CHAPTER 196

LABORATORY STUDY OF SURF-ZONE TURBULENCE ON A BARRED BEACH

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ABSTRACT

Wave height, wave set-up, undertow, and turbulent velocity on a plane beach and a barred beach were compared in the case of regular waves. The study showed that the presence of an offshore bar altered the turbulent flow in the surf zone by altering the characteristics of the broken waves. It was found that the magnitude of undertow and turbulence intensity were smaller in the inner surf zone on the barred beach. These results suggest that it may be possible to reduce the erosive wave action on beaches by construction of underwater berms in the nearshore zone. Further studies are needed to determine the effects of water depth, berm width and crest elevation on surf-zone turbulence under different wave conditions in order to provide explicit design guidance.

INTRODUCTION

This study deals with the characteristics of surf-zone turbulence on a barred beach. The motivation for this work is the effect of offshore bars on beach erosion. It is well known that the dynamic response of a beach under storm wave attack is to sacrifice some beach. Most of the sand removed from the beach are transported offshore and deposited as longshore bars. These bars in turn protect the beach from further erosion. The question which is the basis of this study is how offshore bars protect a beach from erosion. Knowing the how may allow us to develop more effective methods to curb beach erosion. For example, the U.S. Army Corps of Engineers has been using dredged material to construct underwater berms in the nearshore zone (MacLellan 1990, MacLellan and Kraus 1991). Such berms are placed in the form of long linear mounds for the protection of the coastline. It is believed that a berm with sufficient relief will shoal and break the higher erosive waves accompanying storms, forcing the waves to dissipate their energy in the surf zone, and thus reduce the erosive wave action on the beach. In reality, the process is probably more complicated than

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this. Since sediment transport and beach erosion are tied in a fundamental way to the turbulent flow in the surf zone, description of wave characteristics alone will not solve the whole problem. It will be shown that information on flow velocity and turbulence are needed in order to develop explicit design guidance for nearshore berm construction. Moreover, a thorough understanding of mean and turbulent flow characteristics on barred beaches will improve our knowledge of surf-zone dynamics, which is imperative for the development of more reliable coastal models.

There are very few studies which directly address the differences between wave breaking on barred and plane beaches. Smith and Kraus (1991, 1993) studied wave height transformation, reflection, and runup of monochromatic and random waves on barred and plane beach profiles in a wave tank. They found that incident waves with the same characteristics in deep water break differently on barred and plane beaches. For example, some waves that would spill on a plane slope plunge if a bar is present, and some plunging waves on plane slope collapses on a barred profile. Smith and Kraus's study pertained only to macro-features of wave breaking; micro-features of flow velocity and turbulence were not investigated. However, from their description of breaking wave characteristics on plane and barred beaches it may be expected that the presence of offshore bars would alter the turbulent flow in the surf zone by altering the process of wave breaking and turbulence production.

The structure of surf-zone turbulence has a profound influence on sediment transport and beach erosion. Recently, Ting and Kirby (1994) studied the characteristics of mean flow and turbulence in spilling versus plunging breakers. Here, "mean flow" is defined as the organized wave-induced flow which includes the undertow and the orbital wave motion. They found that turbulent kinetic energy was transported seaward under a spilling breaker and landward under a plunging breaker by the mean flow. Considering the common assumption of turbulent energy stirring up sediment and making it available for transport by the mean flow, it may be concluded that the direction of sediment transport would be seaward under spilling breakers and landward under plunging breakers. This is consistent with the field and laboratory observation that spilling breakers tend to result in beach erosion, while plunging breakers produce accretionary beach profiles. It also suggests that the types of beach profiles produced by storm and swell waves are tied in a direct way to the turbulence dynamics in breaking waves, particularly to the relationship between mean flow and turbulent kinetic energy. Because of this, it would be important to compare the mean and turbulent flow characteristics on plane and barred beaches for the same incident wave conditions to determine the effects of offshore bars on the turbulence flow in the surf zone.

In this present study, fluid velocities in a laboratory surf zone were measured using a two-component laser-Doppler anemometer, and surface elevations were measured using a resistance wave gage. Wave height, wave set-up, undertow, and turbulent velocity on a plane beach and a barred beach were compared for the same incident wave conditions. Although experiments were conducted using both regular and irregular waves, only the results for regular waves are presented here. The structure of turbulent flow in irregular waves will be the subject of a separate paper.

EXPERIMENTAL PROCEDURE

A schematic diagram of the experimental arrangement is shown in Fig. 1. The experiments were conducted in a two-dimensional wave tank in the Hydromechanics Laboratory at Texas A&M University. The wave tank was 37 m long, 0.91 m wide, and 1.22 m deep with glasswall throughout. It was equipped with a hinged-flap programmable wavemaker. A 1/35 slope false bottom built of marine plywood was installed in this tank to create a plane beach; the slope was sealed to the tank walls with silicone sealant. The coordinate system was chosen with x measured positive seaward from the shoreline and z extending positive upward from the still water level. The water depth in the constant-depth section was 45.72 cm. The incident wave height was 12.2 cm and the wave period was 2.0 s. The ratio of deep-water wave height H_0 to deep-water wavelength L_0 was 0.02 based on linear shoaling. The waves broke at a water depth of about 20.0 cm in the form of a spilling breaker. The breaking point was defined as the location where air bubbles began to be entrained in the wave crest.

The barred beach was created by placing a submerged solid triangular-shape object on the sloped false bottom. The geometry of the object was selected based on large wave tank studies and field measurements of bars (see, Larson and Kraus 1989). The dimensions of the bar are shown in Fig. 2; it was 9.6 cm high, 145 cm wide, with a seaward bar angle of 6° and a shoreward bar angle of 10°. The bar was located at the breaking point on the plane beach; the still water depth was 23.1 cm at the seaward toe of the bar, 10.4 cm at the bar crest, and 18.8 cm at the shoreward toe of the bar. In order to determine the incident wave heights it was necessary to measure the reflection coefficients for the plane and barred beaches. Therefore, a wave gage was mounted on an instrument carriage which was moved along the constant-depth section of the wave tank to measure the spatial modulations in wave amplitudes created by the interference of the incident and reflected waves. The reflection coefficient K_r was determined from the two extreme wave heights $H_{\max}$ and $H_{\min}$ of the envelope of amplitudes by $K_r = (H_{\max} - H_{\min})/(H_{\max} + H_{\min})$. It was found that the reflection coefficients for the plane and barred beaches were almost the same and in both cases less than 5%. Hence, the bar did not reduce the wave energy reaching the surf zone. Instead, it caused the waves to plunge into the water ahead, and thus dissipated more energy in the outer surf zone.

Water surface elevations and fluid velocities were measured at three locations in the inner surf zone; their exact locations and water depth are given in Table 1. The following notations are used in this paper; ζ is water surface, u is horizontal velocity, w is vertical velocity, H is wave height, d is still water depth, h is mean water depth, and the superscripts overbar, tilde and acute accent denote time average, phase average and turbulent fluctuation, respectively. Surface elevations were measured using a resistance wave gage. The gage was

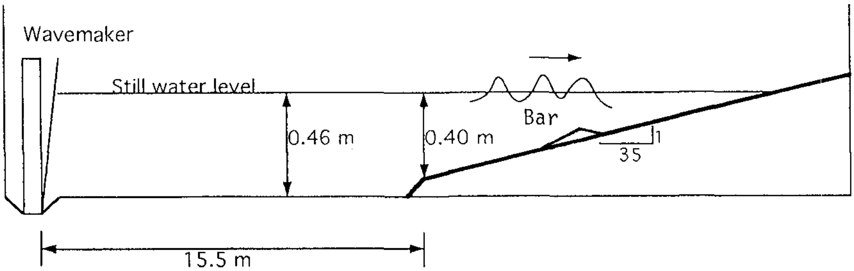

FIG. 1. Schematic Drawing of Wave Tank Arrangement

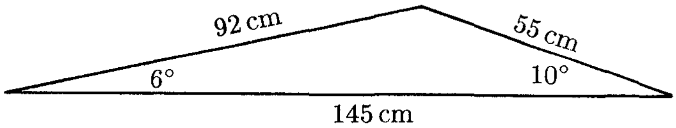

FIG. 2. Schematic Drawing of Bar Profile

Station	x (m)	d (cm)	H (cm)	$\overline{\zeta}$ (cm)	h (cm)	$\frac{H}{h}$
1	4.76	13.62	6.98	0.51	14.13	0.49
2	3.29	9.39	5.23	1.04	10.43	0.50
3	2.21	6.34	3.83	1.32	7.66	0.50

(a) Plane Beach

Station	x (m)	d (cm)	H (cm)	$\overline{\zeta}$ (cm)	h (cm)	$\frac{H}{h}$
1	4.76	13.68	7.79	1.08	14.76	0.53
2	3.29	9.30	4.93	1.44	10.74	0.46
3	2.21	6.28	3.12	1.41	7.69	0.41

(b) Barred Beach

TABLE 1 Locations of Measurements and Water Depths

calibrated in quiescent water, the calibration curve was found by fitting a fourth order polynomial to 15 data points. Water particle velocities were measured using a two-component laser-Doppler anemometer (LDA). Velocity measurements were conducted mainly in the region below trough level and above the bottom boundary layer. The LDA was a backscatter, three-beam system built by Dantec Electronics. It consisted of a 4 W argon-ion laser (Innova 70-5 from Coherent Inc.), transmitting and receiving optics, traverse mechanism, and one frequency tracker and shifter for each velocity component. It was found that the output voltage from the frequency trackers had a non-negligible long-term fluctuation, which could seriously affect the accuracy of time average velocity measurement such as the undertow. Therefore, the output voltage from the frequency trackers in still water condition was recorded in each experiment and used to correct the measured velocity. The estimated error for the undertow was $\pm 1.0\,\mathrm{cm/s}$.

Periodic waves were generated for 15 minutes before data were taken. Thus, the measurements corresponded to a steady-state condition in the wave tank. Data were taken by an IBM compatible 486 computer equipped with a Metra-Byte DASH-16(F) data acquisition board. Sampling frequency was 100 Hz for each channel. The measured velocity was first high-pass filtered at 0.1 Hz to remove any long-term fluctuation due to electronic signal drifting. The orbital wave velocity was obtained by phase averaging the filtered velocity over one hundred and two successive waves. The turbulent velocity was found by subtracting the phase average velocity from the filtered velocity. The frequency tracker had a built-in lock detector to record signal drop-out, which was typically less than 5% in these experiments. Nevertheless, velocity data that were obtained during signal drop-out were not used in computing the mean flow and the turbulent velocity.

RESULTS

Figs 3(a)–3(c) compare the phase average surface profiles at each station on the plane and barred beaches. The control signal to the wave generator has been used to synchronize the surface profiles in different experiments. Table 1 summarizes the major results including wave height and wave set-up. Visual observations showed that the waves broke in the form of a spilling breaker on the plane beach, whereas they plunged into the water shoreward of the bar on the barred beach. It is seen in Figs. 3(a)–3(c) that the waves on the barred beach lagged behind the waves on the plane beach, which is to be expected. The wave set-up was larger on the barred beach but closer to shore the difference became increasingly smaller. On the plane beach, the wave height to water depth ratio H/h remained constant through the inner surf zone; the measured value of 0.5 is typical of spilling breakers. The ratio of wave height and water depth was somewhat smaller on the barred beach and continued to decrease shoreward. Prehaps the most important difference is that the broken waves on the plane beach had a "saw-tooth" profile which varied only slowly from one station to another, whereas the broken waves on the barred beach had a secondary crest and the waves reformed through the surf zone. This behaviour has been observed by Smith and Kraus (1991, 1993), but its significance was not recognized. It is seen that the wave profiles were significantly different on plane and barred beaches. This would have a profound influence on the process of wave breaking, and thus the turbulence dynamics in the surf zone. This is because wave breaking originates from instabilities in the water surface therefore the rate of energy transfer from organized wave motion to turbulent motion (i.e. turbulence production) will be related to the details in the broken waves such as wave height and wave shape. Furthermore, since turbulence transport processes such as turbulent diffusion and viscous dissipation are passive processes which can only proceed at a rate dictated by the behaviour of large-scale structure created by wave breaking we should expect that turbulence dynamics in the surf zone will also depend on the wave characteristics. These ideas will be elucidated further when we examine the structure of undertow and turbulence.

Figs. 4(a)–4(c) plot the variations of undertow with distance from mean water level on the plane and barred beaches. The undertow for the plane beach at stations 1 and 2 were taken from Ting and Kirby (1994), which has virtually the same experimental conditions. It is seen that the magnitude of undertow on the barred beach was generally smaller. This is the result of different wave characteristics on the plane and barred beaches. In these experiments, the wave conditions at each station were recorded using a video camera. The video recording showed that wave breaking in the inner surf zone was less intense on the barred beach. Since the undertow is a return current that is created to balance the water carried shoreward by the surface rollers, we should expect that the magnitude of undertow would be smaller under a weaker breaker. Thus, it appeared that by causing the incident waves to form a plunging breaker, the bar changed the way the broken waves evolved through the surf zone which in turn, altered the turbulent flow.

Figs. 5–7 plot the variations of turbulent velocity with distance from mean water level on the plane and barred beaches. It is seen that the horizontal and vertical components of turbulent velocity decreased with increasing distance from the surface, and the vertical velocity remained smaller than the horizontal velocity; these results are to be expected. The important new result is that these figures clearly show that turbulent velocities in the inner surf zone were considerably smaller on the barred beach. If it is assumed that turbulent velocity fluctuations are responsible for keeping sediment in suspension, and the undertow transports the sediment, then the rates of sediment transport from onshore to offshore would be decreased by the formation of offshore bars. This would have a beneficial effect on the beach profile.

CONCLUSIONS

To examine the effects of offshore bars on wave and turbulence characteristics in the surf zone laboratory experiments were conducted in which measurements of fluid velocity and surface elevation were made on a plane beach and a barred beach. Some experimental results for regular waves are reported here. The following main conclusions can be drawn from this study:

1. The broken waves reformed on the barred beach, the wave profiles in the surf zone were significantly altered in comparison to the broken waves on the plane beach.
2. The offshore bar reduced the magnitude of undertow in the inner surf zone.
3. Wave breaking in the inner surf zone was less intense on the barred beach.
4. Turbulent velocity in the inner surf zone was considerably smaller on the barred beach.
5. This study shows that undertow and turbulence intensity differ on plane and barred beaches. This behaviour is related to the effect of the bar on wave breaking. It is further shown that description of turbulent flow characteristics on barred beach profiles is important for providing the data base for developing explicit design guidance for nearshore berm construction.

ACKNOWLEDGEMENTS

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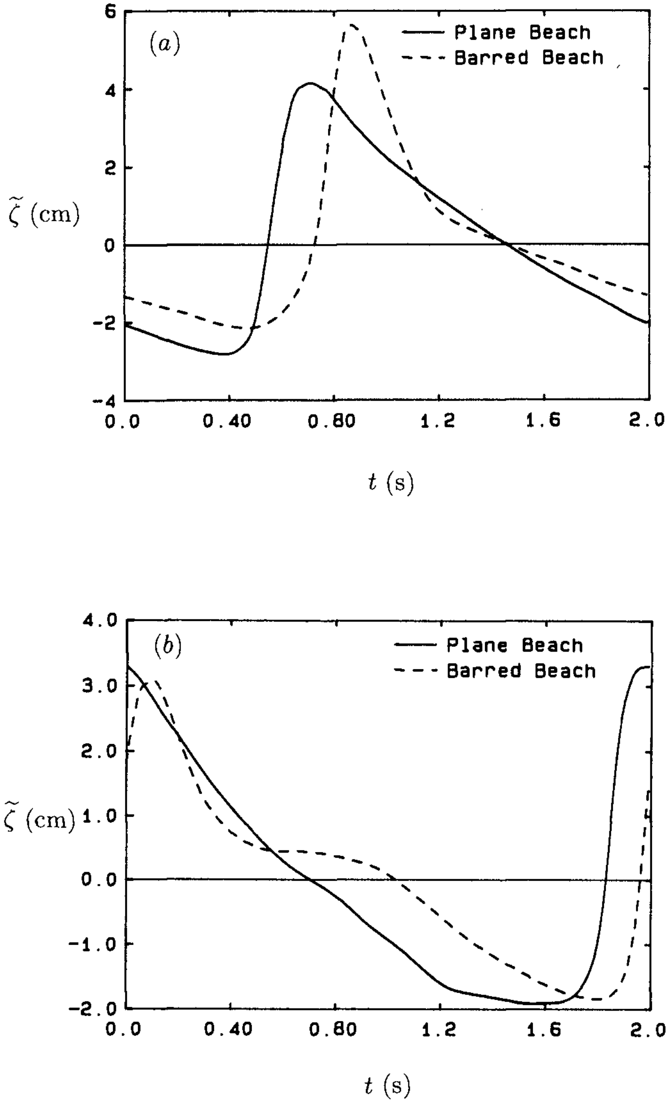


FIG. 3. Phase Average Water Surface Profiles. (a) Station 1, (b) Station 2, (c) Station 3

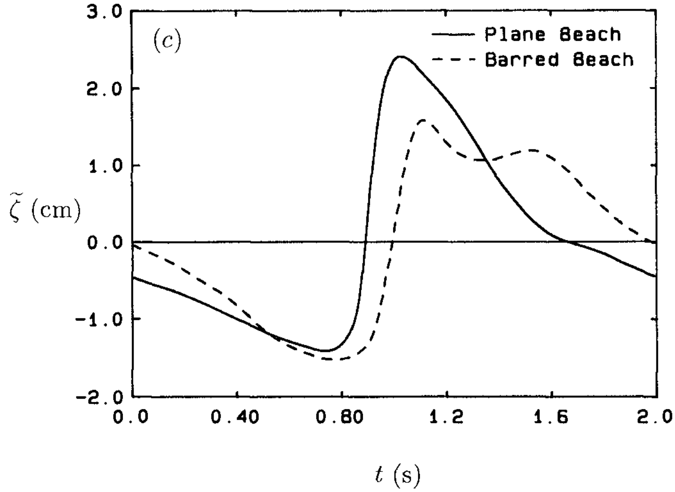


FIG. 3. (Continued)

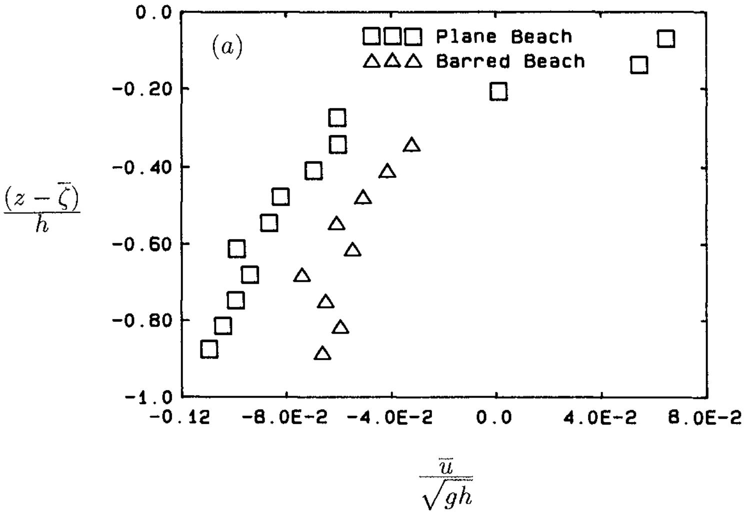


FIG. 4. Variation of Undertow with Depth. (a) Station 1, (b) Station 2, (c) Station 3

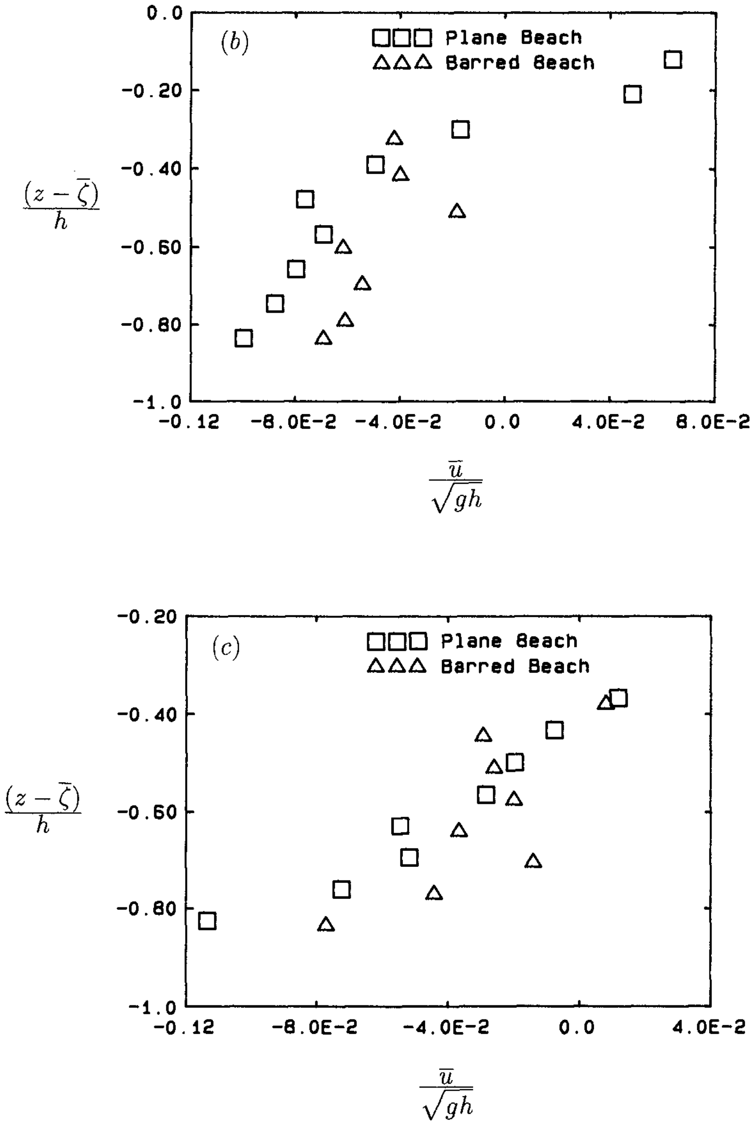


FIG. 4. (Continued)

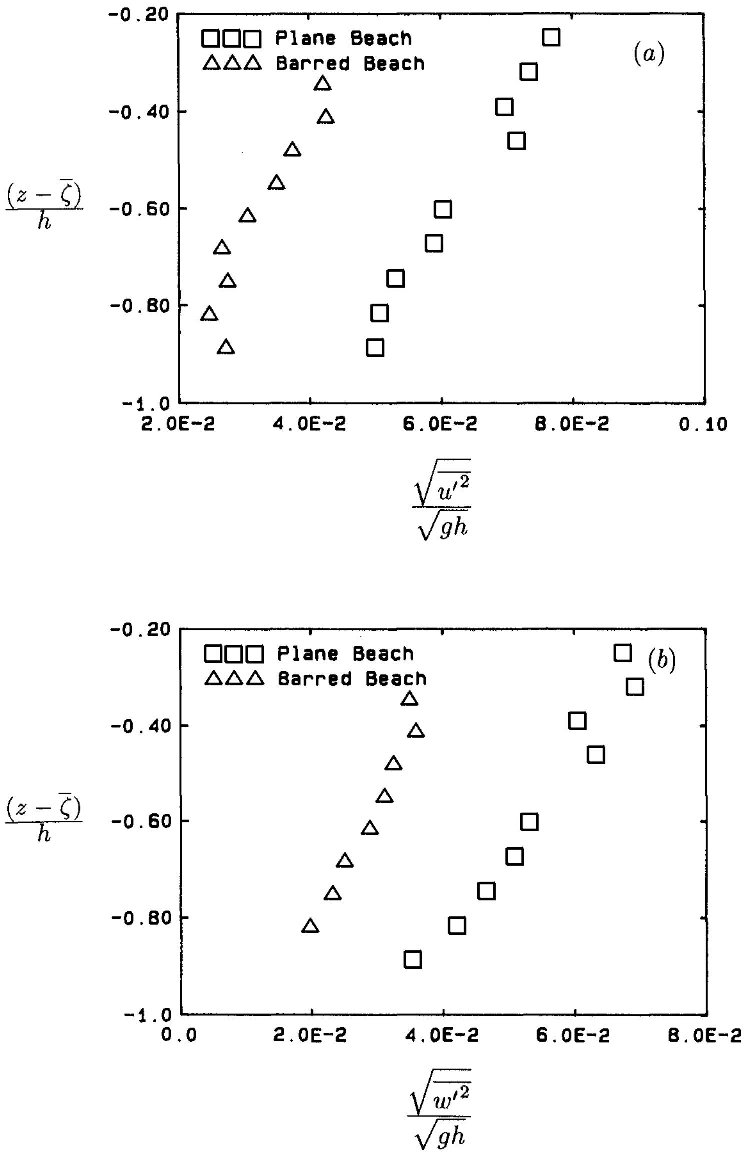


FIG. 5. Variation of Time Average Turbulent Velocity with Depth at Station 1. (a) Horizontal Component, (b) Vertical Component

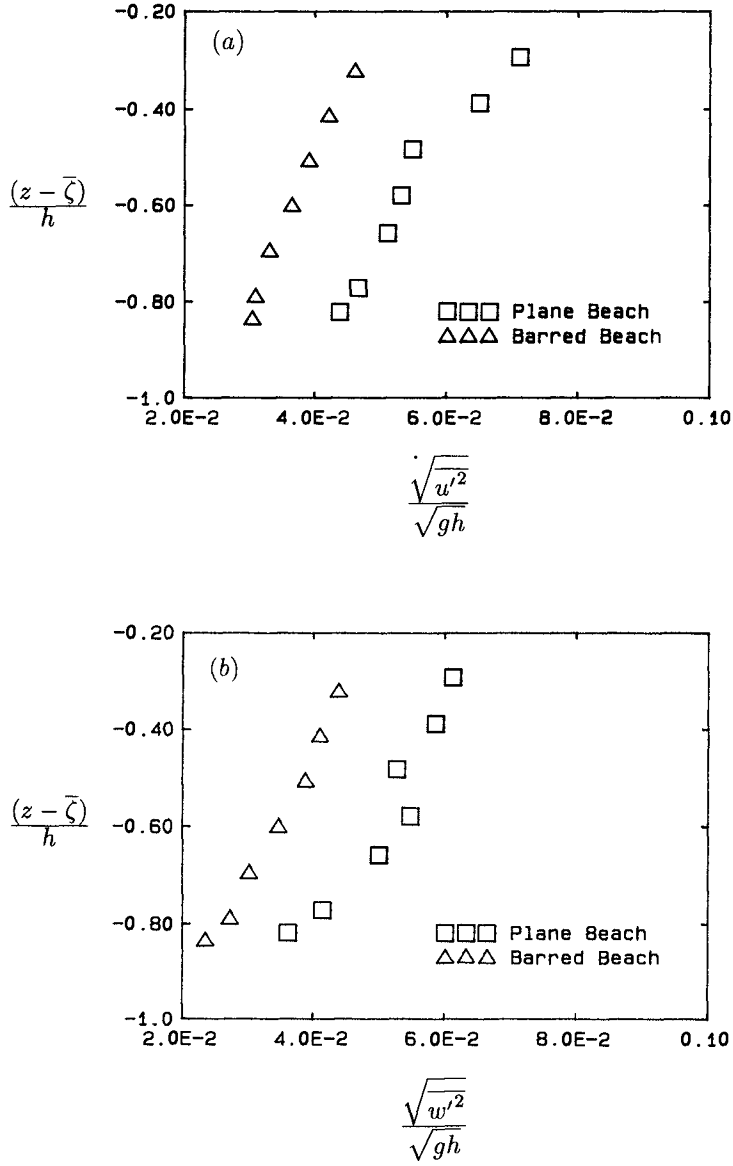
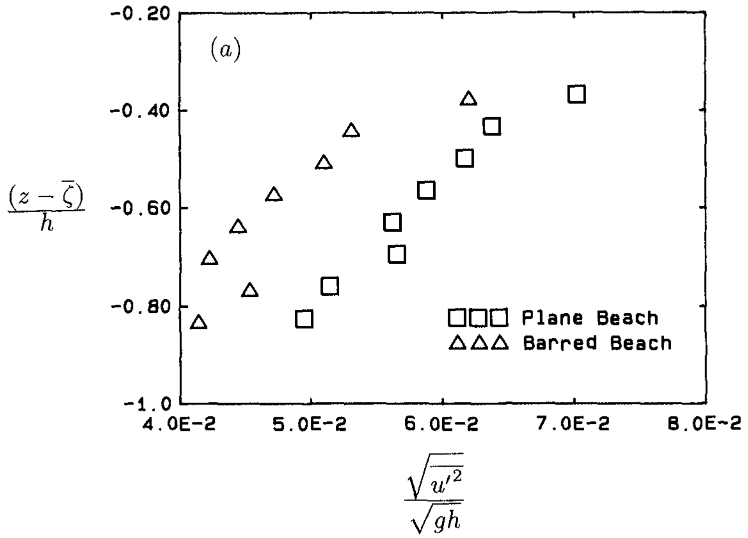


FIG. 6. Variation of Time Average Turbulent Velocity with Depth at Station 2. (a) Horizontal Component, (b) Vertical Component



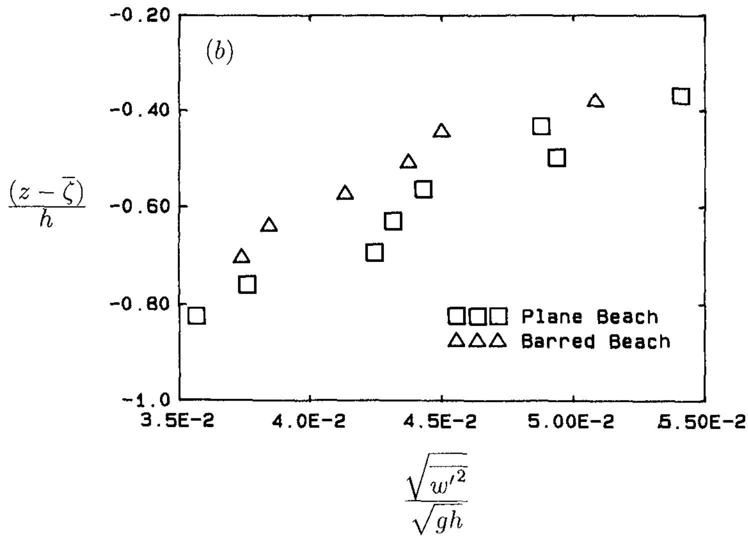


FIG. 7. Variation of Time Average Turbulent Velocity with Depth at Station 3. (a) Horizontal Component, (b) Vertical Component