CHAPTER 66

NEARSHORE BEHAVIOR OF BORE ON A UNIFORMLY SLOPING BEACH

Harry H. Yeh and A. Ghazali*

Using the laser-induced fluorescent method, the detailed transition process from bore to run-up mode is clarified experimentally. The transition process is found to be different from the previous predictions, and might provide an explanation for the discrepancies of the run-up height between the theory and laboratory measurements. Turbulence generated in a bore appears to be highly three-dimensional and sporadic. Turbulence generated close to the shore is advected with the bore-front motion and violent turbulent actions result during the transition from bore to run-up mode.

Introduction

A bore and the ensuing run-up on a uniformly sloping beach have been analyzed based on the inviscid theory with the shallow-water approximation; the shallow-water equations are basically depth-integrated conservation equations of mass and momentum with the assumption of a hydrostatic pressure field. The governing equations form a hyperbolic system, which is often solved by the method of characteristics. A bore front is usually treated by the jump conditions, i.e. the conservation of mass and momentum at the methematical discontinuity. (Note that energy across the jump is not conserved.) Using this formulation, Whitham (1958) found that the height of the bore tends to vanish as it approaches the shoreline while the fluid velocity, u, remains finite. Furthermore, Ho and Meyer (1962) found that singularity of the fluid acceleration occurs at the shoreline, while both the fluid and bore velocities approach their common finite value u* in which the value of u* is totally dependent on the offshore boundary condition. This behavior at a shoreline involving rapid conversion of potential to kinetic energy is often called "bore collapse". Shen and Meyer (1963) extended Ho and Meyer's analysis to the wave run-up after the bore collapse. They found that the maximum run-up height, R, is simply, $R = u^{*2}/2g$. Note that the predicted run-up height is independent of the beach slope.

Using the Lax-Wendroff numerical technique, the behavior of a bore on a beach was solved by Hibberd and Peregrine (1979). Because the jump conditions are not used to model a bore front, energy can be dissipated only via numerical dissipation. Their predictions of the maximum run-up heights appeared to be in excellent agreement with the analytical predictions. This indicates that the numerical dissipation involved is comparable to the energy dissipation involved in the jump

*University of Washington, Seattle, Washington, U.S.A.

conditions. Nonetheless, the analytical and numerical predictions of the maximum run-up height are considerably greater than the experimental results measured by Miller (1968). Packwood and Peregrine (1981) extended Hibberd and Peregrine's (1979) numerical model to incorporate viscous effects by using the Chézy friction term. While good agreements with Miller's (1968) experimental results were obtained for the steep beach-slope condition ($\beta = 15°$), for the mild slope condition ($\beta = 2°$) it was found that the friction effects alone cannot be an explanation for the discrepancy of the maximum run-up heights, i.e. the numerical predictions of the viscous model still considerably exceed Miller's experimental results.

The numerical results reported by Hibberd and Peregrine (1979) could not model the complete bore-collapse phenomenon due to the discretization involved in the numerical scheme which limits resolution of the details. In fact, just like the bore front being a discontinuity in the analytical model, Hibberd and Peregrin's numerical model does not provide physical information about the shape and structure of the front itself; the length of the front is artificially determined by the choice of the discretization in the Lax-Wendroff numerical scheme. However, we also conjecture that the complete bore collapse may not take place in a real fluid environment. First, as Hibberd and Peregrine pointed out, a real bore is not a perfect discontinuity but has a finite width which obscures the sharp transition of a predicted bore-collapse phenomenon. Second, a rapid conversion of potential to kinetic energy must involve significant vertical fluid motion; consequently, the applicability of the shallow-water approximation to that local phenomenon is in question. In his extensive experimental study, Miller (1968) reported that there is no complete collapse of a bore but the transition from bore to run-up mode is a rather gradual process. However, because of the measuring technique available to Miller, the detailed transition process was not revealed.

A qualitative description of turbulence involved in a bore in a uniform depth was suggested by Peregrine and Svendsen (1978). According to their description, turbulence is generated at the toe of the bore front and the initial stage of turbulent flow resembles a mixing layer. After the generation, the turbulence spreads and then interacts with the free-surface and, if the water is shallow enough, the bottom boundary. After the interactions, the turbulence behaves like a wake and decays. Applying the k-ε turbulence model to the depth-integrated governing equations, Svendsen and Madsen (1984) attempted to model a turbulent bore on a mildly sloping beach with $\beta = 1.66°$. A similarity profile of the flow velocity in the turbulent region was assumed based on the results for the hydraulic jumps provided by Madsen and Svendsen (1983). (In coordinates moving with the front, a bore in a uniform depth is often considered to be equivalent to a hydraulic jump.)

In this paper, we investigate behaviors of the bore near the shoreline, in particular, the transition from bore to run-up mode. The necessary definitions for this problem are shown in Fig. 1. Here, the x-coordinate points in the inshore direction from the shoreline, $u(x,t)$ is the depth-averaged fluid particle velocity, $h(x,t)$ denotes the depth of the water and $h_0(x)$ is the quiescent water depth in front of the bore, and g is the acceleration of gravity. Using the laser-induced fluorescence technique (described in the next section), a detailed transition process is revealed experimentally in a precisely controlled laboratory environment. The generation and evolution of turbulence associated with a bore nearshore are also investigated.

Experiment

A series of experiments was performed in a 9.0 m long, 1.2 m wide, and 0.9 m deep wave tank. A schematic view of the experimental setup is shown in Fig. 2. A plane beach is constructed of 1.9 cm thick plexiglass plates bolted on an aluminum frame. This construction assures rigidity of the beach with its precise slope of 7.5 degrees.

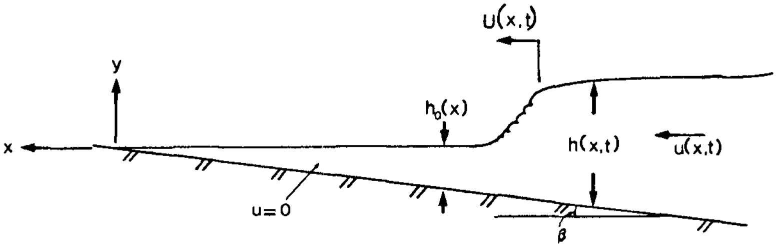


Figure 1. Definition Sketch

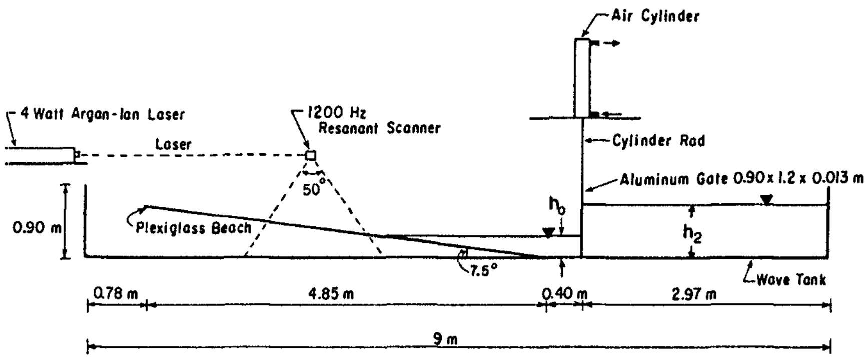


Figure 2. Schematic Drawing of Wave Tank

A single uniform bore is generated by lifting the gate (made of a 12.7 mm thick aluminum plate) which initially separates the quiescent water on the beach from the deeper water behind the gate. This bore-generation scheme has an advantage since the theoretical prediction of the bores can be made without difficulty from the classical dam-break problem. The gate is maintained in a vertical position with the aid of 25.4 mm brass guide channels along the side walls as well as the bottom floor of the tank; the gate itself is sealed against the channel slots by 4.8 mm O-ring rubber embedded in the channels. A pneumatic cylinder with a 10.16 cm bore is used to lift the gate in a controlled manner. The cylinder is electrically activated by a single solenoid valve with the operating air pressure of 650 kPa. It was found that the opening timing is sensitive to bore formation generated at the gate; the faster the opening, the more developed the resulting initial bore. The system is capable of lifting the gate fast enough (the lift-up time of 0.0708 ± 0.0012 sec in 20 cm of travel distance) that developed bores can be generated on the beach.

A 4-watt Argon-ion laser is used for the flow visualization. The emitted laser beam is converted to a thin sheet of laser light through a resonant scanner. The scanner is capable of sweeping the beam at 1200 Hz projected from above in the cross-shore (or longshore) direction and illuminates the vertical longitudinal (or transverse) plane of the water dyed with fluorescein. The fluid motions illuminated with the laser-induced fluorescence were recorded by the 35-mm photo camera. In order to record time directly using photography, a special digital clock was developed; the clock is activated by the initiation of the gate motion with the aid of a photo cell sensor. In addition, an electrical shutter release for the photographic camera was developed; the shutter release is synchronized with a wave sensor in the tank so that the motion at an exact time can be captured by the camera.

Two sets of experiments were performed: experiments for the bore collapse and for the turbulence generation and its development. In the latter experiments, a thin layer (approximately 3 mm thick) of a slightly lighter fluid (diluted ethanol, 0.99 specific gravity) was placed on the water on the beach. Only the upper layer was dyed with fluorescein. When a bore front propagates over the dyed layer, the laser-induced fluorescence indicates the motion of the water engulfed by the toe of the bore. This technique is similar to the one used by Peregrine and Svendsen (1978) who used detergent bubbles as the flow tracer. However, the present laser-induced fluorescence technique can provide the flow visualization in a virtually two-dimensional plane (the laser sheet is approximately 1 mm thick). The flow patterns were recorded by the photographic camera with the motor drive so that evolution of the turbulence can be analyzed. The camera (Nikon F2A Photomic) is capable of taking photographs at the rate of 4 frames per second.

In order to block scattered laser light (mainly at the 488 and 515 nm wave lengths) caused by unwanted particles and, more importantly, air bubbles entrapped in the bore front, the camera was equipped with a high-pass optical glass filter throughout the experiments. Because a relatively fast shutter speed (1/250 and 1/500 sec.) is required to capture the detailed bore motions, fast-exposure professional photographic films (Fujichrome P1600 D) were used.

Results

The performance of the bore generating system was examined with a variety of the initial conditions. It was found, from visual observations, that developed bores can be generated when $h_2/h_0 \geq 2.0$, where h_2 and h_0 are the initial water depths in front of and behind the gate, respectively. In the case of $h_2/h_0 < 2.0$, linear effects of frequency dispersion become significant, hence bores generated were undular instead (although the leading wave is breaking at its crest when $1.6 < h_2/h_0 < 2.0$). It was also found that when $h_2/h_0 > 2.8$, the behavior of generated bores appears to be too transient for measurements. Perhaps this is due to the limited propagation distance available and the finite time involved in lifting up the gate, i.e. the bore could not have enough time to be developed before it reaches the shore. Nonetheless, qualitative behaviors of bores generated with $2.0 \leq h_2/h_0 \leq 2.6$ appeared to be similar in all aspects investigated in the experiments discussed below. Hence, we concentrate hereafter on the examination of the bore generated with the following initial conditions: $h_0 = 9.75$ cm and $h_2 = 22.5$ cm. With this initial condition, the corresponding initial bore height in the uniform depth, h_1, is predicted to be 15.4 cm and the Froude number, $F = U/\sqrt{gh_0}$, is 1.43, where U is the speed of the bore front. (The values of h_1 and U were computed by solving the dam-break problem.) It is noted that the offshore bore strength characterized by F = 1.43 is comparable to F = 1.45 and 1.37 used in the numerical studies by Hibberd and Peregrine (1979) and Svendsen and Madsen (1984), respectively. Furthermore, $F \simeq 1.4$ seems to be typical of bores on a beach according to the results provided by Svendsen, Madsen, and Hansen (1978).

According to Ho and Meyer (1962), as the bore approaches the shore, the bore height diminishes to zero and the fluid velocity, u_1, behind the front approaches that of the front itself. Note that the values of U and u_1 are finite at the shore although the acceleration becomes singular. This complete bore-collapse phenomenon is thought to be unrealistic since the bore front is not really a discontinuity. To circumvent this difficulty, Hibberd and Peregrine (1979) implemented the Lax-Wendroff numerical scheme without using the jump conditions for the bore front. Their results indicate that the transition from bore to run-up mode is rather smooth and gradual. However, it is emphasized that the detailed shape of the front is determined basically by the discretization of the numerical solution but not by the physical causes. The experimental results of the bore near the shore and the transition from bore to run-up mode are shown in the sequence of photographs in Fig. 3. With repeated experiments, each photograph was taken by shifting the probe location for the electric shutter release at 5 cm intervals from x = -15 cm to x = 15 cm. The experimental results clearly indicate discrepancies from the predictions. The bore front itself never reaches the shoreline, but the small wedge-shaped water body along the shore ahead of the front is suddenly pushed forward. This pushed water mass, involving the violent turbulence, initiates the run-up process. During the transition, the bore

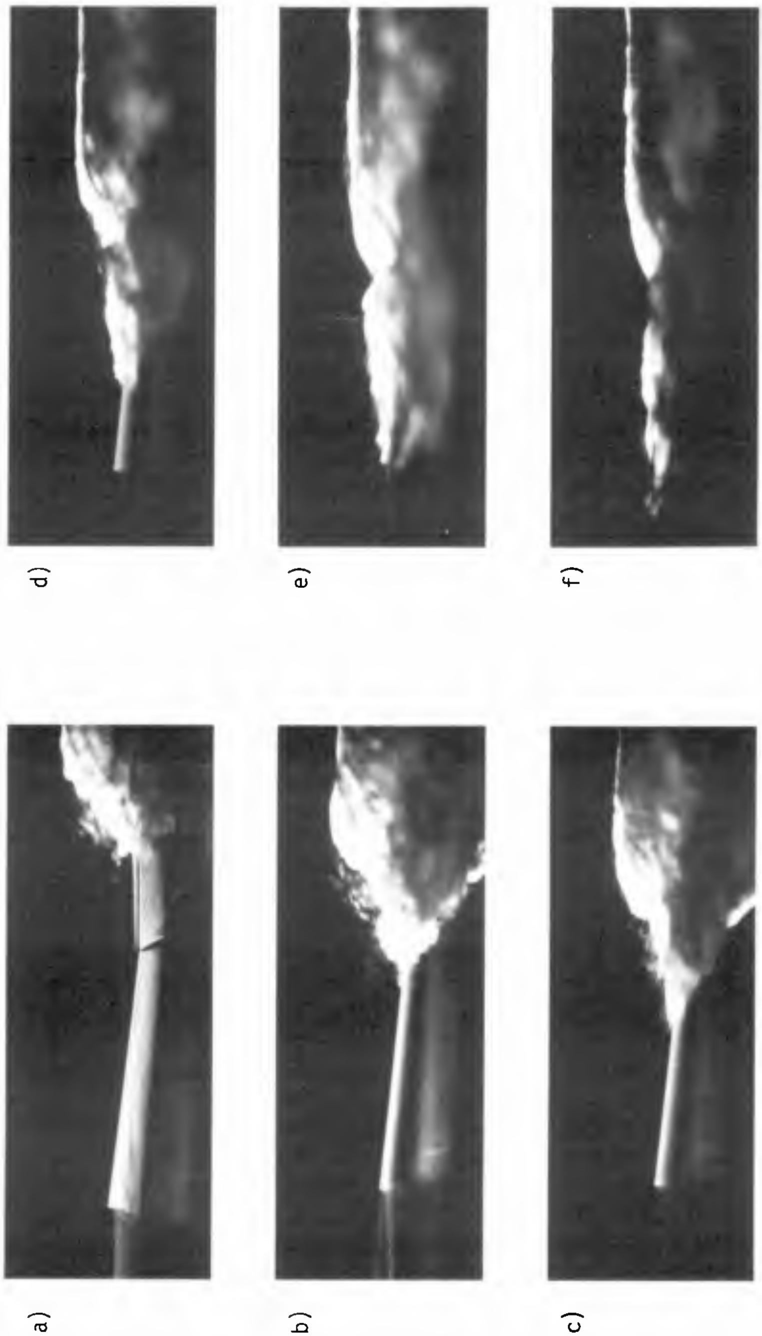


Figure 3. Transition Process from Bore to Run-up Mode. a) x = -15 cm; b) x = -10 cm; c) x = -5 cm; d) x = 0 cm; e) x = +10 cm; f) x = +15 cm

front first steepened and reduces its height. In order to verify this process, we performed another experiment by placing the narrow strip of water dyed with Rhodamine B along the shoreline so that the location of the dyed water can be identified by the red color. It was found that the water along the shore is indeed pushed forward instead of being engulfed by the bore front. By the following argument, this transition process may provide an explanation for the discrepancy on run-up heights between the inviscid theory and experimental measurements as mentioned in the introduction.

Suppose a bore approaching a shore is as shown in Fig. 4. At this instant (t = 0), the water in front of the bore is still quiescent. We assume that, when the ratio h_0/h_1 reaches a certain value, the water in front of the bore is pushed forward with a uniform velocity, u_0. Then, based on the conservation of total energy, the rate of change of kinetic energy of the water in front of the bore is the difference between the energy flux, $\mathcal{F}$, transferred into the control volume through section 1 and the rate of change of energy of the bore, $\mathcal{I}$, i.e.

$$\frac{d}{dt}\left(\frac{1}{2}\rho V_0 u_0^2\right) = \mathcal{F} - \mathcal{I}$$

where ρ is the fluid density, and V_0 is the fluid volume of the water pushed forward. Since $V_0 = 1/2\ h_0^2/\tan\beta$, integrating the equation yields the maximum value of u_0 at $t = t^*$:

$$u_0{*}^2 = (2\tan\beta)/(\rho h_0^2)\int_0^{t^*}(\mathcal{F} - \mathcal{I})dt.$$

Note that, from the initial and final conditions, $\mathcal{F} - \mathcal{I} = 0$ at $t = 0$ and t^*. Hence this suggests that $u_0{*}$ is dependent on the beach slope, and then the maximum run-up height is also dependent on the beach slope. ($u_0{*}$ appears to be proportional to $\tan\beta$, although the real relation remains unknown unless the integration is evaluated.) Together with the viscous effect and the effect of the air-water-beach contact line, this bore collapse process may be an additional explanation for the discrepancy which appeared between Miller's (1968)

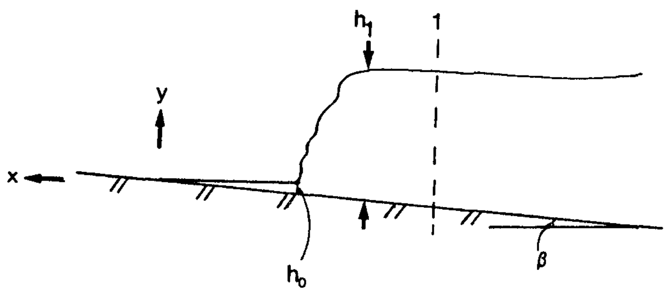


Figure 4. Simplified Model of a Transition from Bore to Run-up Mode.

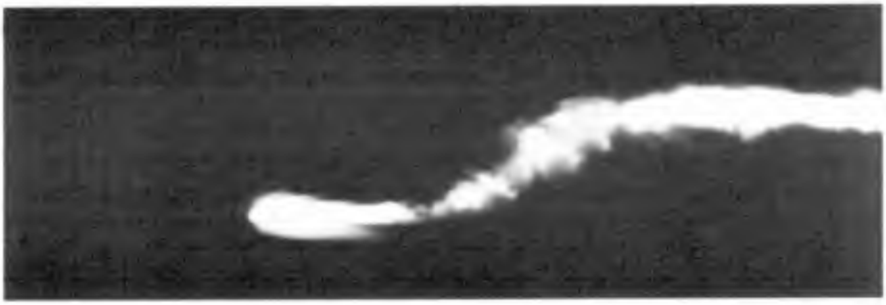
experimental results and the numerical solutions provided by Hibberd and Peregrine (1979) and Packwood and Peregrine (1981).

It is also noticed in Fig. 3 that the bore front becomes very steep (almost vertical) but smooth (less turbulent), while the water in front of it is extremely turbulent. This suggests that the turbulence generated at the front near the shore is advected forward on the beach instead of being left behind. This conjecture is further supported by the experimental results which follow.

In the experiments for turbulence, a thin dyed layer of diluted ethanol was placed on the water to identify vortices formed at the toe of the bore front. A sequence of photographs for generation and development of bore turbulence are shown in Fig. 5. The first photograph, Fig. 5a, shows that the toe of the front is passing at $x = -20$ cm. The mixing-layer type of turbulence generation cannot be detected in the photograph but the turbulent region is extremely thin and limited near the surface. It appears that the turbulence spreads at a much smaller rate than the change in the water surface. Svendsen and Madsen's results appear to form a thicker turbulent region than that in Fig. 5. However the direct comparison cannot be made because of the different beach slope involved (Svendsen and Madsen used $\beta = 1.66°$ whereas the experiments were performed with $\beta = 7.5°$). The observed turbulence behind the bore front is sporadic rather than forming a distinct turbulent region. A clear spread of turbulence can be observed in Figs. 5b and c at a relatively offshore position; these eddies must be generated when the bore was still propagating in the offshore region. Note that the water-particle velocity offshore is substantialy slower than the bore-propagation velocity. Hence, the generated turbulence is advected behind the front. When the bore reaches the shoreline in Fig. 5b, the turbulence behind the front seems to be weak; turbulent motions appear to be concentrated at the front. These behaviors are not limited to this particular case, but also occurred in the experiments with different initial bore strengths in a range of $1.31 < F < 1.48$. Since the magnitude of u_1 approaches the magnitude of U as the bore approaches the shore, the generated turbulence advected by the fluid velocity also tends to move closer with the front. This indicates that the turbulence generated near the shore is accumulated at the front and then released at the transition from bore to run-up modes. On the other hand, less turbulence is left behind the front and stretched horizontally by the velocity difference, hence relatively calm flow pattern results here.

By following the small turbulent eddy which appeared right behind the front in Fig. 5b, it is observed in the subsequent figure the eddy is stretched in a slanting vertical direction; similar behavior was observed in a broken wave in a uniform depth by Nadaoka et al. (1985).

In order to see more definite behaviors, the flow patterns in a vertical plane perpendicular to the propagation, i.e. in the longshore direction, were examined. (This is achieved by rotating the resonant scanner by 90 degrees.) The results are shown in Figs. 6 and 7. Note that the photographs were taken from the side wall so that the resulting images are somewhat distorted. In Fig. 6, the vertical laser



a) t = 0.76 sec

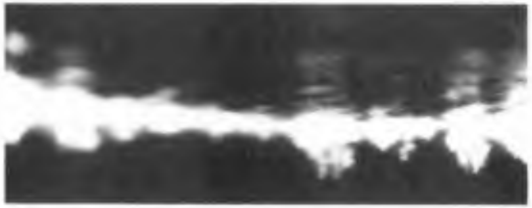
b) t = 1.00 sec

c) t = 1.23 sec

Figure 5. Visualization of Turbulence in a Longitudinal Plane along the Center Line of the Tank. (t = 0 at the gate opening)

a)

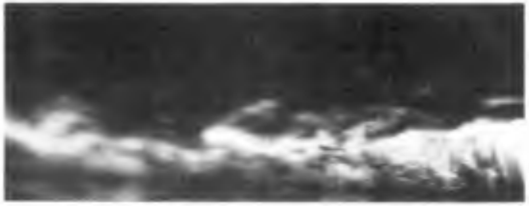
b)



c)

Figure 6. Visualization of Turbulence in a Transverse Plane along $x = -12$ cm, a) at the front; b), c) 0.25 and 0.50 sec later, respectively

a)



b)

c)

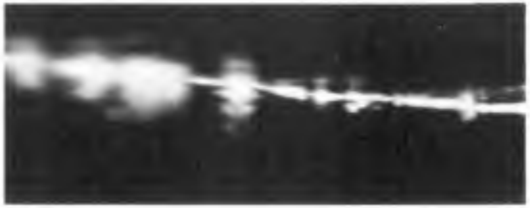


Figure 7. Visualization of Turbulence in a Transverse Plane along $x = 0$ cm, a) at the front; b), c) 0.25 and 0.50 sec later, respectively

sheet parallel to the shoreline was emitted offshore, x = -12 cm. Three-dimensional and sporadic turbulence structures are evident. In Fig. 7, the vertical laser sheet was emitted along the initial shoreline. Figure 7a shows the flow along the bore front at the shoreline; it is evident that the turbulence there is intense. Nonetheless, once the front passes by, the turbulence left behind the front is surprisingly weak and sporadic as seen in Figs. 7b and c. This confirms the observations made for Fig. 5.

The present results suggest that the turbulence is concentrated in the roller at the surface and the vortical motions generated within the roller are advected sporadically behind the bore front. From this point of view, the generation of the turbulence resembles that involved in a flow separation just as assumed by Longuett-Higgins (1973) for his analysis of steady breaker. This evidently differs from the one suggested by Peregrine and Svendsen (1978). The reason is not clear but it is probably because Peregrine and Svendsen observed the turbulence integrated in the tank width whereas the present observation is that in a virtually two-dimensional plane by the laser-induced fluorescence technique.

Conclusion

The detailed process of the transition from bore to run-up mode, i.e. bore collapse, was revealed. It was found that the bore front itself does not reach the shoreline before the large mass of the bore pushes the small wedge-shaped water body along the shore. During the pushing, the bore height decreases with steepening the front face (to almost vertical). The turbulence located on the front face appears to be advected forward onto the beach. This totally different transition process from the previous predictions may provide an additional explanation for the discrepancies of the resulting maximum run-up height between the theory and measurements. The turbulence generated at the bore front near the shoreline seems to resemble that for a flow separation. The generated turbulence is advected behind the bore; there, the turbulence is weak, three-dimensional, and sporadic. Very close to the shore, the generated turbulence is advected with the front. Hence violent turbulent motion results during the transition from bore to run-up mode, whereas right behind the bore front, a relatively calm motion occurs.

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References

Hibberd, S. and Peregrine, D.H., 1979. Surf and run-up on a beach: a uniform bore, J. Fluid Mech., 95, 323-345.

Ho, D.V. and Meyer, R.E., 1962. Climb of a bore on a beach. 1: Uniform beach slope, J. Fluid Mech., 14, 305-318.

Longuet-Higgins, M.S., 1973. A model of flow separation at a free surface, J. Fluid Mech., 57, 129-148.

Madsen, P.A., and Svendsen, I.A., 1983. Turbulent bores and hydraulic jumps, J. Fluid Mech., 129, 1-25.

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

Nadaoka, K., Hino, M. and Koyano, Y., 1986. Turbulent flow field structure of breaking waves in the surf zone, Proc. Conf. Coastal Eng., 20th.

Packwood, A.R., and Peregrine, D.H., 1981. Surf and run-up on beaches: models of viscous effects. Rep. No. AM-81-07, University of Bristol.

Peregrine, D.H. and Svendsen, I.A., 1978. Spilling breakers, bores and hydraulic jumps, Proc. Conf. Coastal Eng., 16th, 540-550.

Shen, M.C., and Meyer, R.E., 1963, Climb of a bore on a beach. 2: non-uniform beach slope, J. Fluid Mech., 16, 108-112.

Svendsen, I.A., Madsen, P.A. and Hansen, J.B., 1978. Wave characteristics in the surf zone, Proc. Conf. Coastal Eng., 16th, 520-539.

Svendsen, I.A., and Madsen, P.A., 1984. A turbulent bore on a beach, J. Fluid Mech., 148, pp. 73-96.

Whitham, G.B., 1958. On the propagation of shock waves through regions of non-uniform area or flow, J. Fluid. Mech., 4, 337-360.