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Rip Currents Generation and Longshore Currents behind Bars
離岸流 生成 原因 및 沿岸砂州 地形에서의 沿岸流 生成

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Abstract □ In this paper, previously proposed mechanisms of generation and maintenance of rip currents are grouped into three broad categories; (1) prismatic topography models, (2) non-prismatic topography models and (3) structural controls by natural and/or constructed features, such as headlands, piers, groins, jetties, etc. The prismatic models can explain the occurrence of a rip current on a planar beach, while non-prismatic model needs undulatory topography inside the surf zone to generate and maintain a rip current. Yet more detailed and thorough studies need to be conducted to include all relevant variables and to clarify the mechanism(s) governing rip current. Next, a simple model is presented to predict mean longshore currents behind a longshore bar (or submerged breakwaters) by considering mass transport over the bar and the bar morphology. This hydrodynamic model could be extended to include the sedimentary feedback mechanism.

要 旨: 本 論文에서는 離岸流의 生成·維持에 대한 模型을 크게 세가지로, 2次元 平面地形에서도 離岸流가 生成되어 維持될 수 있는 프리즘地形 模型 (prismatic topography models), 離岸流의 生成·維持를 위하여 碎波帶内의 3次元 海底地形을 必要로 하는 非프리즘地形 模型(non-prismatic topography models), 그리고 海岸線을 따른 突堤 또는 防波堤 등의 海岸構造物이 生成하는 離岸流 模型 등으로 分類하였다. 그러나 離岸流의 生成 · 維持에 關係되는 모든 變數들을 포함한 支配力學現象을 糾明하기 위해서는 더욱 더 많은 文獻硏究가 必要하다는 것을 알았다. 다음에 沿岸砂州 또는 潛堤 등이 存在하는 海底地形과 그 위로의 海水 傳達을 考慮하여 沿岸砂州와 海岸線 사이에 흐르는 海岸方向으로의 흐름現象을 豫測키 위한 理論的인 模型을 開發하였다. 이 水理模型은 流體力과 海底地形變換間에 서서히 發生하는 相互 干涉(slow feedback)을 고려할 수 있는 堆積物 移動模型과 함께 沿岸地域에서의 海底地形變換 豫測에 使用될 수 있으리라 思慮된다.

1. INTRODUCTION

A beach, the boundary between sea and land, is one of the most interesting places in the world. The beach is quite complex in structure being composed of air, water and sediment, resulting in dynamics characterized by nonlinear and nonequilibrium processes; hence it presents an eternal challenge to the coastal engineer. The challenge is due, in part, to so many processes, of which the underlying physics are still obscure, occurring simultaneously on various temporal and spatial scales with a large number of factors. One of these challenges is understanding and predicting the three-dimensional (3-D) hydrodynamics and sedimentary features associated with rip currents.

Rip currents are seaward-flowing jet-like concentrated currents extending beyond the breakerline, representing a major agent of surf zone water drainage, and carrying large quantities of sediment offshore. They can occur along a long straight beach periodically, near longshore barriers such as jetties or groins, and at relatively narrow and deep channels in sand bars. Rip currents have attracted the

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interest of coastal engineers because (1) they can modify the wave field by refraction and other interaction mechanism, (2) they can change the coastal configuration by removing and transporting significant quantities of sediment offshore, (3) they are a potential danger especially to unwary swimmers, and (4) they can refresh the surf zone water, thus affecting water quality in the nearshore region. Finally, in the design of segmented submerged or emergent breakwaters, there may a design rationale in the spacing of breakwaters to mimic the natural spacing of rip currents.

This paper provides a comprehensive review of previous studies on 3-D cellular circulation and morphology associated with rip currents. Also a simple model is presented to predict mean longshore currents behind a longshore bar by considering mass transport over the bar and the bar morphology.

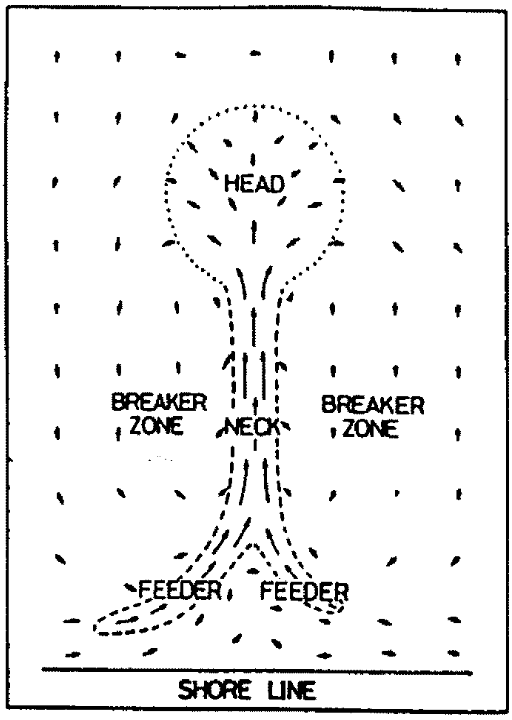

Fig. 1. Characteristics and adopted rip currents terminology (from Shepard, Emery and LaFond, 1941).

2. LITERATURE REVIEW

Considerable research has been carried out during the past 50 years, and has provided a wealth of knowledge in understanding and predicting quite complex beach processes associated with rip currents. Our present knowledge of rip currents is based on a combination of observed characteristics and proposed mechanisms of generation and maintenance.

2.1 Rip Currents in Nature

Shepard, Emery and LaFond (1941) reported the first scientific observations of rip currents, and recognized them as a main feature of the nearshore circulation system, which returned the water piled onto the beach by the waves and carried seaward fine sediments derived from the land. This wonderfully descriptive article clarified many of the physical characteristics of rip currents, primarily along the southern California beaches; many of the results presented are general. The terminology shown in Fig. 1 was advanced with the shore parallel flows toward the rip termed "feeder" currents, the main seaward-flowing current extending beyond the breaker zone, the "neck" and the flows in the offshore region in which the rip current lose its identity as the water spreads out, the "head".

Several features identified were: (1) Rip currents were present in cases where the waves arrived more or less normal to the shoreline, (2) The offshore distance to which the rips extended was approximately 300 to 800 m, (3) The widths of the rips ranged from 20 to 30 m, and (4) Rips usually occur off small indentations in the shoreline. Based in part on discussions with many lifeguards, the following were noted as possible visual indicators of the presence of rip currents: (1) Sediment laden water, (2) Green water at the ends of the rip heads (due to the greater depths in the scour channels), (3) Foam belts on the outer edges of the rip head, (4) Agitated water at the outer boundaries of the rip heads, (5) Gaps in the advancing waves, with the waves breaking much closer to shore, and (6) Seaward movement of floating objects. Based on observations and recordings conducted at Scripps Pier it was found that the incidence of rips was much greater during periods of large waves. The trajectories and velocities associated with rips were explored by tracking drogues that had large drag elements below the wa-

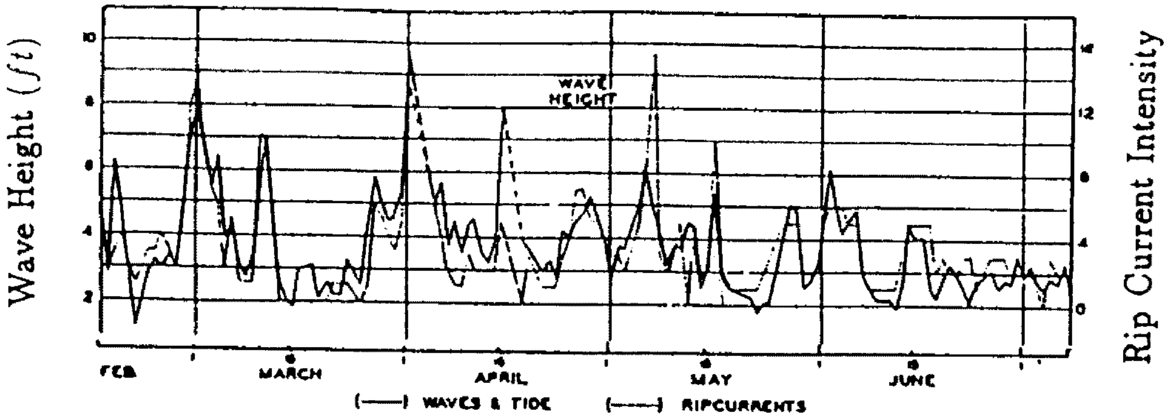

Fig. 2. Measured wave height and rip current intensity (from Shepard, Emery and LaFond, 1941). These data were obtained daily. Note the direct relationship between these two variables. Note the definition of zero intensity of rip current when wave height was 0.6 m (2 ft); which would suggest that wave height must be larger than 0.6 m for rip currents to form.

ter surface. The maximum currents were on the order of 1 m/sec.

It will be interesting to note that Shepard et al. defined zero intensity of rip current (the definition of intensity was not clear in their paper, but it appeared to be represented by the flow velocity in the rip neck) when wave height was 0.6 m (2 ft), as shown in Fig. 2; which would suggest that wave height must be larger than 0.6 m for rip currents to form. If waves were smaller than 0.6 m, then rip currents would disappear.

Another important result was the existence of the channels in the path of a rip current, which were largely confined to the surf zone and deeper than their surroundings. The floor of the channels was found to be decidedly irregular mainly due to the strong rip current. Shepard et al. noted that the position of the channels varied relatively rapidly as well as the positions of rip currents, as stated "three days after the survey, the inner channel had completely disappeared and no appreciable rip could be observed in the locality" (p. 355).

Shepard and Inman (1950a) investigated the nearshore circulation system near areas where diversified submarine topography occurs off relatively straight shorelines and found that the nearshore circulation system was definitely influenced by the wave divergence at the heads of submarine valleys and by the wave convergence over submarine ridges. Longshore currents adjacent to the shore diverged from areas of wave convergence and flowed seaward as rip currents at areas of wave divergence. This work implied the importance of the longshore wave height variations caused by wave refraction due to irregular offshore bottom topography.

In a second paper, Shepard and Inman (1950b) performed a comprehensive series of field measurements, and described the general circulation system on most beaches including two straight beaches with parallel bottom contours. It was found that the direction of the longshore currents was primarly dependent not only on the angle of wave incidence to the shoreline, but also on the longshore distribution of the wave set-up, greater in the zones of higher breakers along the beach. The longshore currents commonly flowed away from the zones of highest breakers toward the rip current. Although Shepard and Inman did not note why there were those variations of the set-up in the longshore direction on uniform beaches, they concluded that cellular circulation systems could occur and be maintained even under normal wave incidence on straight beaches with parallel contours.

McKenzie (1958) observed rip current systems on beaches with smooth offshore topography but undulatory surf zone topography of alternate shoals and channels, and categorized main factors affecting the occurrence of rip currents as summarized in Table 1. As listed in Table 1, McKenzie could not find any direct relationship between the rip cur-

Table 1. Factors affecting the occurrence of rip currents (from McKenzie, 1958)

Factors	Importance	Observation(s)
Size and Regularity of Waves	Determine the strength of rip currents	Small and numerous rips appeared under moderate waves; while larger but fewer rips were developed under large waves.
Tides	Affect the position of rip currents	Falling tides caused the change of channel angle with the beach, or gradually moved channel into new position with the same angle.
Wave Direction	Control wave angle and determine the rip currents direction	Rips tended to turn into the waves within the surf zone, and tended to turn away from the waves outside the surf zone.
Coastal Configuration	Control wave angle and wave energy distribution by wave refraction	No direct relation was observed between the rips and the distribution of wave energy.
Slope and Regularity of the Nearshore	Determine the incidence and strength of rip currents	Due to the amount of water transported landward on mildly sloping beaches, the incidence and strength of rip currents should be greater than on steeper beaches.

rents and longshore wave energy distributions, i.e., wave height distributions; instead, he observed that rip currents "do not, as might be expected, seek that part of the beach with least energy concentration but tend to move seaward in the vicinity of greatest wave activity" (p. 107). This argument seemed to contradict the circulation system flowing from higher energy zones to lower ones, as observed by Shepard and Inman (1950a). However, this could be explained by the difference in the nearshore zone topography, i.e., difference between undulatory offshore but planar surf zone as in the observation by Shepard and Inman and smooth offshore but undulatory surf zone topography as in McKenzie's observation, and also by considering both the correlation between the circulation and the surf zone topography and wave-current interaction at the location of rip currents, as will be discussed later.

Bowen and Inman (1969) performed field studies on the beach having smooth offshore topography and planar surf zone bed in order to confirm their laboratory results, which showed that the rip currents occurred at alternate antinodes of standing edge waves of the same frequency as the incident waves. Bowen and Inman measured incoming wave heights, the breaking wave heights and water depth, the width of the surf zone and also the spacing of the rip currents to confirm whether or not these were equal to the longshore wavelength of the edge waves, and found that rather regular spacing was in good agreement with the calculated longshore wave length of an edge wave of a particular mode. Bowen and Inman suggested that stationary interaction between incident waves and synchronous edge waves resulted in periodic longshore variations of breaking wave heights, which could drive such regular circulations on plane beaches.

Sonu (1972) observed wave-induced nearshore circulation and meandering currents on a beach with smooth offshore topography and surf zone undulations under essentially uniform breaking wave heights. By measuring the spatial distribution of the horizontal velocities, the current patterns, the wave set-up in the surf zone, and the time series of velocities inside the rip channels, he observed that the currents near the shoreline moved from shoal areas of lower waves to rip channel areas of higher waves, of which pattern seemed to contradict Shepard and Inman (1950a) but to agree with McKenzie (1958). Sonu then found that the current patterns followed precisely the same spacings as the undulation wavelength; he concluded that for uniform waves the surf zone undulation was an essential factor to the cellular circulation. By observing that floating balls followed the directions of the measured gradient of water surface. Sonu demonstrated that the currents were not driven by the gradient of the wave heights, but were driven by the gradient of the mean water surface, which were caused by radiation stresses.

2.2 Rip Current Generation Models

2.2.1 Introduction

Since field studies have recognized a longshore variation in the radiation stresses field and the wave-induced set-up as the main driving forces in the formation of rip currents, various analytical and numerical models were developed based on several mechanisms to explain the longshore wave height variability resulting in the variation of the radiation stresses field. The two factors are usually considered: (1) longshore variation in the breaking wave height, and (2) longshore variation in the bottom topography.

In the present analysis, the various mechanisms are divided into three categories: (1) prismatic and (2) non-prismatic topography models, and (3) structural control mechanisms. The distinction between the first two is that prismatic models can explain the occurrence of a rip current on a planar beach, while non-prismatic model needs undulatory topography inside the surf zone to generate and maintain a rip current. Structural control means that natural and/or constructed features, such as headlands, piers, groins, jetties, etc. along the shoreline can cause rip currents. Similarly, Dalrymple (1978) classified the models into (1) wave interaction and (2) structural interaction models according to the same criteria as the present study including the interaction with coastal structures.

Prismatic topography models require hydrodynamic longshore perturbations on a prismatic beach to provide the longshore variability of wave heights, which are enough to drive the rip currents. For the case of normally incident waves on a straight beach with fixed bed, no horizontal circulation is expected with uniform set-up in the longshore direction. However, the prismatic model considers that the wedge-shaped 3-D beach is very sensitive to instabilities in the longshore direction; hence the beach could not maintain the uniform state against longshore perturbations, which are considered mainly due to the wave-wave interactions (Bowen, 1969; Bowen and Inman, 1969, Sasaki and Horikawa, 1975; Dalrymple, 1975) or wave-currents interactions (LeBlond and Tang, 1974; Dalrymple and Losano, 1978) or some instability inherent to the nearshore hydrodynamics (Hino, 1974).

Non-prismatic topography models need undulatory bottom topography (Bowen, 1969; Noda, 1974; Mei and Liu, 1977; Schmidt, 1986) or 3-D bar morphology with rip channels (Dalrymple *et al.*, 1976; Dalrymple, 1978; Deigaard, 1986, 1990) to provide the driving forces which generate and maintain rip currents. Table 2 lists a number of the various models according to the present classification.

Before presenting details, it would be better to start by reviewing Bowen's work (1969) since his model first theoretically approached the rip current problem and furthermore could be classified as ei-

Table 2. Rip current generation mechanisms

(a) Prismatic topography models

Mechanisms	Representative Researcher(s)
Wave-wave interaction	
Synchronous edge wave	Bowen (1969), Bowen and Inman (1969)
Infra-gravity wave	Sasaki and Horikawa (1975)
Intersecting wave trains	Dalrymple (1975)
Wave-current interaction	LeBlond and Tang (1974) Dalrymple and Losano (1974)
2-D Instability with movable bed	Hino (1974)

(b) Non-prismatic topography models

Mechanisms	Representative Researcher(s)
Undulatory bottom topography	Bowen (1969), Noda (1974), Mei and Liu (1977), Schmidt (1986)
Bar morphology without sedimentary feedback	Dalrymple (1976), Deigaard (1986)
Bar morphology with sedimentary feedback	Dalrymple, Dean and Stern (1976), Deigaard (1990), Oh (1994)

ther prismatic or non-prismatic model since it was not clear in his analytical and numerical examples whether or not a longshore variation of the radiation stresses field was induced by the bottom topography's effects on the wave field. Bowen first presented a theoretical model to generate rip currents on a planar beach under normally incident waves having a longshore variation in wave height. Considering two possible mechanisms for such longshore perturbations: (1) a longshore undulation of the surf zone bed, and (2) the interaction of synchronous edge waves with the incident wave field, Bowen demonstrated that cellular circulations were driven by a longshore variation in the radiation stresses field in the surf zone, resulting in the currents flowing from higher to lower waves. Considering that Bowen assumed a linear relationship of local wave heights to the total water depth even at the location of the rips, the circulation would flow from the embayments of higher waves to the shoal areas of low waves, which seemed to be contradictory to most field studies carried out on undulatory beaches.

2.2.2 Prismatic Topography Models

Bowen and Inman (1969) found that progressive or standing edge waves with the same frequency as the incident wave (synchronous edge waves) could generate a nearshore circulation and presented the rip current spacing as,

$$L_r = L_e = L_o \ \sin \ \{(2n+1)\beta\} \qquad (1)$$

where, L_r is the rip current spacing, L_e the edge wave length, $L_o = gT^2/2\pi$, the deep water wave length, g the gravitational acceleration, β the planar beach slope and n is the mode of the edge wave, which is equal to the number of zero crossings of the water surface elevations in the offshore direction. The spacing of rip currents is not dependent on the wave heights but strongly dependent on the incident wave period, which was in good agreement with their field observations but appeared to contradict most of field studies (e.g., Shepard *et al.*, 1941), and has a maximum value of deep water wave length for the case of very steep beaches and/or high mode edge waves.

As given by Equation (1), it is always possible to select a combination of wave period, edge wave mode numbers and beach slope, which can nearly match the observed spacings; this would be a reason why the edge wave model is so attractive. However, Guza and Davis (1974) have shown that only subharmonic edge waves could be excited on a plane beach through a nonlinear resonant mechanism. These subharmonic edge waves were different from those suggested by Bowen and Inman (1969) and could not produce rip currents. Guza and Davis also have shown that surging conditions might be required for an edge wave model to be effective in causing rip currents.

Hino (1974) proposed a rip current generation model based on stability analysis of the steady-state uniform beach system on an initially plane beach but allowing a feedback between the movable bed and the flow field, and found that the system was hydrodynamically unstable for infinitesimal longshore perturbations, resulting in the most preferred spacing of rip currents of about four times the surf zone width,

$$L_r \cong 4X_b \qquad (2)$$

where X_b is the surf zone width, the distance from the shoreline to the breakers. Hino showed that these spacings agreed well with the observed data. Although this model allowed a sedimentary feedback for the growing and maintenance of rip currents, it could generate rip currents on an initially planar beach by hydrodynamic instability; hence, Hino's model was classified as prismatic topography model in the present study. This is the only proposed mechanism that considers a positive feedback between cellular circulation and the sedimentary system, but in practice requires specification of an "initial" condition which tends to include a two-dimensional bar and may not be well defined.

Leblond and Tang (1974) questioned Bowen's (1969) assumption that rip currents were sufficiently small so that their interaction with the wave field was negligible, and first applied energy equation including advection, wave-current interaction and dissipation terms. Together with the shallow water continuity and momentum equations and the fixed bed consideration, LeBlond and Tang posed an eigenvalue problem for the circulation cells inside the surf zone and performed a perturbation analysis. However, in solving the posed eigenvalue problem it was necessary to assume that rip currents would be most likely to occur where the relative rate of energy dissipation is least, i.e., LeBlond and Tang have looked for the longshore wave number that minimized the ratio of energy dissipation rate to the total kinetic energy present in a rip current system.

The resulting circulation pattern was found to be essentially the same as in the uncoupled case where wave-current interaction was neglected, with a somewhat modified wave field such that the energy coupling with the currents attenuated the waves in that area (this contradicts the usual wave-current interaction considerations, especially on a prismatic beach where there is no undulatory bottom topography, i.e., no differences in water depth along the longshore direction.), but the currents predicted by the coupled case were weaker due to hydrodynamic feedback, as excepted. However, their computed values of the longshore wave number were too small and did not compare well with available data. Furthermore, Dalrymple and Losano (1978) later found that LeBlond and Tang's work contained a significant numerical error, and concluded that their results were invalid.

Sasaki and Horikawa (1975) analyzed rip current spacings given by Bowen and Inman (1969) and by Hino (1974) according to the deep water surf similarity parameter, which is defined as the ratio of beach slope to the square root of deep water wave steepness, and found that these two models predicted the spacings which were always smaller than those observed in the field for the very mild beaches and could be applied only on beaches with steep and medium slopes; hence Sasaki and Horikawa proposed an infra-gravity wave model for the gentle beaches with spacings given by

$$L_r = 157\left(\frac{\tan\beta}{\sqrt{H_o/L_o}}\right)^2 X_b \qquad \left(0.22 > \frac{\tan\beta}{\sqrt{H_o/L_o}} > 0.08\right) \quad (3)$$

in which H_o/L_o is the deep water wave steepness. However, the mechanism to generate rip currents was actually the same as that of edge wave except with the forcing given by infra-gravity wave.

Dalrymple (1975) has shown on an open coast that intersecting wave trains of the same period could cause rip currents. If synchronous waves arrive from equal and opposite wave directions with respect to the beach they will cause a stationary longshore periodic set-up along the shoreline; which in turn leads to spatially periodic rip currents at nodal lines of which spacings are determined by the deep water wave length and directions of the waves, as follows:

$$L_r = \frac{L_o}{\sin\theta_1 - \sin\theta_2} \quad (4)$$

where θ_1 and θ_2 are the deep water wave angles of the two wave trains. It was noted that this model had no theoretical maximum spacing but a minimum of one half the deep water wave length. If the waves were not synchronous or the wave directions were not precisely opposite, the locations of wave set-up would propagate in the longshore direction. Dalrymple also carried out laboratory experiments to verify this model and the observed results agreed well with the predicted spacings. The spacings of rip current were strongly dependent on the incident wave period but had no relationship with the wave heights or the surf zone width, which was similar to the relationship proposed by edge wave mechanism.

Assuming an existing rip current, Dalrymple and Losano (1978) developed two analytical models to provide steady rip current system on a prismatic beach based on a hydrodynamic feedback through wave-current interaction. It was noted in their models that the energy equation was considered indirectly by a linear relationship between the wave height H and the total water depth $(h+\eta)$ as

$$H = \kappa(h+\eta) \quad (5)$$

where h is the still water depth, η is the set-up height, and κ is a breaking index of the order of unity (about 0.8).

The first model extended previous studies by LeBlond and Tang (1974) to include only the changes of the local wave length in the presence of rip currents, yet no rip currents occurred. Dalrymple and Losano then included the refraction of the waves on the currents in the second model, and found that this refraction caused the waves to impinge on the beach obliquely by forcing the incident waves to slow over the rip, thus generating longshore currents flowing from regions of high wave energy and set-up towards regions of low energy, i.e., the base of the rip, as suggested by Bowen (1969).

They presented the non-dimensional rip current spacing as a function of one parameter, defined as the ratio of the bottom slope to the friction, and later Dalrymple (1978) proposed an approximate equation

$$\lambda\ X_b \cong \frac{1}{A_D} + 2.8 \tag{6}$$

here, $\lambda X_b \equiv 2\pi X_b/L_r$ is the non-dimensional rip current spacing, $A_D = \kappa\pi \tan\beta/\{f(8+3\kappa^2)\}$, κ is the breaking index and f is a Darcy-Weisbach (constant) friction coefficient. Equation (6) predicts that the rip current spacing increases with increasing wave height as observed in the field. The spacing given in Equation (6) also increase with more smooth bottom, which is not clear in the field since it is difficult to define the bed smoothness in the field.

It was noted that work done by the currents against the radiation stresses appeared to reduce the wave energy at the location of rip currents. However, this mechanism seems to contradict the usual wave-current interaction such that the opposing current tends to increase the wave height due to the wave refraction and interaction on a counter current.

2.2.3 Non-Prismatic Topography Models

Noda (1974) developed a numerical model to obtain a steady-state nearshore circulation pattern considering the effects of bottom topography on an incident wave field, and found that, for an undulatory bottom, wave-bottom topography interaction changed the incident wave field according to bottom undulation, thereby causing spatial variation of the radiation stresses field, and that this variation of the radiation stresses field inside the surf zone ultimately derived the nearshore circulation flowing from the shoals to the embayments.

Although Noda obtained unrealistically large value of the maximum current velocity, numerical examples of his work to various bottom topography have verified the driving mechanism for the nearshore circulation due to the bottom topography's effects on the wave field. It was noted that a feedback between circulation currents and movable bottom should be provided to develop an equilibrium bottom configuration for a given wave forcing. Noda also pointed out that wave-current interaction would tend to modify the incident wave field, resulting in a more uniform breakerline as observed by Sonu (1972), thus reducing spatial variation of wave heights, hence consequently reducing the magnitude of the circulation velocity.

Dalrymple, Dean and Stern (1976) suggested a nearshore circulation model on a 3-D longshore bar crest-trough morphology, with the main driving forces given by the gradients in the set-up values behind the bar. Dalrymple *et al.* considered that these gradients in set-up could be induced both by wave reflection from the submerged sand bar and mass transport over the bar, and presented the circulation flows to regions of lesser set-up at rip channels. It was noted that by roughly considering sedimentary feedback, they could obtain minimum rip current spacings on the barred coastlines. Although no details were given, the basic idea seemed to be correct. The detail formulations of the hydrodynamics are given in Dalrymple (1978).

Mei and Liu (1977) developed a linear analytical model for the nearshore circulation driven by the effects of periodically varying topography confined within and near the surf zone. Assuming a small depth deviation from a plane beach, Mei and Liu found that the circulation pattern would be determined based on two effects: (1) variations in the set-up and in the tangential and transverse components of the radiation stresses to the wave direction which would tend to drive rip currents from the shoals to the embayments, and (2) variations in an additional component of the radiation stresses, representing the flux in the wave direction of the transverse component of momentum, which would tend to drive rip currents from the embayments to the shoals.

Relative magnitude of those two effects was controlled by both the bottom topography and the ratio of the surf zone width to the longshore wave length of the topography variation. However, Mei and Liu found that the circulation was always shorewards near the shoals and seawards near the embayments if the bottom undulations were entirely confined within the surf zone. They also obtained a counter-rotating circulation in a small region near the shoreline.

Dalrymple (1978) presented a model to include the effect of wave reflection from the bar as suggested by Dalrymple *et al.* (1976), and examined mean currents behind a longshore bar by considering (1) the continuity equation, which states that the mass transport over the bar crest should equal the increase in flow in the longshore trough between the bar and the beach, (2) the equation of motion within the trough, which is driven by the set-up differences, and finally (3) the momentum equation, which includes the radiation stresses and the reverse effect of momentum flux due to wave reflection by the bar.

By considering the differences between the set-up corresponding to uniform conditions without net flow (designated as potential set-up) and the set-up with net flow (designated as actual set-up), Dalrymple found that the mass transport over the bar increased continuously toward the rip channels, resulting in the longshore current velocity increasing from zero at the midpoint between two rip channels to the maximum value at the locations of the rip channels. In driving his equations, Dalrymple imposed no mass transport condition (i.e., actual set-up=potential set-up) at the center point of the bar, which seemed to be physically incorrect since mass transport at that point might occur depending on the length of the bar. If the bar length is short, then water would be transported over that point. The symmetric condition for the longshore velocity (i.e., zero longshore velocity) would be enough at that point.

Expecting that the set-up would be zero at the rip channels, Dalrymple obtained the minimum stable spacing of the channels as a function of the wave steepness and sediment size through bottom friction effects as well as several geometric parameters representing 3-D bar morphology. Dalrymple noted that, in addition to wave-current interaction, the sedimentary feedback mechanism should be incorporated into this hydrodynamic model. Even though some equations appears to be incorrect, the basic idea to consider the momentum equation near the bar area seems to be correct to describe the mean currents behind the longshore bar.

Deigaard (1986) presented an analytical model to calculate the longshore currents behind the bar, which was similar to Dalrymple's model (1978) but the reflection from the bar was not taken into account. Deigaard assumed that the flow rate over the bar was simply determined by the energy loss caused by the differences between the potential set-up and the actual set-up, and expressed the flow rate as;

$$q = h\sqrt{2g(\bar{\eta}_o - \bar{\eta})} \tag{7}$$

in which q is the flow rate, h the mean water depth over the bar crest, $\bar{\eta}_o$ the potential set-up, and $\bar{\eta}$ the actual set-up. Equation (7) considers that the total head loss in set-up values is fully contributed to the velocity head loss, thus neglecting unknown loss of internal energy which is usually involved in wave breaking process. Hence, Equation (7) tends to overestimate the flow rate, resulting in decreased longshore velocity. In this aspect, the momentum equation would be better application to the problem of determining the flow rate. This will be discussed in details later.

Deigaard also considered both the momentum equation within the trough neglecting bed friction and the continuity equation. By allowing mass transport at the center point of the bar, which depended on the length of the bar, he then obtained the longshore current velocity as a function of potential set-up and geometric parameters such as the length of the bar and cross sectional area of the trough. His results demonstrated the same trend as Dalrymple's model as the velocity increased and approached the maximum magnitude toward the rip channels.

However, his momentum equation, as presented in Equation (8), appeared to be incorrect since he neglected the first order term, i.e., the bed shear stress, and considered only the second order convective acceleration term. Furthermore, this second order term was considered incorrectly. This will be discussed later.

$$\frac{d}{dy}\left(\eta+\frac{Q^2}{gA^2}\right)=0 \tag{8}$$

Deigaard suggested the minimum stable spacings of rip channels by considering that the longshore velocity in the trough approached the possible maximum longshore velocity beyond certain distance from the center of the bar, which were of the order of two or three times the ratio of cross sectional area of the trough to the mean water depth over the bar crest.

Schmidt (1986) carried out experimental investigations on the hydrodynamics of wave-induced circulation over bar-channel topography which simulated a periodic form parallel to the coast superposed on a regular offshore sloping bottom. By measuring the distribution of wave heights, mean currents and time-dependent wave-induced vorticity, Schmidt concluded that this circulation associated with the bar morphology might be interpreted as a self-maintenance mechanism. During the experiments, Schmidt observed a shoreward-directed flow over the bar crest and a return flow from the trough regions, and concluded that higher breaking waves over the bar crest induced a larger set-up driving the flows to bar trough areas of lower waves and smaller set-up. But he could not observe the counter-circulation in a small region near the shoreline as obtained theoretically by Mei and Liu (1977). This effect was considered to be due to the absence of lateral mixing in the theoretical considerations by Mei and Liu.

Deigaard (1990) presented a model to explain the formation of rip channels on a barred coastline by performing a linear stability analysis. The equilibrium state was characterized by a uniform bar system under normally incident waves along the beach with no net current. The flow was described using essentially the same method as Deigaard (1986); However, in determining the flow rate over the bar crest, he included the momentum exchange inside the surf zone, resulting in an increase in the magnitude of the longshore velocity, thus reducing rip current spacings compared to those suggested by Deigaard (1986).

Deigaard then provided a perturbation to the longshore bar, which was periodic in the longshore direction, causing longshore variations in the set-up, finally resulting in a net circulation with shoreward flows over the bar crest, longshore currents in the trough and rip currents in the channels. By considering sediment transport due both to bed slope of the perturbation and to linearly-varying cross-shore transport with the water depth in the surf zone, Deigaard obtained the spacing of the rip channels, at which the perturbation would grow or decay in time with the maximum rate. When Deigaard considered a specific example, he could obtain the spacing of the order of about twice the surf zone width, which was defined as the distance from the shoreline to the bar crest.

It was noted that low period oscillations of the cross-shore discharge over the bar crest was necessary to obtain a linear theory; however, it is very questionable how he derived his cross-shore flow rate. Furthermore, his sediment transport equation, which showed a linearly varying transport rate with water depth, also seems to be incorrect.

2.2.4 Structural Controls

Natural and/or constructed features, such as headlands, piers, groins, jetties, etc. along the shoreline can cause rip currents. Dean (1978) explained three mechanisms for creating rip currents between groins. For the simplest case, these currents occur on the upwave side of the structure and are simply the seaward deflection of the longshore current induced in the surf zone by oblique waves. Currents can occur on the downwave side through wave sheltering and non-uniform wave heights and wave set-up. These currents have been termed "diffraction" currents by Gourlay (1976). For waves propagating normal to shore, it can be shown that energy losses at a groin cause more momentum transfer in deeper water than would normally occur and thus less shoreline set-up adjacent to the groins. This would tend to position seaward directed currents adjacent to the groins, a feature observed in nature. A similar explanation may apply due to wave energy losses by pilings under piers.

Wind and Vreugdenhil (1986) presented a numerical model to generate a rip current due to the interaction of longshore current with a longshore barrier such as groin and then compared the numerical results with the results of experiments in a closed basin with fixed bed. Their numerical model included all the terms in the depth-integrated momentum equations and the continuity equation, and investigated the relative importance of convection, diffusion and bottom friction in the flow over a sloping bottom.

They demonstrated that the combined effects of the bottom topography and convective terms caused the convergence of rip current streamlines over a seaward sloping bottom. When convective terms were excluded from the momentum equations, the rip current disappeared. They also found that the effect of bottom friction was to decelerate the rip current with diverging streamlines. For a given forcing, the total circulating flow rate was regulated by the bottom friction rather than the magnitude of the viscosity for the lateral shear stresses or convective term, which would be expected from the angular momentum balance of the circulating water mass. The lateral shear stresses were found to be responsible for closed streamlines outside the surf zone.

2.3 Discussions and Conclusions

As noted earlier, previous studies were not yet entirely clear to explain rip current generation; therefore, there are a number of significant issues relating to the mechanisms of rip current generation and/or maintenance. Several of these points are reviewed below.

(a) Can rip currents of significant strength form on a prismatic beach? The available field studies and theoretical investigations differ on this issue. It is possible that weak and ephemeral rip currents may occur, but that stronger and more permanent rips are associated with rip channels.

(b) Are the waves smaller at the location of the rip current? If so, are they smaller because of the presence of a channel and the associated lack of shoaling compared to the adjacent areas or because of refraction divergence associated with the channel or some other mechanism? Dalrymple and Losano (1978) contend that the waves are smaller due to work done by the waves on the currents. Somewhat surprisingly, the analytical treatment of cellular circulation on a plane sloping beach by LeBlond and Tang (1974) concluded that the waves were higher in the vicinity of onshore flows. However, it appeared to be clear based on usual consideration of a wave on a uniform current that the waves reach a greater height against the adverse seaward flowing current than with the assisting current. Laboratory observations on a prismatic beach (Oh, 1994) also have shown that the interaction of a seaward flowing currents with the waves causes an increase rather than a decrease of wave height. In conjunction with field observations that the wave heights are generally lower within the rip current than on either side of it, the most likely cause is that the shoaling/refraction effects caused by a rip channel are so significant that the wave height increase on the opposing current and the wave behavior is dominated by the channel.

Based on the literature review, conclusions are described below. The mechanisms proposed for rip current generation and maintenance range from the relatively simple to the complex, involving still questioned interaction mechanisms between waves and currents. The most simple is the mass transport of water over a beach recovery ridge, with the return of this mass transport being most hydraulically efficient when concentrated on rip channels. Since the wave induced sediment transport would tend to close these channels, they are separated a distance which provides an adequate amount of flow to overcome this closure tendency in a manner which is analogous to the behavior of tidal entrances. Channelization of the rip currents also seems necessary to explain the patterns of the wave-current interaction in the rips as described above. Detail explanation can be found in Oh and Dean (1994).

3. LONGSHORE CURRENTS ON BARRED COASTLINES

In this section, a simple model for calculation of the longshore currents on barred coastlines is

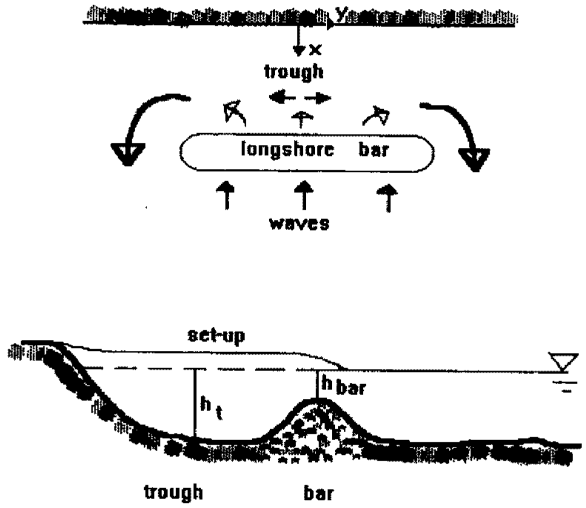

Fig. 3. Definition sketch for mean longshore currents on barred coastlines.

presented based on the basic idea suggested by Dalrymple *et al.* (1976). Fig. 3 shows the definition sketch of the problem. In this figure, the x-axis is directed seaward and the y-axis is located at the still water line, of which origin is located at the center point of the bar. The half length of the bar is designated as L.

3.1 Governing Equations and Boundary Conditions

As discussed in Chapter 2, three equations are necessary to describe the mean currents behind a longshore bar, i.e., (1) the continuity equation, which states that the mass transport over the bar crest should equal the increase in flow in the longshore trough between the bar and the beach, (2) the equation of motion within the trough, which is driven by the set-up differences, and finally (3) the momentum equation, which determines the flow rate over the bar.

The continuity equation is expressed as

$$\frac{dQ}{dy}=q_n \tag{9}$$

where, Q is the longshore discharge within the bar trough, and q_n is the net cross-shore flow rate over the bar.

The equation of motion within the trough can be described as

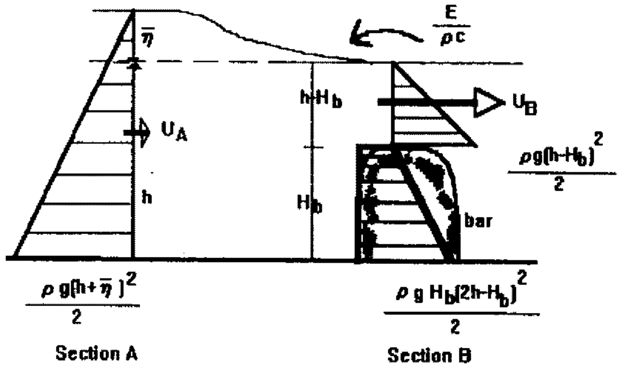

Fig. 4. Momentum theory applied to net flow over a bar.

$$V\frac{dV}{dy}=-g\frac{d\bar{\eta}}{dy}-fV \tag{10}$$

in which, $V(y)$ is the cross-sectionally-and time-averaged longshore current velocity, g the gravitational acceleration, $\bar{\eta}(y)$ the mean water level within the trough measured from the still water level, and f the linearized friction coefficient having the dimensions of [1/time]. The longshore discharge Q is related to the longshore current velocity V as follow:

$$Q=A\ V \tag{11}$$

where, A is the cross-sectional area of the trough. Employing the continuity equation, the Equation (10) can be expressed as

$$\frac{d}{dy}\left(g\bar{\eta}+\frac{Q^2}{A^2}\right)-\frac{Q}{A^2}q_n=-f\frac{Q}{A} \tag{12}$$

Deigaard (1986) considered the longshore momentum equation different from Equation (12), as presented in Equation (8).

$$\frac{d}{dy}\left(g\bar{\eta}+\frac{Q^2}{A^2}\right)=0 \tag{8}$$

Hence, Deigaard neglected the first order frictional force term and considered only the second order convective acceleration term, as discussed earlier. Also his momentum equation includes an error by neglecting the net cross-shore flow rate, which means that his momentum equation in the longshore direction does not satisfy the continuity equation.

Finally, the net cross-shore flow rate over the bar should be determined. Deigaard assumed that the flow rate over the bar was simply determined by the energy loss caused by the differences between the potential set-up and the actual set-up, which appeared inappropriate to this problem, as explained in the Chapter 2. Here, the flow rate is determined by considering the cross-shore momentum equation.

Considering the momentum theory to the broad-crested bar, as shown in Fig. 4, with the assumption that the reaction force from the bar is approximated by the hydrostatic force measured below the still water level within the trough and the shear force exerted on the bar is negligible, the following equation can be written based on the momentum change between section A and section B:

$$\rho(h-H_b)\ U_B^2-\rho h U_A^2=\frac{\rho g}{2}(h+\bar{\eta})^2-\frac{\rho g}{2}(h-H_b)^2-\frac{\rho g}{2}H_b(2h-H_b) \qquad (13)$$

where, h the water depth within the trough and H_b is the height of the bar crest and U_A and U_B represent the depth-averaged cross-shore net flow velocity at the sections A and B, respectively. If U_A can be assumed to be small (i.e., $U_A \cong 0$), then the net cross-shore flow rate, q_n, can be expressed as

$$q_n=\frac{E}{\rho C}-(h-H_b)U_B \qquad (14)$$

here, E is the total energy density of the incoming waves and C is the celerity of the wave. Hence, the first term in the right hand side of Equation (14) represents the inflow rate over the bar by incoming waves and the last term represents the outflow rate by the return flow.

If the longshore bar is uninterrupted by rip channels, no net flow occurs, resulting in the uniform set-up in the longshore direction (designated as the potential set-up, $\bar{\eta}_p$, by Dalrymple, 1978). For the uniform condition, the momentum equation between two sections can be expressed as

$$\rho(h-H_b)U_{Bp}^2=\frac{\rho g}{2}(h+\bar{\eta}_p)^2-\frac{\rho g}{2}(h-H_b)^2-\frac{\rho g}{2}H_b(2h-H_b) \qquad (15)$$

here, the subscript p indicates the potential values and U_{Ap} is assumed to be small. And from the condition that $q_n=0$ under the uniform condition, U_{Bp} can be obtained as

$$U_{Bp}=\frac{E}{\rho C(h-H_b)} \qquad (16)$$

Subtracting Equation (13) from Equation (15), and assuming that $\bar{\eta}_p$ and $\bar{\eta}$ are small relative to h, then

$$\bar{\eta}_p-\bar{\eta}=\frac{1}{g}\left(1-\frac{H_b}{h}\right)(U_{Bp}^2-U_B^2) \qquad (17)$$

Using Equations (14), (16) and the continuity equation, Equation (17) can be written as

$$\bar{\eta}=\bar{\eta}_p-\frac{1}{gh(h-H_b)}\frac{dQ}{dy}\left(\frac{2E}{\rho C}-\frac{dQ}{dy}\right) \qquad (18)$$

and then, $\bar{\eta}$ term can be eliminated from the longshore equation of motion, Equation (10), leaving

$$\frac{2}{h(h-H_b)}\frac{d^2Q}{dy^2}\left(\frac{E}{\rho C}-\frac{dQ}{dy}\right)-\frac{Q}{A^2}\frac{dQ}{dy}-f\frac{Q}{A}=0 \qquad (19)$$

Equations (18) and (19) can be solved if boundary conditions are given. As discussed in Chapter 2, Dalrymple (1978) imposed no mass transport condition at y=0, i.e., $\bar{\eta}=\bar{\eta}_p$ at y=0, which seemed to be incorrect since mass would be transported depending on the length of the bar. Hence, in the present study, the condition of zero longshore velocity is used at y=0, thus allowing mass transport at this point. Here, the boundary conditions are given as follows:

$$Q=0 \text{ at } y=0$$
$$\bar{\eta}=0 \text{ at } y=L \qquad (20)$$

3.2 Perturbation Methods

Equation (19) is a nonlinear equation of the longshore flow discharge Q. The simplest method to solve that equation will be employing linearization. However, the linearization of Equation (19) would be valid near $y=0$, where dQ/dy is considered to be small relative to $E/\rho C$. It may cause a significant error near $y=L$, where the net cross-shore flow rate is not negligible relative to $E/\rho C$: hence, near the base of the rip current, the neglected nonlinear term would play a significant role.

In the present study, Equation (19) is solved using perturbation methods. If the variables Q and $\bar{\eta}$ are decomposed into a summation of perturbed quantities as follows:

$$Q=Q_1+Q_2+\cdots$$
$$\bar{\eta}=\bar{\eta}_1+\bar{\eta}_2+\cdots \tag{21}$$

where the subscripts represent the order of the variables. Hence, the second-order terms are assumed to be much smaller than the first-order terms. Here, the basic state is considered as the uniform condition, where there is no longshore variations.

3.3 Perturbation Solutions

3.3.1 First-Order Perturbation Solutions

Substituting the perturbation expansions, Equation (21) into Equations (18) and (19), and gathering all the terms of first-order, the linear equations result.

$$\frac{d^2Q_1}{dy^2}-k^2Q_1=0 \tag{22}$$

where,

$$k^2=\frac{\rho Chf(h-H_b)}{2EA} \tag{23}$$

and

$$\bar{\eta}_1=\bar{\eta}_p-\frac{2E}{\rho Cgh(h-H_b)}\frac{dQ_1}{dy} \tag{24}$$

From the boundary conditions that $Q_1=0$ at $y=0$ and $\bar{\eta}_1=0$ at $y=L$, the resulting first-order solutions are

$$Q_1=\frac{\rho gCh(h-H_b)}{2Ek}\frac{\sinh ky}{\cosh kL}\bar{\eta}_p \tag{25}$$

$$\frac{\bar{\eta}_1}{\bar{\eta}_p}=1-\frac{\cosh ky}{\cosh kL} \tag{26}$$

3.3.2 Second-Order Perturbation Solutions

To the second-order,

$$\frac{d^2Q}{dy^2}-k^2Q_2=\frac{\rho C}{E}\frac{dQ_1}{dy}\left[\frac{d^2Q_1}{dy^2}+\frac{h(h-H_b)}{2A^2}Q_1\right] \tag{27}$$

$$\bar{\eta}_2=-\frac{2E}{\rho Cgh(h-H_b)}\frac{dQ_2}{dy}+\frac{1}{gh(h-H_b)}\left(\frac{dQ_1}{dy}\right)^2 \tag{28}$$

From the boundary conditions that $Q_2=0$ at $y=0$ and $\bar{\eta}_2=0$ at $y=L$, the second-order solutions can be obtained as follows:

$$Q_2=\frac{\rho C[\rho Cgh(h-H_b)]^2}{8E^3k\cosh^2kL}\left[1+\frac{E}{\rho CAf}\right]\bar{\eta}_p^2 \cdot\left[\left\{\left(\frac{1}{1+\frac{E}{\rho CAf}}-\frac{4}{3}\right)\cosh kL+\frac{2}{3\cosh kL}\right\}\cdot\sinh ky+\frac{1}{3}\sinh 2ky\right] \tag{29}$$

$$\bar{\eta}_2=\frac{\rho^2C^2gh(h-H_b)}{4E^2\cosh^2kL}\left(1+\frac{E}{\rho CAf}\right)\bar{\eta}_p^2 \cdot\left[\left\{\left(\frac{1}{1+\frac{E}{\rho CAf}}-\frac{4}{3}\right)\cosh kL+\frac{2}{3\cosh kL}\right\}\cdot\cosh ky+\frac{2}{3}\cosh 2ky-\frac{1}{1+\frac{E}{\rho CAf}}\cosh^2ky\right] \tag{30}$$

3.3.3 Perturbation Solutions

The first- and second-order solutions include the potential set-up term, $\bar{\eta}_p$, which can be determined by using the condition that $q_n=E/\rho C$ at $y=L$:

$$\bar{\eta}_p=\frac{2(\sqrt{3}-1)E^2}{\rho^2C^2gh(h-H_b)} \tag{31}$$

Then, the final solutions are given as follows:

$$\frac{Q}{A\sqrt{g\bar{\eta}_p}}=\frac{Q_1+Q_2}{A\sqrt{g\bar{\eta}_p}} =\sqrt{\frac{(\sqrt{3}-1)E}{\rho CAf}}\left[\frac{\sinh ky}{\cosh kL}+\frac{(\sqrt{3}-1)}{2\cosh^2kL}\cdot\left(1+\frac{E}{\rho CAf}\right)\left\{\left[\left(\frac{1}{1+\frac{E}{\rho CAf}}-\frac{4}{3}\right)\cosh kL+\frac{2}{3\cosh kL}\right]\sinh ky+\frac{1}{3}\sinh 2ky\right\}\right] \tag{32}$$

and

$$\frac{\bar{\eta}}{\bar{\eta}_p}=\frac{\bar{\eta}_1}{\bar{\eta}_p}+\frac{\bar{\eta}_2}{\bar{\eta}_p} =1-\frac{\cosh ky}{\cosh kL}-\frac{(\sqrt{3}-1)}{2\cosh^2kL}\left(1+\frac{E}{\rho CAf}\right)\cdot$$

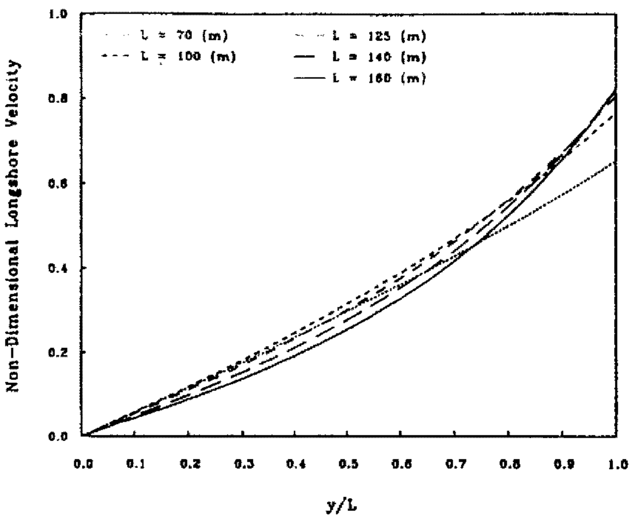

Fig. 5. Non-dimensional longshore velocity. Here L represents the half length of the bar, and y does the longshore distance from the center of the bar. Note the linear pattern of the velocity near $y=0$, while it demonstrates nonlinear pattern near $y=L$.

$$\cdot\left[\left\{\left(\frac{1}{1+\frac{E}{\rho CAf}}-\frac{4}{3}\right)\cosh kL+\frac{2}{3\cosh kL}\right\}\cdot\cosh ky+\frac{2}{3}\cosh 2ky-\frac{1}{1+\frac{E}{\rho CAf}}\cosh^2 ky\right] \qquad (33)$$

As presented in Equations (32) and (33), Q and $\bar{\eta}$ can be expressed as a function of following three dimensionless variables:

$$\frac{E}{\rho CAf},\ \frac{h(h-H_b)L^2}{A^2},\ \frac{y}{L}$$

The first parameter represents the ratio of the inflow rate over the bar to the flow rate in the longshore direction, the second one is defined as the ratio of the flow area in the cross-shore direction to that in the longshore direction. The last one is the non-dimensional distance from the center point of the bar in the longshore direction.

3.4 Numerical Example

Here, one simple numerical example is presented. Based on the following values:

$H_o=1.0$ (m)
$A=50$ (m^2)
$h=1.0$ (m)

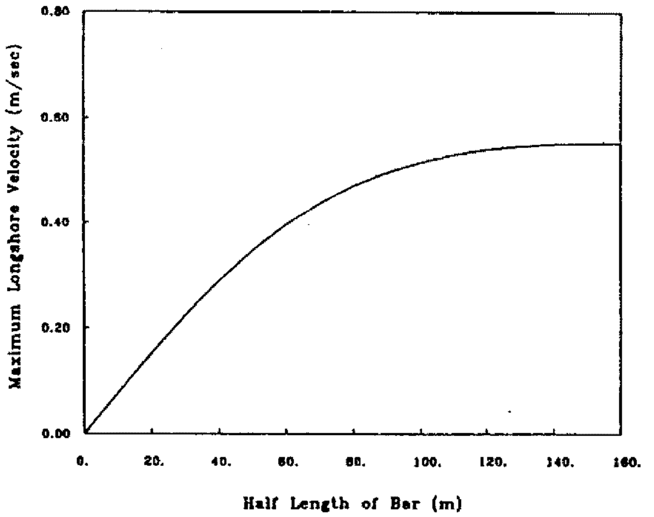

Fig. 6. Maximum longshore velocity. Note that the maximum velocity approaches a limit value as the half length of the bar increases.

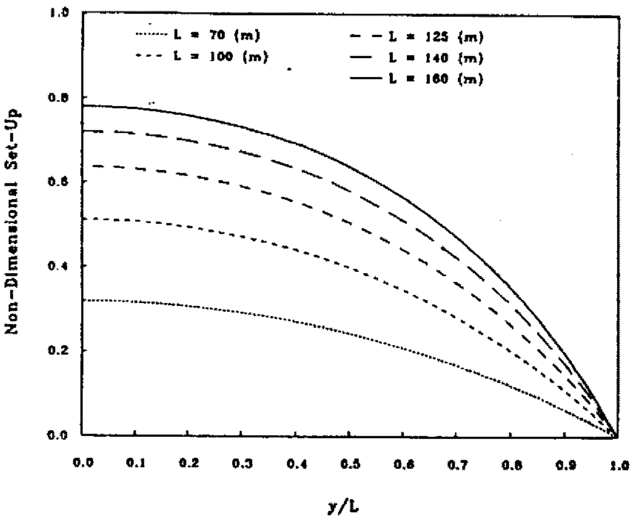

Fig. 7. Non-dimensional set-up. Here L represents the half length of the bar, and y does the longshore distance from the center of the bar.

$h-H_b=0.5$ (m)
$f=0.005$ (1/sec)

then, $\bar{\eta}_p$ and the first non-dimensional parameter are calculated as

$\bar{\eta}_p=0.046$ (m)

$$\frac{E}{\rho CAf}=1.5$$

The variation of the flow velocity presented in Equation (32) in the longshore direction is shown in Fig. 5. As shown in this figure, the longshore velocity increases monotonically toward the rip channel; hence, the maximum velocity for a given length of the bar occurred at the end of the bar ($y=L$). Near the center point of the bar (for small y), the velocity increases linearly; while, it shows nonlinear behavior near the rip channel, as expected. It should be noted that the maximum velocity appeared to approach a limit value. This trend is clearly seen in Fig. 6, which shows the maximum velocity as a function of the half length of the bar. The variation of the non-dimensional set-up presented in Equation (33) is depicted in Fig. 7. As the bar length increases, the actual set-up at $y=0$ approaches the potential set-up, which is expected.

4. SUMMARY AND CONCLUSIONS

In this study, previously proposed mechanisms of generation and maintenance of rip currents are grouped into three broad categories; (1) prismatic topography models, (2) non-prismatic topography models and (3) structural controls. In order to generate and maintain a rip current, the non-prismatic model needs undulatory topography inside the surf zone; while prismatic models can explain the occurrence of a rip current on a planar beach.

As noted earlier, previous studies were not yet entirely clear to explain rip current generation; more detailed and thorough studies need to be conducted to include all relevant variables and to clarify the mechanism(s) governing rip current, specially on the questions whether or not (1) rip currents of significant strength can form on a prismatic beach, and (2) the waves are smaller at the location of the rip current and if so, they are smaller because of the presence of a channel and the associated lack of shoaling compared to the adjacent areas or because of refraction divergence associated with the channel or some other mechanism.

Based on the literature review, it is concluded that the most simple mechanism is the mass transport of water over a beach recovery ridge, with the return of this mass transport being most hydraulically efficient when concentrated in rip channels. Since the wave induced sediment transport would tend to close these channels, they are separated a distance which provides an adequate amount of flow to overcome this closure tendency. Channelization of the rip currents also seems necessary to explain the patterns of the wave-current interaction in the rips.

Next, a simple model was presented to predict mean longshore currents behind a longshore bar (or submerged breakwaters) by considering mass transport over the bar and the bar morphology, which resulted in the nonlinear equation of the longshore velocity and was solved using perturbation method. A numerical example shows that the longshore velocity increases monotonically over the whole length of the bar. This hydrodynamic model could be extended to include the sedimentary feedback mechanism.

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