J. Fluid Mech. (1991), vol. 229, pp. 675-688
Printed in Great Britain

Report on the International Workshop on Long-Wave Run-up

By PHILIP L.-F. LIU[1], COSTAS E. SYNOLAKIS[2]† AND HARRY H. YEH[3]

[1] School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA

[2] Department of Civil Engineering, University of Southern California, Los Angeles, CA 90089, USA

[3] Department of Civil Engineering, University of Washington, Seattle, WA 98195, USA

(Received 19 November 1990)

A workshop reviewing the current research on long-wave run-up was held in the Marine Science Center of the University of Southern California at Catalina Island, California, in August 1990. The workshop covered theoretical, experimental, and field studies of run-up phenomena. The primary application of the research results discussed was in tsunami run-up and flooding and in tsunami run-up hazard mitigation. Certain other applications of long-wave run-up related to wind waves were also discussed. This report summarizes the twenty-six papers presented and it provides one particular view of the current understanding of this run-up process.

1. Introduction

The run-up motion of water waves on a sloping solid boundary is a challenging problem in hydrodynamics involving non-trivial interactions of all three phases of matter. Flow motions near the run-up front display strong nonlinearity in comparison to the motions away from the front. Waves near the front often break, the flows become turbulent and intrinsically three-dimensional. Effects of the bottom friction can become important near the front as the water depth vanishes along the shoreline. In the laboratory, the surface tension effects also become important in the run-up front dynamics. The fluid dynamics of the run-up processes is complex and many aspects are still not well-understood. Nevertheless, an accurate method for estimating run-up motions is crucial for the prediction of forces on man-made structures exposed to ocean environments and of the coastal effects of tsunamis and storm surges.

A workshop to review the current understanding of long-wave run-up was held in the Marine Science Center of the University of Southern California on Catalina Island from 15-18 August 1990. Although topics discussed were focused on 'long' wave run-up, certain other related water-wave problems were also included. The workshop was designed specifically to foster close interactions among a wide spectrum of experts, including fluid mechanicians, tsunami specialists, coastal engineers, oceanographers, and applied mathematicians. Four workshop participants came from Japan, seven from the Soviet Union, one from England, one from Canada, one from Puerto Rico, and twenty-nine from the United States. The secluded location, the diversity of the contributors' backgrounds and the range of their research interests contributed to

† Author to whom correspondence should be addressed.

the stimulating discussions throughout the duration of the workshop. Topics ranged from the fundamental considerations of the contact-line dynamics and its mathematical singularity to tsunami run-up hazard mitigation. A list of the papers contributed is given in the Appendix. In this report we attempt to summarize the papers which are directly related to fluid mechanics; other papers are only mentioned briefly.

In §2 we summarize the papers on the run-up of unbroken waves, including solutions of the potential water-wave theory, the shallow-water wave approximation, and the full Navier–Stokes equations. These rather 'clean' theoretical considerations will be followed in §3 by studies of broken-wave run-up, most of which are primarily based on the shallow-water wave theory. In §4 we discuss controlled laboratory experiments on wave run-up. Engineering applications of the numerical models are reported in §5, followed by field observations in §6.

Since many of the presentations discussed shallow-water wave theory, we first briefly describe this theory. The shallow-water wave theory is based on the depth-averaged equations of mass and momentum conservation. The derivation of these equations involves the assumptions that water is an incompressible and inviscid fluid with no surface tension, that the water depth is small in comparison with the characteristic horizontal lengthscale of the motion; consequences are that the pressure field is hydrostatic everywhere, and that the velocity is uniform throughout the depth. If we consider one-dimensional wave propagation for simplicity, the equations of mass and momentum conservation are, respectively,

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}\{(\eta+h)\,u\} = 0, \tag{1}$$

and

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+g\frac{\partial \eta}{\partial x} = 0; \tag{2}$$

u is the depth-averaged horizontal velocity in the x-direction, η and $-h$ are the water-surface and the bottom-boundary elevations from a reference datum, g is the gravitational acceleration, and x and t denote the horizontal spatial coordinate and time. These equations are known as the shallow-water wave equations.

2. Unbroken waves

The workshop was opened by G. F. Carrier's stimulating lecture on tsunami generation, propagation and run-up. Using the shallow-water wave theory, he discussed the generation of tsunamis from a bottom displacement limited to a finite strip, and then demonstrated the three-dimensional nature of the resulting free-surface elevation. For a typical tsunami, he showed that frequency dispersion is important in the propagation from the source to the coastline, but unimportant in the evolution of the leading wave on a sloping beach, hence the nonlinear shallow-water wave equations, e.g. (1) and (2), are the legitimate equations for modelling certain coastal effects of tsunamis. Carrier then summarized his classic run-up solutions for the nonlinear shallow-water wave equations (Carrier & Greenspan 1958); these solutions were obtained by adopting the hodograph transformation which was first developed for gas dynamics (e.g. Courant & Friedrichs 1948). He pointed out that the reflection of a single positive Gaussian-shaped incident wave forms a longer wave with a strong N-wave character (Carrier & Noiseux 1983), and emphasized the importance of the beach slope on the reflection characteristics of obliquely incident long waves. This was verified in C. E. Synolakis's presentation which showed that even at normal incidence, Gaussian-shaped waveforms produced N-wave-shaped reflections.

C. E. Synolakis discussed extensions of Carrier & Greenspan's theory to solitary and cnoidal waves (Synolakis 1987; Synolakis, Deb & Skjelbreia 1988). He presented a solution to (1) and (2) for the topography of a constant-depth region evolving into a plane beach using Fourier transforms in time and remarked that when comparison with laboratory data is desirable, Fourier decomposition in time appears more advantageous than transforms in the spatial variable. His presentation for solitary waves included contour-integration results for the maximum run-up, the breaking criterion and the evolution far from the shoreline (Synolakis 1991). Asymptotic expansions of the series representations of his contour integrals result in the following expressions: $R/d = 2.83\,(H/d)^{\frac{5}{4}}(\cot\beta)^{\frac{1}{2}}$ for the maximum run-up R; $H/d < (\cot\beta)^{\frac{10}{9}}$ for a breaking criterion during rundown; and $\eta_{max}/H = (d\cot\beta/x)^{\frac{1}{4}}$ for the maximum height evolution. In these expressions, d denotes the constant water depth offshore, H is the offshore wave height at the constant-depth region, $\cot\beta$ is the beach slope, and x is the distance from the shoreline. The behaviour of η_{max} follows Green's law (Green 1837). Synolakis further showed that cnoidal waves of a given wavelength and amplitude produce significantly higher maximum run-up than the corresponding sinusoid with the same kinematic characteristics (Synolakis *et al.* 1988). He emphasized that the apparent excellent predictive capability of the shallow-water wave equations on the evolution of the maximum wave height and on the maximum run-up should not be extrapolated to conclude that the details of the evolution are also modelled equally well in all cases. Lastly, a computer animation of a solitary wave climbing up a sloping beach was presented.

Both Carrier and Synolakis demonstrated that generalizations of their linear or nonlinear theoretical results for continuous frequency distributions are not as straightforward as is often assumed. Several predictions valid for monochromatic waves may not be valid for waveforms with continuous frequency distributions. This is because the phase changes which are introduced during the evolution of a single sinusoid are frequency dependent; even though they may not distort the individual sinusoidal form, they distort the superposition of sinusoids. One good example is the reflection of long waves off a sloping beach; if one uses the linear theory result for periodic waves, one would conclude that the reflected wave would have a similar shape to the incident wave. On the contrary, the reflected wave is quite distorted, and one-signed Gaussian-type incident waves produce two-signed N-wave-type reflections.

Examples of the wave-reflection effects were presented by R. Kh. Mazova based on the linearized shallow-water wave equations. Considering two incoming waves of the form $\eta = H_1 \sin\omega_1 t$ when $-\pi < \omega_1 t < 0$ and $\eta = H_2 \sin\omega_2 t$ when $0 < \omega_2 t < \pi$, she demonstrated that for this particular condition a leading wave with negative elevation produces higher run-up than a leading wave of positive elevation.

E. N. Pelinofsky discussed another extension of Carrier & Greenspan's (1958) shallow-water wave analysis, to channels with a class of symmetrical cross-sectional shapes described by $h(x, y) = h_0 - a|y|^m$, where a is a constant, m is a positive number and y points horizontally in the direction perpendicular to the main flow direction, x. He confirmed the invariance of predictions of the maximum run-up in linear and nonlinear theory. Some aspects of the dissipative nature of the solution obtained by modifying the theory to include frictional effects were also discussed.

A rigorous mathematical analysis of wave run-up phenomenology was presented by R. E. Meyer. He first pointed out the difficulty in selecting a lengthscale for the wave run-up on a uniformly sloping beach. For a small beach slope, it was shown that the shallow-water wave approximation is valid. He then discussed how the breakdown of Carrier & Greenspan's (1958) analysis (which occurs when the Jacobian of the transformation becomes singular) is most often interpreted erroneously as wave breaking. He noted that in their presentations, Kajiura, Pelinofsky, and Synolakis all suggested that breaking criteria based on the singularity of the Jacobian predict earlier breaking than observed in the laboratory and in some numerical simulations. Meyer's explanation of this discrepancy was that, prior to the solution breakdown, the computed fluid acceleration takes values of the order of 10 g indicating that the model scaling is no longer correct; hence the singularity of the Jacobian does not represent physical wave breaking but an intrinsic failure of the shallow-water wave model.

Meyer also presented his analysis on shoreline singularity and its characteristics based on the inviscid theory (Meyer 1988*a*, *b*). To obtain results which are both physically and mathematically correct, Meyer extended his previous analysis for an inviscid fluid by using the Navier–Stokes equations and by including surface-tension and viscous effects (Meyer *et al.* 1991). In the offshore region where the depth is significantly greater than the boundary-layer thickness, the boundary-layer model developed by Mahony & Pritchard (1980) is adequate. However, the boundary-layer approximation becomes inadequate to describe the region near the shoreline where the depth is smaller than or comparable to the local boundary-layer thickness. Meyer showed that this very shallow region (of the order of less than a few centimetres from the shoreline) plays a decisive role in wave reflection. He then discussed the viscous shore singularity, which implies that the Newtonian no-slip boundary condition becomes invalid at the shoreline. This singularity was first noted by Dussan V. & Davis (1974) in the context of the contact-line dynamics. (If the no-slip boundary condition persists, the gas–liquid–solid contact line cannot move because the force at the contact line becomes singular.) The dynamics of this viscous singularity are still not well understood.

M. H. Teng presented a combined analytical and numerical solution for the evolution of weakly nonlinear, weakly dispersive and forced waves in a variety of channel cross-sections. The formulation is based on the integration of the Euler-equation system over the channel cross-section with a perturbation method. She presented the results for the evolution of waves over a step.

C. C. Mei presented a multiple-scale perturbation theory to study a harbour resonance caused by incident wave groups. The harbour entrance was assumed to be much wider than the shortest wavelength and much smaller than the longest wavelength. The approximate analytical solutions were obtained using the geometric ray theory and the parabolic approximation. He then demonstrated how free long waves can be generated and resonated inside a harbour (Mei & Agnon 1989; Wu & Liu 1990).

Numerical models based on the shallow-water wave theory are rapidly becoming obsolete for the basic study of the wave motions, especially when the problem involves no wave breaking. For non-breaking waves, analytical integral expressions are available and they can be evaluated directly without having to discretize the flow field. Also, the recent advances in the boundary-element computational method allow for numerically exact solutions of the full potential water-wave theory. S. Grilli & I. A. Svendsen discussed two-dimensional flows in the vertical plane using their

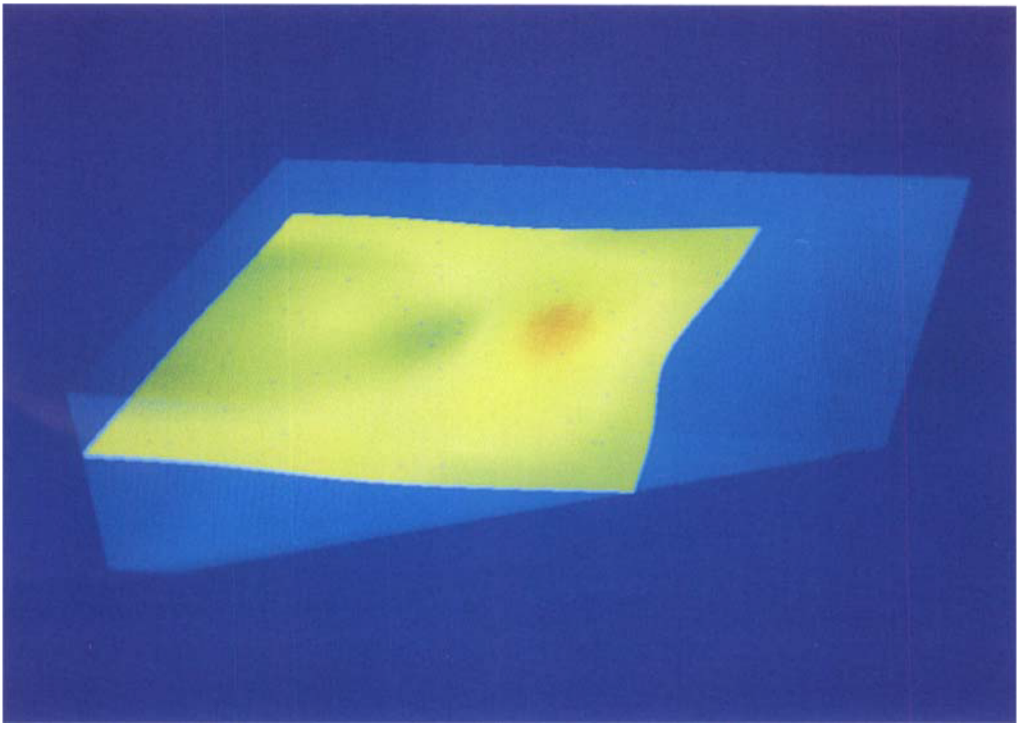

FIGURE 1. A snap shot of numerical solutions for a three-dimensional run-up in a square basin. The still water surface area is 4 units by 4 units and the uniform beach slope is 1:3.5. The constant depth is one unit and it is the characteristic lengthscale. The dimensionless time step size is 0.01 and the entire boundary has been divided into 512 elements.

numerically exact boundary-element algorithm. Unlike Stokes' solution to the potential wave theory, their numerical solution does not involve perturbation expansions, thus it is valid even in shallow water provided that the fluid is inviscid and the flow is irrotational. Grilli & Svendsen presented detailed results for the vertical distribution of the velocity field, and also run-up results for solitary waves. The accuracy of their model was demonstrated by comparing it with laboratory data (Grilli & Svendsen 1990*a*, *b*).

Using a similar boundary-integral method, D. H. Peregrine presented a numerical simulation of a collision of two identical breaking waves propagating in opposite directions. With this set-up, the impact and run-up of a wave breaking onto a vertical wall can be modelled (Cooker & Peregrine 1990). The results of this numerically exact simulation indicate that during the impact of the breaking wave on the wall, the fluid acceleration could reach up to 10000 g. An extremely localized and gigantic pressure rise occurs during wave impact and the transient value of $\partial p/\partial t = 3000\ \rho g^{\frac{3}{2}} h^{\frac{1}{2}}$ was reported (h is the initial depth in front of the wall). Note that such pressure spikes on a vertical wall are known as shock pressures from laboratory experimental data (Hiroi 1919; Bagnold 1938; Minikin 1950). Peregrine's result appears to be the first successful demonstration of the detailed shock-pressure phenomenon without resorting to empiricism; a typical empirical prediction formula is, for example, Minikin's (1950) equation. Peregrine also noted that even at these high pressures compressible effects were estimated to be unimportant.

The boundary-element method was further extended to a three-dimensional flow problem by P. L.-F. Liu. Animated numerical results were shown for a wave sloshing in a square basin and three-dimensional run-up motions on a uniform beach. These motions were generated by initially imposing a Gaussian distribution of negative pressure on the free surface, with its maximum located at the middle of the offshore endwall. This distribution generates a semicircular wave from the middle of the endwall. Multiple reflections from the sidewalls create a wave field with truly three-dimensional features. A typical 'snap shot' of the flow field is shown in figure 1 (plate 1). The velocity potential has been mapped onto the free surface with the red and blue hues corresponding to the wave crests and troughs respectively. Liu's numerical model demonstrated a feasibility of solving for complicated truly three-dimensional run-up motions. Liu stressed that like any other numerical model, his numerical solutions need to be validated with laboratory data.

Grilli, Liu, Peregrine and Svendsen all demonstrated the advancement in numerical solutions of the long-wave evolution and run-up problem. The reported robustness of the algorithms, the flow-detail resolution attained, the large accelerations and the three-dimensional effects that the method can handle indicate that a boundary-element numerical approach is an important tool for understanding the characteristics of run-up phenomena.

3. Broken waves

Once waves break, the fluid motions become turbulent and the potential-theory models are no longer adequate. Obvious alternatives are turbulence closure models based on the Reynolds equations in a full three-dimensional flow field (turbulence is three-dimensional). However, their application to wave run-up has not yet been explored, perhaps because of the difficulties associated with the involvement of the free-surface boundary and the highly unsteady nature of the flow. One of a very few attempts to apply the turbulence closure model was introduced by Svendsen &

Madsen (1984). Even though it is based on the shallow-water wave theory their model is a k-ϵ type of turbulence closure model for the bore propagation. The necessary parameters used were determined from laboratory data on hydraulic jumps. The three-dimensional and higher-order turbulence closure modelling technique has not yet been applied to the run-up of broken waves.

K. Kajiura reviewed the existing wave-breaking criteria and discussed the types of eddy motion created by wave breaking in the laboratory. Based on large-scale laboratory experiments in Japan, a description and classification of wave breaking processes were presented. As a long wave propagates over the continental shelf, it can fission into a series of solitary waves (Madsen & Mei 1969) depending on the wave steepness and the bottom slope. These series of solitary-type waves are generated only at the leading edge of the original carrier long wave and ride on the gradual variation of the main wave. These solitary waves may break, but the energy of the carrier long wave is approximately conserved. Therefore local wave breaking in a very long wave does not influence the maximum wave run-up height significantly.

Numerical simulations of a series of bores on a sloping beach were presented by D. H. Peregrine. First was a discussion of the Lax–Wendroff numerical scheme developed for a single uniform bore (Hibberd & Peregrine 1979) and its extension to a series of bores (Packwood 1980). Peregrine suggested that when a uniform train of bores approaches the shore, the solution settles to a steady state shortly after several bores have climbed up the beach with relatively small shoreline motions. On the contrary, when random perturbations are forced in either the wave frequency or the amplitude, the variations of resulting run-up are significantly enhanced. One can conclude from his results that a uniform train of bores is not an adequate model for natural conditions. It was also suggested that the discrepancy between the predicted and observed maximum run-up height caused by bores (Hibberd & Peregrine 1979; Miller 1968) can be due to surface-tension effects in a laboratory environment. Peregrine also showed comparison with the run-up measurements of Hawkes (reported in Packwood 1980) where the numerical run-up motion was relatively far from the laboratory data; however, Hawkes's equipment measured run-up at a height of 2 mm above the beach and indeed the comparison of the theoretical results with the 2 mm contour data was satisfactory. This observation appears to be another manifestation of the fact that shallow-water wave theory predicts an extremely thin layer of run-up, as also seen in Shen & Meyer (1963).

Z. Kowalik presented a computational algorithm for calculating the run-up of bores in one-dimensional propagation using the shallow-water wave equations modified with a friction term. He also showed some two-dimensional results on the sloshing motion of non-breaking waves inside a closed parabolic basin.

The numerical model for bore run-up based on the Lax–Wendroff scheme was first introduced by Hibberd & Peregrine (1979). This model was extended to include bottom friction effects and to apply to a random bore field by Packwood (1980) and Kobayashi and his colleagues (Kobayashi & Greenwald 1987; Kobayashi *et al.* 1988; Kobayashi, DeSilva & Watson 1989; Kobayashi, Cox & Wurjanto 1990). Because of the scheme's intrinsic ability to handle broken waves (or bore fronts) in the flow, its application has become quite popular. In essence this numerical scheme allows the modelling of a broken wave without having to directly model turbulent dissipation. Applying this model to a surf zone, a symmetrical wave profile outside the breakpoint evolves to an asymmetrical sawtooth-shaped profile in the inner surf zone, a behaviour which is qualitatively consistent with field observations. This prediction is not new nor surprising; Airy pointed out this front face steepening effect of the shallow-water wave theory in 1845 (see, for example, Peregrine 1983).

Because this numerical model is based on the shallow-water wave theory, it adopts the assumptions that the pressure field is hydrostatic and the velocity distribution is uniform in the vertical direction. These assumptions must be satisfied at every discretized point in the numerical scheme, including the bore front. This requirement is in violation of the true physical situation near the bore front. On the other hand, the traditional analytical approach for a single flow jump, by ignoring details at the discontinuity, does not entail calculations on a discrete point of the flow field.

To examine the approximations involved in the shallow-water wave equations, we proceed by integrating the Navier–Stokes equations for an incompressible fluid in the vertical direction. Assuming the bottom slope to be small ($\partial h/\partial x \ll 1$), the equations in the two-dimensional flow field in a vertical plane can be written as

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}\{(\eta+h)\,u\}=0, \tag{3}$$

and

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+g\frac{\partial \eta}{\partial x}=\underset{(a)}{-\frac{1}{\rho}\frac{\partial p}{\partial x}}+\underset{(b)}{\nu\frac{\partial^2 u}{\partial x^2}}\underset{(c)}{\underbrace{-\frac{\partial}{\partial x}\overline{u'u'}-\frac{\partial}{\partial z}\overline{u'w'}}}+\underset{(d)}{\frac{\nu}{h+\eta}\left|\frac{\partial v}{\partial z}\right|_{z=-h}^{z=\eta}}, \tag{4}$$

where v is the horizontal component of the flow velocity, u is the depth-averaged horizontal velocity, η and h are respectively the water-surface elevation and the water depth from a referenced datum, p is the dynamic pressure (i.e. the total pressure minus the hydrostatic pressure), ν is the kinematic viscosity of the fluid, u' and w' are the deviations of the horizontal and vertical components, respectively, from the vertically averaged velocities, and the overbar denotes an average over the depth. The components u' and w' include both the turbulent fluctuations and the time-averaged deviations caused by the non-uniformity of the velocity over the depth. Note that the continuity equation (3) is identical to (1), but that the depth-averaged momentum equation (4) – in comparison to (2) – includes five extra terms on the right-hand side. The approximations in the shallow-water wave version of the conservation of momentum (2) arise from neglecting the dynamic pressure field (term *a*), viscous diffusion effects (term *b*), the excess momentum flux due to turbulence and non-uniformity of the velocity profile in the vertical direction (term *c*), and the shear forces acting on the free surface and the bottom boundary (term *d*). In water waves of reasonable scale, the viscous effects and the shear force at the air–water interface are usually small and can be neglected. Therefore the validity of the shallow-water wave approximation essentially hinges on the magnitude of terms (*a*) and (*c*) and the lower limit of (*d*). The pressure-gradient term (*a*) becomes significant in breaking waves. The importance of (*c*) in a surf zone was demonstrated experimentally by K. Fujima in this workshop and it is discussed in §4.

It is emphasized that a spatially discretized numerical model based on the shallow-water approximation must satisfy the assumptions at every discretized point, which includes the bore front and the regions of strong shear flow. When a single uniform bore is considered (Hibberd & Peregrine 1979), errors caused by the discretization of the bore front may not be significant; however, when a series of bores or broken waves is considered, the validity of the single-bore model is questionable because the flow field is non-uniform in the vertical direction owing to strong shear action, usually arising from the backwash flow; this non-uniformity causes errors which are cumulative and affect the entire flow domain. In the case of a steep bed, for example $\beta = \frac{1}{4}\pi$, the depth-integrated formulations themselves, (3) and (4), become invalid. Interestingly, even though many assumptions of the shallow-water wave theory are violated in the surf zone, certain quantitative and qualitative comparisons of its predictions with the experimental or field data often produce good agreement: this is puzzling.

4. Laboratory experiments

Experiments in a controlled laboratory environment have often been performed to explore the physics of run-up phenomena and to confirm or refute analytical and numerical models. A survey of laboratory run-up investigations was presented by F. Raichlen. Different methods of wave generation were discussed ranging from the state-of-the-art (Goring & Raichlen 1980; Synolakis 1990) to the mechanical wave generator used in a classic work by Hall & Watts (1953). Raichlen suggested that it might not be necessary to generate a very 'clean' solitary wave to study the run-up motion of the first wave; only the shape of the leading portion of the wave is important. On the other hand, if the purpose of the experiment is to compare with a theory or a numerical model, it must consider the complete wave with initial conditions. The need was stressed for three-dimensional experiments on a large scale so that scale effects are minimized. It was noted that scale effects manifest themselves in the laboratory through surface tension, run-up on dry and wet surfaces, bottom and sidewall friction, percolation, and breaking.

The transition processes from a single uniform bore to the run-up motion on an initially dry beach were investigated by Yeh, Ghazali & Marton (1989). They found that for a fully developed bore the process observed experimentally is different from Ho & Meyer's (1962) 'bore collapse' prediction. The experiments showed that the bore front itself does not reach the shoreline directly, but instead the bore collides with and then pushes a small wedge-shaped body of water ahead of it. K.-M. Mok presented a new set of experimental results using a modified laboratory facility like that used by Yeh *et al.* (1989). Using a video system combined with a computer-aided analysis, Mok demonstrated that for a fully developed bore, the bore front is irregular and the transient process is intrinsically three-dimensional. This three-dimensional feature might contribute to the discrepancy in the maximum run-up height between theoretical predictions and laboratory data. Three different run-up processes were identified: a smooth and unbroken run-up, overturning of a bore front onto the dry bed, and the transient process described by Yeh *et al.* (1989). Different run-up processes resulted in different maximum run-up heights.

J. A. Zelt presented his experimental data on the overland flows on a horizontal bed generated by an incident solitary wave. The water depth in the experiments varied gradually and smoothly from a constant-depth section (a horizontal bottom) to a zero-depth section. By comparing his numerical solutions of the one-dimensional Boussinesq equation, Zelt found that the bottom friction is not important during the initial collapse of solitary waves on the horizontal bed (Zelt & Raichlen 1991) but that it becomes a dominating factor in the overland flow.

J. D. Ramsden discussed an experiment on the impact forces on a vertical wall by a broken wave evolved from a solitary wave offshore. He showed that the maximum run-up of the water on the wall occurred prior to the maximum force exerted on the wall (Ramsden & Raichlen 1990).

K. Fujima presented results from two separate laboratory studies, one dealing with the velocity measurements within the bottom boundary layer near the shoreline, and the other with measurements of the velocity field in a stationary hydraulic jump. A laser-Doppler velocimeter was used in both studies. An inclined moving-bottom device made of a smooth hard rubber belt was used in a water tank; the device rendered the run-up motions stationary and allowed for a relatively complete documentation of the flow field near the tip. (Note that the resulting steady flow is not identically equivalent to the run-up motion; the wave run-up is transient and non-uniform in the water-surface elevation.) For this steady flow, the bottom boundary layer appeared to be similar to the logarithmic velocity deficit law for a flat plate, except in the region very near the shoreline tip where the water depth becomes zero and the 'thin' boundary-layer assumption becomes invalid. In the hydraulic jump study, the measured velocity field was used to evaluate the terms in the depth-integrated equation of motions (4). He found that in front of the hydraulic jump the excess momentum flux due to the non-uniform velocity distribution (i.e. the term (*c*) in (4)) is significant and comparable to the magnitude of hydrostatic pressure gradient. Although local flow characteristics are different in a bore and in a hydraulic jump, as shown by Yeh & Mok (1990), Fujima's findings support the discussion in §3. The prediction based on the shallow-water wave theory cannot provide adequate information on the flow field near a bore front.

Experimental results on nonlinear wave motions on a plane beach in a three-dimensional basin were presented by J. Hammack. Two obliquely intersecting cnoidal wave trains were generated from a directional wave maker. Through the nonlinear interaction between these wave trains, a hexagonal wave pattern evolved, which represented a subset of the solutions of the Kadomtsev–Petviashvili equations. The hexagonal wave pattern persisted even after breaking, resulting in periodic rip currents along the beach (Hammack, Scheffner & Segur 1991).

5. Numerical prediction models – field applications

Numerical models designed to predict tsunami-run-up in the field were presented by N. Shuto, C. L. Mader, and V. Titov. Based on his finite-difference numerical solutions of the shallow-water wave equations and on an extensive amount of field observations, Shuto described a wide range of physical details of the phenomenon. He demonstrated that detailed initial conditions are essential for the prediction of coastal effects of tsunamis. The importance of the accurate modelling of three-dimensional bathymetry in the prediction of the wave focusing nearshore was also emphasized. Shuto's numerical results show how three-dimensional tsunamis can be and how multiple wave interactions and reflections must be considered to predict the coastal effects accurately. He suggested that the 1983 Nihonkai-Chubu tsunamis were trapped along a fairly uniform coastline. Field and laboratory data of edge bores were also discussed; edge bores are waves propagating in the longshore direction with wave breaking in the cross-shore direction.

C. L. Mader presented his numerical code which solves the two-dimensional depth-integrated shallow-water wave equations and which includes a Chézy-type friction coefficient. A PC-based computer animation for the leading wave of a sinusoid wave approaching the South Kohala region of the island of Hawaii and the resulting run-up motions was shown.

V. Titov presented the Novosibirsk (USSR) Computing Center's finite-difference-type solution algorithm of the two-dimensional depth-averaged shallow-water wave equations. His algorithm was optimized to run on PC systems in real tsunami time.

This type of model may be very effective in the rapid estimation of adequate shoreline inundation distances for civil defence applications.

6. Field observations

R. T. Guza gave a comprehensive presentation of the nearshore field measurements and of the numerical modelling efforts at the Shore Processes Laboratory in the Scripps Institute of Oceanography. He first described the field instrumentation and its limitations, and outlined the known processes occurring in a natural surf zone (Guza & Thornton 1980; 1981, 1982; Elgar & Guza 1986). Run-up data obtained with a wire wave gauge parallel to the beach face were then presented. Guza pointed out that edge waves are evident in the dispersion-relation diagram. The formation of edge waves implies trapping of energy, necessitating the adoption of three-dimensional formulations for describing the process.

M. Mizuguchi described his field experiments in Japan and discussed the problem of identifying the different wave components of a measured spectrum. He presented methods for separating the incident and reflected waves in wind-wave-generated swells in the surf zone. It was shown that the frequency-domain data do not produce meaningful results for the identification of breaking waves, swash and reflection in the surf zone. He demonstrated the usefulness of the wave-by-wave approach of analysing field data.

Guza & Thornton (1982) and Mizuguchi (1982) suggested that when wind waves climb up a natural beach, the maximum run-up is controlled by the energy in the long-wave part of the spectrum. These waves have periods from 0.5 to 5 min and are commonly referred to as surf beats or infragravity waves. As waves approach a shore, wave shoaling causes the energy to spread over a wide spectrum via nonlinear triad interactions. Then wave breaking causes the energy carried by the shorter waves to dissipate. Observations in the inner surf region suggest that, after breaking, the local height-to-depth ratio is approximately constant: a phenomenon which is now referred to as 'saturation'. By contrast the infragravity waves do not exhibit saturation. Guza & Thornton's (1982) field observations suggested that long-wave energy varies almost linearly with the incident offshore wave energy indicating that, on natural beaches where waves break, the long-period motion drives the run-up process. These field observations and Kajiura's hypothesis, as discussed earlier, imply that the effects of the breaking of the shorter waves in very 'long' wave groups and tsunamis may be of second order for the determination of the maximum run-up height.

R. G. Dean presented a method for calculating the long-wave component of surf beats over a uniformly sloping beach. Instead of using the first-order or the second-order Stokes' wave theory, the stream-function theory (Dean 1965) was used. In deep water both approaches produce similar results, but in shallow water, Stokes' theory breaks down and the stream-function theory gives better results. He showed that his surf-beat wave model can be used to predict the low-frequency spectrum from a given deep-water spectrum. The numerical results were shown to agree reasonably well with those of Goda (1975).

J. F. Lander presented an overview of historical records of tsunami inundation field data. He noted that the existing qualitative observational data base has been enriched significantly by scrupulously researching available sources. The importance of the critical evaluation of qualitative data, when the data are used to validate numerical models, was stressed.

G. D. Curtis described the historical evolution of tsunami zoning in Hawaii and the different empirical formulae that had been used to establish inundation zones. Various evacuation maps were said to be incomplete and obsolete. He emphasized the need for collaboration and interaction between tsunami zoning-type modelling and actual tsunami observations.

E. N. Bernard emphasized the link between the modelling work and actual tsunami zoning and civil defence strategies. He pointed out the importance of the development of both site-specific and source-specific zoning maps. The tsunami inundation was shown to be a function of local site factors and distant source characteristics.

F. I. Gonzalez described the five long-term tsunami monitoring stations near the Shumagin Seismic Gap together with some recent measurements of small tsunamis acquired in the open ocean; these measurements were obtained with pressure gauges with resolution of 1 mm in waves with periods greater than 5 min at a depth of up to 7000 m.

7. Concluding remarks

From the presentations and discussions in this workshop, it is evident that, based on the shallow-water wave theory, analytical solutions can be obtained for the calculation of run-up of different types of one-dimensional non-breaking long waves on a simple beach topography (e.g. a uniformly sloping beach). The run-up of a single bore (a broken wave) can also be solved analytically using the shallow-water wave equations in a fluid domain with a uniformly sloping beach. For a series of bores, the run-up solutions can be obtained numerically. However, these numerical results, especially those involving wave breaking, must be carefully interpreted since the intrinsic assumptions of the shallow-water wave equations may be significantly violated in certain areas of the flow.

Numerical algorithms based on the boundary-element method can provide numerically exact solutions of the full potential water-wave theory including wave run-up motions. The two-dimensional boundary-element model has been shown to be very robust and accurate. The extension of such a numerical model to the flows in a fully three-dimensional fluid domain was promisingly demonstrated. Considering extremely successful implementations of the two-dimensional version of the schemes, further development and validation of the three-dimensional model are anticipated. Shortcomings of the potential water-wave theory are that the models cannot handle the flow after wave breaking, and also that – owing to the strong influence of the boundary – the predicted run-up motions may not be accurate for a real fluid flow environment. Further research is needed to include the dissipative effects in the boundary-integral formulation.

There are many unsolved fluid mechanic problems related to long-wave run-up. Most of the unsolved problems relate to transition to turbulence, in particular in wave breaking. There is no physically sound theory available describing the generation of turbulence by wave breaking. The fluid dynamics of the contact line (where the boundary-layer theory breaks down) are also not well understood. As far as practical engineering applications are concerned, one of the immediate needs for model improvement is to predict accurate effects of three-dimensional bathymetry. In the field, the three-dimensional effects (e.g. wave focusing) on the wave run-up often dominate other detailed factors.

We are grateful to Cliff Astill for his encouragement and suggestion of this workshop. Janine Nghiem is thanked for her administrative work. This workshop was supported by the US National Science Foundation (BCS-9003982). The production of the colour plate was supported by the New York Sea Grant Institute.

REFERENCES

BAGNOLD, R. A. 1938 Interim report on wave pressure research. *J. Inst. Civ. Engrs* **12**, 202–226.

CARRIER, G. F. & GREENSPAN, H. P. 1958 Water waves of finite amplitude on a sloping beach. *J. Fluid Mech.* **17**, 97–110.

CARRIER, G. F. & NOISEUX, C. G. 1983 Reflections of obliquely incident tsunamis *J. Fluid Mech.* **133**, 147–160.

COOKER, M. J. & PEREGRINE, D. H. 1990 Violent water motion at breaking point impact. In *Proc. 22nd Intl Conf. on Coastal Engng, The Hague, Netherlands* (ed. B. L. Edge), pp. 164–176. ASCE.

COURANT, R. & FRIEDRICHS, K. O. 1948 *Supersonic Flow and Shock Waves*. Springer.

DEAN, R. G. 1965 Stream-function representation of nonlinear ocean waves. *J. Geophys. Res.* **70**, 4516–4572.

DUSSAN, V., E. B. & DAVIS, S. H. 1974 On the motion of a fluid–fluid interface along a solid surface. *J. Fluid Mech.* **65**, 71–95.

ELGAR, S. & GUZA, R. T. 1986 Shoaling gravity waves: comparisons between field observations, linear theory and a nonlinear model. *J. Fluid Mech.* **158**, 47–70.

GODA, Y. 1975 Irregular wave deformation in the surf zone. *Coast. Engng Japan* **18**, 13–26.

GORING, D. G. & RAICHLEN, F. 1980 The generation of long waves in the laboratory. In *Proc. 17th Intl Conf. Coastal Engng, Sydney, Australia* (ed. B. L. Edge). ASCE.

GREEN, G. 1837 On the motion of waves in a variable canal of small depth and width. *Camb. Phil. Trans.* **6**, 457–462.

GRILLI, S. & SVENDSEN, I. A. 1990*a* Computation of nonlinear wave kinematics during propagation and run-up on a slope. In *Water Wave Kinematics*, NATO ASI Series, E: Vol. 178, pp. 387–412. Kluwer.

GRILLI, S. & SVENDSEN, I. A. 1990*b* Problems and global accuracy in the boundary element solution of nonlinear wave flows. *Engineering Analysis with Boundary Elements, Nonlinear wave analysis*, 7 (4).

GUZA, R. T. & THORNTON, E. B. 1980 Local and shoaled comparisons of sea surface elevations and pressure. *J. Geophys. Res.* **85**, 1979–1808.

GUZA, R. T. & THORNTON, E. B. 1981 Wave set-up on a natural beach. *J. Geophys. Res.* **86**, 1524–1530.

GUZA, R. T. & THORNTON, E. B. 1982 Swash oscillations on a natural beach. *J. Geophys. Res.* **87**, 483–491.

HALL, J. V. & WATTS, J. W. 1953 Laboratory investigation of the vertical rise of solitary waves on impermeable slopes. *Tech Memo* 33. Beach Erosion Board, US Army Corps of Engineers, 14 pp. (available through NTIS).

HAMMACK, J., SCHEFFNER, N. & SEGUR, H. 1991 A note on the intensity of periodic rip currents. *J. Geophys. Res.* **96**, 4904–4914.

HIBBERD, S. & PEREGRINE, D. H. 1979 Surf and run-up on a beach: a uniform bore. *J. Fluid Mech.* **95**, 323–345.

HIROI, I. 1919 On a method of estimating the force of waves. *J. College of Engng, Tokyo Imperial Univ.* **10**, 1–19.

HO, D. V. & MEYER, R. E. 1962 Climb of a bore on a beach. Part 1. Uniform beach slope. *J. Fluid Mech.* **14**, 305–318.

KOBAYASHI, N., COX, D. T. & WURJANTO, A. 1990 Irregular wave reflection and run-up on rough impermeable slopes. *J. Waterway, Port, Coastal and Ocean Engng Div. ASCE* **116**, 708–726.

KOBAYASHI, N., DESILVA, G. S. & WATSON, K. D. 1989 Wave transformation and swash oscillation on gentle and steep slopes. *J. Geophys. Res.* **94** (C1), 951–966.

KOBAYASHI, N. & GREENWALD, J. H. 1987 Wave reflection and run-up on rough slopes. *J. Waterway, Port, Coastal and Ocean Engng Div. ASCE* **113**, 282–298.

KOBAYASHI, N., OTTA, A. K., ROY, I. & GREENWALD, J. H. 1988 Waterline oscillation and riprap movement. *J. Waterway, Port, Coastal and Ocean Engng Div. ASCE* **114**, 281–296.

MADSEN, O. S. & MEI, C. C. 1969 The transformation of a solitary wave over an uneven bottom. *J. Fluid Mech.* **39**, 781–791.

MAHONY, J. J. & PRITCHARD, W. G. 1980 Wave reflexion from beaches. *J. Fluid Mech.* **101**, 809–832.

MEI, C. C. & AGNON, Y. 1989 Long-period oscillations in a harbour induced by incident short waves. *J. Fluid Mech.* **208**, 595–608.

MEYER, R. E. 1988*a* On the shore singularity of water wave theory. Part I. The local model. *Phys. Fluids* **29**, 3142–3163.

MEYER, R. E. 1988*b* On the shore singularity of water wave theory. Part II. Small waves do not break on gentle beaches. *Phys. Fluids* **29**, 3164–3171.

MEYER, R. E., STRIKWERDA, J. C. & VANDEN-BROECK, J.-M. 1991 Notes on wave attenuation on beaches. *Wave Motion* (submitted).

MILLER, R. L. 1968 Experimental determination of run-up of undular and fully developed bores. *J. Geophys. Res.* **73**, 4497–4510.

MINIKIN, R. R. 1950 *Winds, Waves and Maritime Structures*. London: Charles Griffin, 294 pp.

MIZUGUCHI, M. 1982 A field observation of wave kinematics in the surf zone. *Coastal Engng Japan* **23**, 81–90.

PACKWOOD, A. R. 1980 Surf and run-up on beaches. Ph.D. thesis, University of Bristol.

PEREGRINE, D. H. 1983 Breaking waves on beaches. *Ann. Rev. Fluid Mech.* **15**, 149–178.

RAMSDEN, J. D. & RAICHLEN, F. 1990 Forces on a vertical wall due to incident bores. *J. Waterway, Port, Coastal and Ocean Engng Div. ASCE* **116**, 252–266.

SHEN, M. C. & MEYER, R. E. 1963 Climb of a bore on a beach. Part 3. *J. Fluid Mech.* **16**, 113–125.

SVENDSEN, I. A. & MADSEN, P. A. 1984 A turbulent bore on the beach. *J. Fluid Mech.* **148**, 73–96.

SYNOLAKIS, C. E. 1987 The run-up of solitary waves. *J. Fluid Mech.* **185**, 523–545.

SYNOLAKIS, C. E. 1990 Laboratory generation of long waves. *J. Waterway, Port, Coastal and Ocean Engng Div. ASCE* **116**, 252–266.

SYNOLAKIS, C. E. 1991 Green's law and the evolution of solitary waves. *Phys. Fluids* A **3**, 490–491.

SYNOLAKIS, C. E., DEB, M. K. & SKJELBREIA, J. E. 1988 The anomalous behaviour of the run-up of cnoidal waves. *Phys. Fluids* **31**, 3–5.

WU, J.-K. & LIU, P. L.-F. 1990 Harbour excitations by incident wave groups. *J. Fluid Mech.* **217**, 595–613.

YEH, H., GHAZALI, A. & MARTON, I. 1989 Experimental study of bore run-up. *J. Fluid Mech.* **206**, 563–578.

YEN, H. & MOK, K.-M. 1990 On turbulence in bores. *Phys. Fluids* A **2**, 821–828.

ZELT, J. A. & RAICHLEN, F. 1991 Overland flow from solitary waves. *J. Waterway, Port, Coastal and Ocean Engng Div. ASCE*, **117**, 247–263.

Appendix. List of papers presented at the workshop

BERNARD, E. N. (National Oceanic and Atmospheric Administration, Seattle, WA, USA) The value of run-up research for Tsunami warnings.

CARRIER, G. F. (Harvard University, Cambridge, MA, USA) Analytical results of long wave run-up.

CURTIS, G. D. (University of Hawaii at Manoa, Honolulu, Hawaii, USA) Maximum expectable inundation from tsunami waves.

DEAN, R. G. & LO, J. M. (University of Florida, Gainesville, FL, USA) Run-up due to wave groups.

FUJIMA, K. (National Defense Academy, Kanagawa, Japan) Hydraulic experiments on bottom friction and breaking for long wave run-up.

Gonzalez, F. I. & Bernard, E. N. (National Oceanic and Atmospheric Administration, Seattle, WA, USA) Tsunami field observations.

Grilli, S. & Svendsen, I. A. (University of Delaware, Newark, DE, USA) The effect of submerged breakwaters on long wave run-up.

Guza, R. T. (University of California, San Diego, CA, USA) Observations of run-up on natural beaches: a review.

Hammack, J., Scheffner, N. & Segur, H. (University of Florida, Gainesville, FL, USA) Run-up of 3-D long waves and nearshore cell circulation.

Kajiura, K. (Tokyo, Japan) Effects of wave breaking and bottom friction on tsunami.

Kowalik, Z. (University of Alaska, Fairbanks, AL, USA) Numerical computation of the run-up by finite difference method.

Lander, J. F. (National Oceanic and Atmospheric Administration, Boulder, CO, USA) Lessons from past tsunamis – Learned and unlearned.

Liu, P. L.-F. (Cornell University, Ithaca, NY, USA) Three-dimensional wave run-up.

Mader, C. L. (University of Hawaii at Manoa, Honolulu, Hawaii, USA) Modeling tsunami flooding.

Mazova, R. Kh. (Institute of Applied Physics, USSR Academy of Sciences, Gorky, USSR) The run-up description of monochromatic waves propagating from deep water.

Mei, C. C. (Massachussetts Institute of Technology, Cambridge, MA, USA) Short-wave induced long waves in a harbor.

Meyer, R. E. (University of Wisconsin, Madison, WI, USA) A quest for the reflection coefficient.

Mizuguchi, M. (Chuo University, Tokyo, Japan) Wave run-up and reflection.

Mok, K.-M., Grandinetti, C. L. & Yeh, H. (University of Washington, Seattle, WA, USA) Run-up of bores.

Pelinofsky, E. N. (Institute of Applied Physics, USSR Academy of Sciences, Gorky, USSR.) The nonlinear theory of long wave run-up on a beach and in channels.

Peregrine, D. H. (University of Bristol, Bristol, UK) Is there an upper limit to run-up?

Raichlen, F. (California Institute of Technology, Pasadena, CA, USA) The role of the laboratory in run-up research.

Ramsden, J. D. & Raichlen, F. (California Institute of Technology, Pasadena, CA, USA) Forces on a vertical wall caused by incident bores.

Shuto, N. (Tohoku University, Sendai, Japan) Observed and computed tsunami run-up.

Svendsen, I. A. (University of Delaware, Newark, DE, USA) Nonlinear waves on steep slopes.

Synolakis, C. E., Ruscher, C. & Merculief, P., III (University of Southern California, Los Angeles, CA, USA) Asymptotic analytical results on solitary wave evolution.

Teng, M. H. & Wu, T. Y. (California Institute of Technology, Pasadena, CA, USA) Three-dimensional run-up into shallow water.

Titov, V. (Computing Center, USSR Academy of Sciences, Novosibirsk, USSR) Numerical evaluation of tsunami wave run-up.

Zelt, J. A. & Raichlen, F. (California Institute of Technology, Pasadena, CA, USA) Overland flow from solitary waves.