CHAPTER 94

SEDIMENT MOTION CAUSED BY SURFACE WATER WAVES

by

A G DAVIES* AND R H WILKINSON*

Abstract

This paper describes an experimental study of sand motion on the seabed caused by surface water waves. The observations were made close to a beach, but outside the breaker zone and in a location where steady currents were small. Measurements of water velocity components were made at various heights above both rippled and flat beds, together with measurements of the pressure gradients at the seabed, in order to examine the threshold of motion of the natural coarse sand ($D_{50} \approx 1.4$mm). This motion was monitored with an underwater television system. The flow conditions were predominantly laminar and no flow separation occurred above the lee slopes of the ripples.

Sediment motion was of 'bed load' type and was confined to the crests when the bed was rippled. This motion has been found to be caused by waves having an orbital velocity amplitude (measured in the free stream flow) of about one half of that required to cause motion on a flat bed of the same material. Wherever possible the threshold measurements have been compared with results obtained in the laboratory.

The relative importance of forces on the seabed induced by velocity and pressure gradients has been assessed. It appears that the latter effects are of little or no importance in situations of the kind described, as suggested elsewhere in the literature.

1. Introduction

Most previous experimental work on the threshold of sediment motion by waves has been carried out in the laboratory. Typically, this has involved the definition of 'critical waves' of single frequency which are just capable of causing sediment motion on a flat bed, such waves being defined by their velocity amplitudes and periods, and the bed material by its size and density. Sediment motion arises primarily as a result of the near-bed velocity field; however, a secondary influence which must be investigaed is the possible role of pressure gradients at the bed surface. The velocity induced bed shear stresses are expected to lead the oscillation in the free stream in phase, on account of bottom boundary layer effects; whereas the additional forces on the grains due to the direct action of the fluid pressure field are expected to be in phase with the pressure

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gradients in the free stream outside the boundary layer. Unfortunately, in laboratory work little attention has been given to these phase relationships and, in particular, to the phase angles in the wave cycle between which to- and fro- motion of sediment has been observed. This makes the interpretation of field observations difficult.

A study of incipient sediment movement requires ultimately an understanding of the shear stress distribution in the flow, accompanied by a knowledge of the instantaneous velocity profile in the boundary layer through a wave cycle. Both of these quantities will depend upon the seabed topography; the development of ripples complicates the flow pattern close to the bed, alters the amount of sediment in motion and causes the breakdown of the 'critical wave' formulae derived for flat beds in the laboratory. An important part of such a study involves determining whether the flow in the boundary layer is laminar or turbulent. The transition from laminar to turbulent flow occurs near the threshold of motion for sands and, furthermore, differs for flat and rippled beds (see Davies and Wilkinson (1977)).

In this paper we are concerned with the relevance of laboratory formulae for threshold motion, when applied in the sea where the bed is normally rippled; also with the secondary problem of whether forces induced by pressure gradients in the flow are important at the threshold of motion. We make no attempt here to model the bottom stress and the resulting sediment transport directly. Instead we concentrate on studying the causal link between observations of sediment motion on the seabed and measurements of the flow parameters in the free stream outside the boundary layer. In particular, an attempt has been made to identify the critical conditions which exist instantaneously in the free stream flow at the threshold of motion of coarse sand.

2. Field Studies

Two experiments have been carried out at Blackpool Sands, Start Bay, Devon, England: the first on 22 March 1975 (Davies, Frederiksen and Wilkinson (1977)); the second on 25 - 26 March 1976. Measurements were made at positions close to the beach but well outside the breaker zone (Fig 1). Tidal currents and the effects of shoaling were shown to be of secondary importance at the experimental site, and the flow near the seabed was due primarily to an incoming ocean swell on both occasions. The bottom slope at the position of the rig was about 1 : 17 and the mean water depth was about 5m (Fig 2).

In the first experiment measurements of velocity were made above the crest of a ripple of height about 10 cms, and wavelength about 100 cms; and in the second above the crest of a ripple of height 12 cms and length 85 cms, as well as above an artificially flattened bed. When the bed was rippled, the to- and fro- motion of grains was always confined to the region of the ripple crests, and was of bed load type only. The bed features were almost certainly fossil ripples in both experiments, not in equilibrium with the existing flow field but formed by some previous more active wave-induced flow conditions.

BLACKPOOL SANDS, START BAY.

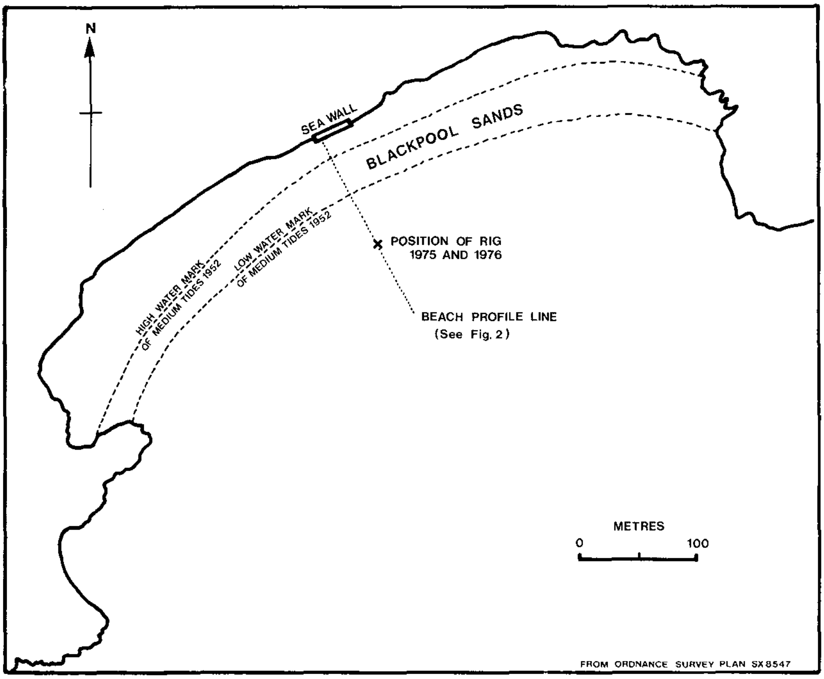

Fig. 1

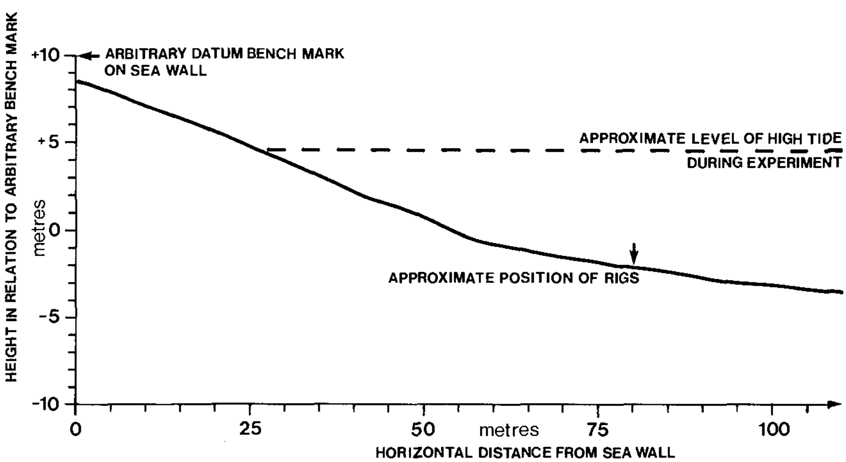

Fig. 2 BEACH PROFILE AND NEARSHORE BOTTOM TOPOGRAPHY.

No flow separation was observed above the lee slopes of the ripples, judging from the behaviour of visible particulate matter in the water, nor was there any obvious sign of turbulent exchange in the flow. Indeed conditions, at least well away from the bed, appeared to be predominantly laminar in both experiments. When the bed had been flattened, grain motion occurred more generally over the bed surface, and again the flow appeared to be laminar.

In both experiments, the surface bed material was a coarse sand on the ripple crests and an even coarser material in the troughs, see Fig 3. In the second experiment, the material on the surface of the artificially flattened bed was predominantly of crest type.

The deployment of the apparatus was carried out by divers; its layout on the seabed is shown in Fig 4, together with the definition of axes and the symbols adopted for the flow parameters. Velocity measurements were made using two electromagnetic flowmeters with 10cm diameter Colnbrook measuring heads, mounted on a tetrahedral frame. These were positioned to measure the horizontal and vertical components of velocity in the vertical plane in the direction of wave advance; one flowmeter was at a height of 1m above the seabed, and the other at a height of 30cms in the first experiment and at a variable height between 15 and 60cms in the second. It was possible also to position the 'lower' flowmeter in a horizontal plane above the rig; this was done before and after runs in the second experiment in order to monitor the directional characteristics of the waves. In this paper, we concentrate for the most part on measurements of the horizontal velocity made with the 'upper' flowmeter.

Also attached to the rig was an underwater television camera, with which an area of the seabed about one half a metre square vertically below the flowmeters was viewed. The resolution of the camera was such that individual sand grains could be detected clearly and, when the bed was rippled, a view along a crest was obtained (as shown schematically in Fig 4). At distances of 5m on either side of the rig, in the direction of wave advance, FM-pressure transducers were positioned in order to obtain a direct estimate of the pressure gradient in the flow. The separation of the transducers was less than one quarter of the expected surface wavelength in order to avoid spatial aliasing.

The velocity and pressure signals were logged on a Bell and Howell FM-tape recorder. In addition, a synchronous video record showing the sediment motion was made with the underwater television system. The first experiment provided continuous data over a two hour period, while, in the second, four forty-minute runs were made on each of two consecutive days.

Before and after the experiments, the FM-flowmeters were calibrated in a towing tank. However, in the second experiment, zero points on the velocity scales were also determined in the field by placing shrouds over the measuring heads; this enabled the drift in the system to be corrected for. The noise of the flowmeter system was equivalent to a pk-pk velocity of about 1 cm/sec, and the pressure transducers could each resolve to about 1 cm of water.

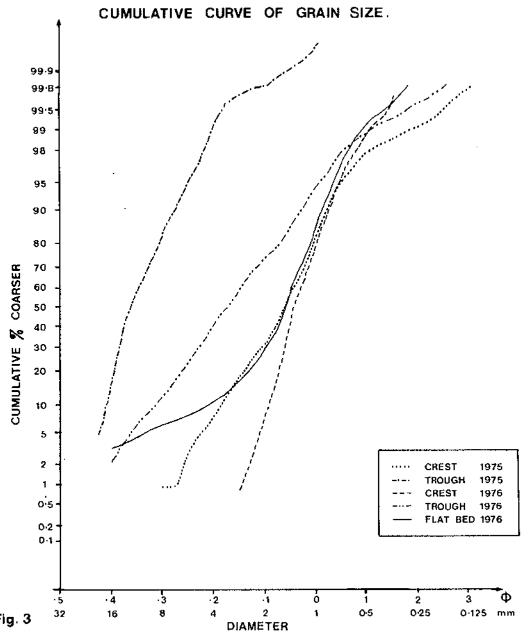
CUMULATIVE CURVE OF GRAIN SIZE.
CUMULATIVE % COARSER
99·9
99·8
99·5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0·5
0·2
0·1
CREST 1975
TROUGH 1975
CREST 1976
TROUGH 1976
FLAT BED 1976
-5 -4 -3 -2 -1 0 1 2 3 Φ
32 16 8 4 2 1 0·5 0·25 0·125 mm
DIAMETER

Fig. 3

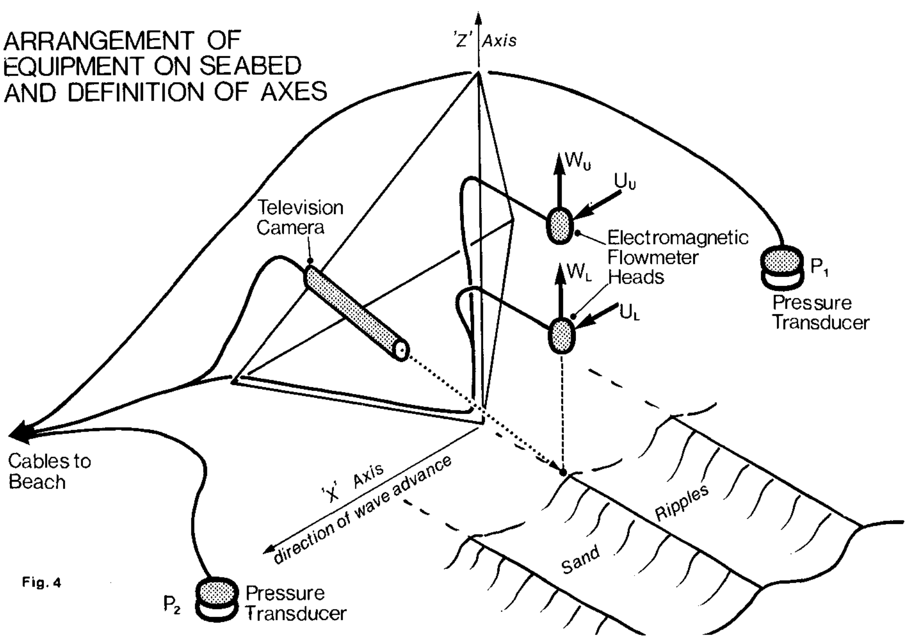
ARRANGEMENT OF EQUIPMENT ON SEABED AND DEFINITION OF AXES
'Z' Axis
Television Camera
Wu
Uu
Electromagnetic Flowmeter Heads
WL
UL
P1
Pressure Transducer
Cables to Beach
'X' Axis
direction of wave advance
Ripples
Sand
P2
Pressure Transducer

Fig. 4

3. The Sediment Threshold Analysis

One of the main objectives of the experiments was to determine the values of the measured parameters at the instants when sediment motion started and stopped in both shoreward and seaward directions. This aspect of the investigation required the times of occurrence of grain motion to be obtained from the video records, and these times were then used to obtain critical velocities from the EM-flowmeters, as well as critical pressure values from the two FM-pressure recorders.

The method adopted was to replay the video tapes to three observers, each of whom recorded automatically an opinion as to whether sediment movement was taking place (for details, see Davies, Frederiksen and Wilkinson (1977)). The three sets of opinions were then averaged in such a way that a series of times was obtained at which sediment motion was considered to have either started or stopped, in both shoreward and seaward directions. These times were used to obtain critical instantaneous values of velocity and pressure from the synchronous analogue data. The means and variances of the critical values were calculated and, due to the subjective nature of the sediment threshold analysis, it was not surprising to find that they contained a considerable amount of scatter. It has been shown that the distribution of the critical values around their means was Gaussian for each parameter.

Under the experimental conditions, the sand on the ripple crest and, even more so, the sand on the flattened bed, remained stationary for most of the time. Sediment movement was observed only occasionally and it was usually associated with a group of higher amplitude surface waves. The number of instances of sediment motion in both shoreward and seaward directions, together with the percentage of the total time that sediment was in motion are shown in Table 1. The most striking feature here is the almost complete inhibition of sediment motion which was brought about by flattening the bed, even though the wave conditions were essentially the same.

For the first experiment, the number of instances of motion has been broken down into values for succeeding intervals of duration 10 minutes. In this form they display a considerable variability which can be associated with the changing wave conditions which were experienced during the experiment. To illustrate this, the number of instances of motion in an interval has been plotted against the variance of u_L , the horizontal velocity at a height of 30 cms, in that interval (see Fig 5). There is clearly an increase in the number of instances of motion with variance as expected; the scatter in the results indicates merely that variance is a crude measure of wave intensity for the present purpose and does not bear any direct relationship to sediment transport. Similar results were obtained by taking the variances of u_U , p_2 and w_L (see Fig 4).

4. Energy Spectra and Probability Density Functions

The analogue velocity and pressure data recorded on the magnetic tape, having been filtered and then digitized at a rate of 5 Hz, was examined from a general statistical point of view. Firstly, the energy content of the signals was investigated by computing variances over intervals of duration 10 mins, and then the frequency composition of these variances was studied using standard spectral analysis techniques

	EXPERIMENT 1		EXPERIMENT 2			
BED TYPE	RIPPLED BED		RIPPLED BED		FLATTENED BED	
Data Collection Period (mins.)	130		125		145	
Direction of Sediment Motion	Seaward (−)	Shoreward (+)	Seaward (−)	Shoreward (+)	Seaward (−)	Shoreward (+)
Number of Occurrences of Motion	214	232	303	260	12	9
% of Total Time that Sediment was in Motion	5·5	5·9	5·3	4·2	0·15	0·13
% of Total Time in which NO Motion Occurred	88·6		90·5		99·72	

TABLE 1

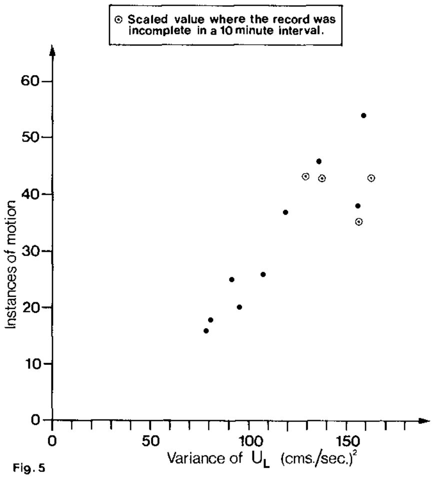

Fig. 5

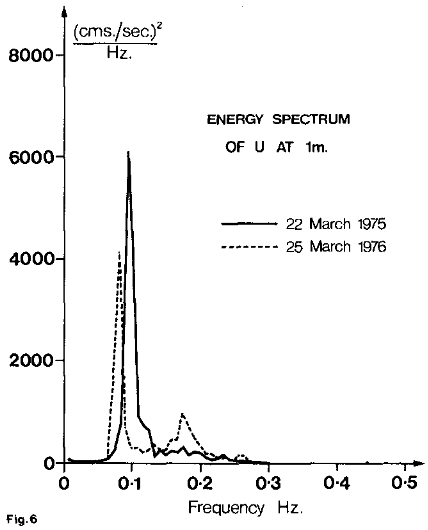

Fig. 6

based on the use of a Fast Fourier Transform. In forming energy spectra, adjacent harmonics were grouped such that spectral estimates were obtained every 1/120 Hz in the frequency domain.

Typical energy spectra of u_v for the two experiments are shown in Fig 6. For the first experiment, the spectrum is dominated by a single peak centred on 0.088 Hz, corresponding to a wave of 11.4 secs period. For the second, in addition to the main peak at 0.080 Hz, a smaller peak can be seen in the range (0.17, 0.19)Hz; this was typical during the experiments on both the rippled and flattened beds. Relatively little activity was measured at frequencies above 0.3 Hz. Thus conditions in both experiments can be seen to have been dominated by a low frequency swell, with a higher frequency contribution also present in the second experiment.

For the purpose of further classifying the observed phenomena, the digitized data from a 10 minute interval is presented in Fig 7 in the form of normalized probability density functions for both u_L and u_v. The normalized Gaussian curve is included for comparison and, since the distributions for both velocity components shown are approximately Gaussian, the signals can be classified as narrow band random noise. This is consistent with the wave group behaviour noted in the velocities and pressures measured during the experiment.

5. Results of Threshold of Motion Studies

(i) The instantaneous threshold of sediment motion

After critical values of the measured velocities and pressures at the times of sediment threshold motion had been established (as described in Section 3), these were sorted into four groups of starting (α) and stopping (Ω) of motion, in the shoreward (+) and seaward (-) directions. Mean values and standard deviations were calculated for each group. Threshold results from the two experiments for u_v, the horizontal velocity measured at a height of 1m above the ripple crest, are shown in Table 2. At threshold the critical velocities in the '+' and '-' directions were approximately equal, and the large standard deviations show that the differences between the magnitudes of the threshold values in the two directions have no statistical significance. Also the results suggest that the asymmetry introduced by an overall beach slope of 1 : 17 did not significantly enhance sediment motion seawards. However smaller critical speeds occur at termination of motion than at initiation. This suggests the persistence of grain motion after the current speed had fallen below the initiation threshold value, possibly as a result of the inertia of the grains in motion. Differences between results for the two experiments can be accounted for in terms of differences in ripple steepness.

The same procedure was carried out on sets of data reduced in such a way that instances of motion were retained for analysis only if the time interval (ΔT) between the initiation of one motion and the cessation of the previous motion exceeded some specified value. This was aimed at studying possible differences in threshold values caused by a "settling of the bed" during a period of no grain motion. It was thought that the longer the interval, the more time the bed would have to "settle out" and become increasingly resistant to subsequent erosion. Results for an interval ΔT = 5 secs are given in Table 2. These show an increase in the initiation threshold values of u_v in both directions, as anticipated. Different values of the interval, ΔT, have been taken for

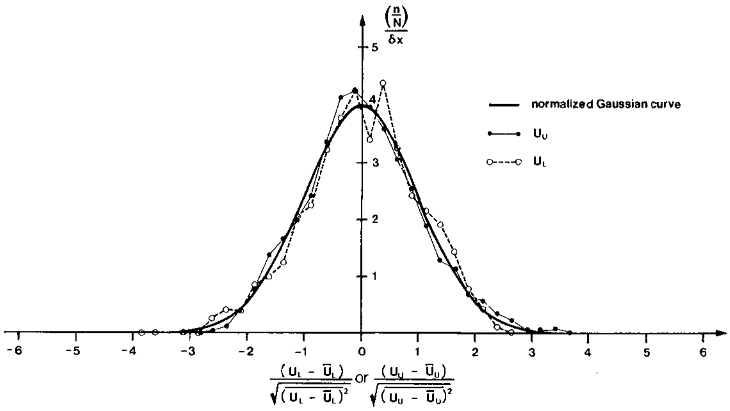

Fig.7 NDRMALIZED PRDBABILITY DENSITY FUNCTIONS OF U_L AND U_U, PLDTTED TDGETHER WITH THE NDRMALIZED GAUSSIAN CURVE. (Notation: n occurrences of the N digitized values overall, lying in a band of width $\delta x = \frac{1}{4} \times$ {standard deviation of the signal}).

THRESHDLD VALUES DF HDRIZDNTAL VELDCITY MEASURED AT A HEIGHT OF 1M. ABDVE THE CREST DF A SAND RIPPLE
RIPPLE STEEPNESS: $1/10$ IN EXPERIMENT 1, $1/7$ IN EXPERIMENT 2

	EXPERIMENT 1				EXPERIMENT 2				
TYPE OF EVENT	$-\alpha$	$-\Omega$	$+\alpha$	$+\Omega$	$-\alpha$	$-\Omega$	$+\alpha$	$+\Omega$	
Mean Velocity	-16·48	-9·37	16·23	11·79	-14·20	-12·97	14·SS	12·7S	ALL MOTIONS INCLUDED
Standard Deviation	7·93	8·69	7·67	8·24	4·38	4·77	4·97	4·S3	
Mean Velocity	-19·41	-8·44	18·17	10·11	-16·6S	-12·10	17·22	12·86	REDUCED DATA: No Motion Interval ΔT = 5 secs.
Standard Deviation	6·12	9·19	6·64	8·56	3·36	4·31	4·30	4·26	

TABLE 2.

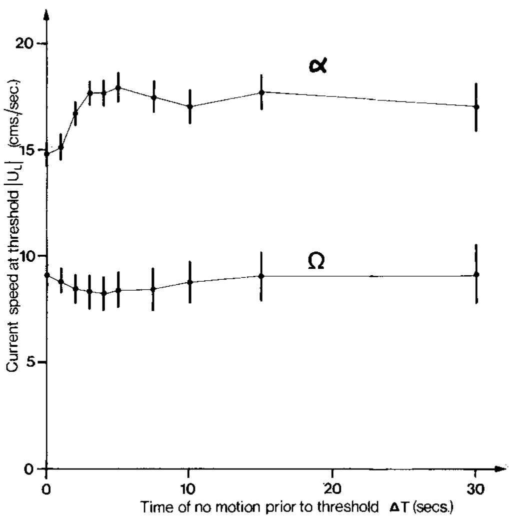

Fig. 8 VARIATION OF THRESHDLD SPEED WITH ΔT AT INITIATION AND TERMINATION DF MDTION FDR THE CASE DF U_L (NEGATIVE). Standard errors are indicated by vartical bars.

the case of u_L, for motion in the (-) seaward direction during the first experiment (Fig 8). For critical current speeds at the initiation of motion (α), a sharp increase can be seen in the range $0 \leq \Delta T \leq 3$ secs but, thereafter, no further statistically significant increase occurs. Standard errors are indicated by vertical bars, and the t-Test for the Two Sample Case (Dayton and Stunkard (1971)) has been used to show that the mean values obtained for u_L with $2 \leq \Delta T \leq 15$ secs, are different from the overall mean value ($\Delta T = 0$) within 95% confidence limits. On the other hand the mean Ω-values, indicating termination of motion, display no such trend as ΔT is varied; for these values, the t-Test indicates that none of the mean values in $1 \leq \Delta T \leq 30$ secs has arisen from a population having a different mean value from the overall mean at $\Delta T = 0$ again within 95% confidence limits. From these typical results (similar results being obtained in the shoreward direction, as well as in u_v) it does seem possible that a sand bed takes a certain length of time to "settle out". However the subjective nature of the sediment threshold analysis might have had a bearing here;in particular, the possibility must be admitted that the longer the grains on the bed surface remained stationary, the slower were the reactions of the observers watching the TV-replay when they eventually moved.

(ii) The critical wave analysis

The critical times indicating the occurrence of sediment motion were used also for a wave by wave analysis. In this case, the aim was to classify individual wave half-cycles in a record according to their velocity amplitudes and periods, noting which waves moved sediment and which did not. This analysis was performed to enable direct comparisons to be made with laboratory findings, and the results described in this section are based on the horizontal velocity data obtained at the 1m height above the bed.

Typical results from the second experiment for the rippled and artificially flattened beds are shown in Figs 9 and 10 respectively, in which the peak velocity (U_M) achieved in a wave half cycle has been plotted against the number of half cycles during the record which had U_M falling within each unit range. The full histogram indicates the distribution of U_M for all waves in the record, and the shaded one is a subset of this indicating only those waves which moved sediment. Positive values indicate the shoreward direction. Fig 9 shows results for a 110 minute data collection period on a rippled bed, and Fig 10 for a 120 minute period on a flat bed.

It can be seen from Figures 9 and 10, firstly, that there is a marked difference between threshold conditions on rippled and flat beds, the measured threshold velocity amplitudes in the latter case being higher by a factor of about two than in the former. Secondly, as expected, the figures show that the waves having high free stream orbital velocity amplitudes moved sediment, and those with low velocity amplitudes did not. Less predictable is the existence of the "transition ranges" between these two situations, in which only a proportion of the waves achieving a particular value of U_M moved sediment. In the case of the rippled bed, the transition range was (-7, -21) cms/sec in the - direction, and (6, 23) cms/sec in the + direction. For the flattened bed, the wave conditions measured in the free stream during the experiment were such that very little motion occurred, despite the

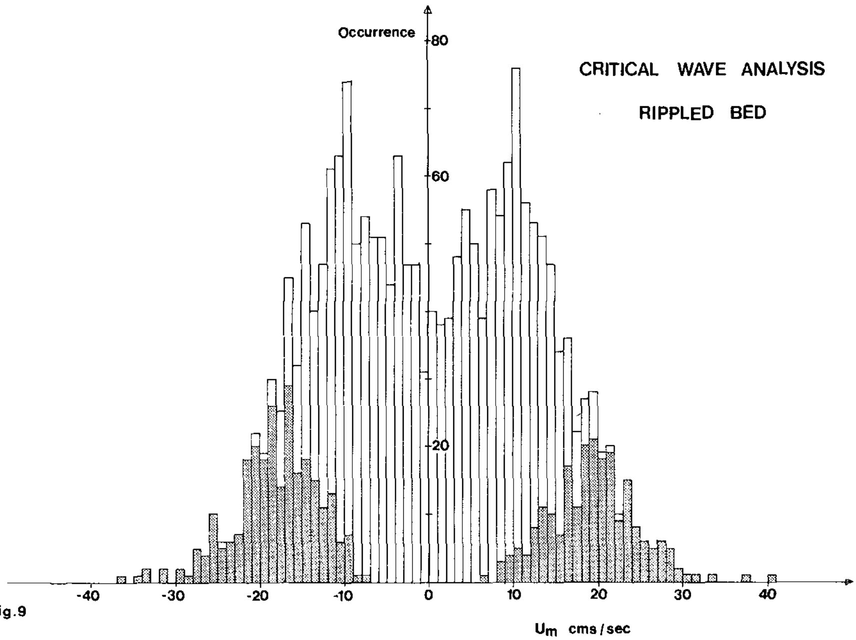
Occurrence
80
60
20
CRITICAL WAVE ANALYSIS
RIPPLED BED
-40
-30
-20
-10
0
10
20
30
40
Um cms/sec

Fig.9

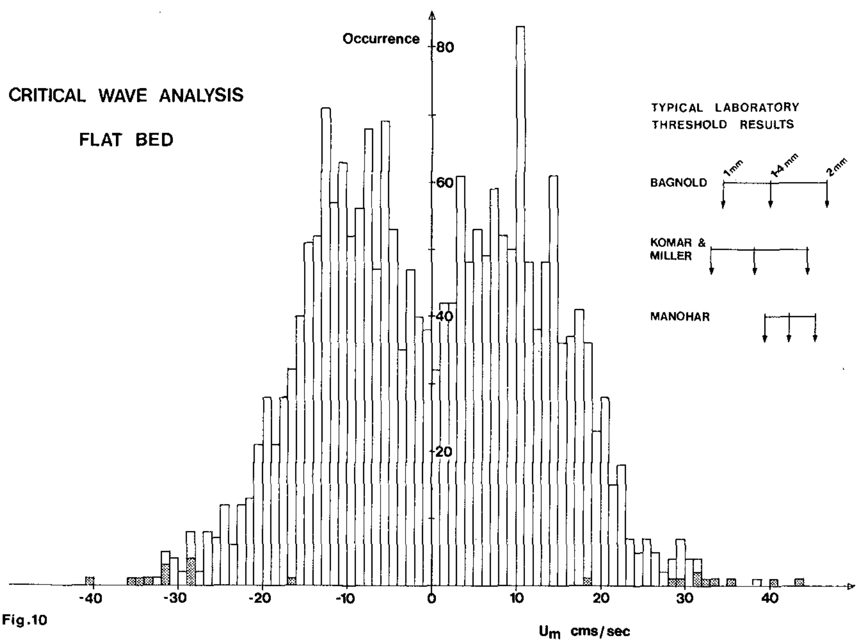
Occurrence
80
60
40
20
CRITICAL WAVE ANALYSIS
FLAT BED
TYPICAL LABORATORY THRESHOLD RESULTS
BAGNOLD
1mm
1·4mm
2mm
KOMAR & MILLER
MANOHAR
-40
-30
-20
-10
0
10
20
30
40
Um cms/sec

Fig.10

fact that these conditions were essentially the same as those during the experiment with the rippled bed; however the start of a transition range can be seen in Figure 10.

Also shown in Fig 10 for the case of the flattened bed are some typical threshold velocity amplitudes obtained on flat beds in the laboratory. The values shown are from the formulae of Bagnold, Manohar, and Komar and Miller (see Table 3). In the calculations the sand grain size has been varied through the range 1 - 2mm, the D_{50} value in the second experiment being 1.4mm. The wave period has been taken equal to 9 seconds, which was a representative mean value obtained from an analysis of zero crossing periods (see Fig 11); in fact, each of the formulae shown is relatively insensitive to wave period, and Manohar's is independent of it. The observed sediment motion can be seen to have occurred at slightly lower values of velocity amplitude than predicted by the three formulae, even allowing for the uncertainty as to which grain size in the range shown was actually moving. It should be realized however that, although an attempt was made to achieve a consistent sediment threshold criterion in the present experiment, it is not possible to compare this criterion objectively with those adopted by the other workers. Nevertheless it can be seen that the parameter U_M does go a considerable way towards explaining the sediment threshold observations on the flattened bed.

(iii) Discussion of the sediment threshold results

The main questions emerging from the critical wave analysis were, firstly, why did the change from a rippled to a flat bed inhibit sediment motion; and, secondly, what was the explanation for the existence of the transition regions, which were particularly evident in the rippled bed results and in which only a fraction of the waves achieving a particular U_M moved sediment.

A quantitative explanation of the apparent discrepancy between the threshold values on flat and rippled beds has been achieved by performing an analysis of the frictionless flow over both real and idealized finite amplitude ripple shapes, assuming a non-separating deep oscillatory flow over the prescribed bed surface. The results of this work have indicated that the measuring height of 1m was well outside the zone of (frictionless) influence of the ripples, and the velocities at this height can, therefore, be said to have been obtained in the unperturbed free stream flow. Calculations of the velocity at the surface of the ripple crest have shown that, for the real sand ripples over which the measurements were made in the second experiment, almost a doubling of the velocity in relation to the unperturbed flow is to be expected (Davies, in prep). This would explain the apparent discrepancy in the sediment threshold findings.

A number of explanations can be proposed for the appearance of the transition regions in the histograms, involving factors of secondary importance in the problem:

(a) the subjective nature of the sediment threshold analysis;
(b) sedimentological considerations of various kinds:- the uncertainty about the grain size in the range (1, 2)mm which was moving at any one time, possible effects of the "settling" of the bed, and changes in the threshold velocity due to the continual changes occurring in the ripple shape during an experiment;

TYPICAL SEDIMENT THRESHOLD FORMULAE FROM THE LABORATORY FOR OSCILLATORY FLOW OVER A FLAT BED

BAGNOLD (1946) $$\frac{\omega^{1/4}\, U_M^{3/4}}{\gamma^{1/2}\, D^{0.325}} = 21\cdot5 \text{ (c.g.s. units)}$$

MANOHAR (1955) $$\frac{U_M}{(\gamma g)^{0.4}(\nu D)^{0.2}} = 8\cdot2$$

KOMAR AND MILLER (1973) $$\frac{\omega^{1/4}\, U_M^{7/4}}{\gamma\, g\, D^{3/4}} = 1\cdot45 \text{ (for } D > \cdot05 \text{ cms.)}$$

where

U_M = velocity amplitude in the free stream
ω = wave frequency = $(2\pi/T)$
D = representative grain diameter
γ = $(\rho_s - \rho_f)/\rho_f$
ρ_f = density of water
ρ_s = density of sediment
g = acceleration of gravity
ν = viscosity of water

TABLE 3

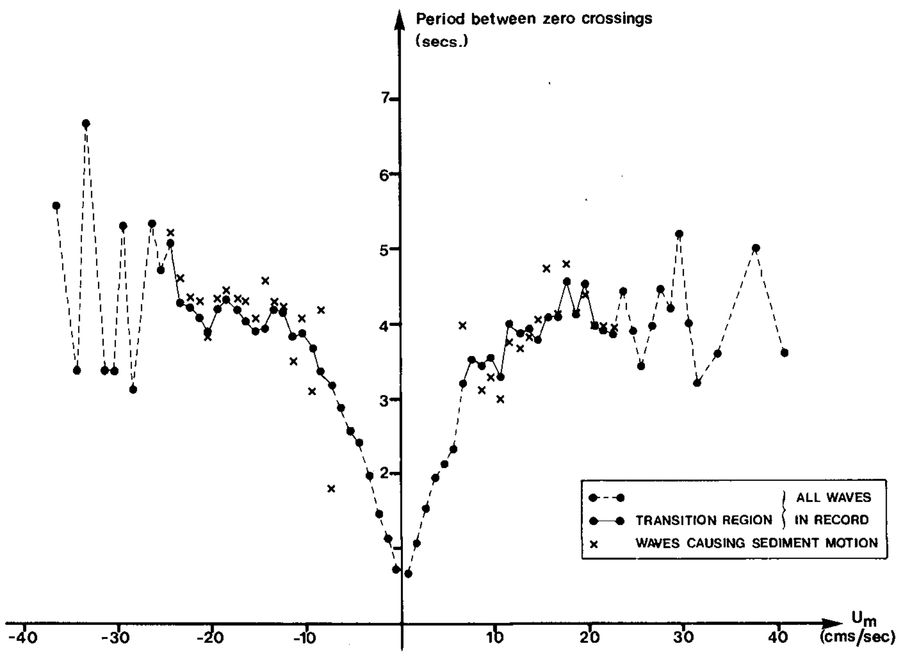

Fig. 11 MEAN PERIOD BETWEEN ZERO-CROSSINGS OF WAVE HALF CYCLES DEFINED BY VALUES OF U_m (IN INTERVALS OF UNIT WIDTH)

(c) slight changes in wave direction - in particular, the transverse velocity component in the direction normal to the plane of the measuring head has been assumed small compared with u and this may not always have been the case;

(d) finally, and probably most important of all, the forces at work at threshold are not being considered directly in concentrating attention on U_m . In particular, an analysis involving bed shear stress is more likely to yield a solution to the problem than one based on the velocity amplitude U_m . However, another possible secondary perturbing influence at threshold is the fluid pressure field, which will give rise to forces on the grains on the bed over and above those forces caused by the fluid velocity field. The discussion in the next section is concerned with the importance of the spatial pressure gradient $\partial p / \partial x$ in the direction of wave advance.

6. The Importance of Pressure Gradients in the Fluid at the Threshold of Sediment Motion

The role of spatial pressure gradients in the fluid acting on individual grains at the initiation of sediment motion is likely to be of secondary importance only and depends, essentially, on whether or not fluid molecular viscosity is an active agent in determining the nature of forces on the exposed sand grains on the bed surface. Davies, Frederiksen and Wilkinson (1977) in discussing a related topic have shown that, depending upon whether fluid momentum is transferred to sand grains on the bed by dynamic pressure effects or by skin friction acting on the exposed top surfaces of grains, the role of pressure gradients is likely to be negligible or of small secondary importance respectively. In deciding which case is relevant in the present problem, it is possible to look for guidance at the comparable and well documented situation of uniform fluid flow past a single sphere; however, unfortunately, the Reynolds number of the flow past the sphere equivalent to the sand grains in question, lies in the intermediate region between linear and quadratic drag law behaviour. The nature of the forces on grains of mixed size on a sand bed is also unclear, and for this reason the data analysis described in this section has been pursued.

In examining the importance of forces resulting from the fluid pressure field at threshold, the analysis of the data has again been carried out both on a wave by wave basis and on the basis of an examination of instantaneous values of the relevant parameters at the initiation of sediment motion.

(i) Further results of the critical wave analysis

The aim in performing this analysis was to determine from the measured parameters whether any decisive difference could be found in the transition regions, between the waves which did and did not move sediment at each value of U_m . Before the measured pressure field was examined, consideration was given to the fluid acceleration. This was done on account of the presence in certain of the laboratory threshold formulae (Table 3) of the wave frequency, in additon to the velocity amplitude, indicating the possible importance of accelerative effects at threshold. In carrying out the analysis, it was assumed that the behaviour of the velocity field in individual wave half cycles in the transition range was approximately sinusoidal, and that a measure of acceleration in a particular wave half cycle could thus be obtained by noting the interval between zero crossing values of velocity. The purpose of proceeding in this way was to see whether the waves in the transition ranges which moved sediment were, on an overall basis, those which displayed shorter periods (and, therefore, greater accelerations) between zero crossings at each value of U_m . It was not possible to seek directly peak values of acceleration itself during half cycles defined by zero-crossing times of measured velocity, due to the quadrature phase relationship between these quantities.

The results of the investigation are shown in Fig 11, in which average values of the interval are plotted against U_m for the rippled bed data in the second experiment. It can be seen that there was no systematic difference of the type sought, the waves moving sediment in the transition regions having a similar interval between zero-crossings to the assembly of all waves in the record. In other words, the examination of the transition regions has revealed that, at a particular U_m , the mean period of the waves causing sediment motion was not significantly different from that of the waves which did not cause motion. In addition, Figure 11 shows that the waves in the transition regions had a half-period of approximately $4\frac{1}{2}$ seconds, or period of 9 seconds.

As argued above, a direct examination of the peak acceleration in each wave half cycle was not possible on account of the phase relationship between u and $\partial u/\partial t$. Clearly, the same phase relationship exists between u , the horizontal velocity measured in the free-stream flow, and $\partial p/\partial x$, the spatial pressure gradient in the direction of wave advance, since, in a frictionless zone and on a linearized analysis, the fluid acceleration is proportional to the pressure gradient. This was approximately so in the field, as can be seen in the typical scatter plot shown in Figure 12. The 3000 points plotted are pairs of digitized values of $\partial u/\partial t$ and $\partial p/\partial x$ from a 10 minute period during the second experiment. Although a general linear relationship is clear in these results, there was thought to be sufficient scatter about the mean line to justify an examination similar to the one described above, but now taking the peak pressure in each wave half cycle instead of the period between zero crossings of u . This was possible on account of the approximately in-phase behaviour of u and p , the waves measured being predominantly of progressive wave type; the pressure was taken as the mean value $p = \frac{1}{2}(p_1 + p_2)$. Then, again at each U_m in the transition regions, the mean peak pressures of the waves which moved sediment were compared with peak pressures for the assembly of all waves in the record.

Figure 13 shows the results obtained for the rippled bed data in the second experiment. It is apparent that the waves which moved sediment were associated at certain values of U_m with higher than average peak pressures through the transition ranges in both shoreward and seaward directions. However, to argue from this that pressure gradients in wave half cycles associated with sediment motion were also generally greater than average, requires further assumptions; these relate both to the sinusoidal nature of individual wave half

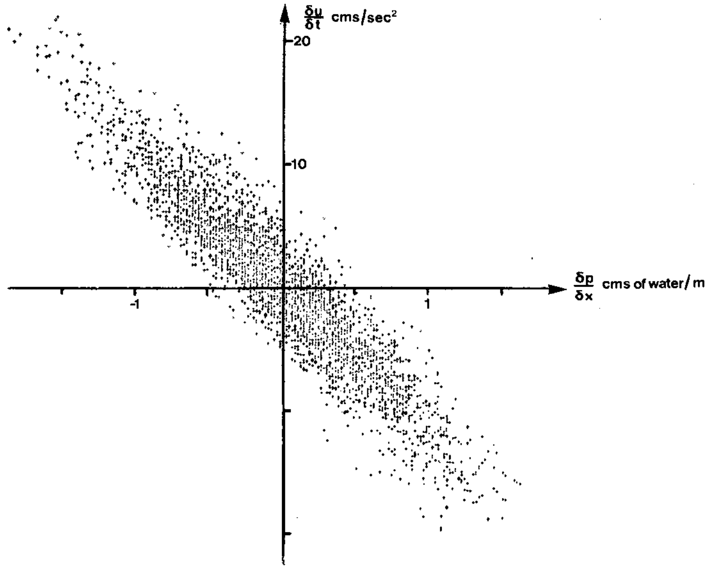

Fig.12 A SCATTER PLOT OF ACCELERATION AGAINST SPATIAL PRESSURE GRAOIENT (3000 values from a 10min run)

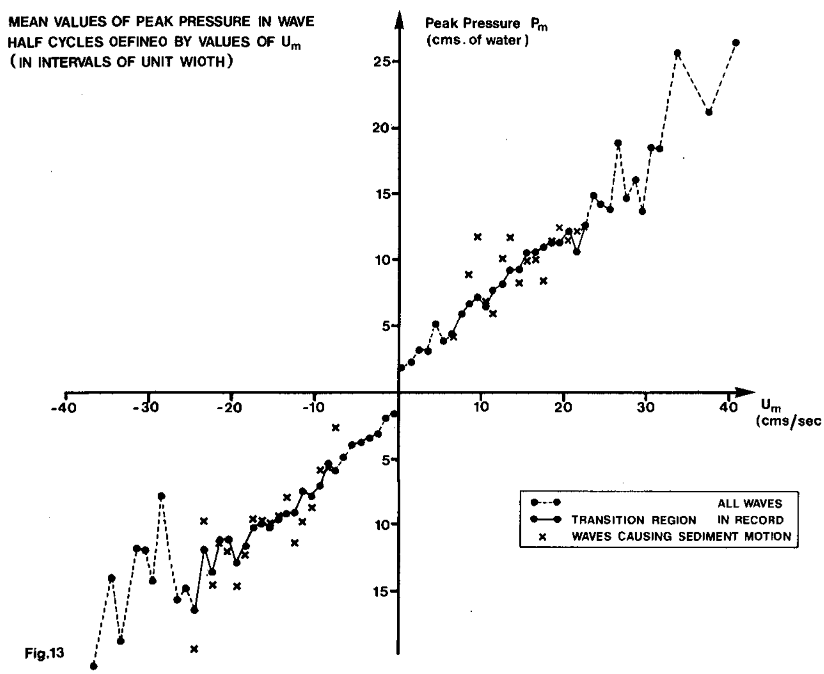

Fig.13

cycles, but more importantly to whether the flow can truly be regarded as two-dimensional. For it is possible that the degree of correlation between p and the total horizontal velocity may have been better than that between p and u ; no suitable experimental evidence was obtained to test this. Thus, on the basis of Figure 13, it cannot be shown that pressure gradients were a significant perturbing influence at threshold, and to resolve this area of ambiguity an analysis of the instantaneous sediment threshold data has been carried out.

(ii) Further results of the instantaneous threshold of motion study

Corresponding to the instantaneous threshold values of u_v , quoted in Table 2 for the case of the rippled bed in the second experiment, mean values of the pressure gradient $\partial p/\partial x \simeq (p_1 - p_2)/\Delta x$ were found to be -0.75 and +0.81 cms of water/metre, at the initiation of motion in the shoreward and seaward directions respectively; the standard deviations were 0.76 and 0.69 cms of water/metre respectively.

In order to assess the importance of pressure gradients at threshold, an attempt has been made to reduce the considerable amount of scatter in the critical values of u_v and $\partial p/\partial x$ on a systematic basis, by combining pairs of critical values to form empirical expressions for the total force on the bed surface, firstly of the type

$$F_1\Big|_r = C_1\, u_v\Big|_r + C_3\, \frac{\partial p}{\partial x}\Big|_r$$

and secondly,

$$F_2\Big|_r = C_2\, \{u_v|u_v|\}\Big|_r + C_3\, \frac{\partial p}{\partial x}\Big|_r$$

where the subscript r indicates the rth data value at threshold. The expressions relate to the cases of linear and quadratic velocity drag law behaviour respectively, and C_1 , C_2 and C_3 are appropriate force coefficients. The aim of this exercise was to determine whether the scatter in $F_{1,2}$ could be shown to be significantly smaller than the scatter in the critical values of $F_{1,2}$ with $C_3 = 0$, by adopting some optimum value of the ratio $C_1 : C_3$ or $C_2 : C_3$ respectively. The method used was a perturbation procedure to determine values of these ratios according to the criterion that the variance in $F_{1,2}$ over all r , should be minimized.

The investigation was carried out for the rippled bed data in the second experiment, over successive data collection periods of 10 minutes. Occurrences of motion in the shoreward and seaward directions were examined separately. The results showed that, although the variance in $F_{1,2}$ could be reduced substantially in almost all the data portions examined by a particular choice of the ratios $C_1 : C_3$ and $C_2 : C_3$ no systematic behaviour was evident in these ratios. In particular, the general trend in the results was for the minimization of variance to be accomplished by a pressure gradient force acting always in one direction regardless of the direction of grain motion. In other words, while the minimization of variance was of numerical significance, it had no physical significance. It is thought that this offers substantial evidence that the pressure gradients in the present problem were of no importance in mobilizing grains on the seabed, despite a weak suggestion in Section 6(ii) to the contrary.

7. Discussion and Conclusions

From the critical wave by wave analysis, two main conclusions have been drawn. Firstly, that for the real sand ripples in the present experiment there was an apparent doubling in the threshold velocity amplitude (measured in the free stream) for sediment motion on a flat bed compared with motion on the crest of a sand ripple. However, a quantitative explanation for this has been obtained from a model of the potential flow over real sand ripple shapes.

Secondly, there was not found to be just one value of velocity amplitude associated with the initiation of grain motion; rather, a wide (transition) range of velocity amplitude values has been identified in which only a fraction of the measured waves moved sediment. Sedimentological considerations, the somewhat subjective nature of the sediment threshold analysis and possible effects of three-dimensionality in the flow, have been proposed as factors of secondary importance in the problem which may go some way towards explaining the presence of the transition regions. Accelerative effects in the flow do not appear to provide an explanation. However more recent work has suggested that a significant narrowing of the transition regions can be accomplished by working a critical wave by wave analysis in terms of bottom stresses at threshold, rather than velocity amplitudes measured in the free stream flow. Despite the improvement in an understanding of the phenomenon which can be achieved in this way, it is thought encouraging that the measured critical velocity amplitude values in the present experiment (when the bed was flattened, or when allowance was made for the effect of ripples) were in reasonable agreement with various well known laboratory threshold results.

The instantaneous threshold of motion study has been used to isolate the critical instants in time at which sediment motion started or stopped, with a view to understanding in more detail the processes at work at the initiation of sediment motion. The study conducted on the importance as a perturbing influence at threshold, of pressure gradients in the flow, has led to the conclusion that pressure induced forces on the surface grains on the bed are of little or no importance in the transport of coarse sands by swell waves. The same may not be true during and after the breaking of waves, where the pressure gradients are much higher at certain instants in each wave cycle. However, outside the breaker zone, it appears that sediment movement by waves is capable of explanation in terms of the near-bed velocity field alone.

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