CHAPTER 61

WAVE BASIN EXPERIMENTS ON BOTTOM FRICTION DUE TO CURRENT AND WAVES

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ABSTRACT

Results are presented of experiments in a wave basin on the increase of the mean bottom frictional stress in a flow when a wave field is superimposed on a current. The bottom friction was derived from the mean water level measured at various places. Measurements of wave orbital and mean current velocities were done both with a micro-propeller and with a new type immersible Laser Doppler Anemometer.

The data indicate an increase of the mean bottom shear stress due to the presence of the waves, but less than predicted by Bijker (1967). A suggestion is made to improve the accuracy of this theory. The bottom stresses as predicted by Fredsøe (1984) are somewhat larger than the experimental results.

1. INTRODUCTION

Since many years it is known that when a wave field is superimposed on a current (see fig. 1), the mean bottom friction will increase.

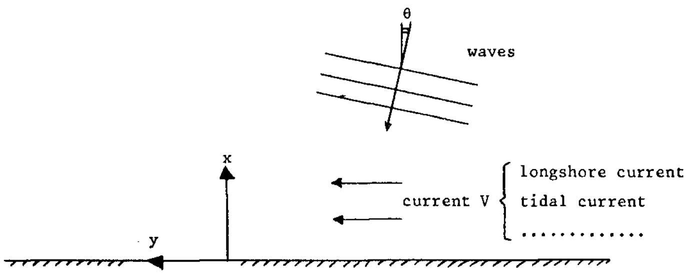

Fig. 1 - Combination of a current and a wave field; θ = angle of incidence, x = coordinate normal to the coast, y = coordinate in longshore direction.

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In the pioneering work of Bijker (1967), this phenomenon was investigated both theoretically and experimentally. Since then many investigators have attacked the problem, both theoretically: Lundgren (1973), Bakker and van Doorn (1979), Grant and Madsen (1979), Fredsøe (1984), Tanaka and Shuto (1984) and van Kesteren and Bakker (1985), and experimentally: Bakker and van Doorn (1979) and Kemp and Simmons (1982, 1983). The studies of the wave boundary layer in case of waves alone have much contributed to the present achievements. In this respect the theories of Kajiura (1968), Jonsson and Carlsen (1976) and Brevik (1981), the experiments and analysis of Jonsson (1963, 1967, 1980), Kalkanis (1964), Horikawa and Watanabe (1969), Kamphuis (1975), Jonsson and Carlsen (1976), Sleath (1982) and van Doorn (1982, 1983) and the empirical analysis of Nielsen (1985) should be mentioned.

The most accurate descriptions of the bottom friction due to current and waves are the models of Fredsøe (1984) and van Kesteren and Bakker (1985). These models also allow an arbitrary angle between the directions of the current and the wave field. Van Kesteren and Bakker assume Prandtl's mixing length hypothesis. Nielsen (1985), however, shows that this hypothesis fails in case of oscillatory flow. The model of van Kesteren and Bakker is also rather complicated. Therefore Fredsøe's model is preferable.

For engineering practice the Bijker (1967) model is often used because of the simplicity and handiness of its solution. Applications of Bijker's description to laboratory data of longshore currents, see Visser (1984, 1985), and to field observations by the Delft Hydraulics Laboratory have, however, indicated that this model overestimates the influence of the waves on the bottom frictional stress.

The present paper describes wave basin experiments on the mean bottom friction due to current and waves. The (effect of the) bottom shear stress was measured by determining the mean water level slope from mean water level observations:

$$\rho g h \frac{\partial h}{\partial y} + \bar{\tau}_{by} = 0 \quad \text{in y-direction ,} \tag{1}$$

where ρ = density of water, g = acceleration of gravity, h = mean water depth, τ_{by} = mean bottom frictional stress in y-direction (= direction of mean current velocity). Equation (1) assumes uniformity along the coast and zero gradients of radiation and Reynolds shear stresses.

The investigation has been restricted to $\theta = 0^o$ in order to prevent recirculation flows on the constant depth part of the wave basin, see Visser (1982). These recirculation flows may disturb the mean water level slope measurements significantly. A further restriction is the application of regular waves.

Actually the investigation is a continuation of Bijker's work. The most important motivations for this study have been: 1. the above mentioned failure of the Bijker model, and 2. the shortage of detailed experimental data in case of small values of θ, in particular for the direct verification via equation (1). The investigation has been carried out within the framework of the Applied Coastal Research programme of the Dutch Public Works Department.

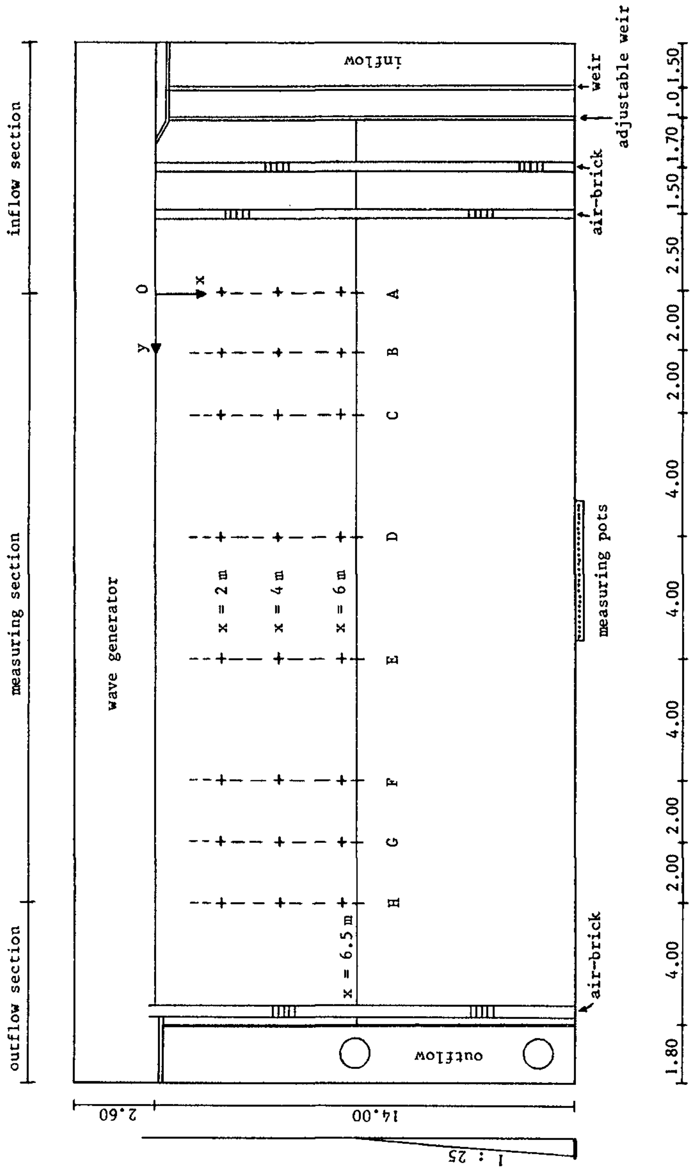

Fig. 2 - Plan view of wave basin (measures in meters, + = tapping for mean water level measurement).

2. DESCRIPTION OF THE EXPERIMENTS

The experiments were performed in the 16.60 * 34.00 m^2 wave basin of the Civil Engineering Department of the Delft University of Technology, see fig. 2. A concrete 1 : 25 beach was built opposite to the wave board in order to minimize reflection of the waves.

A mean current was established in the basin flowing parallel to the shore and the wave board. Much attention was given to the in- and outflow conditions in order to obtain uniformity of this current in the horizontal plane (on the constant depth part of the basin). The details of the experimental set-up are shown in fig. 2. The inflow section of the wave basin consisted of:

- two supply-pipes with a maximum flow rate of 0.8 m^3/s,
- two weirs to distribute the flow over the width of the basin,
- two rows of air-bricks to reduce the turbulence in the current caused by the inflow from the supply-pipes,
- small-mesh wire-netting against one row of air-bricks to adjust the proper vertical velocity distribution at the upstream end of the measuring section.

The outflow section consisted of one row of air-bricks, a small weir and two wells.

The details of the measuring techniques are summarized in table 1. Measurements of orbital and mean current velocity were done with a micro-propeller current meter (in situations with current or waves alone) and with a new type immersible Laser-Doppler Anemometer (LDA),

measurements of	measuring method	sections	number of measuring points per section	number of measuring points per vertical
mean current velocities (current alone)	micro-propeller	D, F(1)	6 - 12	10
	LDA	F	2	14
orbital velocities (waves alone)	micro-propeller	D, E(2)	4 - 7	1(3)
	LDA	F	2	8 - 14
vertical velocity profiles (current and waves)	LDA	D, F	2 - 6	8 - 14
mean water levels	static head in pots connected with tappings in the bottom	A, B, C, D, E, F, G, H	3	measured 5 times
wave heights	resistance wave probes	D, E	4 - 7	

(1) in exp. 1 also in sections C, E and H

(2) in exp. 1 also in sections C, F and G

(3) about 3 cm above the bottom (measurement of u_m, see sketch)

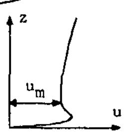

Table 1 - Experimental procedure.

developed by the Delft Hydraulics Laboratory, see Godefroy and Vegter (1984).

This LDA is a very useful tool for velocity measurements in wave basins. A micro-propeller, for instance, fails if there is an angle between mean current direction and wave propagation direction. A disadvantage compared with LDA-measurements through glass side-walls of flumes is the inevitable small disturbance of the flow. An accurate calibration of the instrument, however, can reduce this problem.

The LDA and the probes of the micro-propeller current meter and wave height meter were installed on the measuring carriage of the wave basin.

Six pits were made in the wave basin bottom in sections D and F to be able to measure velocities with the immersible LDA near the bottom, see fig. 3. The pits were covered with perspex plates in order to prevent disturbances on the flow. The perspex plates allowed an exact positioning of the measuring point above it (the contact of the measuring point with the surface of the perspex plate gave a 100% Laser-Doppler signal; in water this was 50 - 60%).

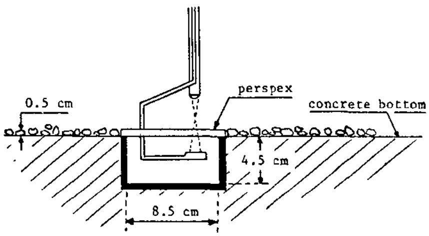

Fig. 3 - Pit in the gravel bottom for the LDA- measurements near the bottom.

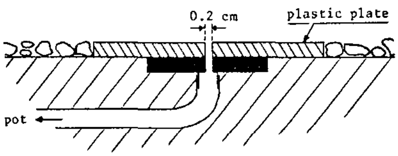

Fig. 4 - Tapping for the mean water level measurement on the gravel bottom.

The mean water level measurements were done in 24 points (see fig. 2) in order to achieve a high accuracy. These observations were made at least five times, since the water level differences were very small and the measuring results showed some scatter.

Experiments were done with a smooth concrete bottom and with a gravel (d_{90} = 8 mm) bottom. Fig. 4 shows a cross-section over a tapping in the gravel bottom. Plastic plates, 10 * 10 cm^2 and 0.6 cm thick were fixed on the concrete bottom in order to obtain horizontal velocities at the tappings (so to prevent dynamic pressures by vertical velocities).

Wave height measurements were only done on the constant depth part of the basin. The observational time was 100 seconds for each measurement.

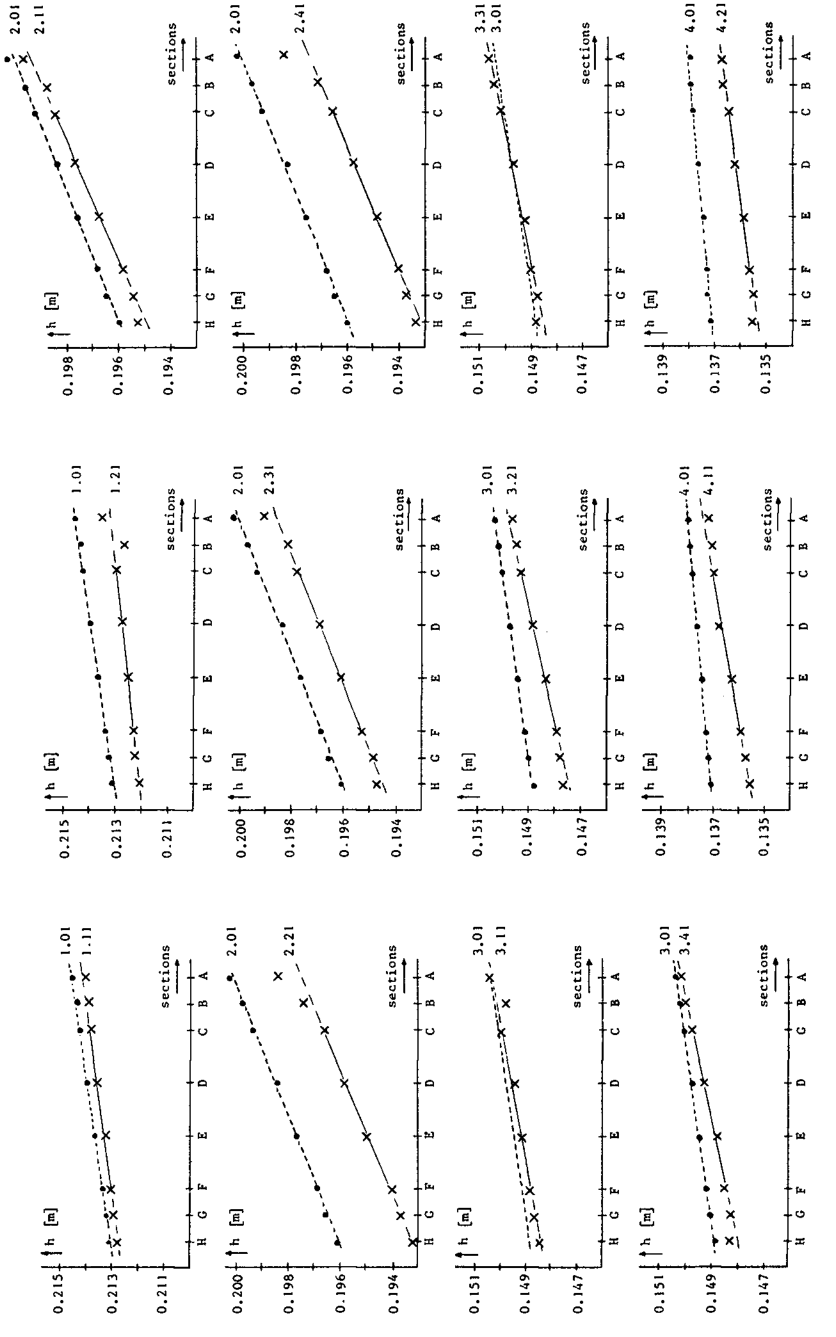

Fig. 5 - Averaged (over width of wave basin) results of mean water level measurements.

3. EXPERIMENTAL RESULTS

The experimental conditions and the main results of the measurements on the constant depth part of the basin regarding averaged wave heights H, mean water depths h, depth-averaged mean current velocities V (V_c in case of current alone, V_{cw} in case of current and waves) and averaged amplitudes of orbital velocities near the bottom u_m are given in table 2. A current alone was present in the experiments 1.01, 2.01, 3.01 and 4.01. The other experimental data of table 2 represent situations of current and waves. V_{cw} was not measured in all experiments. The data (H, u_m) of the experiments with waves alone correspond with those of current and waves. By averaging these data have been incorporated in table 2.

Fig. 5 shows the averaged (three points per section, in time observed at least five times) results of most of the mean water level measurements. The mean water level slopes i (i_c or i_{cw}) in table 2 were calculated by linear regression from the mean water level observations in the sections C, D, E and F. Upstream of section C and downstream of section F the mean water level measurements were influenced by the inflow and outflow conditions, respectively, see fig. 5.

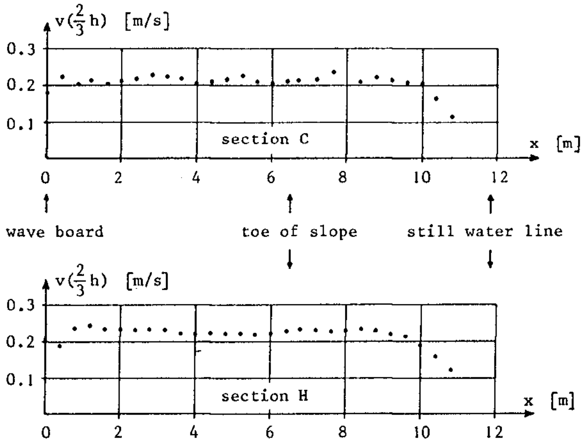

Fig. 6 - Distribution of mean current velocity v at a height of z = 2h/3 in sections C and H in exp. 1.01 (current alone).

Fig. 6 shows the distribution of the mean current velocity v in x-direction at a height of 2h/3 above the bottom in exp. 1.01, measured with the micro-propeller in sections C and H. On the constant depth part of the basin the uniformity of this velocity in x-direction is satisfactory, especially in section H.

Fig. 7 gives examples of the width-averaged results of the

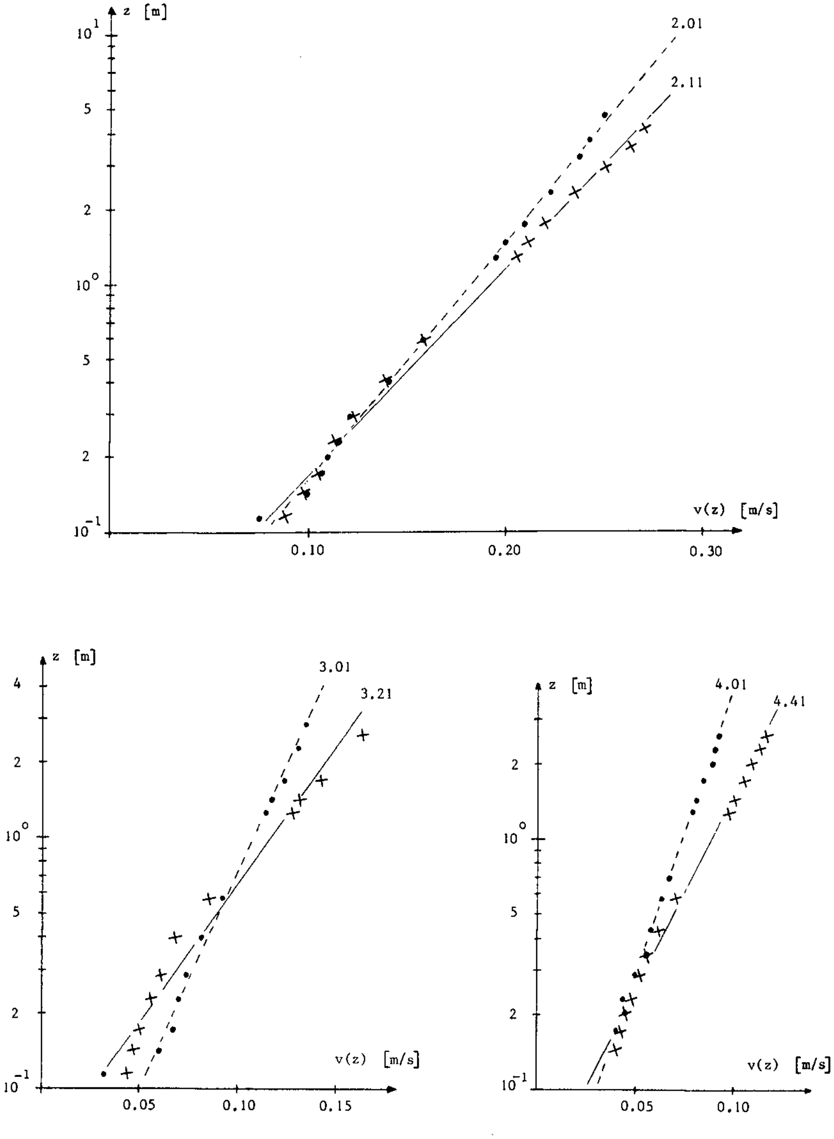

Fig. 7 - Mean current velocities v(z) in section F, averaged over two measuring points x = 3.0 m and x = 5.0 m; z = vertical coordinate, z = 0 at surface of perspex plate (see fig. 3), • • • = current alone, X X X = current and waves.

measurements (in the points x = 3.0 m and x = 5.0 m in section F) of mean current velocity profiles with the immersible LDA.

Fig. 7 reveals also a problem with the mean current velocity data of the experiments on the rough bottom: the velocities on the constant depth part of the basin were larger in the situation with current and waves than in case of current alone, especially at the downstream end of the basin. As such this was not unexpected. Due to the waves the bottom friction on the slope increased more than on the constant depth part of the basin (see also chapter 4). The flow rate Q was the same as in the current alone case and so this gave rise to this larger velocities. But the resulting non-uniformities of the mean current were hard to suppress and therefore the experimental data of V_{cw} (see table 2) are less accurate.

These non-uniformities have also unfluenced the mean water level slope observations. The maximum relative error occurs in exp. 4.21 (see table 2) and is estimated at

$$\frac{V\frac{\partial V}{\partial y}}{g\frac{\partial h}{\partial y}} \simeq \frac{0.09\left(\frac{0.096-0.083}{20}\right)}{10 * 0.69 * 10^{-4}} \simeq 0.085 \; ,$$

which is, fortunately, not extremely large.

A suggestion to avoid this problem in further research is given in chapter 5.

4. COMPARISON WITH THEORETICAL RESULTS

For the combination of a mean current in longshore direction and a wave field (fig. 1), Bijker (1967) has proposed to combine the horizontal mean current and orbital velocity vector in the hypothetical boundary layer (viscous sublayer) at a height z' = e r / 33 (r = Nikuradse bottom roughness parameter) above the bottom. Bijker determined the mean current velocity at this height with Prandtl's mixing length theory and put the horizontal orbital velocity at the height z' equal to $p\, u_m \cos \omega t$, with ω = angular frequency and $p \simeq 0.4$, both theoretically and experimentally. In this way Bijker has derived for the mean bottom frictional stress in y-direction τ_{by}:

$$\tau_{by} = C\, \rho\, V^2\, f(\theta, \xi \frac{u_m}{V}) \; , \tag{2}$$

where

$$f(\theta, \xi\frac{u_m}{V}) = \frac{1}{T}\int_0^T \{1 + 2\,\xi \frac{u_m}{V} \sin\theta \cos\omega t + (\xi\frac{u_m}{V})^2 \cos^2\omega t\}^{\frac{1}{2}} * \\ *(1 + \xi\frac{u_m}{V} \sin\theta \cos\omega t)\, dt \; , \tag{3}$$

$$\xi_B = \frac{p\,\kappa}{\sqrt{C}} \simeq \frac{0.16}{\sqrt{C}} \; , \tag{4}$$

$$C = \left(\frac{\kappa}{\ln \frac{12\,h}{r}}\right)^2 \quad , \tag{5}$$

t = time, T = wave period, C = dimensionless bottom friction coefficient.

The parameter ξ can be condidered as a dimensionless factor depending on how the mean current and orbital velocty near the bottom are combined. If the depth-averaged mean current velocity V and the amplitude of orbital velocity near the bottom u_m are combined, see Visser (1984), then: $\xi = 1$.

Swart (1974) modified Bijker's model to Jonsson's (1963, 1967) experimental results for waves alone and arrived at (2) with (3), (5) and

$$\xi_S = \sqrt{\frac{f_w}{2C}} \quad , \tag{6}$$

in which

$$f_w = \exp\{-5.977 + 5.213(\frac{r}{a_b})^{0.194}\} \qquad \text{for } \frac{a_b}{r} > 1.57 \quad , \tag{7}$$

$$f_w = 0.30 \qquad \text{for } \frac{a_b}{r} < 1.57 \quad , \tag{8}$$

where f_w = Jonsson's wave friction factor and a_b = amplitude of orbital particle excursion near the bottom.

The elliptic integral $f(\theta, \xi u_m/V)$ represents the increase of the bottom friction due to the presence of a wave field. Its dependence on θ and $\xi u_m/V$ is shown in fig. 8. The dashed line in fig. 8 represents an analytical expression with which the elliptic integral can be approximated with an error smaller than 3 %, see Visser (1984).

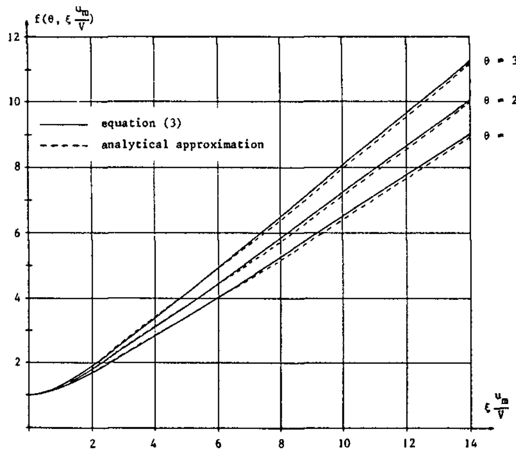

Fig. 8 – $f(\theta, \xi\frac{u_m}{V})$

exp nr	bottom	Q	T	H	h	V_c, V_{cw}	u_m	$i\ 10^4$	$\frac{i_{cw}}{i_c}$	$\frac{u_m}{V_c}$	ξ_B	ξ_S	$f(\theta, \xi \frac{u_m}{V_c})$			$\frac{C_{cw}}{C}$
		(1/s)	(s)	(m)	(m)	(m/s)	(m/s)	(-)	(-)	(-)	(-)	(-)	$\xi=1$	$\xi=\xi_B$	$\xi=\xi_S$	
1.01	smooth concrete $r \approx 0.0023$ m	400	-	-	0.214	0.216	-	0.72	-	-	-	-	-	-	-	-
1.11			1.0	0.046	0.213	0.216	0.119	0.67	0.93	0.55	2.8	3.6	1.07	1.43	1.66	1.2
1.21			1.0	0.070	0.213	0.219	0.179	0.60	0.83	0.83	2.8	3.1	1.15	1.85	2.00	1.3
1.31			1.8	0.043	0.214		0.125	0.68	0.94	0.58	2.8	2.9	1.08	1.48	1.50	1.2
1.41			1.8	0.076	0.213	0.218	0.188	0.71	0.99	0.87	2.8	2.6	1.16	1.93	1.81	1.3
2.01	gravel $r \approx 0.024$ m	350	-	-	0.198	0.218	-	2.06	-	-	-	-	-	-	-	-
2.11			1.0	0.056	0.197		0.152	2.18	1.06	0.70	1.8	4.4	1.11	1.31	2.29	1.4
2.21			1.0	0.100	0.195		0.213	2.10	1.02	0.98	1.8	4.4	1.21	1.62	3.05	1.5
2.31			2.0	0.049	0.197		0.177	2.06	1.00	0.81	1.8	3.8	1.14	1.36	2.34	1.4
2.41			2.0	0.106	0.195		0.258	2.17	1.05	1.18	1.8	3.3	1.28	1.68	2.80	1.6
3.01		135	-	-	0.149	0.120	-	0.75	-	-	-	-	-	-	-	-
3.11			1.0	0.049	0.149		0.154	0.96	1.28	1.28	1.7	4.1	1.31	1.76	3.62	1.6
3.21			1.0	0.080	0.149	0.130	0.201	1.18	1.57	1.67	1.7	4.1	1.49	2.15	4.50	1.8
3.31			2.0	0.045	0.149		0.168	0.95	1.27	1.40	1.7	4.1	1.37	1.88	3.90	1.7
3.41			2.0	0.081	0.149	0.134	0.220	1.09	1.45	1.83	1.7	4.1	1.57	2.32	4.84	1.9
4.01		85	-	-	0.137	0.083	-	0.47	-	-	-	-	-	-	-	-
4.11			1.0	0.066	0.137	0.093	0.200	0.93	1.98	2.41	1.7	4.0	1.90	2.88	6.12	2.1
4.21			2.0	0.068	0.136	0.096	0.207	0.69	1.47	2.49	1.7	3.3	1.95	2.96	5.24	2.1

Table 2 - Experimental conditions and results and comparison of i_{cw}/i_c with theoretical predictions.

Assuming a logarithmic velocity distribution inside as well as outside the wave boundary layer (but with different slopes), Fredsøe (1984) has calculated the mean current profile by use of a depth-integrated momentum equation. Fredsøe derived for the mean bottom frictional stress in y-direction τ_{by} (in the notation of the present paper):

$$\tau_{by} = C_{cw} \, \rho \, V^2 \, , \tag{9}$$

where C_{cw} = dimensionless bottom friction coefficient in case of current and waves:

$$C_{cw} = \left\{ \frac{\kappa}{\ln(\frac{30\,h}{r_w}) - 1} \right\}^2 \, , \tag{10}$$

in which r_w = apparent bed roughness (which is different from the grain roughness r as the wave boundary layer acts as a larger roughness element). The apparent bed roughness r_w can be determined from fig. 7 in Fredsøe's (1984) paper if V, h, u_m, a_b and r are known. The increase of the bottom friction in a flow due to waves can be expressed from (5) and (10) as:

$$\frac{C_{cw}}{C} = \left\{ \frac{\ln \frac{12\,h}{r}}{\ln(\frac{30\,h}{r_w}) - 1} \right\}^2 \, . \tag{11}$$

Table 2 gives the comparison of the measured increase of the bottom friction caused by the presence of waves (i_{cw}/i_c) and the theoretical predictions given by equation (3) with ξ = 1, $\xi = \xi_B$ and $\xi = \xi_S$, respectively, and those given by Fredsøe (= C_{cw}/C).

The bottom roughnesses r have been calculated from the experiments with current alone using (2) with $f(\theta, \xi u_m/V)$ = 1 and (5), see table 2. The value of the diameter of the "roughness elements" of the concrete bottom is estimated at 0.5 - 1.0 mm, d_{90} = 8 mm for the gravel bottom. Thus

$$r/D_{90} \simeq 3, \tag{12}$$

which is in reasonable agreement with Kamphuis' (1975) ratio of 2. With $r/h \simeq 0.01$ and $Re \approx 5 * 10^4$, the flow on the smooth concrete bottom is practically complete rough turbulent.

Table 2 shows that the measured i_{cw}/i_c are somewhat smaller than predicted by Fredsøe (1984), and lower to much lower than the predictions of Bijker (1967) and Swart (1974). The best agreement is obtained with equations (2) and (3) if ξ = 1.

The comparison of theoretical and experimental results for the increase of the bottom friction due to waves has been done using measured V_c in case of current alone. The data of V_{cw} have been ignored for this since these are less accurate (see chapter 3).

Substitution of V_{cw} in $f(\theta, \xi u_m/V)$ and use of it to determine C_{cw}/C will lead to smaller values for both parameters. But these smaller values should also be compared with corrected values for i_{cw}/i_c:

$$\frac{i_{cw}^*}{i_c} = \frac{h_{cw}}{h_c} \left(\frac{V_c}{V_{cw}}\right)^2 \frac{i_{cw}}{i_c} \quad . \tag{13}$$

5. CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

A set of data is presented of wave basin experiments on the increase of the mean bottom frictional stress in a flow when waves are superimposed on a current (angle between directions of current and wave propagation is 90°). Especially the accuracy of the mean water level slope observations (direct measurement of effect of bottom friction) between sections C and F (fig. 5) is satisfactory. The decrement of the mean current velocities on the slope in case of current and waves has decreased the uniformity of the mean current velocities on the constant depth part of the basin, so also the accuracy of the mean current data (particularly V_{cw}) in this situation.

The following conclusions can be drawn from this investigation:

1. A rather laborious adjustment of the inflow is necessary to obtain uniform mean current velocities.
2. An immersible Laser Doppler Anemometer is a very useful instrument for wave basin experiments. Problems can be expected inside the surf zone caused by air-bubbles in the water.
3. The models of Bijker (1967) and Swart (1974), which are practical for engineering applications, do overestimate the bottom friction in case of current and waves.
4. The equation $\tau_{by} = C \rho V^2 f(\theta, \xi u_m/V)$ with $\xi = 1$ gives rather good agreement with the experimental results. This conclusion has also been followed from a comparison of longshore current data with a mathematical model including this expression, Visser (1984, 1985).
5. The bottom stresses as derived by Fredsøe (1984) are somewhat larger than the experimental results.

The following recommendations for further research are given:

1. The present experimental set-up can be improved by reducing the velocities on the slope significantly (for instance by making the bottom of the slope much more rough than the bottom of the constant depth part of the wave basin).
2. It is recommended to compare the model of van Kesteren and Bakker (1985) with the present experimental data.

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