THE PROPER LONGSHORE CURRENT IN A WAVE BASIN

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ABSTRACT

This report describes the investigation into a method how to obtain the proper longshore current in a wave basin. In this method the basin geometry is optimized and the proper recirculation flow through openings in the wave guides is determined by minimizing the circulation flow between the wave guides. Using different wave fields, two beach slopes, two beach roughnesses and for most of the experiments a distribution system in the longshore current opening of the upstream wave guide, the width of the opening in the downstream wave guide and the recirculation flow were varied. The investigation shows that the adjustment of the longshore current has to be done carefully in order to achieve uniformity along the beach and the correct magnitude and distribution normal to the beach. A calculation of the order of magnitude of the terms of the equations of motion with some of the experimental results shows that the non-linear inertial and lateral friction terms cannot be neglected in rip current, non-uniform longshore current and nearshore circulation calculations.
1. INTRODUCTION

Since the introduction of the concept of radiation stresses by Longuet-Higgins and Stewart (1964), the theory of longshore currents induced by waves breaking obliquely on beaches has progressed considerably: Bowen (1969), Thornton (1969), Longuet-Higgins (1970), Battjes (1974, 1975), Jonsson, Skovgaard and Jacobsen (1975), Liu and Dalrymple (1978) and Skovgaard, Jonsson and Olsen (1978). The theoretical achievements obtained by these authors call for an accurate comparison with experimental results, as some of the assumptions done in the studies above mentioned are rather crude. Moreover, most of the longshore current models comprise coefficients which, for the present state of knowledge, have to be derived from experiments. For instance: the model proposed by Skovgaard et al. (1978) comprises two lateral friction coefficients, one for the surf zone resulting from Battjes' (1975) eddy viscosity model and one for the zone seaward of the breaker line, and a bottom friction coefficient.

Measurements of longshore currents have been done, both in the field: see the reviews of Galvin (1967), Galvin and Nelson (1967) and Komar (1975), recently in the Nearshore Sediment Transport Study, see Gable (1981) and Seymour and Gable (1981), and in the laboratory: Putnam, Munk and Traylor (1949), Saville (1950), Brebner and Kamphuis (1963) and Galvin and Eagleson (1965).

In most of the field and laboratory measurements of longshore currents the "longshore current velocity" was measured. In general it is defined as the averaged (over the width of the surf zone) current velocity, but also other definitions have been used. These measurements are not appropriate for a comparison with the present longshore current theories. The variation of the longshore current normal to the shoreline was in fact only measured by Galvin and Eagleson (1965) in the laboratory and in the Nearshore Sediment Transport Study in the field. Care must be taken in comparing Galvin and Eagleson's (1965) measurement results with theoretical longshore current profiles,
since the measured currents were not uniform along the beach.

Komar (1975) concluded "..... that more and better measurements of longshore current generation are required. These should be field rather than laboratory measurements since there appears to be some difficulty with the laboratory data. In some cases this may be the effect of the finite length of the laboratory beach not permitting the current to accelerate to its equilibrium value". More and better longshore current measurements are still required and of course also more and better field measurements of longshore currents. In this respect reference is made to the successful Santa Barbara experiment of the Nearshore Sediment Transport Study, which was performed in 1980, see Guza and Thornton (1980). Field measurements have, compared with wave basin measurements, however, at least two not unimportant disadvantages: field measurements are very expensive and the circumstances are uncontrollable. Therefore, if in a wave basin the longshore current (and the longshore sediment transport) could be properly reproduced, this would be favourable.

Dalrymple, Eubanks and Birkemeier (1977), see also Kamphuis (1977), measured circulation streamlines and "longshore velocities along the surf zone" in the three commonly used wave basin configurations. These are:

(1) a basin as used by Brebner and Kamphuis (1963) with surf zone openings in both wave guide walls to allow recirculation; the recirculation flow takes place behind the wave generator or through a pipe under the beach,

(2) the completely enclosed wave basin as used by Putnam, Munk and Traylor (1949) and Saville (1950),

(3) a basin as used by Calvin and Eagleson (1965) with an opening in the downstream wave guide wall and with an opening under the wave board to allow recirculation.
Dalrymple et al. (1977) concluded: "the type (1) basin would reduce the amount of return flow in the offshore region if a working recirculation procedure could be devised".

The purpose of the present investigation was to develop such a procedure for a basin similar to that of type (1) but equipped with a pump to effect the recirculation and with longshore current openings in the wave guides. This procedure should be as efficient as possible in view of time and installation to obtain the proper uniform longshore current in a wave basin. The investigation was restricted to regular waves.
2. THE PROPER LONGSHORE CURRENT FLOW

To approximate the longshore current flow generated by a uniform wave field on a straight infinitely long and uniform beach, a wave basin configuration was chosen with longshore current openings in both wave guide walls and with an external recirculation which is affected completely by a pump (fig. 2.1). Very likely the choice of such a wave basin is the only way to obtain a uniform longshore current in a straight wave basin *, it means, however, also that values for the following unknown quantities have to be chosen:
- the recirculation flow rate $Q_r$,
- the width of the longshore current opening in the downstream wave guide (= the distance in the direction normal to the coast between the wave set-up line and the end of the downstream wave guide),
- the distribution of the recirculation flow rate $Q_r$ in the distribution system in the opening of the upstream wave guide.

The criterion for the proper longshore current generated by a uniform wave field on a laboratory beach is that the profile is uniform along the beach, or also that the slope of the mean water level in longshore direction is zero. It is, however, impossible to optimize the recirculation procedure from measurements of mean water level in longshore direction. This is caused by the limited length of a wave basin and the inevitable, small variation along the shoreline of wave set-up and set-down. Therefore an alternative method has been developed. In this method the wave basin geometry and the proper (external) recirculation flow $Q_{ru}$ are determined such that the (internal) circulation flow $Q_c$ is minimized (fig. 2.1). $Q_{ru}$ is the recirculation flow $Q_r$ which yields the uniform longshore current.

* The spiral wavemaker of Dalrymple and Dean (1972) operating in the center of a circular wave basin with a circumferential beach eliminates also the end effects present in the types (1), (2) and (3) wave basin configurations.
Fig. 2.1 - Plan view of wave basin (slope 1:10).

Definition sketch $Q$, $Q_c$. 

flow $Q_{u}$. The longshore current flow $Q$ is defined as the flow running parallel to the shoreline between the wave set-up line and the line where the depth averaged current velocity is zero, the circulation flow $Q_{c}$ as the flow parallel to the shoreline between this line and the wave-board. This method is based on the physical expectation that in an optimized wave basin geometry $Q_{c}$ is minimal for $Q = Q_{u}$, because:

- if $Q_{r} < Q_{ru}$, i.e. also $Q < Q_{u}$, the flow $Q$ increases in longshore direction and at the downstream end of the basin this increment returns offshore in $Q_{c}$, yielding an increase of $Q_{c}$,

- if $Q_{r} > Q_{ru}$ the surplus generates a circulation flow in the basin (by convection and lateral friction): resembling an eddy between two groynes in a river.

To verify this method experiments were carried out in which the following quantities (and qualities) were varied:

- the width of the longshore current opening in the downstream wave guide wall,

- the influx of the recirculation flow $Q_{r}$: without or with a distribution system,

- the recirculation flow $Q_{r}$,

- the wave field quantities,

- the slope of the beach and the beach roughness.

The completely enclosed wave basin and the basin with surf zone openings in both wave guide walls and an external recirculation achieved without a pump were also investigated.

Some results of the investigation were published earlier, see Visser (1981).
3. EXPERIMENTAL PROCEDURE

The experiments were performed in the 16.60 × 34.00 m² wave basin (fig. 2.1 and fig. 3.1) of the Laboratory of Fluid Mechanics of the Delft University of Technology. The wave generator is of the snake-type and can produce only regular waves. The wave board consists of rubber panels, each 0.40 m wide. The stroke of the wave board at the bottom can be varied from zero (pure rotation) to the stroke at the still water level (pure translation). In all experiments the combination of translation and rotation was chosen such that the amplitude of secondary waves was expected to be minimal. Opposite to the wave generator smooth concrete beaches were constructed with slopes 1 : 10 (fig. 2.1) and 1 : 20 (fig. 3.1), respectively. The beach in the last experiment (slope 1 : 20) was roughed by bonding 5 - 9 mm gravel with a thin grout on the smooth concrete. The wave guide walls were composed of concrete elements and installed at angles of 15.4 or 31.0 degrees to the normal to the wave board.

The external recirculation took place through a pipe with diameter 0.80 m by means of a pump. The recirculation flow $Q_r$ can be varied continuously from 0 to about 150 l/sec (1=litre).

The distribution system in the longshore current opening of the upstream wave guide consisted of 12 channels each 1.20 m long (in longshore direction) and 0.20 m (1 : 10 slope) or 0.40 m (1 : 20 slope) wide (in the direction normal to the wave board). It was possible to vary the distribution of the recirculation flow $Q_r$ over the 12 channels of the system with gates, slide-valves, etc. The distribution system on the 1 : 20 slope was constructed such that the waves outside the surf zone were guided as well as possible. The recirculation flow $Q_r$ was distributed according to the expected distribution of the longshore current flow.

Fig. 2.1 shows the position of the 7 sections in which measurements of current velocity were performed in the experiments on the 1 : 10 slope, fig. 3.1 shows the position of the 5 sections
Fig. 3.1 - Plan view of wave basin (slope 1:20).
in which current velocity measurements were done in the experiments on the 1:20 slope. The distance in a section between two measuring points was: on the 1:10 slope 0.20 m in the longshore current zone and 0.40 – 0.60 m in the offshore region, and on the 1:20 slope 0.40 m (and 0.20 m near the water line). The current velocity was measured near the surface, at mid-depth (except for the shallow zone very near the water line) and near the bottom. It was measured by timing the excursion of dye (K2MnO4) over a certain distance (0.30, 0.50, 0.80 or 1.00 m, depending on the velocity) perpendicular to a measuring section. To this end, near each measuring section strings were stretched parallel to the section and just above the waves. In the surf zone it was not possible to follow the dye over distances exceeding about 1.00 m because of the rather fast spreading of dye by turbulence in this zone. In view of the accuracy, the number of observations giving one measurement result (that is a velocity in a certain point at a certain depth) was increased and the measurements were conducted by two persons in this zone. Outside the surf zone, the spreading of dye was rather small and there the measured excursion time of dye was at least 3 seconds. The minimum number of observations to obtain a result was:
- in the surf zone : at least 20,
- near the surf zone : at least 10,
- remaining region : at least 5.

The observations were started in different phases of the waves to eliminate the influence of the orbital velocities on the measurement results. Dye was chosen based upon the result of an investigation by the Delft Hydraulics Laboratory (1977), in which the application of floats, dye, the micro-propeller current meter and the Ott propeller current meter was examined.

Wave set-up and set-down were measured in sections 1 and 2 with tappings, flush-mounted in the beach. The horizontal distance between 2 tappings was: on the 1:10 slope 0.10 m in the surf zone and 0.20 m outside the surf zone, on the 1:20 slope 0.20 m in the surf zone and 0.40 m outside this zone. The tappings were connected with pots,
in which the static head was measured.

Measurements of wave heights were performed with resistance wave probes. The distance between two measuring points was: 0.10 m in the surf zone and 0.20 m outside this zone for the measurements on the 1 : 10 slope, 0.20 m for the measurements on the 1 : 20 slope. In the constant depth part of the basin wave heights were measured in 5 sections (yielding a number of about 100 measuring points). In the slope zone wave heights were measured in sections 1 and 2 and, to measure the position of the breaker line and the mean breaker height, in 3 – 5 sections parallel to the wave board on and near the breaker line, each section containing 29 measuring points on a mutual distance of 0.20 m.

Measurements of angles of incidence were done:
- in the constant depth part of the basin with wave probes (directly after the start of the wave generator in a yet undisturbed wave field),
- on the breaker line by photograph.

The results of the measurements of wave heights, angles of incidence, breaker depths, maximum wave set-up and breaker types are listed in table 3.1. These wave field quantities were always measured in the optimized wave basin geometries with the uniform longshore current flows. The wave height and angle of incidence on deep water were calculated from the measured values on constant depth part of the basin using linear wave theory and Snell's law. The breaker line is here defined as the averaged (along the shoreline) position of the measured breaker points. A breaker point is here defined as the point in which the wave height is maximal (in a section normal to the coast): at the shoreward side of this point the wave height decreased (more or less) continuously.

The experiments can be summarized as follows (the numbers correspond with the experiment numbers of table 3.1):

1. extensive series of measurements on the 1 : 10 slope with one wave
<table>
<thead>
<tr>
<th>exp. nr.</th>
<th>beach</th>
<th>tga</th>
<th>T (sec)</th>
<th>h₁ (cm)</th>
<th>θ₁ (deg)</th>
<th>H₁ (cm)</th>
<th>H₀ (cm)</th>
<th>θ₀ (deg)</th>
<th>Hₘₐₓ (cm)</th>
<th>hₘₐₓ (cm)</th>
<th>θₘₐₓ (deg)</th>
<th>ηₘ (cm)</th>
<th>wₛ (cm)</th>
<th>breaker type</th>
<th>(\frac{tga}{H₀/\lambda₀} )</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>smooth</td>
<td>0.101</td>
<td>2.01</td>
<td>39.9</td>
<td>31.1</td>
<td>7.2</td>
<td>9.8</td>
<td>61.5</td>
<td>10.5</td>
<td>10.4</td>
<td>1.00</td>
<td>20.9</td>
<td>4.20</td>
<td>145</td>
<td>pl.</td>
</tr>
<tr>
<td>2</td>
<td>smooth</td>
<td>0.101</td>
<td>1.00</td>
<td>39.9</td>
<td>30.5</td>
<td>9.5</td>
<td>10.2</td>
<td>32.5</td>
<td>10.0</td>
<td>10.9</td>
<td>0.91</td>
<td>24.0</td>
<td>2.78</td>
<td>137</td>
<td>pl.</td>
</tr>
<tr>
<td>3</td>
<td>smooth</td>
<td>0.101</td>
<td>1.00</td>
<td>40.1</td>
<td>15.4</td>
<td>8.9</td>
<td>9.6</td>
<td>16.4</td>
<td>9.7</td>
<td>11.4</td>
<td>0.85</td>
<td>12.1</td>
<td>2.75</td>
<td>142</td>
<td>pl.</td>
</tr>
<tr>
<td>4</td>
<td>smooth</td>
<td>0.050</td>
<td>1.02</td>
<td>35.0</td>
<td>15.4</td>
<td>7.8</td>
<td>8.5</td>
<td>17.0</td>
<td>9.1</td>
<td>11.0</td>
<td>0.83</td>
<td>12.5</td>
<td>1.64</td>
<td>250</td>
<td>pl.</td>
</tr>
<tr>
<td>5</td>
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<td>0.050</td>
<td>1.85</td>
<td>34.8</td>
<td>15.4</td>
<td>7.1</td>
<td>7.5</td>
<td>26.4</td>
<td>10.8</td>
<td>11.8</td>
<td>0.92</td>
<td>11.5</td>
<td>2.45</td>
<td>275</td>
<td>pl.</td>
</tr>
<tr>
<td>6</td>
<td>smooth</td>
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<td>0.70</td>
<td>35.0</td>
<td>15.4</td>
<td>5.9</td>
<td>6.0</td>
<td>15.5</td>
<td>5.8</td>
<td>8.8</td>
<td>0.66</td>
<td>14.3</td>
<td>1.05</td>
<td>192</td>
<td>sp./pl.</td>
</tr>
<tr>
<td>7</td>
<td>rough</td>
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<td>1.02</td>
<td>35.0</td>
<td>15.4</td>
<td>7.8</td>
<td>8.5</td>
<td>17.0</td>
<td>9.0</td>
<td>12.2</td>
<td>0.74</td>
<td>12.2</td>
<td>1.64</td>
<td>272</td>
<td>pl.</td>
</tr>
</tbody>
</table>

Table 3.1 - Beach and wave field properties and quantities;

\(\alpha\) = slope angle, \(T\) = wave period, \(h\) = still water depth, \(\theta\) = angle of wave incidence, \(H\) = wave height, \(\eta_m\) = maximum wave set-up, \(w_s\) = mean width surf zone (from wave set-up line to breaker line), \(\lambda\) = wave length, the indices 0, 1 and br refer to values on deep water, constant depth part of the basin and the breaker line, respectively; \(H₀\) and \(θ₀\) were calculated from \(H₁, h₁\) and \(θ₁\) with the linear wave theory and Snell's law.
field in different wave basin geometries:

1.A. wave basin with undistributed influx of the recirculation flow $Q_r$
    which is effected by a pump:
    - width opening in the upstream wave guide = 1.3 \times width surf zone,
    - width opening in the downstream wave guide varied from 1.0 \times
      width surf zone to 2.0 \times width surf zone (ratios of 0.97, 1.17,
      1.31, 1.45 and 2.00),
    - recirculation flow $Q_r$ varied from 0 l/sec to 59 l/sec,
    - measurements of wave set-up and wave heights for the calculation
      of the longshore current flows and the width of the surf zone,
    - velocity measurements in section 2 (located near the middle of the
      beach) from the wave set-up line to the wave board,
    - for the uniform longshore current situation also velocity measure-
      ments in sections 5 and 6 perpendicular to the wave guides, and
      in the "longshore current zone" in sections 0, 1, 3 and 4.

1.B. wave basin with distributed influx of the recirculation flow $Q_r$
    which is effected by a pump:
    - width opening in the downstream wave guide wall varied from 1.0
      \times width surf zone to 1.6 \times width surf zone (ratios of 0.97, 1.17,
      1.31, 1.45 and 1.59),
    - recirculation flows of 25, 30, 35, 40, 45 and 50 l/sec,
    - velocity measurements in section 2 (located near the middle of the
      beach) from the wave set-up line to the wave board,
    - in the uniform longshore current case also velocity measurements
      in sections 5 and 6 and in the longshore current zone in sections
      0, 1, 3 and 4, and measurements of wave set-up, wave heights and
      angles of incidence.

1.C. completely enclosed wave basin:
    - velocity measurements in section 2 from the wave set-up line to
      the wave board, in sections 0, 1, 3 and 4 in the longshore
      current zone and in sections 5 and 6.

1.D. wave basin with surf zone openings in both wave guides and a free
    external recirculation:
    - free recirculation (no pump), i.e. distributed influx of the
recirculation flow is not possible,
- width opening in both wave guides = width surf zone,
- velocity measurements in section 2 from the wave set-up line to the wave board and in sections 0, 1, 3 and 4 in the longshore current zone.

The experiments 2 through 7 were all performed in the wave basin with longshore current openings in both wave guides and an external recirculation which is effected completely by a pump.

2. experiment on 1 : 10 slope in which
- distribution of the recirculation flow in inlet system,
- width opening in the downstream wave guide = 1.3 * width surf zone,
- recirculation flows of 20, 30, 35, 40, 45, 50, 60 and 70 l/sec,
- velocity measurements in section 2 (located near the middle of the beach) from the wave set-up line to the wave board,
- for the uniform longshore current situation measurements of velocity also in the longshore current zone in sections 0, 1, 3 and 4, and of wave set-up, wave heights and angles of incidence,
- for \( Q_r = 0.8 \times Q_{ru} \) and \( Q_r = 1.2 \times Q_{ru} \) also velocity measurements in the longshore current zone of sections 0, 1, 3 and 4 (to prove that deviations from the proper recirculation flow \( Q_{ru} \) yield deviations in the uniformity of the longshore current).

3. series of measurements on 1 : 10 slope in which
- distributed influx of the recirculation flow,
- width opening in the downstream wave guide = 1.4 * width surf zone,
- recirculation flows of 10, 20, 30, 40, 50, 60, 70 and 80 l/sec,
- velocity measurements in section 2 (located near the middle of the beach) from the wave set-up line to the point in which the direction of the depth averaged current velocity became opposite to the longshore current direction (minimizing of the circulation flow \( Q_c \) by minimizing \( Q - Q_r \)),
- for the "$Q - Q_r$ is minimal" situation measurements of velocity also in sections 0, 1, 3 and 4 in the longshore current zone, and of wave set-up, wave heights and angles of incidence,
- for $Q_r = 0.75 \times Q_{ru}$ and $Q_r = 1.25 \times Q_{ru}$ also velocity measurements in the longshore current zone in sections 0, 1 and 3.

4. experiment on 1 : 20 slope in which
- distribution of the recirculation flow in inlet system,
- width opening in the downstream wave guide $= 1.2 \times$ width surf zone,
- recirculation flows of 30, 40, 50, 60, 70 and 80 1/sec,
- velocity measurements in section 2 as in experiment 3,
- for the uniform longshore current situation measurements of velocity also in sections 0, 1, 3 and 4 in the longshore current zone, and of wave set-up, wave heights and angles of incidence.

5. series of measurements on 1 : 20 slope in which
- distributed influx of the recirculation flow, but not always exactly in conformity with the longshore current profile,
- width opening in the downstream wave guide $= 1.3 \times$ width surf zone,
- recirculation flows of 40, 50, 60, 70 and 80 1/sec,
- velocity measurements in section 2 as in experiment 3,
- for the uniform longshore current situation also velocity measurements in the longshore current zone in sections 0 and 1, and measurements of wave set-up, wave heights and angles of incidence.

6. measurements on 1 : 20 slope in which
- distributed influx of the recirculation flow, but not exactly according to the longshore current profile,
- width opening in the downstream wave guide $= 1.35 \times$ width surf zone,
- recirculation flow of 30 1/sec,
- velocity measurements in section 2 as in experiment 3,
- measurements of wave set-up, wave heights and angles of incidence.

7. experiment on rough 1 : 20 slope in which
- distribution of the recirculation flow in inlet system,
- width opening in the downstream wave guide = 0.9 and 1.1 * width surf zone,
- recirculation flows of 10, 15, 20, 25, 35 and 45 l/sec,
- velocity measurements in section 2 as in experiment 3,
- for the uniform longshore current situation also velocity measurements in the longshore current zone in sections 0, 1 and 3, and measurements of wave heights and angles of incidence.
4. EXPERIMENTAL RESULTS

4.1 Introduction

The depth-averaged current velocity in a measuring point was calculated from the measured current velocities as follows:

\[ V = \frac{1}{4} (V_{\text{surface}} + 2V_{\text{mid-depth}} + V_{\text{bottom}}). \]  

(4.1)

The depth-averaged longshore current velocities are listed in the tables B.1 - B.9 in appendix B, as also the measured mean water depths and mean wave heights in the longshore current zone.

The rate of flow between two adjacent measuring points followed from the mean current velocities and mean water depths measured in these points. The enumeration of these flow rates gave the longshore current flow \( Q \) and the circulation flow \( Q_c \) in section 2, as defined in fig. 2.1, or the flow \( Q_s \) along the coast in the surf zone and the flow \( Q_{2s} \) along the coast in a section with a width of 2 times the width of the surf zone. The longshore current flows \( Q \) in section 2 (and for experiment 1 also the circulation flows \( Q_c \)) are also listed in the tables B.1 - B.9.

4.2 Experiment 1

In the 1.A series of measurements the width of the longshore current opening in the upstream wave guide was constant, namely \( 1.3 \times w_s \) (\( w_s = \) width surf zone) and the width \( w_d \) of the longshore current opening in the downstream wave guide was varied between \( 1.0 \times w_s \) and \( 2.0 \times w_s \). Fig. 4.1 shows the longshore current flows \( Q \) and the circulation flows \( Q_c \) in section 2 following from this series of measurements. From this figure it can be seen that \( Q_c \) is more or less a parabolic function of \( Q_r \) for a given \( w_d/w_s \)-ratio. The locus of the minima of these parabolas gives a graphical relation between
Fig. 4.1 - Longshore current flows $Q$ and circulation flows $Q_c$ measured in section 2 in experiment 1.A.

Fig. 4.2 - Surf zone flows $Q_s$ and flows $Q_{2s}$ ($2s = 2 \times$ width surf zone) measured in different sections in experiment 1.A for $Q_r = 35$ l/sec and $W_d/W_s = 1.31$. 
$w_d/w_s$ and $Q_r$ (such that $Q_c$ is minimal for a given $Q_r$ or $w_d/w_s$).

In the 1.A series of measurements $Q_c$ is minimal for $w_d/w_s = 1.31$ and $Q_r = 35$ l/sec (measurement nr. 1.A.3.4): $Q_c = 13.6$ l/sec and $Q = 48.4$ l/sec. Fig. 4.2 shows the flows $Q_s$ and $Q_{2s}$ in the different sections along the coast which follow from the longshore current velocities (and mean water depths) which were measured in this situation. The criterion $Q_c$ is minimal gave indeed a uniform longshore current, i.e.:
- uniform flows $Q_s$ and $Q_{2s}$ from section 3 to section 0,
- a uniform longshore current profile, but only from section 2 to section 0 due to the undistributed influx of the recirculation flow, see table B.1 of appendix B and fig. C.1 of appendix C.

In order to increase the length of uniformity, a distribution system (as described in the previous chapter) in the longshore current opening of the upstream wave guide was used in the experiments 1.B and 2 through 7.

In the 1.A.5 series of measurements, the internal return flow was located directly next to the longshore current (is in fact a shorter way than in the offshore region) for $Q_r < 30$ l/sec, yielding an opposite circulation in the offshore region. This was caused by the large opening in the downstream wave guide ($w_d/w_s = 2.00$).

Fig. 4.3 shows the longshore current flows $Q$ and the circulation flows $Q_c$ measured in section 2 in the 1.B series of measurements: 6 measurements with $w_d/w_s = 1.31$, 5 with a varying $w_d/w_s$ (in accordance with the locus of the minima in fig. 4.1). The distribution system was adjusted according to the measured distribution of the longshore current flows in the 1.A measurements. Also in the 1.B series of measurements $Q_c$ is minimal for $w_d/w_s = 1.31$ and $Q_r = 35$ l/sec (measurement nr. 1.B.1.5): $Q_c = 19.2$ l/sec and $Q = 52.1$ l/sec. The flows $Q_s$ and $Q_{2s}$ in the different sections along the coast which were measured in this situation are shown in fig. 4.4. The criterion $Q_c$ is minimal gave again a uniform longshore current: both the flows $Q_s$
Fig. 4.3 - Longshore current flows $Q$ and circulation flows $Q_c$ measured in section 2 in experiment 1.B.

Fig. 4.4 - Surf zone flows $Q_s$ and flows $Q_{2s}$ ($2s = 2 \times \text{width surf zone}$) measured in different sections in experiment 1.B for $Q_r = 35 \text{ l/sec}$ and $W_d/W_s = 1.31$. 
and \( Q_{2s} \) and the longshore current profile were uniform from section 3 to section 0 (see table B.2 of appendix B and fig. C.2 of appendix C).

The smallest \( Q_c \) in the 1.B series of measurements is \( Q_c = 19.2 \) l/sec, in the 1.A measurements \( Q_c = 13.6 \) l/sec. The influence of the distribution system on the rate of circulation flow \( Q_c \) does not follow from a comparison of these circulation flow rates due to the fact that not only a distribution system was installed but also some small leaks in the wave guides were closed. To investigate this influence an additional measurement in section 2 was performed without the distribution system, with \( Q_r = 35 \) l/sec and with \( 1.31 \approx w_s \) wide openings in both wave guides. The result of this measurement (nr. 1.A.6): \( Q_c = 29.4 \) l/sec and \( Q = 62.2 \) l/sec.

Table 4.1 gives (again) the flows \( Q_c, Q, Q_s \) and \( Q_{2s} \) resulting from the measurements in section 2 with \( Q_r = 35 \) l/sec and \( w_d/w_s = 1.31 \).

<table>
<thead>
<tr>
<th>measurement nr.</th>
<th>( Q_c ) (l/sec)</th>
<th>( Q ) (l/sec)</th>
<th>( Q_s ) (l/sec)</th>
<th>( Q_{2s} ) (l/sec)</th>
</tr>
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<td>1.A.3.4</td>
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<td>29.4</td>
<td>62.2</td>
<td>28.4</td>
<td>46.0</td>
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</table>

Table 4.1 - Flows \( Q_c, Q, Q_s \) and \( Q_{2s} \) resulting from the measurements 1.A.3.4 (no distribution system, some leaks in wave guides), 1.B.1.5 (distribution system, no leaks in wave guides) and 1.A.6 (no distribution system, no leaks in wave guides).

From this table it can be seen that
- a good distributed influx of the recirculation flow \( Q_r \) decreases the circulation flow \( Q_c \),
- the small leaks in the wave guide walls have reduced \( Q_c \) in 1.A.3.4 (and except 1.A.6 also in the other 1.A measurements).
- the differences in $Q_s$ are negligible and in $Q_{2s}$ not large, in spite of the differences in $Q_c$.

Both in experiment 1.A and experiment 1.B the proper recirculation flow is $Q_r = 35$ l/sec with an optimal width of the opening in the downstream wave guide $w_d = 1.31 \times w_s$. The optimal width $w_d$ is a function of $Q_r$, as followed from fig. 4.1 and as applied in experiment 1.B (fig. 4.3). The flows $Q[0,x]$ along the coast, as defined in fig.

![Diagram](image)

$Q[0,x]$ = flow rate in shaded area extending from $x=0$ (wave set-up line) to $x=x$ (x = coordinate normal to the coast)

Fig. 4.5 - Definition of $Q[0,x]$.

4.5, resulting from experiment 1.B are given in table 4.2 for $x/w_s$ values of 0.97, 1.17, 1.31, 1.45, 1.59, 1.72 and 2.00. From this table, and also from similar results of the 1.A measurements (which are not given here to serve clarity of arrangement), it can be seen that (fig. 4.6):

$Q[0,x] \approx Q_r$ if $x = w_d$ for $w_d =$ optimal (as function of $Q_r$).
<table>
<thead>
<tr>
<th>Measurement nr.</th>
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<th>Qr</th>
<th>Q ( \frac{x}{w_s} )</th>
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<td>44.5</td>
<td>48.8</td>
<td>52.3</td>
<td>55.1</td>
</tr>
</tbody>
</table>

Table 4.2 - Flows Q(0,x) in experiment 1.B for different x.
Fig. 4.6 - \( Q[0,x] = Q_r \) if \( x = w_d \) for \( w_d = \text{optimal} \) (as function of \( Q_r \)).

In other words: the width \( w_d \) of the opening in the downstream wave guide is optimal when the stream-lines are straight from \( x = 0 \) to \( x = w_d \) near (i.e. in and upstream of) this opening.

The longshore current flows \( Q \) and the circulation flows \( Q_c \) following from the measurements in section 2 in the completely enclosed wave basin are \( Q = 128 \text{ 1/sec} \) and \( Q_c = 135 \text{ 1/sec} \), which are remarkably large values. The longshore current is clearly non-uniform; the profile is strongly disturbed by the significantly large circulation flow (see table B.3 of appendix B and fig. C.3 of appendix C).

Also the longshore current measured in the type (I) basin, that is a basin with \( 1.0 \times w_s \) wide openings in both wave guides and with an external recirculation \( Q_r \) without the use of a pump, is clearly non-uniform (see table B.3 of appendix B and fig. C.4 of appendix C). In this experiment the return flow was located directly next to the longshore current, yielding an opposite circulation in the offshore
region. The "free recirculation" was also measured: $Q_r = 12.4$ l/sec, which is about one third of the proper $Q_r$.

The depth averaged longshore current velocities measured in section 2 in the uniform longshore current situations of experiments 1.A and 1.B (measurements 1.A.3.4 and 1.B.1.5), both with practically the same uniform longshore current profile and in the experiments 1.C and 1.D (measurements 1.C.3 and 1.D.3) are shown in fig. 4.7. The differences between the uniform longshore current profiles on the one hand and the non-uniform longshore current profiles near the middle (in longshore direction) of the beach in the completely enclosed wave basin and the type (1) basin on the other hand are clear, especially near the breaker line. Deviations from the uniform longshore current profile can become also considerable in the fig. 2.1 type of basin, especially if the rate of recirculation flow $Q_r$ differs substantially from the proper $Q_r$. This is demonstrated in fig. 4.7 with the help of the longshore current profile measured in the 1.A series of measurements with $Q_r = 59$ l/sec and $w_d/w_s = 2.00$ (measurement 1.A.5.6).

In experiment 1 the velocity measurements in section 2 were done from the wave set-up line to the wave board. By comparing the measured $Q - Q_r$ with the measured $Q_c$ each complete measurement in section 2 could be checked. The difference between $(Q - Q_r)/Q$ and $Q_c/Q$ is 13% for the measurement in section 2 of experiment 1.D and smaller than 10% for the other measurements. For all measurements in section 2 of experiment 1 the average of the absolute values of $(Q - Q_r - Q_c)/Q$ is 4%. The differences between $(Q - Q_r)/Q$ and $Q_c/Q$ are smaller than 4% in the optimized wave basin geometries for not too large absolute values of $Q_r - Q_{ru}$.

Adding all $Q - Q_r$ and all $Q_c$ of the measurements in section 2 gives respectively: $E(Q - Q_r) = 2320 - 1253 = 1067$ l/sec, $E_Q = 1080$ l/sec. The difference of 13 l/sec is only 0.5% of $E_Q$ and 1% of $E_Q_r$. So it can be concluded that the systematic error in the longshore current and circulation velocity measurements is small.
Fig. 4.7 - Depth-averaged longshore current velocities in section 2 following from the measurements 1.A.3.4 and 1.B.1.5 (both uniform profiles), 1.C.3 (completely enclosed wave basin), 1.D.3 (type (1) basin) and 1.A.5.6 ($Q_r = 59 \text{ l/sec}$ and $\omega_d/\omega_s = 2.00$).
The random error of the measured velocity in a certain measurement point at a certain depth was restricted as far as the experimental time this permitted by the number of readings (5, 10 or 20) which gave this velocity. From the above and from the smooth longshore current profiles reflected in fig. 4.7 it can be concluded that rather accurate measurements of longshore currents in a wave basin are possible.

From the experiments 1.A, 1.B, 1.C and 1.D the following conclusions can be made:

1. Rather accurate measurements of longshore currents in a wave basin are possible with dye, in spite of the high rate of turbulence in the surf zone and the combined action of waves of currents.

2. Deviations from the uniform longshore current profile can become considerable in non-optimized wave basin geometries and/or if the adjusted recirculation flow deviates substantially from the proper recirculation flow.

3. The width of the opening in the downstream wave guide is optimal when the stream-lines are straight in and upstream of this opening.

4. A distributed influx of the recirculation flow \( Q_r \) increases the length along which the longshore current is uniform and decreases the circulation flow \( Q_c \) in the wave basin.

5. In an optimized wave basin geometry the longshore current is uniform if the circulation flow \( Q_c \) is minimal (as function of the recirculation flow \( Q_r \)).

In the experiments 2 through 7 the influx of the recirculation flow was always distributed in conformity with the expected distribution of the longshore current flow, and the width of the opening in the downstream wave guide was 1.3 m width surf zone in the first instance and (if necessary) readjusted such that \( Q[0, w_d] = Q_{ru} \).
4.3 Experiments 2 and 3

Also in experiment 2 the velocity measurements in section 2 were performed from the wave set-up line to the wave board. The differences between the measured $Q - Q_r$ and the measured $Q_c$ were, however, larger than in experiment 1. This was caused by the strongly non-linear vertical velocity profiles of the circulation velocities in the offshore region (the vertical velocity profiles in the longshore current zone were almost linear for all experiments described in this report). An improvement was obtained by increasing the number of measuring points per vertical in the offshore region from 3 to 5. This improvement gave, however, little satisfaction:

1. the differences between $Q - Q_r$ and $Q_c$ were still rather large (up to 13% of $Q$),

2. to measure the velocities in the offshore region in 5 (or more) points per vertical took up much more time.

The right part of fig. 4.8 presents the vertical current velocity profiles measured in the offshore region at different distances from the wave board in section 2 in the measurement with $Q_r = Q_{ru} = 50$ l/sec of experiment 2 (measurement 2.11). The velocity profiles are strongly non-linear in contrast with the almost linear velocity profiles on the left part of fig. 4.8, which were measured in the same points in measurement 1.B.1.5.

In consequence of above mentioned, in experiments 3 through 7 the circulation velocities were not measured anymore (which saved also valuable experimental time) and in experiments 2 through 7 the circulation flow was minimized by minimizing $Q - Q_r$.

Fig. 4.9 shows the longshore current flows $Q$ and the "circulation flows $Q - Q_r$" following from the measurements in section 2 of experiment 2: $Q - Q_r$ is minimal for $Q_r = 50$ l/sec. The optimal width of the opening in the downstream wave guide going with this recirculation flow: $w_d = 1.30 \times w_s$.

Fig. 4.10 represents the flows $Q_s$ and $Q_{2s}$ in the different sections
Fig. 4.8 - Vertical velocity profiles measured in the offshore region of section 2 at different distances from the wave board (← = longshore current direction).
Fig. 4.9 - Longshore current flows $Q$ and circulation flows $Q - Q_r$ measured in section 2 in experiment 2 with $w_d/w_s = 1.30$.

Fig. 4.10 - Surf zone flows $Q_s$ measured in different sections in experiment 2 for $Q_r = 50$ l/sec and $w_d/w_s = 1.30$; flows $Q_{2s}$ (2s = 2 x width surf zone) for $Q_r = 40, 50$ and 60 l/sec.
along the coast for $Q_r = 50$ l/sec: the criterion $Q - Q_r$ is minimal
gave again a uniform longshore current (from section 3 to section 0,
see also table B.4 of appendix B and fig. C.5 of appendix C).
Measurements in the longshore current zone in sections 0, 1 and 3 were
also performed for $Q_r = Q_{ru} + 10 = 60$ l/sec and $Q_r = Q_{ru} - 10 = 40$
l/sec. The flows $Q_{2S}$ following from these measurements are also given
in fig. 4.10. A deviation of 20% in the recirculation flow from the
proper one yielded a significant worsening of the uniformity of the
longshore current along the basin beach. The deviation from the uni-
form longshore current profile decreases continuously in the longshore
current direction and becomes in experiment 2 small at the downstream
end of the basin.

The longshore current flows $Q$ and the circulation flows $Q - Q_r$
following from the measurements in section 2 of experiment 3 are given
in fig. 4.11. $Q - Q_r$ is minimal for $Q_r \geq 40$ l/sec, but with a less
pronounced minimum (compared with experiments 1 and 2). The optimal
width of the opening in the downstream wave guide in this experiment:
$w_d = 1.40 \times w_s$. Fig. 4.12 shows that $Q_s$ and $Q_{2S}$ are uniform along the
coast for $Q_r = 40$ l/sec and that also in this experiment a deviation
in this recirculation flow of 10 l/sec yielded a clear decrease of the
uniformity of the longshore current along the coast. In experiment 3
the longshore current was uniform for $Q_r = 40$ l/sec along a very long
part of the basin beach, at least from section 3 to section 0, see
table B.5, of appendix B and fig. C.6 of appendix C.

Experiments 2 and 3 confirm the conclusion of par. 4.2 that in an
optimized wave basin geometry the longshore current is uniform if the
circulation flow $Q_c$ is minimal (as function of the recirculation flow
$Q_r$). Experiments 2 and 3 add to that conclusion:
1. Only the proper recirculation flow $Q_{ru}$ gives a uniform longshore
current flow and profile in the optimized wave basin geometry:
a deviation $Q_r - Q_{ru}$ yields a decrease of the uniformity of the
longshore current along the coast.
Fig. 4.11 - Longshore current flows Q and circulation flows Q - Q_r measured in section 2 in experiment 3.

Fig. 4.12 - Surf zone flows Q_s measured in different sections in experiment 3 with Q_r = 40 l/sec; flows Q_2s (2s = 2 \times width surf zone) for Q_r = 30, 40 and 50 l/sec.
2. It is sufficient to minimize $Q - Q_r$: velocity measurements in the offshore region are not necessary for the adjustment of the uniform longshore current.

4.4 Experiments 4, 5, 6 and 7

The method for the adjustment of the uniform longshore current in a wave basin, as proposed in chapter 2, has been confirmed by the experiments 1, 2 and 3 for different wave fields (but all with plunging breakers) on a smooth 1 : 10 concrete slope. Experiments 4, 5, 6 and 7 can be described as the application (and verification) of this method for different wave fields on a smooth 1 : 20 concrete beach (exp.'s 4, 5 and 6) and a rough 1 : 20 immovable gravel beach (exp. 7, with the same wave field on constant depth part of the basin as in exp. 4).

In experiment 4 the surf similarity parameter $\tan \alpha / \sqrt{H_0 / \lambda_0}$ is 0.22 (table 3.1) and a spilling breaker was expected, see Battjes (1974). The breaker type was, however, more plunging than spilling (but clearly close to the transition into spilling breaker). In experiment 6 the breaker type was pure spilling for $\tan \alpha / \sqrt{H_0 / \lambda_0} < 0.18$. But the wave field in the basin was pretty unstable and non-uniform in longshore direction. For $\tan \alpha / \sqrt{H_0 / \lambda_0} = 0.18$ the transition into a uniform and stable wave field was attended with a transformation of the breaker type from pure spilling to, what has been called in table 3.1, spilling/plunging. Reference is made to Battjes (1974) for a description of the breaker types and of the transition of plunging into spilling. The instability and non-uniformity of the wave field for $\tan \alpha / \sqrt{H_0 / \lambda_0} < 0.18$ in experiment 6 is the reason that pure spilling breakers were not involved in the investigation.

Fig. 4.13 represents the longshore current flows $Q$ and the circulation flows $Q - Q_r$ following from the measurements in section 2 of experiment 4. $Q - Q_r$ is minimal for $Q_r = 50$ l/sec and the optimal $w_d = 1.17 \times w_s$. The flows $Q_s$ and $Q_{2s}$ in the sections 0, 1, 2, 3 and 4
Fig. 4.13 - Longshore current flows $Q$ and circulation flows $Q - Q_r$ measured in section 2 in experiment 4.

Fig. 4.14 - Surf zone flows $Q_s$ and flows $Q_{2s}$ ($2s = 2 \times$ width surf zone) measured in different sections in experiment 4 for $Q_r = 50 \text{l/sec}$ and $\omega_d/\omega_s = 1.20$. 
Fig. 4.15 - Longshore current flows $Q$ and circulation flows $Q - Q_r$ measured in section 2 in experiment 5.

Fig. 4.16 - Surf zone flows $Q_s$ and flows $Q_{2s}$ ($2s = 2 \times$ width surf zone) measured in sections 0, 1 and 2 in experiment 5 for $Q_r = 65$ l/sec and $w_d/w_s = 1.31$. 
which were measured in this situation are shown in fig. 4.14. The criterion $Q_c$ is minimal gave again a uniform longshore current: both the flows $Q_s$ and $Q_{2s}$ and the longshore current profile (see table B.6 of appendix B and fig. C.7 of appendix C) are uniform from section 3 to section 0.

The longshore current flows $Q$ and the circulation flows $Q - Q_r$ measured in section 2 of experiment 5 are shown in fig. 4.15: $Q - Q_r$ is minimal for $Q_r = 65$ l/sec and the optimal $w_d = 1.33 \times w_s$. Fig. 4.16 gives the flows $Q_s$ and $Q_{2s}$ in the sections 0, 1 and 2 which were measured in the $Q - Q_r$ minimal situation: both the flows $Q_s$ and $Q_{2s}$ and the longshore current profile (see appendix B, table B.7 and appendix C, fig. C.8) are uniform. Measurements in sections 3 and 4 were not performed for time reasons and due to the fact that the distribution system was not adjusted exactly in accordance with the longshore current profile, also for time reasons.

In experiments 1 through 5 the uniform longshore current was adjusted by minimizing $Q_c$ or $Q - Q_r$ as function of $Q_r$ in the optimal wave basin geometry. To that end velocity measurements in one section in the middle of the beach (section 2) were performed. It is in principle also possible to adjust the uniform longshore current by measuring the current velocities in 2 or more sections (on different places along the coast) for different $Q_r$ in the optimal wave basin geometry. For instance in sections 0 and 2: if the velocities in section 0 are smaller respectively larger than in section 2, the recirculation flow is too small, respectively too large (iterative method for uniform longshore current adjustment). In experiment 6 this method was applied. But the first $Q_r$ of 30 l/sec was a very fortunate choice. It was the proper recirculation flow as can be seen from fig. 4.17, which represents $Q_s$ and $Q_{2s}$ following from the measurements in sections 0, 1 and 2 with $Q_r = 30$ l/sec and the optimal $w_d = 1.35 \times w_s$ (see also table B.8 of appendix B and fig. C.9 of
Fig. 4.17 - Surf zone flows \( Q_s \) and flows \( Q_{2s} \) measured in experiment 6 for \( Q_r = 30 \) l/sec and \( w_d/w_s = 1.35 \).

appendix C). In paragraph 4.5 this method will be contemplated further.

In order to involve the influence of the bottom roughness in the proposed method for the adjustment of the correct longshore current flow in a wave basin experiment 7 was performed after the 1 : 20 slope was roughed with 5 - 9 mm. gravel. In this experiment the wave set-up was not measured: the mean water depths were figured out the wave set-up data of experiment 4 (with the same wave field on constant depth part of the basin). Fig. 4.18 represents the longshore current flows \( Q \) and the circulation flows \( Q - Q_r \) following from the measurements in section 2 of this experiment, with \( w_d = 1.06 \times w_s \) and the optimal \( w_d = 0.87 \times w_s \); \( Q - Q_r \) has a rather clear minimum for \( Q_r = 20 \) l/sec. The flows \( Q_s \) and \( Q_{1.8s} \) (= the flow along the coast between \( x = 0 \) and \( x = 1.8 \times w_s \)) in the sections 0, 1, 2 and 3 which were measured with \( Q_r = 20 \) l/sec and \( w_d = 0.87 \times w_s \) are given in fig. 4.19: both the flows \( Q_s \) and \( Q_{1.8s} \) and the longshore current profile (see table B.9 of appendix B and fig. C.10 of appendix C) are uniform along the coast. For \( Q_r = 20 \) l/sec two measurements in section 2 were done, one with \( w_d = 0.87 \times w_s \) and one with \( w_d = 1.06 \times w_s \). As can be seen
Fig. 4.18 - Longshore current flows $Q$ and circulation flows $Q - Q_r$ measured in section 2 in experiment 7.

Fig. 4.19 - Surf zone flows $Q_s$ and flows $Q_{1.8s}$ ($1.8s = 1.8 \times \text{width surf zone}$) measured in sections 0, 1, 2 and 3 in experiment 7 for $Q_r = 20 \text{ l/sec}$.
from table B.9 of appendix B (measurements 7.5 and 7.6) the measured longshore current profiles are practically the same. For time reasons it was not possible to investigate the influence of a deviation of the width of the opening in the downstream wave guide from the optimal width on the longshore current further, but this influence seems to be smaller if the slope is rougher and/or the angle of incidence is smaller.

In all measurements in section 2 on the smooth slopes (experiments 1 through 6) the longshore current velocity increased from zero (near the wave set-up line) to a maximum value (near the middle of the surf zone) and then decreased continuously in offshore direction, see fig. 4.7 or the tables in appendix B. In the measurements in section 2 on the rough slope a second maximum, outside the surf zone, occurred in the longshore current profile as soon as $Q_r > Q_{ru}$ (* 20 l/sec), see fig. 4.20.

![Fig. 4.20 - Longshore current profiles measured in section 2 in experiment 7.](image)

Experiments 4, 5, 6 and 7 confirm the conclusion of paragraph 4.2 that in an optimized wave basin geometry the longshore current is uniform if the circulation flow $Q_c$ is minimal (as function of the recirculation flow $Q_r$) and the conclusion of paragraph 4.3 that it is
sufficient to minimize \( Q - Q_r \).

### 4.5 Discussion

The experiments described in this report show that

- in a wave basin with a recirculation through longshore current openings in both wave guides which is effected completely by a pump,
- of which the geometry has been optimized,
- the longshore current is uniform if the circulation flow \( Q_c \) is minimal (as function of the recirculation flow \( Q_r \)) and that it is sufficient to minimize \( Q - Q_r \);
- only the proper recirculation flow \( Q_{ru} \) gives a uniform longshore current profile in the optimized wave basin geometry;
- a deviation \( Q_r - Q_{ru} \) yields a decrease of the uniformity of the longshore current along the coast.

The wave basin has been optimized by a distribution system in the longshore current opening of the upstream wave guide with a dimension normal to the coast of about 1.75 * width surf zone and by adjusting the width \( w_d \) of the longshore current opening in the downstream wave guide such that \( Q_r = Q[0,w_d] \) (then \( Q_c \) is minimal as function of \( w_d \)). The optimal \( w_d \) varied from 0.87 * width surf zone (experiment 7) to 1.40 * width surf zone (experiment 3).

If the width of the "longshore current zone" is defined as the distance normal to the coast from the wave set-up line to the line upon which the uniform longshore current velocity is yet only a few percents of the maximum velocity then the width of the "longshore current zone" was about 2.0 * width surf zone for the experiments on the smooth slopes and about 1.8 * width surf zone for the experiment on the rough slope (see tables in appendix B). Since the longshore current zone was wider than the optimal \( w_d \), part of the longshore current flow circulated in the basin and the minimal \( Q_c \) was not about zero, but varied from 6.0 l/sec (8% of the longshore
current flow $Q$, experiment 5) to 19.4 l/sec (37% of the longshore current flow $Q$, experiment 1.8). The fact that the minimal $Q_c$ was never about zero has been accepted in the present investigation: the maximum depth-averaged current velocity in the offshore region of section 2 in the uniform longshore current situations (measured in experiments 1, 2 and 3) was about 1 cm/sec, which is small compared with the longshore current velocities in the surf zone (the maximum depth-averaged velocity in the offshore region in section 2 in the completely enclosed wave basin was about 14 cm/sec). It has to be possible to decrease the circulation flows in the uniform longshore current situations by installing a distribution system in the longshore current opening of the downstream wave guide too. But such a system makes the adjustment of the proper longshore current more laborious and, because it is in fact not necessary, has not been used in the investigation.

The method of minimizing $Q_c$ can only be applied in wave basins in which a circulation can exist (also if $Q_r > Q_{ru}$). The present experiments were done in a basin with a width - length ratio of about 0.6 ,

$$ (4.2) $$

where width basin = distance between wave set-up line and wave board and length basin = length between wave guides. For all uniform longshore current situations of the experiments is

$$ (width \text{ basin}) / (width \text{ longshore current zone}) > 2.5 . $$

$$ (4.3) $$

Especially the ratio of (4.3) is most likely important for the existence of a circulation in a wave basin for $Q_r > Q_{ru}$. If this ratio is for instance about 1.5 then for $Q_r > Q_{ru}$ the surplus does not generate a circulation, see Delft Hydraulics Laboratory (1976).
In each of the experiments more measurements in section 2 with different recirculation flows $Q_r$ were performed than in fact were necessary to determine the proper recirculation flow $Q_{ru}$: to this end 4 or 5 measurements in the middle of the beach (section 2) are adequate. As already indicated in paragraph 4.4 it is of course also possible to determine the proper recirculation flow with an iterative method, by measuring the velocities in 2 or more sections (on different places along the coast). For instance in sections 0 and 2: if the velocities in section 0 are smaller respectively larger than in section 2, the recirculation flow is too small, respectively too large. This method was applied in experiment 6 and by a fortunate choice of $Q_r$ with success. In general, however, measurements with 3 or 4 different recirculation flows $Q_r$ will likely be necessary, yielding a total number of measurements of 6 to 8, which is more than the 4 or 5 measurements which are necessary to minimize the circulation flow $Q - Q_r$. Further, the longshore current in a wave basin is not always completely uniform, see for instance figures 4.10, 4.12 and 4.19. This is partly caused by the non-uniformity of the wave field in longshore direction in a wave basin due to reflection, secondary waves, etc.: for the present measurements the variation of the (over 90 seconds measured and averaged) wave height in longshore direction was about $\pm 10\%$, the variation of this wave height in time about $\pm 3\%$. 
5. ANALYSIS OF PHYSICAL MECHANISMS

5.1 Introduction

The equations describing the conservation of horizontal momentum for time-averaged (over several wave periods) and depth-averaged steady flow on a beach are

\[ \rho (h + \eta) \left( U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + g \frac{\partial \eta}{\partial x} \right) + \frac{3S_{xx}}{\partial x} + \frac{3S_{xy}}{\partial y} - \frac{3T_{xy}}{\partial y} + \tau_{bx} = 0 , \]  

\[ \rho (h + \eta) \left( U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + g \frac{\partial \eta}{\partial y} \right) + \frac{3S_{xy}}{\partial x} + \frac{3S_{yy}}{\partial y} - \frac{3T_{xy}}{\partial x} + \tau_{by} = 0 , \]

in which

\[ \rho \] = density of the fluid,
\[ h \] = still water depth,
\[ \eta \] = mean water level elevation,
\[ U, V \] = mean velocity components in x (= offshore) and y (= alongshore) direction, respectively,
\[ g \] = acceleration of gravity,
\[ S_{xx}, S_{xy}, S_{yy} \] = radiation stresses,
\[ T_{xy} \] = lateral friction,
\[ \tau_{bx}, \tau_{by} \] = mean bottom stresses.

For an infinitely long beach with straight and parallel depth contours and a uniform (in alongshore direction) wave field it is assumed that there are no gradients in the y direction and equations (5.1) and (5.2) reduce to

\[ \rho g (h + \eta_u) \frac{d \eta_u}{dx} + \frac{dS_{xx}}{dx} + (\tau_{bx})_u = 0 , \]

\[ \frac{dS_{xy}}{dx} - \left( \frac{dT_{xy}}{dx} \right)_u + (\tau_{by})_u = 0 , \]
in which the subscript \( u \) denotes the uniform beach solution.

Equations (5.3) and (5.4) apply to the uniform longshore current situations of the present experiments. For the non-uniform longshore current situations, however, and in general also for the mathematical modeling of nearshore currents and circulations (including rip currents), equations (5.3) and (5.4) are not appropriate and a return to equations (5.1) and (5.2), probably with some simplifications, is inevitable.

Less is known about the order of magnitude of the different terms of equations (5.1) and (5.2). Sometimes the non-linear inertial terms and lateral friction terms are neglected, for instance in the mathematical model for circulations in wave basins of Dalrymple, Eubanks and Birkemeier (1977), or in the nearshore circulation and rip current calculations of Sasaki and Ozaki (1979), whereas Arthur (1962) shows that the action of the convective terms may help to explain the maintenance of a relatively narrow, concentrated pattern of stream-lines observed in rip currents. In the "Primo" model of the Delft Hydraulics Laboratory, see Delft Hydraulics Laboratory (1982), the non-linear inertial terms and lateral friction terms are also neglected, but this model has been set up for restricted applications. Examples of mathematical nearshore current models in which the convective and lateral friction terms have not been neglected are the model of the Laboratoire National d'Hydraulique, Chatou, see Sabaton and Hauguel (1979) and the "Ripcel" model of the Delft Hydraulics Laboratory, see Vreugdenhil (1980). The disadvantage of these models with respect to the more simple models is, however, that the required computational time is so large that the applicability for morphological computations, at least at the moment, is very doubtful. It is therefore important to simplify the equations as far as it is justified.

With the present measuring results it is possible to calculate the magnitude of most of the terms of equations (5.1) and (5.2).
For clarity each of the equations (5.1) and (5.2) is divided into a uniform and a non-uniform part.

5.2 Separation of equations (into uniform and non-uniform parts)

Decompose \( \eta \), \( U \) and \( V \) into a uniform part, in accordance with equations (5.3) and (5.4), and a non-uniform part, denoted with an asterisk:

\[
\eta = \eta_u + \eta^*, \hspace{2cm} (5.5)
\]

\[
U = U_u + U^* = u^*, \hspace{2cm} (5.6)
\]

\[
V = V_u + V^*. \hspace{2cm} (5.7)
\]

In appendix A it is shown that both for weak longshore currents, \( |V_u/u_m| \ll 1 \) (\( u_m \) = maximum value of wave orbital velocity near the bottom), as for strong longshore currents, \( |V_u/u_m| > 1 \), also the bottom friction vector can be decomposed into a uniform part and a non-uniform part:

\[
\tau_{bx}^* = (\tau_{bx})_u + \tau_{bx}^*, \hspace{2cm} (5.8)
\]

\[
\tau_{by}^* = (\tau_{by})_u + \tau_{by}^*, \hspace{2cm} (5.9)
\]

where for \( |V_u/u_m| \ll 1 \) (and not too large angles of incidence)

\[
(\tau_{bx})_u = \frac{1}{\pi} \rho \, C_b \, u_m \, (\sin \theta) \, V_u, \hspace{2cm} (5.10)
\]

\[
\tau_{bx}^* = \frac{4}{\pi} \rho \, C_b \, u_m \left[ u^* + \frac{1}{2} (\sin \theta) \, V^* \right], \hspace{2cm} (5.11)
\]
\( (\tau_{by})_u = \frac{2\pi}{\rho} C_b m u m V_u \), \hspace{1cm} (5.12) \\
\( \tau_{by}^x = \frac{2\pi}{\rho} C_b m \left[ \frac{1}{2} (\sin 2\theta) u + v^x \right] \), \hspace{1cm} (5.13) \\

and for \( \left| \frac{V_u}{u_m} \right| > 1 \) (and not too large angles of incidence) \\
\( (\tau_{bx})_u = \frac{1}{2} \rho C_b u_m^2 \sin 2\theta \), \hspace{1cm} (5.14) \\
\( \tau_{bx}^x = \rho C_b \left[ 1 + \frac{1}{2} \left( \frac{u_m}{V_u} \right)^2 \right] V_u u^x \), \hspace{1cm} (5.15) \\
\( (\tau_{by})_u = \rho C_b \left[ 1 + \frac{1}{2} \left( \frac{u_m}{V_u} \right)^2 \right] v^2 \), \hspace{1cm} (5.16) \\
\( \tau_{by}^x = 2 \rho C_b \left[ 1 + \frac{1}{2} \left( \frac{u_m}{V_u} \right)^2 \right] V_u v^x \). \hspace{1cm} (5.17) \\

Assuming a gradient type diffusion, the lateral friction is written as \\
\( T_{xy} = \rho u_e (h + \eta) \left( \frac{3V}{3x} + \frac{3U}{3y} \right) \), \hspace{1cm} (5.18) \\

in which \( u_e \) = kinematic turbulent viscosity. Substitution of 
(5.5), (5.6) and (5.7) into (5.18) yields \\
\( T_{xy} = (T_{xy})_u + T_{xy}^x \), \hspace{1cm} (5.19) \\

in which \\
\( (T_{xy})_u = \rho u_e (h + \eta) \frac{dV}{dx} \), \hspace{1cm} (5.20) \\
\( T_{xy}^x = \rho u_e (h + \eta) \left( \frac{3V}{3x} + \frac{3U}{3y} \right) \), \hspace{1cm} (5.21)
where \( h + \eta \sim h + \eta_u \) since \( |\eta|^\ast \ll h + \eta_u \).

For a wave basin as shown in fig. 2.1 it is assumed (except in the longshore current openings of both wave guides) that

\[
\frac{\partial S}{\partial y} = \frac{\partial S}{\partial x} = 0 . \tag{5.22}
\]

Substituting (5.5) through (5.9), (5.19) and (5.22) into (5.1) and (5.2), and (5.3) and (5.4) into the results yields

\[
\rho (h + \eta) \left( V \frac{\partial u^\ast}{\partial y} + g \frac{\partial \eta^\ast}{\partial x} \right) + \rho g \eta^\ast \frac{\partial u^\ast}{\partial x} \frac{\partial \eta^\ast}{\partial y} - \frac{\partial T^\ast}{\partial y} + \tau_{bx}^\ast = 0 , \tag{5.23}
\]

\[
\rho (h + \eta) \left( \frac{\partial v}{\partial x} + V \frac{\partial v^\ast}{\partial y} + g \frac{\partial u^\ast}{\partial y} \right) - \frac{\partial T^\ast}{\partial x} + \tau_{by}^\ast = 0 , \tag{5.24}
\]

where in (5.23) \( u^\ast \frac{\partial u^\ast}{\partial x} \) and \( \frac{\partial v}{\partial y} \frac{\partial u^\ast}{\partial y} \) and in (5.24) \( u^\ast \frac{\partial v^\ast}{\partial x} \) and \( v^\ast \frac{\partial v^\ast}{\partial y} \) have been neglected, i.e. it is assumed that the "disturbances" \( \eta^\ast, u^\ast \) and \( v^\ast \) are small compared with the uniform quantities.

Outside the surf zone is \( |\eta_u|^\ast \ll h \) and equation (5.23) reduces to

\[
\rho (h + \eta) \left( V \frac{\partial u^\ast}{\partial y} + g \frac{\partial \eta^\ast}{\partial x} \right) - \frac{\partial T^\ast}{\partial y} + \tau_{bx}^\ast = 0 . \tag{5.25}
\]

5.3 Order of magnitude of terms of equations of motion

Assuming linear wave theory and shallow water, then the radiation stress terms of (5.3) and (5.4) can be written for not too large angles of incidence (say \( \theta < 25^\circ \)) as
\[
\frac{dS_{xx}}{dx} = + \frac{3}{8} \gamma^2 \frac{\rho g \tan \alpha (h + \eta)}{1 + \frac{3}{8} \gamma^2} \quad \text{surf zone, (5.26)}
\]

\[
\frac{dS_{xx}}{dx} = - \frac{3}{32} \rho g \tan \alpha \frac{H^2}{h} \quad \text{outside surf zone, (5.27)}
\]

\[
\frac{dS_{xy}}{dx} = - \frac{5}{16} \gamma^2 \frac{\rho g^{3/2} \tan \alpha \sin \theta_0}{c_0} \frac{(h + \eta)^{3/2}}{1 + \frac{3}{8} \gamma^2} \quad \text{surf zone, (5.28)}
\]

\[
\frac{dS_{xy}}{dx} \sim 0 \quad \text{outside surf zone, (5.29)}
\]

where

\( \tan \alpha \) = beach slope,
\( H \) = wave height,
\( \gamma \) = \( H/(h + \eta) \) inside surf zone,
\( \theta_0 \) = angle of wave incidence on deep water,
\( c_0 \) = phase velocity on deep water.

The gradient of \( S_{xy} \) in x direction is not exactly zero but small outside the surf zone, see Thornton (1969). For above expressions reference is made to the literature, for instance Battjes (1974).

Battjes (1975) derived an expression for the kinematic turbulent viscosity inside the surf zone, which can be written, if wave set-up is taken into account, as

\[
\nu_e = M \left( \frac{5}{16} \gamma^2 \frac{\tan \alpha}{\sqrt{1 + \frac{3}{8} \gamma^2}} \right)^{1/3} (h + \eta) \left[ g(h + \eta) \right]^{1/3}, \quad (5.30)
\]

in which \( M \) is a coefficient which is "expected to be of order one".

The kinematic turbulent viscosity outside the surf zone is written by Skovgaard, Jonsson and Olsen (1978) as
\[ \nu_e = L \, h_{br} \, V_{br} \]  \hspace{1cm} (5.31)

in which the subscript br refers to the breaker line and L is a lateral friction coefficient.

With equations (5.10) through (5.17), (5.20), (5.21) and (5.26) through (5.31) and the results of the present experiments it is possible to calculate the magnitude, and certainly the order of magnitude of the terms of equations (5.3), (5.4), (5.23) and (5.24) (except terms with \( \eta^M \)) if the coefficients M, L and \( C_b \) are known. A comparison of calculated uniform longshore current profiles with the measured uniform longshore currents gives:

\[ M \approx 1.25 \, \eta^M, \quad C_b \approx 0.002 \quad \text{for the smooth bottom} \, \eta^M, \]
\[ L \approx 0.08 \, \eta^M, \quad C_b \approx 0.007 \quad \text{for the rough bottom} \, \eta^M. \]

A well known bottom friction coefficient in civil engineering practice is the Chezy coefficient of bottom friction \( C \), which can be expressed in \( C_b \) as follows:

\[ C = \left( \frac{2}{C_b} \right)^{\frac{1}{3}}. \]  \hspace{1cm} (5.32)

From (5.32) follows that if \( C_b = 0.002 \) then \( C = 70 \, m^{\frac{1}{3}}/sec \) and if \( C_b = 0.007 \) then \( C = 37 \, m^{\frac{1}{3}}/sec \).

---

\( \eta^M \) With some restriction: by using (5.30) and (5.31) a discontinuity in the eddy viscosity at the breaker line is introduced, consequently also a discontinuity in the lateral friction at the breaker line. This discontinuity is physically incorrect and introduces some loss (or gain) of momentum in equation (5.4). At the time of writing this report (oktober 1982) work on an "improved" model of turbulence in the longshore current zone and a mathematical model of uniform longshore currents is still in progress.
<table>
<thead>
<tr>
<th>exp.</th>
<th>beach</th>
<th>tga</th>
<th>T</th>
<th>$\theta_{br}$</th>
<th>$\frac{V_u}{u_m}$ max</th>
<th>$\frac{V_u}{u_m}$ at $x = \frac{2}{3}x_{br}$</th>
<th>$x_{br}$</th>
<th>$\frac{4}{3}x_{br}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>smooth</td>
<td>0.101</td>
<td>2.01</td>
<td>20.9</td>
<td>3.60</td>
<td>1.36</td>
<td>0.41</td>
<td>0.23</td>
</tr>
<tr>
<td>3</td>
<td>smooth</td>
<td>0.101</td>
<td>1.00</td>
<td>12.1</td>
<td>2.90</td>
<td>1.21</td>
<td>0.60</td>
<td>0.33</td>
</tr>
<tr>
<td>4</td>
<td>smooth</td>
<td>0.050</td>
<td>1.02</td>
<td>12.5</td>
<td>1.40</td>
<td>1.13</td>
<td>0.50</td>
<td>0.28</td>
</tr>
<tr>
<td>7</td>
<td>rough</td>
<td>0.050</td>
<td>1.02</td>
<td>12.2</td>
<td>0.88</td>
<td>0.63</td>
<td>0.23</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 5.1 – Calculated values of $\frac{V_u}{u_m}$; $u_m$ calculated with linear wave theory.

The experiments selected for the calculation of the order of magnitude of the terms of the equations of motion are given in table 5.1. The following measurements are used:

- 1.B.1.4 - 1.B.1.6, 3.8 - 3.10, 4.4 - 4.6 and 7.4 - 7.7: the measurements in sections 1, 2 and 3 of the uniform situations of experiments 1, 3, 4 and 7.
- 1.C.2 - 1.C.4: the measurements in sections 1, 2 and 3 of the completely enclosed wave basin situation of experiment 1.
- 1.C "rip current": the measurement in section 5 in the return current near the downstream wave guide in the completely enclosed wave basin (see table 5.2); for the calculation of the different terms it is assumed that the distribution of the return current near the breaker line differed not significantly from the distribution of this current near section 5 (it is an order of magnitude calculation).
- 4.9: the measurement in section 2 in the situation with $Q_r = 70\ l/sec = 1.4 \times Q_{ru}$ of experiment 4; to calculate the gradients in y direction it is assumed that at the downstream end of the beach the uniform longshore current profile was present.
7.9: The measurement in section 2 in the situation with $Q_r = 35 \text{ l/sec} = 1.75 \times Q_{ru}$ of experiment 7; also here it is assumed that at the downstream end of the beach the uniform longshore current profile was present.

<table>
<thead>
<tr>
<th>distance (m)</th>
<th>0.20</th>
<th>0.40</th>
<th>0.80</th>
<th>1.20</th>
<th>1.60</th>
<th>2.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>velocity (m/sec)</td>
<td>0.20</td>
<td>0.17</td>
<td>0.13</td>
<td>0.10</td>
<td>0.08</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Table 5.2 - Results of the measurements in section 5 of experiment 1.C; distance = distance from wave guide, velocity = depth-averaged mean velocity parallel to wave guide.

Table 5.3 presents the order of magnitude of the terms of the equations of motion calculated for $x = \frac{2}{3} x_{br}$ ($x = 0$ at the wave set-up line), that is inside the surf zone, and $x = \frac{4}{3} x_{br}$, that is outside the surf zone. From this table the following conclusions can be drawn:

1. In x direction the terms $\frac{\partial u}{\partial x}$ and $\frac{\partial S_{xx}}{\partial x}$ dominate (outside the rip current even completely),
2. The non-linear inertial terms become very large in rip currents,
3. The non-linear inertial terms and lateral friction terms cannot be ignored in non-uniform longshore currents or nearshore circulations.

Implications for experimental work in wave basins are:
- For experiments on wave set-up, set-down and wave run-up it is not necessary to adjust the recirculation flow accurately,
- For measurements on uniform longshore currents it is necessary to adjust the proper longshore current flow accurately.
<table>
<thead>
<tr>
<th>Measurement</th>
<th>1.0 - 1.4</th>
<th>1.4 - 1.6</th>
<th>3.0 - 3.10</th>
<th>4.4 - 4.6</th>
<th>7.4 - 7.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho g(h + n_u) \frac{d\eta}{dx}$ (N/m)</td>
<td>17</td>
<td>1.5</td>
<td>14</td>
<td>1.7</td>
<td>6</td>
</tr>
<tr>
<td>$\frac{dS_{xh}}{dx}$ (n/m)</td>
<td>16</td>
<td>4.3</td>
<td>14</td>
<td>4.5</td>
<td>6</td>
</tr>
<tr>
<td>$(\tau_{bx})_u$ (N/m)</td>
<td>0.06</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>$\frac{dS_{xy}}{dx}$ (n/m)</td>
<td>3</td>
<td>1.8</td>
<td>0.8</td>
<td>0.8</td>
<td>2</td>
</tr>
<tr>
<td>$(\tau_{bx})_u$ (N/m)</td>
<td>1</td>
<td>0.05</td>
<td>0.5</td>
<td>0.05</td>
<td>0.3</td>
</tr>
<tr>
<td>Measurement</td>
<td>1.0 - 1.4</td>
<td>1.4 - 1.6</td>
<td>3.0 - 3.10</td>
<td>4.4 - 4.6</td>
<td>7.4 - 7.7</td>
</tr>
<tr>
<td>$\rho (h + n_u) \frac{3\nu u}{\partial y}$ (N/m)</td>
<td>0.13</td>
<td>0.04</td>
<td>3</td>
<td>0.9</td>
<td>0.03</td>
</tr>
<tr>
<td>$\frac{\partial T_{xy}}{\partial y}$ (N/m)</td>
<td>0.04</td>
<td>0.005</td>
<td>0.1</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>$\tau_{bx}$ (N/m)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.2</td>
<td>0.02</td>
<td>0.004</td>
</tr>
<tr>
<td>$\rho (h + n_u) \frac{\partial u}{\partial x}$ (N/m)</td>
<td>0.7</td>
<td>0.3</td>
<td>7</td>
<td>3</td>
<td>0.07</td>
</tr>
<tr>
<td>$\rho (h + n_u) \frac{3\nu u}{\partial x}$ (N/m)</td>
<td>0.9</td>
<td>0.06</td>
<td>11</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>$\frac{\partial T_{xy}}{\partial x}$ (N/m)</td>
<td>1.4</td>
<td>0.09</td>
<td>0.7</td>
<td>0.04</td>
<td>0.7</td>
</tr>
<tr>
<td>$\tau_{by}$ (N/m)</td>
<td>0.3</td>
<td>0.02</td>
<td>0.8</td>
<td>0.02</td>
<td>0.09</td>
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</tbody>
</table>

Table 5.3 - Order of magnitude of terms of equations of motion calculated from measurement results.
6. CONCLUSIONS AND RECOMMENDATIONS

The purpose of the present investigation was to develop a method for the adjustment of the proper (uniform) longshore current in a wave basin. A wave basin configuration was chosen with a recirculation through longshore current openings in both wave guide walls which is effected completely by a pump. Experiments with different wave fields, a smooth 1:10 beach, a smooth and a rough 1:20 beach and for most of the experiments a distribution system in the opening of the up-stream wave guide were performed in which the recirculation flow and the width of the opening in the downstream wave guide were varied. These experiments have yielded a number of conclusions which can be resumed as follows:

1. Fairly accurate measurements of longshore currents in a wave basin are possible with dye.

2. Deviations from the uniform longshore current profile can become considerable in non-optimized wave basin geometries and/or if the adjusted recirculation flow \( Q_r \) deviates substantially from the proper one.

3. The width of the opening in the downstream wave guide is optimal when the stream-lines are straight in and upstream of this opening.

4. A distributed influx of the recirculation flow \( Q_r \) increases the length along which the longshore current is uniform and decreases the circulation flow \( Q_c \) in the wave basin.

5. The longshore current is uniform in an optimized wave basin geometry if the circulation flow \( Q_c \) is minimal (as function of the recirculation flow \( Q_r \)).

6. Only the proper recirculation flow \( Q_{ru} \) gives a uniform longshore current in the optimized wave basin geometry: a deviation \( Q_r - Q_{ru} \) yields a decrease of the uniformity of the longshore current along the coast.

7. It is sufficient to minimize \( Q - Q_r \).

The calculations of the order of magnitude of terms of the equations of motion with some of the measurement results have
yielded the following conclusions:

8. In the equation of motion for the direction normal to the coast
the terms ρg(h + ηu)dn_u/dx and dS_x/y/dx dominate (outside rip
currents even completely).

9. In the equation of motion for the alongshore direction the non-
linear inertial terms become very large in rip currents and
10. the non-linear inertial terms and lateral friction terms may not
be ignored in mathematical modeling of non-uniform longshore
currents or nearshore circulations.

From the present investigation the following "wave basin
prescription" for the adjustment of the uniform longshore current in a
wave basin as shown in fig. 2.1 or fig. 3.1 can be recommended:
1. No leaks in the wave guide walls.
2. In the opening of the upstream wave guide a distribution system
with a width of 1.7 to 2.0 m (expected) width surf zone, and
constructed such that the waves outside the surf zone are still
guided as best as possible.
3. The width of the opening in the downstream wave guide ≈ 1.2 m
(expected) width surf zone.
4. Measurements of wave heights to position the breaker line and of
wave set-up and set-down to determine the mean water depths;
for these measurements it is not necessary to adjust the correct
recirculation flow, a rough approximation of the proper recircu-
lation flow is sufficient (for instance by a rough minimization
of the return current near the downstream wave guide); from the
wave height and mean water level measurements follows also the width
of the surf zone; if necessary the width of the opening in the
downstream wave guide is readjusted.
5. Measurements of longshore current velocities in a section (normal
to the coast) near the middle of the beach for different recircu-
lation flows Q_r, while the distribution of Q_r in the distribution
system and the width of the opening in the downstream wave guide
are readjusted if necessary: the minimal circulation flow
Q - Q_x yields the proper recirculation flow Q_{ru}, the optimal \omega_d is such that Q[0, \omega_d] = Q_{ru}.
ACKNOWLEDGEMENTS

The author wishes to thank Prof. J.P.Th. Kalkwijk for his critical comments during the investigation. The author is greatly indebted to Mr. D.C. Post who performed most of the many measurements, at the beginning of the investigation together with the author and later on together with Mr. P. de Boer, who's contribution is also appreciated. Finally, the author wishes to thank Mr. J. Groeneveld and his staff for preparing the wave basin for the experiments, Mrs. T. Capel for the typing work and again Mr. D.C. Post for drawing the figures.
**LIST OF SYMBOLS**

\( C_b \) = bottom friction coefficient,  
\( c \) = phase velocity,  
\( g \) = acceleration of gravity,  
\( H \) = wave height,  
\( h \) = still water depth,  
\( L \) = lateral friction coefficient outside surf zone,  
\( M \) = lateral friction coefficient inside surf zone,  
\( Q \) = longshore current flow,  
\( Q_c \) = circulation flow,  
\( Q_T \) = recirculation flow,  
\( Q_{ru} \) = proper recirculation flow,  
\( Q_s \) = flow along the coast in the surf zone,  
\( Q_{2s} \) = flow along the coast in a section with a width \( 2w_s \),  
\( Q_u \) = uniform longshore current flow,  
\( Q_0[x] \) = flow along the coast in a section extending from \( x=0 \) to \( x=x \).  

\( S_{xx}, S_{xy}, S_{yy} \) = radiation stresses,  
\( T \) = wave period,  
\( T_{xy} \) = lateral frictional stress,  
\( t \) = time,  
\( U \) = mean velocity component in \( x \) direction (depth-averaged),  
\( u_x \) = \( U \),  
\( u_b \) = instantaneous velocity vector near the bottom,  
\( u_m \) = maximum value of wave orbital velocity near the bottom,  
\( V \) = mean velocity component in \( y \) direction (depth averaged),  
\( V_u \) = uniform longshore current velocity (depth averaged),  
\( v_x \) = \( V - V_u \),  
\( w_d \) = width opening in downstream wave guide,  
\( w_s \) = width surf zone,  
\( x \) = horizontal coordinate perpendicular to the coast (\( x=0 \) at wave set-up line),  
\( y \) = horizontal coordinate along the straight coast.
\( \alpha \) = slope angle with respect to the horizontal,
\( \gamma \) = \( H/(h + \eta) \) inside the surf zone,
\( \eta \) = mean water level elevation,
\( \eta_u \) = wave set-up or set-down,
\( \eta^k \) = \( \eta - \eta_u \),
\( \theta \) = angle of wave incidence,
\( \lambda \) = wave length,
\( \mu_e \) = kinematic turbulent viscosity,
\( \rho \) = density of the fluid,
\( \mathbf{I}_b \) = instantaneous bottom stress vector,
\( \tau_{bx}', \tau_{by}' \) = mean bottom stress components,
\( (\tau_{bx})_u, (\tau_{by})_u \) = mean bottom stresses in uniform longshore current situation,
\( \tau_{bx}^k = \tau_{bx} - (\tau_{bx})_u \),
\( \tau_{by}^k = \tau_{by} - (\tau_{by})_u \),
\( \omega \) = angular frequency.

subscripts

0 refers to a value on deep water,
1 refers to a value on constant depth part of wave basin,
b refers to bottom,
br refers to breaker line,
u refers to a uniform longshore current situation.
LIST OF REFERENCES


BATTJES, J.A., 1974, Computation of set-up, longshore currents, run-up and overtopping due to wind-generated waves, Communications on Hydraulics, Department of Civil Engineering, Delft University of Technology, Report no. 74-2.


BLIJKER, E.W., 1967, Some considerations about scales for coastal models with movable bed, Delft Hydraulics Laboratory, Publication no. 50.


APPENDIX A: BOTTOM FRICTIONAL STRESSES

The instantaneous stress $\tau_b$ excited by the water on the bottom can be expressed as

$$\tau_b = \rho C_b \left| u_b \right|,$$

(A.1)

in which $u_b$ = instantaneous velocity vector near the bottom and $C_b$ is a bottom friction coefficient. Assuming linear wave theory then the horizontal orbital velocity near the bottom is $u_m \cos \omega t$ (in which $\omega$ = angular frequency and $t$ = time). Since $(u^x, V)$ = mean velocity vector, the instantaneous velocity vector near the bottom can be written as

$$u_b = (u_m \cos \theta \cos \omega t + u^x, u_m \sin \theta \cos \omega t + V),$$

(A.2)

where $\theta$ = angle of wave incidence. The absolute value of this velocity can be written as

$$\left| u_b \right| = \left[ (u^x)^2 + 2 u^x u_m \cos \theta \cos \omega t + u_m^2 \cos^2 \omega t + V^2 +
+ 2 V u_m \sin \theta \cos \omega t \right]^{\frac{1}{2}}.$$  

(A.3)

Substitution of (A.2) and (A.3) into (A.1) and next taking the time average over the wave period $T$ yields

$$\tau_{bx} = \frac{1}{T} \rho C_b \int_0^T \left[ (u^x)^2 + 2 u^x u_m \cos \theta \cos \omega t + u_m^2 \cos^2 \omega t + V^2 +
+ 2 V u_m \sin \theta \cos \omega t \right]^{\frac{1}{2}} (u^x + u_m \cos \theta \cos \omega t) \, dt,$$

(A.4)
\[
\tau_{by} = \frac{1}{T} \rho C_b \int_0^T \left[ (u^*)^2 + 2 u^* u_m \cos \theta \cos \omega t + u_m^2 \cos^2 \omega t + V^2 + 
+ 2 V u_m \sin \theta \cos \omega t \right]^{\frac{1}{2}} (V + u_m \sin \theta \cos \omega t) \, dt . 
\] (A.5)

For the principle of above derivation reference is made to Bijker (1967).

Equations (A.4) and (A.5) can be simplified for two cases:
1. weak longshore currents and weak disturbances \((u^*, V^*)\), both in comparison with \(u_m\),
2. strong longshore currents and weak disturbances \((u^*, V^*)\), both in comparison with \(u_m\).

**Weak longshore currents**

In this case it is assumed that

\[
\left| \frac{V}{u_m} \right| \ll 1, \quad \left| \frac{u^*}{u_m} \right| \ll 1 \quad \text{and} \quad \left| \frac{V^*}{u_m} \right| \ll 1 .
\] (A.6)

Then equations (A.4) and (A.5) reduce to

\[
\tau_{bx} = \frac{2}{\pi} \rho C_b u_m \left[ (1 + \cos^2 \theta) u^* + (\sin \theta \cos \theta) V \right] , 
\] (A.7)

\[
\tau_{by} = \frac{2}{\pi} \rho C_b u_m \left[ (\sin \theta \cos \theta) u^* + (1 + \sin^2 \theta) V \right] . 
\] (A.8)

Substitution of \( V = V_u + V^* \) into (A.7) and (A.8) gives

\[
\tau_{bx} = (\tau_{bx}^u + \tau_{bx}^*) , 
\] (A.9)

\[
\tau_{by} = (\tau_{by}^u + \tau_{by}^*) , 
\] (A.10)

in which
\[
(t_{bx})_u = \frac{2}{\pi} \rho C_b u_m \left( \sin \theta \cos \theta \right) V_u ,
\]

\[
\tau_{bx}^* = \frac{2}{\pi} \rho C_b u_m \left[ (1 + \cos^2 \theta) u_m^* + (\sin \theta \cos \theta) V_u^* \right] ,
\]

\[
(t_{by})_u = \frac{2}{\pi} \rho C_b u_m (1 + \sin^2 \theta) V_u - ,
\]

\[
\tau_{by}^* = \frac{2}{\pi} \rho C_b u_m \left[ (\sin \theta \cos \theta) u_m^* + (1 + \sin^2 \theta) V_u^* \right] .
\]

If the angle of wave incidence is very small, equations (A.7) and (A.8) reduce to

\[
\tau_{bx} = \frac{4}{\pi} \rho C_b u_m u^* ,
\]

\[
\tau_{by} = \frac{2}{\pi} \rho C_b u_m V^* ,
\]

which are the bottom friction components derived by LeBlond and Tang (1974).

**Strong longshore currents**

In this case it is assumed that

\[
\left| \frac{u}{u_m} \right| > 1 , \quad \left| \frac{u^*}{u_m} \right| \ll 1 ,
\]

\[
\left| \frac{V}{u} \right| \ll \left| \frac{V}{u} \right| .
\]

With (A.17) and with the approximation

\[
\left[ 1 + 2 \left( \frac{u_m}{V} \cos \omega t \right) \sin \theta + \left( \frac{u_m}{V} \cos \omega t \right)^2 \right]^{\frac{1}{2}} \approx
\]

\[
\approx 1 + \left( \frac{u_m}{V} \cos \omega t \right) \sin \theta + \frac{1}{2} \left( \frac{u_m}{V} \cos \omega t \right)^2 \cos^2 \theta ,
\]

\[(A.19)\]
see Liu and Dalrymple (1978), equations (A.4) and (A.5) reduce to

\[
\tau_{bx} = \rho C_b \left[ 1 + \frac{1}{2} \left( \frac{u}{V} \right)^2 \cos^2 \theta \right] \frac{u^*}{u^*} + \frac{1}{2} \frac{um}{V} \sin \theta \cos \theta \right] V_x, \tag{A.20}
\]

\[
\tau_{by} = \rho C_b \left[ 1 + \frac{1}{2} \left( \frac{u}{V} \right)^2 (1 + \sin^2 \theta) \right] v^2. \tag{A.21}
\]

Substitution of \( V = V_u + v^* \) into (A.20) and (A.21), and (A.18) into the result yields

\[
\tau_{bx} = (\tau_{bx})_u + \tau_{bx}^*, \tag{A.22}
\]

\[
\tau_{by} = (\tau_{by})_u + \tau_{by}^*, \tag{A.23}
\]

in which

\[
(\tau_{bx})_u = \frac{1}{2} \rho C_b \frac{um}{V} \sin \theta \cos \theta, \tag{A.24}
\]

\[
\tau_{bx}^* = \rho C_b \left[ 1 + \frac{1}{4} \left( \frac{u}{V} \right)^2 \cos^2 \theta \right] V_u u^*, \tag{A.25}
\]

\[
(\tau_{by})_u = \rho C_b \left[ 1 + \frac{1}{4} \left( \frac{um}{V} \right)^2 (1 + \sin^2 \theta) \right] v^2_u, \tag{A.26}
\]

\[
\tau_{by}^* = 2\rho C_b \left[ 1 + \frac{1}{4} \left( \frac{um}{V} \right)^2 (1 + \sin^2 \theta) \right] v_u v^*. \tag{A.27}
\]
APPENDIX B: MEASUREMENT RESULTS

This appendix contains the tables B.1 - B.9. These tables present the depth-averaged current velocities in longshore direction, the mean water depths and the mean wave heights, all in the measurement points of the longshore current zone.

Table B.1: results of experiment 1.A

<table>
<thead>
<tr>
<th>B.2</th>
<th>B.3</th>
<th>B.4</th>
<th>B.5</th>
<th>B.6</th>
<th>B.7</th>
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<th>B.9</th>
</tr>
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<tr>
<td>1.B</td>
<td>experiments 1.C and 1.D</td>
<td>experiment 2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

The x coordinates of the measurement points are given with x = 0 at the wave set-up line. The position of the still water line can be found from

\[ x_{s.w.\ line} = \frac{\eta_m}{\tan \alpha} \]  \hspace{1cm} (B.1)

in which \( \eta_m \) is the maximum wave set-up which is given in table 3.1.
<table>
<thead>
<tr>
<th>Measurement nr.</th>
<th>( \frac{w}{w_n} )</th>
<th>( Q_R ) ( 1/sec )</th>
<th>( Q ) ( 1/sec )</th>
<th>( Q_C ) ( 1/sec )</th>
<th>( x ) ( (m) )</th>
<th>( V(x) ) in cm/sec</th>
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</thead>
<tbody>
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<td>1.A.1.1</td>
<td>0.97</td>
<td>0</td>
<td>62.4</td>
<td>57.0</td>
<td>2</td>
<td>48.0 53.3 53.5 50.1 36.4 21.0 9.3 5.4 5.3 5.2 5.0 4.8 3.6 3.8</td>
</tr>
<tr>
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<td>15</td>
<td>39.7</td>
<td>21.8</td>
<td>2</td>
<td>37.6 55.4 61.4 62.6 56.2 37.1 19.7 9.5 4.2 2.2 2.0 2.1 1.8 1.8 1.5</td>
</tr>
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<td>40.6</td>
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<tr>
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<td></td>
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</tr>
</tbody>
</table>

Table B.1 - Depth-averaged longshore current velocities measured in experiment 1.A, flows \( Q \) and \( Q_C \) resulting from the measurements in section 2.
<table>
<thead>
<tr>
<th>measurement nr.</th>
<th>( u_d )</th>
<th>( Q_r )</th>
<th>( Q )</th>
<th>( Q_c )</th>
<th>( x ) (m)</th>
<th>( V(x) ) in cm/sec</th>
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<td>0.0 33.1 40.0 41.4 41.5 41.3 40.1 34.0 19.6 7.3 3.4 1.8 1.1 0.6 0.0</td>
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Table B.1 continuation - Depth-averaged longshore current velocities measured in experiment 1.A, flows \( Q \) and \( Q_c \) resulting from the measurements in section 2.
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Table B.2 - Depth-averaged longshore current velocities, mean water depths and mean wave heights measured in experiment 1.B, flows $Q$ and $Q_c$ resulting from the measurements in section 2.
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Table B.3 - Depth-averaged longshore current velocities measured in experiments 1.C and 1.D, flows Q and Q_c resulting from the measurements in section 2.
| measurement nr. | \( \frac{w}{u_0} \) | \( Q_x \) | \( Q \) | \( Q_c \) | \( \frac{x}{s} \) | \( -0.03 \) | 0.17 | 0.37 | 0.57 | 0.77 | 0.97 | 1.17 | 1.37 | 1.57 | 1.77 | 1.97 | 2.17 | 2.37 | 2.57 | 2.97 |
|----------------|----------------|--------|--------|--------|----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 2.1            | 1.30           | 20     | 45.7   | 2      | 2.49           | 54.2   | 69.9   | 70.2   | 63.1   | 52.7   | 35.4   | 24.6   | 14.0   | 7.9    | 6.7    | 2.8    | 0.7    | 0.5    | 0.0    |
| 2              | 1.30           | 30     | 47.5   | 2      | 2.58           | 60.1   | 68.5   | 71.7   | 66.5   | 52.3   | 34.5   | 23.8   | 14.3   | 9.7    | 5.3    | 3.0    | 1.8    | 0.9    | -0.1   |
| 3              | 1.30           | 35     | 48.8   | 2      | 2.64           | 58.1   | 69.3   | 70.0   | 68.0   | 54.3   | 37.1   | 24.1   | 16.7   | 8.7    | 6.1    | 3.2    | 2.0    | 0.8    | -0.8   |
| 4              | 1.30           | 40     | 57.9   | 0      | 0.0             | 59.6   | 71.4   | 72.8   | 68.7   | 55.4   | 43.9   | 30.7   | 20.4   | 14.8   | 9.4    | 5.9    | 3.8    | 1.6    | -1.1   |
| 5              | 1.30           | 40     | 55.5   | 1      | 2.16           | 61.3   | 71.0   | 71.6   | 65.5   | 55.5   | 39.9   | 28.6   | 19.3   | 14.2   | 10.0   | 4.9    | 3.4    | 1.2    | -1.0   |
| 6              | 1.30           | 40     | 51.8   | 2      | 2.70           | 59.7   | 70.5   | 70.3   | 65.2   | 53.0   | 37.6   | 26.0   | 16.8   | 11.5   | 7.1    | 4.5    | 2.7    | 1.1    | 0.1    |
| 7              | 1.30           | 40     | 50.9   | 3      | 2.12           | 59.9   | 68.7   | 69.9   | 62.0   | 49.8   | 36.1   | 24.1   | 16.7   | 11.1   | 7.1    | 4.1    | 2.6    | 2.1    | 0.6    |
| 8              | 1.30           | 45     | 55.0   | 2      | 2.66           | 60.2   | 68.1   | 70.3   | 64.1   | 50.9   | 37.5   | 27.4   | 18.9   | 12.3   | 9.1    | 6.4    | 3.7    | 2.9    | 0.2    |
| 9              | 1.30           | 50     | 59.2   | 0      | 0.0             | 61.2   | 71.6   | 73.0   | 67.0   | 55.6   | 43.3   | 32.7   | 23.3   | 14.9   | 10.0   | 6.4    | 4.4    | 1.2    | -1.7   |
| 10             | 1.30           | 50     | 62.4   | 1      | 3.51           | 65.1   | 71.2   | 73.8   | 68.1   | 58.7   | 42.7   | 32.6   | 24.3   | 16.4   | 12.2   | 6.8    | 3.6    | 2.3    | 0.0    |
| 11             | 1.30           | 50     | 60.6   | 2      | 2.62           | 60.8   | 69.3   | 69.7   | 65.6   | 52.3   | 43.1   | 30.0   | 20.9   | 15.8   | 10.7   | 6.8    | 4.6    | 2.8    | 0.7    |
| 12             | 1.30           | 50     | 62.1   | 3      | 2.56           | 65.3   | 71.6   | 71.5   | 67.7   | 58.1   | 42.7   | 31.3   | 23.6   | 16.2   | 10.7   | 6.3    | 4.0    | 2.4    | 1.1    |
| 13             | 1.30           | 50     | 57.3   | 4      | 0.0             | 30.0   | 55.4   | 65.9   | 68.7   | 60.2   | 48.6   | 33.1   | 20.0   | 14.3   | 9.5    | 5.8    | 2.6    | 1.5    | 0.3    |
| 14             | 1.30           | 60     |        | 0      | 0.0             | 62.3   | 73.3   | 74.0   | 69.1   | 57.8   | 44.7   | 30.0   | 23.0   | 18.0   | 12.6   | 8.2    | 5.0    | 3.3    | 1.1    |
| 15             | 1.30           | 60     |        | 1      | 3.23           | 66.1   | 72.0   | 74.2   | 68.7   | 57.3   | 42.4   | 31.3   | 24.6   | 17.8   | 13.8   | 10.7   | 5.8    | 4.2    | 2.0    |
| 16             | 1.30           | 60     | 73.1   | 2      | 2.61           | 57.9   | 72.9   | 74.7   | 70.3   | 60.5   | 43.4   | 35.0   | 27.1   | 18.7   | 14.8   | 10.5   | 7.2    | 5.4    | 2.4    |
| 17             | 1.30           | 60     |        | 3      | 2.75           | 64.7   | 72.9   | 74.0   | 71.0   | 59.8   | 43.3   | 32.2   | 26.9   | 21.1   | 16.5   | 12.0   | 9.3    | 6.3    | 2.4    |
| 18             | 1.30           | 70     | 92.1   | 2      | 2.95           | 69.2   | 77.2   | 76.8   | 75.0   | 65.1   | 51.8   | 36.6   | 29.8   | 23.1   | 19.6   | 15.4   | 11.8   | 8.7    | 4.3    |

Table B.4 - Depth-averaged longshore current velocities, mean water depths, mean wave heights and longshore current flows Q measured in experiment 2.
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**Table B.5** - Depth-averaged longshore current velocities, mean water depths, mean wave heights and longshore current flows \( Q \) measured in experiment 3.
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<td>3.3</td>
<td>4.5</td>
<td>6.4</td>
<td>10.0</td>
<td>10.8</td>
<td>10.4</td>
<td>9.7</td>
<td>9.0</td>
<td>8.7</td>
<td>8.3</td>
<td>7.8</td>
<td>7.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table B.7 - Depth-averaged longshore current velocities, mean water depths, mean wave heights and longshore current flows \( Q \) measured in experiment 5.
<table>
<thead>
<tr>
<th>measurement nr.</th>
<th>$w_d$ / $w_s$</th>
<th>$Q_x$ / sec</th>
<th>$Q$ / sec</th>
<th>$x$ (m)</th>
<th>0.10</th>
<th>0.30</th>
<th>0.50</th>
<th>0.90</th>
<th>1.30</th>
<th>1.70</th>
<th>2.10</th>
<th>2.50</th>
<th>2.90</th>
<th>3.30</th>
<th>3.70</th>
<th>4.10</th>
<th>4.50</th>
<th>4.90</th>
<th>5.30</th>
<th>5.70</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>1.35</td>
<td>30</td>
<td>38.3</td>
<td>0</td>
<td>4.6</td>
<td>15.9</td>
<td>26.2</td>
<td>31.4</td>
<td>33.5</td>
<td>27.7</td>
<td>17.2</td>
<td>10.3</td>
<td>6.7</td>
<td>4.1</td>
<td>2.8</td>
<td>1.1</td>
<td>0.8</td>
<td>-0.2</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.35</td>
<td>30</td>
<td>40.0</td>
<td>1</td>
<td>2.3</td>
<td>15.4</td>
<td>26.4</td>
<td>29.9</td>
<td>31.8</td>
<td>26.6</td>
<td>18.6</td>
<td>11.2</td>
<td>7.0</td>
<td>4.0</td>
<td>2.7</td>
<td>1.4</td>
<td>0.8</td>
<td>0.7</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>1.35</td>
<td>30</td>
<td>40.4</td>
<td>2</td>
<td>7.0</td>
<td>21.2</td>
<td>25.7</td>
<td>31.0</td>
<td>30.7</td>
<td>24.8</td>
<td>17.5</td>
<td>11.1</td>
<td>7.6</td>
<td>5.4</td>
<td>3.3</td>
<td>2.1</td>
<td>1.2</td>
<td>0.2</td>
<td>-0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>6.2 and 6.3</td>
<td>mean water depth (cm)</td>
<td>0.4</td>
<td>1.3</td>
<td>2.2</td>
<td>3.2</td>
<td>4.9</td>
<td>6.6</td>
<td>8.6</td>
<td>10.6</td>
<td>12.6</td>
<td>14.7</td>
<td>16.7</td>
<td>18.7</td>
<td>20.7</td>
<td>22.7</td>
<td>24.8</td>
<td>26.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>mean wave height (cm)</td>
<td>1.3</td>
<td>2.2</td>
<td>4.1</td>
<td>5.5</td>
<td>5.2</td>
<td>5.4</td>
<td>5.5</td>
<td>5.4</td>
<td>5.5</td>
<td>5.6</td>
<td>5.8</td>
<td>5.7</td>
<td>5.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table B.8 – Depth-averaged longshore current velocities, mean water depths, mean wave heights and longshore current flows $Q$ measured in experiment 6.
| Measurement nr. |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | V(x) in cm/sec |
| 7.1             | 0.87 | 10 | 26.5 | 2 | 0 | 5.6 | 9.1 | 14.7 | 18.5 | 20.8 | 18.5 | 16.9 | 9.9 | 5.8 | 3.2 | 0.9 | 0.3 | 0.1 | 0.0 | -0.6 |
| 2               | 0.87 | 15 | 28.2 | 2 | 0 | 5.9 | 9.0 | 14.0 | 18.1 | 19.2 | 14.5 | 10.0 | 6.0 | 4.1 | 2.2 | 1.4 | 1.0 | 0.0 | |
| 3               | 0.87 | 20 | 30.3 | 0 | 0 | 5.7 | 10.4 | 16.3 | 23.5 | 26.8 | 19.2 | 11.5 | 5.8 | 2.5 | 1.4 | -0.2 | -0.1 | -0.9 | |
| 4               | 0.87 | 20 | 30.4 | 1 | 0 | 5.3 | 9.2 | 15.4 | 18.8 | 19.7 | 17.8 | 12.7 | 6.9 | 4.1 | 2.0 | 0.6 | -0.1 | -0.4 | |
| 5               | 0.87 | 20 | 31.1 | 2 | 0 | 6.8 | 11.3 | 14.2 | 19.9 | 20.6 | 16.6 | 11.4 | 6.4 | 4.0 | 2.8 | 1.6 | 1.3 | 0.6 | -0.4 |
| 6               | 1.06 | 20 | 30.1 | 2 | 0 | 7.9 | 12.4 | 15.0 | 20.3 | 20.0 | 17.2 | 10.7 | 6.2 | 3.4 | 2.2 | 1.4 | 1.2 | 0.5 | -0.2 |
| 7               | 0.87 | 20 | 33.6 | 3 | 0 | 4.2 | 8.2 | 15.0 | 20.0 | 22.0 | 17.9 | 12.0 | 6.6 | 4.0 | 2.4 | 1.9 | 0.9 | 0.0 | -0.3 |
| 8               | 1.06 | 25 | 36.2 | 2 | 0 | 5.7 | 10.2 | 13.1 | 20.2 | 19.6 | 14.8 | 10.1 | 6.6 | 5.4 | 6.0 | 3.6 | 1.6 | 0.7 | 0.2 | -0.2 |
| 9               | 1.06 | 35 | 49.2 | 2 | 0 | 3.2 | 7.3 | 15.0 | 21.0 | 20.4 | 17.2 | 10.8 | 6.9 | 7.7 | 7.7 | 4.4 | 1.8 | 0.8 | 0.6 | |
| 10              | 1.06 | 45 | 61.6 | 2 | 0 | 4.9 | 8.8 | 13.3 | 21.2 | 22.8 | 20.7 | 13.6 | 9.0 | 8.0 | 12.1 | 12.3 | 6.6 | 3.1 | 1.5 | 0.9 |
| 7.4 and 7.5     | mean water depth (cm) → | 0.6 | 1.6 | 2.4 | 3.5 | 4.9 | 6.6 | 8.3 | 10.0 | 12.0 | 14.3 | 16.0 | 18.1 | 20.3 | 22.3 | 24.7 | 26.6 |
| 7.5             | mean wave height (cm) → | 0.9 | 1.9 | 2.9 | 4.1 | 6.0 | 8.9 | |

Table B.9 - Depth-averaged longshore current velocities and mean wave heights measured in experiment 7, mean water depths resulting from the wave set-up measurements in experiment 4, longshore current flows $Q$. 
APPENDIX C : FIGURES C.1 - C.10

The figures C.1 - C.10 show the depth-averaged current velocities in the different sections measured in the following experiments:

Fig. C.1 : uniform situation of experiment 1.A

" C.2 : " " " " 1.B
" C.3 : experiment 1.C
" C.4 : " 1.D
" C.5 : uniform situation of experiment 2
" C.6 : " " " " 3
" C.7 : " " " " 4
" C.8 : " " " " 5
" C.9 : " " " " 6
" C.10: " " " " 7
Fig. C.1 - Depth-averaged longshore current and circulation velocities in uniform situation of experiment 1.A (Q_r = 35 l/sec, w_d/\omega_s = 1.31).
Fig. C.2 - Depth-averaged longshore current and circulation velocities in uniform situation of experiment 1.8 ($Q_r = 35 \text{ l/sec}, \nu_d/\nu_s = 1.31$).
Fig. C.3 - Depth-averaged longshore current and circulation velocities in completely enclosed wave basin situation of experiment 1 (experiment 1.C).
Fig. C.4 – Depth-averaged longshore current and circulation velocities in experiment 1.0 (wave basin with surf zone openings in both wave guides and an external recirculation without the use of a pump).
Fig. C.5 - Depth-averaged longshore current and circulation velocities in uniform situation of experiment 2 (Q_r = 50 l/sec, u_d/u_s = 1.30).
Fig. C.6 - Depth-averaged longshore current and circulation velocities in uniform situation of experiment 3 (\( Q_T = 40 \text{l/sec}, \omega_d/\omega_s = 1.39 \)).
Fig. C.7 - Depth-averaged longshore current and circulation velocities in uniform situation of experiment 4 (\( Q_r = 50 \text{ l/sec}, \frac{w_d}{w_s} = 1.20 \)).
Fig. C.8 - Depth-averaged longshore current and circulation velocities in uniform situation of experiment 5 (Q_r = 65 l/sec, \( \omega_d / \omega_s = 1.31 \)).
Fig. C.9 - Depth-averaged longshore current and circulation velocities in (uniform situation of) experiment 6 (Q_r = 30 l/sec, \( \omega_d/\omega_s = 1.35 \)).
Fig. C10 - Depth-averaged longshore current and circulation velocities in uniform situation of experiment 7 (Q_r = 20 l/sec, w_d/w_s = 0.87).