experiments. Since the spectral model in its present form only predicts the purely oscillating part of the velocity, the time-averaged velocity component, such as the undertow velocity, was filtered from the measured signals.

For experiment 1a, the incident wave conditions are such that the wave breaking is strong (H_{m0}= 0.9 m and T_p= 4.9 s). These conditions correspond to highly erosive storm conditions. The monotonic sandy beach profile (Figure 8a) allows for wave breaking to take place over a large distance; the experiments showed a gradual decrease of the significant wave height at distances from 100 m up to about 140 m from the wave board, beyond which the wave breaking gets strong. In experiment 1c on the contrary, a barred beach profile is present (Figure 8b). The conditions are H_{m0}= 0.6 m and T_p= 8.0 s which are gentle accretive conditions corresponding to the recovery stage of a beach after a storm. The wave breaking is mild and is concentrated behind the bar, the crest of which is located around 138 m.

Wave Parameters Which Are Used in the Comparison of Measurements and Computations

The comparison between measurements and computations was carried out on surface elevations, bottom velocity time series, measured at 10 cm above the bed, velocity variance and skewness. Only the results of the comparisons on variance and skewness are discussed in this paper, since they are the most important parameters for sediment transport. For details on the comparison of measured and computed surface elevations and bottom velocity time series, reference is made to Elderberky and Battjes (1996) and Bosboom *et al.* (1997), respectively.

The variance $\langle u^2 \rangle$, the mean of the velocity time series squared, is a measure for the energy contained in the measured in and computed signals. The skewness $\langle u^3 \rangle$, the mean of the velocity time series raised to the third power, is a measure for the asymmetry between the forward and backward motion.
The total velocity variance $\langle u^2 \rangle$, the short wave variance $\langle u_{hi}^2 \rangle$ and the long wave variance $\langle u_{lo}^2 \rangle$ were computed for both the measured and the computed bottom velocity time series, using half the peak frequency for the lowest short wave frequency.

Analogous, the total skewness $\langle u^3 \rangle$ and the short wave and long wave contributions, $\langle u_{hi}^3 \rangle$ and $3\langle u_{hi}^2 u_{lo} \rangle$ respectively, were determined.

The comparisons between the predicted and measured velocity moments are given in Figures 9 and 10 for test 1a and test 1c, respectively.

Results of the Comparison Between Measurements and Computations

Figure 9 (lefthand side) shows that, except for the last station, the short wave velocity variance is very well predicted. The model slightly underestimates the total velocity variance for the stations closest to the bar.

This can be seen to originate from the inaccurate reproduction of the long wave velocity variance for these stations. This could be the result of the fact that the dissipation formulation, which describes the energy dissipation owing to wave breaking, reduces the long wave and short wave energy in the same proportion.

It can be argued that in case of wave breaking, the dissipation of the shorter (and higher) waves is stronger than that of the longer (and lower) waves.

This would mean that a dissipation formulation which depends on the wave frequency or which is only applied for the shorter waves is needed. Another possible

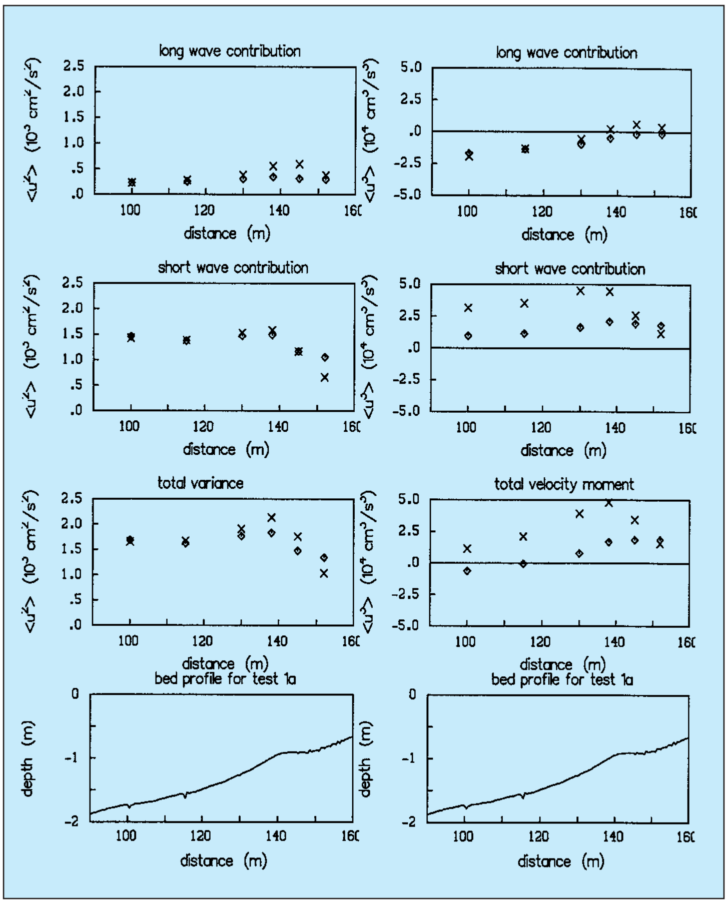


Figure 9. Comparison of measured (crosses) and computed (diamonds) bottom velocity variance (left) and skewness (right): long wave contribution, short wave contribution and total moment respectively; experiment 1a.

explanation might be the presence of a standing low-frequency wave pattern near the beach with a node in the low-frequency surface elevation and hence large velocity amplitudes around station 5. Standing waves are not reproduced by the model because of the assumption of uni-directional wave propagation.

The plots on the righthand side of Figure 9 show the results for the third velocity moment velocity skewness, which is important for the sediment transport. It can be seen that the long wave contribution is predicted fairly well. At deeper water where the long wave is travelling with the wave group this contribution is negative.

This is the case since the trough of the long wave, with offshore (negative) velocities, coincides with the highest waves in the group. Further onshore, closer to the surf zone, the long wave is released from the group, such that the correlation between the group and the long waves becomes smaller and the long wave contribution to the velocity moment becomes less and less important.

However, the third velocity moment can be seen to be dominated by the short wave asymmetry. This term is underestimated by the model. The agreement is reasonable for the last two stations where strong wave breaking occurs. The underestimation means that the computed surface elevation and velocity signals are too symmetrical.

Although not shown here, it was found that this occurs because the model underestimates the peak values of the highest waves. This is believed to partly originate from the transformation of the time-domain Boussinesq equations into the presently used frequency domain equations. Those frequency domain equations are known to yield lower crest values than its time-domain counterpart (Madsen and Sørensen, 1993).

Test 1c shows an encouraging agreement between measured and predicted bottom velocity time series (Bosboom *et al.* 1997), variance and skewness (Figure 10), especially up to the bar crest. The short wave velocity variance in test 1c is predicted well.

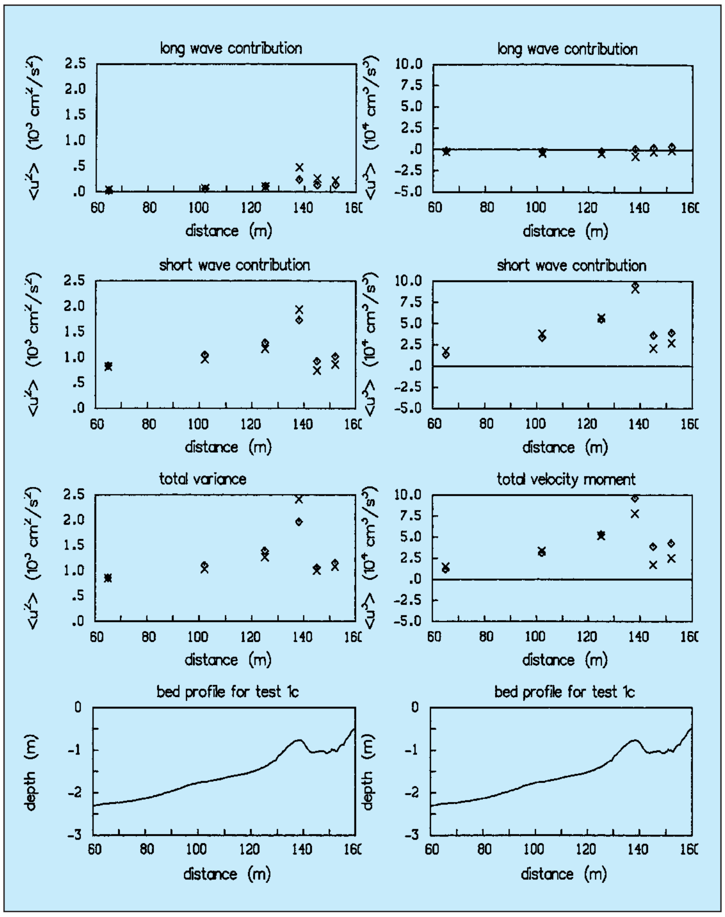


Figure 10. Comparison of measured (crosses) and computed (diamonds) bottom velocity variance (left) and skewness (right): long wave contribution, short wave contribution and total moment respectively; experiment 1c.

The difference between the total velocity variance determined from the computed and measured time series at the bar crest is for the larger part the result of the incorrect representation of the long wave energy. As for test 1a, this can possibly be ascribed to a standing wave pattern near the beach or to too strong a reduction of low-frequency energy by the breaking formulation.

It can be concluded that for test 1c, the velocity skewness compares very well with the measurements. This is a direct result of the good prediction of both the peak values and shape of the velocity signal, with a less significant underestimation of the peak crest values than in test 1a. The less good agreement beyond the bar crest, also found by Eldeberky and Battjes (1996) for surface elevation spectra, can possibly be ascribed to the relatively steep bottom beyond the bar crest, which is in contrast with the assumption of slowly-varying bottom used to derive the equations.

Conclusions

For test 1a as well as 1c, the short wave energy is predicted well by the model. The underprediction of the short wave asymmetry by the model in test 1a must therefore be the result of an incorrect representation of the wave shape. This might be partly owing to the larger ratio of wave height to water depth in test 1a as compared to test 1c, such that the wave breaking already occurs at 100 m from the wave board and continues for a large propagation distance. Note that the Boussinesq equations are only valid for relatively low waves. Besides, the peak period and thus the wave length is smaller which means that the assumption underlying the Boussinesq equations that we are dealing with (fairly) long waves is less appropriate in test 1a than in test 1c.

It can be concluded from the comparison of measured and computed velocity skewness indicates that for moderately long waves the Boussinesq model can be succesfully used to compute velocity moments, relevant to sediment transport predictions. For shorter waves the crest velocity values of the higher waves are significantly underestimated and as a result the short wave velocity skewness as well.

Additional research is relevant in order to determine whether the discrepancies result from the water-depth restrictions of the Boussinesq equations or from additional assumptions made in the derivation of the frequency domain equations underlying the present model. Further, attention should be paid to the inclusion of the mean velocity in the velocity computations and the validity of the wave breaking formulation in the low-frequency band.

It is further interesting to mention that a great deal of research is currently being performed by various institutes and universities in order to further improve the characteristics of the Boussinesq models. This means that improved models may become available which would give better predictions in the case of test 1a with the short and high waves.

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